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Spaceborne SAR Attitude Steering Method for Smart Imaging mode

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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 illuminate the scene along the satellite flying direction. It means that if the interested area is not along the flying direction, more SAR observations from different satellite orbits at different times are required, which will take a long time to cover the interested area. The ScanSAR or TOPS mode can be employed to mitigate this problem by enlarging the range-swath coverage, but at the cost of resolution [3]. Therefore, the smart imaging mode is required, which can be employed for illuminating the scene along a given direction by implementing three-axis attitude steering. In current spaceborne SAR systems, the main purpose of attitude steering is to minimize the Doppler centroid frequency, such as the one-axis (yaw) steering method with the circular orbit assumption [4], and the two-axis (yaw and pitch) steering method by taking the eccentricity into consideration [5].

In this letter, a novel attitude steering method is proposed for the smart imaging mode with three-axis (yaw, pitch and roll) steering. The mathematical model of attitude steering is first derived by considering the restrictive conditions of zero Doppler centroid requirement and the position of interested area, followed by the optimization algorithm for three-axis steering; finally, experiments are performed to validate the proposed method.

Steering Model: There are two conditions for realizing the smart imaging mode. The first one is that the sensor should illuminate the scene along a required direction determined by the control points located in the interested area. Since the satellite platform is discretely steered, we can obtain N antenna-beam-pointing footprints on the surface during the whole observation time. We define the sum of distances between the footprints and the linear trajectory that goes through the control points as follows:

$$\mathrm{D}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)=\sum_{\mathrm{k}=1}^{\mathrm{N}}\mathrm{d}_{\mathrm{k}}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right) \tag{1}$$

where d_{k} is the distance between the k-th footprint and the linear trajectory, N is the total number of steering footprints, θ_{y} and θ_{p} are the yaw steering angle and pitch steering angle, respectively. θ_{r} is the roll steering angle, given by

$$\theta_{\mathrm{r}}=\Delta\mathrm{t}\cdot\omega_{\mathrm{r}}\cdot\mathrm{k} \tag{2}$$

where $\Delta\mathrm{t}$ is the time interval of attitude steering, ω_{r} is the angular rate. For illuminating the scene along the required direction, the minimum value of $\mathrm{D}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)$ should be satisfied.

The second condition is the requirement of zero Doppler centroid, which has significant benefits for image formation [6]. The Doppler centroid is given by

$$\mathrm{f}_{\mathrm{d}}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)=-\frac{2}{\lambda}\frac{\vec{\mathrm{R}}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)\cdot\vec{\mathrm{R}}'\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)}{\mathrm{R}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)} \tag{3}$$

where λ is the wavelength, $\vec{\mathrm{R}}=\vec{\mathrm{R}}_{\mathrm{s}}-\vec{\mathrm{R}}_{\mathrm{f}}$ with the position vector of satellite $\vec{\mathrm{R}}_{\mathrm{s}}$ and that of antenna-beam-pointing footprint $\vec{\mathrm{R}}_{\mathrm{f}}$, $\vec{\mathrm{R}}'$ is the derivative of $\vec{\mathrm{R}}$, and R is the modulus of $\vec{\mathrm{R}}$.

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

$$\begin{cases}\left(\hat{\theta}_{\mathrm{y}},\hat{\theta}_{\mathrm{p}},\hat{\theta}_{\mathrm{r}}\right)=\min\limits_{\left(\theta_{\mathrm{y}},\theta_{\mathrm{r}}\right)}\mathrm{D}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)\\ \mathrm{f}_{\mathrm{d}}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)=0\end{cases} \tag{4}$$

Optimized Algorithm: Theoretically, the problem in (4) has infinite number of solutions. However, a special solution is given by adopting the following θ_{p} [5]

$$\theta_{\mathrm{p}}=\mathrm{acos}\left(\frac{1+\mathrm{e}\cos\beta}{\sqrt{1+\mathrm{e}^2+2\mathrm{e}\cos\beta}}\right) \tag{5}$$

where e is the eccentricity, and β 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 $\vec{\mathrm{R}}_{\mathrm{f}}$ by

$$\vec{\mathrm{R}}_{\mathrm{f}}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)=\mathrm{A}_1\mathrm{A}_2\left[0\quad\mathrm{R}\quad0\right]^{\mathrm{H}}+\vec{\mathrm{R}}_{\mathrm{s}}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right) \tag{6}$$

