Channel Imbalances and Along-Track Baseline Estimation for the GF-3 Azimuth Multichannel Mode

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Abstract: Azimuth multichannel (AMC) synthetic aperture radar (SAR), which contains multiple receiving antennas along the azimuth, can prevent the minimum antenna area constraint and provide high-resolution and wide-swath (HRWS) SAR images. Channel calibration and along-track baseline estimation are important topics in an AMC SAR system, since they have a great impact on image quality. Based on the signal model for stationary target of AMC SAR, this paper first analyses the influence of the along-track baseline and channel imbalances on SAR images by simulation. Then, a novel method to simultaneously estimate the along-track baseline, phase imbalance and range sample time imbalance (RSTI) based on the azimuth cross-correlation in the two-dimensional frequency domain is addressed. In addition, with the help of simulations and real data acquired by Gaofen-3 (GF-3), the effectiveness of this method is verified by comparing with some existing methods. Finally, this paper analyzes the estimation accuracy of this method under different scenarios and signal-to-noise ratios (SNRs), and points out the direction for future research.

Keywords: azimuth multichannel SAR; channel calibration; phase imbalance; range sample time imbalance; along-track baseline; Gaofen-3

1. Introduction

Since the first spaceborne synthetic aperture radar (SAR) SEASAT was launched in 1978, SAR has been an effective means of earth observation with an excellent capability to work in all-weather and all-time. For the conventional single-channel SAR system, azimuth high-resolution and wide-swath (HRWS) is an irreconcilable conflict [1]. On the one hand, azimuth high-resolution can be achieved by processing a wide Doppler bandwidth, which requires a high pulse repetition frequency (PRF) to avoid azimuth aliasing. On the other hand, wide-swath requires a low PRF to avoid range ambiguities. This conflict is known as the minimum antenna area constraint [2,3]. For the purpose of improving azimuth resolution and widening the swath, a lot of new SAR systems have been proposed. One of the approaches is medium earth orbit (MEO) SAR [4,5] which increases the orbit altitude. Then, users can get the same azimuth resolution as in low earth orbit (LEO) with greater coverage. However, the increase in orbit altitude also brings a series of problems, such as reduced SNR, bigger antenna size, more power planning requirements and radiations [4]. Another approach is the multistatic SAR [6] which operates with distinct transmit and receive antennas mounted on different platforms [7,8].
By reasonably setting the antenna beam shape, satellite orbit and PRF, the user also can obtain HRWS SAR images [9–11], but there are additional technical problems associated with time and phase synchronization of the transmit and receive system [12]. Moreover, it is necessary to launch several satellites, which means a high cost and complicated system. Based on the phased array antenna, Currie et al. proposed the azimuth multichannel (AMC) SAR which is also called displaced phase center multibeam SAR in [13]. The AMC SAR transmits the signal with a broadened beam and receives an echo signal using multiple beams along the azimuth. The additional spatial samples along the azimuth can substitute temporal samples, which means that the azimuth sampling rate can be M times the PRF, where M is the number of receiving apertures. Then, the PRF of this system can be relatively low to ensure sufficient swath, so the AMC SAR can avoid the minimum antenna area constraint and provide HRWS SAR images [13,14]. Compared with the MEO SAR and multistatic SAR, the AMC SAR is more feasible under the current technical conditions.

Gaofen-3 (GF-3) is a Chinese C-band spaceborne SAR which was launched in August 2016, in Taiyuan (Shanxi Province, China), and then went through a four-month payload performance commission phase and a two-month application performance commission phase [15,16]. Since January 2017, GF-3 has provided customers with advanced, commercially-available spaceborne SAR products which have fully polarization mode, and the azimuth resolution can be as fine as 0.55 m in a staring spotlight experiment [17]. GF-3 is the first Chinese spaceborne AMC SAR which contains two receiving apertures along the azimuth, and has acquired more than 20,000 images in ultrafine stripmap (UFS) mode, i.e., the dual-receive stripmap mode described in [15]. In UFS mode, GF-3 can provide SAR images with an azimuth resolution of 3 m and a swath width of 30 km. These images not only play an important role in the fields of ocean surveillance, disaster reduction and military reconnaissance, but also provide high-quality data for scientific experiments, such as the channel phase correction method based on joint quality function [18], strong clutter suppression [19], SAR-ground moving target indication (SAR-GMTI) experiment [20], and unambiguous imaging of both static scenes and moving targets [21].

