Error Analysis of Bistatic SAR Imaging and Stereoscopy Bistatic SAR

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Abstract—The flexible geometry configuration of the bistatic synthetic aperture radar (SAR) has many advantages. However, it causes serious measurement error in the bistatic SAR system, which degrades the quality of the SAR images and the precision of the digital elevation model (DEM) obtained using stereoscopy bistatic SAR. In this paper, the influence of the scene height estimation error, trigger delay, transmitter position measurement error, receiver position measurement error, and transmission line length measurement error are analyzed. These analyses are very useful in bistatic SAR system design. The scene height estimation error, trigger delay, transmitter position measurement error, and synchronization receiver position measurement error affect both the quality of the images and the precision of the DEM obtained by stereoscopy bistatic SAR slightly. The echo receiver position measurement error and transmission line length measurement error affect the quality of the imaging only slightly, but seriously affect the precision of the DEM obtained by stereoscopy bistatic SAR. Luckily, their measurement precision can be quite satisfactory. Simulations and real bistatic experimental results verify the proposed theoretical analysis.

Index Terms—Bistatic synthetic aperture radar (SAR) imaging, stereoscopy bistatic SAR, system error analysis.

I. INTRODUCTION

The bistatic synthetic aperture radar (SAR) system and its configurations have been attracting scientists’ interests in the last few years. Because of the advantages of bistatic SAR, such as better flexibility, many bistatic SAR experiments have been carried out [1]–[7], such as bistatic imaging and stereoscopy bistatic SAR. Stereoscopy bistatic SAR is a technique of obtaining the DEM by SAR image pair. Compared to InSAR, which uses the phase of the SAR data to obtain the DEM, the stereoscopy bistatic SAR uses only the imaging geometry information and the slant range of SAR images to obtain the DEM. However, compared to monostatic SAR, bistatic imaging and stereoscopy bistatic SAR processing are more challenging. Because the receiver is separated from the transmitter, it requires time synchronization, phase synchronization, and precise geometry measurement in the bistatic SAR system, which affects the quality of SAR image and the precision of the DEM obtained using stereoscopy bistatic SAR.

The error in synchronization has been analyzed by many researchers. In the literature [8], the frequency error between the transmit carrier frequency and receiver’s oscillator frequency has been analyzed. The frequency error was divided into a fixed frequency error and a stochastic frequency error and it was concluded that the fixed frequency error makes a shift of the main lobe of azimuth compress signal and the stochastic frequency error leads to an increase in the side lobes of the azimuth compress signal. The model and effects of the phase synchronization errors between transmitters and receivers were analyzed in [9]–[11]. The chirp ratio error and a nonlinear phase error were considered in [9]. These errors brought about a shift in the main lobe and an increase in side lobes during compression. In [10], the phase error was divided into a fixed phase error, a linear phase error, and a random phase error. The fixed and linear phase errors, which give rise to an apparent Doppler centroid [11], introduce a range migration error, and the random phase error affects the integrated side-lobe ratio. In [11], more analysis on the random phase error was carried out, reaching the conclusion that the high-frequency parts result in spurious side lobes, whereas the low-frequency parts reduce the azimuth resolution and shift the targets along the range direction. In [12], an error model of antenna directing synchronization was established and the effects of the antenna directing synchronization error were analyzed. In [13], an error transfer model was established from the error of the time and frequency synchronization to the error of the interferometric phase. The time and the frequency errors were also divided into a fixed part and a random part. It was concluded that the fixed interferometric phase error and the linear time synchronization error bring about a linear phase error to the interferometric phase, and the fixed time synchronization error gives rise to a constant phase error to the interferometric phase. However, the measurement error of the bistatic SAR, including scene height estimation error, trigger delay, transmitter position measurement error, receiver position measurement error, and transmission line length measurement error, were not dealt with. These error analyses are also important in bistatic imaging and stereoscopy bistatic SAR processing.

In this paper, we analyze the influence of measurement error on bistatic SAR imaging and on the precision of
DEM obtained by the stereoscopy bistatic SAR technique. In Section II, the bistatic SAR backpropagation (BP) algorithm and stereoscopy bistatic SAR algorithm are presented. In Section III, influence of the measurement error is analyzed. In Section IV, simulations and experiments are carried out to verify the presented error analysis. Conclusions are reported in Section V.

II. PROCESSING OF BISTATIC SAR IMAGING AND STEREOSCOPY BISTATIC SAR

A. Configuration of Stereoscopy Bistatic SAR

The presented bistatic SAR system fixed the transmitter subsystem on the satellite and the receiver subsystem on the ground, as shown in Fig. 1. The ground receiver subsystem contains two categories of receivers [14]. One is the synchronization receiver, which directly receives the chirp signal from the transmitter on the satellite, shown as receiver $A$ in Fig. 1. The other is echo receiver, which receives the echo from the ground, shown as receiver $B_n$ in Fig. 1. The synchronization receiver has two applications. First, the synchronization receiver triggers the echo receivers to sample the echo. Second, the signal sampled by the synchronization receiver is used as the match filter to compress the echo data sampled by the echo receiver during the range compression process.

The geometry of the bistatic SAR configuration is shown in Fig. 1. The position of satellite $S$ is $S(x_s, y_s, z_s)$. The position of the synchronization receiver $A$ is $A(x_A, y_A, z_A)$ and the position of the echo receiver $B_n$ is $B_n(x_{B_n}, y_{B_n}, z_{B_n})$. The position of the target on the ground is $T(x_T, y_T, z_T)$.

Fig. 2 shows the block diagram of our bistatic SAR receiver subsystem. The direct signal is received by the synchronization receiver, and the echo is received by the echo receiver. Both the received signal in the synchronization receiver and echo receiver are mixed using the same oscillator. An A/D converter uses the same local clock. Fig. 2(a) is a block diagram of one synchronization receiver and one echo receiver. Fig. 2(b) is a block diagram of one synchronization receiver and two echo receivers.

The stereoscopy bistatic SAR has two configurations, namely a double-pass single-receiver configuration, and a single-pass double-receiver configuration [5], [6]. In the first configuration, the satellite passes over the scene twice and the ground receiver subsystem has only one echo receiver. This configuration is shown in Fig. 3(a) and the block diagram is shown in Fig. 2(a). Comparing with the stereoscopy monostatic SAR, the position of the ground receiver can be arranged to get perfect geometrical parameters, but the time decorrelation is also very serious. Another drawback of this configuration is that the measurement error of the satellite orbit seriously affects the precision of DEM, and high-precision measurement of the satellite orbit is difficult to carry out. In the second configuration, the satellite passes over the scene only once and the ground receiver subsystem has two echo receivers. That configuration is shown in Fig. 3(b) and its block diagram is shown in Fig. 2(b). Besides its geometrical parameter flexibly, this configuration can overcome the time decorrelation problem. Another advantage of this configuration is that the measurement error of the satellite orbit only slightly affects the precision of the DEM. Though the measurement error of the receiver position seriously affects the precision of the DEM, high-precision measurement of the receiver position is easy to carry out.

B. Process of Receiving Synchronization Signal and Echo

The working mode of the proposed system is shown in Fig. 4. The receiver subsystem has two states: the monitor state and the record state. In the monitor state, the synchronization receiver and the echo receiver only sample their received...
signal, but do not record the data. In the record state, the synchronization receiver and the echo receiver sample and record their received signals. In the beginning, the state of the receiver is in monitor state. When the synchronization receiver detects the chirp signal, the state of the receiver changes into the record state. The receiver holds the record state for a fixed time, which is shorter than pulse repetition interval; then it changes to the monitor state.

C. Bistatic SAR Imaging Processing

The bistatic SAR imaging algorithms can be classified into two categories: frequency-domain algorithms and time-domain algorithms [16]–[26]. Although the computational complexity of time-domain algorithms is higher than that of the frequency-domain algorithms, its precision, especially the phase precision, is higher, which is very important in the bistatic InSAR processing. With the development of graphics processing units, the time-domain bistatic SAR imaging algorithms can be applied in massively parallel processors, which relieves the drawback of high computational complexity [26]. All the bistatic BP algorithms analysis uses the same chirp signal as the matched filter in each range line to carry out the range compression process. The proposed analysis uses the signal received by a synchronization receiver to compress the echo in the range direction, which brings in some advantages. First, the proposed method can reduce the precision requirements of the measurement. Second, the proposed method can reduce additional time and phase synchronization operations. Third, the proposed method can reduce the effect of trigger delay. However, this method using the synchronization signal to compress the echo in the range compression requires a high signal-to-noise ratio (SNR) at the output of the synchronization antenna. Generally, the SNR is high enough in our experiment, as shown in Fig. 5. Fig. 5(a) is the compressed result of synchronization signal using L-band SAR and Fig. 5(b) is the compressed result of synchronization signal using X-band SAR.
SAR (TerraSAR-X). If the SNR is not high enough, the synchronization signal can be reconstructed by an estimation method.

The processing of the bistatic data with the BP algorithm needs two steps. In the first step, range compression is carried out, and in the second step the process of azimuth compression is done.

