An In-Orbit Joint Calibration Scheme for Slant-Range of Space-Borne SAR

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Abstract. Slant-Range precision of the space-borne SAR is the one of most important factor for imaging quality, especially for geo-location and azimuth imaging quality. In this paper, In-Orbit joint calibration scheme is proposed and implemented for the first time at home. Material content include: Firstly, the error model of slant-range accuracy is established, and effect factor is analyzed. Secondly, in-orbit joint calibration scheme is researched to upgrading slant-range accuracy. Finally, math analysis is used to ensure the feasibility and validity of the scheme.

Introduction

Ranging is one of the main functions of radar. With the rapid development of solid-state devices, integrated circuits, digitization, computer software and other fields, the automation degree, measurement accuracy and reliability of radar ranging are greatly improved. Radar develops from simple ranging and angle measurement to imaging of targets, i.e. synthetic aperture radar. At present, Synthetic Aperture Radar (SAR), as a high-resolution microwave remote sensing device, plays an important role in the field of remote sensing imaging. Its all-day, all-weather, large-area imaging capability enables it to develop in space-to-ground detection. Since the slant range parameter is one of the important parameters of SAR imaging processing, especially for high-resolution or ultra-high-resolution space-borne synthetic aperture radar, the accuracy of slant range measurement becomes one of the important factors that restrict the imaging quality (including spatial resolution indicators and positioning accuracy indicators)[1].

Many scholars have studied and analyzed the positioning accuracy of two high-resolution space-borne SAR systems, TerraSAR-X and Radarsat-2. The positioning accuracy of the TerraSAR-X satellite can reach 10m, and the positioning accuracy of the Radarsat-2 satellite can reach 30m. According to foreign literature research [2,8], foreign countries mainly obtain high-precision slant range values by time delay calibration, but no specific calibration scheme is given. It is only proposed to carry out atmospheric modeling, and it is impossible to correct the delay error caused by other factors. There is no specific technical study that can be easily manipulated in the aspect of intrinsic high-precision slant range acquisition, nor does it study the factors affecting the slant range accuracy from the angle system of the space-borne SAR satellite. This paper proposes a space-borne SAR slope accuracy improvement scheme based on on-orbit joint calibration technology, which can realize a series of fixed error calibrations such as system equipment and atmospheric transmission.

This paper will start from the error modeling of slant range measurement, and explore the error factors affecting the accuracy of space-borne synthetic aperture radar slant range measurement. At the same time, according to the satellite-ground integration characteristics of space-borne synthetic aperture radar, the method of joint calibration of slant distance in orbit is studied. Finally, the validity and feasibility of the in-orbit joint calibration method are verified by mathematical analysis.
Slant-Range Measurement Error Modeling

The slant range of the space-borne synthetic aperture radar refers to the distance from the target to the phase center of the antenna, that is, the distance the radio wave travels in the atmosphere, but usually the delay time of the space-borne SAR measurement also includes the generation of the transmitter pulse control signal to the pulse from the elapsed time of the transmission on the antenna, plus the time it takes for the echo to pass from the antenna through the receiver to the ADC, which is called the electrical delay. Let the whole echo delay be $t$, the electrical delay be $t_e$, and the propagation speed of the echo be $c$, then the corresponding ranging formula is [9],

$$\frac{(t-t_e)}{2}.c = R$$  \hspace{1cm} (1)

From the ranging formula, we can see the factors affecting the measurement accuracy, and calculate the full differential for the equation (1) to obtain:

$$dR = \frac{\partial R}{\partial c} dc + \frac{\partial R}{\partial t} dt + \frac{\partial R}{\partial t_e} dt_e = \frac{R}{c} dc + \frac{c}{2} dt + \frac{c}{2} dt_e$$  \hspace{1cm} (2)

Using increments instead of differentials, the ranging error is:

$$\Delta R = \frac{R}{c} \Delta c + \frac{c}{2} \Delta t + \frac{c}{2} \Delta t_e$$  \hspace{1cm} (3)

In the formula, $\Delta c$ is the error of the average value of the wave propagation velocity, $\Delta t$ is the error of the measurement target echo delay time, and $\Delta t_e$ is the error of measuring the electrical delay time. It can be seen from equation (3) that the ranging error is composed of the error $\Delta c$ of the propagation velocity $c$ of the electric wave, the measurement error $\Delta t$ of the echo delay, and the measurement error $\Delta t_e$ of the electrical delay, and the uneven distribution of the atmospheric medium causes the electric wave to refract, the path of propagation of the electric wave is not a straight line but a curved trajectory, so the ranging error also includes errors due to atmospheric refraction. The various factors that cause the ranging error will be studied in detail below.

