GEOSYNCHRONOUS SAR IMAGE FORMATION BASED ON ADVANCED HYPERBOLIC RANGE EQUATION

Xiu Wu[1], *Shunsheng Zhang*[1,2], *Jing Li*[1], *Wenchen Cao*[1]

[1]University of Electronic Science and Technology of China,
Research Institute of Electronic Science and Technology, Chengdu 611731, China
[2]Key Laboratory of Integrated Electronic System, Ministry of Education
E-mail:xiuwu11@163.com

ABSTRACT

Based on an advanced hyperbolic range equation (AHRE), this study presents an advanced Range Doppler (RD) algorithm for Synthetic aperture radar on geosynchronous satellites (GEO SAR) cases. Since the orbit altitude reaches up to about 36,000 km in GEO SAR, the integration time becomes longer and curved flight path is generated accordingly. Thus, the AHRE is introduced in this paper, which can compensate the error of the conventional hyperbolic range equation (CHRE) in GEO SAR. Then, the two dimensional (2-D) frequency spectrum (PTFS) expression of a point target is obtained by the method of series reversion (MSR). Finally the advanced RD algorithm based on the new spectrum is proposed. Point target simulation results show that the presented algorithm obtains fine performance in GEO SAR cases.

***Index Terms*—** synthetic aperture radar on geosynchronous satellites (GEO SAR), an advanced hyperbolic range equation (AHRE), advanced Doppler-Range (RD) algorithm.

1. INTRODUCTION

Synthetic aperture radar on geosynchronous satellite (GEO SAR) is an innovative SAR system in remote sensing field [1]-[2]. It has significant potential advantages over conventional low-Earth orbit (LEO) radar, such as, frequent revisit cycles for interesting place, extra long observing time and very large coverage area [3]. However, the system also comprises some inherent challenges. The complicated geometric structure and relative motion are quite different from straight line required by SAR, and the influence of yaw due to the Earth's rotation is no longer negligible.

In order to enjoy the expected benefits of GEO SAR system, the problems mentioned above should be solved. Firstly, an advanced hyperbolic range equation (AHRE) is introduced in this paper, which is formed by the conventional hyperbolic range equation (CHRE) plus a additional linear component [4]. Most formulations of a point target signal processing in LEO SAR are based on the CHRE that is derived from straight path geometric structure. For short integration time cases, it is sufficient. In GEO SAR, However, as the satellite resides in geosynchronous orbit and the integration time becomes very long, the phase error of CHRE becomes more and more obvious. The straight path had better be replaced by the curved one. In other words, the AHRE changes straight path of the CHRE into a curved one and improves the precision of the actual GEO SAR path approximation.

Furthermore, many algorithms are available in LEO SAR, including the familiar Range Doppler algorithm (RDA), the chirp scaling algorithm (CSA), the range migration algorithm (RMA) as well as various extended algorithms. However, these algorithms are not proper in processing the GEO SAR imaging directly. For example, the conventional RD algorithm depends on two necessary conditions [5], which become invalid as the altitude increases and the swath extends in the GEO cases. Hence, the advanced RD algorithm will be proposed based on the AHRE in this study.

This paper is structured as follows. In Section 2, the AHRE is introduced for GEO SAR signal processing briefly. Furthermore, using the method of series reversion (MSR) [6], two dimensional (2-D) frequency spectrum expression of a point target (PTFS) is derived based on AHRE. In Section 3, the advanced RD algorithm and phase functions are deduced in detail. In Section 4, the simulation results are shown to validate correctness of AHRE and the efficient of the advanced RD algorithm in GEO SAR. Finally, the conclusion is drawn in Section 5.