D. Step 1: Range Compression

In the range compression, the signal sampled and recorded by the synchronization receiver $A$ is used as reference signal to compress the echo signal. The signal sampled and recorded by the synchronization receiver $A$ is [27]

$$S_A (\tau, \eta) = W_\tau (\tau - R_D (\eta)/c) W_{AT} (x_s (\eta) - x_A) W_{AR} (x_s (\eta) - x_A) \times \exp[-j2\pi f_0 R_D (\eta)/c] \exp[j\pi K_s (\tau - R_D (\eta)/c)^2]$$

where $W_\tau (\tau)$ is the envelope of transmitted radar pulse, $W_{AT} (\eta)$ is the transmitter’s antenna beam pattern in the azimuth direction, $W_{AR} (\eta)$ is the synchronization receiver’s antenna beam pattern in azimuth direction, $R_D (\eta)$ is the range between the satellite $S$, and the synchronization receiver $A$ at azimuth time $\eta$

$$R_D (\eta) = \sqrt{(x_s (\eta) - x_A)^2 + (y_s (\eta) - y_A)^2 + (z_s (\eta) - z_A)^2}.$$  

The echo signal of the target $T(x_T, y_T, z_T)$ sampled and recorded by the echo receiver $B$ is

$$S_B (\tau, \eta; x_T, y_T, z_T) = \sigma (x_T, y_T, z_T) W_\tau (\tau - R_B (\eta; x_T, y_T, z_T)/c) \times W_{AT} (x_s (\eta) - x_T) W_{BT} (x_T, y_T, z_T) \times \exp[-j2\pi f_0 R_B (\eta; x_T, y_T, z_T)/c] \times \exp[j\pi K_s (\tau - R_B (\eta; x_T, y_T, z_T)/c)^2]$$

$$R_B (\eta; x_T, y_T, z_T) = \sqrt{(x_s (\eta) - x_T)^2 + (y_s (\eta) - y_T)^2 + (z_s (\eta) - z_T)^2} \quad (3)$$

where $\sigma (x_T, y_T, z_T)$ is the backscatter coefficient of the target, $T, W_\tau (\tau)$ is the envelope of the transmitted radar pulse, $W_{AT} (\eta)$ is the antenna beam pattern in the azimuth direction of the transmitter, $W_{BT} (x_T, y_T, z_T)$ is the antenna beam pattern of the ground echo receiver for the target $T$. $R_T (\eta; x_T, y_T, z_T)$ is the range between the satellite $S$ and target $T$ at azimuth time $\eta$, $R_B (x_T, y_T, z_T)$, is the range between the ground echo receiver $B$, and target $T$. Here we assume that all the antenna beam patterns are rectangle functions.

Equations (1) and (3) in the frequency domain are derived by Fourier transform based on the principle of stationary phase (POSP) [27]

$$\hat{S}_A (f, \eta) = W_f (f) W_a (x_s (\eta) - x_A) \times \exp[-j2\pi f_0 R_D (\eta)/c] \times \exp[j\pi f^2/K_s] \hat{S}_B (f, \eta; x_T, y_T, z_T) \quad (5)$$

$$\hat{S}_B (f, \eta; x_T, y_T, z_T) = \sigma (x_T, y_T, z_T) W_f (f) W_a (x_s (\eta) - x_T) \times W_{BT} (x_T, y_T, z_T) \exp[-j2\pi f_0 + f] \times R_B (\eta; x_T, y_T, z_T)/c \exp[j\pi f^2/K_s]. \quad (6)$$

Matched filtering can be implemented in the frequency domain using conjugate multiplication [27]

$$\hat{S} = \hat{S}_B (f, \eta; x_T, y_T, z_T) \cdot \hat{S}_A^*(f, \eta)$$

Applying inverse Fourier transform to $\hat{S}$ based on POSP yields [27]

$$S (\tau, \eta) = \sigma (x_T, y_T, z_T) p_s (\tau - [R_B (\eta; x_T, y_T, z_T) - R_D (\eta)]/c) \times W_a (x_s (\eta) - x_A) W_{BT} (x_T, y_T, z_T) W_a (x_s (\eta) - x_T) \times \exp[-j2\pi f_0 [R_B (\eta; x_T, y_T, z_T) - R_D (\eta)]/c]$$

$$= \sigma (\eta; x_T, y_T, z_T) \times \exp[-j2\pi f_0 R_B (\eta; x_T, y_T, z_T)/c] \quad (8)$$
where

\[ R(\eta; x_T, y_T, z_T) = R_B(\eta; x_T, y_T, z_T) - R_D(\eta) \]
\[ = \sqrt{(x_s(\eta) - x_T)^2 + (y_s(\eta) - y_T)^2 + (z_s(\eta) - z_T)^2} \]
\[ - \sqrt{(x_s(\eta) - x_A)^2 + (y_s(\eta) - y_A)^2 + (z_s(\eta) - z_A)^2} \]
\[ + \sqrt{(x_B - x_T)^2 + (y_B - y_T)^2 + (z_B - z_T)^2} \]  
(9)

E. Step 2: Azimuth Compression

Note that the range-compressed data are oversampled along the range direction by zero-padding the spectrum, using a property of Fourier transformation [27]. Then we set the image grid on the ground plane \((x_n, y_m)\) and estimate the average height of the scene \(z_{ave}\). Assume that the interval of the image grid along the azimuth and range direction are \(\rho_a\) and \(\rho_r\). Then

\[
\begin{align*}
x_n &= n \rho_a, \quad n = 1, 2, \ldots, N \\
y_m &= m \rho_r, \quad m = 1, 2, \ldots, M.
\end{align*}
\]  
(11)

The azimuth focusing formulation is

\[ d(n, m) = \sum_{i=0}^{N-1} d_r(i, \text{index}(\eta_i; x_n, y_m)) \cdot \phi_c(\eta_i; x_n, y_m) \]  
(12)

where \(d(n, m)\) is an element of the image, \(d_r(i, \text{index}(\eta_i; x_n, y_m))\) is an element of the range-compressed data, \(\phi_c(\eta_i; x_n, y_m)\) is the compensation phase, and \(\eta_i\) is the azimuth time of the \(i\)th range line

\[
\text{index}(\eta_i; x_n, y_m) = \text{round}(R(\eta_i; x_T, y_T, z_{ave})F\beta/c)
\]  
(13)

\[ \phi_c(\eta_i; x_n, y_m) = \exp[j2\pi f_0R(\eta_i; x_T, y_T, z_{ave})/c] \]  
(14)

where \(\text{round}(X)\) is a function of rounding the elements of \(X\) to the nearest integers, \(F_s\) is the range sampling rate, and \(\beta\) is the range oversampling ratio.

F. Processing of Stereoscopy Bistatic SAR

Stereoscopy bistatic SAR obtains the DEM using only the geometry information. Compared to InSAR, which uses the phase information to obtain DEM for distributed scatters, stereoscopy bistatic SAR has some advantages. The equivalent phase of the distributed scatters changes with the variation of the look angle, which affects the precision of the DEM obtained by InSAR. However, stereoscopy bistatic SAR does not use the phase to obtain the DEM, so the change of the equivalent phase does not affect the precision of the DEM obtained by stereoscopy bistatic SAR. If the image matching precision can be satisfied for the distributed scatters, the precision of the DEM will not be affected.

First, images should be matched to each other. Therefore, we assume \(d_1(n, m)\) in image 1 is matched with \(d_2(n, m)\) in image 2.

Based on the geometry of the double-pass single-receiver configuration, we have the set (18), shown at the bottom of the page, and based on the geometry of the single-pass double-receiver configuration, we have the set (19), shown at the bottom of the page. Then we solve the set (18) or (19) to get the height information of the scene. We assume that \(y_T, z_T\) is the solution of (18) or (19), and the height of \((x_n, y_T)\) is \(z_T\). Comparing with the double-pass single-receiver configuration, the single-pass double-receiver configuration has three advantages. First, time decorrelation can be overcome. Second, the baseline of this configuration is more flexible than that of the double-pass single-receiver configuration. Third, the precision of the baseline measurement of this configuration is more precise than that of the double-pass single-receiver configuration.

