Analysis of Ionospheric Disturbance on X-band SAR Image Registration

Huixiang Liu¹, *, Yang Liu², Peili Xi², Jie Chen¹, Wei Yang¹ and Hongcheng Zeng¹

¹School of Electronic Information Engineering, Beihang University, Beijing, China
²Shanghai Institute of Satellite Engineering, Shanghai 201109, Shanghai, China

*Corresponding author e-mail: qianywq055@nbt.edu.cn

Abstract. The atmosphere is a very important factor that affects the accuracy of X-band SAR image registration, and the ionosphere effect has the most intricate influence. In response to this problem, this paper introduces the mathematical model of ionospheric dispersion effect and scintillation effect. Then, echo simulation, imaging processing, and image registration are used to calculate the image offset caused by the ionosphere, which can determine whether the ionosphere effect needs to be compensated during image registration. Simulation experimental results show that in the X-band image registration, the dispersion effect needs to be compensated, and the impact of the scintillation effect can be ignored.

1. Introduction
Electromagnetic waves propagate using the atmosphere as a medium, and their echoes will be affected by the atmosphere [1], resulting in a decrease in the quality of images obtained by Synthetic Aperture Radar (SAR) imaging. In image interference processing, image registration is a very critical step for the success of subsequent processing. The degradation of SAR image quality caused by atmospheric influence will directly affect the accuracy of image registration. Therefore, it is necessary to analyze the influence of the atmosphere on the image registration. The atmospheric environment is complex and changeable. The ionosphere contains a large number of charged particles and has the most complex impact on electromagnetic waves [2]. In order to improve the accuracy of image registration, it is necessary to model the impact of the ionosphere and quantitatively analyze the effect of the ionosphere on SAR images. The second section of this paper introduces the ionospheric dispersion effect and scintillation effect models. Then, the third section analyzes the image registration method and simulation data analysis and the fourth section summarizes the conclusions.

2. Ionospheric model
When electromagnetic wave signals propagate in the ionosphere, the ionosphere will have various effects on signal propagation, such as dispersion effects, scintillation effects, etc[3]. These phenomena seriously affect the amplitude, phase, and polarization state of the received signal, resulting in degradation of image quality. The following mainly introduces the dispersion effect model and scintillation effect model in the ionosphere.
2.1. Dispersion effect model

When the SAR signal passes through the ionosphere, the chromatic dispersion effect will cause the phase delay of the echo. Since the propagation path of the SAR signal is two-way, the two-way additional phase can be expressed as [4]:

$$\Delta \phi_{\text{iono}}(f_r) = -\frac{4\pi K \cdot \text{TEC}}{c(f_r + f_0)}$$

(1)

Where TEC is the total electron quantity and 1 TECU = $10^{16}$ electrons/m$^2$, $c$ is the speed of light in vacuum, $K = 40.28$, $f_0$ is the centre frequency, and $f_r$ is the range frequency.

Suppose that the signal received by the spaceborne SAR under ideal conditions is $S(f_r, t)$. Under the influence of the dispersion effect, the two-way additional phase given by equation (1) is added, and the signal under the influence of the ionosphere is:

$$S_{\text{iono}}(f_r, t) = S(f_r, t) \cdot \exp\left(j \Delta \phi_{\text{iono}}(f_r)\right)$$

(2)

Under the influence of the dispersion effect, the SAR range signal pulse will undergo changes in time delay and pulse width, resulting in a change in the signal modulation frequency, which in turn affects the range pulse compression, and image translation and defocusing. It can be seen from equation (1) that the dispersion effect is related to the signal carrier frequency and the size of the TEC. The lower the carrier frequency, the greater the TEC value, and the greater the SAR signal is affected by the dispersion effect. On the contrary, when the carrier frequency is higher, the influence of the dispersion effect on SAR imaging will be weakened.

2.2. Scintillation effect model

The structure of the ionosphere is very complex. There are both large-scale background ionosphere and small and medium-sized irregularities with scales ranging from meters to kilometers. Their random changes cause rapid temporal and spatial changes in signal amplitude and phase. That is, the random fluctuation of ionospheric electron density causes the scintillation effect, which is a complex random problem in nature, so only statistical methods can be used to describe the scintillation effect. The TEC power spectral density model is selected to describe the random fluctuation characteristics of irregular bodies [5][6].

$$\text{PSD}_{\text{TEC}}(k) = T'_{\text{TEC}} \cdot (\sqrt{k^2 + k'^2})^{-p}$$

(3)

Among them, $k$ represents the spatial wave number. $k_0 = \frac{2\pi}{l_0}$, $l_0$ indicates the outer dimension of the end flow of the irregular body. $p$ is the power spectrum index. $T'_{\text{TEC}}$ is a constant proportional to the ionospheric disturbance, expressed as:

$$T'_{\text{TEC}} = G \cdot \sec \theta \cdot CkL \cdot T'_{\text{CIL}}$$

(4)

Among them, $G$ is the geometric constant, $\theta$ is the radar viewing angle, and $CkL$ represents the intensity of ionospheric disturbance at the scale of 1 km, $T'_{\text{CIL}}$ is expressed as [5]:

$$T'_{\text{CIL}} = \frac{\sqrt{\pi \Gamma(p/2)}}{(2\pi)^{3/2} \Gamma((p+1)/2)} \left(\frac{2\pi}{1000}\right)^{p+1}$$

(5)

Spaceborne SAR scintillation simulation uses a phase screen theoretical model. The signal passes through the phase screen twice to simulate the process of SAR signal passing through ionospheric
irregularities. Therefore, the irregular body introduces a high-order random phase factor to the azimuth signal, resulting in a mismatch during pulse compression, resulting in defocusing of the azimuth signal.

