MILLIMETER-WAVE RADAR FOR UAV-BASED CROP HEIGHT MAPPING

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MOTIVATION

Accurate measurement of crop canopy height is a critical factor in modern precision agriculture, enabling more informed decisions in yield prediction, phenotyping, and overall crop health assessment. Traditional remote sensing technologies such as optical and LiDAR systems often struggle under challenging environmental conditions - particularly in the presence of dust, fog, or low-light scenarios, which are common in agricultural settings.

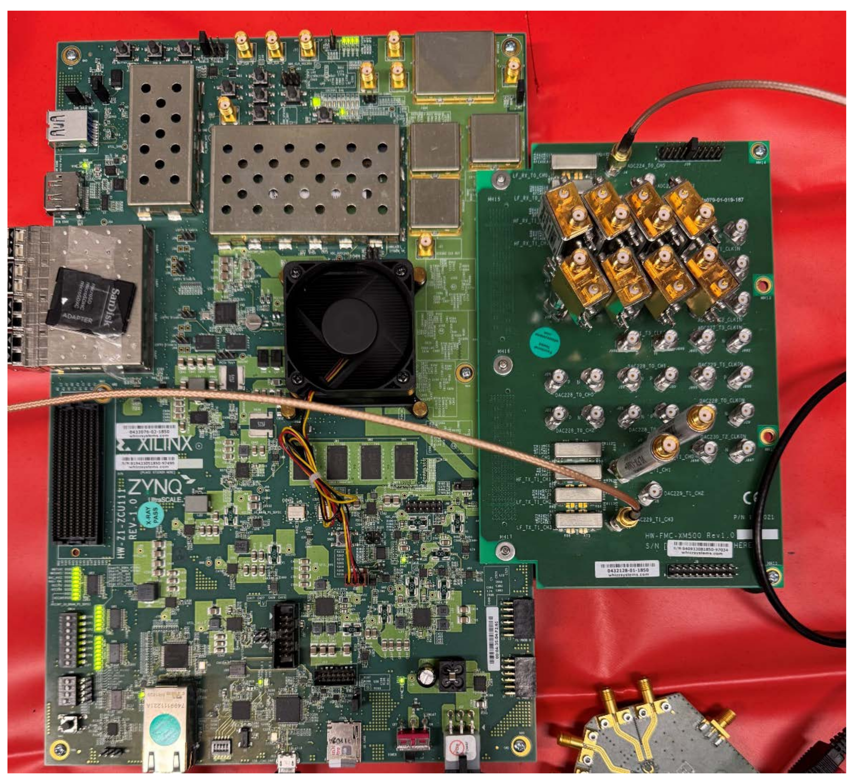
In contrast, millimeter-wave radar offers a robust alternative, operating reliably across all weather conditions and lighting environments. Its ability to penetrate obstructions and maintain accuracy regardless of ambient conditions makes it a promising candidate for agricultural sensing.

This project seeks to address the need for a compact, lightweight radar platform capable of being mounted on unmanned aerial vehicles (UAVs). The goal is to enable high-resolution, drone-based canopy height mapping that supports scalable and resilient data collection for agricultural applications.