III. ERROR ANALYSIS

A. Estimation Error of the Scene Average Height

Because the imaging grid is built on the ground plane, the scene height must be estimated first. The scene height is variable and its precise value cannot be obtained, so the estimated scene average height is used in image processing. Assume that the satellite travels along the \(x\)-axis, the velocity is \(v\), and the scene height estimation error is \(\Delta z\) in the \(z\)-direction. Note that \(z\) and \(z'\) present the real value and the
value with the scene height estimation error, respectively

\[ z' = z + \Delta z. \]  \hfill (15) \]

Assume that the imaging position shift caused by the scene height estimation error is \( \Delta y \)

\[
R(\eta; x_T, y_T + \Delta y, z_T) = \sqrt{(x_s + \eta v_0 - x_T)^2 + (y_s - (y_T + \Delta y))^2 + (z_s - z_T)^2} \\
- \sqrt{(x_s + \eta v_0 - x_A)^2 + (y_s - y_A)^2 + (z_s - z_A)^2} \\
+ \sqrt{(x_B - x_T)^2 + (y_B - (y_T + \Delta y))^2 + (z_B - z_T)^2} 
\]  \hfill (16) \]

Due to using the same data for processing, we have

\[
R(\eta; x_T, y_T, z_T + \Delta z) = R(\eta; x_T, y_T + \Delta y, z_T). \]  \hfill (20) \]

Since \( \Delta y = R_T(\eta; x_T, y_T, z_T) \), \( \Delta y = R(x_T, y_T, z_T) \) and \( \Delta z = R(x_T, y_T, z_T) \), (16) and (17) can be simplified by expanding them using the first-order Taylor series

\[
R(\eta; x_T, y_T + \Delta y, z_T) = R(\eta; x_T, y_T, z_T) - \left( \frac{y_s - y_T}{R_T(x_T, y_T, z_T)} + \frac{y_B - y_T}{R_R(x_T, y_T, z_T)} \right) \Delta y \]  \hfill (21) \]

\[
R(\eta; x_T, y_T, z_T + \Delta z) = R(\eta; x_T, y_T, z_T) - \left( \frac{z_s - z_T}{R_T(x_T, y_T, z_T)} + \frac{z_B - z_T}{R_R(x_T, y_T, z_T)} \right) \Delta z \]  \hfill (22) \]

where \( R_T \) represents \( R_T(\eta; x_T, y_T, z_T) \) and \( R_R(\eta; x_T, y_T, z_T) \) represent \( R(x_T, y_T, z_T) \).

Solving (20) for \( \Delta y \) yields

\[
\Delta y = \frac{z_s - z_T}{R_T(x_T, y_T, z_T)} + \frac{z_B - z_T}{R_R(x_T, y_T, z_T)} \Delta z. \] \hfill (23) \]

Expanding (23) using the first-order Taylor series with \( \eta \), we obtain

\[
\Delta y = \Delta y_{\text{const}} + \Delta y(\eta) \] \hfill (24) \]

\[
|\Delta y_{\text{const}}| = \left| \frac{\cos \theta_T + \cos \theta_R}{\sin \theta_T + \sin \theta_R} \right| |\Delta z| \] \hfill (25) \]

\[
|\Delta y(\eta)| \approx \left| \frac{\sin (\theta_R - \theta_T) (x_s - x_T) \theta R}{(\sin \theta_T + \sin \theta_R)^2 R_T^2 R_T^0} \right| |\Delta z| \] \hfill (26) \]

where \( L_s \) is the synthetic aperture length and \( R_{T0} \) represents \( R_T(0; x_T, y_T, z_T) \)

\[
\sin \theta_T = \frac{y_s - y_T}{R_T(0; x_T, y_T, z_T)} \] \hfill (27) \]

\[
\cos \theta_T = \frac{z_s - z_T}{R_T(0; x_T, y_T, z_T)} \] \hfill (28) \]

\[
\sin \theta_R = \frac{y_B - y_T}{R_R(0; x_T, y_T, z_T)} \] \hfill (29) \]

\[
\cos \theta_R = \frac{z_B - z_T}{R_R(0; x_T, y_T, z_T)} \] \hfill (30) \]

Equation (24) shows that the effect of \( \Delta y \) contains a constant part and a variable part. The amplitude of the constant part is similar to \( \Delta z \) and it changes with the look angle of the transmitter and the receiver. The larger the look angle, the smaller the amplitude. The look angle of the transmitter and the receiver both increase with the distance between the target and the receiver. That is to say, the scene height estimation error will change the imaging position, and a target near to the receiver changes more than a far target. The amplitude of the variable part is much smaller than \( \Delta z \), because the synthetic aperture length is several kilometers or tens of kilometers and the range is hundreds of kilometers, so \( (L_s/R_{T0})^2 \) is very small. That is to say, the scene height estimation error affects the properties of the images slightly.

Fig. 6(a) shows the change of \( y \) with a 30-m scene height estimation error. The simulation parameters are listed in Table I. Fig. 6(a) shows the change of \( y \) for a near target and Fig. 6(b) shows the change of \( y \) for a far target. The simulation result shows that a 30-m scene height estimation error brings about a 27.26-m shift along the \( y \)-direction for a near target and an 18-m shift along the \( y \)-direction for a far target. And the variation of the shift for both the near and far targets is less than 1 mm, which is much smaller than the wavelength of the L-band and the X-band.

Equations (18) and (19) show that the DEM obtained by stereoscopy bistatic SAR is not related to \( \Delta y \) and \( \Delta z \). So the scene height estimation error does not affect the result of the DEM.

Table I shows the parameters used for analyzing the effect of scene average height estimation error.

**B. Trigger Delay of the Synchronization Receiver**

Because of the noise and the attenuation as the chirp signal passes through the aerosphere, the amplitude of the

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Unit</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective radar velocity</td>
<td>Km/s</td>
<td>7.2</td>
</tr>
<tr>
<td>Transmitter center position</td>
<td>(X, Y, Z)</td>
<td>(0, 400, 693)</td>
</tr>
<tr>
<td>Receiver position (X, Y, Z)</td>
<td>km</td>
<td>(0, 0, 533)</td>
</tr>
<tr>
<td>Near target position (X, Y, Z)</td>
<td>m</td>
<td>(0, -900, 120)</td>
</tr>
<tr>
<td>Far target position (X, Y, Z)</td>
<td>m</td>
<td>(0, -9000, 120)</td>
</tr>
</tbody>
</table>

**SIMULATED BISTATIC SAR PARAMETERS**
chirp signal changes when it arrives at the synchronization receiver. Thus the first several chirp signals cannot trigger the synchronization receiver. Because the echo receivers need the synchronization receiver to trigger to sample and record the echo, trigger delay exists in both the synchronization receiver and the echo receivers. The trigger delay time of the synchronization receiver is the same as that of the echo receivers.

The synchronization signal and the echo signal with trigger delay is

\[
S_A(\tau, \eta) = W_r(\tau - R_D/c) \times \exp\{-j2\pi f_0 R_D/c\} \\
\times \exp\{j\pi K_r(\tau - R_D/c)^2\} \\
\tau = \left[\frac{R_D + \Delta T}{c} - \frac{T_r}{2}, \frac{R_D}{c} - \frac{T_r}{2} + T\right]
\]

(31)

\[
S_B(\tau, \eta) = W_r(\tau - R_B/c) \times \exp\{-j2\pi f_0 R_B/c\} \\
\times \exp\{j\pi K_r(\tau - R_B/c)^2\} \\
\tau = \left[\frac{R_D + \Delta T}{c} - \frac{T_r}{2}, \frac{R_D}{c} - \frac{T_r}{2} + T\right]
\]

(32)

where \(\Delta T\) denotes trigger delay, \(T_r\) is the transmitted pulse time duration, and \(T\) is the sample time duration. In order to obtain more precise expressions, the correlation computation is used in time domain. The range-compressed result using the synchronization signal is

\[
S'(\tau) = \int_{-\infty}^{+\infty} S_B(t) S_A^*(t - \tau) dt \\
W_r'(t - R_B/c) \times \exp\{-j2\pi f_0 R_B/c\} \\
= \int_{-\infty}^{+\infty} \left\{j\pi K_r(\tau - R_B/c)^2\right\} W_r'(t - \tau - R_D/c) dt \\
\times \exp\{j2\pi f_0 R_D/c\} \exp\{-j2\pi K_r(\tau - R_D/c)^2\}
\]

when

\[
\tau = (R_B - R_D)/c
\]

(34)

\[
S(\tau)\) reaches the maximum value, which is

\[
S'(R_B - R_D)/c \\
= \exp\{-j2\pi f_0 [R_B - R_D]/c\} \int_{-\infty}^{+\infty} W(t - R_B/c) dt \\
= \exp\{-j2\pi f_0 [R_B - R_D]/c\} \int_{-T_r/2+\Delta T}^{+T_r/2} 1 dt \\
= (T_r - \Delta T) \cdot \exp\{-j2\pi f_0 [R_B - R_D]/c\}.
\]

(35)

The synchronization signal and the echo signal without trigger delay are expressed as

\[
S_A(\tau) = W_r(\tau - R_D/c) \\
\times \exp\{-j2\pi f_0 R_D/c\} \exp\{j\pi K_r(\tau - R_D/c)^2\} \\
\tau = \left[\frac{R_D}{c} - \frac{T_r}{2}, \frac{R_D}{c} + \frac{T_r}{2} + T\right]
\]

(36)

\[
S_B(\tau) = W_r(\tau - R_B/c) \\
\times \exp\{-j2\pi f_0 R_B/c\} \exp\{j\pi K_r(\tau - R_B/c)^2\} \\
\tau = \left[\frac{R_D}{c} - \frac{T_r}{2}, \frac{R_D}{c} + \frac{T_r}{2} + T\right].
\]

(37)

The synchronization signal is used to compress the echo signal

\[
S(\tau) = \int_{-\infty}^{+\infty} S_B(t) S_A^*(t - \tau) dt \\
W_r(t - R_B/c) \exp\{-j2\pi f_0 R_B/c\} \\
= \int_{-\infty}^{+\infty} \exp\{j\pi K_r(\tau - R_B/c)^2\} W_r(t - \tau - R_D/c) dt \\
\times \exp\{j2\pi f_0 R_D/c\} \exp\{-j2\pi K_r(\tau - R_D/c)^2\}
\]

when

\[
\tau = (R_B - R_D)/c
\]

(38)

\[
S(\tau)\) reaches the maximum value, which is

\[
S(R_B - R_D)/c = \exp\{-j2\pi f_0 [R_B - R_D]/c\} \int_{-\infty}^{+\infty} W(t - R_B/c) dt \\
= \exp\{-j2\pi f_0 [R_B - R_D]/c\} \int_{-T_r/2}^{+T_r/2} 1 dt \\
= T_r \cdot \exp\{-j2\pi f_0 [R_B - R_D]/c\}.
\]

(39)

The error at the maximum value position of \(S(\tau)\) is

\[
e_S = S(R_B - R_D)/c - S'(R_B - R_D)/c \\
= \Delta T \cdot \exp\{-j2\pi f_0 [R_B - R_D]/c\}.
\]

(40)

From (34) and (39), we can find that the trigger delay does not affect the maximum value position and it also does not affect the phase of the compressed signal at the maximum value position. It only affects the amplitude of the maximum value a little, and the ratio of the error to the signal is \(\Delta T/T_r\). Based on (18) and (19), because the maximum value position is not changed, the trigger delay does not affect the value of the stereoscopy bistatic SAR. Fig. 7 shows the effect of the trigger delay.

