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Spaceborne SAR Attitude Steering Method for Smart Imaging mode

Wei Yang, Xiao-Cong Ma, Wei Liu, Jie Chen*

The current spaceborne synthetic aperture radar (SAR) systems are operated to illuminate the scene along the satellite flying direction. However, in many cases, the interested areas are not parallel to the flying direction, so an innovative smart imaging mode is acquired, which can be employed for illuminating scene along a given direction. In this paper, a novel three-axis attitude steering method is proposed for smart imaging mode. First, mathematical model of the attitude steering is built by considering the restrictive conditions of zero Doppler centroid requirement and the position of interested area. Then, an iterative optimization algorithm is designed to calculate the three-axis steering angles. Finally, experiment results using the satellite tool kit (STK) tool validate the proposed methods well, especially in the case of coastline imaging.

Introduction: State-of-the-art spaceborne SAR systems have the capability of operating in different imaging modes, such as stripmap, ScanSAR, spotlight, Terrain Observation by Progressive Scans (TOPS), and sliding spotlight [1-2]. However, all of the imaging modes are limited in the restrictive conditions of zero Doppler centroid requirement and the position of interested area. There is no analytical solution for (4), which has significant benefits for image formation [6]. The Doppler centroid is given by

where \( \lambda \) is the wavelength, \( \mathbf{R} = \mathbf{R}_{w} - \mathbf{R} \), with the position vector of satellite \( \mathbf{R}_{w} \) and that of antenna-beam-pointing footprint \( \mathbf{R} \), \( \mathbf{R}' \) is the derivative of \( \mathbf{R}_{w} \), and \( \mathbf{R} \) is the modulus of \( \mathbf{R} \).

So, the problem is transformed into a joint parameter estimation problem, formulated as follows

\[
\begin{align*}
\mathbf{D}(\theta_{x}, \theta_{y}, \theta_{z}) & = \min_{(\theta_{x}, \theta_{y}, \theta_{z})} \mathbf{D}(\theta_{x}, \theta_{y}, \theta_{z}) \\
\mathbf{f}_{1}(\theta_{x}, \theta_{y}, \theta_{z}) & = 0
\end{align*}
\]

Optimized Algorithm: Theoretically, the problem in (4) has infinite number of solutions. However, a special solution is given by adopting the following \( \theta_{k} \),

\[
\theta_{k} = \arccos \left( \frac{1 + e \cos \beta}{\sqrt{1 + e^2 + 2e \cos \beta}} \right)
\]

where \( e \) is the eccentricity, and \( \beta \) is the true anomaly. (5) has an explicit physical meaning, which is used to accommodate the effect on Doppler centroid caused by the elliptical orbit.

Analysing (1) and (3), the key point is to calculate \( \mathbf{R}'_{w} \) by

\[
\mathbf{R}'_{w} \left( \theta_{x}, \theta_{y}, \theta_{z} \right) = \mathcal{A}_{1} \left[ 0 \mathbf{R}_{w} 0 \mathbf{R}_{w} \right] + \mathbf{R} \left( \theta_{x}, \theta_{y}, \theta_{z} \right)
\]

with matrices \( \mathcal{A}_{1} \) and \( \mathcal{A} \) given by

\[
\begin{align*}
\mathcal{A}_{1} & = \begin{bmatrix} \cos(\theta_{x}) - \sin(\theta_{x}) \sin(\theta_{y}) \\ 0 \\ \sin(\theta_{x}) \cos(\theta_{x}) - \sin(\theta_{y}) \sin(\theta_{z}) \\ 0 \end{bmatrix} \\
\mathcal{A} & = \begin{bmatrix} \cos(\Omega - \phi) - \sin(\Omega - \phi) \\ \sin(\Omega - \phi) \cos(\Omega - \phi) - \sin(\Omega - \phi) \\ 0 \\ 0 \end{bmatrix}
\end{align*}
\]

where \( \theta_{x} \) is the elevation angle, \( \Omega \) is the right ascension of ascending node (RAAN), \( \phi \) is the Greenwich hour angle, \( \theta_{y} \) is the orbit inclination angle, \( \Phi \) is the argument of perigee.

Then, dimension-reduced operation is employed by deriving the relationship of yaw steering angle and roll steering angle as follows:

\[
\begin{align*}
\alpha_{1} & = \sin \theta_{x} \theta_{x} + \alpha_{2} \sin \theta_{y} + \alpha_{3} 0 = 0 \\
\alpha_{1} & = \begin{bmatrix} \mathbf{R}_{w} \sin \theta_{x} - \mathbf{z} \mathbf{R}_{w} \sin \theta_{y} \cos \theta_{x} \cos \theta_{y} \\ \mathbf{z} \mathbf{R}_{w} \sin \theta_{x} \sin \theta_{y} \cos \theta_{y} \sin \theta_{x} \end{bmatrix} + \begin{bmatrix} \mathbf{z} \mathbf{R}_{w} \sin \theta_{x} \cos \theta_{x} \sin \theta_{y} \cos \theta_{y} \\ \mathbf{z} \mathbf{R}_{w} \cos \theta_{x} \cos \theta_{y} \sin \theta_{x} \sin \theta_{y} \end{bmatrix}
\end{align*}
\]

where \( \mathbf{z} \) is the earth’s rotation velocity.

