Software-Defined Ground Penetrating Radar Using COTS SDRs and GNU Radio Companion

2025 GNU Radio Conference

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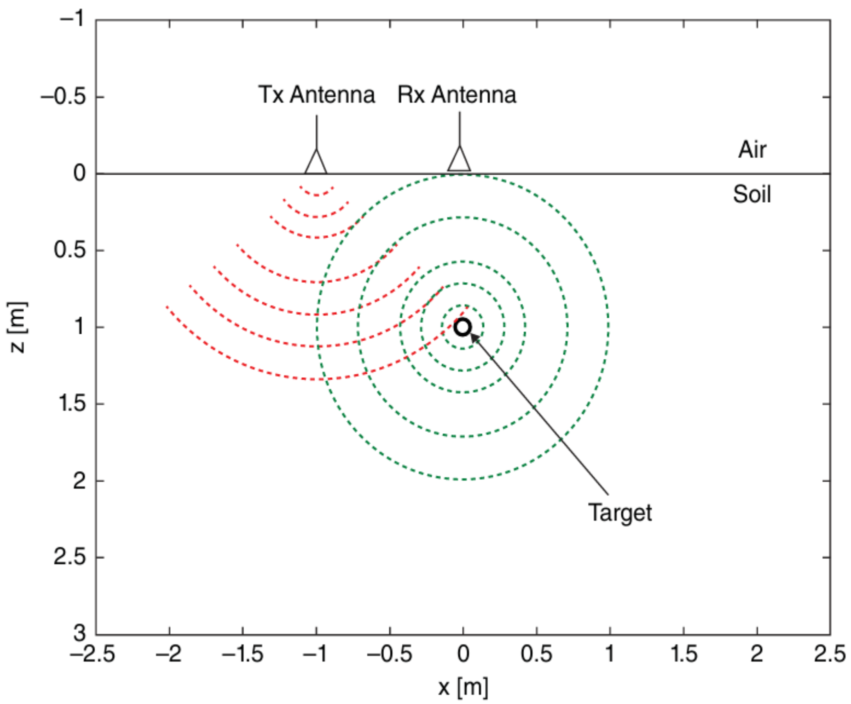
Collaboration with the 309th SWEG under the Educational Partnership Agreement (EPA) between Weber State University and Hill AFB

Project Overview

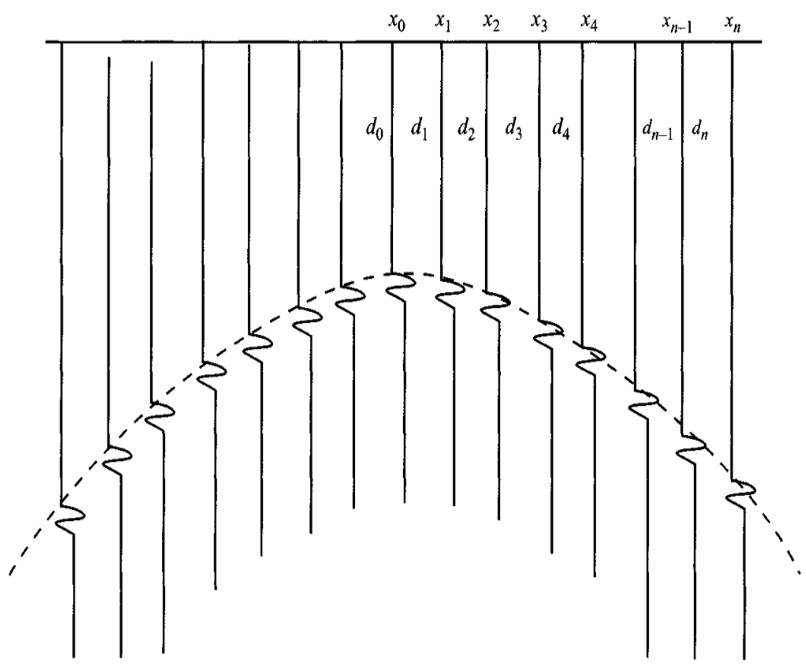
- Collaboration with 309th Software Engineering Group:
  - Landmine detection: Shallow Depth, High Resolution
    - Size: 8 – 30 cm wide
    - Depth: < 30 cm
- Goal:
  - Explore SD-GPR viability for detection of shallowly buried targets
- Evaluation:
  - Characterize performance against known targets and COTS product

Background

- GPR: a radar to identify subsurface discontinuities



The working principle of a GPR (R. Persico 2014)



B-scan Radargram Construction (D. J. Daniels 2004)

Traditional GPR System (R. Persico 2014)

Motivation

- Interest in drone-based GPR systems
  - Reduces:
    - Labor
    - Time
    - Risk
  - Issues:
    - Expensive
    - Power-Intensive
    - Large and Heavy

- SDRs are a potential solution

Drone-Based GPR System

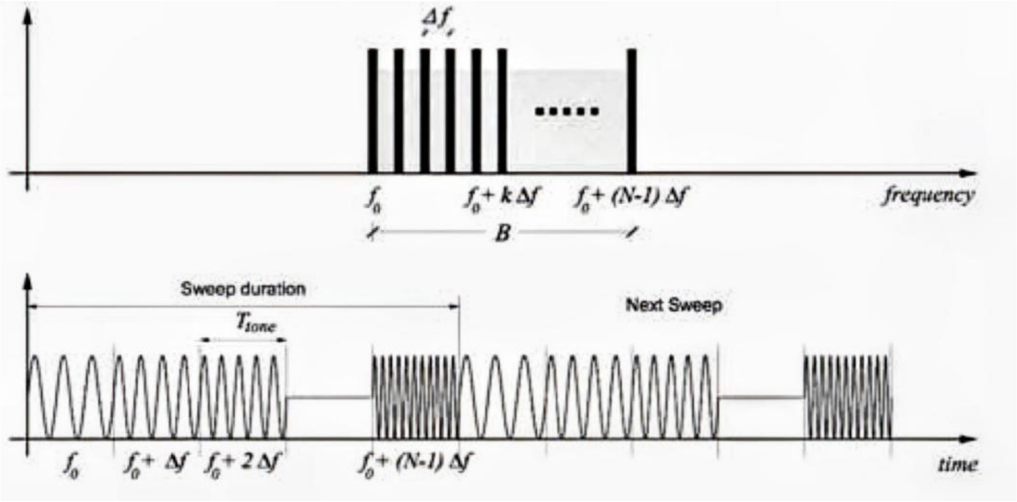
Approach

- Stepped Frequency Continuous Wave Radar (SFCW)
  - Low power requirements
  - High SNR

