Study on Pointing Accuracy Effect on Image Quality of Spaceborne Video SAR

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Abstract. Effect of satellite pointing accuracy on spaceborne video SAR imaging quality has been studied in this paper to solve the problem of indicators decomposition. First, the effect model of pointing error on the single frame image quality was established based on the rough and precise imaging. Then the relationship between the stability of Video SAR and pointing accuracy error has been analysed. Finally, the simulations prove the validity of the analysis. The analysis and the simulation results show that the attitude pointing error mainly affects the resolution, sidelobe ratio, ambiguity and radiation performance. For the video mode, the shift and rotation of the beam covering area were caused by the attitude pointing error. The result of the report can be used to distribute the system error and establish the index system.

1. Introduction
Spaceborne video SAR system is a new kind of spaceborne microwave remote sensing system, which upgrades the static remote sensing of traditional SAR satellites. The SAR image stream of observation scene is acquired by rapid imaging in a short time. The time dimension of information acquisition is effectively expanded on the basis of traditional imaging, and the spaceborne SAR is transformed from the traditional "photo" type. Static remote sensing is changing to a new type of "video" dynamic remote sensing. Video-based microwave remote sensing system has stronger dynamic information acquisition ability, and is more suitable for the observation of moving targets and time-varying scenes[1-3].

Compared with optical video satellites and ordinary spaceborne SAR system, video SAR has its unique application advantages. Compared with optical video satellites, spaceborne video SAR has the characteristics of all-day and all-weather observation ability, and the imaging resolution is not limited by the orbit height in principle. Compared with traditional spaceborne SAR system, spaceborne video SAR has developed from traditional two-dimensional imaging to three-dimensional imaging with time-dimensional information. Therefore, spaceborne video SAR has a broad application prospect in the fields of moving target detection, motion parameter estimation, imaging and tracking, and time-varying scene monitoring.

Attitude error is one of the key factors affecting the imaging quality of spaceborne video SAR. It is of great theoretical and engineering significance to study the quantitative relationship between attitude error and the imaging quality of spaceborne video SAR. In the published data, only the influence of attitude error on image quality is analyzed, but the quantitative relationship between attitude error and image quality is not established yet. This will lead to insufficient decomposition of some indexes in engineering applications and increase the difficulty of system implementation.
In this paper, a complete analysis system of the effect of attitude errors on the imaging quality of spaceborne video SAR imaging mode is established. From the angle of coarse imaging and fine imaging, the influence of attitude pointing error on the imaging quality of a single video frame is analyzed, and the quantitative correlation between the two kinds of errors and the corresponding imaging quality indexes is established. At the same time, the relationship between the two kinds of errors and the stability of video imaging and the size of imaging area is studied. The research results and conclusions can provide a basis for the overall design of spaceborne video SAR satellite and the error compensation and correction in the imaging process. It has important theoretical and engineering significance.

2. Influence of attitude pointing accuracy on imaging quality of single video frame

2.1. Quick look imaging

In the process of quick look imaging, azimuth matching filtering is performed by using Doppler parameters calculated from ephemeris data and radar parameters. In this case, beam pointing error is one of the main factors affecting the error of Doppler parameters. Therefore, the beam pointing error will affect the focusing performance of azimuth and lead to the azimuth offset and defocus.

In the process of quick look imaging, the effect of attitude error on SAR imaging quality is mainly reflected by the influence of Doppler characteristics. The Doppler center frequency in the application of spaceborne video SAR is

\[ f_{DC} = - \frac{2}{R \lambda} (V_i - V_s) \cdot (\mathbf{R}_s - \mathbf{R}_e) - \frac{2}{R \lambda} R^2 [V_i + (\mathbf{R}_s \times \omega_e)] \]  

(1)

Where \( V_i \) is the velocity of satellite, \( V_s \) is the velocity of the target scene with the rotation of the earth, \( \mathbf{R}_s \) is the vector of the satellite relative to the earth center, \( \mathbf{R}_e \) is the earth’s radius vector, \( \omega_e \) is the angular velocity of earth rotation, \( \lambda \) is the wavelength.

The Doppler frequency rate of the spaceborne video SAR can be expressed as

\[ f_{DR} = - \frac{2}{\lambda R} \left( \mathbf{A}_s \cdot (\mathbf{R}_s - \mathbf{R}_e) + V_i \cdot V_s + (\omega_e \times \mathbf{R}_s) \times (\omega_e \times \mathbf{R}_s) \right) \\
+ 2 \omega_e \cdot (V_i \times \mathbf{R}_s) \left( \frac{V_i \cdot (\mathbf{R}_s - \mathbf{R}_e) + \omega_e \times (\mathbf{R}_s \times \mathbf{R}_e)}{R^2} \right)^2 \]  

(2)

Where \( \mathbf{A}_s \) is the satellite acceleration vector. In the process of video imaging, the variation of yaw, roll and pitch angles of satellites are \( \psi(t) \), \( \phi(t) \) and \( \theta(t) \), if the attitude pointing error is \( \Delta \psi \), \( \Delta \phi \) and \( \Delta \theta \).

