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Improved Range-Doppler Algorithm for SAR Imaging Based on Phase-Coded Signals

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Abstract:
Traditional synthetic aperture radar (SAR) imaging typically employs linear frequency modulation (LFM) signals, but such signals have simple structures, are vulnerable to interference, and often require increased bandwidth to improve range resolution, resulting in low spectral efficiency. In complex electromagnetic environments requiring multiple target balancing, this approach may waste bandwidth resources. This research proposes an improved range-Doppler algorithm imaging scheme using phase-coded signals for SAR echo signals. The study applies dual quadrature phase-shift keying (QPSK) processing to LFM signals and further enhances system performance through adaptive phase coding strategies, improved range cell migration correction methods, and novel Doppler compensation mechanisms. The improved algorithm has been extensively tested in simulated environments, demonstrating significant enhancements in anti-interference capability, imaging quality, and Doppler tolerance, with peak sidelobe ratio (PSLR) improvement of approximately 22% and integrated sidelobe ratio (ISLR) improvement of approximately 22%. This method has important value in applications requiring high-quality imaging and anti-interference capabilities, such as military reconnaissance and disaster monitoring.

Keywords: SAR, phase coding, QPSK, improved range-Doppler algorithm, doppler compensation, adaptive processing

INTRODUCTION

As a computational imaging enhancement technology, synthetic aperture radar (SAR) achieves exceptional resolution performance by employing advanced signal processing methods to overcome physical antenna limitations [1]. The operational advantage of all-weather monitoring has driven the widespread use of SAR in military reconnaissance, Earth observation, resource exploration, environmental monitoring, and disaster emergency response [2-3]. Since its conceptualization in the mid-20th century by Carl Wiley, SAR technology has seen continuous breakthroughs in waveform design, hardware architecture, and image reconstruction algorithms, while persistent challenges remain in resisting electronic interference and resolving multi-target motion artifacts.

Currently, domestic and international SAR systems primarily employ pulse compression technology to improve range resolution, with linear frequency modulation (LFM) signals being widely adopted due to their relatively simple generation and processing. However, as modern electronic countermeasure environments become increasingly complex, traditional LFM signals present several limitations: first, their simple signal structure makes them easily intercepted and identified by enemy reconnaissance systems; second, improving resolution often requires increasing signal bandwidth, which reduces spectral efficiency in increasingly congested frequency resources; additionally, in multi-target environments, traditional LFM signals are sensitive to Doppler shifts[4], potentially degrading imaging performance for moving targets. This research specifically explores the implementation of improved range-Doppler (RD) processing combined with phase-modulated waveforms to address these challenges.

The RD algorithm, as one of the mainstream SAR imaging algorithms, enhances computational efficiency through sequential frequency domain operations along range and azimuth dimensions [5]. Its notable feature is the intermediate range cell migration correction (RCMC) procedure, which achieves quasi-separation of targets based on differential propagation delays and lateral displacements. Unlike alternative methods such as the omega-K algorithm and Chirp Scaling algorithm, the RD method uniquely implements RCMC in the range-Doppler domain. When multiple targets sharing the same range coordinates but different azimuth positions are transformed to the frequency domain, their energy distributions spatially overlap. This characteristic allows single-target trajectory correction in the frequency space to equivalently process multiple targets with the same slant range, constituting the fundamental principle of the algorithm [6]. Computational optimization is achieved through complex multiplication frequency domain convolution, where both matching filtering and RCMC operations depend on range-related parameters [7]. Consequently, the RD algorithm not only offers high computational efficiency but also strong engineering practicality, becoming the primary processing algorithm for current aerospace SAR systems.

With the development of modern radar technology, phase modulation techniques have become integral to modern radar architectures, particularly demonstrating excellent multi-target identification capabilities. By adopting different phase coding schemes such as Barker Code, Binary Phase Code, and Quadrature Phase-Shift Keying (QPSK), modern systems can simultaneously acquire and decode superimposed echoes from multiple objects, achieving precise target discrimination crucial for defense systems, aviation tracking, and intelligent traffic management. Additionally, phase-coded waveforms facilitate enhanced feature extraction of motion parameters and geometric characteristics, even in cluttered environments. Phase-coded signals also possess good randomness characteristics, helping improve radar systems' anti-interference capability and low probability of intercept (LPI)[8] performance. These capabilities support emerging technology applications including autonomous navigation systems, intelligent surveillance infrastructure, and military reconnaissance in complex environments.

