Fast Time-domain Imaging Method for Bistatic Circular SAR

Hongtu Xie\textsuperscript{1,2,3,4,∗}, Shaoying Shi\textsuperscript{3}, Junfa Mao\textsuperscript{1,∗}, Daoxiang An\textsuperscript{4}, Fuhai Li\textsuperscript{2}, Zhimin Zhou\textsuperscript{4} and Guoqian Wang\textsuperscript{5,∗}

\textsuperscript{1}Key Laboratory of Ministry of Education of Design and Electromagnetic Compatibility of High Speed Electronic Systems, Shanghai Jiao Tong University, Shanghai, China
\textsuperscript{2}College of Electrical and Information Engineering, Hunan University, Changsha
\textsuperscript{3}Air Force Early Warning Academy, Wuhan, China
\textsuperscript{4}College of Electronic Science, National University of Defense Technology, Changsha
\textsuperscript{5}Hunan Institute of Traditional Chinese Medicine, Changsha, China

\textsuperscript{∗}Hongtu Xie and Guoqian Wang are the co-first authors, and Junfa Mao is the corresponding author.

*e-mail: xht20041623@163.com

Abstract. Fast time-domain algorithm (FTDA) for the one-stationary bistatic circular synthetic aperture radar (OS-BCSAR) imaging is presented. In this paper, the subimage is represented in the slant-range plane instead of ground plane. FTDA includes the fast backprojection algorithm (FBPA) with the subaperture and elliptical polar grid processing and the FBPA with the subaperture and polar grid processing. Experimental results are given to prove its validity.

1. Introduction

Based on the synthetic aperture radar (SAR), bistatic SAR (BSAR) system was developed by several countries, and some experiment results were obtained [1]. One-stationary bistatic SAR (OS-BSAR) [2] [3] is a special BSAR, which has a moving radar and a stationary radar. OS-BSAR has the advantage of the reducing vulnerability, improving the detectability, getting additional information, and lower cost. Circular SAR (CSAR) [4] is a SAR with a circular aperture, which is able to provide the higher resolution image and increased information in comparison to the SAR with a linear aperture (LSAR).

Bistatic CSAR (BCSAR) has advantages of the BSAR and CSAR, so it has gained wide attention [5] [6]. Australian Defence Science and Technology Organisation conducted a one-stationary BCSAR (OS-BCSAR) experiment [5], and the monostatic and bistatic data were collected by operating the Ingara radar in a circular spotlight mode in conjunction with a stationary ground-based receiver. A BCSAR experiment has been carried out by Chinese Academy of Sciences [6], and the transmitter and receiver fixed in different platforms move in parallel with equal radiuses but the different heights.

BSAR imaging algorithm includes frequency-domain algorithm (FDA) and time-domain algorithm (TDA). FDA usually aims to minimize processing time, but it leads to some limitations. Conversely, TDA doesn’t face to the limitations, but it has the high computation load. Time-domain backprojection algorithm (BPA) is considered as a linear transformation from the echo into SAR images, so it can be used directly to the mono and bistatic CSAR. To reduce the computation load, the fast implementation of the BPA was used for the monostatic CSAR imaging, i.e., fast backprojection algorithm (FBPA) [4]. However, the FBPA has not been investigated for the BCSAR imaging in the earlier publications.
This paper explores two FBPA for OS-BCSAR imaging, including the FBPA based on subaperture and elliptical polar grid processing and the FBPA based on subaperture and polar grid processing.

2. BPA for OS-BCSAR imaging

OS-BCSAR imaging geometry is shown in Figure 1, which has a moving radar fixed on an airplane and a stationary radar placed on a mountain. Solid circle is the moving radar’s track, with the position \( r_d(\phi) = (x_d(\phi), y_d(\phi), z_d) \) \( = (R_o \cos(\phi), R_o \sin(\phi), z_d) \). \( \phi \in [0, 2\pi] \) is the angular variation of moving radar, i.e. \( \phi(\eta) = V_o \eta / R_o \) at slow time \( \eta \). \( V_o \) is the moving radar’s speed at \( \phi \). \( R_o \) and \( z_d \) are radius and altitude of the moving radar’s circular track, respectively. \( r_s = (x_s, 0, z_s) \) is the stationary radar position. \( p \) is an arbitrary scattering target in the scene, with the position \( r_p = (x_p, y_p, 0) \). The ranges from the moving and stationary radars to the scattering target \( p \) at \( \phi \) is \( R(\phi, r_p) = R_d(\phi, r_p) + R_s(\phi, r_p) \).