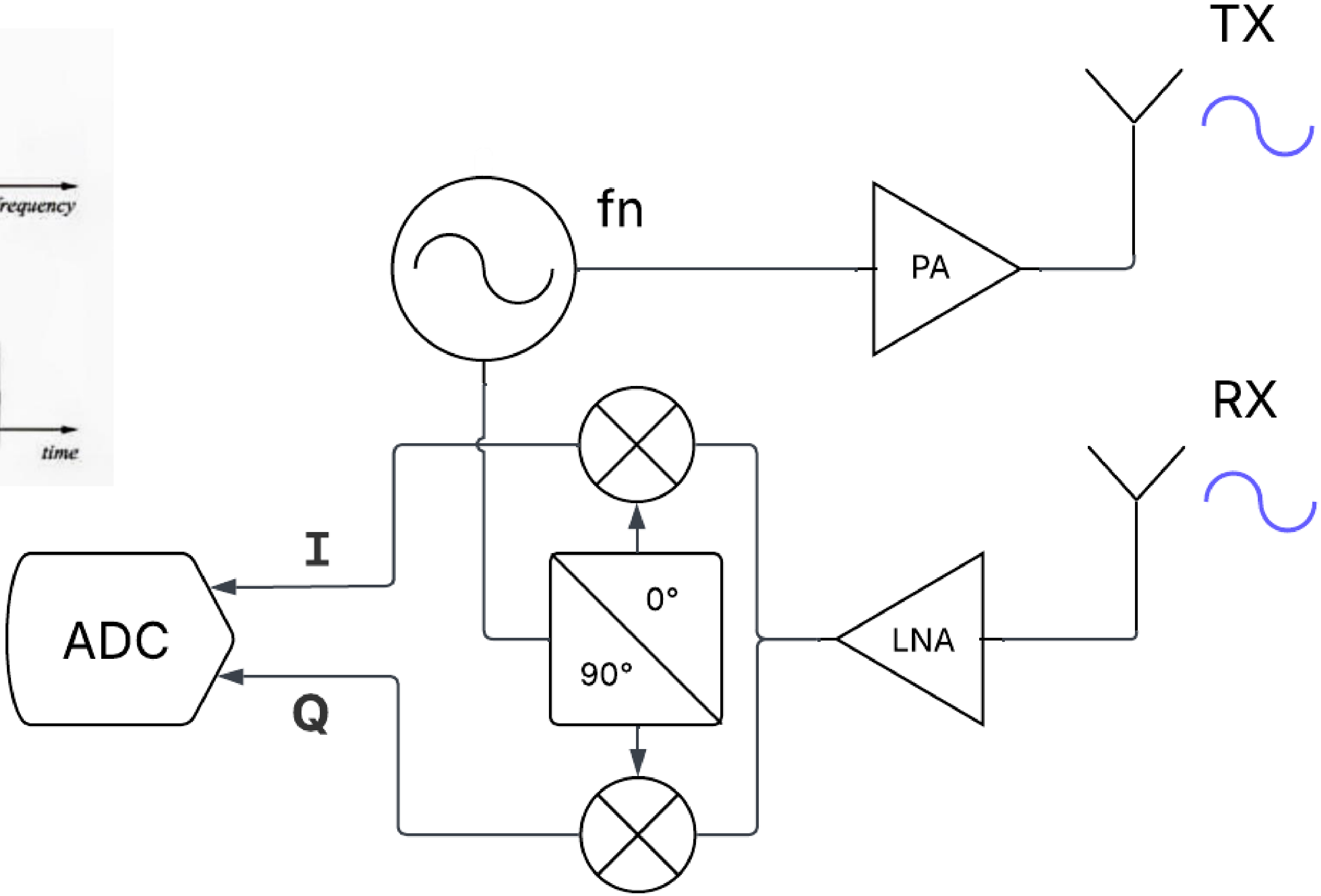
- COTS SDR Platform
  - BladeRF 2.0 Micro xA9

- Open-Source Software
  - GNU Radio Companion
  - Python3

SFCW Theory of Operation



SFCW waveform in frequency and time (C. Gentile 2010)



Radar Specifications

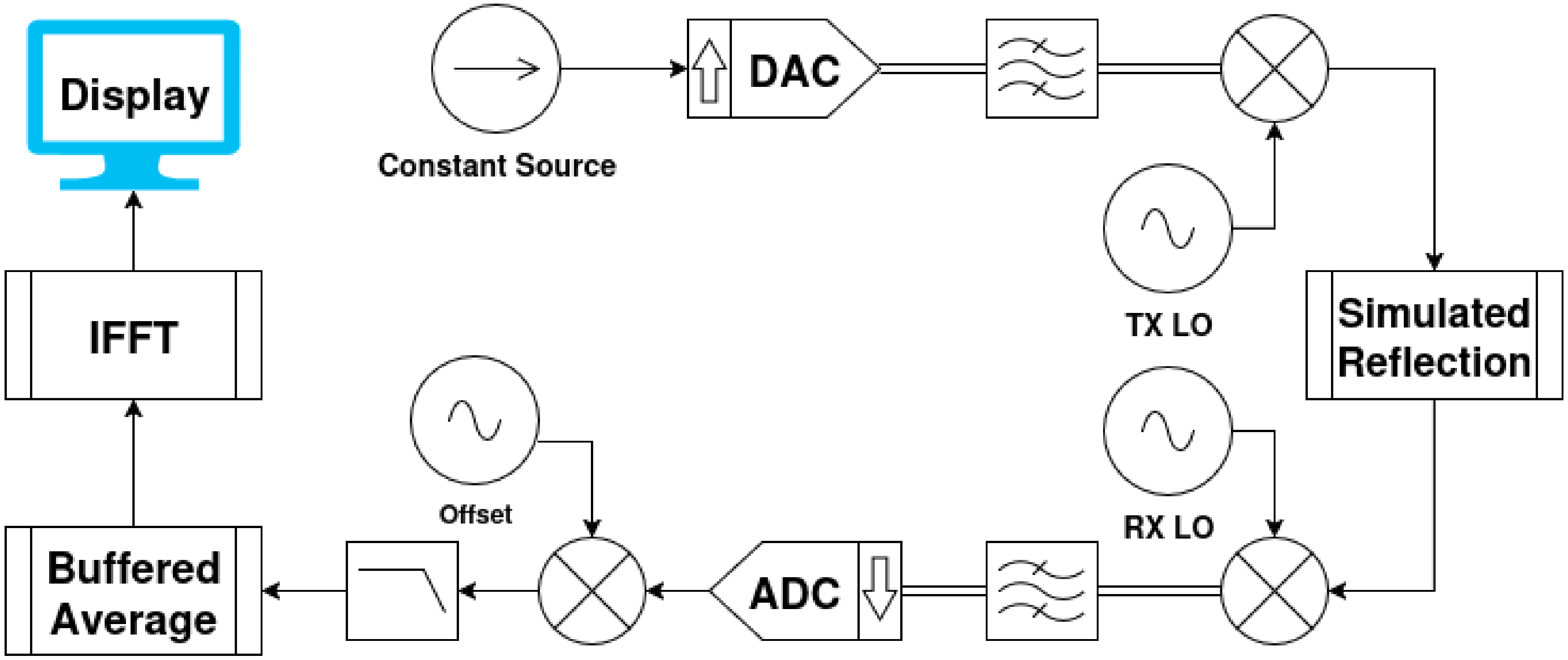
$$\Delta R = \frac{c}{2B} = \frac{c}{2N\Delta f}$$

