OPTIMAL GEOMETRY CONFIGURATION OF BISTATIC FORWARD-LOOKING SAR

Junjie Wu, Jianyu Yang, Haiguang Yang, Yulin Huang

School of Electronic Engineering
University of Electronic Science and Technology of China
Sichuan, P. R. China 610054

ABSTRACT

With appropriate geometry configurations, bistatic Synthetic Aperture Radar (SAR) can break through the limitations of monostatic SAR on forward-looking imaging. With such a capability, bistatic forward-looking SAR (BFSAR) has extensive potential applications. In this paper, based on the resolution calculation using gradient theory, we give a general rule to determine the optimal geometry configuration of different modes of BFSAR. The results can be used to design BFSAR flight campaign and measure the performance of a specific BFSAR system.

Index Terms— Bistatic SAR, forward-looking, synthetic aperture radar(SAR), resolution

1. INTRODUCTION

Synthetic Aperture Radar (SAR) has been applied in civilian and military fields very widely. Nevertheless, because of the inherent characteristic of monostatic SAR, it can not image the forward-looking terrain of the aerocraft [1]. The consequence is SAR technology can not play sufficient role in self-landing, navigation, etc.

As an emerging SAR technology and with many advantages, bistatic SAR is receiving considerable attention at present [2]. With the choice of proper geometry, bistatic SAR can image in the receiver's flight direction or backwards. We call the former case bistatic forward-looking SAR (BFSAR). This might result in some new applications of bistatic SAR in aviation by imaging obstacles (e.g. mountains) in flight direction which are covered by fog, rain and clouds. With such systems, we can also improve the safety of landing airplanes by imaging the runway in dirty weather conditions [3, 4].

In SAR imaging, its geometry has to be evaluated and optimized in order to image the selected area with highest quality. This paper researches the optimal geometry configuration of BFSAR. Section II presents the resolution results of BFSAR briefly and proposes a criterion to measure its imaging performance. In Section III, we give the optimal geometry configurations of three modes of BFSAR using this rule. Section IV is the simulation. The conclusions are given in Section V.

2. BFSAR RESOLUTION

A general derivation of the spatial resolution using the gradient theory for BFSAR can be found in [5, 6]. It results in the following range resolution ρ_r and azimuth resolution ρ_a of a certain target point on the ground plane:

$$\boldsymbol{\rho}_r = \frac{1/B}{|\bigtriangledown \tau_{dg}|}\frac{\bigtriangledown \tau_{dg}}{|\bigtriangledown \tau_{dg}|} \tag{1}$$

$$\boldsymbol{\rho}_a = \frac{1/T}{|\bigtriangledown f_{dg}|}\frac{\bigtriangledown f_{dg}}{|\bigtriangledown f_{dg}|} \tag{2}$$

where B and T are the range signal bandwidth and coherent accumulation time; $\bigtriangledown\tau_{dg}$ and $\bigtriangledown f_{dg}$ are the range and azimuth gradients projected onto the ground.

According to geometry theory, after the projection onto $x-y$ plane using the projection matrix $\mathbf{\Gamma}_{xy} = \boldsymbol{I} - \boldsymbol{z}\boldsymbol{z}^T$, $\boldsymbol{I} \in \boldsymbol{R}^3$, the z component vanishes for all vectors. For simplicity, we use the projected geometry vectors directly in this paper. So

$$\bigtriangledown\tau_{dg} = \frac{2cos(\beta_g/2)}{c}\mathbf{\Phi}_{bg} \tag{3}$$

$$\bigtriangledown f_{dg} = -\frac{1}{\lambda}\Big\{\omega_{Tg}\mathbf{\Gamma}_{Tg} + \omega_{Rg}\mathbf{\Gamma}_{Rg}\Big\} \tag{4}$$

where β_g is the projected bistatic angle and $\mathbf{\Phi}_{bg}$ is the unit vector along the bisector of β_g; ω_{Tg} and ω_{Rg} are the effective rotating angle speeds of transmitter and receiver on the ground; $\mathbf{\Gamma}_{Tg}$ and $\mathbf{\Gamma}_{Tg}$ are the unit vectors along these angle speeds.

Note that the azimuth resolution depends on the angular rates of the transmitter and receiver about the point. The range resolution is irrelative with the velocities, but has a closed relation with the platform location geometry.

In the optimal sense, we can give the general conditions of SAR imaging as follows:

(1)The range resolution should be minimum: min$\{\rho_r\}$.

(2)The azimuth resolution should be minimum as well: min$\{\rho_a\}$.

(3)Two resolutions should be orthogonal: $\langle\boldsymbol{\rho}_r, \boldsymbol{\rho}_a\rangle = 0$.