2. SIGNAL MODEL FOR GEO SAR

2.1. Advanced Hyperbolic Range Equation (AHRE)

The geometrical configuration of the radar flight trajectory in geosynchronous SAR is illustrated in Fig.1, where the satellite moves along the black solid line, the straight path of CHRE is represented by red dashed line and the curved path

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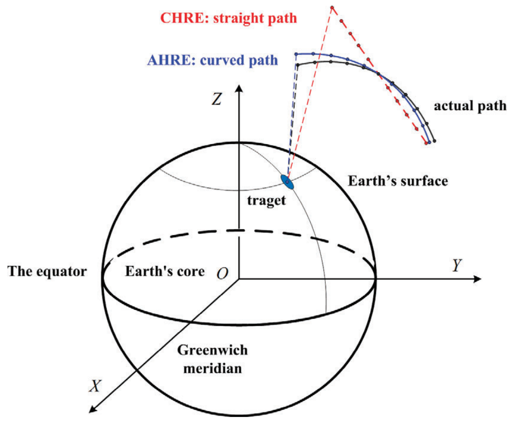


Fig. 1. The geometrical configuration of flight trajectory in GEO SAR

of AHRE is depicted by the blue solid line, respectively; and the sampling positions are represented by dots.

In general case, the range history equation is established based on the straight path of spaceborne SAR geometry. It can be described as two essential factors: the equivalent radar velocity to the scaling effect caused by orbit curvature and the equivalent squint angle to the Doppler centroid frequency caused by Earth rotation [5]. Nevertheless, for the long integration time and high orbit altitude in GEO SAR, the straight path approximation is not adequate. A new range history equation based on the curved path approximation need to be formed, as vividly illustrated in Fig.1. So an additional linear component is introduced into the CHRE to change the straight path into a curved one. It is so called the AHRE, which can be written as

$$R(\eta) = \sqrt{R_0^2 + V_r^2\eta^2 - 2R_0 V_r \sin\theta_{sq}\eta} + \delta\eta \tag{1}$$

where η is the azimuth time, R_0 is the slant range of the beam center crossing time, V_r is the equivalent radar velocity, θ_{sq} is the equivalent squint angle, and δ is an additional linear coefficient, which can be considered as a curved factor.

The linear coefficient in the equation (1) can be estimated by Doppler parameters around beam center crossing time $\eta = 0$, viz., center frequency, Doppler chirp rate, and the rate of Doppler chirp rate. The operation of them by means of vector analysis is detailed in [7]-[8].

2.2. Point Target Spectrum Based on AHRE

The 2-D spectrum of GEO SAR based on AHRE will be detailed in this section. In order to develop efficient processing algorithms such as the advanced RD algorithm, the principle of stationary phase (PSP) and the method of series reversion (MSR) will be introduced to derive the expression of point target spectrum.

After demodulated to baseband, the received signal in 2-D time domain is expressed as

$$\begin{aligned} S_0(\tau,\eta) = {} & w_r\left[\tau - \frac{2R(\eta)}{c}\right]\exp\left\{j\pi k_r\left[\tau - \frac{2R(\eta)}{c}\right]^2\right\} \\ & \times w_a(\eta)\exp\left\{-j\frac{4\pi f_c R(\eta)}{c}\right\} \end{aligned} \tag{2}$$

where τ and η are range time and azimuth time, and c denotes the speed of light. The symbol f_c and k_r are the carrier frequency and FM rate respectively. The operator $w_r(\cdot)$ stands for the pulse envelope and $w_a(\cdot)$ is the antenna beam pattern in the azimuth direction and $R(\eta)$ is modeled by the AHRE.

Then the MSR and the PSP are employed to turn the signal from 2-D time domain to 2-D frequency domain, and the 2-D spectrum is obtained

$$S_2(f_\tau, f_\eta) = W_r(f_\tau)\, W_a(f_\eta - f_{dc})\exp\{j\phi(f_\tau, f_\eta)\} \tag{3}$$

where $W_r(\cdot)$ denotes the envelope of range spectrum, $W_a(\cdot)$ is the antenna beam pattern in the azimuth direction, and f_{dc} is the Doppler centroid frequency. The phase term in (3) is given by

$$\phi(f_\tau, f_\eta) = -\pi\frac{{f_\tau}^2}{k_r} - \pi\frac{4(f_c + f_\tau)R(\eta^*)}{c} - 2\pi f_\eta \eta^* \tag{4}$$