In order to suppress the ambiguity in the azimuth, the PRF of AMC SAR must be elaborately selected, and the platform has to move one half of the whole azimuth antenna aperture between two adjacent radar pulses [22], but in some incident angles, such a rigid requirement on PRF may conflict with the timing diagram, so the real PRF will deviate from the selected PRF which is also called the ideal PRF. Then, there will be ambiguities (or false targets) in the azimuth. To solve this problem, Fox et al. limited the number of active columns in the receiving apertures to adjust the positions of the phase centers in RadarSat-2 ultrafine imaging mode [23,24], and the product can be found in [25], but the flexibility of this method is constrained by the number and spacing of active columns. Based on the digital beamforming (DBF) technology, Krieger at al. proposed an innovative reconstruction filter to process the non-uniform sampling SAR signal [22,26]. This method can achieve unambiguous reconstruction and has been used in many spaceborne SAR systems, such as TerraSAR-X [27–29], ALOS-2 [30,31] and GF-3 [21]. In order to design the Krieger filter, some parameters such as the velocity of the platform, PRF and the along-track baseline must be known in advance [22]. In spaceborne SAR systems, the velocity of the platform and PRF can be obtained from the flight control system, and the along-track baseline can be measured before launch. However, in the operational AMC SAR system, the actual value of the along-track baseline used to design the Krieger filter may not be equal to the previous measurement. First, the size and shape of the antenna may change slightly in the harsh space environment. In addition, some transmit-receive modules (TRm) may break down after working for a long time. Furthermore, the attitudes of the antenna will also affect the along-track baseline. All these factors will change the along-track baseline and have a negative influence on the performance of reconstruction filter. However, there are currently few studies to analyze the along-track baseline. In this paper, the effect of the along-track baseline on the performance of the reconstruction filter is analyzed. At the same time, a method for estimating the along-track baseline is proposed, and its reliability has been verified by simulation and real data required by GF-3 in UFS mode.
The reconstruction filter not only has strict requirements on the along-track baseline, but also the channel consistency. For the AMC SAR system, channel imbalances occur, which can cause ambiguous azimuth and energy leak of the main target, so, the role of channel imbalance estimation and correction in AMC SAR imaging is crucial. In general, the channel imbalances include amplitude imbalance, phase imbalance and range sample time imbalance (RSTI).

The amplitude imbalance can be estimated by channel balancing technology which can be found in [27] and [21]. Since the concept of AMC SAR was proposed, various methods to estimate the phase imbalance have been put forward. One of these methods is the subspace method which includes the orthogonal subspace method (OSM) [32] and signal subspace comparison method (SSCM) [33]. Both of these methods are based on the fact that the subspace spanned by signal eigenvectors is equal to the subspace spanned by steering vectors. The accuracy of this method is high, but some operations such as matrix inversion and eigenvalue decomposition are required, which are computationally intensive. Another method is based on the antenna pattern and does not need matrix decomposition and inversion [33]. However, it has higher requirements on the antenna pattern and is only suited for uniform scenes, such as a rainforest. Considering the efficiency and precision, Liu et al. proposed the time-domain correlation method [34], and Feng et al. proposed the azimuth correlation method to estimate the phase imbalance and RSTI [35]. In fact, these methods proposed by Liu et al. and Feng et al. are similar to the “Sign-Doppler Estimator” proposed by Madsen which was used to estimate the Doppler centroid in time domain [36], but the Doppler centroid is coupled to the phase imbalance, and the accuracy of phase imbalance estimation is limited by the accuracy of Doppler centroid estimation. In the TerraSAR-X system, the channel balancing is operated in the two-dimensional frequency domain and there is no need to estimate the Doppler centroid in advance [27]. In order to have a deeper understanding of these methods, Yang et al. compared these channel imbalance estimation methods, and the performance of each is analyzed with respect to its computational complexity and precondition [37]. Jin et al. derived the Cramer-Rao low bound (CRLB) for these methods [38] and compared their accuracy and effectiveness under different clutter distributions and signal-to-noise ratios (SNRs) [39]. Based on the azimuth cross-correlation in the two-dimensional frequency domain, this paper proposed a novel method to simultaneously estimate the along-track baseline and channel imbalances including phase imbalance and RSTI without estimating the Doppler centroid. At the same time, this paper also analyzes the impacts of phase imbalance and RSTI on SAR images, especially the RSTI which is rarely involved in current literature. Using the real data acquired by GF-3 in UFS mode, the estimation results of this method under different scenarios and SNR are given, and the images before and after channel imbalances correction are compared.

This paper begins in Section 2 with an overview of the signal model of the AMC SAR in both the time and frequency domain. After describing and analyzing the channel imbalances and along-track baseline, Section 3 proposes the general estimation method based on the interferometric phase in the two-dimensional frequency domain. Section 4 presents the experiment based on the simulation and GF-3 data. Section 5 summarizes the results of experiments with some discussion. Section 6 give the conclusions and research perspectives for the future.

2. Signal Model for Stationary Target of AMC SAR

In this paper, the following symbols will be employed:
In Equation (1), the first exponent describes the chirp signal generated by radar; the second exponent describes the azimuth time-modulation of AMC SAR; the third exponent describes a constant phase offset which is the same on different channels; and the last exponent describes a constant phase offset which is introduced by the separated receiving apertures and can be omitted since $d$ is far less than $R_0$ in the spaceborne SAR system.

According to [22], the AMC SAR system can be regarded as an equivalent monostatic SAR system with additional time and phase shift for each receiving channel, but in the operational AMC SAR system, there will inevitably be channel imbalances such as amplitude, phase and range sample time, which will have a negative influence on the performance of the reconstruction filter. The source and
classification of these channel imbalances can be found in [21]. Taking the signal received by Rx0 as a reference, the signals received by the mth channel can be expressed as follows:

\[ s_m(\tau, \eta) = \Gamma_m \cdot S_0(\tau - \tau_m, \eta + \eta_m) \cdot \exp\{j\phi_m\} \]  \hspace{1cm} (2)

where \( \eta_m \) is the time shift which is related to the along-track baseline \( d \) and it can be expressed as Equation (3). For simplicity, \( \Gamma_m, \tau_m, \phi_m \) and \( \eta_m \) are assumed to be independent of frequency and time in the same scene.

\[ \eta_m = \frac{m \cdot d}{2V_s} \]  \hspace{1cm} (3)

As shown in Figure 1b, the angle between the real antenna and the velocity of a satellite in slant range plane is \( \theta \), and \( \theta \) may not be 0 due to the satellite attitude control errors. The current processing method needs to project the real antenna into the flight direction, that is the green equivalent antenna in Figure 1b. Compared with the reference channel, the range history of the \( m \)th channel and the reference channel along the reference orbit (the orbit of reference channel) is \( d_m \), which is not equal to \( d \).