In monostatic side-looking case, the points along the boresight line can satisfy these conditions at the same time. Thus, we always think the boresight mode is the optimal imaging geometry of monostatic SAR. However, the above three terms can not be met simultaneously in many cases, such as some BFSAR. So we have to find the best compromise between the desired spatial resolution and the orthogonality.

In [7], the condition (3) was adopted to build a metric for general bistatic SAR. Unfortunately, this result is not applicable for BFSAR, because the two resolutions are not orthogonal forever in some BFSAR configurations. In [4], the authors think the trajectory of the transmitter should always be orthogonal to its line of sight (LOS) to obtain largest Doppler gradient. However, the result is no Doppler change occurrence, thus no azimuth resolution.

Resolution cell area is a fine parameter to show the resolving power of an imaging system. It was first proposed for bistatic radar in [8]. In [9], this concept was discussed based on the general ambiguity function for bistatic SAR. Bistatic resolution cell area (BRCA) is defined as:

$$BRCA = \frac{\rho_r \rho_a}{sin(\theta_g)} = \frac{\rho_r^2 \rho_a^2}{|\boldsymbol{\rho}_r \times \boldsymbol{\rho}_a|} \tag{5}$$

where θ_g is the separation angle between ρ_r and ρ_a, as shown in Fig.1. The dashed lines are the iso-Doppler contours and the solid lines represent the iso-range contours. BRCA is the area (the shade part in Fig.1) of the gridding intersection of these two kinds of lines.

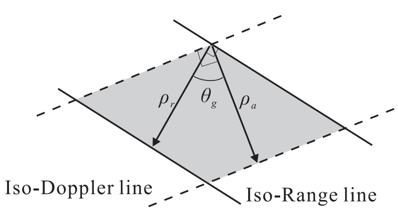


Fig. 1. Bistatic resolution cell area.

From (5) we can find that the concept of BRCA can integrate all the three conditions above to measure the bistatic SAR imaging performance. So in this paper, we use BRCA as a parameter to determine the optimal system geometry configuration of BFSAR. In this sense, the BRCA in the receiver's forward-looking direction should be minimum for the optimal BFSAR. In the next section, we will use this criterion to research the optimal geometry configuration of different kinds of BFSAR.

In addition, it should be mentioned that under the BRCA criterion, the resolutions of range and azimuth maybe not orthogonal enough. This would result in some degree of coupling between these two directions thus some processing difficulties. But the result is optimal in the sense of information acquisition.

3. BFSAR OPTIMAL GEOMETRY CONFIGURATION

In BFSAR, the receiver always works in forward-looking mode and has specified imaging area. This means the transmitter platform plays the key role in defining the optimal geometry. So in essence, the optimal geometry configuration of BFSAR means the determination of transmitter's location relative to the receiver and the irradiation style, which is usually determined by the squint angle.

According to the geometry configuration, we can categorize BFSAR into three modes [5], as shown in Fig.2: (1) Mode I–Translational Invariant (TI) airborne BFSAR; (2) Mode II–Translational Variant (TV) airborne BFSAR; (3) Mode III–airborne/ground based BFSAR. In Fig.2, Tr and Rev denote the transmitter and receiver's nadir locations, while $\boldsymbol{V}_{Tg}$ and $\boldsymbol{V}_{Rg}$ are their velocity vectors projected onto the ground, respectively; θ_{sTg} is the transmitter's projected squint angle; Φ_g is the angle between the transmitter and receiver's flight trajectories; $dir(\cdot)$ means the direction of $(\cdot)$; L_g is the distance between two flight trajectories.

As we have mentioned in [5], these three modes have different imaging principles. In Mode I and II, the Doppler gradient is mainly resulted from the transmitter lateral movement while the contribution of the receiver can be neglected comparing with the transmitter. As for Mode III, the Doppler element is totally brought about by the receive moving platform. So in these modes of BFSAR, only one platform plays dominant role to produce Doppler component. Thanks to this characteristic, we can simplify the calculation of the azimuth resolution by neglecting the minor contribution of the other platform.

