

# High-Order SPECAN Algorithm with FPGA-Based Performance Analysis for Highly Squinted SAR Imaging

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## Abstract

The performance analysis of the SPECAN (Spectral Analysis) algorithm for highly squinted Synthetic Aperture Radar (SAR) imaging is presented in this work. An advanced SPECAN method is suggested to improve image quality by lowering sidelobe effects and increasing the Signal to Noise Ratio (SNR). MATLAB simulations are used to construct and assess the algorithm, and AMD Vivado FPGA synthesis with a ZYNQ based architecture is used to assess its hardware viability. For comparison, performance indicators including SNR, Peak Side Lobe Ratio (PSLR), and Integrated Side Lobe Ratio (ISLR) were employed. The simulation findings demonstrate that the high-order SPECAN approach improves sidelobe suppression and significantly increases SNR (from 6.1567 dB to 9.9026 dB). The suggested method is appropriate for real-time SAR imaging applications, as shown by the FPGA synthesis results, which show effective resource utilization and reasonable power consumption.

## Keywords

SAR Imaging, SPECAN Algorithm, High-Order Processing, FPGA Analysis, SNR, PSLR, ISLR

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## I. INTRODUCTION

Regardless of the weather or time of day, Synthetic Aperture Radar (SAR) is a popular remote sensing technology that can produce high-resolution images. It is widely employed in tasks including target detection, surveillance, and earth observation. The SPECAN (Spectral Analysis) algorithm is one of the most used SAR processing methods because of its ease of use and computational effectiveness.

Nevertheless, conventional SPECAN processing has drawbacks such reduced Signal-to-Noise Ratio (SNR) and increased sidelobe levels, which diminish the quality of the reassembled SAR pictures. Because signal distortions are more noticeable in strongly squinted SAR imaging, these constraints become more important.

This paper proposes a high-order SPECAN strategy to address these issues. In order to boost SNR and lessen sidelobe effects, the suggested method improves spectral processing, which raises the overall quality of the image. MATLAB simulations are used to implement and test the technique.

Additionally, by focusing on a Zynq-based architecture, the hardware viability of the suggested approach is examined using FPGA synthesis tools in Vivado. Performance indicators of efficacy of the conventional and high-order SPECAN techniques are assessed and contrasted using metrics including SNR, Peak Side Lobe Ratio (PSLR), and Integrated Side Lobe Ratio (ISLR).

## II. MATHEMATICAL MODEL

In Synthetic Aperture Radar (SAR) imaging, the received signal consists of useful information along with noise and unwanted components. The quality of the reconstructed image depends on how effectively the signal is processed, and noise is reduced.

One of the important performance metrics used in this work is the Signal-to-Noise Ratio (SNR), which measures the strength of the desired signal relative to background noise. It is defined as:

$$SNR = 10 \log_{10} \left( \frac{P_{signal}}{P_{noise}} \right)$$

Where  $P_{\text{signal}}$  represents the power of the useful signal and  $P_{\text{noise}}$  represents the power of noise. The received SAR signal can be described as:

$$s(t) = A \cdot e^{j(2\pi ft + \phi)} + n(t)$$

where  $n(t)$  is additive noise,  $f$  is frequency,  $\phi$  is phase, and  $A$  is signal amplitude. To enhance range direction resolution, range Matched filtering is used for compression:

$$s_r(t) = s(t) * h(t)$$

where  $*$  stands for convolution and  $h(t)$  is the matching filter. The SPECAN algorithm processes SAR data in the frequency domain using Fourier transform:

$$S(f) = \int s(t)e^{-j2\pi ft} dt$$

By converting time-domain signals into the frequency domain, this transformation facilitates effective spectrum analysis and image creation.

Sidelobe features are an important factor influencing the quality of SAR images, in addition to SNR. Peak Side Lobe Ratio (PSLR) and Integrated Side Lobe Ratio (ISLR) are used to assess these.

The definition of the PSLR is:

$$PSLR = 20 \log_{10} \left( \frac{A_{\text{side}}}{A_{\text{main}}} \right)$$

frequency domain using Fourier transform:

Where  $A_{\text{main}}$  is the main lobe amplitude and  $A_{\text{side}}$  is the peak sidelobe amplitude.