The traveling distance from the moving and stationary radars to the scattering target \( p \) at \( \phi \) is \( R(\phi, r_p) = R_d(\phi, r_p) + R_s(\phi, r_p) \). The transmitted baseband signal is \( p(\tau) \), so the range compressed signal of the scattering target \( p \) is \( s_p(\tau, \phi) = \sigma_p p(\tau) [B(\tau - R(\phi, r_p)/c)] \). \( \tau \) is the fast time, \( \sigma_p \) is the scattering coefficient of the scattering target \( p \), \( c_0 \) is the speed of light, \( B \) is the transmitted signal bandwidth, \( p(\tau) \) is the range compressed pulse envelope. The backprojection (BP) of the BPA for the OS-BCSAR imaging is performed over the elliptical mapping. \( r = (x, y, 0) \) is the position of an arbitrary sample in the scene, \( f \) is the radar frequency, then the value of the OS-BCSAR image at the sample \( r \) is

\[
I(r) = \int_0^{2\pi} s_p(\tau, \phi) B[R(\phi, r_p)/c_0] d\phi \exp[j2\pi fR(\phi, r)/c_0] d\phi
\]

\[
= \int_0^{2\pi} \sigma_p p(\tau) [B[R(\phi, r) - R(\phi, r_p)/c_0]] \exp[j2\pi fR(\phi, r)/c_0] d\phi
\]

3. FBPA with subaperture and elliptical polar grid processing

Imaging geometry for FBPA with subaperture and elliptical polar grid processing is given in Figure 2. For the \( n \)-th subaperture, \( \phi_n \) is the angle corresponding to the \( n \)-th subaperture center \( A_{mn} \), and \( \phi_{tn} \) is its integration angle. \( r_m(\phi_n) = (x_m(\phi_n), y_m(\phi_n), z_m) \) is the moving radar’s position at \( \phi_n \). The ranges from the moving and stationary radars to the sample \( r \) at \( \phi_n \) are \( R_m \) and \( R_s \), with the magnitudes \( R_{mn} \) and \( R_{sn} \). \( \rho_n \) is the bistatic range from the moving and stationary radars to sample \( r \), and \( \theta_n \) is the angle between the vectors \( R_m \) and \( I_{mn} \) at \( \phi_n \). The elliptical polar coordinates \( (\rho_n, \theta_n) \) of the sample \( r \) are

\[
\rho_n = R_{mn} + R_{sn} = R_m(\phi_n, r) + R_s(\phi_n, r); \quad \theta_n = \arccos\left(\frac{(R_{mn}, I_{mn})/|R_{mn}|}{|R_{mn}|}\right)
\]
Figure 3. Top view in Figure 2.

I_m is \((\sin(\phi), -\cos(\phi), 0)\), with the origin at \(A_{m0}\), which is anti-parallel to \(V_m\). Figure 3 shows the top view of the imaging geometry in Figure 2. In Figure 3, we define a local coordinate system \((X_n, Y_n, Z_n)\) with the origin at \(A_{m0}\). It is the tangent to the circumference, which is translated to \(A_{m0}\) and rotated an angle \(\alpha_n\) with respect to the global Cartesian coordinate system \((X, Y, Z)\). \(\alpha_n\) is the angle between the axes \(X\) and \(X_n\), and it is found that \(\alpha_n = \phi_n - \pi/2\). The sample \(r\) in the Cartesian coordinate system is

\[
r = Br_0 + r_M(\phi_n)
\]

Where, \(r_0 = (x_0, y_0, z_0) = \left[R_{m0}\cos{\theta}_n, \sqrt{(R_{m0}\sin{\theta}_n)^2 - z_M^2}, z_M \right]\) is the position of the sample \(r\) in the local coordinate system, and \(B = \begin{bmatrix} \cos{\alpha_n} & -\sin{\alpha_n} & 0 \\ \sin{\alpha_n} & \cos{\alpha_n} & 0 \\ 0 & 0 & 1 \end{bmatrix}\) is the rotation matrix.