The amplitude imbalance can be estimated using the channel balancing technology, so \( \Gamma_m \) can be neglected in the following sections. Then, in the two-dimensional frequency domain, Equation (2) can be written as follows:

\[ S_m(f_r, f_\eta) = \exp\{j\phi_m\} \cdot \exp\{-j2\pi f_r \tau_m\} \cdot \exp\{j2\pi f_\eta \eta_m\} \cdot S_0(f_r, f_\eta) \]  \hspace{1cm} (4)

In Equation (4), the phase imbalance \( \phi_m \) is separated to the first exponential term, the RSTI \( \tau_m \) is separated to the second exponential term, and the time shift of \( \eta_m \) is separated to the third exponential term. The interferometric result between \( S_0(f_r, f_\eta) \) and \( S_m(f_r, f_\eta) \) can be written as follows:

\[ IN_m = S_m(f_r, f_\eta) \cdot S_0^*(f_r, f_\eta) = \exp\{j\phi_m\} \cdot \exp\{-j2\pi f_r \tau_m\} \cdot \exp\{j2\pi f_\eta \eta_m\} \cdot S_0(f_r, f_\eta) \cdot S_0^*(f_r, f_\eta) \]  \hspace{1cm} (5)

where the symbol * indicates the conjugate operation. In order to minimize the noise effects, an average is calculated and the mathematical expectation of Equation (5) can be expressed as follows:

\[ E(IN_m) = \exp\{j\phi_m\} \cdot \exp\{-j2\pi f_r \tau_m\} \cdot \exp\{j2\pi f_\eta \eta_m\} \cdot E(S_0(f_r, f_\eta) \cdot S_0^*(f_r, f_\eta)) \]  \hspace{1cm} (6)

where the symbol \( E[] \) indicates the mathematical expectation for azimuth or range frequency. Obviously, \( E(S_0(f_r, f_\eta) \cdot S_0^*(f_r, f_\eta)) \) is a real number, and the phase of \( E(IN_m) \) can be expressed as follows:

\[ \angle(E(IN_m)) = \phi_m - 2\pi f_r \tau_m + 2\pi f_\eta \eta_m \]  \hspace{1cm} (7)

where the symbol \( \angle() \) indicates the phase of the exponential term in parentheses. As shown in Equation (7), \( \angle(E(IN_m)) \) contains vital information including the phase imbalance, RSTI and the along-track baseline, and these parameters are needed to generate unambiguous SAR images.

3. General Method

GF-3 is the first Chinese spaceborne SAR equipped with dual-receiving channels. In this section, the analysis and general method will be introduced separately using the parameters of GF-3 in UFS mode which are listed in Table 1. Based on this method, the processing flow is finally proposed.
### 3.1. Range Sample Time Imbalance

Ideally, all receiving apertures of the AMC SAR system receive the echo reflected from the ground simultaneously. In other words, the range migration curves of the same target in different channels should be on the same range gate after range migration correction (RMC) \([41]\). If the echo signals received by each channel are directly spliced in order without reconstruction, the range migration curve of the same target will be a relatively smooth curve, just as shown in Figure 2a. However, the range sample time of each channel may be inconsistent for some reasons which can be mainly divided into two categories. First, the electronic components of each receiving aperture are not all the same, resulting in inconsistent time delays of the echo signal in different channels. Second, the attitudes of the satellite will cause different apertures to be on different orbits, just as shown in Figure 1b. As shown in Table 1, a range sampling cell is about 1.1242 m i.e., 7.5 ns when the sampling rate is 133.33 MHz. If the RSTI is 7.5 ns, the range migration curve before reconstruction will no longer be smooth but jagged as shown in Figure 2b. In the image domain, RSTI will have a negative influence on the range and azimuth.

#### Table 1. Some parameters of GF-3 in UFS mode.

| Parameter                   | Value               |
|-----------------------------|---------------------|
| Channel number (M)          | 2                   |
| Wavelength (\(\lambda\))   | 0.0556 m            |
| Platform velocity (\(V_s\))| 7571.68 m/s         |
| Signal bandwidth (\(B_r\))  | 100 MHz             |
| Sampling Rate               | 133.33 MHz          |
| PRF                         | 1976.93 Hz          |
| Ideal PRF                   | 2019.12 Hz          |
| Antenna length (\(D_a\))    | 7.5 m               |
| Along-track baseline (d)    | 3.75 m              |