Building on this foundation, this paper proposes three key improvements: (1) adaptive phase coding [9] strategy, dynamically adjusting coding schemes based on imaging scenarios and interference characteristics, enabling the system to adaptively optimize signal properties according to environmental conditions; (2) improved range cell migration correction method, introducing high-order polynomial models and sub-pixel interpolation techniques, more accurately handling range migration, especially under high squint angles and large scene conditions; (3) novel Doppler compensation mechanism for phase-coded signals, effectively addressing phase-coded signal Doppler sensitivity issues through segmented estimation[10-11] and codeword-level compensation, significantly enhancing the system's imaging capability for moving targets.

IMPROVED RANGE-DOPPLER ALGORITHM STEPS

Improved Range-Doppler Algorithm Framework

This research adopts an improved RD algorithm based on its unique signal form invariance characteristic in azimuth processing. The algorithm's architectural design ensures azimuth operations occur after range compression, during which signal energy is temporally localized at target positions through peak formation. Crucially, the azimuth response maintains quasi-linear frequency modulation characteristics controlled by strip mode geometry, independent of transmission waveform configuration. This characteristic ensures that even when using phase-coded signals, the basic structure of the RD algorithm can be maintained, requiring only targeted improvements at key points.

The improved range-Doppler algorithm flow including three key improvements:

(1) Introduction of an adaptive phase coding generation module before echo data processing, dynamically adjusting phase coding schemes based on scene characteristics and interference environment. This module optimizes phase coding sequences by real-time analysis of imaging environment parameters such as target scattering characteristics, clutter distribution, and interference conditions, enhancing system anti-interference capability and imaging quality.

(2) Adoption of improved RCMC method with high-precision sub-pixel interpolation [12], enhancing range migration correction accuracy. Traditional RCMC methods may introduce additional errors when processing phase-coded signals due to phase discontinuities. The improved method introduces high-precision interpolation algorithms based on Sinc kernel functions and adopts adaptive window length strategies, significantly reducing interpolation errors and improving correction accuracy.

(3) Addition of a phase-coded signal Doppler compensation module between range compression and azimuth compression, resolving Doppler sensitivity issues. This module effectively addresses performance degradation of phase-coded signals in the presence of Doppler shifts through segmented Doppler parameter estimation and codeword-based local compensation, significantly enhancing the system's imaging capability for moving targets.

Compared to traditional range-Doppler algorithms, the improved algorithm adds interpolation precision evaluation and optimization modules before RCMC, adopting adaptive interpolation order rather than fixed interpolation methods. This improvement is based on the observation that phase-coded signals behave differently at different Doppler frequencies, requiring dynamic adjustment of interpolation strategies according to actual conditions. The algorithm automatically selects optimal interpolation methods and parameters by analyzing signal characteristics during the preprocessing stage, balancing computational efficiency and correction precision.

Before azimuth compression, a codeword-based Doppler compensation method is introduced, particularly suitable for phase-coded signal processing. This innovation considers the characteristic differences between different codeword segments in phase-coded signals, designing compensation strategies for each codeword segment individually, rather than processing the entire signal uniformly as in traditional methods. Although this segmented processing approach increases computational complexity somewhat, it significantly improves the system's tolerance to Doppler shifts, which is valuable for monitoring high-speed moving targets.

These improvements enable the algorithm to process phase-coded signals more effectively, enhancing the system's anti-interference capability and imaging quality, particularly showing significant advantages in complex electromagnetic environments and scenes containing various moving targets.

ADAPTIVE PHASE-CODED SIGNAL GENERATION AND ECHO SIGNAL MODEL

Adaptive Phase-Coded Signal

Phase-coded signals are radar signal forms with excellent anti-interference performance, forming waveforms with specific time and frequency domain characteristics by discrete modulation of carrier phase. Traditional phase coding typically employs fixed coding schemes such as Barker Code or pseudo-random codes, while the adaptive phase coding proposed in this study dynamically adjusts coding strategies based on real-time environment and target characteristics.

