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Beam scan mode analysis and design for geosynchronous SAR

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Abstract The beam velocity of geosynchronous synthetic aperture radar (GEO SAR) varies seriously with the orbital position and the scene position, which leads to a significant variation of the scene length and the azimuth resolution in the stripmap (SM) mode. To obtain uniform scene length and azimuth resolution, beam scan modes can be utilized in GEO SAR, such as the sliding spotlight (SLL) mode and the terrain observation by progressive scans (TOPS) mode. However, the conventional design method of the beam scan mode is based on the straight line model (SLM), which does not consider the effects of the curved satellite track and the spherical earth surface. To solve this problem, a curvature circle model (CCM) is proposed considering the actual satellite-earth relationship. By using the CCM, the beam velocity after the beam scan is derived. The scene length and the azimuth resolution are analyzed. The SLL mode and the TOPS mode are recommended for GEO SAR. After that, a design method of the beam scan mode is proposed based on the CMM. The performance of the proposed method is verified by computer simulations.

Keywords GEO SAR, beam scan, mode design, azimuth resolution, scene length

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1 Introduction

Geosynchronous synthetic aperture radar (GEO SAR) is a SAR system running on the geosynchronous orbit with a height of 36000 km [1, 2]. GEO SAR has the advantages of wide coverage and short revisit time. With a single GEO SAR, the coverage range can be more than 4000 km, and the revisit time is less than 24 h [3]. Because of these advantages, GEO SAR becomes a hot topic on geoscience remote sensing. Researchers have achieved significant progress in the theory research, and are making efforts on the engineering application [4, 5]. However, there are still many problems in GEO SAR. GEO SAR imaging faces the problem of serious spatial variances, which also exist in the bistatic SAR [6–9]. GEO SAR system design has trouble in the significant variation of the scene length and the azimuth resolution.

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Stripmap (SM) mode is frequently used in the conventional airborne SAR and low-earth-orbit SAR (LEO SAR). However, the beam velocity of the SM mode varies with the orbital position and the scene position in GEO SAR [10]. The beam veolicty can affect the scene length and the azimuth resolution. For GEO SAR with an inclination of 30°, the azimuth resolution of the SM mode varies from 0.5 m to 260 m, whereas the scene length varies from 60 km to 7500 km if a work time of 1 h is utilized. The significant variation of the azimuth resolution and the scene size means the SM mode is not the optimal option for GEO SAR imaging.

A feasible solution is using the beam scan mode, including the terrain observation by progressive scans (TOPS) mode, the sliding spotlight mode (SLL), the spotlight (SL) mode and so on. The beam scan mode can form the uniform azimuth resolution and scene length by controlling the beam velocity [11]. Currently, the beam scan mode has been widely used in LEO SAR, such as TerraSAR-X and Sentinel-1 [12, 13]. Because LEO SAR has short integration time and a small scene, the satellite track and the beam track are approximate to two straight lines. Thus, the analysis and design of the beam scan mode are all based on this straight line model (SLM) in LEO SAR. However, GEO SAR has a curved satellite track in the long integration time and a large scene on the spherical earth surface [14–16]. Therefore, the conventional SLM is ineffective in GEO SAR. The geometry model based on the actual satellite-earth relationship should be researched, and the mode design method for the beam scan mode should be studied.

In this paper, a curvature circle model (CCM) is proposed to describe the satellite-earth relationship of GEO SAR. The effects of the curved satellite track, the spherical earth surface, the beam scan and the squint observation are all considered in this model. After that, the expressions of the beam velocity, the azimuth resolution and the scene length are derived based on the CCM, and then the detailed work modes are discussed. Finally, the design method of the beam scan mode is proposed to realize specific azimuth resolution and scene length for GEO SAR.

The subsequent sections of the paper are organized as follows: Section 2 introduces the problem in the SM mode of GEO SAR; Section 3 proposes the CCM, and analyzes the performance parameters of the beam scan mode; Section 4 proposes the design method based on the CCM; Section 5 draws the final conclusion.

2 Stripmap mode analysis for GEO SAR

In the conventional airborne SAR and LEO SAR, the platform is supposed to move along a straight line, which produces a negative Doppler rate. However, GEO SAR has a curved satellite track, which causes that the Doppler rate can be not only negative, but also positive or zero [10]. Thus, the conventional SLM is not feasible in GEO SAR.

To solve this problem, we had proposed a curvature circle model to describe the curved track of GEO SAR [10], which is illustrated in Figure 1. The earth center is at point O, and the satellite moves from point S to point S'. The curved track can be approximately described with a curvature circle, whose center point is P, rotation axis is OP and rotation radius is r_s. The angle between the rotation axis and the orbital radius OS is defined as the curvature circle inclination ϕ. The zero-Doppler plane OSP rotates with the satellite around the OP axis.