In the range, the RMC cannot be completed perfectly due to the RSTI. Then, the power of the point-target will be dispersed on two or more range gates which will lead to the deterioration of performance. To illustrate this problem, three simulations whose RSTI is 0 ns, 3 ns and 7.5 ns were conducted. Only one point-target located at the center of imaging scene is considered in these simulations whose parameters can be found in Table 1. The contours of the focused point-target after 16 times interpolation in both the range and azimuth under different RSTI are illustrated in Figure 3, where the cross becomes thinner in the range as the RSTI increases. In order to make a more vivid description of this phenomenon, the compression result in the range is intercepted at the peak of the point-target, as shown in Figure 4 whose performances can be found in Table 2. Without the RSTI, the range compression result shown in Figure 4a is close to the ideal sinc function and the detailed description of this phenomenon, the compression result in the range is intercepted at the peak of the point-target, as shown in Figure 4 whose performances can be found in Table 2. Without the RSTI,
the range compression result shown in Figure 4a is close to the ideal sinc function and the detailed performances can be found in the first row in Table 2. When the RSTI is 3 ns where the range migration curves of two-channel differ by about 0.4 range sampling cells, the range compression result is shown in Figure 4b and the performances shown in the second row of Table 2 have changed somewhat. As the RSTI increases to 7.5 ns where the range migration curves of two-channel happen to differ by a range sampling cell, the range compression result is shown in Figure 4c and the performances shown in the third row of Table 2 have varied dramatically. It can be seen from Figure 4 and Table 2 that as the RSTI increases, the range resolution decreases, and both the peak side lobe ratio (PSLR) and the integrated side lobe ratio (ISLR) improve. The effect of RSTI on the focused SAR image in the range is similar to the weighting function. At the same time, the maximum value of the contour becomes smaller and the energy of the main target has decreased. There are two main reasons for energy leakage: pulse broadening (i.e., decreased resolution) and azimuth ambiguity (described in more detail below). In the azimuth, the performances listed in Table 2 (except Max Value) have little to do with RSTI, and a more detailed explanation can be found below.

![Figure 3](image1.png)

**Figure 3.** The contour of the focused point target with 16 times interpolation in both azimuth and range under different RSTIs: (a) The RSTI is 0 ns; (b) The RSTI is 3 ns; (c) The RSTI is 7.5 ns.

![Figure 4](image2.png)

**Figure 4.** The compression results of the focused point target with 16 times interpolation in the range: (a) The RSTI is 0 ns; (b) The RSTI is 3 ns; (c) The RSTI is 7.5 ns.

| RSTI (ns) | Max Value | Resolution (m) | PSLR (dB) | ISLR (dB) |
|-----------|-----------|----------------|-----------|-----------|
| 0.0       | 215405.79 | 1.308          | -13.263   | -10.070   |
| 3.0       | 207463.67 | 1.548          | -13.927   | -10.851   |
| 7.5       | 168900.21 | 1.667          | -18.719   | -16.626   |

| 1 The “Max Value” means the maximum value in the contour shown in Figure 3. |
To further investigate the impact of RSTI on SAR images in the azimuth, another simulation of RSTI was conducted. Using parameters shown in Table 1, the echo signal was generated at first. Then, a series of RSTIs are added into the echo signal. After reconstruction, a SAR image of a point-targets was obtained with the help of chirp scaling (CS) imaging algorithm [42]. The simulation results show that RSTI will cause azimuth ambiguity, i.e., false targets. As shown in Figure 5a, the well-focused point located in the middle of the scene is the main target. Two false targets are symmetric about the main target, and they are defocused due to a position offset in the azimuth. The partial detailed view of both the main target and false targets can be found in red boxes. For most scenes, false targets are usually submerged in clutter, but for strong targets with weak background clutter, such as an island on the ocean, false targets will be particularly obvious and seriously affect image quality. In general, false targets can be ignored when their intensity is lower than −40 dB compared with the main target. The relationship between azimuth ambiguity-to-signal ratio (AASR) [27] and RSTI can be found in Figure 5b. In order to limit the AASR to below −40 dB, the range sample time error must no more than 2.2 ns.

![Figure 5](image_url)

**Figure 5.** Results of the two-dimensional simulation of RSTI: (a) The focused main target and its false targets due to RSTI; (b) The relationship between AASR and RSTI.

Through the above analysis, RSTI will have a negative impact on SAR images, so it is necessary to estimate and correct RSTI before reconstruction. As shown in Equation (7), \( \mathcal{L}(E[I_{N,m}]) \) is a linear function of the range frequency \( f_r \) with the redundant phase \( \phi_m + 2\pi f_H \eta_m \), and the slope is \( 2\pi \tau_m \). Then, the RSTI \( \tau_m \) can be estimated by fitting the slope of \( \mathcal{L}(E[I_{N,m}]) \) with respect to the range frequency \( f_r \), just as shown in Equation (8).

\[
\hat{\tau}_m = -\frac{1}{2\pi} \cdot \frac{d}{df_r} \mathcal{L} \left( E_{f_H} \left[ I_{N,m} \right] \bigg|_{f_H \in [-\sigma, \sigma]} \right) \tag{8}
\]

where \( E_{f_H} \left[ \cdot \right] \bigg|_{f_H \in [-\sigma, \sigma]} \) is the mathematical expectation of the samples within \( [-\sigma, \sigma] \) in the azimuth frequency.

According to the properties of the Fourier transform, the time delay can be equivalent to a constant phase shift in the frequency domain [43], so, the RSTI of \( m \)th channel can be corrected by Equation (9) in the two-dimensional frequency domain.

\[
S_{m1}(f_x, f_H) = S_m(f_x, f_H) \cdot \exp[-j2\pi f_r \hat{\tau}_m] \tag{9}
\]
where $S_m(f, f_\eta)$ is the two-dimensional spectrum after RSTI correction. Then, the start sample time of each channel is the same as the reference channel.

