Antenna Directing Synchronization for Bistatic Synthetic Aperture Radar Systems

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***Abstract*—Bistatic synthetic aperture radar (BiSAR) operates with a separate transmitter and receiver that are mounted on separate platforms. This spatial separation provides several operational advantages like reduced vulnerability for military applications and increased radar cross section. However, efficient spatial synchronization (antenna direction synchronization), time synchronization, and phase synchronization must be ensured for BiSAR systems. A literary search reveals that BiSAR synchronization, especially spatial synchronization, is still a technical challenge, and little work has been reported. As such, the impact of antenna directing synchronization errors including range dimension and azimuth dimension are analyzed with statistical models. Simulation results show that efficient spatial synchronization compensation is required for BiSAR high-resolution imaging. Hence, an antenna directing synchronization approach with multi-antenna on receive is proposed.**

***Index Terms*—Antenna directing synchronization, bistatic radar, bistatic synthetic aperture radar (BiSAR), multiple antennas, spatial synchronization.**

I. Introduction

THE interest in bistatic synthetic aperture radar (BiSAR) has been increasing rapidly over the last years for its special advantages like exploiting additional information contained in bistatic reflectivity and reduced vulnerability in military applications [1], [2]. However, BiSAR is subject to technical challenges that lies in the synchronization between independent transmitter and receiver: 1) time synchronization—the receiver must precisely know when the transmitter fires; 2) phase synchronization—the receiver and transmitter must be coherent over extremely long periods of time [3]; 3) spatial synchronization (antenna directing synchronization)—the receiving and transmitting antennas must simultaneously illuminate the same region on the ground [4].

Consequently, although the feasibility of the BiSAR concept was already demonstrated by experimental investigations [5], BiSAR synchronization, especially spatial synchronization, is still a technical challenge. A literary search reveals that little work on this topic has been reported. The requirement of antenna directing synchronization for interferometric Cartwheel SAR was analyzed in [6]. Some attitude and antenna directing parameter strategies for satellite formation configuration were proposed in [4]. The comparison of attitude and antenna pointing design strategies of noncooperative spaceborne bistatic radar were investigated in [7].

This letter concentrates on antenna directing synchronization for passive BiSAR systems, i.e., the receiver is passive without transmitting any active signal. The theoretical analysis and simulations are performed to evaluate the impacts of antenna directing synchronization errors in range and azimuth on BiSAR imaging, and a spatial synchronization solution with multi-antenna on receive is proposed. Although the use of multi-antenna for radar applications is not novel [8], [9], the originality of this letter lies in the use for BiSAR spatial synchronization. The remaining sections are organized as follows. In Section II, the impact of antenna directing synchronization errors in range-dimension is analyzed with an error statistical model, followed by the impact of antenna directing synchronization errors in azimuth-dimension in Section III. Next, to reach spatial synchronization, a possible solution with multi-antenna on receive is proposed in Section IV. This letter is concluded in Section V.

II. Impact of Range Antenna Directing Errors

Without loss of generality, we consider a rather general BiSAR configuration, in which the transmitter and receiver are mounted on different platforms. As a typical example, suppose the normalized transmit antenna gain is

$$G_{\rm T}(\theta_{\rm T},\phi_{\rm T})=\exp\left\{-2\alpha\left[\left(\frac{\theta_{\rm T}}{\theta_{\rm T3\ dB}}\right)^2+\left(\frac{\phi_{\rm T}}{\phi_{\rm T3\ dB}}\right)^2\right]\right\} \tag{1}$$

where α is the Gauss parameter that is often assumed to be 1.3836, and $\theta_{\rm T}$ and $\phi_{\rm T}$ are the antenna beamwidth in range and azimuth, respectively. Correspondingly, $\theta_{\rm T3\ dB}$ and $\phi_{\rm T3\ dB}$ are their 3-dB beamwidth. If there are range antenna directing errors $\Delta\theta_{\rm T}$, we then have

$$\frac{\Delta G_{\rm T}(\theta_{\rm T},\phi_{\rm T})}{G_{\rm T}(\theta_{\rm T},\phi_{\rm T})}=-\frac{4\alpha\theta_{\rm T}\Delta\theta_{\rm T}}{\theta^2_{\rm T3\ dB}}. \tag{2}$$