In the SM mode, the beam is on the zero-Doppler plane. The beam velocity equals to the rotation velocity of the zero-Doppler plane at the target position, which is defined as the Doppler velocity. In the SM mode of the conventional airborne SAR and LEO SAR, the beam always moves forward, and the beam velocity is approximate to the platform velocity. However, it is more complicated in GEO SAR according to the CCM. For GEO SAR, the rotation axis divides the ground scene into three parts. The beam moves forward at the near range, almost hold still near the rotation axis, and moves backward at the far range. Additionally, the absolute value of the beam velocity is smaller when the scene is nearer to the rotation axis. This indicates that the beam velocity of SM mode (or the Doppler velocity) in GEO SAR significantly varies with the scene position. What's more, the curvature circle varies with the orbital position. Thus, the Doppler velocity changes both with the range scene position and the azimuth orbital

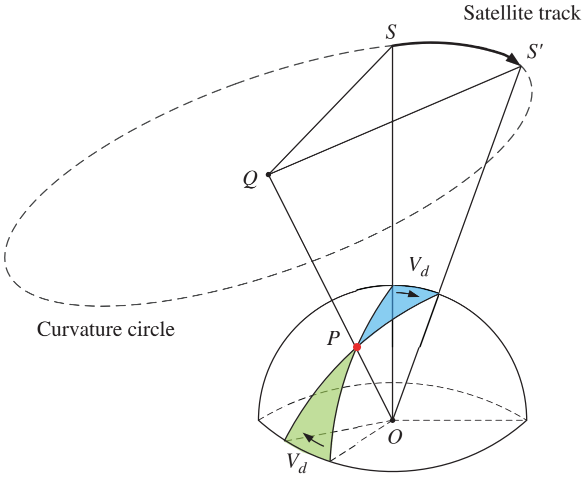


Figure 1 (Color online) Curved satellite track and spherical earth surface in GEO SAR.

Table 1 Parameters of GEO SAR

Parameter	Value	Unit
Semi-major	42164	km
Eccentricity	0	
Orbital inclination	30	degree
Signal wavelength	0.1	m
Antenna size	30	m

position.

The azimuth resolution of the SM mode can be written as

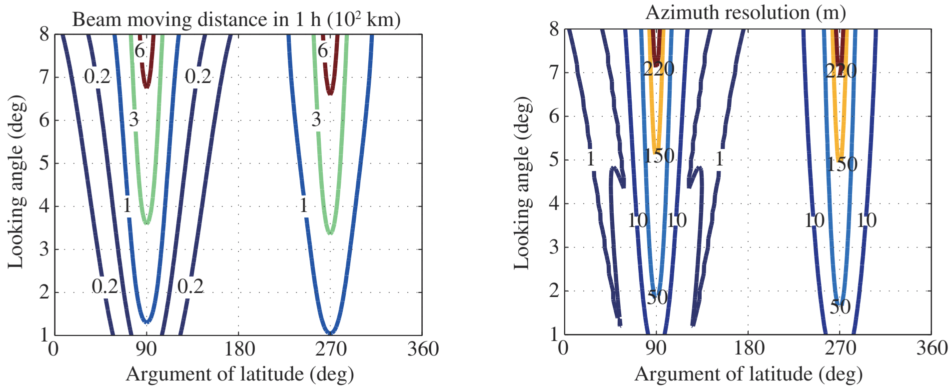
$$\rho_a = \frac{V_g}{V_s} \cdot \frac{D_a}{2}, \tag{1}$$

where V_d is the Doppler velocity, V_s is the satellite velocity, and D_a is the azimuth antenna length. The scene length can be expressed approximately as

$$W_a \approx V_g T_w, \tag{2}$$

where T_w is the working time of the SM mode. According to (1) and (2), the spatial variation of the Doppler velocity will affect the azimuth resolution and the scene length of the SM mode in GEO SAR. If the work time is fixed, the azimuth resolution and the scene length of the SM mode will vary with the orbital position and the scene position in GEO SAR.

Table 1 shows a set of typical parameters of GEO SAR. Using these parameters, we simulate the azimuth resolution and the scene length for a work time of 1 h. The contour simulation results are presented in Figure 2. For different orbital positions and scene positions, the scene length varies from 60 km to 7500 km, and the azimuth resolution varies from 0.5 m to 260 m. The nonuniform distribution of the azimuth resolution and the scene length will weaken the advantage of GEO SAR, and it is not conducive to the generation of standardized SAR productions. If we expect an azimuth resolution of 20 m and a scene length of 600 km, only 30% of the positions satisfy the demand. This weakens the advantage of width coverage of GEO SAR. Even in the region where the demand is satisfied, the azimuth resolution varies from 3 m to 20 m. Thus, extra processing (such as the multilook processing) has to be made to obtain the uniform product, which increases the complexity of data processing. In general, due to the variant Doppler velocity, the SM mode is not the best choice for GEO SAR imaging.



(a) (b)

Figure 2 (Color online) Parameter of SM mode. (a) Scene length for 1 h; (b) azimuth resolution.