Similarly, the elliptical polar coordinates \((\rho_n, \theta_n)\) of the scattering target \(p\) at \(\phi_n\) are defined. Define that \(R(\phi, \rho_n, \theta_n) = R(\phi, r_p)\) and \(R(\phi, \rho_n, \theta_n) = R(\phi, r)\), then the BPA for the \(n\)-th subaperture is

\[
I_n(\rho_n, \theta_n) = \int \sigma_p P \left[ B \left( R(\phi, \rho_n, \theta_n) - R(\phi, \rho_n, \theta_n) \right) \right] c_0 \exp \left[ j2\pi f R(\phi, \rho_n, \theta_n)/c_0 \right] d\phi
\]

Figure 4. Bistatic range error.

First, the bistatic range sampling requirement for elliptical polar grids of subimages is \(|\Delta \alpha| \leq \epsilon_c/B\).

Second, the angular sampling requirement for elliptical polar grids of subimages needs to calculate the bistatic range error between two consecutive angular samples, which is depicted in Figure 4. \(A_{m\phi}\) is the moving radar’s position at \(\phi_n\), with \(\phi \in (\phi_n - \phi_n/2, \phi_n + \phi_n/2)\). \(d_{m\phi}\) is the range from \(A_{m0}\) to \(A_{m\phi}\). \(\alpha_{m\phi}\) is the angle from \(d_{m\phi}\) to \(I_{m0}\). \(r_{A_{m\phi}}\) and \(r\) are two consecutive angular samples, with the elliptical polar coordinates \((\rho_n, \theta_n \pm \Delta \theta_n)\) and \((\rho_n, \theta_n)\). The ranges from the moving and stationary radars to the sample \(r_{A_{m\phi}}\) at \(\phi_n\) are \(R_{m\phi+\Delta\theta_n}\) and \(R_{m\phi-\Delta\theta_n}\), with the magnitudes \(R_{m\phi+\Delta\theta_n}\) and \(R_{m\phi-\Delta\theta_n}\). The ranges from the position \(A_{m\phi}\) to the samples \(r\) and \(r_{A_{m\phi}}\) can be calculated and approximated as

\[
\begin{align*}
R_{m\phi+\Delta\theta_n} &= R_{m\phi} + \Delta R_n = R_{m\phi} + R_n \sin(\theta_n - \alpha_{M\phi}) \\
R_{m\phi-\Delta\theta_n} &= R_{m\phi} - \Delta R_n = R_{m\phi} - R_n \sin(\theta_n - \alpha_{M\phi})
\end{align*}
\]

According to \(R_{m\phi+\Delta\theta_n} + R_{m\phi-\Delta\theta_n} = R_{m\phi} + R_n\), the bistatic range error between the samples \(r\) and \(r_{A_{m\phi}}\) is

\[
\Delta R_n = R_{m\phi+\Delta\theta_n} + R_{m\phi-\Delta\theta_n} - (R_{m\phi} + R_n) \approx d_{m\phi} \left( \cos(\theta_n - \alpha_{M\phi}) - \cos(\theta_n - \alpha_{m\phi} \pm \Delta \theta_n) \right) \approx d_{m\phi} \sin(\theta_n - \alpha_{m\phi}) \Delta \theta_n
\]

\(d_{m\phi}\) is the length of the \(n\)-th subaperture, \(-d_{m\phi}/2 \leq d_{m\phi} \leq d_{m\phi}/2\), thus the upper bound of \(\Delta R_n\) is
and \( \theta_n \).

For the \( n\)-th subaperture, \( a_n \) and \( b_n \) are major and minor axes of the dashed ellipse, and the linear eccentricity is defined as \( e_n = \sqrt{a_n^2 - b_n^2} \). The polar coordinates \((\rho_n, \theta_n)\) of the sample \( r \) are defined. First, the polar grid’s origin is the center point of the stationary radar’s position and the considered moving radar’s subaperture center, i.e., \((x_n, y_n, z_n)\). Second, the polar range \( \rho_n \) is the distance from the polar grid’s origin to sample \( r \), and the polar angle \( \theta_n \) is the angle from \( a_n \) to \( b_n \). The polar coordinates \((\rho_n, \theta_n)\)

\[
\rho_n = \sqrt{(x_n + x_m(\phi_n))^2 + y_m(\phi_n)^2 + (z_n + z_m(\phi_n))^2}
\]

\[
\theta_n = \arccos\left(\frac{c_n^2 + \rho_n^2 - (x_n - x)^2 + y_n^2 + z_n^2}{2\rho_nc_n}\right)
\]