3.1. Mode I and Mode II

Using (5), we can obtain the BRCA of Mode I as:

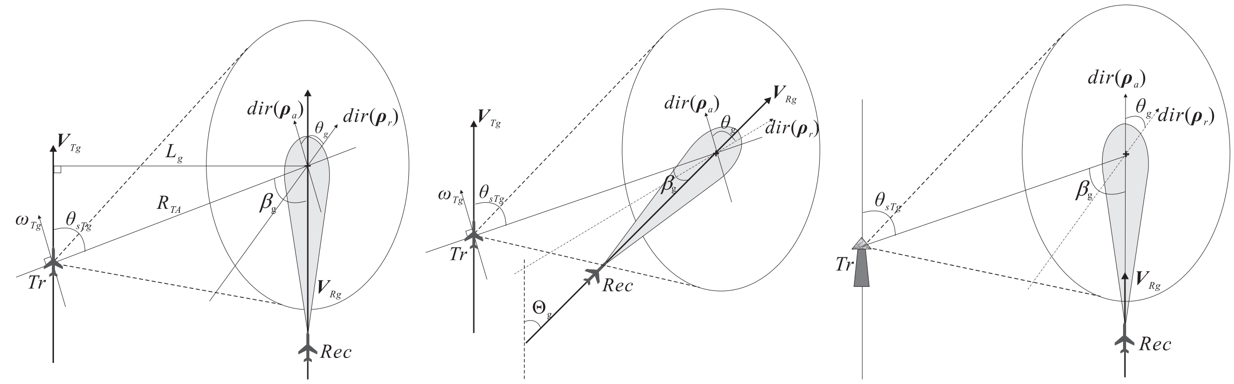
$$\begin{aligned} BRCA &= \frac{\rho_r \rho_a}{sin(\theta_g)} \\ &= \frac{1/B}{|\bigtriangledown \tau_{dg}|} \frac{1/T}{|\bigtriangledown f_{dg}|} \frac{1}{sin(\theta_g)} \\ &= \frac{c}{2Bcos(\beta_g/2)} \frac{\lambda L_g}{V_{Tg} T sin(\theta_{sTg})^2} \frac{1}{sin(\theta_g)} \end{aligned} \tag{6}$$

From Fig.2(a), we can find that $\theta_{sTg} = \beta_g$, $\theta_g = \pi/2 - \theta_{sTg}/2$. Then:

$$BRCA = \frac{c/2B}{cos(\theta_{sTg}/2)} \frac{\lambda L/(V_{Tg} T)}{sin(\theta_{sTg})^2} \frac{1}{cos(\theta_{sTg}/2)} \tag{7}$$

So the optimization problem becomes how to choose a projected squint angle θ_{sTg} of the transmitter to make the below condition satisfied:

$$max \left\{ cos(\theta_{sTg}/2)^2 sin(\theta_{sTg})^2 \right\} \tag{8}$$



(a) Mode I (b) Mode II (c) Mode III

Fig. 2. Geometry configurations of three BFSAR modes.

According to the properties of trigonometric function, the max value of (8) is near 0.6 when the optimal θ_{sTg} is 0.4π.

As for Mode II, $\theta_{sTg} - \Theta_g = \beta_g$, $\theta_g = \pi/2 - (\theta_{sTg} - \Theta_g)/2$. Then we get the following condition which should be satisfied:

$$max\left\{cos\left(\frac{\theta_{sTg} - \Theta_g}{2}\right)^2 sin(\theta_{sTg})^2\right\} \tag{9}$$

Now we have to determine two parameters θ_{sTg} and Θ_g. If we can choose them freely, the result which could make the $BRCA$ minimum is $\theta_{sTg} = \Theta_g = \pi/2$. This means the optimal geometry is that the transmitter flies towards the direction orthogonal to the receiver's trajectory and irradiates in boresight mode. In fact, this is also the optimal case among all modes of BFSAR, because we can get the minimum BRCA of $\frac{c\lambda L_g}{2BV_{Tg}T}$, which is an half of the RCA for boresight monostatic SAR. The result is that the three conditions in Section. II are satisfied simultaneously in this case. This is different with Mode I, where this relationship does not exist for any point on the ground and any geometry configuration.

If we design the system geometry with a determined θ_{sTg} or Θ_g, then the other parameter can be determined using (9) as well. Then we can get an optimal configuration under that condition.

3.2. Mode III

The geometry of Mode III BFSAR is shown in Fig.2(c). In this mode, the transmitter is stationary. So the Doppler element is totally brought about by the receive moving platform, which can not be neglected at this time.

Assume the transmitter downward-looking angle is θ_{dl} and the flying height is H, the azimuth resolution becomes:

$$\rho_a = \frac{\lambda/T}{V_R sin(\theta_{dl})^3/H} \tag{10}$$

We can find that ρ_a is inversely proportional with the cubic sine of the downward-looking angle and is irrelevant with the transmitter. In addition, the azimuth resolution always points to the receiver's flight path. Theoretically ρ_a is very low, but even so we can still obtain 2D resolving because of the separation of ρ_a and ρ_r. In practical applications, one should try to increase the downward-looking angle and the co-irradiation time to extend the Doppler bandwidth as far as possible.

