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High-precision angle estimation based on phase ambiguity resolution for high resolution radars

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Dear editor,
In case of tracking radars, performing high-precision angle estimation is crucial to determine the spatial position of a target [1]. Majority of the modern radars use a monopulse technique, which is a classical high-precision method for estimating the angle of target [1–3]. However, most of the previous studies related to angle-estimation algorithms have been mainly applied to narrowband radar systems [1–3], and the target angle is estimated based on the rarely considered bandwidth waveform. In case of traditional narrowband radar, the energy of the target with respect to an echo signal is primarily concentrated within a single range cell when the spatial size of the target is smaller than the range resolution of the radar. In a high-resolution radar, the range resolution increases because of the expansion of the bandwidth of radar-transmitting signals [4]; further, a target will occupy multiple range cells, which can be commonly referred to as the range spread target (RST) [5]. Because a target is extended in the radial range dimension, the energy of the target becomes less concentrated. Therefore, the energy of the target is observed to be dispersed in wideband radar systems when compared to that observed in narrowband radar systems. When the estimations that are performed using traditional angle methods are adopted in wideband radar systems, only strong scattering center(s) can be used for estimating the target angle, and the dispersive energy of the target cannot be accumulated leading to a loss in the signal-to-noise ratio (SNR) and the low performance of angle estimation [6]. Therefore, wideband radars still employ narrowband waveforms for searching and tracking a target. Thus, such waveforms can be completely adopted in high-resolution radar systems without transmitting narrowband signals when a high degree of precision can be achieved for estimating the target angle using wideband or ultra-wideband waveforms, and this would benefit the dwell scheduling based on the high update rates of the track states [7]. Besides, wideband radars exhibit several distinct advantages, such as target-detection with decreased radar cross section (RCS) fluctuation losses, increased radar measurement accuracy, better interference immunity and electromagnetic compatibility [8]. Therefore, effective angle-estimation methods for RST are considered to be particularly important with respect to wideband radar systems.

In this study, we propose a method for performing high-precision angle estimation based on phase comparison monopulse obtained using phase difference extraction and phase ambiguity resolution in case of wideband radars. The basic principles of the phase comparison monopulse are given in Appendix A. First, the target energy is concentrated and the phase difference is extracted from the echo signals based on the cross-correlation operation. Further, an unambiguous angle can be obtained by calculating the frequency based on this cross-

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correlation result. This angle value is considered to be a coarse estimate, and the wave path difference estimated from this coarse estimate is used to resolve the ambiguity of the phase difference. Thus, we can obtain the results of unambiguous angle estimation with a high degree of precision based on the resolved phase difference, and no special restrictions are imposed on the baseline length in the proposed method.

In [6], the authors introduced a method for estimating the target angle based on the cross-correlation operation. The energy of an RST can be concentrated after performing the cross-correlation operation using two received echoes. Subsequently, the signal term in the result of the cross-correlation operation can be expressed as [6]

$$s_{\mathrm{se}}(\tilde{t}) = \sum_{p=1}^{P} A_{1,p} \exp\left[\mathrm{j}2\pi\left(\varphi_1 \tilde{t} + \varphi_2\right)\right], \quad (1)$$

where $A_{1,p}$ denotes the signal strength of the p-th scatterer, $\varphi_1 = k(\tau_{2p} - \tau_{1p})$, and $\varphi_2 = f_c(\tau_{2p} - \tau_{1p}) + k(\tau_{1p}^2 - \tau_{2p}^2)/2$. k denotes the frequency modulated rate and τ_{ip} denotes the time delay between the p-th scatterer and the i-th antenna. After compensating for the undesired residual phase [9] and applying Fourier transform to the cross-correlation result, the phase of the signal term can be extracted from the main peak in the frequency domain of the cross-correlation result, which is, $\Delta\tilde{\phi} = 2\pi f_c \Delta\tau = 2\pi f_c \Delta R/c$, where $\Delta\tau = \tau_{2p} - \tau_{1p}$; further, this is considered to be the value of phase difference between the two echoes, which could be considered to be an ambiguous phase value. We can obtain the unambiguous estimation of the phase difference using the ambiguity resolution method that will be subsequently discussed.