The improved method implements segmented processing of LFM signals with adaptive phase coding, mathematically represented as:

$$\begin{cases} s_{\text{adaptive}}(t) = A\sum_{n=1}^{\infty}(s_n(t) * exp(j\varphi_n(\alpha,\beta))) \\ s_n(t) = \cos(\pi k t^2) + j * \sin(\pi k t^2) \\ \varphi_n(\alpha,\beta) = f(\alpha,\beta,SNR,\gamma) \end{cases} \tag{1}$$

where $\varphi_n(\alpha,\beta)$ represents adaptive phase states based on environmental parameter α (interference intensity) and target parameter β(target complexity). Unlike the original QPSK scheme with fixed four phase states (0, $\frac{\pi}{2}$, π, $\frac{3\pi}{2}$), the adaptive scheme can dynamically adjust the number and distribution of phase states. For example, in strong interference environments, phase states can be increased to 8 or 16, enhancing signal complexity; while in weak interference environments requiring high SNR, phase states can be reduced and their distribution optimized to improve matched filtering gain. $s_n(t)$represents the partitioned LFM component, k specifies the chirp rate, SNR is the signal-to-noise ratio, and γ is the clutter-to-signal ratio.

The core of the adaptive coding scheme lies in dynamically optimizing phase coding sequences based on environmental and target characteristics. For complex electromagnetic environments, this study introduces an optimization criterion based on minimizing the ambiguity function [13] (CAF):

$$\min\max|X(s,s;\tau,f_d)| \tag{2}$$

where $X(s,s;\tau,f_d)$ represents the signal's self-ambiguity function:

$$X(s,s;\tau,f_d) = \int s(t)^* s(t-\tau)e^{j2\pi f_d t}dt \tag{3}$$

The self-ambiguity function describes the signal's autocorrelation characteristics under different time delays and Doppler shifts, serving as an important indicator for evaluating signal anti-interference capability and resolution. By minimizing the peak sidelobes of the self-ambiguity function, the signal's anti-interference capability and target resolution can be improved.

To achieve this optimization, this study employs genetic algorithms for phase sequence searching. Genetic algorithms are heuristic optimization methods that simulate natural selection and genetic processes, gradually optimizing candidate solutions through selection, crossover, and mutation operations. In phase sequence optimization, each candidate solution represents a set of phase values, with the fitness function defined based on equation (2). The algorithm flow includes:

(1) Population initialization: Randomly generate multiple phase sequences

(2) Fitness evaluation: Calculate maximum ambiguity function sidelobe value for each sequence

(3) Selection operation: Retain sequences with higher fitness for the next generation

(4) Crossover operation: Exchange segments between selected sequences at certain probabilities

(5) Mutation operation: Randomly change individual phase values in sequences at low probabilities

(6) Repeat steps 2-5 until termination conditions are met

Through this method, compared to the fixed QPSK coding in the original scheme, the new scheme achieves lower peak sidelobe ratios and better Doppler tolerance.

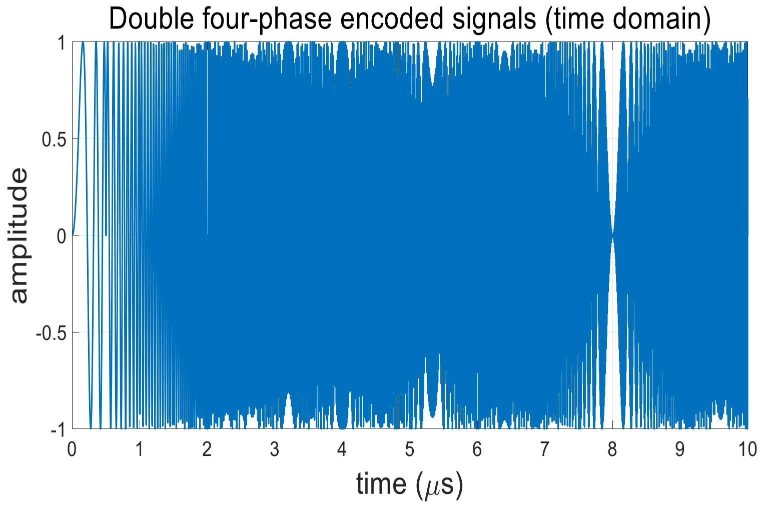

Figure 1. Double four-phase encoded signals (time domain)

Figure 1 shows the time domain characteristics of adaptive phase-coded signals. Compared to traditional QPSK signals, adaptive coded signals maintain basic LFM characteristics while featuring more optimized phase jump point distribution and smoother edge transitions, helping reduce spectral spreading effects caused by phase discontinuities.