In this mode, BRCA is:

$$BRCA = \rho_a \frac{c}{2Bcos(\beta_g/2)} \frac{1}{sin(\theta_g)} \tag{11}$$

From Fig.2(c), we can know that $\theta_g = \beta_g/2$ and $\theta_{sTg} = \beta_g$. So, the condition becomes:

$$max\left\{cos(\theta_{sTg}/2) sin(\theta_{sTg}/2)\right\} \tag{12}$$

The result is θ_{sTg} should be $\pi/2$. That means the transmitter should irradiate with a beam vertical to the receiver's flight path. Then the bistatic angle becomes $\pi/2$, the angle between the two resolutions is $\pi/4$.

4. SIMULATIONS

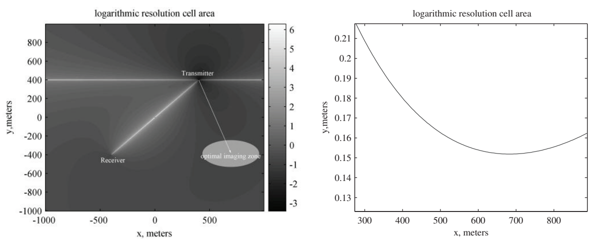
Below are given the simulation results of the proposed criterion for different modes of BFSAR. The simulation parameters are listed in Table I.

Fig.3(a) shows the logarithmic resolution cell area of Mode I BFSAR. In the figure, the nadir locations of transmitter and receiver are marked. The optimal imaging zone is at the forward squint area of the transmitter. Fig.3(b) is the BRCA slice along the receiver's forward-looking direction. From the curve, we can find the position of the minimal value, which is around $x = 685m$. Then we can calculate the squint angle of the transmitter as: $\theta_{sTg} = arctan\left(\frac{400+400}{685-400}\right) \approx 0.4\pi$.

The BRCA of Mode II BFSAR is shown in Fig.4(a). The optimal imaging zone is along the transmitter's side-looking

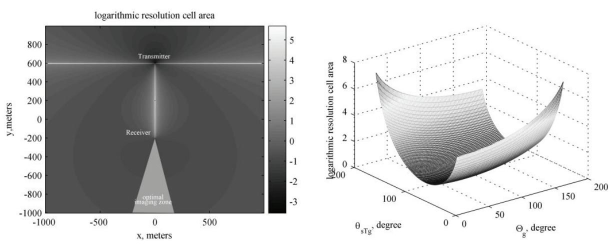
Table 1. Simulation Parameters

	Parameters	Symbol	Quantity
Mode	Wavelength	λ	0.03 m
	Bandwidth	B	100 MHz
	Synthetic Interval	T	2 s
I	Tr velocity vector	$\boldsymbol{V}_{Tg}$	[200, 0] m/s
	Tr location	Tr	[400, 400] m
	Rec location	Rev	[-400, -400] m
II	Tr velocity vector	$\boldsymbol{V}_{Tg}$	[200, 0] m/s
	Tr location	Tr	[0, 600] m
	Rec location	Rev	[0, -200] m



(a) BRCA of Mode I (b) BRCA along the forward-looking direction

Fig. 3. BRCA of Mode I.



(a) BRCA of Mode II (b) BRCA versus θ_{sTg} and Θ_g

Fig. 4. BRCA of Mode II.

area. In Fig.4(b) the BRCA is calculated in dependence on the transmitter's squint angle and the trajectory separation angle. From this figure, the minimal BRCA can be obtained when $\theta_{sTg} = \Theta_g = \pi/2$. And we can also find these two angles almost give the equal contributions to the BRCA. Because the BRCA of Mode III has a simple relation with the transmitter's squint angle, we do not give the simulation here.

5. CONCLUSIONS AND FUTURE WORK

The resolving performance and the consequential optimal configuration can not be sufficiently described only by range resolution, azimuth resolution or the angle between them. Based on the concept of resolution cell area, this paper proposed a criterion which can integrate all these three parameters. Using this criterion, we researched the optimal geometry configuration of BFSAR and obtained the following results:

(1) For Mode I, the transmitter should illuminate the forward-looking area of the receiver with a projected squint angle about 0.4π.

(2) For Mode II, the transmitter should fly along the vertical direction of the receiver's trajectory and working in side-looking mode. This is also the best configuration of BSAR, which could obtain a half resolving power of monostatic SAR.

(3) For Mode III, the transmitter's beam should point to the norm direction of the receiver's flight path.

These results are just the theoretical optimal geometry configurations of BFSAR in the sense of information acquisition. In practice, due to the processing limitations, the separation angle between the two resolutions should not be very small because of the resulting coupling. So one should find the best compromise between the BRCA, practical processing level and application requirement.

In the future, we will explore the imaging algorithms for different mode BFSAR.

6. REFERENCES

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