Echo Delay Measurement Error

Space-borne SAR emits the linear frequency modulation pulse, beam illumination as shown in Figure 1. Generally, the digital ranging method [2] is adopted, and a high-stability reference frequency source (crystal oscillator) is used as the counting pulse, and the counting pulse is started by the counter at the same time as the transmitting pulse, and the counting is stopped until the echo pulse is reached. As long as the number $n$ of counting pulses during this period is recorded and multiplied by the period $T$ of the counting pulse, the delay time $nT$ can be obtained. In order to reduce the reading error, the counting pulse generator and the radar timing trigger pulse are usually synchronized in time. Figure 2 shows a schematic diagram of echo delay measurement.

![Figure 1. Beam illumination diagram.](image-url)
The echo signal generally reaches the receiver through an integer of m PRT times, wherein the PRT is p integer multiple of T, and the receiver samples at a frequency of f MHz, and the echo delay measurement expression corresponding to the i-th sampling point is:

$$t = m \cdot PRT + n \cdot T + i \cdot f = (m \cdot p + n) \cdot T + i \cdot f$$

(4)

It can be seen from equation (4) that the factors affecting the echo delay measurement error mainly include the clock unit T and the sampling frequency. The current space-borne SAR reference frequency source can reach 100MHz, its stability can reach 5e-11, and the error of clock unit T can be neglected, so the main factor causing the echo delay measurement error is the sampling frequency. The equation (3) is available. When the sampling frequencies are 60MHz, 300MHz, and 960MHz, the slanting errors caused by the echo delay measurement error are about 2.50m, 0.50m, and 0.16m, respectively.

Error Caused by Changes in Radio Wave Propagation Speed

The propagation velocity c of electromagnetic waves in the atmosphere is: $c = \frac{C}{n}$, Where C is the velocity of the electromagnetic wave in vacuum, and n is the refractive index of the atmosphere. The refractive index of the atmosphere changes with time, place, height and other factors. When the refractive index n of the atmosphere on the test path is accurately measured, the actual velocity of the electromagnetic wave propagating in the atmosphere can be obtained, and the actual atmospheric refractive index on the measurement path should be is the integral mean of the refractive index of the atmosphere over the entire measurement path.

It can be known from equation (3) that the relative ranging error due to the calculation error of the propagation speed of the radio wave is:

$$\frac{\Delta R}{R} = \frac{\Delta c}{c}$$

(5)

As the distance R increases, the ranging error $\Delta R$ caused by the error of the radio wave speed also increases. Since the average propagation velocity of the electric wave in the atmosphere differs from the speed of light and varies with the operating wavelength, the value of c in the ranging formula (1) should also be calibrated according to the actual situation; otherwise it will cause systematic error.

Error due to Atmospheric Refraction

When the electric wave propagates in the atmosphere, the electric wave is refracted due to the uneven distribution of the atmospheric medium, so the path of the electric wave propagation is not a straight line but a curved trajectory. In the case of positive refraction, the wave propagation path is a downwardly curved arc.
It can be seen from Fig. 3 that although the true distance of the target is $R_0$, since the propagation of the electric wave is not a straight line but a curved arc, the measured echo delay time $t_R = 2R/c$, which produces a ranging error (and also an error of the elevation angle $\Delta\beta$).

$$\Delta R = R - R_0$$

(6)

The size of $\Delta R$ is directly related to the refractive index of the electric wave. If the relationship between the refractive index and the height is known, the distance error caused by the atmospheric refraction of the target of different heights and distances can be calculated, so that the measured value is corrected as necessary. When the target distance is further and the height is higher, the ranging error $\Delta R$ caused by the refraction is also larger.