with matrices A_1 and A_1 given by

$$\mathrm{A}_1=\begin{bmatrix}\cos\left(\theta_{\mathrm{y}}\right) & 0 & -\sin\left(\theta_{\mathrm{y}}\right)\\ 0 & 1 & 0\\ \sin\left(\theta_{\mathrm{y}}\right) & 0 & \cos\left(\theta_{\mathrm{y}}\right)\end{bmatrix}\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\left(\theta_{\mathrm{s}}-\theta_{\mathrm{r}}\right) & -\sin\left(\theta_{\mathrm{s}}-\theta_{\mathrm{r}}\right)\\ 0 & \sin\left(\theta_{\mathrm{s}}-\theta_{\mathrm{r}}\right) & \cos\left(\theta_{\mathrm{s}}-\theta_{\mathrm{r}}\right)\end{bmatrix} \tag{7}$$

$$\begin{aligned}\mathrm{A}_2=&\begin{bmatrix}\cos\left(\Omega-\varphi\right) & -\sin\left(\Omega-\varphi\right) & 0\\ \sin\left(\Omega-\varphi\right) & \cos\left(\Omega-\varphi\right) & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\left(\theta_{\mathrm{i}}\right) & -\sin\left(\theta_{\mathrm{i}}\right)\\ 0 & \sin\left(\theta_{\mathrm{i}}\right) & \cos\left(\theta_{\mathrm{i}}\right)\end{bmatrix}\\ &\begin{bmatrix}-\sin\left(\Phi+\beta-\theta_{\mathrm{p}}\right) & -\cos\left(\Phi+\beta-\theta_{\mathrm{p}}\right) & 0\\ \cos\left(\Phi+\beta-\theta_{\mathrm{p}}\right) & -\sin\left(\Phi+\beta-\theta_{\mathrm{p}}\right) & 0\\ 0 & 0 & 1\end{bmatrix}\end{aligned} \tag{8}$$

where θ_{s} is the elevation angle, Ω is the right ascension of ascending node (RAAN), φ is the Greenwich hour angle, θ_{i} is the orbit inclination angle, Φ 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:

$$\mathrm{a}_1\cdot\sin^2\theta_{\mathrm{y}}+\mathrm{a}_2\cdot\sin\theta_{\mathrm{y}}+\mathrm{a}_3=0 \tag{9}$$

with a_1, a_2 and a_3 given by

$$\mathrm{a}_1=\left(\left|\vec{\mathrm{R}}_{\mathrm{s}}'\right|\sin\theta_{\mathrm{t}}-\xi\left|\vec{\mathrm{R}}_{\mathrm{s}}\right|\sin\theta_{\mathrm{s}}\cos\theta_{\mathrm{i}}\cos\theta_{\mathrm{p}}\right)^2+\left(\xi\left|\vec{\mathrm{R}}_{\mathrm{s}}\right|\sin\theta_{\mathrm{t}}\sin\theta_{\mathrm{i}}\cos\Phi\right)^2 \tag{10}$$

$$\mathrm{a}_2=2\cdot\left(\left|\vec{\mathrm{R}}_{\mathrm{s}}'\right|\sin\theta_{\mathrm{t}}-\xi\left|\vec{\mathrm{R}}_{\mathrm{s}}\right|\sin\theta_{\mathrm{t}}\cos\theta_{\mathrm{i}}\cos\theta_{\mathrm{p}}\right)\cdot\left(\xi\left|\vec{\mathrm{R}}_{\mathrm{s}}\right|\cos\theta_{\mathrm{t}}\cos\theta_{\mathrm{i}}\sin\theta_{\mathrm{p}}\right) \tag{11}$$

$$\mathrm{a}_3=\left(\xi\left|\vec{\mathrm{R}}_{\mathrm{s}}\right|\cos\theta_{\mathrm{t}}\cos\theta_{\mathrm{i}}\sin\theta_{\mathrm{p}}\right)^2-\left(\xi\left|\vec{\mathrm{R}}_{\mathrm{s}}\right|\sin\theta_{\mathrm{t}}\sin\theta_{\mathrm{i}}\cos\Phi\right)^2 \tag{12}$$