$$R_{max} = \Delta R N = \frac{c}{2\Delta f}$$

Equations for Range Resolution (ΔR) and Maximum Unambiguous Range (R_{max})

- $\Delta R = 6\ cm$
- $R_{max} = 6\ m$
- $B = 2.5\ GHz$ (600 MHz – 3.1 GHZ)
- $N = 100$
- $\Delta f = 25\ MHz$

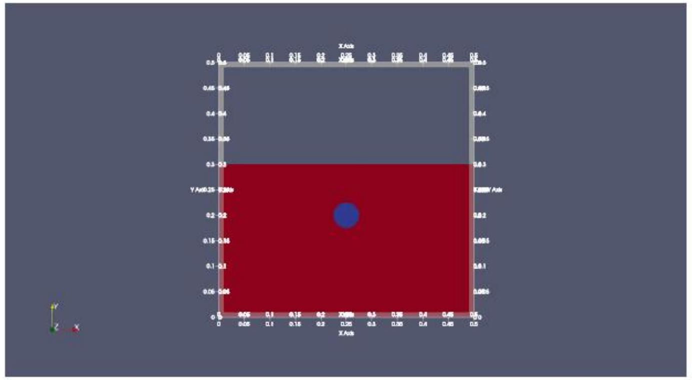
Simulated Architecture



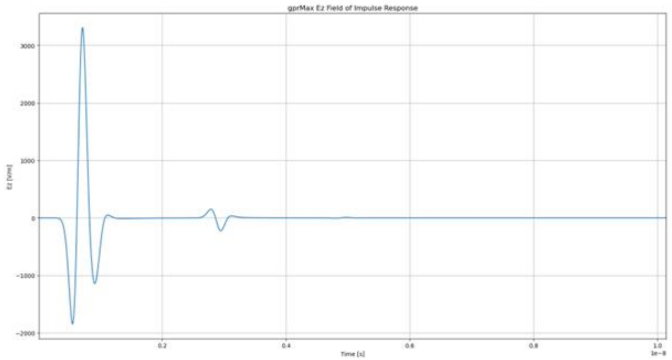
Simulated Reflection

- GPR system can be approximated as LTI
- gprMax generates impulse response and comparison

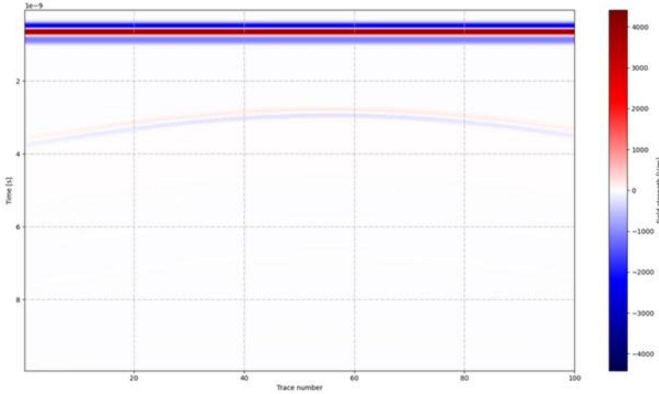
- Python3 Processing
  - Frequency Synthesis
  - Convolution
  - Range Correlation