Assuming that the antenna is fixed to the satellite and is mounted along the Z axis, the actual pointing of the satellite antenna beam in a single video frame synthesis time is

\[ \mathbf{R}_b = \mathbf{R}_{ob} \cdot \mathbf{R}_b \]  

(3)

Where \( \mathbf{R}_b \) is the beam pointing vector in the orbit coordinate system, \( \mathbf{R}_{ob} \) is the installation vector of the antenna in the body coordinate system, \( \mathbf{R}_{ob} \) is the transformation matrix from the body coordinate system to the orbit coordinate system. It can be expressed as

\[
\mathbf{R}_{ob} = \begin{bmatrix}
\cos \theta & \cos \psi & -\cos \theta \sin \psi \\
\sin \phi \sin \theta \cos \psi + \cos \phi \sin \psi & -\sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi & -\sin \phi \cos \theta \\
-\cos \psi \cos \theta \sin \psi + \sin \phi \sin \psi & \cos \phi \sin \theta \sin \psi + \sin \phi \cos \psi & \cos \phi \cos \theta
\end{bmatrix}
\]  

(4)
\[
\begin{align*}
\psi' &= \psi(t) + \Delta \psi \\
\phi' &= \phi(t) + \Delta \phi \\
\theta &= \theta(t) + \Delta \theta
\end{align*}
\]

Where \(\phi' = \phi(t) + \Delta \phi\) is three axis attitude angle with attitude pointing error.

In the process of SAR imaging, the high resolution of azimuth direction is determined by the Doppler phase history. When the Doppler parameters have errors, it will lead to the mismatch of azimuth matched filter, then affect the focusing performance of azimuth direction and cause the degradation of image quality.

Assuming that there is a pointing error, the actual azimuth echo signal is

\[
S(t) = \exp \left\{ j [2\pi (f_{dc} + \Delta f_{dc}) t + \pi (f_{dr} + \Delta f_{dr}) t^2] \right\}
\]

(5)

Where \(f_{dc}\) and \(f_{dr}\) is the Doppler center frequency and Doppler frequency rate without pointing error, \(\Delta f_{dc}\) and \(\Delta f_{dr}\) is the Doppler center frequency and Doppler frequency rate error. Then the extension function of the point target is

\[
S_{out}(t) = S(t) * h(t)
\]

(6)

Where \(h(t) = S_{ht}(-t) = \exp \left\{ j [2\pi f_{dc} t - \pi f_{dr} t^2] \right\}\) is the matched filter, \(S_{ht}(t)\) is the azimuth echo signal without pointing error. Then \(S_{out}(t)\) can also be expressed as

\[
S_{out}(t) = \exp(j2\pi f_{dc} t) \exp(-j\pi f_{dr} t^2) \int_{-\infty}^{\infty} \exp(j2\pi f_{dr} (t + \frac{\Delta f_{dc}}{f_{dr}}) u) \exp(j\pi \Delta f_{dr} u^2) du
\]

(7)

From the above analytical expression, the target location error caused by the Doppler center frequency error is \(\Delta x = \frac{v_g \Delta f_{dc}}{f_{dr}}\), where \(v_g\) is the ground velocity.

**Figure 1.** Relationship between azimuth displacement and Doppler center frequency error

The relationship between azimuth displacement and Doppler center frequency error was shown in Figure 1. The Doppler center frequency error will lead to the point target to shift. Then the displacement is related to the error of Doppler center frequency. The larger the error, the greater the displacement.

The influence of Doppler center frequency error on point target spread function was shown in Figure 2. The Doppler center frequency error does not affect the focus effect of the point target, only affects the position of the target.
Figure 2. Influence of Doppler center frequency error on point target spread function

The influence of Doppler frequency rate error on point target spread function was shown in Figure 3. The errors of Doppler frequency rate mainly affect the secondary phase error, which will lead to the main lobe broadening, then the peak sidelobe ratio and the integral sidelobe ratio deteriorating. Figure 3 is the focusing result in azimuth direction when the errors of Doppler frequency rate are 2 Hz and 3 Hz, respectively. The discrimination rate gradually decreases and the side lobe increases, leading to the deterioration of the side lobe ratio performance.

Figure 3. Influence of Doppler frequency rate error on point target spread function

From the above analysis, it can be seen that in the application of quick look imaging, the attitude error has a great influence on the focusing performance of azimuth, so it is difficult to meet the accuracy requirement to directly apply the Doppler parameters obtained from ephemeris data, orbit and attitude parameters and radar parameters to the imaging, which requires corresponding compensation algorithm based on echo data to compensate for the deterioration of image quality caused by attitude error.