### 3.2. Phase Imbalance

Just like RSTI, the phase imbalance can be caused by two sources that are electronic components imbalance and the attitude of the satellite. As shown in Figure 1b, the phase imbalance $\phi_m$ caused by the path delay of $m$th channel $\Delta R_m$ can be expressed as follows:

$$\phi_m = \frac{2\pi \Delta R_m}{\lambda} = \frac{2\pi d_m \sin \theta}{\lambda}$$

(10)

Taking the UFS mode of GF-3 as an example, $\phi_m$ is about $4.2^\circ$ when $\theta$ is $0.01^\circ$. The main influence of phase imbalance on SAR images is to introduce false targets, just as shown in Figure 5a, but has little to do with the performances listed in Table 2 of the main target. The relationship between AASR and phase imbalance can be found in Figure 6, and in order to limit the AASR to below $-40$ dB, the phase imbalance must no more than $38^\circ$.

![AASR versus Phase Imbalance](image)

Figure 6. The relationship between AASR and phase imbalance.

Before estimating the phase imbalance $\phi_m$, there are two aspects to consider. First, the Doppler spectrum of SAR echo signal is modulated by the antenna pattern in the azimuth, and the maximum gain, i.e., maximum SNR, is obtained in the antenna boresight direction where is the zero azimuth frequency. Second, in order to minimize the effects of $2\pi f_\eta \eta_m$, $f_\eta$ should be selected symmetrically around azimuth zero frequency where $2\pi f_\eta \eta_m$ is about 0. Considering the above two aspects, the average operation in Equation (7) should select samples with symmetric distribution on both sides of the zero azimuth frequency. In the range frequency domain, the samples of the mathematical expectation should be selected within the bandwidth of the LFM signal to ensure higher SNR. The estimation of phase imbalance can be expressed as Equation (11).

$$\hat{\phi}_m = \mathcal{L}\left(\mathcal{E}_{f_\eta f_\epsilon} [\mathcal{I}N_m] \bigg|_{f_\eta \in [-\sigma, \sigma], f_\epsilon \in [-\epsilon, \epsilon]} \right)$$

(11)

where $\sigma$ cannot be too large, and $\epsilon < B_r/2$. More discussions about $\sigma$ can be found below. Then, the phase imbalance of the $m$th channel can be corrected in the two-dimensional domain by Equation (12).

$$S_m(f, f_\eta) = S_m(f, f_\eta) \cdot \exp\left[-j\hat{\phi}_m\right]$$

(12)

where $S_m(f, f_\eta)$ is the two-dimensional spectrum after phase imbalance correction. Of course, the phase imbalance is also able to be corrected in the two-dimensional time domain by Equation (13).

$$s_m(\tau, \eta) = s_m(\tau, \eta) \cdot \exp\left[-j\hat{\phi}_m\right]$$

(13)
where \( s_{m2}(\tau, \eta) \) is the two-dimensional time signal after phase imbalance correction.

3.3. Along-Track Baseline

After correcting amplitude imbalance, phase imbalance and RSTI, the echo signals received by different channels are consistent. However, these signals are still non-uniform samplings unless the PRF happens to be the ideal PRF which can be expressed as Equation (14).

\[
PRF_{\text{ideal}} = \frac{2V_s}{D_a}
\]  

Considering the azimuth signal as the ideal low-pass signal, John et al. deduced the minimum two-norm solution of the multi-channel periodic non-uniform signal [44]. Based on John’s theory, the reconstruction filter proposed by Krieger can decompose the azimuth signal into a uniform sampling signal. In designing the filter, some parameters such as platform velocity, PRF and along-track baseline must be accurately given. The platform velocity and PRF can be obtained from the flying control system, and the along-track baseline can only be measured before the satellite is launched, but there may be installation errors when equipping the antenna, and the antenna may be deformed due to the harsh space environment. At the same time, satellite attitudes will also change the along-track baseline just as shown in Figure 1b.

In order to illustrate the impact of the along-track baseline on the performance of the reconstruction filter, a large number of simulations were carried out. First, the echo signal was generated using parameters listed in Table 1. In addition, a series of reconstruction filters were designed using different along-track baselines and these filters were used to process the echo signal separately. Then, SAR images were produced by CS imaging algorithm. It can be seen from these images that along-track baseline error is similar to phase imbalance which hardly affects the performance of the main target, but only produces false targets in the azimuth. Finally, the intention of false targets was measured and the relationship between AASR and along-track baseline can be found in Figure 7. In this figure, we can see that the AASR is still below \(-55\) dB even through the along-track baseline is 3.5 m, and the reason is that the GF3 has only two receiving apertures and the resolution is about 3 m in the azimuth.

![Figure 7. The relationship between AASR and along-track baseline.](image)

After correcting the phase imbalance and RSTI, Equation (7) can be expressed as follows:

\[
\angle(E[I_{m}]) = 2\pi f_{m} \eta_{m} = \pi \frac{m \cdot d}{V_s} f_{\eta}
\]  

(15)
where $\zeta(E_{INm})$ is a linear function of azimuth frequency $f_\eta$ and the slope is $\pi \frac{d}{d_\eta}$. Then, the along-track baseline can be estimated by fitting the slope of $\zeta(E_{INm})$ in the azimuth frequency domain, just as shown in Equation (16).

$$d = \frac{V_s}{\pi \cdot m} \frac{d}{d_\eta} \zeta(E_{INm})$$ (16)

Using the estimated $d$ to design the reconstruction filter, false targets introduced due to the along-track baseline error can be eliminated.