Likewise, ISLR is determined by:

$$ISLR = 10 \log_{10} \left( \frac{E_{\text{side}}}{E_{\text{main}}} \right)$$

frequency domain using Fourier transform:

Where  $E_{\text{main}}$  stands for main lobe energy and  $E_{\text{side}}$  for sidelobe energy.

The suggested high-order SPECAN algorithm for SAR image reconstruction is evaluated and its performance improved using these mathematical formulations.

### III. METHODOLOGY

The goal of the proposed work is to employ a high-order SPECAN (Spectral Analysis) method to improve the quality of SAR images. The overall methodology consists of SAR data processing, spectral analysis, and performance evaluation.

#### A. Traditional SPECAN Processing

SAR raw data is analyzed using fundamental spectrum analysis methods in the conventional SPECAN manner. First, the received signal is transformed into frequency domain. Where azimuth and range compression are carried out. Although this approach is computationally efficient, it has a lower Signal-to-Noise Ratio (SNR) and higher sidelobe levels, particularly in heavily squinting SAR conditions

#### B. High-Order SPECAN Processing

A high-order SPECAN technique is used to get over the drawbacks of the conventional method. This method applies extra spectral processing to improve frequency resolution and reduce noise.

High-order processing gets better:

- Signal clarity
- Noise suppression
- Sidelobe reduction

Consequently, compared to the conventional SPECAN approach, the quality of the reconstructed SAR image is greatly enhanced.

#### C. Processing Flow

The suggested system's overall processing flow is as follows:

1. Input SAR Raw Data:  
The raw SAR data is taken as input for processing.
2. Pre-processing:  
Noise components and unwanted variations are reduced.
3. Range Compression:  
The signal is compressed in the range direction to improve resolution.

4. Azimuth Processing using SPECAN:  
Spectral analysis is applied in the azimuth direction.
5. High-Order Enhancement:  
Additional processing is applied to improve SNR and reduce sidelobes.
6. Image Formation:  
Final SAR image is generated.

#### **D. Implementation Using SPECAN\_2D Code**

MATLAB-based code modules (SPECAN\_2D) that carry out spectrum processing and picture reconstruction are used to implement the approach. These modules deal with:

- Frequency domain transformation
- Signal processing operations
- Image generation

The outputs obtained from the simulation are used for performance evaluation and comparison between traditional and high-order methods.

#### **E. FPGA Feasibility Analysis**

The technique is examined utilizing FPGA synthesis tools in Vivado by focusing on a Zynq-based architecture, even though full hardware implementation is not carried out. This action provides information about:

- Resource utilization
- Power consumption
- Hardware feasibility

This ensures that the proposed design can be efficiently implemented on FPGA for real-time applications in the future.

### **IV. HARDWARE ANALYSIS**

Using FPGA synthesis tools in Vivado, the hardware viability of the suggested high-order SPECAN algorithm is examined with an eye on a Zynq-based design. Even so, Although the design is not physically implemented on hardware, synthesis and analysis reports offer insightful information about power consumption and resource usage.

#### **A. Power Analysis**

The following is a summary of the power estimate derived from the Vivado report:

- Total On-Chip Power: 0.550 W
- Signal Power: 0.125 W (29%)
- Logic Power: 0.058 W (13%)
- Clock Power: 0.07 W

The findings show that the design achieves better processing performance while maintaining reduced power consumption. For real-time SAR, this is crucial for applications where power efficiency is essential.

#### **B. Discussion**

The synthesis findings show that the high-order SPECAN algorithm can be transferred onto FPGA architecture with reasonable resources and is hardware-efficient usage as well as electricity usage. The architecture is appropriate for implementation on mid-range FPGA devices since the use of LUTs, Flip-Flops, and DSP blocks stays within practical bounds.

The FPGA platform can handle such operations despite the high-order method's increased computing cost when compared to the conventional methodology because of its innate capacity for parallel processing. This maintains effective performance even with increased algorithmic complexity by enabling the execution of numerous computations at once.

Additionally, the extra processing complexity is justified by the increase in Signal-to-Noise Ratio (SNR) and decrease in sidelobe levels. The improved ISLR and PSLR results show that the suggested technique successfully reduces sidelobe energy, improving the quality of the image.