where η^* is the stationary point, as given by

$$\begin{aligned} \eta^*(f_\tau, f_\eta) = {} & \frac{1}{2k_2}\left[\frac{-cf_\eta}{2(f_c+f_\tau)} - k_1\right] \\ & - \frac{3k_3}{8k_2^3}\left[\frac{-cf_\eta}{2(f_c+f_\tau)} - k_1\right]^2 \\ & + \frac{9k_3^2 - 4k_2k_4}{16{k_2}^5}\left[\frac{-cf_\eta}{2(f_c+f_\tau)} - k_1\right]^3 \end{aligned} \tag{5}$$

where k-coefficients are the coefficients of AHRE by Taylor series expansion respectively. For simplicity, equation (5) is expanded in a power series of f_τ for development of processing algorithms. In order to avoid significant deterioration of the image performance, the uncompensated phase error is within 0.25π. Then the terms are approximated up to the third order as follow

$$\begin{aligned} \phi(f_\tau, f_\eta) = {} & \phi_0(f_\eta, R_0) + \phi_1(f_\eta, R_0) f_\tau \\ & + \phi_2(f_\eta, R_0) f_\tau^2 + \phi_3(f_\eta, R_0) f_\tau^3 \end{aligned} \tag{6}$$

Each term of phase history in equation (6) can be interpreted and discussed in the following list.

- The first part $\phi_0(f_\eta, R_0)$, solely dependent on f_η, which consists of the azimuth modulation and the residual.

- The second term $\phi_1(f_\eta, R_0)$ a linear phase with f_τ, dependent both on f_τ and f_η, which represents of the cross coupling between the range and the azimuth, i.e., the range cell migration (RCM).

- The coefficient $\phi_2(f_\eta, R_0)$ is the quadratic phase term in f_τ, which indicates the range modulation.

- The last term $\phi_3(f_\eta, R_0)$ is the third order coefficient, which becomes significant and should be considered in the GEO cases.

3. ADVANCED RD ALGORITHM FOR GEO SAR

The range cell migration correction (RCMC) only considers the linear term in f_τ of phase in conventional RD algorithm. In GEO SAR, however, the RCM becomes significant because of the unique geometry. Therefore, the conventional RD algorithm is collapsed and the advanced RD algorithm, based on the 2-D spectrum mentioned above, will be put forward. The block diagram of the algorithm is shown in Fig.2.

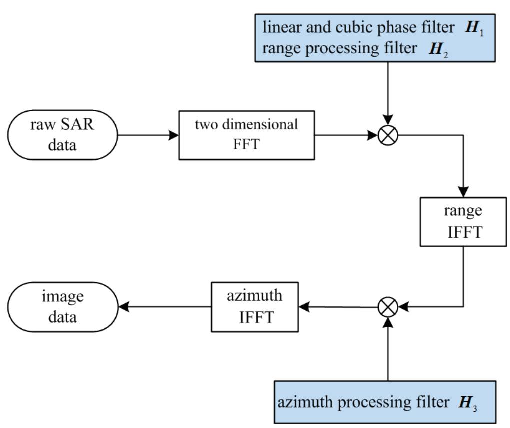


Fig. 2. Block diagram of the advanced RD algorithm

The operating steps of the advanced algorithm are shown as

(a) After it is demodulated to the baseband, the received point target signal in the 2-D time domain is transformed into 2-D frequency domain by fast Fourier transform (FFT).

(b) Using linear and cubic phase filter function $H_1(f_\tau, f_\eta)$ and range processing filter $H_2(f_\tau, f_\eta)$, the range matched filtering and coupling terms correction can be implemented in the 2-D frequency domain, respectively. The filter function are given by

$$H_1 = \exp\{-j\phi_1(f_\eta, R_0)f_\tau\}\exp\{-j\phi_3(f_\eta, R_0)f_\tau^3\} \tag{7}$$

$$H_2 = \exp\{-j\phi_2(f_\eta, R_0)f_\tau^2\} \tag{8}$$

(c) After range compression, the inverse fast Fourier transform (IFFT) turn the 2-D data to range time domain and azimuth frequency domain. The azimuth compression can be implemented by the azimuth matched filtering function given by

$$H_3 = \exp\{-j\phi_0(f_\eta, R_0)\} \tag{9}$$

(d) Finally, an azimuth IFFT is applied and a well point target imaging is generated.

