Doppler Properties of Spaceborne/Airborne Hybrid Bistatic Synthetic Aperture Radar

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Abstract In this paper, a special geometry case of spaceborne-airborne bistatic SAR (SA-BiSAR) is considered, in which satellite and aircraft flight paths are parallel and their antennas are steering at the strip map. This case is a simple but typical application example, which is applicable for non-cooperative illumination. The integration time of SA-BiSAR system is derived via the motion of transmitter and receiver footprint. In parallel and stripmap mode, Doppler frequency is obtained through the combination between spaceborne and airborne SAR. Other Doppler properties have been envisaged, including Doppler bandwidth and azimuth resolution. The overall simulation experiments are conducted and some characteristics are exhibited. The critical parameters, which have the significant effect on the SA-BiSAR Doppler properties, are extracted by analytical expressions and numerical simulations. In parallel and strip map mode and with reference to ENVISAT-1, SA-BiSAR system possesses the potential of yielding 10 m azimuth resolution and 0.5 s integration time for C-band via the analysis of simulation results.

Keywords bistatic synthetic aperture radar; integration time; Doppler frequency; azimuth resolution

CLC number P237.3

Introduction

Bistatic synthetic aperture radar (SAR) is spatially separated between the transmitter and receiver, which can be carried by different platforms, such as satellite and aircraft. Compared to monostatic SAR, bistatic SAR has many advantages, such as, improving object scattering coefficients, increasing system survival, and enhancing stealth in military applications, etc. For spaceborne bistatic SAR system, Moccia et al. have performed many excellent studies. [1-5] They have comprehensively studied the performance of spaceborne bistatic SAR system: orbit and Doppler properties in parallel and squint mode, steering of transmitter and receiver antennas, swath overlap and spatial resolution.

The configurations of SA-BiSAR (Spaceborne/airborne BiSAR) consist of spaceborne transmitter and airborne receiver. Because of the different velocity of spaceborne (7000 m•s^{-1}) and airborne (100-200 m•s^{-1}) SAR, the integration time and azimuth resolution are the comparatively basic questions. As far as cooperative mode of SA-BiSAR system is concerned, some preliminary studies and experiments have been performed. The advantages and challenges of SA- BiSAR are described and its feasibility has been confirmed by the experiments. [6-7] The combination methods of antenna steering are presented, which is satellite steering antenna in slide spotlight or spotlight and aircraft steering antenna in footprint chasing mode, in order to enlarge the azimuth dimension of the scenario. [8]
The appearance of SA-BiSAR system indicates an increasing military demand and technique allowance at present. The SA-BiSAR system can conduct original scientific experiments, surveillance and reconnaissance as well as remote sensing. Nevertheless, its application scope is limited by practical factors including the radar satellite numbers and orbit parameters. In this paper, we perform the comprehensive analysis of Doppler properties of SA-BiSAR system in parallel and strip map mode, which include Doppler centroid frequency, Doppler frequency rate, the integration time and azimuth resolution. With reference to ENVISAT-1, the overall simulation experiments are performed and some characteristics are extracted.

1 Integration time

In our case, we consider the satellite as the transmitter platform and the aircraft as the receiver platform. The aircraft flight path is parallel to the satellite path and aircraft is deployed between satellite and target. Transmitter and receiver antennas are steering at the strip map. This geometry configuration can cause the SA-BiSAR system to possess large integration time and small bistatic angle. Additionally, we suppose that the receiver footprint is totally covered by transmitter footprint. It is justified since transmitter footprint is wider than receiver footprint. The geometry model of the SA-BiSAR system is shown in Fig.1(a). ‘S’ denotes the satellite, ‘A’ denotes the aircraft and ‘T’ denotes the center target within the explored area.

High resolution is an essential characteristic of synthetic aperture radar. Azimuth resolution depends on the synthetic aperture length, which is closely related to synthetic aperture time. Therefore, integration time is a vital parameter for synthetic aperture radar. The illuminating time of target within the receiver footprint is

$$T_a = \frac{R_a \Delta \beta_a}{V_a} = \frac{W_a}{V_a}$$

(1)

where $W_a$ is the azimuth width of receiver footprint and is equal to $W_{2,a} - W_{1,a}$, $\Delta \beta_a$ is the azimuth angle of receiver beam, $V_a$ is the velocity of aircraft on the ground, respectively, $R_{a0}$ is the distance between receiver and center target at the mid aperture time.

Similarly, the illuminating time of target within the transmitter footprint is

$$T_s = \frac{R_s \Delta \beta_s}{V_s} = \frac{W_s}{V_s}$$

(2)

where $W_s$ is the azimuth width of the transmitter footprint and is equal to $W_{2,s} - W_{1,s}$, $\Delta \beta_s$ is the azimuth angle of transmitter beam, $V_s$ is the velocity of satellite on the ground, $R_{s0}$ is distance between transmitter and center target at the mid aperture time.

In parallel and strip map mode, the time of receiver footprint within transmitter illuminating is

$$T_{as} = \frac{A_0}{V_g - V_a}$$

(3)

where $A_0$ is the position of the target within the transmitter footprint, which is equal to $A_t - W_{1,t}$ and is less than $W_s$. Fig. 1(b) shows the time history process of SA-BiSAR. It is obvious that the above three different times determine the integration time together. The minimum of $T_s$, $T_a$ and $T_{as}$ is the integration time

$$T_{int} = \min(T_s, T_a, T_{as})$$

(4)
Ts and Ta usually vary from a few tenths to a few seconds, which depend on the relative position of target-spacecraft and target-aircraft. However, Ta strongly depends on the variant A0. Thus, the integration time is range dependent.

