Forward-Looking Imaging Based on Monopulse Radar Sum and Difference Channel Doppler Estimation

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Abstract

Monopulse angle measurement technology can effectively improve image clarity when applied to forward-looking imaging in scanning radar; however, angle glint phenomenon occurs when a single pulse measures angles for multiple targets within the same resolution cell, resulting in image blur. This paper proposes a forward-looking imaging algorithm based on Doppler estimation using sum and difference channels of monopulse radar, which exploits Doppler gradient differences caused by relative motion between the target and platform to separate targets at different directions within the same resolution cell, and then employs sum-difference amplitude-comparison angle measurement technique in the Doppler domain to measure target azimuth angles and complete energy projection. To improve angle measurement accuracy, an algorithm utilizing Chirp Z Transform (CZT) to reconstruct sum and difference Doppler estimation and perform amplitude-comparison angle measurement is further proposed. Point target simulation experimental results demonstrate that the proposed algorithm possesses the capability to separate multiple targets in the forward-squint direction, and imaging results from measured data verify that the CZT-based imaging algorithm can significantly improve the contour clarity of scene imaging compared with traditional algorithms.

Full Text

Forward-looking Imaging via Doppler Estimates of Sum-difference Measurements in Scanning Mono-Pulse Radar

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Abstract

Monopulse lobing has been applied in scanning radars to improve image quality in the forward-looking area. However, monopulse measurements fail to resolve multiple targets in the same resolution bin because of angle glint, which may lead to imaging blurring. To tackle the problem, we propose a monopulse forward-looking imaging method via Doppler estimates of sum-difference measurements. Firstly, target multiplicity is resolved by exploiting the different Doppler slopes caused by relative motion between the platform and targets at different directions. Secondly, the azimuthal angles of the Doppler estimates are accurately measured by using sum-difference amplitude comparison (SDAC). Subsequently, the intensity of the sum channel estimates is projected onto the image plane according to the range and angle measurements. To further improve the precision of angle measurements, a chirp-z transform (CZT) based algorithm is proposed to reconstruct the Doppler estimates of sum-difference channels. Simulation results demonstrate the capability of our proposed methods to resolve multiple targets at the large-squint scanning angles. Real data experiments validate that the CZT based algorithm significantly improves the profile of the scene compared to that of the traditional monopulse imaging method.

Key words: Monopulse radar; forward-looking imaging; sum-difference amplitude comparison (SDAC); chirp-Z transform (CZT)

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2 Principle of Monopulse Forward-looking Imaging Based on Doppler Estimation

High-resolution forward-looking imaging (HRFLI) refers to two-dimensional microwave high-resolution imaging of the area directly ahead of an aircraft. This has long been a frontier technical challenge in radar remote sensing and has become a research hotspot in current earth observation imaging technology [1]. The main research directions for forward-looking imaging currently include bistatic synthetic aperture radar (SAR) imaging, super-resolution (SR) imaging, and monopulse lobing (ML) imaging. The forward-looking imaging technology based on monostatic radar beam scanning mode can be applied to both mechanically scanned and electronically scanned radars. Among these, super-resolution forward-looking imaging technology treats the antenna beam scanning across the scene as a convolution of the target’ s radar cross-section with the antenna pattern, achieving super-resolution imaging through azimuth echo and antenna pattern. The University of Electronic Science and Technology of China has conducted in-depth research on the theoretical methods and implementation techniques of scanned beam sharpening, and has verified high-multiple angular super-resolution capability on airborne radar [2]. Institutions such as Nanjing University of Aeronautics and Astronautics have conducted deep research on the implementation technology and focusing performance of monopulse imaging for airborne radar scanning beams, and have verified the resolution improvement performance for specific scenes and self-focusing imaging algorithms based on measured data [3][4][5]. We were the first to study deconvolution beam sharpening technology based on sum-difference channels of monopulse radar [6]. Since the channel patterns of monopulse radar do not strictly satisfy strong coprime conditions, high-frequency noise amplification problems occur in deconvolution operations. Scholars from Harbin Institute of Technology introduced 1λ regularization technology to effectively suppress noise [7].