Similarly, the polar coordinates \((\rho_{wp}, \theta_{wp})\) of the target \( p \) are defined. Since \( R(\phi, r_p) = R(\phi, \rho_{wp}, \theta_{wp}) \) and \( R(\phi, r) = R(\phi, \rho_n, \theta_n) \), the value of the polar subimage at \((\rho_n, \theta_n)\) for the \( n\)-th subaperture imaging is

\[
I_n(\rho_n, \theta_n) = \int_{\phi_n - \phi_{wp}/2}^{\phi_n + \phi_{wp}/2} \sigma_p p\left[B\left(R(\phi, \rho_n, \theta_n) - R(\phi, \rho_{wp}, \theta_{wp})\right)/c_0\right]\exp\left[j2\pi fR(\phi, \rho_n, \theta_n)/c_0\right]d\phi
\]

To investigate the sampling requirements for the polar grids, we need to calculate the bistatic range from the moving and stationary radars to the sample \((\rho_n, \theta_n)\), which is shown in Figure 6. \( A_{\phi\theta} \) is the moving radar position at \( \phi \), with \( \phi \in (\phi_{wp} - \phi_{wp}/2, \phi_{wp} + \phi_{wp}/2) \). \( R_m(\phi, \rho_n, \theta_n) \) is the distance from \( A_{\phi\theta} \) to \((\rho_n, \theta_n)\). \( \mu_{\phi\theta} \) is the range between \( A_{\phi\theta} \) and \( A_{\psi\phi} \), which is the distance between the lines \( \mu_{\phi\theta} \) and \( R_{\phi\theta} \), and \( \psi_{\phi\theta} \) is the angle between straight lines \( \mu_{\phi\theta} \) and \( a_n \). \( \phi_{\phi\theta} \) is the angle between the lines \( R_{\phi\theta} \) and \( a_n \). \( d_{\phi\theta} \) is the length of the \( n\)-th subaperture, \(-d_{\phi\theta}/2 \leq \mu_{\phi\theta} \leq d_{\phi\theta}/2 \). Thus, the bistatic range at \( \phi \) is

\[
|\Delta R_n| \leq d_{\phi\theta} |\sin(\theta_n - \alpha_{\phi\theta})| |\Delta \theta_n| \leq d_{\phi\theta}|\Delta \theta_n|/2
\]

The maximum phase error is \( \Delta \Phi_{\text{max}} = 2\pi|\Delta R_{\text{max}}|/\lambda_{\text{min}} \), where \( \lambda_{\text{min}} \) is the minimum of the wavelength. If \( \Delta \Phi_{\text{max}} \leq \pi/8 \), the phase error effect can be neglected. Thus, the angular sampling requirement is

\[
|\Delta \theta_n| \leq \lambda_{\text{min}}/8d_{\phi\theta}
\]

4. FBPA with subaperture and polar grid processing

Imaging geometry for FBPA with subaperture and polar grid processing is shown in Figure 5. For the \( n\)-th subaperture, \( a_n \) and \( b_n \) are major and minor axes of the dashed ellipse, and the linear eccentricity is defined as \( e_n = \sqrt{a_n^2 - b_n^2} \). The polar coordinates \((\rho_n, \theta_n)\) of the sample \( r \) are defined. First, the polar grid’s origin is the center point of the stationary radar’s position and the considered moving radar’s subaperture center, i.e., \((x_n, y_n, z_n)\). Second, the polar range \( \rho_n \) is the distance from the polar grid’s origin to sample \( r \), and the polar angle \( \theta_n \) is the angle from \( a_n \) to \( b_n \). The polar coordinates \((\rho_n, \theta_n)\)

\[
\rho_n = \sqrt{(x_n + x_M(\phi_n))^2 + y_M(\phi_n)^2 + (z_n + z_M(\phi_n))^2}
\]

\[
\theta_n = \arccos\left(\frac{c_n^2 + \rho_n^2 - (x_n - x)^2 + y_n^2 + z_n^2}{2\rho_nc_n}\right)
\]