2 Doppler properties

2.1 Doppler frequency

Doppler frequency includes Doppler centroid frequency and Doppler frequency rate. In parallel and strip map mode, it is obvious that Doppler frequency is just the scalar sum of those of spaceborne and airborne SAR. Doppler frequency of spaceborne and airborne SAR has been well studied, and the details derivation can be found in reference. As a consequence, Doppler centroid frequency is

\[ f_{dc} = -\frac{1}{\lambda R_{st}}\left[ (V_s \cdot R_s) + \omega_s \cdot (R_s \times R_t) \right] + \frac{V_s \sin \theta_s}{\lambda} \] (5)

Also, Doppler frequency rate is

\[ f_r = -\frac{1}{\lambda R_{st}}(A_s \cdot R_s + V_s \cdot V_s) - \frac{V_s^2 \cos^2 \theta_s}{\lambda R_{st}} \] (6)

where \( R_s \) is the distance vector between the satellite and the earth centre, \( R_t \) is the distance vector between the target and the earth centre, \( R_{st} \) is the distance vector between the satellite and the center target, \( V_s \) is the velocity vector of the satellite, \( A_s \) is the acceleration vector of the satellite, \( \omega_s \) is the rotation angle velocity of the earth, \( \theta_s \) is the squint angle of the receiver.

2.2 Azimuth resolution

From different points of views, spatial resolution of bistatic SAR has been well investigated. Based on the general bistatic geometry, the azimuth resolution of bistatic SAR is derived. It is rewritten as

\[ \rho_s = \frac{\lambda}{\min(T_s, T_a, T_{as}) \sqrt{\frac{V_s^2}{R_{st}^2} + \frac{V_s^2}{R_{at}^2} + 2 \frac{V_s V_a}{R_s R_a} \cos(\theta_t - \theta_s)}} \] (7)

where, \( \theta_t \) and \( \theta_s \) are the squint angle of the satellite and aircraft, respectively. The definition of \( \theta_t \) is similar to that of the airborne SAR, which is 0 for the side-looking mode.

3 Simulations

To investigate the Doppler properties of the SA-BiSAR system, simulation experiments are conducted. In all the following simulations the satellite antenna is pointing at boresight. With reference to ENVISAT-1, satellite orbit parameters are as follows: eccentricity is 0.001165; inclination is 98.55°; right ascension of ascending node is 133.0121°; argument of perigee is 90°; time period is 100 min. Elevation angle of satellite is 20°, aircraft velocity is 150 m•s⁻¹; Aircraft height is 5 km; Azimuth width of receiver antenna is 10 m; the nearest distance of receiver-center target is 20 km; Wavelength is 0.056 m.

Using Eqs.(1), (2), (3) and (4), the integration time as a function of \( \lambda \) and \( A_0 \) is evaluated. Its numerical values are listed in Table 1. The integration time varies from 0.2 s to 2.0 s. Both \( \lambda \) and \( A_0 \) have a significant impact on the integration time.

| \( A_0 \) | \( \lambda = 0.03 \) | \( \lambda = 0.05 \) | \( \lambda = 0.10 \) | \( \lambda = 0.22 \) |
|----------|----------------|----------------|----------------|----------------|
| 0.25Vs   | 0.11s          | 0.20s          | 0.35s          | 0.77s          |
| 0.5Vs    | 0.20s          | 0.38s          | 0.67s          | 1.47s          |
| 0.75Vs   | 0.30s          | 0.55s          | 0.99s          | 2.18s          |

Figs.2(a) and 2(b) indicate the variation of Doppler frequency with mean anomaly. The variations of Doppler frequency are similar to those of spaceborne SAR because the effect of the receiver on Doppler frequency is constant along the whole orbit.

In order to study the effect of the elevation angle of the satellite and the squint angle of the receiver on Doppler frequency, the position of the target must be fixed first. We suppose that the target is located at the northern latitude 30°. Figs.3(a) and 3(b) indicate Doppler frequency as a function of the elevation angle of the satellite. Doppler centroid frequency is more dy-
Doppler with the elevation angle of the satellite. Doppler frequency rate is more sensitive to the elevation angle of the satellite and less sensitive to the squint angle of the receiver.

![Fig.2 Doppler frequencies against orbit mean anomaly](image1)

![Fig.3 Variation of Doppler frequencies with the elevation angle of satellite](image2)

In this simulation, the aircraft antenna is steering at the side-looking mode. Using Eq.(8), the azimuth resolution is calculated and its numerical values are plotted in Fig.4. In order to evaluate the impact of $A_0$ on the azimuth resolution and integration time, the integration time as a function of $A_0$ is also plotted in Fig.4. When $A_0$ is less than half of the azimuth width of the satellite footprint, it can result in too short integration time and azimuth resolution is rather worse. When $A_0$ is more than half of the azimuth width of the satellite footprint, the SA-BiSAR system can possess enough integration time and bring on better aspects on Doppler bandwidth and azimuth resolution.

From Fig.4, the SA-BiSAR system can possess the potential of both 10m-resolution in azimuth and 0.5 s integration time if $A_0$ is properly chosen.

### 4 Conclusion

In parallel and stripmap mode, the Doppler properties of SA-BiSAR are studied including Doppler frequency, Doppler bandwidth and azimuth resolution. The overall simulation experiments are performed and some characteristics are extracted via analytical expressions and simulation results: Doppler fre-
frequency is similar to those of spaceborne SAR along the whole orbit. Doppler frequency is more sensitive to the elevation angle of the satellite and less sensitive to the squint angle of the receiver. \( A_0 \) has a significant impact on the azimuth resolution and integration time, which is the position of the receiver footprint within the satellite footprint. The above conclusions are applicable for parallel and stripmap mode of the SA-BiSAR system. These appreciated results are helpful in gaining further insight into the design issues of non-cooperative SA-BiSAR systems.

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