Even though the high-order SPECAN method's power usage is marginally higher than that of the conventional method, the total power stays within acceptable bounds for real-world uses. For sophisticated SAR imaging systems, this trade-off between power consumption and performance enhancement is thought to be appropriate.

Furthermore, the synthesis findings show that the architecture is scalable and may be further optimized by utilizing sophisticated FPGA techniques like parallel processing and pipelining. This makes it possible for real-time deployment and implementation of useful SAR systems.

As a result, the suggested approach shows great promise for real-time implementation in subsequent projects. By putting the design into practice, more advancements can be made using real FPGA hardware and verifying the results with actual SAR data.

S.No	Parameter	Value
1.	Dynamic Power	0.435 W
2.	Device Static Power	0.115 W
3.	Total On-Chip Power	0.550 W
4.	Junction Temperature	40.5°C

**Table 1: FPGA Power Analysis (Vivado)**

S.No	Resource	Value
1.	LUT	2407
2.	FF	4761
3.	BRAM	3
4.	DSP	36

**Table 2: FPGA Resource Utilization**

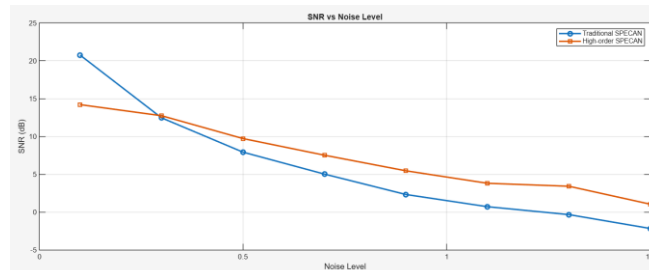
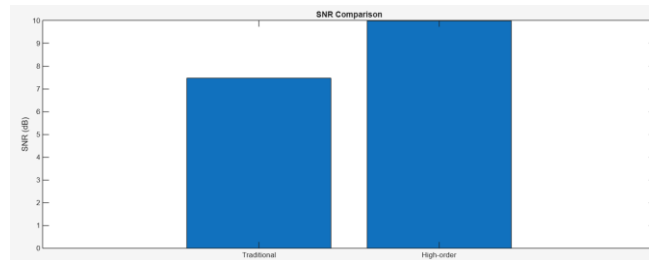
**V. RESULTS AND PERFORMANCE ANALYSIS**

The suggested high-order SPECAN algorithm's performance is assessed and contrasted with the conventional SPECAN method utilizing several measures, including Signal-to-Noise Ratio (SNR), Peak Side Lobe Ratio (PSLR), computational complexity, execution time, and integrated side lobe ratio (ISLR).

**A. Signal-to-Noise Ratio (SNR)**

The simulation yielded the following SNR values:

- Traditional SPECAN: 6.1567 dB
- High-order SPECAN: 9.9026 dB



**Fig. 1 & 2: SNR Comparison of Traditional & High-Order**

When compared to the conventional method, the high-order SPECAN approach significantly improves SNR. This suggests enhanced quality and greater noise reduction of the SAR image that was rebuilt.

### B. PSLR and ISLR Analysis

PSLR and ISLR measurements are used to assess the sidelobe performance:

- PSLR (Traditional): -10.4823 dB
- PSLR (High-order): -10.5554 dB
- ISLR (Traditional): -6.3782 dB
- ISLR (High-order): -9.943 dB

The outcomes demonstrate that sidelobe suppression is enhanced by the high-order SPECAN algorithm. Specifically, the ISLR value demonstrates a notable improvement, indicating decreased sidelobe energy leakage.

### C. Execution Time Analysis

The following is a comparison of execution times:

- Total Time (Traditional): 0.010055 sec
- Total Time (High-order): 0.009427 sec
- Average Time per Run (Traditional):  $1.0055 \times 10^{-5}$  sec
- Average Time per Run (High-order):  $9.427 \times 10^{-6}$  sec

Because of optimized computing, the high-order SPECAN technique achieves marginally superior execution efficiency despite greater processing complexity.