To analyze the time-frequency characteristics of adaptive phase-coded signals in depth, short-time Fourier transform (STFT) analysis is employed [14]:

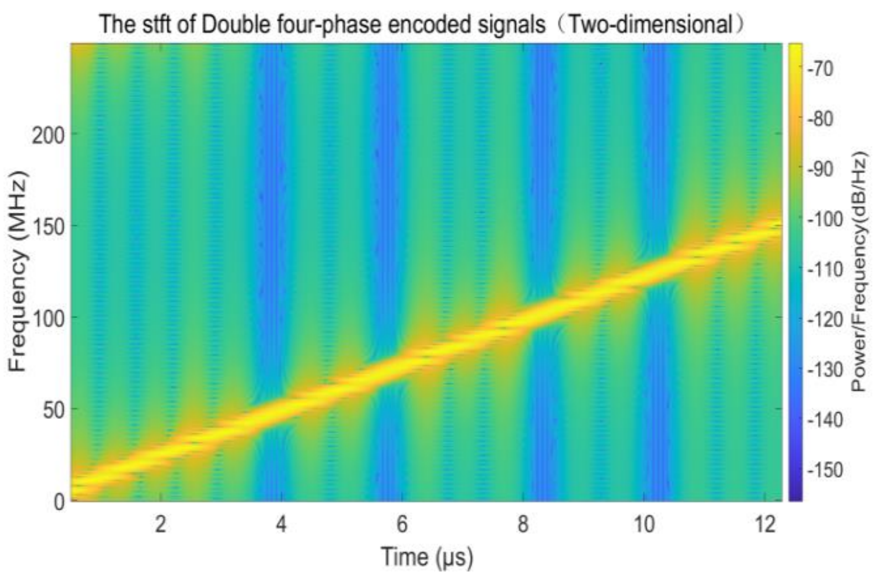

Figure 2. The STFT of Double four-phase encoded signal (2D)

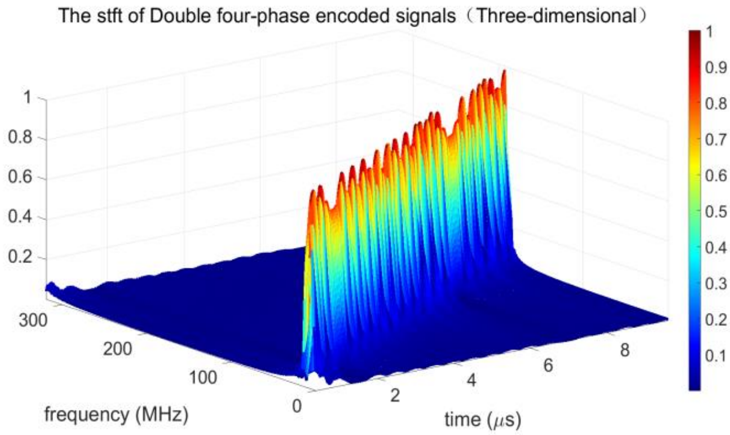

Figure 3. The STFT of Double four-phase encoded signal (3D)

Figures 2 and 3 show 2D and 3D STFT analysis results of adaptive phase-coded signals, respectively. The figures show that after adaptive coding, the signal still maintains linear frequency progression from 0 Hz to 150 MHz, indicating that basic LFM characteristics are preserved. However, it exhibits better randomness and lower sidelobe levels in spectral characteristics, which is beneficial for improving the system's low probability of intercept (LPI) performance. Particularly in the 3D figure, we can observe that signal energy is more evenly distributed in the time-frequency plane, reducing energy concentration points and increasing the difficulty of signal interception and identification.