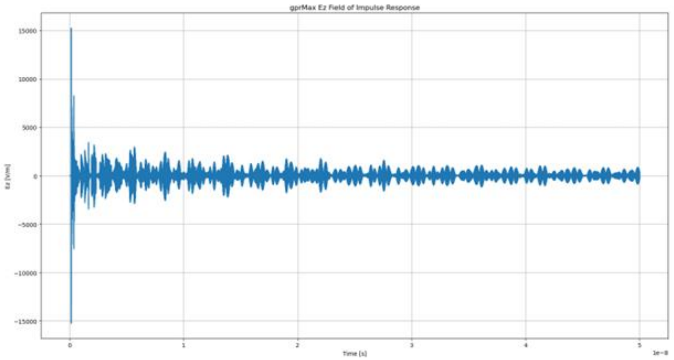
(a) Visualization of GPR Environment



(b) Gaussian Dot Norm A-scan for System

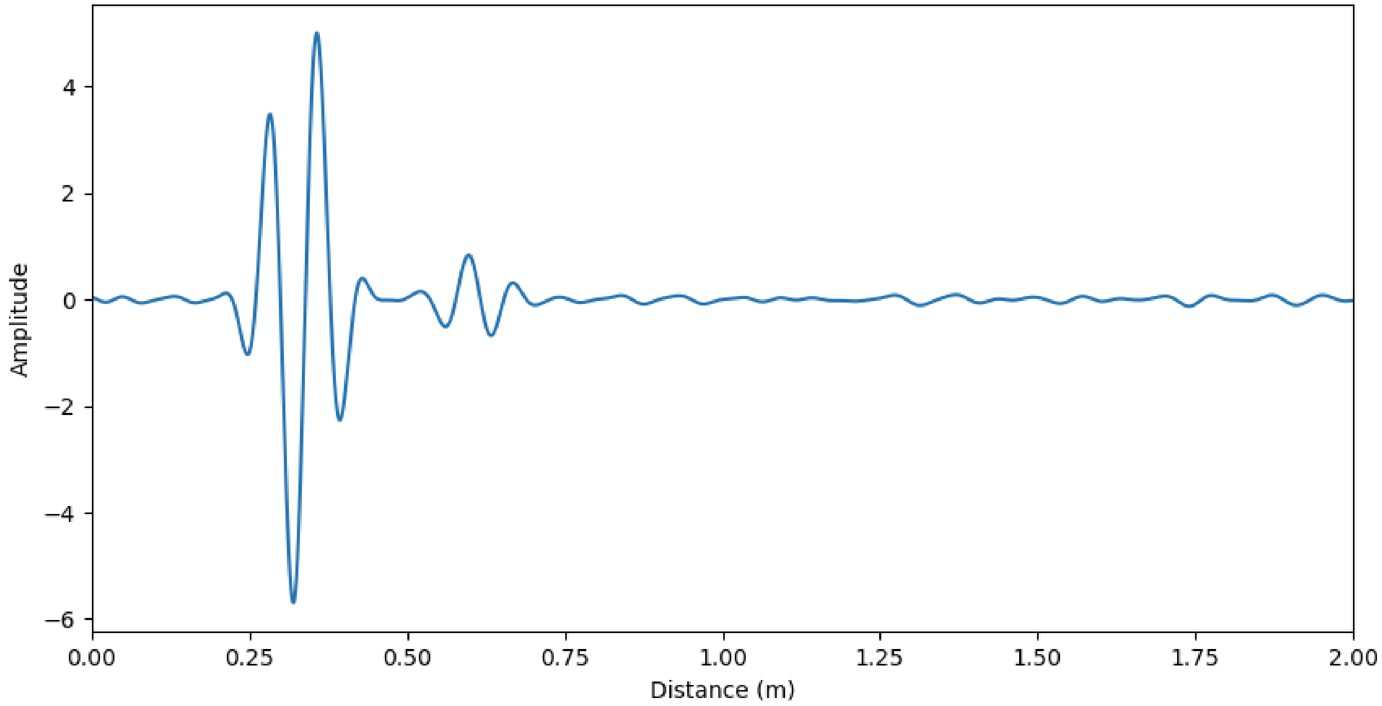


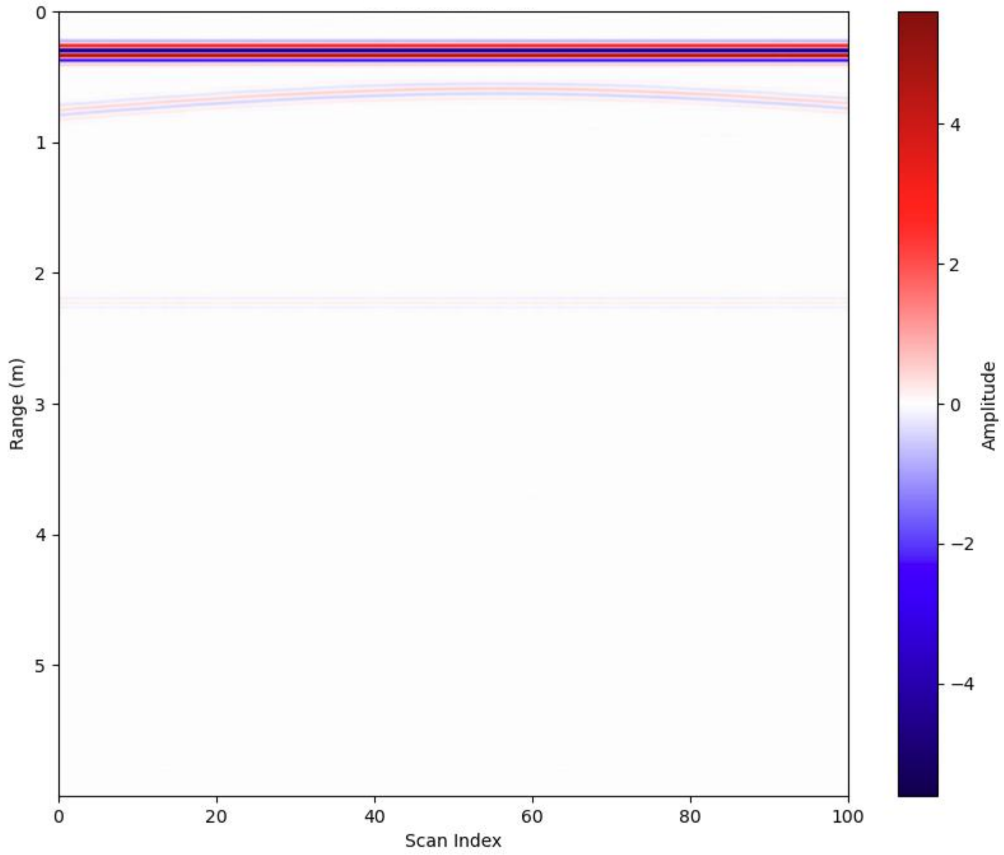
(c) Gaussian Dot Norm B-scan for System



(d) Impulse Response Generated by gprMax

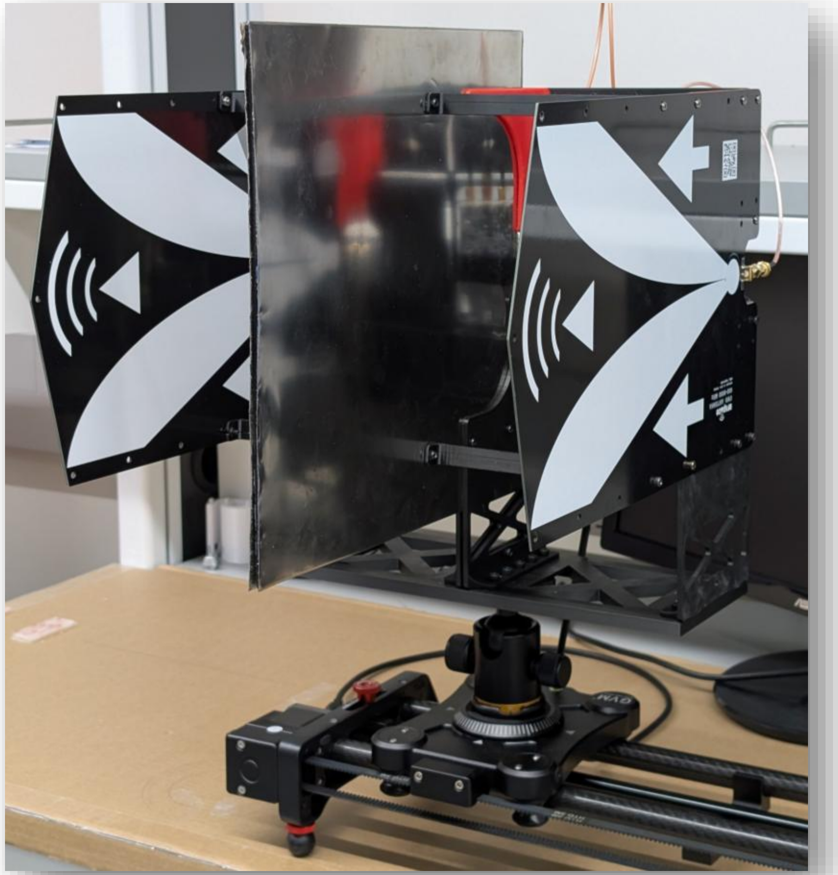
Simulation Results