Similarly, for the receive antenna we have

$$\frac{\Delta G_{\rm R}(\theta_{\rm R},\phi_{\rm R})}{G_{\rm R}(\theta_{\rm R},\phi_{\rm R})}=-\frac{4\alpha\theta_{\rm R}\Delta\theta_{\rm R}}{\theta^2_{\rm R3\ dB}}. \tag{3}$$

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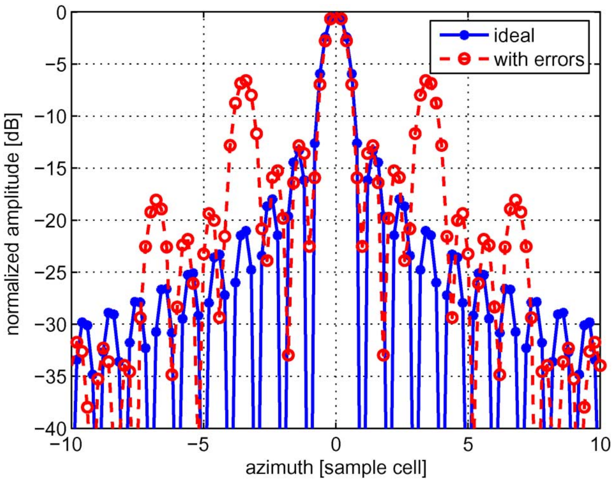

Fig. 1. Zoomed impact of antenna directing synchronization errors in range.

Then, there is [10]

$$\begin{aligned}\frac{\Delta A}{A} &= \frac{1}{2}\left[\frac{\Delta G_{\mathrm{T}}(\theta_{\mathrm{T}},\phi_{\mathrm{T}})}{G_{\mathrm{T}}(\theta_{\mathrm{T}},\phi_{\mathrm{T}})} + \frac{\Delta G_{\mathrm{R}}(\theta_{\mathrm{R}},\phi_{\mathrm{R}})}{G_{\mathrm{R}}(\theta_{\mathrm{R}},\phi_{\mathrm{R}})}\right] \\ &= -2\alpha\left[\frac{\theta_{\mathrm{T}}}{\theta^2_{\mathrm{T3\ dB}}}\Delta\theta_{\mathrm{T}} + \frac{\theta_{\mathrm{R}}}{\theta^2_{\mathrm{R3\ dB}}}\Delta\theta_{\mathrm{R}}\right]. \end{aligned} \tag{4}$$

To evaluate the impact of antenna directing synchronization errors on SAR imaging performance, linear and quadratic errors are usually assumed in existent papers. In fact, antenna directing error usually is oscillatory for practical systems. Therefore, we use an oscillatory model

$$\Delta\theta_{\mathrm{T}}(t) = \Delta\theta_{\mathrm{R}}(t) = A_{\mathrm{r}}\cos(\omega_{\mathrm{r}}t + \varphi_0) \tag{5}$$

with A_{r}, ω_{r}, and φ_0 are the amplitude, frequency, and initialization angle in range, respectively. Take an azimuth-invariant X-band BiSAR as an example, in which the transmitter and receiver are moving in parallel tracks with a constant and identical velocities $v = 150$ m/s using the following parameters: $\theta_{\mathrm{T}}(t) = 8^\circ$, $\theta_{\mathrm{R}}(t) = 5^\circ$, $A_{\mathrm{r}} = 1$, $\omega_{\mathrm{r}} = 1.98$, and $\varphi_0 = 0$; the corresponding impacts are illustrated in Fig. 1. It is seen that antenna directing synchronization errors manifest themselves as a deterioration of the impulse response function. They may defocus BiSAR image and introduce a significant increase of the sidelobes.

III. Impact of Azimuth Antenna Directing Errors

Similarly, suppose the azimuth antenna directing synchronization errors are represented by

$$\Delta\beta_{\mathrm{T}} = \Delta\beta_{\mathrm{R}} = A_{\mathrm{a}}\cos(\omega_{\mathrm{a}}t + \beta_0) \tag{6}$$

where A_{a}, ω_{a}, and β_0 are the amplitude, frequency, and initialization angle in azimuth, respectively. The corresponding transmit/receive azimuth antenna figure can be represented by

$$w(t) = w_{\mathrm{a}}\left[t - A_{\mathrm{a}}\sin(\omega_{\mathrm{a}}t + \beta_0)\right] \tag{7}$$

