IMPROVED SECONDARY RANGE COMPRESSION FOCUSING METHOD IN GEO SAR

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ABSTRACT

The paper firstly analyses the error caused by the linear trajectory model and the Fresnel approximation because of the long synthetic aperture time in Geosynchronous Synthetic Aperture Radar (GEO SAR), and then proposes an improved Secondary Range Compression (SRC) focusing algorithm to overcome the effect of linear trajectory model and the Fresnel approximation. The improved focusing algorithm adopts the curved trajectory model on basis of Norm operator to remove the error caused by the linear trajectory, derives and compensates the third order phase in two-dimensional frequency domain to overcome the large range migration. Finally, imaging results verify the improved focusing algorithm.

Index Terms— GEO, SAR, SRC, Linear trajectory, Fresnel approximation

1. INTRODUCTION

With the application development of synthetic aperture radar (SAR), low earth orbit (LEO) SAR becomes more and more difficult to meet the application requirement. Thus, geosynchronous synthetic aperture radar (GEO SAR) system was proposed by K.TomiyaSu in 1978 [1]. In 1983, K.TomiyaSu discussed the GEO SAR system in detail [2]. However, since imaging algorithms and the hardware technologies were immature at that time, the idea got into quiet for a long time. With the coming of the 21st century, the GEO SAR turns into a hot topic in accordance with the fast development of relevant technology and the maturity of LEO SAR imaging algorithms. The most representative organizations are Jet Propulsion Laboratory (JPL) and Cranfield University which both went deeply into studying the system [3]-[5]. The advantages of the GEO SAR are obvious, such as the huge coverage, the fine temporal sampling and the short interference period and so on. The above advantageous conditions make the tremendous potentiality of the GEO SAR in forecasting the earthquake and volcanoes, the hydrological cycle and monitoring vegetation changes etc [4][6]. However there is a fact which is not neglected with the increase of the satellite orbit height, namely that an atmosphere impact on the SAR focusing needs to be taken into consideration. Reference [7] and [8] analyzed the impacts on focusing from ionosphere and troposphere.

Imaging is an important aspect of GEO SAR. Reference [9], [10] and [11] studied imaging algorithms of GEO SAR, and reference [12] analyzed the resolution of GEO SAR, and reference [13] focused on the attitude control. According to the analysis of the above literatures, we can know many differences exist between LEO SAR and GEO SAR, such as the longer synthetic aperture time and the more complex attitude control in GEO SAR etc.; furthermore LEO SAR imaging algorithms cannot be directly used in GEO SAR. Therefore, the main emphasis of the paper is placed on the imaging algorithms at equator. A great error will appear if the classical imaging algorithms are used at equator; in addition, some factors that can be neglected in the classical imaging algorithms will not be neglected in GEO SAR. The paper modifies the secondary range compression (SRC) algorithm [14] which is popular in LEO SAR, and verifies the correctness of the improved SRC algorithm.

This paper is organized as follow. Section 2 presents and analyzes the problem which is caused by the linear trajectory model and the Fresnel approximation. Section 3 proposes the improved SRC. Section 4 presents the simulation results of the SRC algorithm proposed, and makes a comparison with the results of the classical SRC. Finally, the conclusion is drawn.

2. ANALYSIS OF THE LINEAR TRAJECTORY MODEL AND THE FRESNEL APPROXIMATION

Many algorithms are available in LEO SAR, including the familiar SRC [14], the chirp scaling (CS) [15] algorithm, the range migration algorithm (RMA) [16] as well as various extended algorithms. Those algorithms are derived under some model assumption or mathematical approximation, such as the linear trajectory model and the Fresnel approximation.

The trajectory of the satellite in LEO is considered as the rectangular line (red line in Figure 1). This consideration is proper in processing the LEO SAR imaging, but the situation is of difference when it comes to GEO SAR due to thousands of kilometers of synthetic aperture length, for example, the error caused by the linear trajectory at the center of the scene at equator is up to 0.16 meter...
(wavelength order). The simulated results of error caused by
the linear trajectory model and the Fresnel approximation are
shown in Figure 2. The parameters of the satellite orbit are:
the orbit inclination 53 degrees, the argument of perigee 270
degrees, and the right of ascend nod 265 degrees.