C. Orbital Measurement Error

The measurement precision of the satellite position is limited, meaning there are measurement errors of the satellite position. The measurement this position error can be classified as two types: the orbital measurement systematic error, and the orbital measurement random error. The orbital measurement systematic error does not vary as the platform position changes, which is generally larger than the random orbital measurement error.
1) Orbital Measurement Systematic Error: Assume that the satellite travels along the x-axis at a velocity \( v \), and the orbital measurement systematic error is \( \sigma_{cy} \) in the y-direction. \( y_s(\eta) \) and \( y'_s(\eta) \) present the real value of the satellite position and the measurement value of the satellite position with orbital measurement systematic error, respectively

\[
y'_s(\eta) = y_s(\eta) + \sigma_{cy}, \tag{42}
\]

Assume that the imaging position shift caused by the orbital measurement systematic error is \( \Delta y_y \)

\[
R\left( \eta; x_T, y_T + \Delta y_y, z_T \right)
= \sqrt{(x_s + \eta v - x_T)^2 + (y_s - (y_T + \Delta y_y))^2 + (z_s - z_T)^2}
- \sqrt{(x_s + \eta v - x_A)^2 + (y_s - y_A)^2 + (z_s - z_A)^2}
+ \sqrt{(x_B - x_T)^2 + (y_B - (y_T + \Delta y_y))^2 + (z_B - z_T)^2} \tag{43}
\]

\[
R'\left( \eta; x_T, y_T, z_T \right)
= \sqrt{(x_s + \eta v - x_T)^2 + (y_s + \sigma_{cy} - y_T)^2 + (z_s - z_T)^2}
- \sqrt{(x_s + \eta v - x_A)^2 + (y_s + \sigma_{cy} - y_A)^2 + (z_s - z_A)^2}
+ \sqrt{(x_B - x_T)^2 + (y_B - y_T)^2 + (z_B - z_T)^2} \tag{44}
\]

Due to using the same data for processing, we have

\[
R\left( \eta; x_T, y_T + \Delta y_y, z_T \right) = R'\left( \eta; x_T, y_T, z_T \right). \tag{45}
\]

Since \( \sigma_{cy} = y_s(\eta) \) and \( \Delta y_y = y_T \), (44) can be reformulated using the Taylor series

\[
R\left( \eta; x_T, y_T + \Delta y_y, z_T \right)
= R(\eta; x_T, y_T, z_T) - \left( \frac{y_s - y_T}{R_T} + \frac{y_B - y_T}{R_R} \right) \Delta y_y \tag{46}
\]

\[
R'\left( \eta; x_T, y_T, z_T \right)
= R(\eta; x_T, y_T, z_T) + \left( \frac{y_s - y_T}{R_T} - \frac{y_s - y_A}{R_D} \right) \sigma_{cy}. \tag{47}
\]

Solving (45) for \( \Delta y \) yields

\[
\Delta y_y = -\frac{y_s - y_T}{R_T(\eta; x_T, y_T, z_T)} - \frac{y_s - y_A}{R_T(\eta; x_T, y_T, z_T)} \sigma_{cy}.
\]

\[
\Delta y_y = -\frac{y_s - y_T}{R_T(\eta; x_T, y_T, z_T)} - \frac{y_s - y_A}{R_R(\eta; x_T, y_T, z_T)} \sigma_{cy}. \tag{48}
\]

Expanding (48) in first-order Taylor series gives

\[
\Delta y_y = \Delta y_{y_{\text{const}}} + \Delta y_y(\eta) \tag{50}
\]

\[
|\Delta y_{y_{\text{const}}}| \leq \frac{R_R}{R_T} |\sigma_{cy}| \leq \frac{R_R}{R_T} |\sigma_{cy}| \tag{51}
\]

\[
|\Delta y_y(\eta)| \approx \frac{\sin^2 \theta_R}{(\sin \theta_T + \sin \theta_R R_{R_T})^2} \left( \frac{R_R}{R_T} \right)^2 |\sigma_{cy}|. \tag{52}
\]

Similar to the analysis of orbital measurement systematic error in the y-direction, the effect along the z-direction is presented as

\[
\Delta y_z = \Delta y_{z_{\text{const}}} + \Delta y_z(\eta) \tag{53}
\]

\[
|\Delta y_{z_{\text{const}}}| \leq \frac{R_R}{R_T} |\sigma_{cz}| \leq \frac{R_R}{R_T} |\sigma_{cz}| \tag{54}
\]

\[
|\Delta y_z(\eta)| \leq \frac{R_R}{R_T} \left( \frac{L_z}{R_T} \right)^2 |\sigma_{cz}|. \tag{55}
\]

The orbital measurement systematic error along the x-direction causes an imaging shift both along the x- and y-direction, which is different from the monostatic SAR. The orbital measurement systematic error along the x-direction causes the imaging shift only along the x-direction for monostatic SAR. Similar to the analysis of the orbital measurement systematic error in the y-direction, the orbital measurement systematic error is presented as

\[
\Delta x = \Delta x_{x_{\text{const}}} + \Delta x(x) \tag{56}
\]

\[
|\Delta x_{x_{\text{const}}}| \leq \frac{R_R}{R_T} |\sigma_{cx}| \leq \frac{R_R}{R_T} |\sigma_{cx}| \tag{57}
\]

\[
|\Delta x(x)| \leq \left( \frac{R_T - R_D}{R_T} \right)^2 \left( \frac{x_A - x_T}{R_T} + \frac{R_D}{R_D} \right) |\sigma_{cx}|. \tag{58}
\]

Equation (56) shows that \( \Delta x \) has a fast variation term of variation \( \eta \), and \( \sigma_{cx} \) has both a fast variation term and a slow variation term of variation \( \eta \), so

\[
\Delta x = \frac{R_T - R_D}{R_T} \Delta x_{x_{\text{const}}} \approx \frac{R_R}{R_T} \sigma_{cx}. \tag{57}
\]

\[
\Delta y_x = -\frac{y_s - y_T}{R_T(\eta; x_T, y_T, z_T)} - \frac{y_B - y_T}{R_R(\eta; x_T, y_T, z_T)} \sigma_{cx}. \tag{58}
\]

Then we assume

\[
\Delta y_x = \Delta y_{x_{\text{const}}} + \Delta y_x(\eta) \tag{59}
\]

\[
|\Delta y_{x_{\text{const}}}| \leq \frac{R_R}{R_T} |\sigma_{cx}| \leq \frac{R_R}{R_T} |\sigma_{cx}|. \tag{60}
\]

\[
|\Delta y_x(\eta)| \leq \left( \frac{L_x}{R_T} \right)^2 \left( \frac{R_R}{R_T} \right)^2 |\sigma_{cx}|. \tag{61}
\]

So the orbital measurement systematic error along the range direction is presented as

\[
\Delta y = \Delta y_x + \Delta y_y + \Delta y_z = \Delta y_{x_{\text{const}}} + \Delta y(\eta) \tag{62}
\]

\[
|\Delta y_{x_{\text{const}}}| \leq \frac{R_R}{R_T} |\sigma_{ec}| \tag{63}
\]

|\Delta y(\eta)| \leq \left( \frac{L_y}{R_T} \right)^2 \left( \frac{R_R}{R_T} \right)^2 |\sigma_{ec}|. \tag{64}
\]
error affects the property of the imaging only slightly. Even than \( \sigma \) is very small. The amplitude of the variable part is much less orbital measurement systematic error along the X-direction. (c) Range error. measurement systematic error along Y-direction and Z-direction. (b) Effect of Fig. 8. Effect of orbital measurement systematic error. (a) Effect of orbital measurement systematic error along Y-direction and Z-direction. (b) Effect of orbital measurement systematic error along the X-direction. (c) Range error. measurement systematic error along the range direction and is referred to as the range error. We assume that the bistatic system contains SAR only slightly.