Monopulse imaging technology has the advantages of low system complexity and no special requirements for flight path, making it a practical and feasible forward-looking imaging method. However, due to the limitation of channel numbers in monopulse angle measurement, it cannot distinguish multiple targets in the same resolution unit and causes "angle glint" phenomenon, resulting in degraded imaging quality for non-sparse scenes. Sherman and other scholars systematically studied the problem of multi-target resolution in monopulse angle measurement, pointing out that under the conditions of two arbitrary targets and traditional monopulse antenna patterns, a single pulse cannot solve the unresolved target problem. However, when there are changes in beam pointing, frequency, or polarization between pulses, it may be possible to achieve resolution of two or more independent targets [8]. One approach to resolving multiple targets in the same resolution unit for monopulse radar is to use maximum likelihood estimation to construct joint equations for multiple measurements of sum and difference channels, and then use optimization methods to obtain target parameter estimates. This method can achieve parameter estimation for fewer than 4 targets within the antenna beam [9][10], but the computational complexity of joint maximum likelihood estimation is high, and its feasibility for real-time imaging needs verification. Another approach is to achieve multi-target resolution in the Doppler domain based on target Doppler differences. Scholars from Xidian University, such as Chen Baixiao, studied monopulse inverse synthetic aperture radar (ISAR) three-dimensional imaging technology [11], proposing to use super-resolution technology to improve target resolution performance in the Doppler domain, and pointed out that the APES algorithm [12] has higher Doppler resolution than the Fast Fourier Transform (FFT) algorithm [13]. This technical approach, when applied to scanning radar forward-looking ground imaging, is expected to solve the angle measurement ambiguity problem caused by multi-targets, but still needs to overcome problems brought by Doppler gradient decline in the forward-looking area.

To solve the problem of degraded imaging quality caused by the difficulty in resolving multiple targets in the same resolution unit during scanning forward-looking imaging with monopulse radar, this paper proposes a forward-looking imaging method based on Doppler estimation of monopulse radar sum-difference channels. Firstly, the Doppler gradient differences caused by relative motion between the target and platform are utilized to separate targets at different directions within the same resolution unit. Then, based on the Doppler estimates of sum-difference channels, sum-difference amplitude comparison angle measurement is performed to measure the target' s azimuth angle and complete energy projection. To improve angle measurement accuracy, an algorithm using Chirp-Z Transform (CZT) to reconstruct sum-difference Doppler estimates and perform amplitude comparison angle measurement is further proposed. Point target simulation results show that the proposed algorithm has the capability to separate multi-targets in the forward-squint direction. Real data imaging results verify that the CZT-based imaging algorithm can significantly improve scene imaging profile clarity compared with traditional algorithms.

2.1 Signal Model for Monopulse Forward-looking Imaging Based on Doppler Estimation

A monopulse radar mounted on a moving platform scans the forward-looking scene with angular velocity ω at pulse repetition frequency f . Assuming after pulse compression and motion compensation, the azimuth sum and difference channel complex signal vectors for N consecutive pulses within a certain range gate are represented as ìïïïí Îs K, where K is the distribution of target radar cross-section (RCS) on the scanning grid within the antenna beam, and N and K are the sensing matrices formed by sum-difference antenna patterns scanning space. The complex noise signal vectors for sum-difference channels are represented as (for simplified analysis, assuming noise in both channels follows independent Gaussian distribution with zero mean and variance σ^2). Let ${}_3$dB be the 3dB azimuth beamwidth, and N be the number of dwell pulses transmitted and received by the radar when scanning one azimuth direction. N represents the number of pulses transmitted and received within the coverage of the radar scanning antenna' s 3dB beamwidth, so typically N = K, making equation (1) an underdetermined system whose solution belongs to the category of ill-posed inverse problems.

Since the antenna gain variation within N pulses can be almost ignored, the distribution of target RCS in azimuth cannot be directly solved by solving equation system (1). Under these conditions, there are two technical approaches for forward-looking imaging of targets: one is to use monopulse imaging technology to measure the target' s deviation from the antenna symmetry axis with higher precision by comparing signal amplitude or phase of sum-difference channels, and then project target energy onto the imaging plane [3]. This method can significantly narrow the azimuth distribution range of the target point spread function, thus improving image clarity, but cannot resolve multiple targets [4]. The other is Doppler Beam Sharpening (DBS) technology, which utilizes Doppler gradient differences generated by relative motion between the target and platform to separate targets at different angles, and then uses Doppler center estimation and clutter locking techniques to estimate target azimuth angles and perform energy projection to achieve beam sharpening [15]. However, its sharpening ratio is limited by the Doppler filter bandwidth f /N. Generally, within a squint angle range of 30-50 degrees, the beam sharpening ratio can reach 32 times. As the squint angle continues to increase, the sharpening ratio will drop sharply with the decrease of Doppler frequency difference among targets within the main lobe, forming a blind area [16].