Similarly, the polar coordinates \((\rho_{wp}, \theta_{wp})\) of the target \( p \) are defined. Since \( R(\phi, r_p) = R(\phi, \rho_{wp}, \theta_{wp}) \) and \( R(\phi, r) = R(\phi, \rho_n, \theta_n) \), the value of the polar subimage at \((\rho_n, \theta_n)\) for the \( n\)-th subaperture imaging is

\[
I_n(\rho_n, \theta_n) = \int_{\phi_n - \phi_{wp}/2}^{\phi_n + \phi_{wp}/2} \sigma_p p\left[B\left(R(\phi, \rho_n, \theta_n) - R(\phi, \rho_{wp}, \theta_{wp})\right)/c_0\right]\exp\left[j2\pi fR(\phi, \rho_n, \theta_n)/c_0\right]d\phi
\]

To investigate the sampling requirements for the polar grids, we need to calculate the bistatic range from the moving and stationary radars to the sample \((\rho_n, \theta_n)\), which is shown in Figure 6. \( A_{\phi\theta} \) is the moving radar position at \( \phi \), with \( \phi \in (\phi_{wp} - \phi_{wp}/2, \phi_{wp} + \phi_{wp}/2) \). \( R_m(\phi, \rho_n, \theta_n) \) is the distance from \( A_{\phi\theta} \) to \((\rho_n, \theta_n)\). \( \mu_{\phi\theta} \) is the range between \( A_{\phi\theta} \) and \( A_{\psi\phi} \), which is the distance between the lines \( \mu_{\phi\theta} \) and \( R_{\phi\theta} \), and \( \psi_{\phi\theta} \) is the angle between straight lines \( \mu_{\phi\theta} \) and \( a_n \). \( \phi_{\phi\theta} \) is the angle between the lines \( R_{\phi\theta} \) and \( a_n \). \( d_{\phi\theta} \) is the length of the \( n\)-th subaperture, \(-d_{\phi\theta}/2 \leq \mu_{\phi\theta} \leq d_{\phi\theta}/2 \). Thus, the bistatic range at \( \phi \) is
can be calculated by as follows
\[ R(\phi, \rho_n, \theta_n) = R_\theta(\phi, \rho_n, \theta_n) + R_\phi(\rho_n, \theta_n) = \sqrt{\rho_n^2 + \mu_{\phi}^2 - 2R_\theta \mu_{\phi} \cos(\theta_n)} + R_{\phi_n} \approx R_{\phi_n} + R_{\theta_n} - \mu_{\phi} \cos(\theta_n) \]
\[ \approx \sqrt{\rho_n^2 + c_n^2 + 2\rho_n c_n \cos(\theta_n) + \sqrt{\rho_n^2 + c_n^2 - 2\rho_n c_n \cos(\theta_n) - \mu_{\phi} \cos(\theta_n)} \quad (11) \]
From the imaging geometry in Figure 6, \( \cos(\theta_{M}) = \cos(\phi_{M} + \Psi_{M}) = c_n \cos(\Psi_M) + \rho_n \cos(\theta_n + \Psi_M) \)
\[ \sqrt{\rho_n^2 + c_n^2 + 2\rho_n c_n \cos(\theta_n)} \]
Two-dimensional Fourier transforms of \( I_n(\rho_n, \theta_n) \) with respect to \( \rho_n \) and \( \theta_n \) is
\[ I_{F_{\rho\theta}}(k_{\rho}, k_{\theta}) = \int \int I_n(\rho_n, \theta_n) \exp[-j2\pi(k_{\rho} \rho_n + k_{\theta} \theta_n)] \, d\rho_n, d\theta_n \quad (13) \]
Where \( k_{\rho} \) and \( k_{\theta} \) are wavenumbers corresponding to polar range \( \rho_n \) and polar angle \( \theta_n \), respectively. Substituting (17) into (20), then the stationary phase condition is given by
\[ \frac{\partial}{\partial \rho_n} \left( 2\pi fR(\phi, \rho_n, \theta_n)/c_0 - 2\pi k_{\rho} \rho_n \right) = 0 \]
\[ \frac{\partial}{\partial \theta_n} \left( 2\pi fR(\phi, \rho_n, \theta_n)/c_0 - 2\pi k_{\theta} \theta_n \right) = 0 \quad (14) \]
Solving the above equations shows that \( I_{F_{\rho\theta}}(k_{\rho}, k_{\theta}) \) is nonzero, when
\[ \left[ \begin{array}{c} f_{\rho_{\text{max}}} \left( c_0 \sqrt{1 + \delta_n^2} \right) \leq k_{\rho} \\ -f_{\rho_{\text{max}}} \left( c_0 \sqrt{1 + \delta_n^2} \right) \leq k_{\rho} \leq f_{\rho_{\text{max}}} \left( c_0 \sqrt{1 + \delta_n^2} \right) \end{array} \right] \]
\[ \left[ \begin{array}{c} f_{\theta_{\text{max}}} \left( 2c_0 \sqrt{1 + \delta_n^2} \right) \leq k_{\theta} \\ -f_{\theta_{\text{max}}} \left( 2c_0 \sqrt{1 + \delta_n^2} \right) \leq k_{\theta} \leq f_{\theta_{\text{max}}} \left( 2c_0 \sqrt{1 + \delta_n^2} \right) \end{array} \right] \quad (15) \]
Where \( \delta_n \) is the ratio of \( c_n \) to \( \rho_n \) (i.e., \( \delta_n = c_n/\rho_n \)). The bounds of \( k_{\rho} \) and \( k_{\theta} \) can be translated into the sampling requirements of \( \rho_n \) and \( \theta_n \) for the \( n \)-th polar subimage, which are given by
\[ \left[ \begin{array}{c} |\Delta \rho_n| \leq c_0 \sqrt{1 + \delta_n^2} / 2(f_{\rho_{\text{max}}} - f_{\rho_{\text{min}}}) = c_0 \sqrt{1 + \delta_n^2} / 2B \\ |\Delta \theta_n| \leq c_0 \sqrt{1 + \delta_n^2} / f_{\theta_{\text{max}}} d_{\text{Mn}} = \lambda_{\text{max}} \sqrt{1 + \delta_n^2} / d_{\text{Mn}} \end{array} \right] \quad (16) \]
5. Experimental Results
To give a comparison of two proposed FBPA, the experimental results are shown in this section. The simulation parameters of the OS-BCSAR system are shown in Table 1. Five point targets labeled as A~E are located in the scene (both 50m in the X and Y axes), which are shown in Figure 7.