with $w_{\mathrm{a}}(t) = \sin c^2((\pi L_{\mathrm{a}} v_{\mathrm{s}}/\lambda R_{\mathrm{c}})(t - t_{\mathrm{c}}))$, where L_{a}, v_{s}, λ, R_{c}, and t_{c} are the antenna length, platform velocity, wave length, nearest range from the platform to the scene, and its corresponding time, respectively. Suppose the transmit signal is

$$S_{\mathrm{T}}(t) = w(t)\exp\left[j2\pi\left(f_{\mathrm{c}}t + \frac{1}{2}k_{\mathrm{r}}t^2\right)\right] \tag{8}$$

where f_{c} and k_{r} are the carrier frequency centra and chirp rate, respectively. From SAR processing procedure, we know the azimuth signal after range and azimuth compressions are

$$S_{\mathrm{out}}(t) = \exp(j2\pi f_{\mathrm{c}}t - j\pi k_{\mathrm{r}}t^2)\cdot\int_{-T_{\mathrm{a}}/2}^{T_{\mathrm{a}}/2} w(\tau)\exp(2\pi k_{\mathrm{r}}t\tau)\mathrm{d}\tau \tag{9}$$

with T_{a} the synthetic aperture time. Since

$$t \gg A_{\mathrm{a}}\sin(\omega_{\mathrm{a}}t + \beta_0) \tag{10}$$

according to the principle of Taylor series expansion, from (7) we have

$$w(t) = w_{\mathrm{a}}(t) - A_{\mathrm{a}}\sin(\omega_{\mathrm{a}}t + \beta_0)\cdot w'_{\mathrm{a}}(t). \tag{11}$$

Substitute (11) to (9), and we get

$$\begin{aligned} S_{\mathrm{out}}(t) &= \exp(j2\pi f_{\mathrm{c}}t - j\pi k_{\mathrm{r}}t^2) \\ &\quad\cdot\int_{-T_{\mathrm{a}}/2}^{T_{\mathrm{a}}/2} w_{\mathrm{a}}(\tau)\exp(2\pi k_{\mathrm{r}}t\tau)\mathrm{d}\tau \\ &\quad-\exp(j2\pi f_{\mathrm{c}}t - j\pi k_{\mathrm{r}}t^2) \\ &\quad\cdot A_{\mathrm{a}}\int_{-T_{\mathrm{a}}/2}^{T_{\mathrm{a}}/2} \sin(\omega_{\mathrm{a}}\tau + \beta_0)\exp(2\pi k_{\mathrm{r}}t\tau)\mathrm{d}\tau \\ &= S_{\mathrm{ideal}}(t) - S_{\mathrm{err}}(t) \end{aligned} \tag{12}$$

where $S_{\mathrm{ideal}}(t)$ and $S_{\mathrm{err}}(t)$ are the processed results without and with antenna directing synchronization errors. We can see that, in a like manner as the range antenna directing synchronization errors, azimuth antenna directing synchronization errors also introduce paired echoes. The amplitude ratio between the paired echoes and the ideal central one can be evaluated by

$$K_{\mathrm{am}} = \frac{\pi L_{\mathrm{a}} A_{\mathrm{a}}}{4\lambda}. \tag{13}$$

To evaluate the quantitative impact, we suppose an antenna length $L_{\mathrm{a}} = 1$ (the other parameters are defined as the same as previously). Fig. 2 shows the ratios between the paired echoes and the ideal central one as a result of azimuth antenna directing synchronization errors as a function of the oscillatory amplitude. We can conclude that to obtain satisfactory imaging performance, a high-precision antenna directing synchronization should be ensured for BiSAR high-resolution imaging.

IV. Solutions to Antenna Directing Synchronization

As concluded previously, high-precision spatial synchronization is required for BiSAR imaging. To avoid significant per-

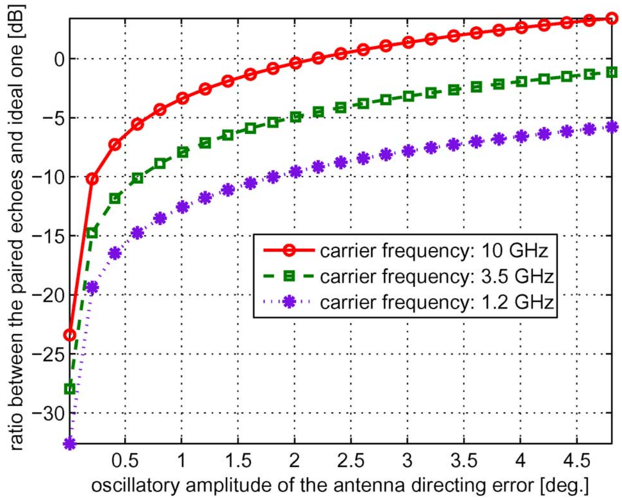

Fig. 2. Impact of antenna directing synchronization errors in azimuth.