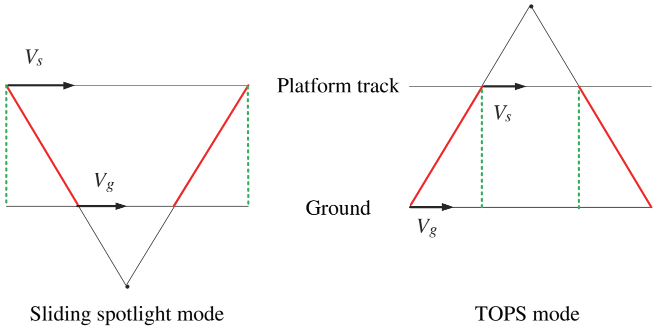


Figure 3 (Color online) Straight line model.

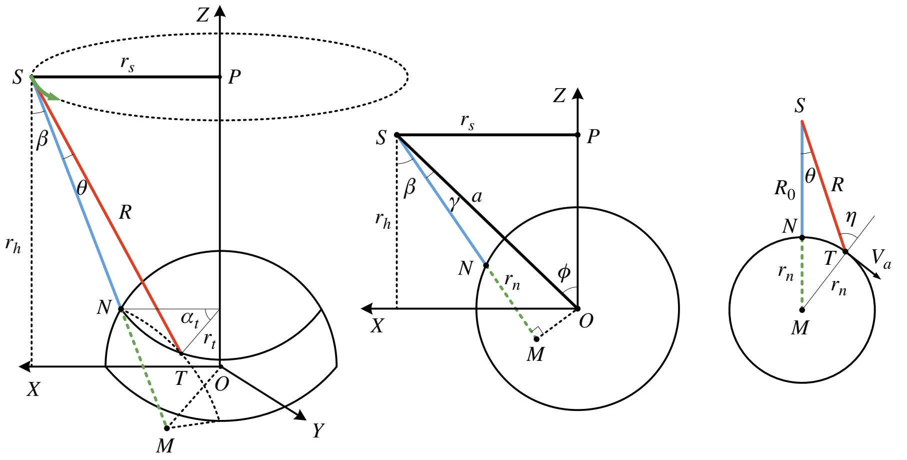
3 Beam scan mode analysis for GEO SAR

To solve the problem, the work modes based on the azimuth beam scan can be used to control the beam velocity and maintain uniform azimuth resolution and scene length. The beam scans forward to enlarge the scene length in the TOPS mode, and scans backward to shorten the scene length in the SLL mode. Figure 3 shows the TOPS mode and the SLL mode based on the SLM, which is used in the conventional airborne SAR and LEO SAR. In this model, the platform track is assumed to move along a straight line; the ground is supposed to be a plane, and is represented by a parallel line to the platform track. The Doppler plane (dash line) is perpendicular to the track, and the beam (red line) scans forward or backward. However, GEO SAR has a curved satellite track, which cannot be approximate to a straight line. Besides, the spherical earth surface has to be considered in GEO SAR. Thus, the traditional SLM fails in GEO SAR. The design method of the beam scan mode based on the SLM is no longer efficient in GEO SAR.

3.1 Curvature circle model

To design the beam scan mode for GEO SAR, the curved satellite track and the spherical earth surface should be considered firstly. Besides, the squint observation, which will be widely used in GEO SAR to promote the coverage performance, also needs to be taken into count.

Considering these demands, we establish the geometry model of GEO SAR as illustrated in Figure 4. At the aperture center time, the satellite is at point S, the satellite track is along a curvature circle whose radius is r_s. The earth is described with a sphere whose center is at O and radius is R_e. The orbital semi-major a is the distance from O to S. The beam center illuminates the earth surface at point T. The beam direction is represented by the elevation angle β, the squint angle θ and the slant range R. The slant range is the distance from the T to S, the squint angle is angle between the slant range and the zero-Doppler plane OSP, and the elevation angle is angle between the slant plane SNT and the rotation



(a) (b) (c)

Figure 4 (Color online) Curvature circle model for beam scan mode. (a) 3-D model; (b) the X-Z plane; (c) the slant range plane.

axis OP. The distance between the target and the rotation axis is r_t, and the angle between r_t and the zero-Doppler plane OSP is the target angle α_t . Besides, the looking angle of the satellite is γ, and it satisfies

$$\phi = \beta + \gamma. \tag{3}$$

The slant plane SNT intersects the earth surface, and forms a circle whose center is at point M and radius is r_n.

The coordinate system is defined as follows: the original point is earth center O, the Y axis is along the satellite velocity direction at the center of work time, the Z axis is along the rotation axis OP, and the X axis is along the rotation radius.