### 3.4. Processing Flow

In this subsection, a processing flow of GF-3 in UFS mode is proposed and it can be found in Figure 8. After acquiring the raw echo data of all receiving apertures, the two-dimensional fast Fourier transform (FFT) is first performed. In the two-dimensional frequency domain, some parameters including amplitude imbalance, RSTI, phase imbalance and the along-track baseline are estimated. According to the energy conservation law and the characters of FFT, the channel balancing technology can be operated in both time and frequency domain to estimate the amplitude imbalance. Since the method proposed in this paper is performed in the two-dimensional frequency domain, the amplitude imbalance estimation and correction are also performed in the frequency domain. In fact, the estimation order of RSTI, phase imbalance and the along-track baseline can be arbitrary. In other words, the order does not affect the estimation results. Then, the channel imbalance correction was conducted and the detailed approach can be found in Equation (9) and Equation (12). Of course, the correction order of channel imbalances can be arbitrary which has no influence on the quality of SAR images. At this point, there are no imbalances between the signals acquired by all apertures and the reference signal. Next, the two-dimensional inverse FFT (IFFT) transforms the signals from the frequency domain to the time domain. Then, the Krieger construction filter, which is designed using the estimated along-track baseline, processes these signals into uniform samples in the azimuth. Finally, a well-focused SAR image can be obtained by using the CS imaging algorithm of the standard stripmap mode [42] to process the signals produced by the Krieger reconstruction filter.

![Figure 8. The processing flow of GF-3 in UFS mode.](image-url)
4. Simulation and Real Data Processing

In the above sections, the signal model and a novel method based on the interferometric phase in the two-dimensional frequency domain are proposed to estimate channel imbalances and along-track baseline of AMC SAR system. In order to validate this method, a simulation is carried out at first. In this simulation, channel imbalances are artificially added, in other words, they are known in advance. Therefore, it can be demonstrated that the method proposed in this paper is effective by comparing the estimating results with true values. In addition, the real data acquired by GF3 in UPS mode are processed by the method proposed in this paper. The drawback of using real data is that channel imbalance and the along-track baseline are unknown in advance, but the validity of the method can be illustrated by comparing SAR images before and after processing.

4.1. Simulation Data Processing

The parameters of this simulation can be found in Table 1, and the echo signal of 25 stationary deterministic point-targets is generated. These point-targets are located in a $5 \times 5$ square where the distance of adjacent targets along the range and azimuth both are 2.5 km, and the total zero Doppler steering technique \([45–47]\) is used in this simulation which is the same as the operational GF-3 system. After the echo signal with different SNR is generated, some imbalances are artificially introduced on the 1st channel, where the RSTI is 7.5 ns and phase imbalance is $20^\circ$. When the SNR is 20 dB, the focused results can be found in Figure 9, where Figure 9a is the ambiguous image before channel imbalances estimation and correction, and Figure 9b is the well-focused image after channel imbalance estimation and correction. It can be seen from Figure 9a that there is obvious ambiguity before channel imbalance correction, and it is necessary to estimate and correct channel imbalances to obtained the well-focused and unambiguity image.

![Figure 9](image-url)

**Figure 9.** Comparison of the ambiguous image and the corrected image in the simulation data processing when the SNR is 20 dB: (a) Ambiguous image; (b) Corrected image.

After the two-dimensional FFT, interfering the signals of two channels and the relationship between the interferometric phase and the range/azimuth frequency is shown in Figure 10. In Figure 10a, the black line represents the relationship between the interferometric phase and range frequency, and it
has a non-zero slope due to RSTI which can be estimated by fitting the slope of the line. In Figure 10b, the black line represents the relationship between the interferometric phase and azimuth frequency. According to Equation (11), the phase imbalance is estimated using the samples at the green line, called as valid samples. The black line also has a non-zero slope due to the along-track baseline which can be estimated by fitting the slope of the black line. After removing the slope of the black line, the red line in Figure 10b was obtained. At this time, the estimated value of phase imbalance can also be obtained by taking the mean of valid samples on the red line using the valid samples.

Figure 10. The relationship between interferometric phase and frequency in the simulation data processing when the SNR is 10 dB: (a) Interferometric phase versus range frequency; (b) Interferometric phase versus azimuth frequency.

Under different SNR values, the estimated values of RSTI, phase imbalance and along-track baseline are listed in Table 3. As can be seen from this table, there are deviations between the real values and the estimated values. The reason for this phenomenon is that various factors are coupled with each other, and one of the estimations is affected by others. In addition, noise can also affect the estimation where the higher the SNR, the higher the overall estimation accuracy. After channel imbalance estimation and correction, only the focused main targets remain as shown in Figure 9b. Fortunately, the estimation residual error is small enough and the AASR is less than $-40$ dB when the SNR is greater than 5 dB, which confirms the effectiveness of the proposed method in this paper.