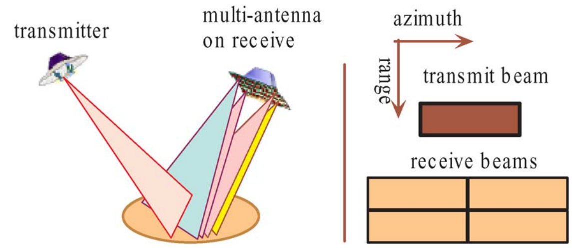

Fig. 3. Illustration of the antenna directing synchronization.

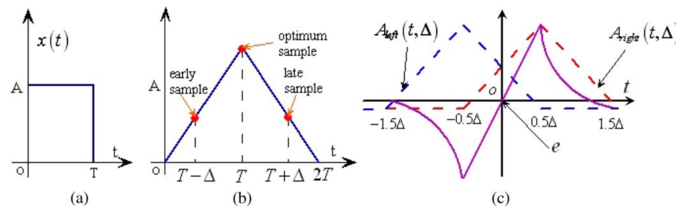

Fig. 4. Illustration of the estimator: (a) rectangular signal pulse; (b) its matched filter output; (c) estimate illustration.

formance degradation, in one synthetic aperture time, the range drift in azimuth should be satisfied with

$$x_{\mathrm{ad}} < \frac{1}{2}(\theta_{\mathrm{T}} R_{\mathrm{Tc}} - \theta_{\mathrm{R}} R_{\mathrm{Rc}}) \tag{14}$$

where R_{Tc} and R_{Rc} are the nearest range from the target to the transmitter and receiver, respectively. Up to now, the crucial parameters such as baseline length and antenna orientation are usually determined using global navigation satellite systems (GNSS). The achievable accuracy of a differential GNSS receiver in real time is about 19 cm only. However, higher efforts are needed for high-resolution BiSAR imaging.

As the antenna direction has to be determined in real-time to align it, an approach by installing a dedicated navigation unit on the transmitter and one on the receiver platform is proposed in [11]. The transmitter navigation unit generates a signal from the stable local oscillator and splits it into four individual navigation signals. These four channels are modulated, each one with an unique binary pseudorandom noise sequence. Each of them is transmitted over separate antennas, which are distributed over the transmitter platform. On the receiver platform, likewise there are four navigation antennas installed. This idea shows the possible combination of different travel paths from the transmitter to the receiver platform for the navigation signals. However, this proposed solution has an inherent drawback that the calibration signals have to be generated on all participating platforms and have to be transferred to the other platforms. As a consequence, no passive receiver exists, and the whole system can easily be detected.

To overcome this disadvantage, this letter proposes a passive antenna directing synchronization approach for BiSAR systems using two antennas on the receiver only, as shown in Fig. 3. Next, the principle of late-and-early gate that was used in [3] can be further employed. To describe this method, let us consider a rectangular pulse $x(t)$, $0 \leq t \leq T$, as shown in Fig. 4(a). The output of the filter matched to $x(t)$ attains its maximum value at time $t = T$, as shown in Fig. 4(b). Thus, the output of the matched filter for a maximum output is at $t = T$, i.e., at the peak of the correlation function. In the presence of noise, the identification of the peak value is generally difficult. Instead of sampling the signal at peak, suppose we sample early at $t = T - \Delta$ and late at $t = T + \Delta$. The absolute value of the early samples $|S(n(T-\Delta))|$ and the late samples $|S(n(T+\Delta))|$ will be smaller than the samples $|S(nT)|$. Since the autocorrelation function is even with respect to the optimum sampling time $t = T$, the absolute values of the correlation function at $t = T - \Delta$ and $t = T + \Delta$ are equal. Under this condition, the proper sampling time is the midpoint between $t = T - \Delta$ and $t = T + \Delta$. This condition forms the basis for our method.