![Figure 1. The geometrical configuration of the linear trajectory and
the curved trajectory](image)

![Figure 2. The error of models at the center of scene at equator](image)

According to Figure 2, we can find that the model error
cannot be neglected. For this reason, the error must be
removed and some filtering functions need to be modified.
This paper modifies the SRC algorithm and validates the
improved SRC by the simulation results. The main
processing method is as follow. Firstly, the error caused by
the linear trajectory model will be compensated before the
beginning of the SRC algorithm, and the error compensation
function is processed in the range-Doppler domain. Secondly,
because of the effect of earth rotation and long
synthetic aperture time, we find that the range migration
is so large that the high order phase neglected in LEO SAR
imaging must be considered in GEO SAR. Furthermore, the
high order phase error and range migration correction will be
detailedly analyzed and compensated in two-dimensional
frequency domain.

3. IMPROVED SRC ALGORITHMS

According to Figure 1, the curved trajectory can be
expressed via Norm operator, namely $R_0(\eta) = \|\vec{R}_m - \vec{R}_m\|$
where $R_0(\eta)$ represents the range history, $\vec{R}_m$, $\vec{R}_m$
respectively represent the positions of satellite and the
target, and $\eta$ denotes the azimuth time. Based on the
geometry configuration of GEO SAR system, the echo can
be written as,

$$s(\eta,t) = \sigma \cdot a_\sigma(t) \cdot a(t-2 \cdot R_0(\eta)/c) \cdot \exp\left[ j \cdot \alpha \cdot \left( t - 2 \cdot R_0(\eta)/c \right) \right] \exp(-j \cdot 4 \cdot \pi \cdot R_0(\eta)/\lambda)$$

where $t$ is the range time, $\sigma$ stands for the backward
scattering coefficient, $a_\sigma(t)$ and $a(t)$ denote the envelope
functions of the azimuth and the range respectively. $\alpha$
denotes the range FM rate, $\lambda$ is the wavelength and $c$
is the speed of light.

The first step is the range Fourier transform, and the
range-frequency expression of echo can be given as

$$s(\eta,f) = \sigma \cdot a_\sigma(\eta) \cdot A(f) \cdot \exp(-j \cdot \pi \cdot f^2/\alpha) \cdot \exp\left[ -j \cdot 4 \cdot \pi \cdot R_0(\eta) \cdot (f + f_0)/c \right]$$

where $A(f)$ is the frequency expression of the range
envelope, $f_c$ is the range frequency and $f_0$ is the center
frequency of the transmitted pulse. Next, the range
compression will be implemented, and the reference function
can be written as

$$H_1 = \exp\left( j \cdot \pi \cdot f_c^2/\alpha \right)$$

The following processing of classical SRC algorithm is
to transform the echo of range compression into the two-
dimensional frequency domain, where the range $R_0(\eta)$ in (2)
is regarded as the linear trajectory, we have

$$R_0(\eta) = \sqrt{\vec{R}_m^2 + (V \cdot \eta)^2 - 2 \cdot \vec{R}_m \cdot V \cdot \eta \cdot \sin \theta}$$

where $V$ is the satellite velocity, $\theta$ is the squint angle,
and $\vec{R}_0$ is the range between the beam center and the central
target of scene. $V$, $\theta$ and $\vec{R}_0$ can be obtained via the curve
fitting, which can satisfy the focusing demand in LEO SAR.
while in GEO SAR, the error of curve fitting is very large,
especially at equator. Thus, we need to compensate a phase
to eliminate the effects of the curve fitting error before the
azimuth FFT, and the phase compensation function can be
written as

$$H_2 = \exp\left[ j \cdot 4 \cdot \pi \cdot (f + f_0) \cdot \Delta R_0/c \right]$$

where

$$\Delta R_0 = \|\vec{R}_m - \vec{R}_m\| - \sqrt{\vec{R}_m^2 + (V \cdot \eta)^2 - 2 \cdot \vec{R}_m \cdot V \cdot \eta \cdot \sin \theta}$$

here $\vec{R}_m$ denotes the target coordinate of the scene centre.