where $\theta_{\mathrm{t}}=\theta_{\mathrm{s}}-\theta_{\mathrm{r}}=\theta_{\mathrm{s}}-\Delta\mathrm{t}\cdot\omega_{\mathrm{r}}\cdot\mathrm{k}$, ξ 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 ω_{r}. 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 $\mathrm{D}\left(\theta_{\mathrm{y}},\theta_{\mathrm{p}},\theta_{\mathrm{r}}\right)$ in this letter. As for a wrong value for ω_{r}, the accumulated error Θ increases rapidly with k, resulting in exceeding the threshold value D_{g} only by adding a few values of d_{k}. So, it is not needed to calculate all the values of d_{k}, which improves processing efficiency significantly. On the contrary, the accumulated error increases slowly w.r.t the optimum value of ω_{r}.

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 $\Delta\omega_r$ and the threshold value D_g.

Step 2: Start the iteration with the initialization of iteration index k and ω_r.

Step 3: Given k, calculate the corresponding θ_r, θ_p and θ_y by (2), (5) and (9), respectively.

Step 4: Substituting θ_r, θ_p and θ_y into (6), calculate $\vec{R}_f$, the corresponding distance d_k and the accumulated error Θ.

Step 5: Compare Θ with D_g: if Θ is larger than D_g, return to Step 2 to start a new iteration by modifying ω_r with $\omega_r = \omega_r + \Delta\omega_r$; 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 $D_i\left(\theta_y, \theta_p, \theta_r\right)$.

Step 6: Compare $D_i\left(\theta_y, \theta_p, \theta_r\right)$ with $D_{i-1}\left(\theta_y, \theta_p, \theta_r\right)$: if $D_i\left(\theta_y, \theta_p, \theta_r\right)$ is larger, return to Step 2; otherwise, end the iteration.

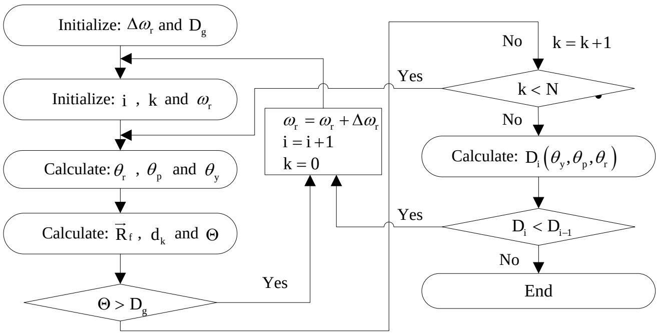


Fig. 1 Flow chart of the proposed method.

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

TABLE I Experimental parameters

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

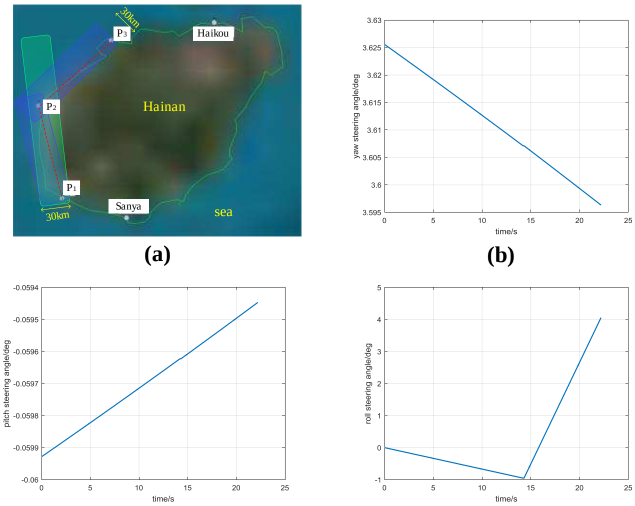
The coastline of Hainan province, China, is selected as the experimental scene, as shown in Fig. 1. Since the coastline is sinuous and not in parallel to the flying direction, it is hard to illuminate the coastline in one time using the existing imaging modes, as mentioned at the beginning.

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

Mode	Resolution/m	Observation Times	Roll rate/ deg/s
Stripmap	3	3	0
Scan or TOPS	15	1	0
Smart	3	1	-0.067/0.634

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).



(a) **(b)**

(c) **(d)**

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.

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 observation 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 roll steering 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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