In the method proposed in [6], the target angle is measured using the estimated frequency of the cross-correlation function, and this estimation is considered to be a coarse estimation, i.e., $\tilde{\theta}_{\mathrm{coarse}} = \arcsin(c\tilde{f}'/kd)$, where $\tilde{f}'$ denotes the estimated frequency of the main spectral line of the cross-correlation result. Based on the coarse estimate of target angle, we can obtain the corresponding coarse estimate of wave path difference, which is $\Delta\tilde{R} = \Delta\tau c = \tilde{f}'c/k$. According to the linearly proportional relation between the wave path difference and the phase difference of the two echo signals, the wave-path difference can be considered to be a periodically changing parameter with a period of λ. Therefore, we obtain $\Delta\tilde{R} = \lambda N_f + \mathrm{mod}\,(\Delta R, \lambda) + \varepsilon_f c/k$, where ε_f is considered to be the estimation error for frequency f', and N_f is the modulo number required to ensure $0 \leqslant \Delta R - \lambda N_f < \lambda$. The wave path difference of the periodic expression can be given as

$$\frac{\Delta\tilde{R}}{\lambda} = \frac{c\tilde{f}'}{k\lambda} = N_f + R_{\mathrm{res}} + \frac{\varepsilon_f c}{k\lambda}, \quad (2)$$

where $R_{\mathrm{res}} = \mathrm{mod}\,(\Delta R, \lambda)/\lambda$ denotes the period residual of the wave-path difference, and $0 \leqslant R_{\mathrm{res}} < 1$.

With respect to the phase difference, we obtain $\Delta\tilde{\phi} = \mathrm{mod}(\Delta\Phi, 2\pi) + \varepsilon_\phi = \Delta\Phi - 2\pi N_\phi + \varepsilon_\phi$ by considering the estimation errors, where N_ϕ is the modulo number that is required to ensure $0 \leqslant \Delta\Phi - 2\pi N_\phi < 2\pi$, and ε_ϕ denotes the estimation error of the phase difference $\Delta\phi$. To resolve phase ambiguity, we need to obtain the estimated value of modulo number $\tilde{N}_\phi$. Further, we obtain the unambiguous phase $\Delta\tilde{\Phi}$, which can be represented as $\Delta\tilde{\Phi} = \Delta\tilde{\phi} + 2\pi\tilde{N}_\phi$.

By considering that the phase exhibits a periodic change at an interval of 2π, we can change the expression into the periodic form, which can be given as

$$\frac{\Delta\tilde{\phi}}{2\pi} = \Phi_{\mathrm{res}} + \frac{\varepsilon_\phi}{2\pi}, \quad (3)$$

where $\Phi_{\mathrm{res}} = \mathrm{mod}(\Delta\Phi, 2\pi)/2\pi$ is the period residual of the phase difference, which is $0 \leqslant \Phi_{\mathrm{res}} < 1$.

Now, we subtract (3) from (2), round off the result, and obtain

$$\tilde{N} = \left[N_f + R_{\mathrm{res}} + \frac{\varepsilon_f c}{k\lambda} - \Phi_{\mathrm{res}} - \frac{\varepsilon_\phi}{2\pi}\right], \quad (4)$$

where $[*]$ denotes the rounding off operator. Based on the proportional relation between the wave path difference and phase differences, we obtain $R_{\mathrm{res}} = \Phi_{\mathrm{res}}$ and $N_f = N_\varphi$; therefore,

$$\tilde{N} = \left[N_f + \frac{\varepsilon_f c}{k\lambda} - \frac{\varepsilon_\phi}{2\pi}\right] = [N_f + \varepsilon_N], \quad (5)$$

where $\varepsilon_N = \left(\frac{\varepsilon_f c}{k\lambda} - \frac{\varepsilon_\phi}{2\pi}\right)$ denotes the estimation error of the modulo number. Further, we can obtain the unambiguous estimated phase difference value as $\Delta\tilde{\Phi} = 2\pi\tilde{N} + \Delta\tilde{\phi}$. Thus, the unambiguous angle of a target can be calculated as

$$\tilde{\theta} = \arcsin\left(\frac{c\Delta\tilde{\Phi}}{2\pi f_c d}\right). \quad (6)$$

Therefore, the phase ambiguity can be successfully resolved, and we can obtain accurate target angle estimation with relatively small root mean squared errors (RMSEs). The constraint conditions for phase ambiguity resolution are analyzed and provided in Appendix B.