3.2 Beam direction and velocity

According to the above model, the satellite moves along the curvature circle with a constant speed, and the satellite rotation angle on the curvature circle plane can be expressed as

$$\alpha_s = k_s t = \frac{V_s t}{r_s}, \tag{4}$$

where k_s is the rotation angular speed. Thus, the satellite position can be written as

$$\boldsymbol{S} = \begin{bmatrix} r_s \cos\alpha_s \\ r_s \sin\alpha_s \\ r_h \end{bmatrix}, \tag{5}$$

where r_h is the distance from the earth center to the curvature circle plane and satisfies

$$r_h = \sqrt{a^2 - {r_s}^2}. \tag{6}$$

The slant range vector can be written as

$$\boldsymbol{R} = R \begin{bmatrix} \cos\theta\sin\beta\cos\alpha_s + \sin\theta\sin\alpha_s \\ \cos\theta\sin\beta\sin\alpha_s - \sin\theta\cos\alpha_s \\ \cos\theta\cos\beta \end{bmatrix}, \tag{7}$$

and the target position can be expressed as

$$\boldsymbol{T} = \boldsymbol{S} - \boldsymbol{R} = \begin{bmatrix} r_s\cos\alpha_s - R\left(\cos\theta\sin\beta\cos\alpha_s + \sin\theta\sin\alpha_s\right) \\ r_s\sin\alpha_s - R\left(\cos\theta\sin\beta\sin\alpha_s - \sin\theta\cos\alpha_s\right) \\ r_h - R\cos\theta\cos\beta \end{bmatrix}. \tag{8}$$

The beam scan is supposed to be along both the range and azimuth directions. Thus, the looking angle and the squint angle both change with the time. The azimuth scan angular speed can be defined as k_a, and the range scan angular speed is k_r . Besides, the beam scan also changes the slant range. The relationship between the slant range and the squint angle can be written as

$$\begin{cases} R^2 + a^2 - 2aR\cos\theta\cos\gamma = {R_e}^2, \\ R_0 + r_n = a\cos\gamma = \frac{\sin\eta}{\sin(\eta-\theta)}R, \end{cases} \tag{9}$$

where η is the incident angle on the slant range plane as shown in Figure 4(c). According to (9), the slant range variation rate can be written as

$$\frac{\mathrm{d}R}{\mathrm{d}t} = R\tan\eta\left(k_a + k_r\frac{\tan\gamma}{\tan\theta}\right). \tag{10}$$

The target radius and the target angle satisfy

$$\begin{cases} r_t\cos\alpha_t = r_s - R\cos\theta\sin\beta, \\ r_t\sin\alpha_t = R\sin\theta. \end{cases} \tag{11}$$

Thus, by taking derivation of the target point, the beam velocity at the center of the work time can be expressed as

$$\begin{aligned} \boldsymbol{V}_g = {} & V_d\begin{bmatrix} -\sin\alpha_t \\ \cos\alpha_t \\ 0 \end{bmatrix} + V_a\begin{bmatrix} -\sin\beta\sin\delta \\ \cos\delta \\ -\cos\beta\sin\delta \end{bmatrix} \\ & + \frac{k_rR}{\cos\eta\cos\gamma\tan\theta}\begin{bmatrix} \cos\eta\cos\gamma\sin\theta\cos\beta - \sin\eta\sin\gamma\cos\theta\sin\beta \\ \sin\eta\sin\gamma\sin\theta \\ -\cos\eta\cos\gamma\sin\theta\sin\beta - \sin\eta\sin\gamma\cos\theta\cos\beta \end{bmatrix}, \end{aligned} \tag{12}$$

where $\delta = \eta - \theta$.

According to (12), the beam velocity consists of three items. The first item is the Doppler velocity, which is produced by the satellite motion. The Doppler velocity stands for the rotation velocity of the zero-Doppler plane at the target distance. Its direction is along the rotation direction of the satellite, and its value can be expressed as

$$V_d = k_sr_t. \tag{13}$$

The second item is the azimuth scan velocity, which is produced by the azimuth beam scan or the variation of the squint angle. Its direction is perpendicular to MT on the slant range plane as shown in Figure 4(c), and its value can be expressed as

$$V_a = \frac{k_aR}{\cos\eta}. \tag{14}$$

The third item is the range scan velocity, which is produced by the range beam scan or the variation of the elevation angle. Its value satisfies

$$V_r = k_rR\frac{\sqrt{(\sin\eta\sin\gamma)^2 + (\cos\eta\cos\gamma\sin\theta)^2}}{\cos\eta\cos\gamma\tan\theta}. \tag{15}$$

The three items are along different directions on the earth surface as shown in Figure 5. Define the angle between the Doppler velocity and the azimuth direction as the Doppler velocity angle Λ_s, and the angle between the range beam scan velocity and the azimuth direction as the range velocity angle Λ_r. They satisfy

$$\begin{cases} \cos\Lambda_s = \cos(\eta-\theta)\cos\alpha_t + \sin\beta\sin(\eta-\theta)\sin\alpha_t, \\ \cos\Lambda_r = \frac{\sin^2\eta\sin\gamma}{\sqrt{(\sin\eta\sin\gamma)^2+(\cos\eta\cos\gamma\sin\theta)^2}}. \end{cases} \tag{16}$$

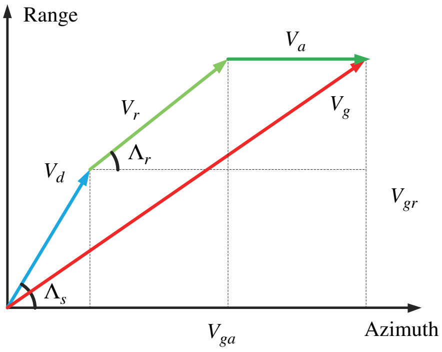


Figure 5 (Color online) Beam velocity.