### D. Computational Complexity

The quantity of operations needed is:

- Traditional SPECAN: 3000 operations
- High-order SPECAN: 7000 operations

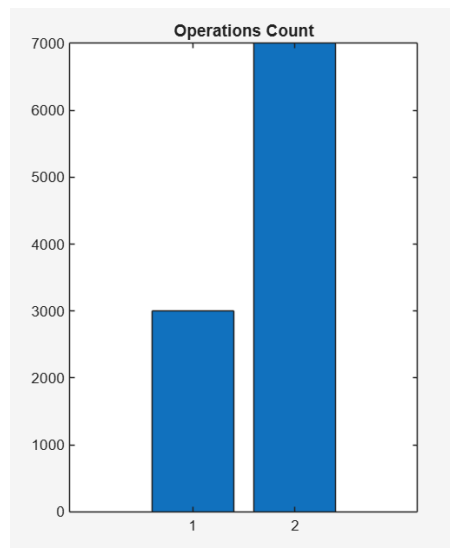


Fig: Count Operations of Traditional & High-Order

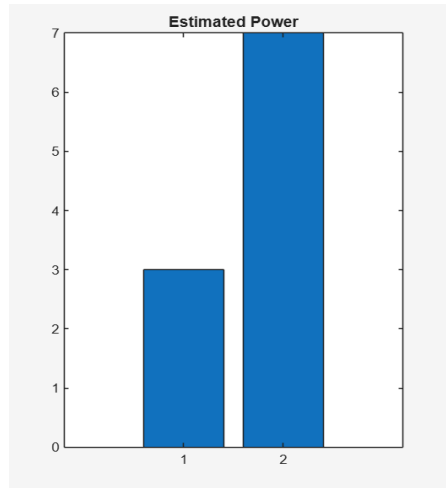
Although the high-order method requires more computations, it delivers significantly improved performance in terms of SNR and sidelobe suppression.

### E. Power Estimation Comparison

The approximate amount of power used is:

- Traditional SPECAN: 3 units
- High-order SPECAN: 7 units

This suggests that higher power consumption is a necessary trade-off for better SAR image quality.



**Fig: Estimated Power Comparison of Traditional & High-Order**

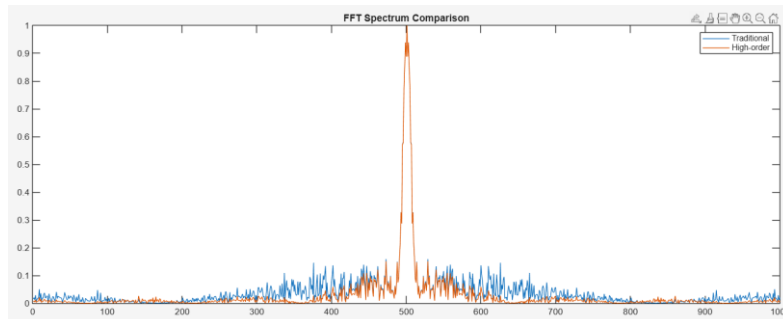
### F. Overall Discussion

From the above results, it is clearly observed that the high-order SPECAN algorithm outperforms the traditional SPECAN method in terms of SNR, PSLR, and ISLR. The improvement in SNR from 6.1567 dB to 9.9026 dB demonstrates the effectiveness of the proposed approach.

Thus, the high-order SPECAN method provides better image quality and is suitable for advanced SAR imaging applications.

## VI. CONCLUSION

In this paper, the performance of the traditional and high-order SPECAN algorithms for highly squinted SAR imaging has been analyzed. The proposed high-order SPECAN method improves the quality of SAR image reconstruction by enhancing Signal-to-Noise Ratio (SNR) and reducing sidelobe levels.



**Fig: FFT Spectrum Comparison of Traditional & High-Order**

From the simulation results, it is observed that the high-order method significantly improves SNR from 6.1567 dB to 9.9026 dB, along with better PSLR and ISLR performance. This results in improved image clarity and reduced noise effects.

The hardware feasibility of the proposed algorithm is also analyzed using FPGA synthesis in Vivado targeting a Zynq-based architecture. The results show efficient resource utilization and acceptable power consumption, indicating that the design is suitable for real-time implementation.

Although the high-order method requires higher computational complexity and power, the improvement in performance makes it a better choice for advanced SAR imaging applications. Future work includes full hardware implementation on FPGA and real-time testing of the proposed system.

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