![Figure 3. Refraction of electric waves in the atmosphere.](image)

**Delay (Electrical Delay) Measurement Error of the Radar System Transceiver Link**

Since the echo delay measured by the space-borne SAR system includes the time when the radio wave propagates in the system transceiver link, this time component is not needed in the slant range measurement. In theory, the electrical delay amount is corrected. When the radar is required to be compensated, it is difficult to compensate in perfect operation, and a certain random error will remain.

The electrical delay value can be obtained by a certain method after multiple measurements and averaged. After compensating for the fixed value, the residual amount will be a random quantity with the instability of the device itself. Equation (1), (2) In equation (3), $t_e$ is a fixed value of electrical delay obtained by multiple measurements, and $dte$ is a residual electrical delay random error.

**Summary**

According to the analysis of the error factors of the slant distance measurement mentioned above, the accuracy of the slant range measurement is improved. First, the measurement accuracy of the echo delay is improved. Second, the atmospheric environment monitoring and modeling are performed to correct the propagation velocity and refraction of the electric wave in the atmosphere. The third is to accurately measure the delay of the system's transceiver link (electrical delay) and control the residual system error range.

Since the whole slant range measurement process involves system equipment and atmospheric propagation, the idea of integration of satellite and ground can be adopted, and the whole system error is measured and corrected by the method of joint calibration in the orbit, and the measurement precision of the slant range is improved. The in-orbit joint calibration method will be studied in detail below.
In-orbit Joint Calibration Method

The error can be divided into two types according to its nature: system error and random error. The system error refers to the error caused by the fixed delay of the signal in each part of the system during the ranging, and the space-borne SAR slant distance measurement involves atmospheric modeling correction. Propagation velocity and refraction error, electrical delay measurement compensation system transmission link delay value, atmospheric modeling and electrical delay measurement can be combined measurement calibration through the idea of satellite integration, mainly through GPS equipment and ground calibration equipment Establish a satellite link, use GPS to accurately measure the position of the antenna phase center and the position of the ground calibration equipment. The distance between the two positions is taken as the true value of the slant range, and then compared with the slant distance measured by the system, and measured in multiple times. The average value is used as the systematic error, and the system error can be compensated. In the actual process, it is impossible to completely compensate the system error and still have a certain error.

The TerraSAR satellite in Germany used the Amazon rainforest calibration field data to carry out image geometric correction research. By compensating for the distance delay, the slant range error is significantly reduced, as shown in Figure 4[3].

![Figure 4. Relationship between slant-range error and perspective after TerraSAR delay compensation.](image)

Calibration Method

If there are control points with known latitude and longitude on the SAR image, then the distance between the satellite and the control point can be calculated by combining the GPS orbit determination data on the star. This distance can be compared to the radar ranging to obtain a ranging deviation. This deviation includes GPS orbit determination error, control point position error, and system and atmospheric delay errors described in the previous section. In order to obtain a high-precision slant range fixed deviation, an average value is taken by multiple measurements. The ground application system corrects the fixed deviation for the slant range value during the imaging processing and the geometric positioning processing, that is, the positioning accuracy can be greatly improved. The use of corner reflectors without system delay can effectively solve this problem.

Calibration Process

The process of slant range calibration is as follows:
Data Processing

Firstly, the angular reflector position and the satellite orbit position in the calibration field are accurately measured, and the actual slope distance value is calculated. Secondly, the calibration field data is processed, the corner reflector target is extracted, and the radar ranging value is obtained. Finally, the actual slant range value is compared with the radar ranging value, and the final correction value is obtained by multiple measurement or multi-point measurement.

Mathematical Analysis and Verification

In the simulation experiment, the influencing factors are divided into fixed values and random errors. The specific settings are shown in Table 1. The selected calibration conditions correspond to a certain atmospheric temperature, pressure, humidity distribution and illumination angle of view. And assume that the true slant range is 700Km.