When the squint angle is zero, $\cos\Lambda_s = \pm 1$, and the Doppler velocity, the azimuth scan velocity, and the range scan velocity are all along the azimuth direction. Besides, Λ_s also indicates the scene position. When $\cos\Lambda_s > 0$, the scene is at the near range; when $\cos\Lambda_s \approx 0$, the scene is near the rotation axis; when $\cos\Lambda_s < 0$, the scene is at the far range.

The beam velocity along the range direction can be written as

$$V_{gr} = V_d \sin\Lambda_s + V_r \sin\Lambda_r. \tag{17}$$

The scene extends along direction of the total beam velocity which may not be along the azimuth direction. If the scene is along the azimuth direction, the range beam velocity should satisfy $V_{gr} = 0$. Thus, the range scan angular speed can be written as

$$k_r = -\frac{V_d}{R} \cdot \frac{\tan\Lambda_s \cos\gamma \tan\theta}{\sin\Lambda_r \sqrt{(\sin\eta \sin\gamma)^2 + (\cos\eta \cos\gamma \sin\theta)^2}}. \tag{18}$$

The total beam velocity equals to the beam velocity along the azimuth direction, and can be expressed as

$$V_g = V_{ga} = V_d \cos\Lambda_s + V_r \cos\Lambda_r + V_a = V_{da} + \frac{k_b R}{\cos\eta}, \tag{19}$$

where V_{da} is the Doppler velocity along azimuth direction, and k_b is the equivalent scan angular speed. They satisfy

$$\begin{cases} V_{da} = V_d \cos\Lambda_s, \\ k_b = k_a + k_r \frac{\sin^2\eta \tan\gamma}{\tan\theta}. \end{cases} \tag{20}$$

3.3 Azimuth resolution and scene length

The beam scan will affect the scene length and the azimuth resolution directly. In the work time, the moving distance of the satellite is given by

$$L_s \approx V_s T_w. \tag{21}$$

Meanwhile, the scene length after the beam scan can be written as

$$L_g \approx V_g T_w = A L_s, \tag{22}$$

where A is the spotlight coefficient (SC) of GEO SAR. It can be expressed as

$$A = \frac{V_g}{V_s} = A_0 + \frac{k_b R}{V_s \cos\eta}, \tag{23}$$

where A_0 is the SC in the SM mode and can be defined as the basic spotlight coefficient (BSC). It satisfies

$$A_0 = \frac{V_{da}}{V_s}. \tag{24}$$

Table 2 Parameter range of different modes

		ITOPS	SL	SLL	SM	TOPS
$A_0 > 0$	A	< 0	0	$(0,A_0)$	A_0	$> A_0$
	k_b	$< -\frac{V_{da}}{R}$	$-\frac{V_{da}}{R}$	$(-\frac{V_{da}}{R},0)$	0	> 0
	V_g	< 0	0	$(0,V_{da})$	V_{da}	$> V_{da}$
$A_0 = 0$	A	< 0	0	0	0	> 0
	k_b	< 0	0	0	0	> 0
	V_g	< 0	0	0	0	> 0
$A_0 < 0$	A	> 0	0	$(A_0,0)$	A_0	$< A_0$
	k_b	$> -\frac{V_{da}}{R}$	$-\frac{V_{da}}{R}$	$(0,-\frac{V_{da}}{R})$	0	< 0
	V_g	> 0	0	$(V_{da},0)$	V_{da}	$< V_{da}$

The beam width along the azimuth direction can be expressed as

$$L_a = \frac{\lambda R}{D_a \cos\eta}. \tag{25}$$

The integration time of a specific target can be written as

$$T_a = \frac{L_a}{V_g} = \frac{\lambda R}{V_g D_a \cos\eta}. \tag{26}$$

Thus, the azimuth resolution is given by [17]

$$\rho_a = K_g \frac{\lambda R}{2V_s T_a \cos\theta} = AK_g \cdot \frac{D_a}{2} \cdot \frac{\cos\eta}{\cos\theta}, \tag{27}$$

where K_g is the projection coefficient from the slant plant to the ground.

A_0 and A are the key parameters of the beam scan mode. A_0 is the ratio of the azimuth Doppler velocity and the satellite velocity. It indicates the satellite-earth relationship formed by the curved satellite track and the spherical earth surface, and stands for the curved degree of the satellite-earth relationship. $A_0 \approx 1$ in LEO SAR, wheras A_0 can be larger than 10 in GEO SAR. A is the ratio of the beam velocity and the satellite velocity. It affects the azimuth resolution and the scene length, and indicates the effects of the beam scan. Besides, A_0 and A are closely related to the detailed work modes, which will be discussed in the following subsection.