Equation (62) shows that the effect along the range contains a constant part and a variable part. Because \( R_R \) is much smaller than \( R_{T0} \)—generally \( R_R / R_{T0} \approx 0.01 \)—the amplitude of the constant part is much smaller than \( \sigma_c \). Because the synthetic aperture length is several kilometers or tens of kilometers and the range is hundreds of kilometers, \((L_s / R_{T0})^2\) is very small. The amplitude of the variable part is much less than \( \sigma_c \). That is to say, the orbital measurement systematic error affects the property of the imaging only slightly. Even though the shift caused by the orbital measurement systematic error is quite large, the shift is almost constant, which affects the BP algorithm slightly.

\[
|\Delta y(\eta)| \leq \frac{R_R}{R_{T0}} \left( \frac{L_s}{R_{T0}} \right)^2 \sigma_c
\]  
(64)

where

\[
\sigma_c \leq |\sigma_{cx}| + |\sigma_{cy}| + |\sigma_{cz}|
\]  
(65)

where \( \sigma_c \) is the total orbital measurement systematic error along the range direction and is referred to as the range measurement error.

Equation (62) shows that the effect along the range contains a constant part and a variable part. Because \( R_R \) is much smaller than \( R_{T0} \)—generally \( R_R / R_{T0} \approx 0.01 \)—the amplitude of the constant part is much smaller than \( \sigma_c \). Because the synthetic aperture length is several kilometers or tens of kilometers and the range is hundreds of kilometers, \((L_s / R_{T0})^2\) is very small. The amplitude of the variable part is much less than \( \sigma_c \). That is to say, the orbital measurement systematic error affects the property of the imaging only slightly. Even though the shift caused by the orbital measurement systematic error is quite large, the shift is almost constant, which affects the BP algorithm slightly.

\[
|\Delta y_s| \leq \left| \frac{R_R}{R_{T0}} \right| \sigma_{x,s}
\]  
(66)

\[
|\Delta y_y| \leq \left| \frac{R_R}{R_{T0}} \right| \sigma_{y,s}
\]  
(67)

\[
\sigma_y \approx \frac{(\sin \theta_D - \sin \theta_T) (\cos \theta_R - \cos \theta_R) \sigma_y + (\cos \theta_D - \cos \theta_T) (\cos \theta_R - \cos \theta_R) \sigma_{zc} + (\sin \theta_D - \sin \theta_T) (\sin \theta_R - \sin \theta_R) \sigma_{yc} + (\cos \theta_D - \cos \theta_T) (\sin \theta_R - \sin \theta_R) \sigma_{zc}}{\cos \theta_T} \leq \frac{R_R}{R_T} \sigma_c
\]  
(68)

\[
\sigma_z \approx \frac{(\sin \theta_D - \sin \theta_T) (\sin \theta_R - \sin \theta_R) \sigma_y + (\cos \theta_D - \cos \theta_T) (\sin \theta_R - \sin \theta_R) \sigma_{yc} + (\sin \theta_D - \sin \theta_T) (\cos \theta_R - \cos \theta_R) \sigma_{zc} + (\cos \theta_D - \cos \theta_T) (\cos \theta_R - \cos \theta_R) \sigma_{yc}}{\cos \theta_T} \leq \frac{R_R}{R_T} \sigma_c
\]  
(69)

Fig. 8 shows that effect of orbital measurement systematic error (33 m along the X-direction, 33 m along the Y-direction, and 34 m along the Z-direction). Fig. 8(a) is the effect of orbital measurement systematic error along the Y- and Z-direction. The result shows that the orbital measurement systematic error causes a 0.07-m change of \( Y \). Fig. 8(b) is the effect of orbital measurement systematic error along the X-direction. It causes a 0.20-m change of \( X \) and almost zero change of \( Y \). Fig. 8(c) is the range error. The maximum error is less than 0.02 mm, which is much less than the wavelength of the L-band and the X-band.

Similar to the analysis of the effect of the orbital measurement systematic error for imaging derived from (19), we obtain (69), shown at the bottom of the page, and (70), where \( \theta_D \) is the angle between the satellite and the synchronization receiver, which shows that the orbital measurement systematic error affects the DEM obtained by the stereoscopy bistatic SAR only slightly.

Fig. 9 shows the error in DEM caused by the orbital measurement error.

2) Orbital Measurement Random Error: Assume that the orbital measurement random errors are \( \sigma_{x,s}, \sigma_{y,s}, \) and \( \sigma_{z,s} \) in the \( x \)-, \( y \)-, and \( z \)-direction, respectively. Similar to the analysis of the orbital measurement systematic error, we obtain

\[
|\Delta y_s| \leq \left| \frac{R_R}{R_{T0}} \right| \sigma_{x,s}
\]  
(66)

\[
|\Delta y_y| \leq \left| \frac{R_R}{R_{T0}} \right| \sigma_{y,s}
\]  
(67)
The synchronization receiver position measurement error along the x-direction causes an imaging shift both along the x- and y-directions. Similar to the analysis of orbital measurement systematic error in the x-direction, the synchronization receiver position measurement error is presented as

\[ x_{A} + \eta \theta - x_{A} \frac{x}{R_{D}} \sigma_{x_{\text{syn}}} \approx \frac{x_{B} - x_{T}}{R_{R} (x_{T}, y_{T}, z_{T})} \sigma_{x_{\text{syn}}} \]

Based on (49)

\[ x_{A} + \eta \theta - x_{A} \frac{x}{R_{D}} \sigma_{x_{\text{syn}}} \approx \frac{x_{B} - x_{T}}{R_{R} (x_{T}, y_{T}, z_{T})} \sigma_{x_{\text{syn}}} \]


\[ y_{A} = y_{A} + \sigma_{y_{\text{syn}}} \]

Assume that the imaging position shift caused by the synchronization receiver measurement error is \( \Delta y_{s} \); similar to the analysis above

\[ \Delta y_{s} = \Delta y_{s_{\text{const}}} + \Delta y_{s} (\eta) \]

\[ | \Delta y_{s_{\text{const}}} | \approx \frac{\sin \theta_{R} - \sin \theta_{T}}{\sin \theta_{T} + \sin \theta_{R}} \sigma_{y_{\text{syn}}} \]

\[ | \Delta y_{s} (\eta) | \approx \frac{\sin \theta_{R} \sin \theta_{T}}{\sin \theta_{T} + \sin \theta_{R}} \frac{\left( x_{B} - x_{T} \right) \eta \sigma_{y_{\text{syn}}}}{R_{R} (x_{B}, y_{T}, z_{T})} \]

\[ \leq \left( \frac{L_{A}}{R_{T_{0}}} \right)^{2} \sigma_{y_{\text{syn}}} \]
kilometers and the range is hundreds of kilometers, the synthetic aperture length is several kilometers or tens of measurements. Because the shift caused by the synchronization receiver position measurement error will change the imaging position. Although smaller than \( \sigma \) is very small. The amplitude of the variable part is much smaller than \( \sigma \).

Equation (85) shows that \( \Delta y \) contains a constant part and a variable part. The amplitude of the constant part is similar to \( \sigma_{\text{syn}} \). That is to say, synchronization receiver position measurement error will change the imaging position. Although the shift caused by the synchronization receiver position measurement error is large, the shift is almost constant. Because the synthetic aperture length is several kilometers or tens of kilometers and the range is hundreds of kilometers, \( (L_s/R_0)^2 \) is very small. The amplitude of the variable part is much smaller than \( \sigma_{\text{syn}} \). That is to say, the synchronization receiver position measurement error affects the property of the imaging only slightly.

Similar to the analysis of the orbital system measurement error derived from (19), we obtain (90) and (91), shown at the bottom of the page.

Clearly, the high estimation error is similar to the synchronization receiver position measurement error.

Fig. 11 shows the 10-m synchronization receiver position measurement error (3 m along the X-direction, 3 m along the Y-direction, and 4 m along the Z-direction). Fig. 11(a) shows the effect of synchronization receiver measurement error along the Y- and Z-directions. The result shows that the orbital measurement systematic error causes a 6.60-m change of \( Y \). Fig. 11(b) shows the effect of synchronization receiver measurement error along the X-direction. It causes a 3-m change of \( X \) and a 0.35-mm change of \( Y \). Fig. 11(c) is the range error. A 10-m synchronization receiver position measurement error only causes less than 0.15 mm range error, which affects the imaging quality only slightly.

Fig. 12 shows the error of DEM caused by synchronization receiver position measurement error. The result shows that a 0.6-m synchronization receiver position measurement error will bring about a 1.56-m error to DEM.