Goal: Create a lightweight, compact radar for drone-based height mapping

SIGNAL GENERATION AND PROCESSING

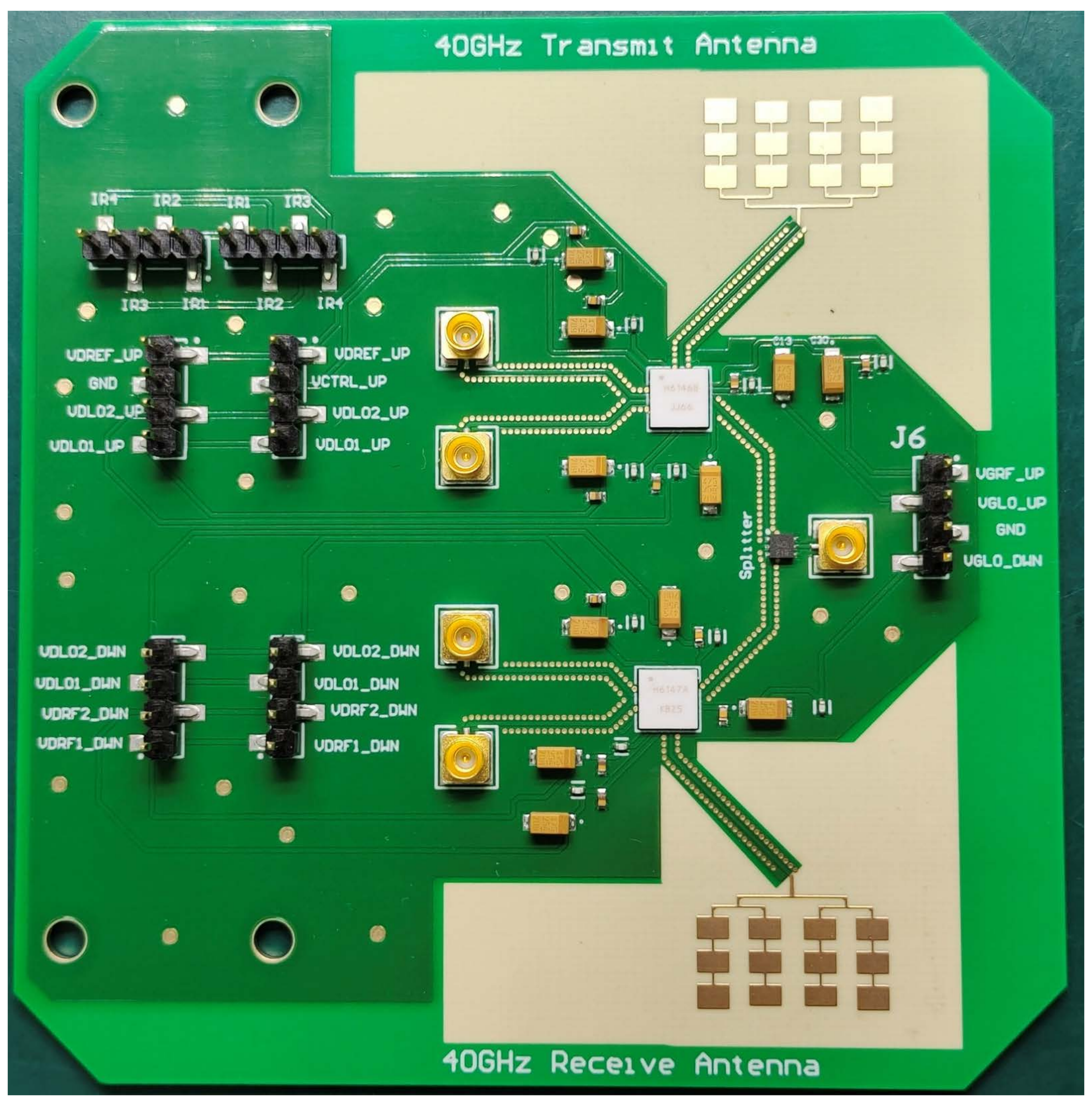
Signal generation and data acquisition were performed using the Xilinx ZCU111 RFSoC, which provides high-speed digital-to-analog and analog-to-digital converters capable of supporting up to 4 GHz of instantaneous bandwidth. The transmit and receive paths were directly interfaced with the onboard DACs and ADCs, enabling seamless generation and sampling of the FMCW chirp waveform. The received signal was mixed with the original chirp to produce an intermediate frequency beat signal, which was then processed in MATLAB/Simulink. Frequency-domain analysis of this beat signal enabled extraction of key target parameters, including range, velocity, and reflection strength, supporting robust detection and classification in dynamic sensing environments.



