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Short communication

Synthetic bandwidth azimuth modulation imaging radar for airborne single-channel forward-looking imaging

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ABSTRACT

An efficient airborne single-channel forward-looking radar (ASFLR) imaging framework to improve the azimuth resolution performance with synthetic bandwidth azimuth modulation imaging radar (SBAMIR) is proposed. During the framework, we incorporate azimuth modulation to the transmitted signal with a coded sequence in azimuth direction, and derive the SBAMIR imaging model for the first time. In SBAMIR, the synthetic bandwidth of the received echo is not only determined by the Doppler bandwidth, but also by the modulation bandwidth. Even though the Doppler bandwidth has little contribution to the synthetic bandwidth in ASFLR, the modulation bandwidth can be utilized to increase the synthetic bandwidth. Accordingly, a high azimuth resolution can be achieved after azimuth matched filtering. Achievable azimuth resolution and performance to SNR are analyzed later. Simulation results are given to verify the effectiveness of the proposed algorithm.

1. Introduction

Airborne forward-looking radar (AFLR) system has been widely used in many civilian and military fields [1–3], which can image forward-looking terrain of the Earth ground in flight direction of the aircraft. Recently, forward-looking imaging has become an active research topic since it can improve the safety of auto-navigation and self-landing in bad weather conditions.

Several researches have been made to improve the azimuth resolution of AFLR, such as: Sector Imaging Radar for Enhanced Vision (SIREV) [4], Mono-Pulse imaging [5], Bistatic Synthetic Aperture Radar (BiSAR) [6–8] with appropriate geometry configurations (Bistatic forward-looking SAR [9–11]), DBS imaging with specific antenna functions [12] and deconvolution [13,14]. However, for airborne single forward-looking Radar (ASFLR), the first three methods fail because of their additional configuration. Though deconvolution and DSB imaging with specific antenna functions are adopted for ASFLR imaging, the imaging performance degrades with the decrease of signal-to-noise ratio (SNR) [14]. Therefore, high resolution forward-looking imaging for ASFLR is a key challenge for current low SNR radar system.

In this paper, we adapt azimuth modulation matched filtering (AMMF) [15] technique to the ASFLR system for the first time. Specifically, we propose a novel SBAMIR framework and derive its imaging model. In the framework, we modulate the transmitted signal with a coded modulated sequence in azimuth direction (or in slow time), and perform azimuth matched filtering after compensating the Doppler phase term to enhance the azimuth resolution. Different from conventional Synthetic Aperture radar (SAR) [16,17], we do not need the change of the Doppler history but directly operate on the azimuth modulation, thus taking advantage of the fact that azimuth modulation will bring in additional modulation bandwidth. Therefore, the synthetic bandwidth of the received signal is not only determined by the Doppler bandwidth, but also by the modulation bandwidth. Even in the case of small Doppler bandwidth in ASFLR, we can increase the modulation bandwidth to enhance the azimuth resolution. Simulation results show that the proposed algorithm can improve the azimuth resolution performance of ASFLR and perform well in low SNR situations.

This rest of this paper is organized as follows. The ASFLR imaging model is introduced in Section 2. In Section 3, we derive the novel echo model of SBAMIR and present its imaging framework. Then, the azimuth resolution performance is analyzed later. Section 4 provides the numerical simulations and results to confirm the effectiveness of SBAMIR method. Finally, conclusions are drawn in Section 5.

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2. ASFLR imaging model

For ASFLR, the geometry relationship between the airborne radar and the imaging area is illustrated in Fig. 1(a), where the reference coordinate is defined by *Oxyz*.The aircraft flies at velocity v along the $X-axis$.The azimuth angle between beam axis and aircraft velocity is θ and the pitching angle is φ. The 3-dB azimuth beam width is denoted as $\Delta\theta$, and λ is the wavelength of radar. R_0 denotes the initial slant range and H denotes the flight height of the aircraft. Suppose that the radar transmits a linear frequency-modulated (LFM) signal with the chirp rate γ, and the echoes can be expressed as [13]

$$s(\hat{t},t)=A\cdot rect\left(\frac{\hat{t}-\frac{2R(t)}{c}}{T_p}\right)\cdot\exp\left\{j2\pi\left[f_c\left(\hat{t}-\frac{2R(t)}{c}\right)+\frac{\gamma}{2}\left(\hat{t}-\frac{2R(t)}{c}\right)^2\right]\right\} \tag{1}$$

where $\hat{t}$ and t denote fast time and slow time, respectively. f_c is the carrier frequency, c is the velocity of light, T_p denotes the pulse width.

According to the ASFLR geometry, the instantaneous slant range between the scattering center and radar can be written as

$$R(t)\approx R_0-v\cdot\cos\ \theta\cdot\cos\ \varphi\cdot t \tag{2}$$

And the Doppler centroid is given as

$$f_d=\frac{2v\cdot\cos\ \theta\cdot\cos\ \varphi}{\lambda} \tag{3}$$

where λ is the wavelength. We assume that the upper and lower boundaries of the beam with the center azimuth angle θ are $\theta-\Delta\theta/2$ and $\theta+\Delta\theta/2$, which correspond to the Doppler shift f_{dh} and f_{dl} respectively. $\Delta\theta$ is the 3-dB antenna azimuth beamwidth.