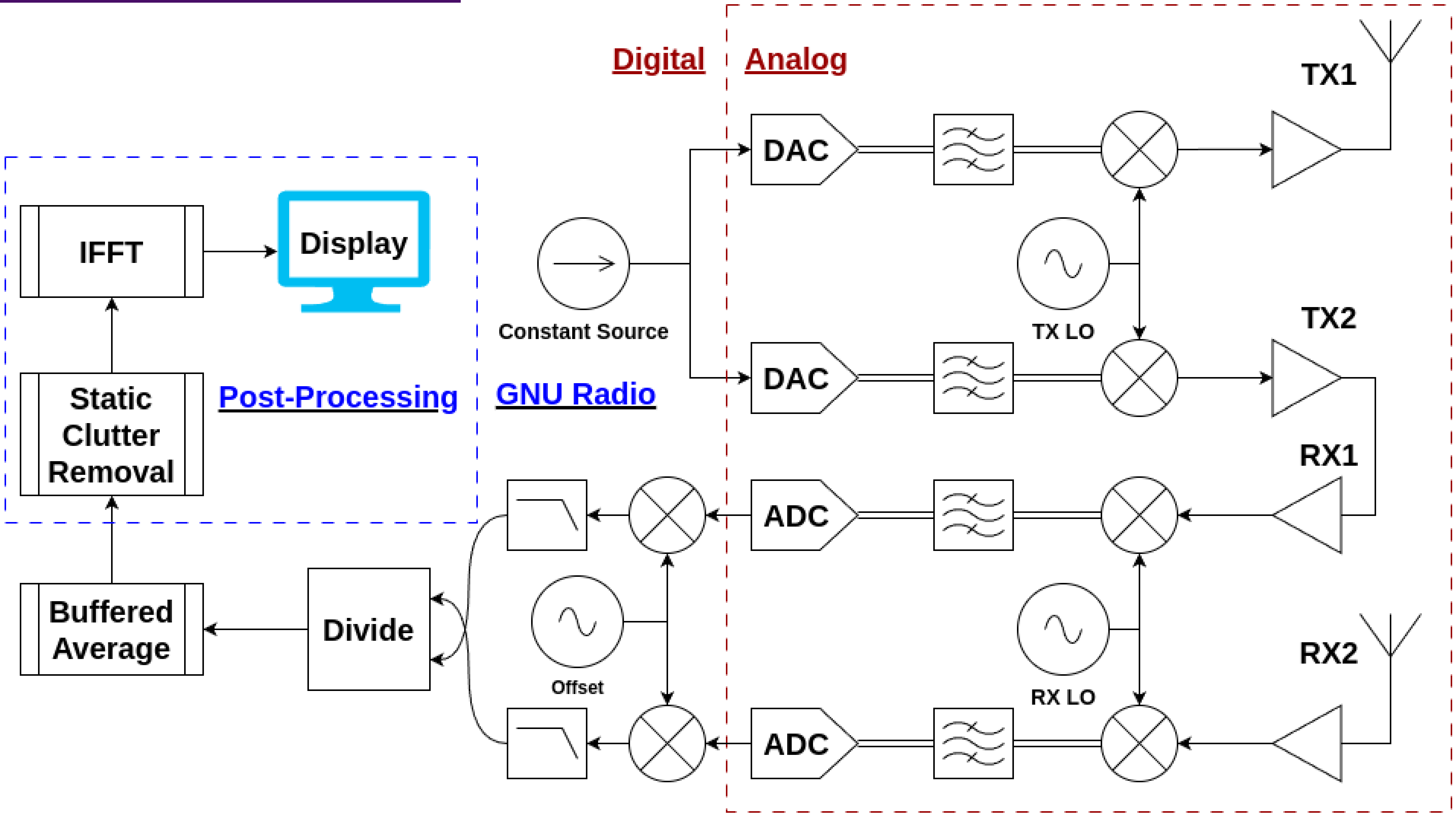
Hardware Overview

- SDR: BladeRF 2.0 Micro
  - 2x2 MIMO transceiver
  - 12-bit ADCs/DACs
  - Tuning range : 47 MHz – 6 GHz
- Antennas: TSA600 Vivaldi antennas
  - High performance, wideband: 600 MHz – 6 GHz
- Shared clock source but separate RX and TX oscillators
  - Precisely Same Frequency
  - Non-Deterministic Phase Difference