ZCU111 BOARD

RADAR ARCHITECTURE

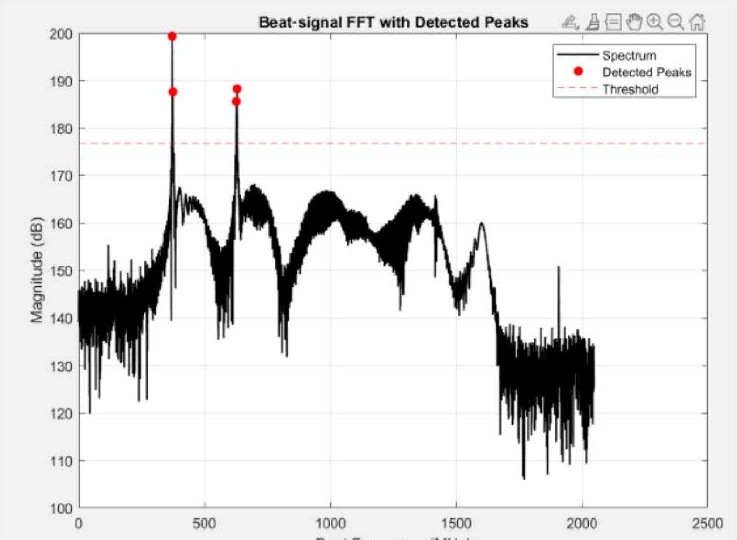
The radar system is built around a Frequency-Modulated Continuous Wave (FMCW) architecture, which offers a power-efficient solution for simultaneous range and velocity estimation. Unlike pulsed radar systems that require high peak power and complex timing circuitry, FMCW radar continuously transmits a linearly modulated chirp signal, allowing for the extraction of time-delay and Doppler information with minimal power overhead. This continuous operation model is particularly well-suited for UAV-based applications, where size, weight, and power constraints are critical. By leveraging the inherent efficiency of FMCW techniques, the system achieves high-resolution sensing while maintaining a lightweight and energy-conscious profile ideal for aerial deployment.