Since the yaw steering angle can be represented by the roll steering angle, the problem is further transformed into searching for the optimum solution of \( \alpha_{2} \). Because there is no analytical solution for (4), an optimization method, based on the idea of the sequential similarity detection algorithm (SSDA) [7], is proposed to find the optimum value. The basic idea of SSDA is based on the accumulated error analysis, which corresponds to \( \mathbf{D}(\theta_{x}, \theta_{y}, \theta_{z}) \) in this letter. As for a wrong value for \( \alpha_{2} \), the accumulated error \( \Theta \) increases rapidly with \( k \), resulting in exceeding the threshold value \( D_{t} \) only by adding a few values of \( \lambda \).

So, it is not needed to calculate all the values of \( \lambda \), which improves processing efficiency significantly. On the contrary, the accumulated error increases slowly w.r.t the optimum value of \( \alpha_{2} \).
Algorithm Implementation: The SSDA algorithm (details can be found in [7]) is applied to obtain the optimum result. The flow chart is shown in Fig. 1, and the detailed steps are given below:

Step 1: Determine the iteration step \( \Delta \theta \) and the threshold value \( D_y \).

Step 2: Start the iteration with the initialization of iteration index \( k \) and \( \omega_i \).

Step 3: Given \( k \), calculate the corresponding \( \theta_1 \), \( \theta_2 \) and \( \theta_3 \) by (2), (5) and (9), respectively.

Step 4: Substituting \( \theta_1 \), \( \theta_2 \) and \( \theta_3 \) into (6), calculate \( \bar{R}_i \), the corresponding distance \( d_i \), and the accumulated error \( \Theta \).

Step 5: Compare \( \Theta \) with \( D_y \); if \( \Theta \) is larger than \( D_y \), return to Step 2 to start a new iteration by modifying \( \omega_i \) with \( \omega_i = \omega_i + \Delta \omega_i \); otherwise, compare \( k \) with \( N \); if \( k \) is smaller than \( N \), return to Step 3 to continue the iteration by changing \( k \) with \( k=k+1 \); otherwise, calculate \( D(\theta_1, \theta_2, \theta_3) \).

Step 6: Compare \( D(\theta_1, \theta_2, \theta_3) \) with \( D_y \); if \( D(\theta_1, \theta_2, \theta_3) \) is larger, return to Step 2; otherwise, end the iteration.

Experimental results and discussions: The proposed method is validated by the use of the STK tool, with parameters listed in TABLE I.

TABLE I Experimental parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eccentricity</td>
<td>0.0011</td>
</tr>
<tr>
<td>Right ascension of ascending node</td>
<td>50.0</td>
</tr>
<tr>
<td>/deg</td>
<td></td>
</tr>
<tr>
<td>Orbit inclination angle /deg</td>
<td>97</td>
</tr>
<tr>
<td>Argument of perigee /deg</td>
<td>90</td>
</tr>
<tr>
<td>Semi-major axis /km</td>
<td>700.323</td>
</tr>
<tr>
<td>Interval of attitude steering /s</td>
<td>0.1</td>
</tr>
<tr>
<td>Iteration step /deg/s</td>
<td>1.0e-3</td>
</tr>
<tr>
<td>Elevation /deg</td>
<td>30</td>
</tr>
</tbody>
</table>

The coastline of Hainan province, China, is selected as the experimental scene, as shown in Fig. 1. Since the coastline is sinuous and not in parallel to the flying direction, it is hard to illuminate the coastline in one time using the existing imaging modes, as mentioned at the beginning.

Using the smart imaging mode by the proposed attitude steering method, first, two linear trajectories are used to fit the sinuous coastline, which are determined by the given control points \( P_1 \), \( P_2 \), and \( P_3 \); then, the smart imaging mode is performed for each linear trajectory by three-axis steering. The performance comparison results are shown in TABLE II.

TABLE II Performance comparison results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Resolution/m</th>
<th>Observation Times</th>
<th>Roll rate / deg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stripmap</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Scan or TOPS</td>
<td>15</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Smart</td>
<td>3</td>
<td>1</td>
<td>-0.067/0.634</td>
</tr>
</tbody>
</table>

The illuminating trajectories by the stripmap mode and the smart mode are illustrated in Fig. 2(a) using the STK tool, and the three-axis steering results corresponding to smart mode are shown in Fig. 2(b)–(d).

Conclusions: A novel attitude steering method has been proposed for operating in the smart imaging mode, which overcomes the limitation of illuminating direction and improves the flexibility of visibility without resolution loss. Based on the required illuminating direction and zero Doppler centroid, the three-axis steering model was firstly provided. In order to obtain the required solution, a dimension-reduction operation was employed by deriving the relationship between the yaw and rolling angles. Then, the idea of SSDA algorithm was applied to estimate the three-axis steering angles. Experimental results have shown that the proposed method can solve the problem effectively.

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Fig. 2 Experimental results: (a) illuminating trajectories by stripmap mode (green color), and smart mode (blue color); (b) yaw steering results; (c) pitch steering results; (d) roll steering results.

References


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