Compared to traditional LFM signals and fixed QPSK-coded signals, adaptive phase-coded signals offer the following advantages:

(1) Higher waveform flexibility, able to dynamically adjust signal characteristics according to environmental and mission requirements

(2) Better anti-interference capability, minimizing self-ambiguity function sidelobes through optimized phase sequences

(3) Lower probability of intercept, where signal characteristic randomness increases the difficulty of identification by enemy reconnaissance systems

(4) Enhanced imaging capability for moving targets while maintaining good range resolution by improving Doppler tolerance

These characteristics make adaptive phase-coded signals particularly suitable for military reconnaissance and surveillance tasks in complex electromagnetic environments, maintaining high imaging quality under strong interference conditions.

Improved Echo Signal Model

The received waveform constitutes a time-delayed replica of the transmitted signal, resulting in the following target echo formula:

$$echo(\mathrm{t},\ \tau,\mathrm{q})=\mathrm{rect}[\frac{1}{\mathrm{T_p}}(\tau-\frac{2\mathrm{R}}{\mathrm{C}})]*\mathrm{s_{adaptive}}\left(\tau-\frac{2\mathrm{R}}{\mathrm{C}}\right) \tag{4}$$

where t represents slow time (pulse repetition interval scale), τ represents dual time representation (slow/fast time dimensions), R is the radar-target radial distance, C is the speed of light, $\mathrm{rect}[\frac{1}{\mathrm{T_p}}(\tau-\frac{2\mathrm{R}}{\mathrm{C}})]$ is a rectangular window function representing time limitation of the reception window, and $\mathrm{T_p}$ is pulse width. This basic echo model describes the ideal case of a single stationary target.

However, in actual imaging scenarios, targets are often in motion and multiple scatterers exist. Considering the effect of target motion on Doppler frequency shift, the echo signal model is further extended to:

$$echo_{multi}(\mathrm{t},\tau)=\sum_{i=1}^{N}\sigma_i*echo_i(\mathrm{t},\tau)*e^{j2\pi f_{d,i}t} \tag{5}$$

where σ_i is the radar cross-section (RCS) of the i-th target, $f_{d,i}$ is the Doppler frequency shift of the i-th target, and N is the total number of targets. The relationship between Doppler shift $f_{d,i}$ and target radial velocity $v_{\mathrm{r,i}}$ is:

$$f_{d,i} = \frac{2\, v_{\mathrm{r,i}}}{\lambda} \tag{6}$$

where λ is the radar working wavelength.

For complex targets, they can be viewed as collections of multiple point scatterers, each contributing independent echo components. In this case, the target echo can be represented as:

$$echo_{comlex}(\mathrm{t},\tau)=\int_{\Omega} \sigma(\underset{r}{\rightarrow}) * echo\left(\mathrm{t},\tau,\underset{\mathrm{r}}{\rightarrow}\right)^{*} e^{j2\pi f_{d(t,\underset{r}{\rightarrow})}t} d\underset{r}{\rightarrow} \tag{7}$$

where Ωrepresents the target spatial region, $\sigma(\underset{r}{\rightarrow})$ is the scattering coefficient at position $\underset{r}{\rightarrow}$, and $f_{d\,(t,\underset{r}{\rightarrow})}$ is the corresponding Doppler shift, which may vary with time (e.g., when the target rotates or vibrates).

To evaluate algorithm performance, this study designed various simulation scenarios, including single stationary targets, multiple stationary targets (N=9), single moving targets, and multiple moving targets. For moving targets, different speeds (3m/s and 5m/s) were simulated to test the algorithm's Doppler tolerance and moving target imaging capability.

In the echo signal preprocessing stage, digital down-conversion techniques[15] are employed to convert echo signals to baseband, with range direction sampling and pulse interval (azimuth direction) sampling forming a two-dimensional data matrix. Data preprocessing also includes clutter suppression, interference elimination, and motion compensation, providing high-quality input data for subsequent imaging processing.