Then, we can get the Doppler bandwidth

$$\Delta f_d=\frac{2v\cdot\cos\ \varphi}{\lambda}\ \sin\ \theta\cdot\Delta\theta \tag{4}$$

After range compression, the received signal becomes

$$s(\hat{t},t)=A\cdot rect\left(\frac{t}{T_s}\right)\cdot\text{sinc}\left[B\left(\hat{t}-\frac{2R(t)}{c}\right)\right]\cdot\exp\left(-j4\pi\frac{R_0}{\lambda}\right)\cdot\exp(j2\pi f_d t) \tag{5}$$

where $T_s=N\cdot T_r$, T_s is the scanning time of the antenna in one CPI (Coherent Processing Interval) or in a look direction, T_r is the pulse repetition interval (PRI), N is coherent pulse number.

Applying azimuth Fourier transform, we can get the cross-range compressed result as follows

$$S(\hat{t},f)=A\cdot\text{sinc}\left[B\left(\hat{t}-\frac{2R(t)}{c}\right)\right]\cdot\sin\ c\left[T_s(f-f_d)\right]\cdot\exp\left(-j4\pi\frac{R_0}{\lambda}\right) \tag{6}$$

where $f\in[-f_r/2,f_r/2]$ is the Doppler extent.

Since the ASFLR radar works in a forward-looking mode, the scanning azimuth angle θ is no more than 10°, the slow change of phase term $4\pi\cdot R(t)/\lambda$ makes the Doppler band Δf_d very small, which is the reason that causes the azimuth resolution degraded. In this paper, we focus on increasing not the Doppler bandwidth but the modulation bandwidth to improve the azimuth resolution.

3. SBAMIR for ASFLR imaging

From above analysis, we can know that the azimuth resolution is proportional to the Doppler bandwidth. However, the Doppler bandwidth is very small when the radar works in the forward looking mode. Inspired by pulse compression in range direction, we propose the SBAMIR framework to increase the synthetic bandwidth in ASFLR. Different from conventional coherent processing in SAR, we do not need the Doppler bandwidth but directly operate on the azimuth modulation and compression, thus taking advantage of the fact that azimuth modulation will bring in additional modulation bandwidth. Therefore, the synthetic bandwidth of the receiving signal has two parts: the modulation bandwidth and the Doppler bandwidth. We can enhance the azimuth resolution by increasing the modulation bandwidth even in the case of small Doppler bandwidth in ASFLR.

3.1. SBAMIR algorithm

In the proposed SBAMIR, we modulates each pulse with a series of coded sequence while maintains the envelope of the transmitted signal in azimuth direction. As illustrated in Fig. 1(b), the radar transmits a LFM signal in range direction, and the LFM signal is simultaneously modulated by a coded sequence in the azimuth direction. The value of the coded sequence is constant during a pulse repetition interval, which is quite necessary in order to guarantee range pulse compression is not affected when AMMF is performed in slow time domain. On the one hand, the envelope of the transmitted signal in range direction maintains its previous waveform; on the other hand, the amplitude of each pulse varies slowly with the coded sequence in azimuth direction. This is the key point of our SBAMIR framework. Since the modulated coded sequence is known, we can perform azimuth matched filtering on the received echo with the known modulated sequence in the azimuth direction.

Therefore, the synthetic bandwidth of the received signal corresponding to slow time is not only determined by the Doppler bandwidth, but also by the modulation bandwidth introduced by

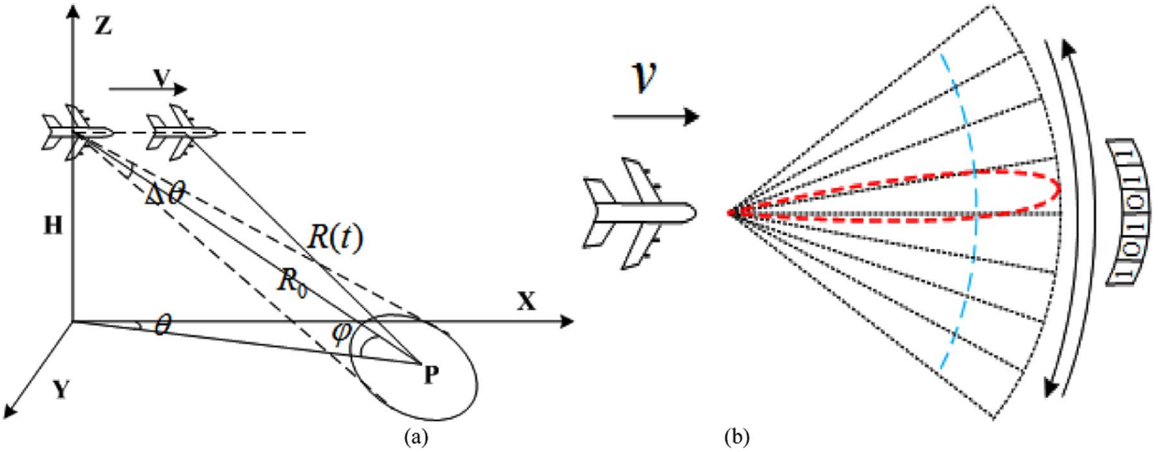

Fig. 1. Illustration of ASFLR and SBAMIR. (a) Geometry relationship of ASFLR (b) Illustration of SBAMIR in azimuth direction.