<table>
<thead>
<tr>
<th>No.</th>
<th>Error parameter</th>
<th>Fixed value</th>
<th>Random error (variance)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Atmospheric propagation delay</td>
<td>4.6ms</td>
<td>20ns/3m</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Electrical delay</td>
<td>30ns</td>
<td>3ns/0.45m</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Timing</td>
<td>0</td>
<td>1ns/0.15m</td>
<td>Normal distribution</td>
</tr>
<tr>
<td>4</td>
<td>GPS Orbital</td>
<td>0</td>
<td>0.5m</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Corner reflector position</td>
<td>0</td>
<td>0.5m</td>
<td></td>
</tr>
</tbody>
</table>

Therefore,
1) Atmospheric propagation delay \( \Delta t_{atm} = (4.6 \times 10^{-3}) + (20 \times 10^{-9}) \cdot \text{randn}(1,100000) \) s, electrical delay \( \Delta t_{ele} = (30 \times 10^{-9}) + (3 \times 10^{-9}) \cdot \text{randn}(1,100000) \) s, total transmission delay \( T = \Delta t_{atm} + \Delta t_{ele} + 10^{-9} \cdot \text{randn}(1,100000) \) s, then measuring the slant range \( R_m = c \cdot T / 2 \), average value \( R_m_{avg} = 690004.037 \) m, variance \( R_m_{std} = 3.0322 \approx \sqrt{32 + 0.452 + 0.152} \) m, it can be seen that if the slant range correction is not performed, the measured deviation and the true slant distance have a fixed deviation of 9999.963 m.

2) Calibration slant-range \( R_{cal} = (700 \times 10^{3}) + \sqrt{0.52 + 0.52} \cdot \text{randn}(1,100000) \) m, slant-range deviation \( R_d = R_m - R_{cal} \), average value \( R_d_{avg} = 9995.9652 \) m, variance \( R_d_{std} = 3.1145 \approx \sqrt{32 + 0.452 + 0.152 + 0.52} \) m, theoretically, the slant range deviation value, is obtained by calibration measurement, i.e. the mean value \( R_d_{avg} \), corrected measurement slope \( R_m_{cal} = R_m - R_d_{avg} \), average value \( R_m_{cal_{avg}} = 699999.997 \) m, variance \( R_m_{cal_{std}} = 3.0388 \) m, it can be seen that the fixed deviation is accurately compensated by the slant-to-rail joint calibration, and there is only a random error with a variance of 3.0322 m.

3) However, in the actual on-orbit joint calibration, a large number of measurements cannot be performed. If the calibration is only performed once, the corrected slope error is \( 4.3543 \approx \sqrt{R_m_{std2} + R_d_{std2}} \), If the calibration is averaged twice, the corrected slope error is \( 3.7616 \approx \sqrt{R_m_{std2} + \text{std}((R_d1 + R_d2)/2)^2} \) m. For this reason, the calibration error can be reduced by multiple measurements, and the slant range accuracy can be greatly improved.

Through simulation calculation and analysis, the in-orbit joint calibration technology can effectively correct the fixed error of the slant range, and verify the effectiveness and feasibility of the technology. At the same time, because the refractive distance and the average refractive index are different under different atmospheric temperature, pressure and humidity distributions, in order to more accurately complete the slant range correction under different atmospheric environments and different viewing angles, in addition to on-orbit calibration In addition to fixing the fixed error, it is also necessary to obtain the refractive distance and the average refractive index under different working conditions according to different orbits, propagation angles, and atmospheric environment modeling calculations, and normalize the processing conditions at the track timing, and finally realize Fixed slant range error correction for slant range calculations under different operating conditions.

**Conclusions**

In this paper, from the imaging quality requirements of space-borne SAR, especially the high resolution requirements of imaging processing and positioning accuracy on slant range accuracy, it is necessary to study and improve the slant range accuracy. Firstly, the error factors affecting the accuracy of the slant range measurement are studied. Secondly, according to the influencing factors of the error, the method of joint calibration of the slant range in orbit is given. Finally, the effectiveness and feasibility of the slant-in-orbit joint calibration method is analyzed by mathematical analysis. Sexual verification. The improvement of the slant range accuracy will greatly improve the imaging quality and positioning accuracy of space-borne SAR, and provide support for the quantitative application of space-borne SAR.

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References