2.2. Precise imaging

In order to obtain better azimuth focusing performance, precise Doppler parameters must be used. The Doppler parameters of spaceborne video SAR can be obtained from orbit data, attitude data and radar parameters. However, due to the error of each parameter, the Doppler parameters obtained can’t meet the accuracy requirements. The Doppler center frequency and Doppler frequency rate can be estimated from the echo data.
(a) Doppler center frequency estimation

Because the sampling frequency of azimuth direction is PRF, the frequency of azimuth direction is periodic with pulse repetition frequency, it leads to the ambiguity of Doppler center frequency. The Doppler center frequency can be expressed as

$$f_{DC} = f'_{DC} + mPRF$$

(8)

Where $f'_{DC}$ is the Doppler center frequency base band center, $m$ is the fuzzy number, The estimation of Doppler center frequency includes the estimation of baseband center and the estimation of fuzzy number. The method of automatically determining Doppler center frequency is usually called clutter locking.

The estimation of baseband center by clutter locking mainly includes Doppler spectrum analysis, energy equalization, minimum mean square error estimation and time domain correlation. Doppler spectrum analysis uses the peak of Doppler spectrum to determine the Doppler center frequency. The estimation accuracy is limited. Square error estimation method and time-domain correlation method are both initial values of given Doppler center frequency. The objective function of estimation is given. The estimation accuracy is achieved by iterative processing according to the corresponding criteria. If the initial value of Doppler center frequency has a small error with the true value, the estimation efficiency can be improved and the high estimation accuracy can be achieved simultaneously.

(b) Doppler frequency rate estimation

Doppler frequency estimation is also called autofocus. Similarly, the Doppler frequency calculated by ephemeris data can’t meet the accuracy requirements in accurate imaging. It is necessary to estimate Doppler frequency rate by using echo data autofocus. Subaperture correlation method, phase gradient autofocus algorithm and optimal contrast method are commonly used in Doppler frequency rate estimation. Subaperture correlation method uses non-overlapping sub-aperture images for correlation processing, and estimates the error of Doppler frequency rate by estimating relative offset. The position of the correlation peak is relative offset. Then set certain step size to iterate until the threshold is met. Phase gradient autofocus algorithm does not assume the phase error polynomial. It can estimate the phase error of any order. The phase gradient is estimated by using the strong scattering points in the range direction after shifting and windowing, and then the phase error is estimated. After designing a certain error threshold, the phase compensation is realized by iterative processing. Contrast optimum method is a method of estimating Doppler frequency modulation error directly from SAR image. Firstly, the initial value of Doppler frequency is given for imaging, then the direction and step of Doppler frequency are set. After imaging, the contrast of the image is evaluated, and the change and step size are adjusted until the threshold of contrast is met.

3. Influence of attitude pointing accuracy on video imaging

3.1. Pointing accuracy of pitch and roll

In the process of video imaging, the staring of target scene is realized by three-axis attitude maneuver, and the staring of the center point in the beam-covered area can be realized by pitching and rolling attitude maneuver. Under the assumption that the satellite attitude pointing accuracy is a constant in the statistical sense, the attitude pointing accuracy of the satellite pitching and rolling will lead to waves. The movement of the center point of the beam coverage only affects the sensitivity and ambiguity of the single frame image, but does not affect the stability of the video image.

3.2. Pointing accuracy of yaw

The satellite can stare at the center of the scene by rolling and pitching attitude control during video imaging. If the yaw control is not carried out, the beam coverage area will rotate, resulting in incomplete resolution of the scene edge or the area of the observable area in video imaging. The mismatch between the beam coverage area and the scene is shown in Figure 4, in order to obtain the maximum observation range and stable video frame image, agile satellite yaw compensation is needed.
to realize the rotation-free control of the beam coverage area. If there is a small angle error of yaw angle, the rotation of the beam coverage area occurs relative to beam coverage area without pointing accuracy error.

![Figure 4. Influence of yaw attitude pointing error on beam coverage area](image)

4. Conclusion

In this paper, the effect of attitude pointing error on the imaging quality of video SAR is analyzed. First, the effect of attitude pointing error on the imaging quality of a single video frame is studied from two aspects of coarse and fine imaging. Then, the effect of attitude error on video imaging is researched. A complete attitude pointing error on imaging is established. The simulation results show that the attitude pointing accuracy directly affects the Doppler parameters and then the azimuth focusing performance of the coarse imaging. However, for the fine imaging, the Doppler parameter estimation method has been quite mature, and in principle, the Doppler parameter estimation method has been applied to the coarse imaging. Without considering the estimation efficiency, the azimuth focusing performance can lower the requirement of attitude pointing accuracy. The attitude pointing accuracy does not affect the continuity and stability of video SAR imaging, but only causes the overall shift and rotation of the beam coverage area, and leads to the degradation of single frame image quality in video SAR. The research results in this paper can provide theoretical support for error allocation and index system construction of video SAR satellite.

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