3.4 Detailed work modes

According to the equivalent scan angular speed k_b and the SC, the beam scan mode can be further divided into more detailed modes, including the TOPS mode, the SL mode, the SLL mode, the SM mode and the invert TOPS (ITOPS) mode. For the different BSCs, the divisions are different as shown in Table 2. When the BSC is positive, the detailed modes are similar to those in LEO SAR. When the BSC equals to zero, the SL mode, the SLL mode and the SM mode are the same. When the BSC is negative, the sign of the parameter range is different. Figure 6 shows the simplified satellite-earth relationship in the case of negative BSC. The zero-Doppler plane (the dash line) intersects between the satellite track and the ground. The beam (red line) moves backward in the SM mode, SLL mode and TOPS mode; it moves forward in the ITOPS mode. The beam moving directions are opposite to those in the case of positive BSC.

In the above modes, the SM mode, SL mode and ITOPS mode are quite special. The beam does not scan in the SM mode. The SL mode has a zero beam velocity, so Eqs. (26) and (27) are ineffective. In the SL mode, the integration time equals to the work time, and the azimuth resolution can be expressed as

$$\rho_a = K_g \frac{\lambda R}{2V_s T_w \cos\theta}. \tag{28}$$

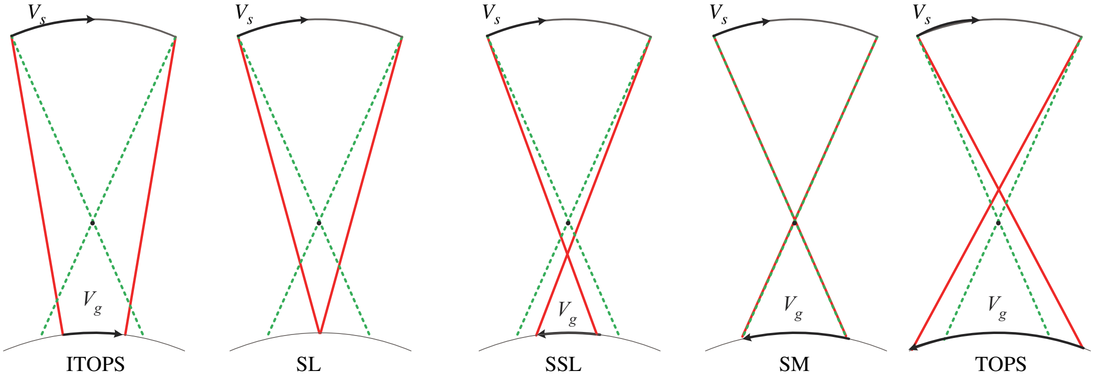


Figure 6 (Color online) Detailed beam scan modes with a negative BSC.

The scene length is the beam width, which normally cannot satisfy the demand of the large scene. The SL mode is therefor not suitable for GEO SAR. The ITOPS mode has a beam velocity invert to that of the SM mode, so the beam velocity is over compensated. The SL mode or TOPS mode can realize the same resolution and scene length with a smaller scan angle, so the ITOPS mode is not the optimal option for GEO SAR.

Normally, the TOPS mode and the SLL mode are more suitable for GEO SAR to realize the wide coverage and modest resolution. If the SM mode has a high resolution and insufficient scene length, the TOPS mode can be used to decrease the azimuth resolution and enlarge the scene length. If the SM mode has a low resolution and a large scene length, the SLL mode can be utilized to promote the azimuth resolution and shorten the scene length.

4 Beam scan mode design for GEO SAR

4.1 Mode design method

According to (19) and (27), the azimuth resolution and the beam velocity are both related to the squint angle, which is time-variant. In the system design, we normally aim to realize the desired values of the azimuth resolution and the beam velocity at the center of the work time.

The detailed design procedure is shown as follows:

(1) Calculate the slant range R and R_0 according to the looking angle and squint angle.

(2) Calculate the curvature circle parameters by using

$$\begin{cases} r_s = \frac{{V_s}^2}{A_s}, \\ \phi = \arcsin\left(\frac{r_s}{a}\right), \end{cases} \tag{29}$$

where A_s is the satellite acceleration perpendicular to the satellite velocity.