When the antenna direction is synchronized, the outputs of both left and right antennas are identical. In this case, their outputs are equal then, and the error signal is zero as shown Fig. 4(c). However, when there is an offset in antenna direction, their outputs will be unequal, and the error signal $e(t, \Delta)$ is positive or negative. Its polarity depends on

$$e(t, \Delta) = |A_{\mathrm{left}}(t, \Delta)| - |A_{\mathrm{right}}(t, \Delta)|, \quad \text{subject to } e(t, \Delta) = 0. \tag{15}$$

This suggests the following way to estimate the antenna directing synchronization errors. Two antennas that are separated by Δ in the direction are employed in the passive receiver. We take the return signals from the two antennas in range direction (or azimuth direction) and perform range (azimuth) compression processing. Next, their magnitude difference (see Fig. 5) can be derived from (15), which gives the estimate of antenna directing errors required to realign the antenna direction. In this way, antenna direction can then be adjusted in real-time. Equally, the antenna directing synchronization can be ensured.

One important performance criteria is the estimation accuracy. Under the assumption that the error is in the linear estimation area, the estimation error can be represented by [3], [12]

$$\sigma = \theta_{\mathrm{b}} \sqrt{\frac{\Delta \cdot \omega_l}{2SNR}}, \tag{16}$$

where θ_{b} is receive antenna beamwidth, ω_l is the filter bandwidth since the estimator can be seen as a tracking filter, and

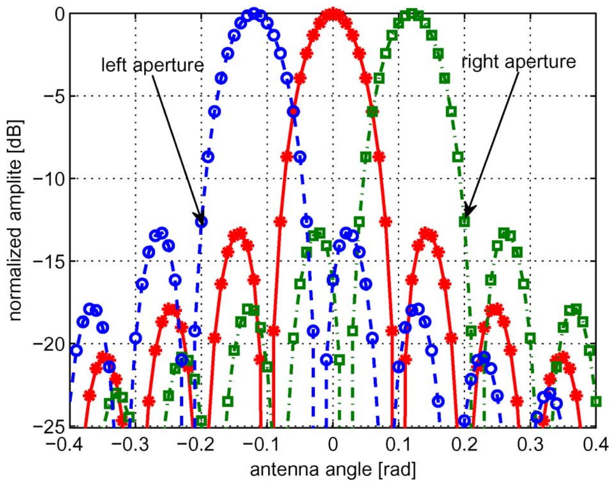

Fig. 5. Passive antenna synchronization using two antennas on receive only.

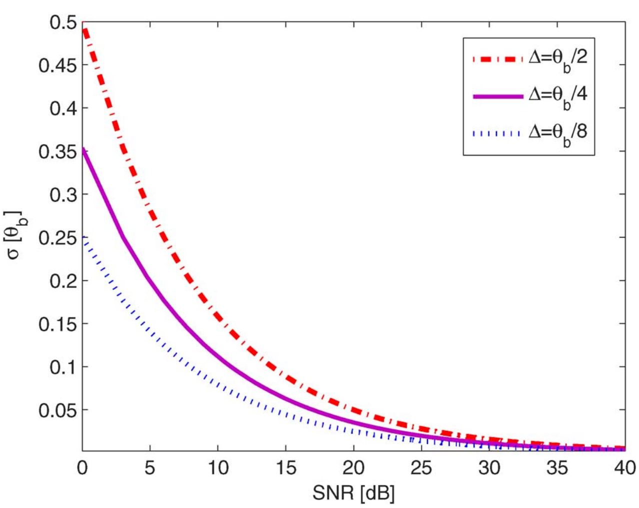

Fig. 6. Estimation performance versus SNR.

SNR is the signal-to-noise ratio (SNR). Note that the unit of the σ is same to the unit of the Δ in degree. Fig. 6 gives the track performance versus SNR. The smaller antenna separation gives a higher accuracy, but a slightly smaller threshold acquisition range and a substantially smaller quasilinear region. Generally, an accuracy of $0.1\theta_{\rm b}$ is required for BiSAR. From Fig. 6, it can be seen that this can be achieved using this method.

V. Conclusion

This letter made an investigation of antenna directing synchronization for BiSAR systems. The impact of antenna directing synchronization errors including range dimension and azimuth dimension are analyzed with directing error statistical models. As the simulation results show that high-precision antenna directing synchronization compensation should be provided, we propose an antenna directing synchronization approach using two antennas on receive for passive BiSAR systems. Future work plans to concentrate on beamforming [13], [14] and spatial synchronization combined solutions.

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