Table 3. The real value and estimated value in the simulation under different SNRs.

| SNR (dB) | RSTI (ns) | Phase Imbalance (°) | Along-Track Baseline (m) |
|----------|-----------|---------------------|--------------------------|
| 0        | 7.0456    | 19.5255             | 3.6944                   |
| 5        | 7.2120    | 20.2442             | 3.7340                   |
| 10       | 7.4017    | 19.7183             | 3.7524                   |
| 15       | 7.4342    | 19.6788             | 3.7506                   |
| 20       | 7.4621    | 19.9009             | 3.7502                   |

4.2. Real Data Processing

The real data acquired by GF-3 in UFS mode are also applied to test the method proposed in this paper. In a boot time in UFS mode, the GF-3 acquires 40 images around the Pacific and Southeast Asia in August 2018 with the orbit ID of 10825, and they are shown in Figure 11. And these images contain particularly rich scenes, including ocean, plain, mountain, the ocean-land boundary, etc. With the help of these images, the effectiveness of the proposed method can be verified, and the accuracy of the method in different scenes can be analyzed. This subsection first illustrates the estimation process and results based on the 12th image in Figure 11, and then illustrates the estimation results of all images.
Under different SNR values, the estimated values of RSTI, phase imbalance and along-track baseline are listed in Table 3. As can be seen from this table, there are deviations between the real values and the estimated values. The reason for this phenomenon is that various factors are coupled with each other, and one of the estimations is affected by others. In addition, noise can also affect the estimation where the higher the SNR, the higher the overall estimation accuracy. After channel imbalance estimation and correction, only the focused main targets remain as shown in Figure 9b. Fortunately, the estimation residual error is small enough and the AASR is less than -40dB when the SNR is greater than 5dB, which confirms the effectiveness of the proposed method in this paper.

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4.2. Real Data Processing

In order to make it easier to find the azimuth ambiguity, the selected image is an island in the ocean, where the ambiguity of the island is clearly visible due to the weak scattering of the sea clutter. Before the correction, the ambiguous image is shown in Figure 12a. The intensity of false targets in the yellow box in Figure 12a is stronger than the main targets in the red box, and the ripples on the sea are not clear. Using the method proposed in this paper to estimate channel imbalances and the along-track baseline, the relationship between the interferometric phase and the range/azimuth frequency is shown in Figure 13. In addition to the slope caused by RSTI, the line shown in Figure 13a has significant fluctuations which will affect the estimation of phase imbalance, but limiting ε in Equation (11) to a smaller range can reduce this effect. Phase imbalance and the along-track baseline can be estimated through the black line in Figure 13b, and the estimation results are listed in Table 4.

Combined with the previous analysis, the RSTI is only about 0.2 ns and its effect on the image can be neglected. The estimated along-track baseline differs from the theoretical value (3.75 m) by about 8 cm, and its effect on the image is also tiny. This shows that the consistency of the two channels of GF-3 is particularly good. The main reason for the existence of false targets in Figure 12a is the phase imbalance which is about −167º. In the operational product generation subsystem (PGS) of GF-3, the amplitude and phase imbalances are first calibrated using the inner calibration signal. Then, channel imbalances are corrected accurately by the estimation results based on the echo signal [15]. After correction, false targets are suppressed and the produced image shown in Figure 12b presents a remarkable improvement; the false target is completely submerged in the sea clutter in the yellow box.
In order to analyze the accuracy of this method in different scenes, the estimation of all these 40 images in Figure 11 is performed, and the results are shown in Figure 14. To distinguish different scenes, the black points represent land, the red stars represent the ocean, and the green circles represent the ocean-land boundary. One of the important differences of the echo signal reflected from ocean and land is SNR. Figure 14a shows the SNR of difference scenes after reconstruction, and it shows that the echo signal reflected by land has higher SNR. Figure 14b describes the phase imbalance estimation of different scenes. The back line is obtained by the method proposed in this paper, and the cyan line imbalances are corrected accurately by the estimation results based on the echo signal [15].

|                     | Estimated Value |
|---------------------|-----------------|
| RSTI (ns)           | 0.218           |
| Phase Imbalance (°) | -167.541        |
| Along-track baseline (m) | 3.681         |

Figure 12. Comparison of the ambiguous image and the corrected image in the GF-3 data processing where the vertical direction indicates azimuth and the horizontal indicates range, and the red box indicates the position of real target and the yellow box indicates the position of the false target: (a) Ambiguous image; (b) Corrected image.

Figure 13. The relationship between interferometric phase and frequency in the GF-3 data processing: (a) Interferometric phase versus range frequency; (b) Interferometric phase versus azimuth frequency.

Table 4. The estimation result in the real GF-3 data procession.
line is obtained by SSCM. Obviously, the results obtained by these two methods are very consistent which can be also used to illustrate the accuracy of the method proposed in this paper. In land scenes, the estimation result is very stable, and the phase imbalances of scenes from 14 to 27 constitute a straight line with a non-zero slope as the blue line in Figure 14b which may be generated due to satellite attitudes. In practice, to obtain the zero Doppler centroid, the satellite attitudes have been slowly changing but the control error may cause the θ in Figure 1b to not equal 0. Through removal of the influence of satellite attitudes, the estimation results of ocean scenes, on the one hand fluctuate greatly where the phase imbalances of two adjacent images can reach 1° difference, on the other hand, have a fixed bias from the blue line. As for the ocean-land boundary whose SNR is between land and ocean, the estimation results are between the blue line and red stars. Figure 14c describes the RSTI estimation of different scenes, and RSTI estimation is stable for the whole scenes, mostly between 0.15 ns and 0.25 ns. Figure 14d describes the along-track baseline estimation of different scenes. Similar to phase imbalance estimation, the results are very stable for land and fluctuate greatly in the ocean and ocean-land boundary. Combining the previous analysis and considering the processing efficiency, the operational GF-3 imaging processor can ignore RSTI and along-track baseline error.