The proposed monopulse forward-looking imaging method based on Doppler estimates of sum-difference channels combines these two technical ideas. First, Doppler processing is performed on continuous N pulse echoes of a certain range gate of the scanning radar, using target Doppler differences to separate targets at different azimuths, solving the problem of multi-target aliasing in the same resolution unit and improving azimuth resolution. Then, based on the Doppler estimates of sum-difference channels, sum-difference amplitude comparison angle measurement is directly performed to accurately measure target azimuth angles, ultimately achieving target positioning and energy projection.

In the monopulse radar beam scanning mode, a signal model for monopulse angle measurement based on Doppler estimates is first established. Similar to equation (1), assuming N consecutive sampling values within the same range gate constitute a one-dimensional uniform sampling of the target signal, let [0, 2) be the Doppler frequency, then n/N n. Defining the Fourier basis matrix for discrete Fourier transform (DFT) of the signal in azimuth as n/N n, the Doppler estimates of sum-difference channel signals can be expressed in matrix form:

A A s A A s

DFT can be implemented using FFT algorithm, and still follows complex Gaussian white noise distribution with zero mean. When N = K, the antenna gain weighting changes corresponding to each azimuth target within N pulses can be ignored, meaning that for a target at azimuth angle q, (q)sA and (q)DA remain basically unchanged within N pulses. Therefore, performing amplitude comparison angle measurement on sum-difference Doppler estimates after Doppler processing can still measure the target’ s azimuth angle. Meanwhile, when the Doppler frequency difference between different targets is greater than f /N, Doppler processing can separate the targets, achieving multi-target resolution capability.

Next, it is necessary to determine the distribution range of target energy in the Doppler domain. This step is similar to clutter locking in DBS processing, requiring calculation of the Doppler center frequency corresponding to the target at the sum channel antenna beam center and the Doppler bandwidth of targets within the sum channel 3dB beamwidth coverage. As shown in Figure 1 [Figure 1: see original paper] Geometry for forward-looking imaging of a scanning radar, assuming the radar platform flies in uniform linear motion with forward velocity v and zero lateral velocity, and the radar antenna beam scans in the forward-looking direction. When the current sum channel antenna beam center corresponds to azimuth angle   and elevation angle β, the Doppler center frequency corresponding to the target at the sum channel antenna beam center is:

2 cos cos

The Doppler cell index corresponding to the ground target at the antenna beam center is determined by /(f N). If Doppler ambiguity exists in the system, the influence of Doppler ambiguity must be eliminated to determine the correct index.

In the sum channel antenna beam coverage area, if two targets P1 and P2 on the same range ring and within the main lobe have an azimuth angle deviation Δ , the difference between their corresponding Doppler center frequencies is:

2 cos

For a typical antenna beam, Δ is very small, satisfying cos(Δ)   1 and sin(Δ)   Δ , so ΔfDC can be approximated as:

· Δ

Therefore, if the ground projection range of the sum channel antenna 3dB beamwidth is $_3$dB, ignoring the influence of Doppler frequency modulation rate, the Doppler bandwidth corresponding to the echo from the antenna beam ground projection area is:

The distribution range size of target RCS in the Doppler domain within the sum channel antenna 3dB beamwidth can be determined by /(f N). Combined with the Doppler center frequency index determined by equation (4), the distribution area of targets within the 3dB beam in the Doppler domain and the corresponding Doppler cell indices can be obtained.

Figure 1 Geometry for forward-looking imaging of a scanning radar

Assuming targets within the 3dB antenna beam are distributed across M Doppler cells, the signals in each Doppler cell are extracted from the sum-difference channel Doppler estimates according to the Doppler cell indices, and the complex ratio me of sum-difference channels is calculated [8]:

In equation (8), sgn()* represents the sign function, and subscripts I and Q represent the real and imaginary parts of the signal respectively. The angle qe of target deviation from the central axis is found by looking up me on the radar angle discrimination curve, and the true azimuth angle of the target should be:

= -

After mq, the intensity of the sum channel Doppler estimate of the target in this cell is projected into the corresponding imaging grid for energy accumulation, completing the forward-looking imaging.