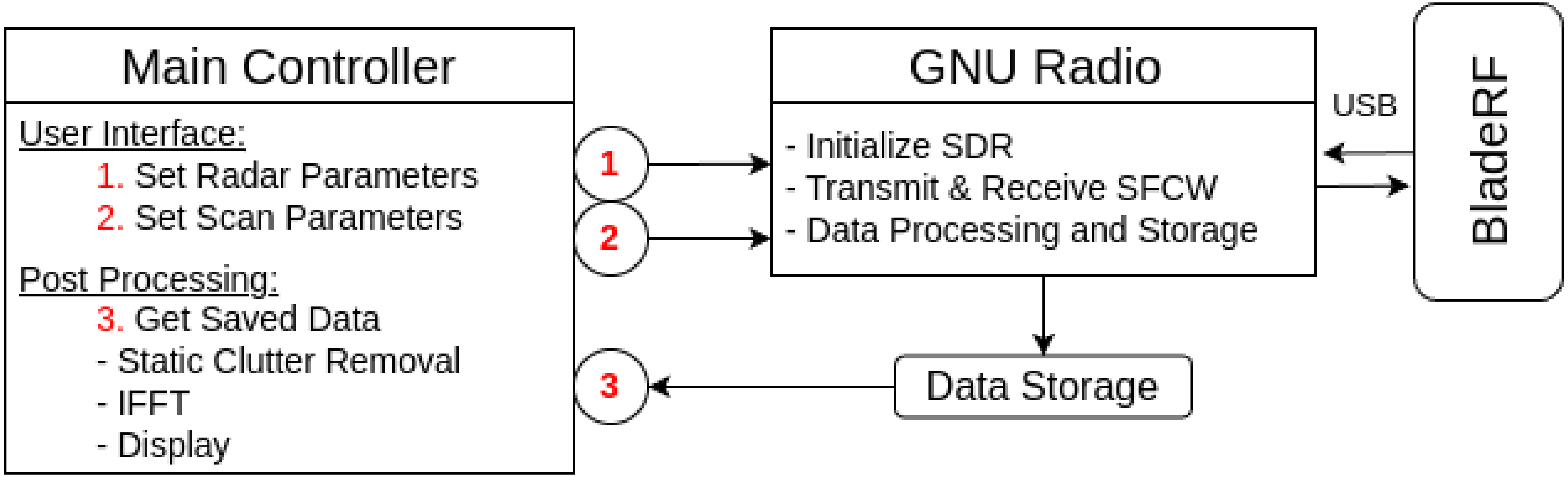


SD-GPR Test Rig

Proposed SD-GPR Architecture

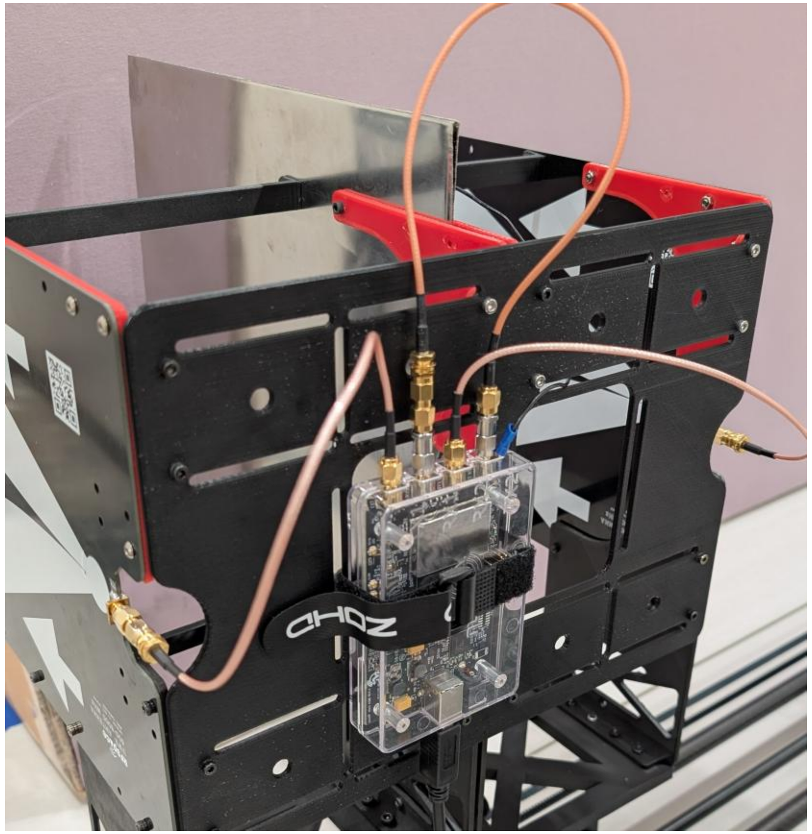


Software Overview



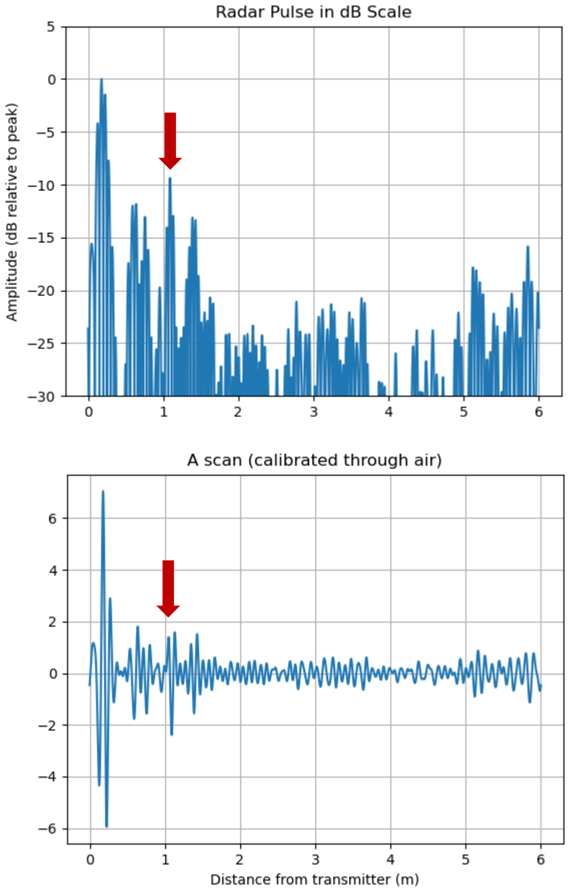
Receiver Calibration

- Two Phase Offsets:
  - Local Oscillator(LO) Phase Difference
  - Signal Propagation Phase Offset
- LO Phase Difference:
  - Reference Line Division
  - Isolates Absolute Change in Mag./Phase
- Signal Propagation Offset
  - Measured
  - Constant Phase Shift Applied