3. X-band simulation results under the influence of the ionosphere

In this paper, the influence of ionosphere is added to the echo simulation, and then SAR imaging is carried out. Finally, the influence of ionosphere on the accuracy of image registration is verified. First, the spatial geometric relationship is constructed according to the input satellite orbit parameters and scene parameters, and the X-band load signal is generated for echo simulation to obtain the original echo data. Then add the dispersion effect to the frequency domain of the range, and add the scintillation effect to the frequency domain of the azimuth to obtain the echo signal affected by the ionosphere, and then use the chirp scaling algorithm to perform imaging processing, and finally perform image registration. The specific flow chart is shown in Figure 1:

![Simulation flow chart with ionospheric influence.](image)

Among them, image registration is mainly divided into rough registration and precise registration. Rough registration uses fast Fourier transform to calculate the cross-power spectrum between images to find the best position and perform pixel-level registration. Precise registration, as a key step of SAR image correlation registration, mainly includes the steps of precise image registration based on real coherence function and calculation of image offset[7]. The minimum accuracy requirement for image registration is 0.1 pixels. The main flow chart of image registration is shown in Figure 2:
Set a 5×5 point targets for simulation (100m between points), and the parameters of echo simulation are set as follows:

| Carrier frequency | Bandwidth  | Imaging mode | Resolution | Antenna angle | Pulse repetition frequency |
|-------------------|------------|--------------|------------|---------------|----------------------------|
| 9.6GHz            | 100MHz     | Stripe       | 3m         | 30°           | 3200Hz                     |

The image result of the 5×5 point targets is as follows:

![Point targets result](image)

Change the parameters of the ionospheric model (select the total electron amount as the independent variable in the dispersion effect, and select the intensity of the irregular body as the independent variable in the scintillation effect) to obtain the lattice imaging results under different conditions, and perform image registration to analyze the image deviation Shift, the following are the results of image shift under the influence of dispersion effect and scintillation effect.
3.1.  X-band simulation results obtained under the influence of dispersion effect

**Table 2. Simulation parameters (dispersion effect).**

| Carrier frequency | Bandwidth  | Pulse repetition frequency | Total electron quantity |
|-------------------|------------|---------------------------|-------------------------|
| 9.6GHz            | 100MHz     | 3200Hz                    | 0~100TECU               |

Different Point targets results are obtained by changing the total electron amount, and the image registration offset obtained by image registration with the total electron amount as follows:

![Figure 4. Change curve of image offset with TEC.](image)

3.2.  X-band simulation results obtained under the influence of scintillation effect

**Table 3. Simulation parameters (scintillation effect).**

| Carrier frequency | Bandwidth  | Pulse repetition frequency | Irregular body strength |
|-------------------|------------|---------------------------|-------------------------|
| 9.6GHz            | 100MHz     | 3200Hz                    | $10^{32}$~$10^{34}$    |

The simulation analysis shows that the image offset varies with the intensity of the irregular body in the image registration as follows:

![Figure 5. Change curve of image offset with CkL.](image)
4. Conclusion
Based on the X-band simulation analysis in Figure 4 and Figure 5, it is shown that the dispersion effect will cause a decrease in the accuracy of the image registration in the range direction, and the larger the TEC, the lower the accuracy of the registration. Normally, the minimum registration accuracy requirement of image registration is 0.1 pixels. Therefore, the dispersion effect must be compensated if the TEC is bigger than 25 TECU. The scintillation effect will cause a decline in the registration accuracy of the image in the azimuth direction, but the image offset is within 0.1 pixels, and the impact can be ignored.

Acknowledgments
This work was supported by Shanghai Aerospace Science and Technology Innovation Fund SAST2019-030.

References
[1] Quegan S., Lamont J. Ionospheric and tropospheric effects on synthetic aperture radar performance[J]. International Journal of Remote Sensing, 1986, 7(4):525-539.
[2] Xu X. J., Huang P. K. Radar system and its information processing[M]. Beijing: Publishing House of Electronics Industry, 2010.
[3] Ishimaru A. Ionospheric effects on synthetic aperture radar at 100 MHz to 2 GHz[J]. RadioScience, 1999, 34(1):257-268.
[4] Budden G. S. The propagation of radio wave: the theory of radio waves of low power in the ionosphere and magnetosphere [M]. Cambridge University Press, 1985.
[5] Rino C. L. On the application of phase screen models to the interpretation of ionospheric scintillation data[J]. Radio Science, 1982, 17(4):855-867.
[6] Zhao W. L., Liang D. N., Zhou Z. M. Analysis of distance and direction deflection caused by ionospheric refraction[J]. Chinese Journal of Radio Science, 2001, 16(1):85-88.
[7] Brown L G. A Survey of Image Registration Techniques[J]. ACM Computing Surveys, 1992, 24(4):326-376.