2) Echo Receiver: Assume that the echo receiver measurement error is \( \sigma_{\text{echo}} \) in the y-direction. \( y_B \) and \( y'_B \) represent the real echo receiver position and the measurement echo receiver position with measurement error, respectively

\[
y'_B = y_B + \sigma_{\text{echo}}. \tag{89}\n\]

Assume the image position shift caused by the echo receiver measurement error is \( \Delta y_B \). Similar to the analysis above

\[
\Delta y_B = \Delta y_{\text{const}} + \Delta y_B (\eta) \tag{92}\n\]

\[
|\Delta y_{\text{const}}| \approx \frac{\sin \theta_R}{\sin \theta_T + \sin \theta_R} \sigma_{\text{echo}} \tag{93}\n\]

\[
\sigma_y \approx \frac{\sin \theta_D (\cos \theta_R - \cos \theta_R) \sigma_{\text{syn}} + \cos \theta_D (\cos \theta_R - \cos \theta_R) \sigma_{\text{syn}}}{\sin \theta_T + \sin \theta_R} \approx \sigma_{\text{syn}} \tag{90}\n\]

\[
\sigma_z \approx \frac{\sin \theta_D (\sin \theta_R - \sin \theta_R) \sigma_{\text{syn}} + \sin \theta_D (\sin \theta_R - \sin \theta_R) \sigma_{\text{syn}}}{\sin \theta_T + \sin \theta_R} \approx \sigma_{\text{syn}} \tag{91}\n\]
\[
|\Delta y_y(\eta)| \approx \frac{\sin \theta_T \sin \theta_R (x_s - x_T) \eta}{(\sin \theta_T + \sin \theta_R)^2 \frac{R_{T0}}{R_T}} \sigma_{y,\text{echo}} \\
\leq \left( \frac{L_s}{R_{T0}} \right)^2 \sigma_{y,\text{echo}}. \quad (94)
\]

Similar to the analysis of the echo receiver location measurement error in the \( y \)-direction, the effect along the \( z \)-direction presented as

\[
\Delta y_z = \Delta y_{z,\text{const}} + \Delta y_z(\eta)
\]

\[
|\Delta y_{z,\text{const}}| \approx \sigma_{z,\text{echo}}
\]

\[
|\Delta y_z(\eta)| \leq \left( \frac{L_s}{R_{T0}} \right)^2 \sigma_{z,\text{echo}}. \quad (97)
\]

The echo receiver position measurement error along the \( x \)-direction causes an image shift both along the \( x \)- and \( y \)-directions. Similar to the analysis of the orbital measurement systematic error in the \( x \)-direction, the echo receiver position measurement error presented as

\[
\frac{x_B - x_T}{R_R(x_T, y_T, z_T)} \sigma_{x,\text{echo}}
\]

\[
= -\left( \frac{x_s + \eta_0 - x_T}{R_T(\eta_0, x_T, y_T, z_T)} + \frac{x_B - x_T}{R_R(x_T, y_T, z_T)} \right) \Delta x \\
- \left( \frac{y_s - y_T}{R_T(\eta_0, x_T, y_T, z_T)} + \frac{y_B - y_T}{R_R(x_T, y_T, z_T)} \right) \Delta y_x. \quad (98)
\]

Equation (98) shows that \( \Delta x \) is a fast variation term of variation \( \eta \), and \( \sigma_{x,\text{echo}} \) is slow variation term of variation \( \eta \) so

\[
\Delta x = 0
\]

\[
\Delta y_x = -\frac{x_B - x_T}{R_R(x_T, y_T, z_T)} \sigma_{x,\text{echo}} \quad (100)
\]

Then

\[
\Delta y_x = \Delta y_{x,\text{const}} + \Delta y_x(\eta)
\]

\[
|\Delta y_{x,\text{const}}| \approx -\frac{R_R(x_T, y_T, z_T)}{\sin \theta_T + \sin \theta_R} \sigma_{x,\text{echo}}
\]

\[
|\Delta y_x(\eta)| \leq \left( \frac{L_s}{R_{T0}} \right)^2 \sigma_{x,\text{echo}}. \quad (103)
\]

So the total echo receiver position measurement error along the range presented as

\[
\Delta y = \Delta y_x + \Delta y_y + \Delta y_z = \Delta y_{\text{const}} + \Delta y(\eta)
\]

\[
|\Delta y_{\text{const}}| \approx \sigma_{\text{echo}} \quad (104)
\]

\[
|\Delta y(\eta)| \leq \left( \frac{L_s}{R_{T0}} \right)^2 \sigma_{\text{echo}} \quad (105)
\]

where

\[
\sigma_{\text{echo}} = \sigma_{x,\text{echo}} + \sigma_{y,\text{echo}} + \sigma_{z,\text{echo}} \quad (107)
\]

with \( \sigma_{\text{echo}} \) being the total echo receiver location measurement error along the range direction and referred to ad the range measurement error.

The influence of the echo position measurement error is the same as that of the synchronization receiver position measurement error along the range direction, but the echo position measurement error along the \( x \)-direction does not cause an image shift along the azimuth direction.

Similar to the analysis of the orbital system measurement error derived from (19), we obtain (112) and (113), shown at the bottom of the next page.

Because \( \theta_T1 \) is similar to \( \theta_T2 \), the denominator is close to 0, so the precision of the echo position measurement seriously affects the precision of stereoscopy bistatic SAR

\[
|\sigma_y| \approx \frac{R_{T0}}{R_R} \left( |\sigma_{\text{echo},1}| + |\sigma_{\text{echo},2}| \right) \quad (108)
\]

\[
|\sigma_z| \approx \frac{R_{T0}}{R_R} \left( |\sigma_{\text{echo},1}| + |\sigma_{\text{echo},2}| \right). \quad (109)
\]

Fig. 13 shows the 10-m echo receiver position measurement error (3 m along the \( X \)-direction, 3 m along the \( Y \)-direction, and 4 m along the \( Z \)-direction). Fig. 15(a) is the effect of echo receiver position measurement error along the \( Y \)- and \( Z \)-directions. The result shows that the echo receiver position measurement error causes a 4.23-m change of \( Y \). Fig. 13(b) is the effect echo receiver position measurement error along the
line from the synchronization antenna to the ADC is different from the length of the transmission line from the echo antenna to the ADC. So the length of each transmission line must be measured. The measurement error brings an error to the imaging and stereoscopy bistatic SAR processing.

Assume that the time delay of the synchronization receiver is \( T_A \) and the time delay of the echo receiver is \( T_B \)

\[
S_A (\tau, \eta) = W_a (\tau - [R_D (\eta)/c + T_A]) W_{aT} (x_{s1} (\eta) - x_A) \times W_{aR} (x_{s1} (\eta) - x_A) \exp[-j2\pi f_0 [R_D (\eta)/c + T_A] c] \times \exp[j\pi K_s (\tau - [R_D (\eta)/c + T_A])^2] \quad (110)
\]

\[
S_B (\tau, \eta; x_T, y_T, z_T) = \sigma (x_T, y_T, z_T) \times W_t (\tau - [R_B (\eta; x_T, y_T, z_T)/c + T_B]) \times W_{at} (\eta - \eta_t; x_T, y_T, z_T) \times \exp[-j2\pi f_0 [R_B (\eta; x_T, y_T, z_T)/c + T_B]] \times \exp[j\pi K_s (\tau - [R_B (\eta; x_T, y_T, z_T)/c + T_B])^2] \quad (111)
\]

Carrying out the same operations, we can get a formulation similar to (10)

\[
S (\tau, \eta) = \sigma (x_T, y_T, z_T) \times W_t (\tau - [R (\eta; x_T, y_T, z_T)/c + T_{delay}]) \times W_{at} (\eta - \eta_t; x_T, y_T, z_T) \times \exp[-j2\pi f_0 [R (\eta; x_T, y_T, z_T)/c + T_{delay}]] \times \exp[j\pi K_s (\tau - [R (\eta; x_T, y_T, z_T)/c + T_{delay}])^2] \quad (114)
\]

\[
T_{delay} = T_B - T_A. \quad (115)
\]

Assuming that the imaging position shift caused by the time delay is \( \Delta y \), similar to the previous analysis, we get

\[
\Delta y = \Delta y_{const} + \Delta y (\eta) \quad (119)
\]

\[
|\Delta y_{const}| \approx \frac{1}{\sin \theta_T + \sin \theta_R} |c T_{delay}| \quad (120)
\]

\[
|\Delta y (\eta)| \approx \frac{1}{\sin \theta_T + \sin \theta_R} |(x_s - x_T) \cdot \eta/|R_T| |c T_{delay}| \quad (113)
\]

\[
\sigma_y \approx \frac{\sin \theta_{R1} (\cos \theta_T + \cos \theta_{R2}) [\sigma_{z, echo, 1}]}{(\sin \theta_T + \sin \theta_{R1}) (\cos \theta_T + \cos \theta_{R2}) - (\sin \theta_T + \sin \theta_{R2}) (\cos \theta_T + \cos \theta_{R1})} \frac{\sin \theta_{R2} (\cos \theta_T + \cos \theta_{R1}) [\sigma_{z, echo, 2}]}{(\sin \theta_T + \sin \theta_{R2}) (\cos \theta_T + \cos \theta_{R1}) - (\sin \theta_T + \sin \theta_{R1}) (\cos \theta_T + \cos \theta_{R2})} + (\sin \theta_{R2} (\cos \theta_T + \cos \theta_{R1}) [\sigma_{z, echo, 2}]) \quad (112)
\]

\[
\sigma_z \approx \frac{\sin \theta_{R1} (\cos \theta_T + \cos \theta_{R2}) [\sigma_{y, echo, 1}]}{(\sin \theta_T + \sin \theta_{R1}) (\cos \theta_T + \cos \theta_{R2}) - (\sin \theta_T + \sin \theta_{R2}) (\cos \theta_T + \cos \theta_{R1})} \frac{\sin \theta_{R2} (\cos \theta_T + \cos \theta_{R1}) [\sigma_{y, echo, 2}]}{(\sin \theta_T + \sin \theta_{R2}) (\cos \theta_T + \cos \theta_{R1}) - (\sin \theta_T + \sin \theta_{R1}) (\cos \theta_T + \cos \theta_{R2})} + (\sin \theta_{R2} (\cos \theta_T + \cos \theta_{R1}) [\sigma_{y, echo, 2}]) \quad (113)
\]

**E. Transmission Line Time Delay Error**

For the ground receiver subsystem, the signal received by synchronization antenna and the echo received by echo antenna are sampled at the same analog-to-digital converter (ADC). And the antennas are connected to the ADC using transmission lines. So there are time delays for transmitting the signal from the synchronization antenna to the ADC or from the echo antenna to the ADC. The length of the transmission

- \( X \)-direction. It causes zero change of \( X \) and \( 0.33 \text{-mm change of } Y \). Fig. 13(c) is the range error. A 10-m synchronization receiver position measurement error only causes less than 0.025 mm range error, which affects the imaging quality only slightly.