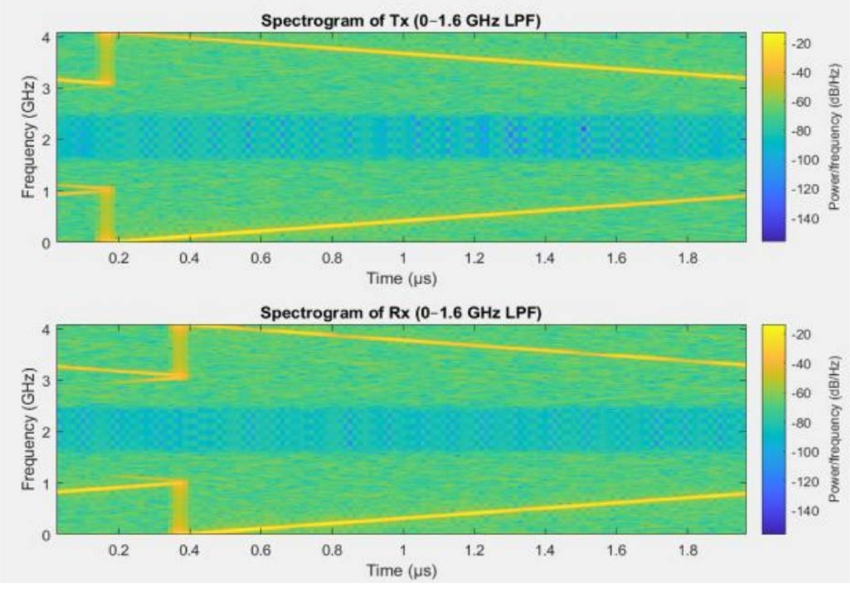
RADAR BOARD

PCB AND RF FRONT-END DESIGN

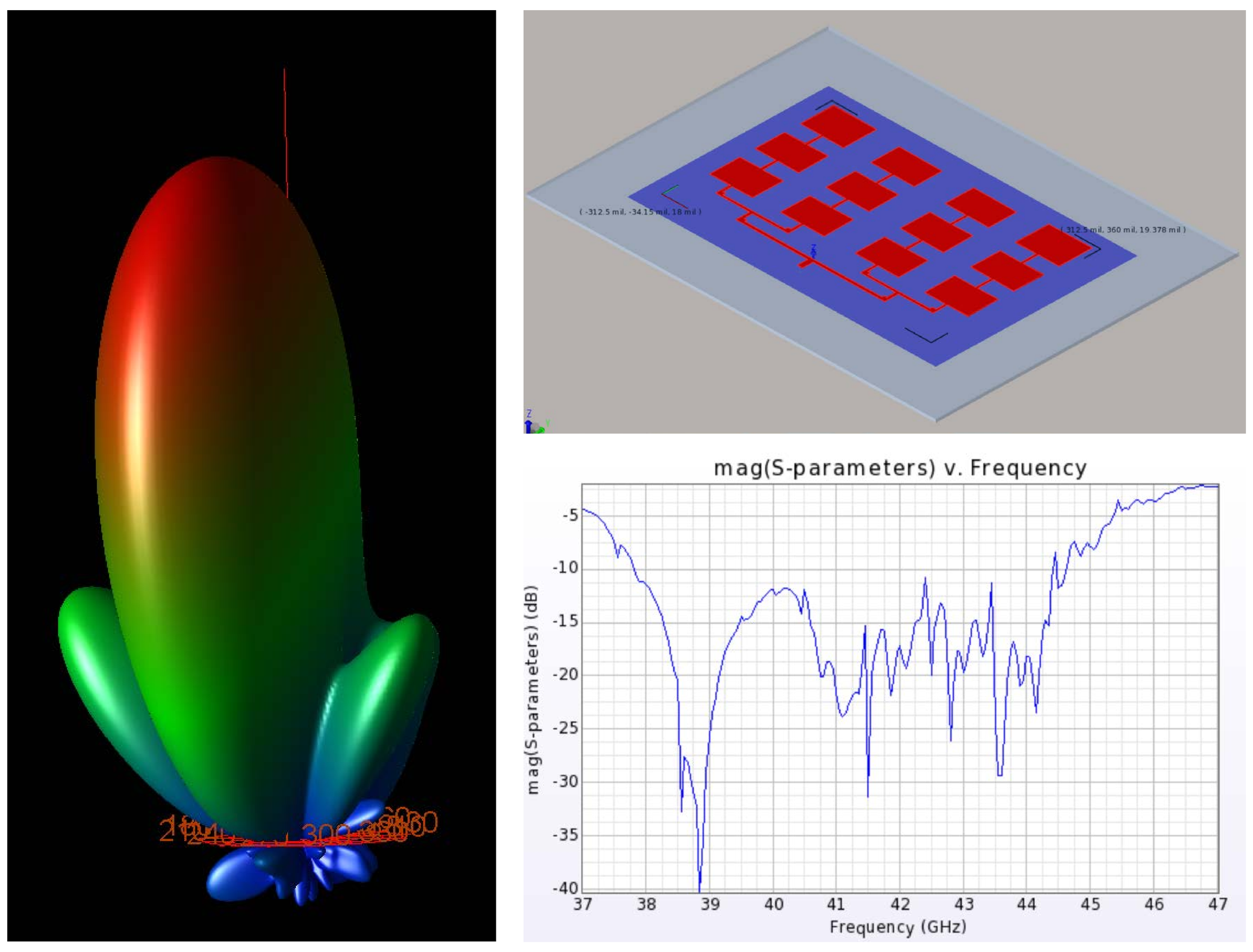
A compact four-layer RF printed circuit board was designed in Altium specifically for operation in the 40–44 GHz frequency band. The layout incorporates internal ground planes to ensure effective noise isolation and maintain controlled impedance throughout high-frequency signal paths. The board integrates up- and down-conversion chains to support both transmit and receive functions, enabling full FMCW radar operation. GCPW are used to reduce parasitics and insertion loss, optimizing signal integrity at millimeter-wave frequencies. Additionally, the PCB's backside includes an exposed copper region to facilitate direct thermal contact during cryogenic or chamber-based testing.



BEAT SIGNAL DETECTION



TX & RX SPECTROGRAM



ANTENNA PARAMETERS FROM ADS

ANTENNA DESIGN

The antenna system was designed as a 3×4 microstrip patch array using Keysight ADS, fabricated on an 8-mil Rogers 4003C substrate to support wideband operation in the 40–44 GHz range. Electromagnetic simulations confirmed a return loss below -10 dB across the band, ensuring effective impedance matching and minimal signal reflection. The array achieved a simulated directivity of 13.2 dBi and a realized gain of 12.24 dBi, making it well-suited for short-range radar applications where both spatial resolution and efficient power delivery are critical.

HARDWARE PERFORMANCE

- **Footprint:** 9.06 cm × 8.80 cm (≈ 80 cm^2) four-layer PCB, compact enough for small UAV airframes.
- **Mass:** 28 g fully populated, lightweight for easy drone integration.
- **Power Draw:** 1.41 W at 3 V during continuous chirp acquisition, a low-power design that supports multi-minute flights on common drone batteries.

FUTURE WORK

- Characterize SMA cable delays to correct time offsets and improve range accuracy
- Convert MATLAB DSP pipeline (FFT + peak detection) to run on FPGA
- Increase the current bandwidth for greater range resolution
- Use Vivado or Simulink HDL Coder to implement real-time signal processing

GLOSSARY

ADS: Advanced Design System

PCB: Printed Circuit Board

FMCW: Frequency Modulated Continuous Wave

dBi: Decibels relative to isotropic

RF: Radio Frequency

GCPW: Grounded coplanar waveguides

ACKNOWLEDGEMENTS

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