Figure 7 gives the imaging results by two proposed FBPA, and it is shown that the simulated scene is well reconstructed. From the top row, the CSAR feature for the targets A, C and D by the FBPA with the subaperture and elliptical polar grid processing is similar to those at the top row. However, the focusing quality of targets A, C and D at the bottom row is slightly degraded compared with those at the top row, due to the different grids of subimages.

Measured parameters (Resolution (RES) and PSLR) of the selected targets are computed in Table 2, which shows that they are close for two proposed FBPA. Processing time of two proposed FBPA is 49.9s and 46.6s, respectively, which shows that the imaging efficiency of two proposed FBPA is close.

**Table 1. Simulation parameters of the OS-BCSAR system.**

| Parameter                | Value       | Parameter                | Value       |
|--------------------------|-------------|--------------------------|-------------|
| Carrier frequency        | 400MHz      | Signal bandwidth         | 200MHz      |
| Sampling frequency       | 220Hz       | Pulse duration           | 1us         |
| Pulse repetition frequency| 100Hz       | Stationary radar position | (-1500, 0, 100)m |
| Moving radar angular speed| 6/5s        | Radius and altitude of the circular track | 1400m (500m) |
Figure 7. Imaging results obtained by two algorithms. Top row: FBPA with the subaperture and elliptical polar grid processing; Bottom row: FBPA with the subaperture and polar grid processing.

Table 2. Measured parameters of the selected targets.

| Algorithm                                           | Measured parameters | Target A | Target C | Target D |
|----------------------------------------------------|---------------------|----------|----------|----------|
| FBPA with the subaperture and elliptical polar grid processing | RES (m) X axis     | 0.279    | 0.270    | 0.280    |
|                                                    | Y axis              | 0.271    | 0.278    | 0.281    |
|                                                    | PSLR (dB) X axis    | -8.417   | -7.958   | -8.373   |
|                                                    | Y axis              | -8.228   | -8.731   | -8.241   |
| FBPA with the subaperture and polar grid processing | RES (m) X axis     | 0.284    | 0.275    | 0.281    |
|                                                    | Y axis              | 0.271    | 0.278    | 0.283    |
|                                                    | PSLR (dB) X axis    | -7.197   | -7.882   | -8.326   |
|                                                    | Y axis              | -7.167   | -8.833   | -8.321   |

6. Conclusion
In this paper, we present the FTDA for the OS-BCSAR imaging. It shows that the FBPA with the subaperture and elliptical polar grid processing and the FBPA with the subaperture and polar grid processing are generally available for the OS-BCSAR imaging.

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