Fig. 14 shows the error of DEM caused by the orbital measurement error. The result shows that a 0.01-m measurement error will bring about a 0.3-m error to DEM. The ratio is more than 20. So the precision of the echo receiver position measurement seriously affects the precision of DEM.
Equation (116) shows that the effect of $\Delta y$ contains a constant part and a variable part. The amplitude of the constant part is similar to $cT_{\text{delay}}$. That is to say, a different transmission time delay will change the imaging position. Although the shift caused by the different transmission time delay error is large, the shift is almost constant. Because the synthetic aperture length is several kilometers or tens of kilometers and the range is hundreds of kilometers, $(L_s/R_T)^2$ is very small. The amplitude of the variable part is much smaller than $cT_{\text{delay}}$. That is to say, the transmission time delay error affects the property of the imaging only slightly

$$T_{\text{delay},1} = T_{R,1} - T_A$$  \hspace{1cm} (122)$$
$$T_{\text{delay},2} = T_{R,2} - T_A.$$  \hspace{1cm} (123)

Equations (124) and (125), shown at the bottom of the page, show that the high estimation is affected by the transmission time delay. If the sign of $T_{\text{delay},1}$ is same as that of $T_{\text{delay},2}$, the effect of the transmission line time delay is reduced. But if the sign of the $T_{\text{delay},1}$ is different from that of $T_{\text{delay},2}$, the effect of the transmission line time delay is enhanced. We assume

$$T_{\text{delay},1} = -T_{\text{delay},2}.$$  \hspace{1cm} (124)

Then, we obtain

$$\sigma_y \approx \frac{R_T}{R_R} cT_{\text{delay},1}$$  \hspace{1cm} (125)$$
$$\sigma_z \approx \frac{R_T}{R_R} cT_{\text{delay},1}. $$  \hspace{1cm} (126)

So the effect of transmission line time delay is very serious. Fig. 15 shows the error of DEM caused by the transmission line error. The result shows that a 0.02-m measurement error will bring a 0.8-m error to DEM. The ratio is more than 40. So the precision of the transmission line error seriously affects the precision of DEM.

### IV. Simulation Results

In this section, simulations and real data experiments are carried out to verify the proposed theoretical analysis. The simulation parameters are listed in Table II and the experimental parameters are listed in Table III.

Fig. 16 is the processed result of the simulation data and Fig. 17 is the experimental result using TerraSAR-X as the transmitter subsystem. Those results are used as reference results to compare with other results with measurement error.

Fig. 18 is the experimental result of the stereoscopy bistatic SAR using space-based L-band SAR as the transmitter subsystem. The receiver subsystem is fixed on a hill, located at the upper right in Fig. 18. The stereoscopy bistatic configuration is the double-pass single-receiver configuration shown in Fig. 3(a). Fig. 18(a) is the imaging result. Fig. 18(b) is the result of mapping the DEM information on the SAR image. Fig. 18(c) is the result of mapping the DEM information on the optical image.

#### A. Scene Average Height Estimation Error

Using the simulation parameter list in Tables II and III, the simulation is carried out with a 30-m scene height estimation error for the far target to verify the proposed theoretical analysis. Real data result with a 30-m scene height estimation error is also analyzed.

Fig. 19 is the processed result with 30-m scene height estimation error of the simulated data. Fig. 19(a) is the
Fig. 16. Processed result of the simulated data. (a) Amplitude contour of the compressed result. (b) Profile along range direction. (c) Profile along azimuth direction.

Fig. 17. Processed result of the real data using the X-band (TerraSAR-X).

amplitude contour of the compressed result. Fig. 19(b) is the amplitude profile of compressed result. Fig. 19(c) is the angle profile of compressed result. The upper figure is the profile along the range direction, and lower figure is the profile along the azimuth direction. The blue line is the compressed result without scene height estimation, and the red line is the compressed result with scene height estimation. Those compressed results show that the scene height estimation error only brings a shift along the y-direction and the shift value is similar to the scene height estimation error. The imaging property is almost
The focus result

range (m)

azimuth (m)

The focus result along range

The result without error

The result with error

range (m)

The focus result along azimuth

The result without error

The result with error

azimuth (m)

The focus result along range

The result without error

The result with error

range (m)

The focus result along azimuth

The result without error

The result with error

azimuth (m)

---

Fig. 19. Processed result with 30-m scene height estimation error using the simulated data. (a) Amplitude contour of the compressed result. (b) Amplitude profile of compressed result. (c) Angle profile of compressed result.

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The shift along the Y-direction is 18 m, which is similar to the result of the theoretical analysis.

Fig. 20 shows the imaging result with 50-m scene height estimation error. Comparing with Fig. 17, the imaging quality is almost the same. Fig. 20(b) shows the difference between the imaging result with and without the 50-m scene height estimation error. The imaging result without error is in red, and the imaging result with error is in green. If the image with and without error is the same, the combination result will be yellow. The combination result shows that the image with and without the scene height estimation error is almost yellow. That is to say, the imaging results with and without the error are almost the same. In order to show the detail, a part of Fig. 20(b) is enlarged and shown in Fig. 20(c). The figure shows that the scene height estimation error only brings a shift along the y-direction and the imaging property is almost unaffected.

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Fig. 20. Imaging result with 50-m scene height estimation error using the experimental data. (a) Imaging result with 50-m scene height estimation error. (b) Result comparison with and without 50-m scene height estimation error. (c) Partial result comparison.

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The simulation result and the result obtain from the presented bistatic experiment verified the proposed theoretical analysis. And we can conclude that the scene height estimation error causes an imaging shift along the range direction and that the target near the receiver shifts larger than the target.
far from the receiver; however, the imaging quality is only affected slightly.

B. Trigger Delay of the Synchronization Receiver

In order to verify the proposed theoretical analysis of the trigger delay, we cut off the first several data of received signal both of the synchronization channel and of the echo channel and use the signal of the synchronization channel as the match filter to compress the echo to carry out the range compression. The simulation with the trigger delay is also applied to verify the proposed theoretical analysis.

Fig. 21(a) shows the simulation results with a 32-point trigger delay and Fig. 21(b) shows the simulation results with a 128-point trigger delay. The total transmitted pulse has 2161 points. The results show that the trigger delay only affects the amplitude. The result also shows that the loss of more points affects the amplitude more, whereas the maximum value position and phase at the maximum value position are not affected by the trigger delay. Compared to Fig. 7, the simulation result verified the theoretical analysis that the trigger delay only affects the amplitude of the main lobe and does not shift the position of the main lobe. The trigger delay affects the phase of the main lobe only slightly. In this simulation, losing 128 points from 2161 points only causes error of the phase in the main lobe, but the phase at the peak value position is not affected.

Fig. 22(a) and (b) shows the results of the 32- and 128-point trigger delay. The upper figure is the amplitude. The red line is the compressed result with the trigger delay, the blue line is the compressed result without the trigger delay, and the black line is the error caused by the trigger delay. The middle figure is the error of the angle. The lower figure is a part of the amplitude. The results show that the trigger delay affects the compressed result only slightly.

The simulation results and the results obtained from the bistatic experiments verified the proposed theoretical analysis. Thus, we can conclude that the loss of the first several chirp signal data only slightly affects the result of the imaging using BP algorithm, which is an advantage because we can use the data received by the synchronization receiver to compress the echo data obtained by the echo receiver in the range direction. While using a general chirp signal to compress the echo receiver in the range direction, the trigger delay of the synchronization receiver will introduce a shift $\Delta T/T_\text{r}$ of the maximum position in range direction, which seriously affects the result.

C. Error of the Orbital Measurement

In the simulation, we assume the satellite movement along the $X$-direction, 100-m orbital measurement systematic error (33 m along the $X$-direction, 33 m along the $Y$-direction, and 34 m along the $Z$-direction), and $\pm 1$-m the orbital measurement random error. We also add those orbital measurement errors to the simulation.
errors to the precise orbit of the satellite in the experimental data to verify the proposed theoretical analysis.