The next step is transforming the echo data into the
two-dimensional frequency domain, and then two-
dimensional spectrum is obtained. In consequence, the
range migration correction will be implemented and the third
order phase frequency neglected in LEO SAR imaging will
also be compensated. In addition, the SRC function can be expressed as
\[ H_1 = \exp \left( -j \cdot \pi \cdot \frac{f^2}{\alpha_{\text{src}}} \right) \] (6)
The range migration correction function can be shown as
\[ H_2 = \exp \left( j \cdot 4 \cdot \pi \cdot \frac{R_0}{c} \cdot a \left( f_0 \right) \cdot f_r \right) \] (7)
The third order phase compensation function can be written as
\[ H_3 = \exp \left( \frac{j \cdot \pi \cdot R_0 \cdot \cos \theta \cdot \lambda^4 \cdot \frac{f^2}{f_0^2}}{2 \cdot c^3 \cdot V^2 \cdot \left[ 1 - \left( \frac{\lambda \cdot f_r}{2 \cdot V} \right)^2 \right]^{2.5}} \right) \] (8)
where
\[ a(f_0) = \cos \theta \cdot \sqrt{1 - \left( \frac{\lambda \cdot f_r}{2 \cdot V} \right)^2} - 1 \]
\[ \alpha_{\text{src}} = 2 \cdot V^2 \cdot c^2 \cdot \frac{\lambda^6 \cdot f_r^2}{R_0 \cdot \cos \theta \cdot \lambda^4 \cdot f_0^2} \]
here \( f_0 \) denotes the azimuth time.

The last step is the azimuth matching filtering which will be carried out in the Range-Doppler domain, and the azimuth reference function can be written as
\[ H_4 = \exp \left( j \cdot 4 \cdot \pi \cdot \frac{R_0}{c} \cdot \lambda \cdot \frac{f_0}{2 \cdot V} \right) \] (9)
A fine focusing can be achieved after the azimuth IFFT. The basic processing flow-chart is shown in Figure 3.

Figure 3. Flow-chart of the improved SRC algorithm

4. SIMULATION RESULTS

The simulated parameters are as follow: the radar wavelength is 0.09375m, the bandwidth is 10MHz, the transmitted pulse width is 20 \( \mu \)s, the pulse repeat frequency is 100MHz and the sampling frequency is 12MHz. The imaging scene size is 5 kilometers \( \times \) 5 kilometers shown in Figure 4; nine targets are uniformly distributed into the scene in range direction and azimuth direction. Synthetic aperture time is assumed to be 40 seconds. Figure 5 compares the contour of the classical SRC algorithm with that of the improved SRC algorithm. It's quite obvious that the asymmetry side-lobes appear in both the range direction and the azimuth direction in Figure 5-a, where the range profile and the azimuth profile are respectively shown in Figure 6-a and Figure 6-b. Compared with the asymmetric side-lobes of the classical SRC algorithm, the symmetric side-lobes of the improved SRC algorithm are presented in Figure 5-b. Figure 6-c and Figure 6-d are the range profiles and the azimuth profiles. Peak side-lobe ratio (PSLR) and integrated side-lobe ratio (ISLR) results are listed in TABLE 1. By these simulated results, we can find that the improved SRC algorithm can achieve the focusing requirement, while the classical SRC algorithm can't meet the focusing requirement in GEO SAR.
The improvement of imaging results obtained by the proposed SRC algorithm is apparent compared with the imaging results obtained by the classical SRC algorithm, furthermore the imaging scene reaches the 5 kilometers under 40 seconds synthetic aperture time. However, the imaging scene is still small in GEO SAR, and will decrease when the synthetic aperture time increases. Thus, the imaging algorithm used for large scene is the main research work in future.

5. CONCLUSION

The paper analyses the error caused by the linear trajectory model and the Fresnel approximation, and it is found that the third order phase error can reach up to 0.7 rad under the 40 seconds synthetic aperture time, which results in the asymmetrical side lobes and thus it is necessary to be compensated. The paper proposes an improved SRC algorithm to overcome the curved trajectory, and verifies the correctness of improved algorithm as well via the simulation results. As an excellent imaging algorithm to deal with the range-variance, CS algorithm has been widely applied in LEO SAR. Via combining the method proposed by the paper, CS algorithm may solve the imaging for large scene under the long synthetic aperture time. Therefore, CS algorithm need to be further studied.

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7. REFERENCES