4. SIMULATION RESULTS

To verify the correctness and effectiveness of advanced RD algorithm based on AHRE for GEO SAR, the simulation results are illustrated in this section. The system parameters are listed in Table I.

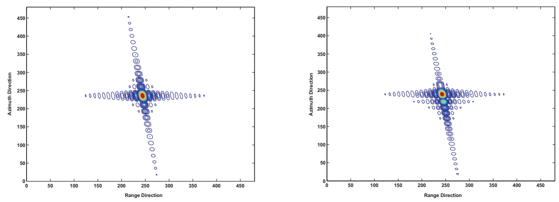
Table 1. GEO SAR SYSTEM PARAMETERS

Specifications	**Value**
Orbit height	36,000 km
Orbit inclination	60 degrees
Transmitted bandwidth	18 MHz
Pulse width	20 μs
Range sampling rate	22 MHz
Wavelength	0.024 m
Pulse repetition frequency	220 Hz
Synthetic aperture time	46 s
Off-nadir angle	4.65 degrees

The performance of a given range equation is mainly determined by the azimuth phase error. In general, the uncompensated azimuth phase error is within 0.25π rad. The maximum phase error of the point target is almost 10^{-2} rad based on the AHRE when the integration time is about 60 seconds. It is smaller than the threshold value of 0.25π rad. Thus, the AHRE can better fit GEO SAR signal processing.

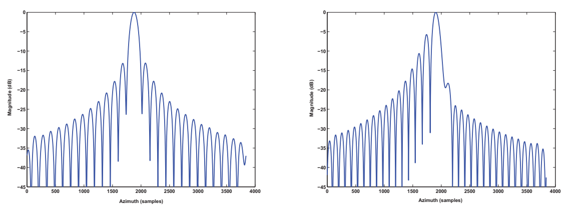
Fig.3 shows the contour plots of one target based on the advanced RD algorithm and conventional RD algorithm, respectively. As can be seen from it, the focusing performance of the AHRE-based advanced RD algorithm is better than the traditional one. The magnitude of the azimuth and range profile of the processed image of the point target are shown in

Fig.4 and Fig.5. The performance of conventional RD algorithm is not as well as the advanced one. The image qualities are measured and compared in Table 2. It can be seen that they are all close to the ideal values.



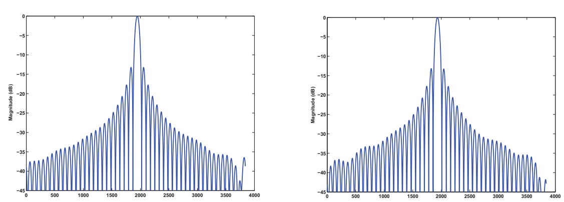
(a) (b)

Fig. 3. (a) Contour plots of compressed one target by advanced RD algorithm. (b)Contour plots of compressed one target by conventional RD algorithm.



(a) (b)

Fig. 4. The azimuth profile of point target imaging. (a) The AHRE-based advanced RD algorithm. (b) The CHRE-based conventional RD algorithm.



(a) (b)

Fig. 5. The range profile of point target imaging. (a) The AHRE-based advanced RD algorithm. (b) The CHRE-based conventional RD algorithm.

5. CONCLUSIONS

This paper presents a modified RD algorithm based on the AHRE for GEO SAR cases. Since the unique geometry and relative motion are quite different from straight line required by SAR, the AHRE is introduced to take over the CHRE in GEO SAR. In other words, the AHRE can change the straight path of the CHRE into a curved one and fit the actual GEO SAR path better. Besides, the new point target spectrum based on the AHRE is obtained by MSR, which develop efficient modified RD algorithm. The simulation results demonstrate that the advanced algorithm can achieve better focusing performance.

Table 2. IMAGE QUALITIES

RD algorithm	range		azimuth	
	PSLR	ISLR	PSLR	ISLR
AHRE-based	-13.21	-9.84	-13.09	-9.95
CHRE-based	-13.17	-9.83	-5.73	-5.42

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