1) Orbital Measurement Systematic Error: Fig. 23 shows the processed result with 100-m orbital measurement systematic error. Fig. 23(a) is the amplitude contour of the compressed result. Fig. 23(b) is the amplitude profile of the compressed result. Fig. 23(c) is the angle profile of the compressed result along the range and azimuth direction, respectively. The blue line is the compressed result without 100-m orbital measurement systematic error, and the red line is the compressed result with 100-m orbital measurement systematic error. The results show that the orbital measurement systematic error only brings a shift of the image, and that the shift value is much smaller than the orbital measurement systematic error. Fig. 23(b) shows that the shift along the azimuth direction is more serious than the shift along range direction with the same error, which supports our theoretical analysis. The imaging property is almost unaffected, but the phase is affected seriously.

Fig. 24 is the imaging result with 100 m orbital measurement systematic error. Comparing with Fig. 17, the imaging property is almost the same. Fig. 24(b) shows the difference between the imaging result with and without error. The imaging result without error is in red, and the imaging result with error is in green. The combination result shows that the imaging result with and without the error is almost same. Fig. 24(c) is one part of Fig. 24(b) to show the detail of the comparison. The figure shows that the 100-m orbital measurement systematic error introduces a slight shift. The imaging property is almost unaffected.

2) Orbital Measurement Random Error: Fig. 25 shows the processed result with ±1-m orbital measurement random error. Fig. 25(a) is the amplitude contour of the compressed result. Fig. 25(b) is the amplitude profile of the compressed result. Fig. 25(c) is the angle profile of the compressed result along the range and the azimuth direction, respectively. The blue line is the compressed result without error and the red line is the compressed result with error. The results show that the orbital measurement random error affects the imaging property, but the influence of the main lobe is very slight. The imaging position and the phase of the main lobe are only slightly affected.

Fig. 26(a) is the imaging result with ±1-m orbital measurement random error. Comparing with Fig. 17, the imaging property is almost the same. Fig. 26(b) shows the difference between the imaging result with and without ±1-m orbital measurement random error. The imaging result without error is in red, and the imaging result with error is in green. The combination result shows that the imaging result with and without the error is almost same. Fig. 26(c) is one part of
Fig. 23. Processed result with 100-m orbital measurement systematic error using the simulated data. (a) Amplitude contour of the compressed result. (b) Amplitude profile of compressed result. (c) Angle profile of compressed result.

Fig. 24. Imaging result with 100-m orbital measurement systematic error of the experimental data. (a) Imaging result with 100-m orbital measurement systematic error. (b) Result comparison with and without 100-m orbital measurement systematic error. (c) Partial result comparison.

The simulation results and the results obtained from the bistatic experiment verified the proposed theoretical analysis. And we can conclude that both the orbital measurement systematic error and the orbital measurement random error only slightly affect both the imaging results using the BP algorithm. That is also the advantage of using the synchronization signal as the match filter to compress the echo data in the range compression process. Using this method, the requirement of the measurement precision can be reduced, which is very useful for the real-time imaging applications. The precise orbital measurement information cannot be obtained in reasonable time. It takes a lot time to transmit the orbital information from the satellite to the station. However, the proposed method can...
D. Error of the Receiver Location

In this simulation, we assume a satellite moving along the X-direction, 10-m synchronization receiver location measurement error (3 m along the X-direction, 3 m along the Y-direction, and 4 m along the Z-direction) and 10-m echo receiver location measurement error. We also add those location measurement errors to the precise location measurement of the receiver in the experimental data to verify the proposed theoretical analysis.

1) Synchronization Receiver: Fig. 27(a) is the processed result with 10-m synchronization receiver position measurement error. Fig. 27(b) is the amplitude profile of the compressed result. Fig. 27(c) is the angle profile of the compressed result along the range and azimuth direction, respectively. The blue line is the compressed result without error, and the red
The synchronization receiver position measurement error introduces a shift both along both the y- and x-directions. Comparing the shift caused by orbital measurement error, the synchronization receiver position measurement error is much more serious, but the precision of the synchronization receiver position measurement is much higher than the precision of the orbital measurement. The imaging property is almost unaffected, but the phase is affected seriously.

Fig. 28(a) is the imaging result with 10-m synchronization receiver position measurement error. Comparing with Fig. 17, the imaging property is almost the same. Fig. 28(b) shows the difference between the imaging result with and without 10-m synchronization receiver position measurement error. The imaging result without error is in red, and the imaging result with error is in green. The combination result shows that the imaging result with and without the error is almost the same. Fig. 28(c) is one part of the Fig. 28(b). The figure shows that the error of the 10-m synchronization receiver position measurement error brings an obvious shift, comparing with 100-m orbital measurement error, but the imaging property is almost unaffected. However, the precision of the synchronization receiver position measurement is much higher than the orbital measurement. In our experiment, the precision of GPS is 5 mm and the precision of the orbital measurement is larger than 1 m.

2) Echo Receiver: Fig. 29(a) is the processed result with 10-m echo receiver position measurement error. Fig. 29(b) is the amplitude profile of the compressed result. Fig. 29(c) is the angle profile of the compressed result along the range and azimuth direction, respectively. The blue line is the compressed result without error, and the red line is the compressed result with error. The results show that the echo receiver position measurement error only brings a shift along the y-direction. Comparing the shift caused by orbital measurement error, the echo receiver position measurement error is much more serious, but the precision of the echo receiver position measurement is much higher than the precision of the orbital measurement. The imaging property is almost unaffected, but the phase is affected seriously.

Fig. 30(a) is the imaging result with 10-m echo receiver position measurement error. Comparing with Fig. 17, the imaging property is almost the same. Fig. 30(a) shows the difference between the imaging result with and without 10-m echo receiver position measurement error. The imaging result without error is in red, and the imaging result with error is in green. The combination result shows that the imaging result with and without the error is almost the same. Fig. 30(a) is one part of the Fig. 30(a). The figure shows that the error of the 10-m echo receiver position measurement error brings about an obvious shift, but the imaging property is almost unaffected. Comparing with the effect of the synchronization receiver location measurement error, the shift along the azimuth of the echo receiver location measurement error is much less than that of the synchronization receiver location measurement error with the same error, which is the same as in the theoretical analysis.

The simulation and real data results verified the proposed theoretical analysis. And we conclude that both the synchronization receiver position measurement error and the echo receiver position measurement error affect the imaging property using BP algorithm only slightly, but both of them introduce a shift of the image, which is much more serious than the shift caused by the orbital measurement error. The location measurement error of the synchronization receiver causes larger shift than that of the echo receiver.
Fig. 28. Imaging result with 10-m synchronization receiver position measurement error of the experimental data. (a) Imaging result with 10-m synchronization receiver position measurement error. (b) Result comparison with and without 10-m synchronization receiver position measurement error. (c) Partial result comparison.

E. Measurement Error of the Transmission Line Length

Though the synchronization and echo receiver are colocated and part of the same receiver subsystem, each receiver uses a different antenna. The antennas are connected to the receiver using different transmission lines. We only measure the positions of the antennas’ phase center. Though the synchronization correction is carried out before the experiment, there is also error of the synchronization correction. That error is referred to as the transmission line length error. In order to verify the proposed analysis, we add the 3-m transmission line length measurement error to the real experimental data. We also simulate the effect of the measurement error of the transmission line length with 3-m error.

Fig. 29. Imaging result with 10-m echo receiver position measurement error of the simulated data. (a) Amplitude contour of the compressed result. (b) Amplitude profile of compressed result. (c) Angle profile of compressed result.

Fig. 31(a) is the processed result with 3-m transmission line difference. Fig. 31(b) is the amplitude profile of the compressed result. Fig. 31(c) is the angle profile of the compressed result along the range and the azimuth direction, respectively. The blue line is the compressed result without error, and the red line is the compressed result with error. The results show that the echo receiver position measurement error
only brings a shift along the y-direction. The imaging property is almost unaffected.

Fig. 32(a) is the imaging result with a 3-m transmission line difference. Comparing with Fig. 17, the imaging property is almost the same. Fig. 32(b) shows the difference between the imaging result with and without 100-m orbital system measurement error. The imaging result without error is in red, and the imaging result with error is in green. The combination result shows that the imaging result with and without the error is almost same. Fig. 32(c) is one part of the Fig. 32(b). The figure shows that the error of the 3-m transmission line difference introduces a little shift, but the imaging property is almost unaffected.

The simulation and real data results verified the proposed theoretical analysis. We can that the measurement error of the transmission line affects the imaging property using BP algo-
measurement precision of the transmission line is very high; in the presented experiment the precision is 10 mm.

V. CONCLUSION

The simulations and real bistatic experimental results verified the proposed theoretical analysis. The scene height estimation error, trigger delay, transmitter position error, receiver position error, and transmission line length measurement error affected quality of imaging only slightly. All of these measurement errors caused an image shift along the range direction. The synchronization receiver position measurement error caused the image shift along the azimuth direction. The scene height estimation error, trigger delay, transmitter position error, and synchronization receiver position measurement error affected the precision of DEM obtained by stereoscopy bistatic SAR. However, the echo receiver position measurement error and transmission line length measurement error seriously affected the precision of DEM obtained by stereoscopy bistatic SAR. Luckily, the measurement precision of the echo receiver position and length of the transmission line can be very satisfactory.

REFERENCES

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