According to the relation between the SNR of the received signal and that of the cross-correlation result [6], the Cramer-Rao lower bound (CRLB), the theoretical limitation of the RMSE of target angle estimation can be expressed as

$$\mathrm{CRLB}(\tilde{\theta}) = \frac{c}{2\pi f_c d\cos\theta \mathrm{SNR}_{\mathrm{st}}}\sqrt{\frac{2\mathrm{SNR}_{\mathrm{st}}+1}{2N_s}}. \quad (7)$$

The proof of this theoretical limitation can be observed in Appendix C.

Performance evaluation results. The experimental results are presented to demonstrate the effectiveness and to investigate the performance of the proposed method. An X-band wideband radar works at a carrier frequency of 10 GHz and a target containing 17 scatterers are simulated for performing the experiments mentioned in this section. A target angle of 12° is simulated in this experiment. To verify the performance of the proposed method in the noisy background, 1000 Monte Carlo simulations are conducted for each SNR ranging from −10 to 20 dB with a step of 1 dB. Additionally, four parameters sets of different signal bandwidths, pulse durations and sampling rates are simulated in this experiment. RMSE is used for evaluating the precision of the angle estimation. An antenna separation of 1.5 m is adopted in this experiment. However, the baseline length is not only limited to this value. Flexible antenna deployment with various baseline lengths can be applied using our proposed method without any ambiguity in the angle measurements, while such length or measurable scope of target angle will be limited for performing the conventional phase comparison method because of the angle ambiguity phenomenon.

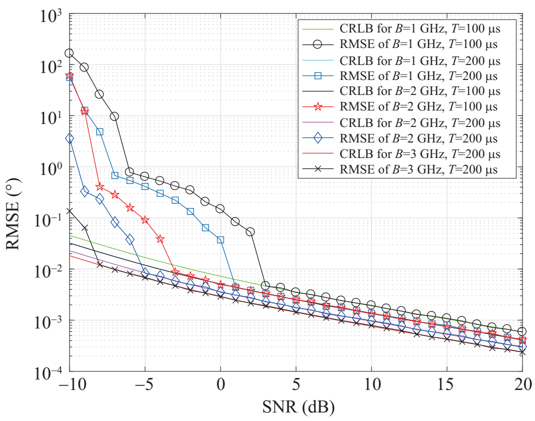

Figure 1 (Color online) RMSE and CRLB results of the proposed method with different values of system parameters in different SNR conditions.

Figure 1 depicts the results of RMSE and CRLB for the proposed method with different values of system parameters in different SNR conditions. From the overall perspective, as depicted in Figure 1, we can observe that the RMSE of the estimation is within a small range indicating that a high precision of angle estimation can be obtained using the proposed method.

Conclusion. In this study, a method has been proposed for ensuring high-precision target angle estimation for a high-resolution radar. Additionally, numerical simulations have been conducted for evaluating the performance of the proposed method. Subsequently, the experimental and analysis results were used to denote the high performance of the proposed method, which exhibited the considerable potential of the proposed method in terms of applications, especially for wideband and ultra-wideband radars.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Tullsson B E. Monopulse tracking of Rayleigh targets: a simple approach. IEEE Trans Aerosp Electron Syst, 1991, 27: 520–531
2 Rhodes D R. Introduction to Monopulse. Boston: McGraw Hill, 1959
3 Sherman S M, Barton D K. Monopulse Principles and Techniques. Boston: Artech House, 2011
4 Wehner D R. High Resolution Radar. Boston: Artech House, 1995
5 Trees H V. Detection, Estimation, and Modulation Theory, Part III: Radar-Sonar Signal Processing and Gaussian Signals in Noise. Hoboken: John Wiley & Sons, 2002
6 Zhang Y X, Liu Q F, Hong R J, et al. A novel monopulse angle estimation method for wideband LFM radars. Sensors, 2016, 16: 817
7 Spasojevic Z, Dedeo S, Jensen R. Dwell scheduling algorithms for phased array antenna. IEEE Trans Aerosp Electron Syst, 2013, 49: 42–54
8 Shirman Y D, Leshchenko S P, Orlenko V M. Advantages and problems of wideband radar. In: Proceedings of International Conference on Radar, 2003. 15–21
9 Middleton R J C. Dechirp-on-receive linearly frequency modulated radar as a matched-filter detector. IEEE Trans Aerosp Electron Syst, 2012, 48: 2716–2718