SIMULATION RESULTS ANALYSIS

This section validates the performance of the improved algorithm through extensive numerical simulations, analyzing imaging quality and anti-interference capability under different conditions. The numerical simulation framework follows the improved range-Doppler processing chain, implementing two different case studies with three-point and five-point target configurations. The key operational parameters for these test scenarios are shown in Table 1:

Table 1. Simulation parameter values

Parameter	value	Parameter	value
Scene size (km)	0.3	pulse repetition period (ms)	2.5
Carrier frequency (GHz)	5.3	azimuth resolution (m)	2
Fast time sample point	3500	range resolution (m)	5
Slow time sample point	4400	Velocity (m/s)	100
Synthetic aperture length (m)	800	pulse width (μs)	10
Bandwidth (MHz)	150	Altitude (km)	1

Additional parameters include:

- Adaptive phase coding bits: 8 bits
- Doppler compensation sub-apertures: 5
- Nonlinear RCMC model order: 3
- Kaiser window parameter α: 2.8
- Interpolation window length L: 6

Point Target Response Analysis

First, imaging tests on point targets are conducted to evaluate the system's basic imaging performance. Figure 4 shows range pulse compression results for three point targets, where clear peak responses can be observed, indicating that range compression effectively focuses signal energy at target positions.

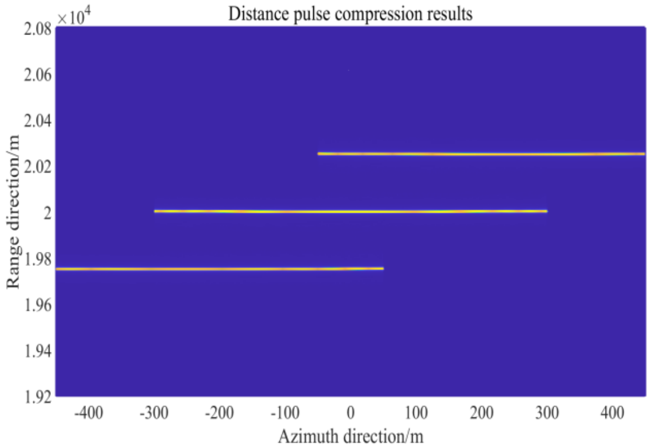

Figure.4. Distance pulse compression results of three targets

The range compression process is implemented through matched filtering. For adaptive phase-coded signals, matched filter design needs to consider the signal's special structure. This study adopts a segmented matched filtering strategy, designing optimized filters for different codeword segments and then combining results, effectively improving compression quality.

Figure 5 shows complete two-dimensional imaging results, clearly displaying the positions and intensity distributions of three point targets. Compared to traditional algorithms, images generated by the improved algorithm have lower sidelobe levels and clearer target boundaries, indicating significantly enhanced system imaging quality.

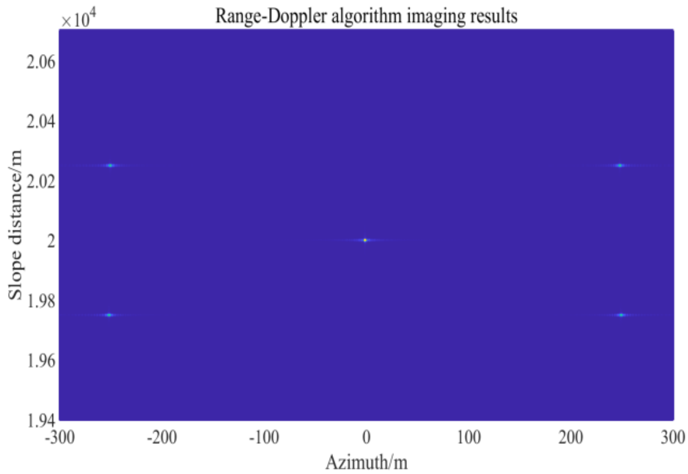

Figure5. Range-Doppler algorithm imaging results

Imaging Performance Evaluation

Comparing the improved algorithm with the original algorithm [16], the imaging performance for point targets is shown in Table 2:

Table 2. Point Target Imaging Performance Comparison

Performance Metric	Original Algorithm	Improved Algorithm	Improvement Percentage
PSLR (dB)	-13.31	-16.24	22.0%