(3) Calculate the target parameters by using

$$\begin{cases} \beta = \phi - \gamma, \\ r_t = \sqrt{(r_s - R\cos\theta\sin\beta)^2 + (R\sin\theta)^2}, \\ \alpha_t = \arcsin\left(\frac{R\sin\theta}{r_t}\right). \end{cases} \tag{30}$$

Table 3 Parameters of GEO SAR

Parameter	Value	Unit
Resolution	20	m
Looking angle	4.5	degree
Squint angle	3	degree
Ground spread ratio	1.2	

(4) Calculate the velocity angles with

$$\begin{cases} r_n = \sqrt{{R_e}^2 - (a\sin\gamma)^2}, \\ \eta = \arcsin\left(\frac{R_0 + r_n}{r_n}\sin\theta\right), \\ \Lambda_s = \arccos\left[\cos(\eta-\theta)\cos\alpha_t + \sin\beta\sin(\eta-\theta)\sin\alpha_t\right], \\ \Lambda_r = \arccos\frac{\sin^2\eta\sin\gamma}{\sqrt{(\sin\eta\sin\gamma)^2 + (\cos\eta\cos\gamma\sin\theta)^2}}. \end{cases} \tag{31}$$

(5) Calculate the BSC and the azimuth Doppler velocity with

$$\begin{cases} A_0 = \frac{r_t\cos\Lambda_s}{r_s}, \\ V_{da} = A_0 V_s. \end{cases} \tag{32}$$

(6) Calculate the SC and the beam velocity with

$$\begin{cases} A = \mathrm{sign}(A_0)\cdot\frac{1}{K_g}\cdot\frac{\cos\theta}{\cos\eta}\cdot\frac{2\rho_a}{D_a}, \\ V_g = AV_s. \end{cases} \tag{33}$$

Here, the symbolic function is used to avoid the ITOPS mode, and it can be written as

$$\mathrm{sign}(A_0) = \begin{cases} 1, & A_0 \geqslant 0, \\ -1, & A_0 < 0. \end{cases} \tag{34}$$

(7) Calculate the scan angular speeds and the work time by using

$$\begin{cases} k_b = (A - A_0)\frac{V_s\cos\eta}{R}, \\ k_r = -\frac{V_d\tan\Lambda_s\cos\gamma\tan\theta}{R\sqrt{(\sin\eta\sin\gamma)^2 + (\cos\gamma\sin\theta)^2}}, \\ k_a = k_b - k_r\frac{\sin^2\eta\tan\gamma}{\tan\theta}, \\ T_w \approx \frac{L_g}{V_g}. \end{cases} \tag{35}$$

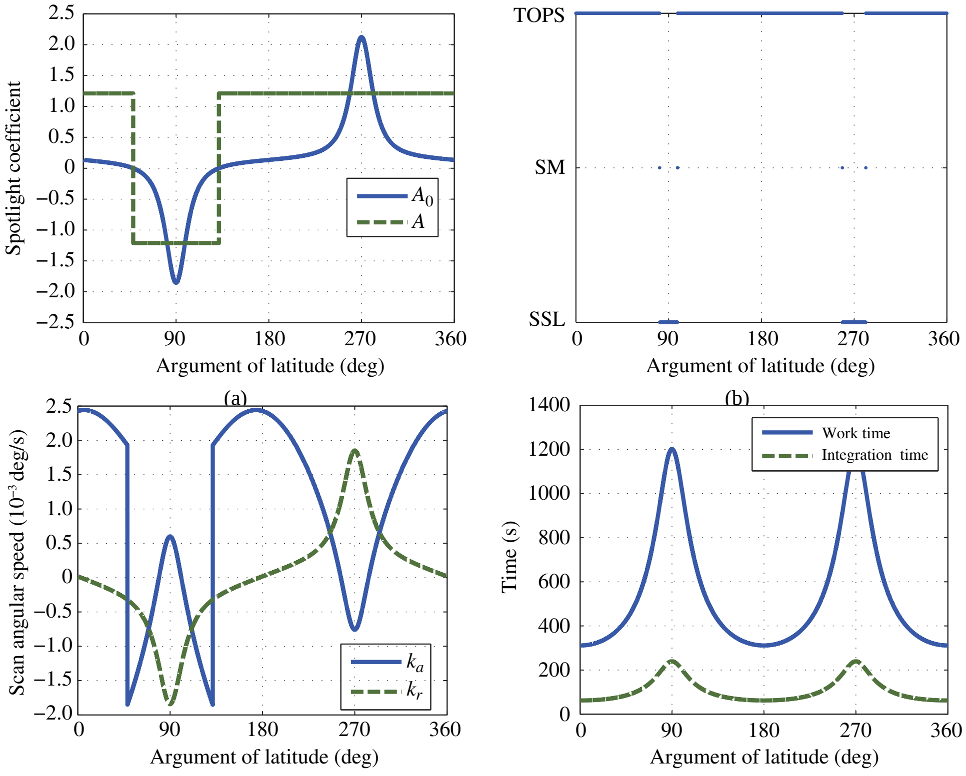
4.2 Design example

Computer simulations are carried out to verify the design method. The parameters of GEO SAR are given in Table 1. The other parameters are shown in Table 3.

4.2.1 *Design results*

The mode design is performed following the procedures presented in Subsection 4.1, and the design results are illustrated in Figure 7. Figure 7(a) shows the BSC and the SC of GEO SAR, and Figure 7(b) shows the detailed modes used for different orbital positions. Figure 7(c) shows the scan angular speeds, and Figure 7(d) shows the required work time and integration time.