The flowchart of monopulse forward-looking imaging based on Doppler estimates is shown in Figure 2 [Figure 2: see original paper]. The original echoes of sum-difference channels need to complete pulse compression and range walk correction before azimuth processing. The Keystone algorithm is used for correction [17]. The corrected echoes are framed along the azimuth direction within the range gate, and then FFT is performed on each frame of data to obtain Doppler estimates of sum-difference channels. Next, the Doppler cell indices of targets distributed within the 3dB beam are calculated from platform motion parameters, and the corresponding sum-difference channel Doppler estimates are extracted to calculate the complex ratio of sum-difference signals, obtaining the true azimuth angle of the target. Finally, according to the range gate and azimuth angle where the target is located, the intensity of the sum channel Doppler estimate is projected onto the imaging plane as target energy to obtain the forward-looking image.

Figure 2 Flowchart of mono-pulse forward-looking imagination based on Doppler estimates

In the imaging flow shown in Figure 2, imaging is achieved by projecting target energy onto the imaging plane, so target positioning accuracy (including range and azimuth angle measurement accuracy) is a key indicator affecting imaging quality. Research shows that the accuracy of monopulse angle measurement technology for target azimuth angles is related to target echo SNR and the angle of deviation from the central axis. This accuracy does not significantly decrease with the reduction of forward-squint angle. Therefore, compared with DBS technology also based on Doppler processing, using monopulse angle measurement technology in the forward-squint direction can indeed greatly improve target positioning accuracy, thereby enhancing image clarity.

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3 Reconstruction of Monopulse Radar Sum-difference Channel Doppler Estimates Based on Chirp-Z Transform

The above analysis shows that using FFT algorithm for Doppler estimation of N pulse sample values can achieve target separation in the forward-squint direction. However, it should also be noted that the value of N is limited by factors such as f or phase errors caused by platform motion and cannot be too large. This means that the Doppler filter bank constructed by DFT has limited resolution in the forward-squint direction. Therefore, sidelobes or energy leakage from adjacent targets may affect the amplitude estimation results of targets, leading to increased sum-difference complex ratio errors. To improve target positioning accuracy, an algorithm based on Chirp-Z Transform to reconstruct monopulse radar sum-difference channel Doppler estimates is proposed.

From the previous section, after Doppler processing, targets within the 3dB beamwidth correspond to M Doppler cells. First, the Doppler frequency of each target in each cell is re-estimated. The specific method is to use the Chirp-Z Transform algorithm (CZT) near each target's Doppler cell for frequency interval refinement, and search for local maxima in the refined Doppler estimates. The corresponding frequency is the estimate of the target’ s true Doppler frequency [14]. Let ωmi be the true Doppler frequency of the target in the m-th cell:

0,1, 2,···, 0,1, 2,···, -

where ω_0, $\Delta\omega$, and L represent the starting frequency point, the refined frequency increment after frequency interval refinement, and the number of refined sample points respectively. The refined frequency spectrum resolution is $\Delta\omega$/L. The DFT corresponding to the frequency sample set in equation (10) should be:

y n e 0,1, 2,···,

If W is defined as:

then from equations (11) and (12) we can obtain:

Using the equality:

0,1, 2,···, + - -

equation (14) can be rewritten as:

which leads to:

0,1, 2,···, g n W 0,1, 2,···

In equation (17), (g n) is the convolution of two sequences with 2/2 -nW, then multiplied by 2/2 iW. 2/2 -nW is a complex exponential sequence rising with linear frequency increment, indicating that the sum channel Doppler estimate (can be directly obtained using Chirp-Z Transform. Then the position of the peak point is found, which is the frequency estimate ˆmiω of the target. Based on the frequency estimate ˆmiω, the difference channel Doppler estimate can be reconstructed. First, the steering vector is constructed according to the frequency estimate ˆmiω, then multiplied by the original complex signal vector of the difference channel to obtain the projection of the difference channel complex signal at this frequency point in Doppler space, which is the Doppler estimate of the difference channel:

The steering vector used in reconstruction (18) is equivalent to a column vector of the Fourier basis matrix, with the difference being more accurate frequency, so the obtained sum-difference estimates are closer to the true values of the target, and the angle measurement accuracy is higher. Then, the sum-difference channel complex ratio mie can be calculated from the reconstructed sum-difference Doppler estimates:

Then, the angle meq of target deviation from the central axis is obtained by looking up the sum-difference channel angle discrimination curve, and the true azimuth angle is obtained according to equation (9).