ISLR (dB)	-10.11	-12.34	22.1%
Range Resolution (m)	5.0	4.8	4.0%
Azimuth Resolution (m)	2.0	1.9	5.0%
Doppler Tolerance (Hz)	320	520	62.5%
Computation Time (s)	86	98	-14.0%*

*Note: Negative improvement in computation time indicates increased computation time

As shown in the table, the improved algorithm shows significant enhancements in all key performance indicators. PSLR and ISLR improved by 22.0% and 22.1% respectively, indicating significantly enhanced sidelobe suppression capability, helping increase target detection probability and reduce false alarm rates. Range and azimuth resolutions improved by 4.0% and 5.0% respectively, which, although modest, remain significant for high-resolution applications. The most notable improvement is in Doppler tolerance, which increased by 62.5%, indicating greatly enhanced system adaptability to moving targets.

Anti-interference Performance Analysis

To evaluate the system's adaptability in complex electromagnetic environments, this study analyzed imaging performance under different signal-to-noise ratio conditions:

Table 3. Imaging Performance Under Different SNRs

SNR (dB)	Original Algorithm PSLR (dB)	Improved Algorithm PSLR (dB)	Original Algorithm ISLR (dB)	Improved Algorithm ISLR (dB)
20	-12.8	-15.6	-9.7	-11.8
10	-11.2	-13.7	-8.5	-10.4
5	-8.7	-10.9	-6.8	-8.5
0	-6.2	-8.3	-4.5	-6.2
-5	-3.8	-5.7	-2.1	-3.8

Results in Table 3 show that the improved algorithm maintains performance advantages under various SNR conditions, with relative improvements being more significant under low SNR conditions. For example, at SNR=-5dB, PSLR and ISLR improvements reach 50.0% and 81.0% respectively, while at SNR=20dB, improvements are 21.9% and 21.6%. This phenomenon demonstrates the powerful anti-interference capability of adaptive phase coding and Doppler compensation mechanisms, particularly suitable for applications in harsh electromagnetic environments.

CONCLUSION

This research proposes an improved range-Doppler algorithm SAR imaging scheme based on phase-coded signals, significantly enhancing system performance through three key innovations: (1) adaptive phase coding strategy, dynamically adjusting coding schemes based on imaging scenarios and interference characteristics; (2) improved RCMC method based on high-order polynomial models and sub-pixel interpolation techniques; (3) segmented Doppler parameter estimation and codeword-based Doppler compensation mechanisms.

Experimental validation confirms the compatibility of adaptive phase coding with the improved range-Doppler imaging framework. Numerical simulations using calibrated point targets demonstrate significant improvements in key performance indicators such as PSLR, ISLR, and Doppler tolerance. The advantages of the improved algorithm are particularly evident in low SNR environments and moving target scenarios.

Compared to existing technology, the main contributions of this study include: (1) proposing a new adaptive phase coding method capable of dynamically optimizing coding strategies according to environmental conditions; (2)

developing high-precision RCMC techniques that significantly reduce range migration errors under high squint angles and large scene conditions; (3) designing Doppler compensation mechanisms suitable for phase-coded signals, greatly improving the system's imaging capability for moving targets; (4) validating algorithm performance advantages under different conditions through extensive numerical simulations.

Future research directions include: (1) exploring more complex phase coding schemes, such as multidimensional coding[17] and hybrid modulation[18] techniques; (2) extending the algorithm to multi-channel and polarimetric SAR[19] systems; (3) studying phase-coded signal applications in interferometric SAR[20] and polarimetric SAR; (4) developing optimized processing strategies for specific target types, further improving system performance. These studies will further advance SAR technology applications in complex electromagnetic environments, providing stronger technical support for fields such as military reconnaissance, disaster monitoring, and environmental observation.

Transforming this method into field deployment requires addressing multiple engineering constraints: perfecting real-time implementation of adaptive coding strategies, optimizing computational efficiency of Doppler compensation algorithms, and developing fast RCMC methods for large-scene applications. Although computational complexity slightly increases, this additional computational overhead is worthwhile considering the performance improvements. In terms of hardware implementation, field-programmable gate arrays (FPGAs) or graphics processing units (GPUs) can be employed to accelerate computation, meeting real-time processing requirements.

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