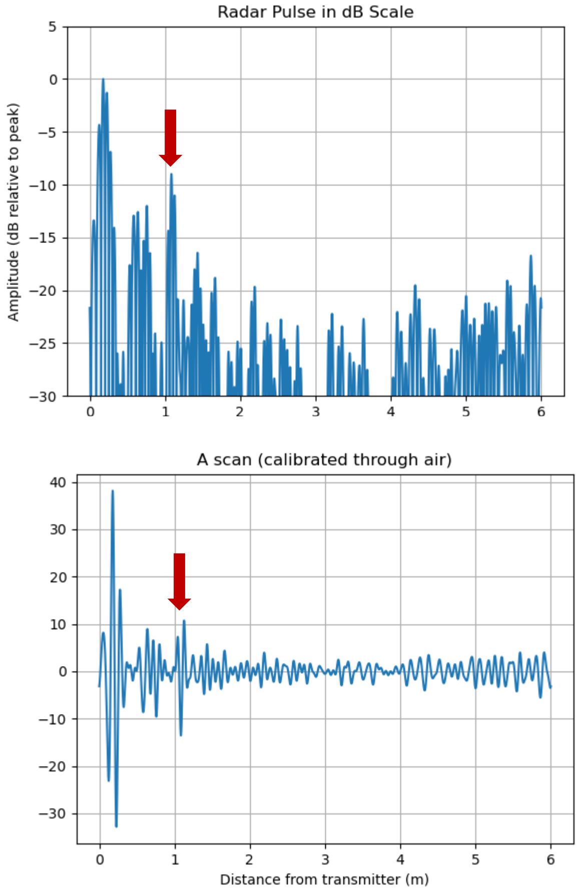


Reference Line Connections

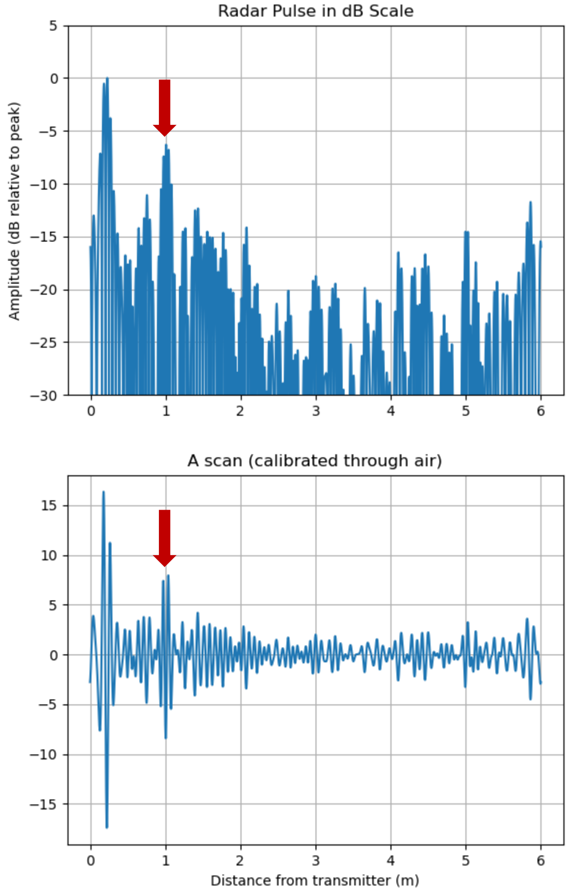
Transmitter Calibration



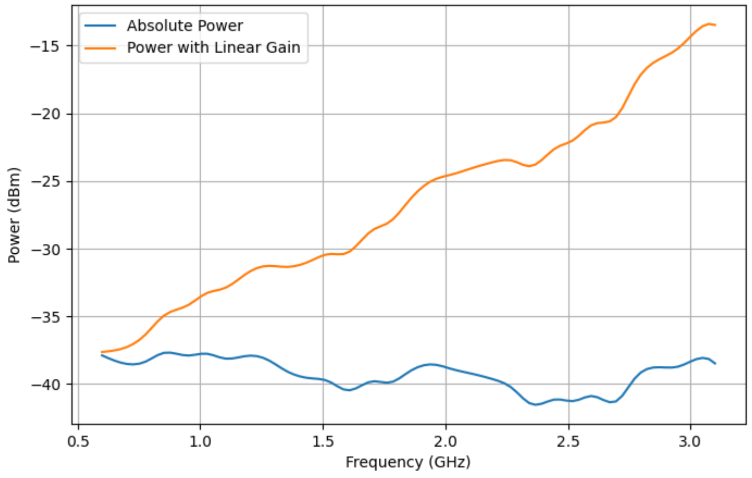
Constant Gain: 15 dB



Constant Gain: 30 dB