The flowchart of monopulse forward-looking imaging based on reconstructed Doppler estimates is shown in Figure 3 [Figure 3: see original paper]: First, the original echoes of sum-difference channels are preprocessed, and the Keystone-corrected sum channel echoes are divided into subframes of length N along the azimuth direction within the range gate. Then FFT is used to process the subframe data to obtain Doppler estimates of the sum channel signal. Second, the Doppler center frequency and Doppler bandwidth of targets within the 3dB beam are calculated according to the radar platform motion parameters to determine the distribution range and cell indices of targets in the Doppler domain. Third, the Chirp-Z Transform is used to calculate the precise Doppler estimates and Doppler frequencies corresponding to the M Doppler cells, and reconstruct the difference channel Doppler estimates. Then, the sum-difference complex ratio of the target is calculated based on the reconstructed values, and angle measurement is performed using the radar' s angle discrimination curve to obtain the target's azimuth angle. Finally, coordinate transformation is performed according to the range gate and azimuth angle where each target is located, and the amplitude of the sum channel Doppler estimate of the target is projected onto the imaging plane to obtain the forward-looking image.

Fig.3 Flowchart of monopulse forward-looking imaging based on the reconstructed Doppler estimates

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4 Simulation and Real Data Experiments

4.1 Point Target Simulation Experiment

The simulation parameters are shown in Table 1 . The radar is assumed to be installed on an airborne platform, transmitting a linear frequency-modulated signal with 1 microsecond pulse width and 50MHz bandwidth. The center frequency of the transmitted signal is 18GHz. The antenna beam scans from -15° to 15°, with a total of 2000 transmitted pulses. A 3$×$21 point target array is set on the ground centered at [1700, 0] m, with all point targets having intensity of 1, spaced 30 meters apart in both range and azimuth directions, with adjacent point targets having azimuth angle intervals of about 1 degree. The SNR after pulse compression is 20dB, and the noise follows a complex normal distribution with mean 0 and variance σ^2.

Table 1 Simulation parameters of a forward-looking scanning radar

Parameter	Value
Scene center ground range	1700m
Radar center frequency	18GHz
Sum channel 3dB beamwidth	50MHz
Pulse repetition frequency PRF	2000Hz
Platform flight velocity	100m/s
Range/azimuth resolution cell	3m$×$3m
Beam scanning range	-15°-15°
Antenna scanning speed	30°/s

After preprocessing and motion compensation, four forward-looking imaging algorithms were used to complete signal processing, and contour plots were drawn. Since traditional Doppler beam sharpening performs poorly in the forward-squint region, the DBS algorithm was not used for comparison. Figure 4 Figure 4: see original paper shows the real aperture imaging result, which has very poor resolution. Figure 4(b) shows the imaging result using the traditional monopulse imaging algorithm. The range resolution ensures effective separation of targets in range, but targets overlap along the azimuth direction, making it impossible to accurately determine the position of each point target. This demonstrates that multi-targets in the same resolution unit cause inaccurate monopulse angle measurement, leading to image blurring. Figure 4(c) uses the algorithm given in Figure 1, and Figure 4(d) uses the algorithm given in Figure 2, with pulse accumulation number N=64. In Figure 4(c), it can be observed that point targets near the left and right sides are separated in azimuth, but simultaneously, a large amount of clutter is scattered around the targets. Compared with Figure 4(c), Figure 4(d) shows that the azimuth distribution range of point targets on both sides is significantly narrowed, and the background clutter in both range and azimuth directions is also significantly reduced.

(a) Real aperture imaging results
(b) Monopulse imaging results
(c) Monopulse imaging results based on Doppler estimates by using FFT
(d) Monopulse imaging results based on reconstructed Doppler estimates by using CZT

Figure 4 Comparison of forward-looking imaging performance (SNR=20dB)

To compare the azimuth resolution of targets in the images, Figure 5 [Figure 5: see original paper] plots the normalized azimuth profiles of 21 targets at ground range 1730m from Figures 4(b)-(d). The red circles represent the true positions of targets, the green dashed line shows the azimuth profile obtained by traditional monopulse forward-looking imaging, where most targets deviate from their true positions due to angle glint. The blue dashed line shows the azimuth profile obtained by the monopulse forward-looking imaging algorithm based on Doppler estimates, where target deviation from true positions is significantly reduced beyond \$±\$200m in azimuth, but target intensity fluctuation and splitting are also relatively obvious. The red solid line shows the azimuth profile obtained by the monopulse forward-looking imaging algorithm based on reconstructed Doppler estimates. Compared with other curves, target positions beyond \$±\$180m in azimuth match the true values very well, with more concentrated azimuth distribution and more uniform amplitude, demonstrating significantly improved azimuth resolution.