The TOPS mode, the SM mode and the SLL mode are used for different orbital positions. For the position with negative SCs, the SLL mode and the TOPS mode are used instead of the ITOPS mode to reduce the required scan angle and scan angular speed.



(a) (b)

(c) (d)

Figure 7 (Color online) Design results. (a) BSC and SC; (b) work mode; (c) scan angular speed; (d) work time and integration time.

The scan angular speeds are relatively low and are −0.002–0.0025 deg/s approximately. In theory, phased array antenna (PAA) can realize any beam direction, and can vary the direction smoothly and continuously. A typical example is TerraSAR-X. TerraSAR-X can realize a resolution of 0.2 m with a scan angle of 4.4 deg, and the scan angular speed is about 0.008–0.014 deg/s. A simplified method is to adjust the beam direction discretely instead of smoothly. In the design results above, the azimuth scan angle can be adjusted 0.01 deg per 4 second at the equator. The discrete adjusting of the beam direction may cause some loss to the radiation performance, but it is simple for PAA to realize.

4.2.2 *Comparison between the CMM and the SLM*

We select four orbital positions, and compare the design results of the CMM with those of the SLM. The design results are presented in Table 4. According to the CCM, TOPS mode and SLL mode should be used for the selected orbital positions. Meanwhile, the SLM only corresponds to a BSC of one which is smaller than the SC of the selected orbital position, so GEO SAR works only in the TOPS mode if the SLM is used.

To verify the scene length and the azimuth resolution, we simulate according to the designed results shown in Table 5. The scene length is obtained by simulating the beam illumination position and integrating the moving distance. The azimuth resolution is obtained by imaging with the back projection algorithm, and the target is set at the scene center. When the CMM is used, the scene lengths are quite close to 600 km, and the azimuth resolutions are 20 m approximately. Meanwhile, the conventional SLM cannot obtain the desired scene length and azimuth resolution. This proves that the proposed CMM and the beam scan mode design method can realize the required performance, and it is better than the conventional SLM.

As mentioned above, the azimuth resolution varies along the azimuth direction, and reaches the largest value at the scene edges. The design method can obtain the desired azimuth resolution at the scene center,

Table 4 Design results

	CMM				SLM			
Argument of latitude (deg)	0	30	60	90	0	30	60	90
A_0	0.135	0.077	−0.122	−1.854	1	1	1	1
A	1.212	1.212	−1.212	−1.212	1.11	1.11	1.11	1.11
k_a (10^{-3} deg/s)	2.427	2.261	−1.287	0.601	0.271	0.238	0.149	0.07
k_r (10^{-3} deg/s)	0.009	−0.082	−0.247	−0.921	0	0	0	0
T_w (s)	311	355	568	1202	340	388	620	1312

Table 5 Verification of scene length and azimuth resolution

	CMM				SLM			
Argument of Latitude (deg)	0	30	60	90	0	30	60	90
Scene length (km)	601.4	601.9	599.9	598	126.4	80.6	569.1	696.8
Azimuth resolution (m)	19.98	19.97	19.97	19.94	4.22	3.64	3.64	43.47

and an iteration design can be done to obtain a desired azimuth resolution at the scene edges. Firstly, design the parameters with the proposed method. Then, calculate the azimuth resolution at the scene edges based on the design results, and obtain the deterioration ratio of the azimuth resolution at the scene edges with respect to that at the scene center. Thirdly, design the parameters again considering the resolution deterioration ratio. In the above design example, the azimuth resolutions at the scene edges are calculated to be 19 m and 21 m at the equator. Thus, the ratio is 1.05 approximately, and a desired azimuth resolution of 19 m at the scene center can be used in the mode designed.

5 Conclusion

The beam velocity of GEO SAR varies with the orbital position and the scene position seriously. This causes a significant variation of the azimuth resolution and the scene length in the SM mode. Therefore, the SM mode is unsuitable for the engineering application of GEO SAR. To obtain uniform azimuth resolution and scene length, beam scan modes can be used to control the beam velocity. However, the conventional design method of the beam scan mode is based on the SLM, which is not feasible in GEO SAR. To solve the problem, a curvature circle model is proposed to describe the satellite-earth relationship, and facilitate the mode design of GEO SAR. Based on the CMM, the beam velocity is derived and analyzed. It is found that 2-D beam scans are needed to ensure the azimuth scene direction. Then, the expressions of the azimuth resolution and the scene length are derived. According to the SC, the beam scan mode is further divided into the TOPS mode, SM mode, SLL mode, SL mode and ITOPS mode. The TOPS mode and the SLL mode are recommended for GEO SAR to obtain wide coverage and a modest resolution. Finally, a design method is proposed to realize specific azimuth resolution and scene length, and its performance is verified by the computer simulation.

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Conflict of interest The authors declare that they have no conflict of interest.

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