![Figure 14](image.png)

Figure 14. The result of estimation based on GF-3 echo signal: (a) SNR; (b) Phase imbalance estimation; (c) RSTI estimation; (d) Along-track baseline estimation.
5. Discussion

The method proposed by this paper has been confirmed by processing the simulation and real data, and the real data of GF-3 in UFS mode are used to illustrate the estimation results in different scenarios. For the land scenarios, the estimation accuracy is very high. Taking the 20th image in Figure 11 as an example, the azimuth spectrums of the two channel signals after amplitude imbalance correction are shown in Figure 15a, where the ordinate is the normalized spectrum and the abscissa is the beam width corresponding to the imaging scene. In order to obtain a wider swath, the single-channel signal of AMC SAR is usually under-sampled which means that the azimuth spectrum must have aliasing. In SAR signal processing, the azimuth antenna pattern can be reflected by the azimuth spectrum of echo signals. In Figure 15a, the antenna pattern is somewhat reflected, but the maximum and minimum values differ by less than 1 dB, and apparently serious aliasing has occurred. Only in the vicinity of the zero frequency where the antenna gain is the highest, the azimuth spectrum is less affected by aliasing when the Doppler centroid is about 0 Hz. Therefore, the method proposed in this paper only uses the samples around the zero azimuth frequency. Here, the real data acquired by GF-3 are used to explain why $\sigma$ in Equation (11) cannot be too large. In Figure 15b, the green line is the azimuth spectrum of the signal after reconstruction filtering, and the black line is the actual azimuth antenna pattern corresponding to the imaging scene. The azimuth spectrum in Figure 15b is very similar to the antenna pattern which means that the reconstruction filter can restore the Doppler spectrum very well. Considering accuracy and efficiency, this method only uses the samples near zero frequency in the two-dimensional frequency domain. The fewer samples used, the higher the efficiency. In addition, the samples near azimuth zero frequency correspond to the antenna boresight direction, where the higher SNR can be obtained and the effect of aliasing can be minimized. Finally, the interference phase of the real data acquired by GF-3 fluctuates greatly in the range frequency domain, so the estimation results obtained by using the samples near zero frequency are highly reliable.

![Azimuth Spectrum of single channel signal](image1.png)

![Azimuth Spectrum after Reconstruction](image2.png)

**Figure 15.** The azimuth spectrum and antenna pattern of the 20th image in Figure 11: (a) Azimuth spectrum of single channel signal, where the red line and blue line correspond to the reference channel and 1st channel, respectively; (b) The azimuth spectrum after reconstruction (green line) and the antenna pattern (black line).

For the ocean-land boundary, just like the 12th and 13th in Figure 11, the land with stronger radiation intensity may not be illustrated by the complete antenna beam in the azimuth; the symmetry center of the azimuth spectrum is not the zero frequency as shown in Figure 16 which will make a negative influence on the estimation results. Therefore, in practical engineering, the echo of the uniform terrestrial scene should be selected as much as possible to estimate the channel imbalances.
The AMC SAR can prevent the minimum antenna area constraint and provide HRWS images, but such a system has a particularly high requirement for the consistency between receiving apertures. This paper analyzes the effects of RSTI and phase imbalance on SAR images with the help of simulations. RSTI not only introduces pairs of false targets in the azimuth, but also affects the performance of the point-target in the range which is similar to the weighting function. Phase imbalance only introduces pairs of false targets in the azimuth. This paper proposes a novel method based on the interferometric phase in the two-dimensional frequency domain to estimate the along-track baseline and channel imbalances including phase imbalance and RSTI without Doppler centroid estimation, which is necessary for existing methods based on the azimuth cross-correlation in the time domain.

More than 70% of the earth surface is covered by the ocean, and all-weather and all-day observation of the ocean is very important for fisheries, disaster relief and military. The AMC SAR is capable of providing HRWS images and is ideal for observing the ocean. Therefore, it is necessary to study the relationship between phase imbalance and ocean parameters such as wind speed, wind direction and ocean current in the future.

TerraSAR-X next generation (TerraSAR-X NG) will combine AMC SAR with staring spotlight (ST) SAR [48] or sliding spotlight (SL) SAR [49] to obtain the SAR image with 0.5 m resolution and 20 km swath in VHS MAPS mode [50], and the effect of non-uniform sampling on SAR image quality in ST mode can be found in [51]. Therefore, it is necessary to conduct a more in-depth study of the along-track baseline.

This method is established under the assumption that the antenna patterns of all the channels are completely the same and symmetrical, but in practice, this assumption is difficult to satisfy due to some factors such as design and manufacturing. Furthermore, in order to increase the signal power and improve the SNR, the AMC SAR typically combines all receiving channels into one large-aperture antenna to transmit a signal, but the larger the antenna aperture, the narrower the beam, which is bad for improving the azimuth resolution. To solve this problem, the transmit antenna pattern can

![Figure 15. The azimuth spectrum and antenna pattern of the 20th image in Figure 11.](image)

![Figure 16. The azimuth spectrum of two-channel: (a) The 12th image in Figure 11; (b) The 13th image in Figure 11.](image)
be reshaped where the beam will be broadened but no longer symmetrical. In addition, in order to further expand the swath, the AMC SAR may be combined with ScanSAR [52], where the antenna patterns corresponding to each burst are different and incomplete [53].

In summary, in the field of AMC SAR, there is still a lot of work to be done in the future, such as designing the reconstruction filter considering along-track baseline error for more receiving apertures, analyzing the relationship between antenna attitude and satellite attitude, studying how the ocean conditions affect channel imbalance estimation, channel imbalance estimation under special shape antenna patterns and so on.

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