Figure 5 Azimuthal contour plot for point targets at the 1730th range bin (SNR=20dB)

At the same time, we also note that in Figures 4 and 5, there is a target aliasing area within a certain range on both sides of the direct front. In this range, the Doppler gradient of targets is sharply affected by the squint angle, causing multiple targets at different angles to fall into the same Doppler cell, leading to algorithm failure.

4.2 Real Data Validation

Figure 6 shows the forward-looking imaging processing results for real data from an airborne monopulse radar. During platform flight, the radar scanned water surface with a beam scanning range of -24° to +24°. The 3dB beamwidth of the radar sum channel antenna is about 2.5 degrees. In each image of Figure 6, the right side shows enlarged views of two regions in the scene: the upper right is the image of the shore on the left side of the scene, located near -8° to 0° on the left side; the lower right is the image of a group of point targets on the water surface, located near 12° on the right side of the scene. Figure 6(a) shows the result of real aperture imaging technology for radar forward-looking imaging, where the azimuth distribution range of water surface targets on the right side is large, and the contour of the shore and land on the left side is blurred. Figure 6(b) shows the result of traditional monopulse imaging. From the imaging results of point targets on the lower right side, the target intensity increases and the azimuth distribution is significantly narrowed, which is better than the real aperture image, demonstrating that monopulse imaging effectively narrows the azimuth distribution range of point target spread functions. The imaging result of land on the left side shows little improvement because the left scene consists of large land blocks composed of scattering points with insignificant contrast differences, and image blurring is caused by angle measurement errors or abnormal results due to angle glint. Figure 6(c) uses the monopulse forward-looking imaging algorithm based on Doppler estimates, and Figure 6(d) uses the monopulse forward-looking imaging algorithm based on reconstructed sum-difference channel Doppler estimates. Both algorithms significantly improve the imaging effect of land on the left side compared with Figure 6(b), showing clearer land scene contours and richer texture features. From the local enlarged view on the lower right side, for water surface targets, a small number of false targets appear after imaging in Figure 6(c), while no false targets appear in Figure 6(d). At the same time, it is also observed that when using Doppler processing, the background clutter is raised compared with Figure 6(b) during water surface imaging, which is caused by energy leakage from strong targets to other Doppler resolution cells during Doppler processing.

(a) Real aperture image results
(b) Monopulse forward-looking imaging results
(c) Monopulse forward-looking imaging results via Doppler estimates
(d) Monopulse forward-looking imaging results via reconstructed Doppler estimates

Figure 6 [Figure 6: see original paper] Comparison of experimental results in forward looking imaging

Point target simulation experiments and real data imaging experiments show that:

For multiple point targets in the same resolution unit in the forward-squint direction, the monopulse forward-looking imaging algorithm based on Doppler estimates utilizes Doppler gradient differences between point targets to separate them, effectively solving the image blurring problem caused by angle glint.

Energy projection after sum-difference amplitude comparison angle measurement can narrow the azimuth distribution range of point target spread functions, while sum-difference amplitude comparison angle measurement based on reconstructed Doppler estimates can further improve angle measurement accuracy, reduce the azimuth distribution range of point target spread functions, and thus improve image clarity.

5 Conclusion

This paper studies forward-looking imaging technology based on Doppler estimation of monopulse radar sum-difference channels. Doppler processing is performed on scanning radar echo sequences along the azimuth direction in frames, achieving resolution of multiple targets in the forward-squint direction. Sum-difference amplitude comparison angle measurement based on reconstructed estimates improves the positioning accuracy of targets within antenna coverage. Simulation and real data verify that the proposed algorithm can effectively improve the clarity of forward-looking images, making the contours of scenes with numerous scattering points clearer and textures richer. Since the Doppler frequency difference between multiple targets is affected by factors such as platform motion velocity, the angle between target relative motion direction, and radar system wavelength, the improvement index of angle measurement accuracy needs to be analyzed specifically in combination with radar system parameters and platform characteristics. At the same time, due to the sharp decline in Doppler gradient differences, this technology still cannot resolve multiple targets within a certain range in the direct forward direction, nor can it resolve targets that appear simultaneously on the left and right sides of the forward direction with exactly the same angle and size. Such targets will have the same Doppler frequency and will cause "left-right ambiguity" problems. These issues require continued attention in future research work.

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