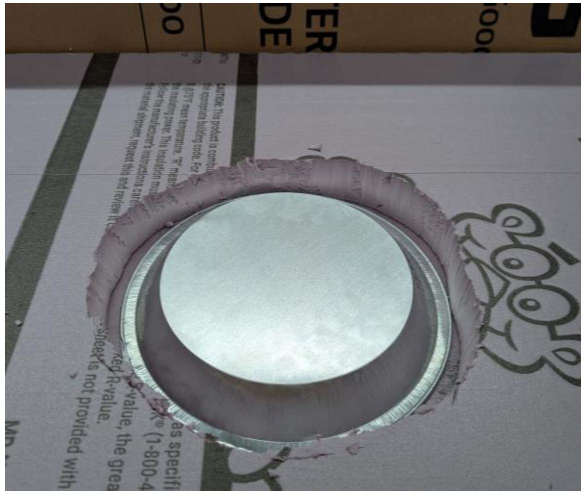
Linearly Ramping Gain



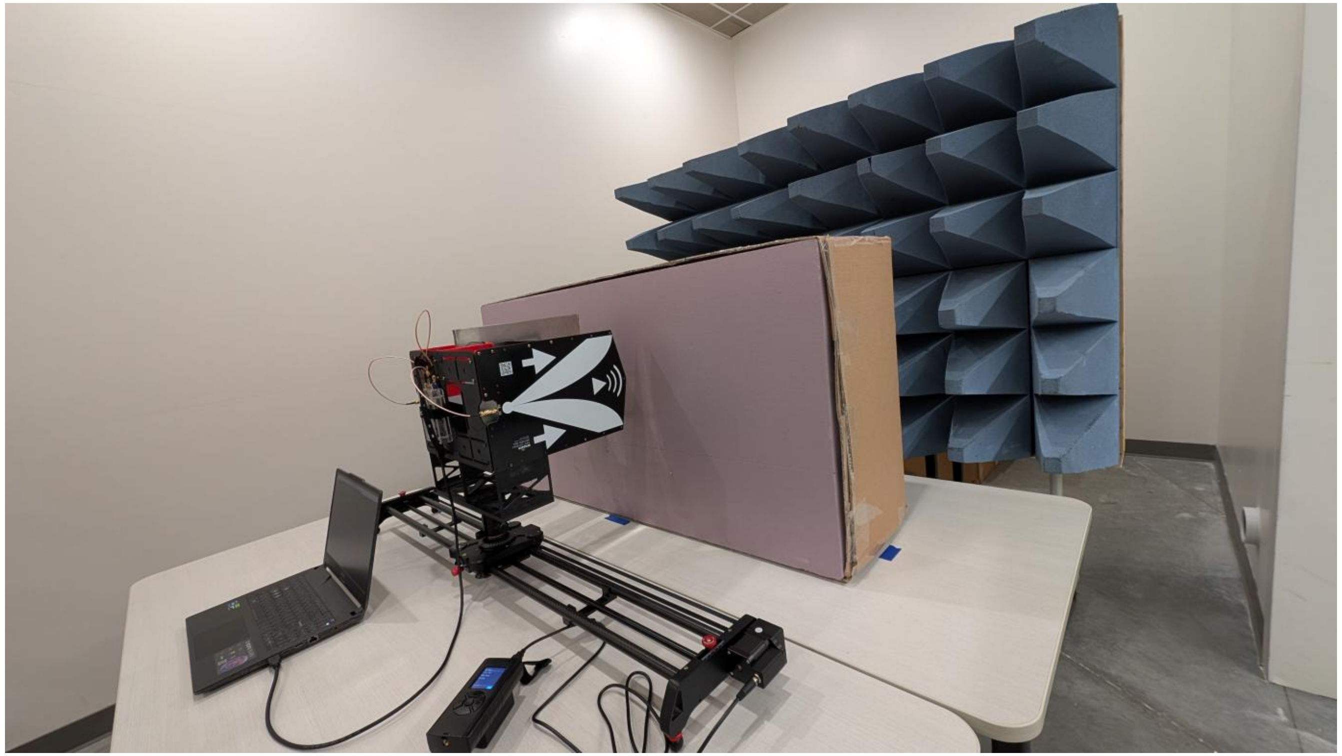
TX Power Frequency Response

Experiment Setup

COTS GPR

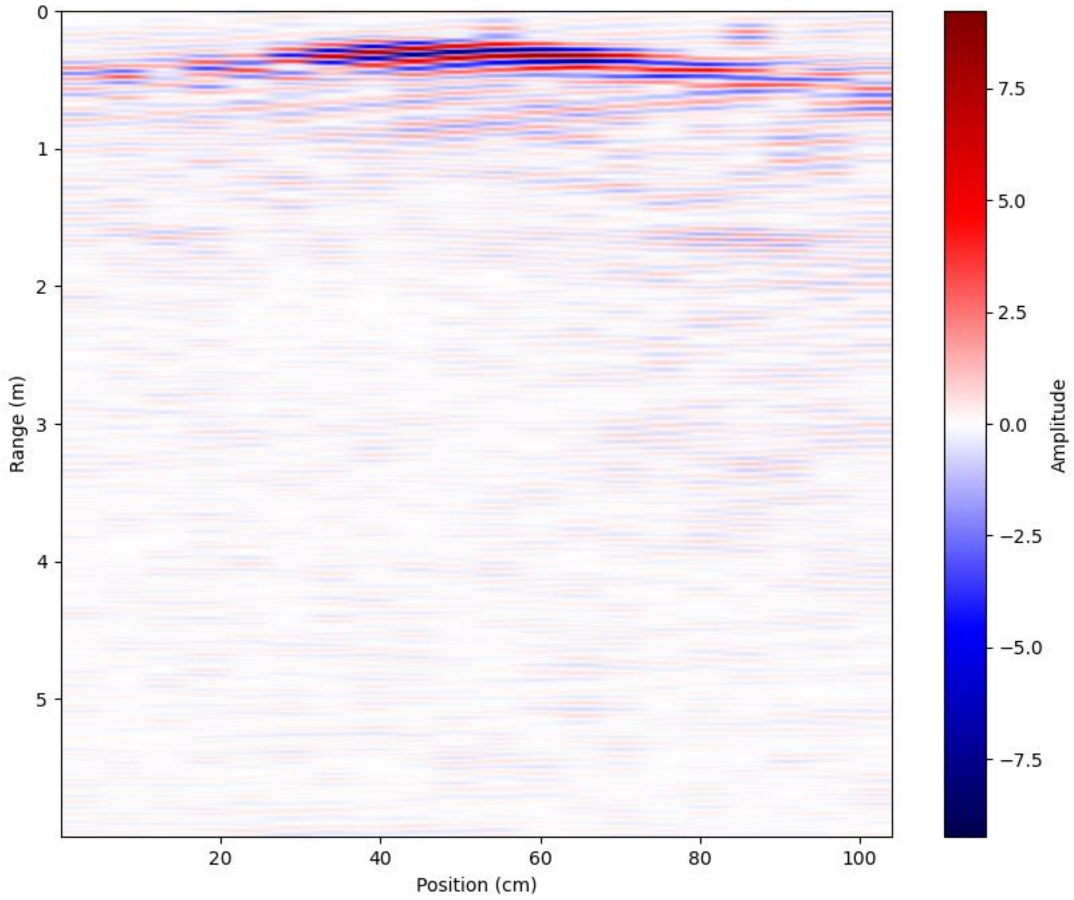


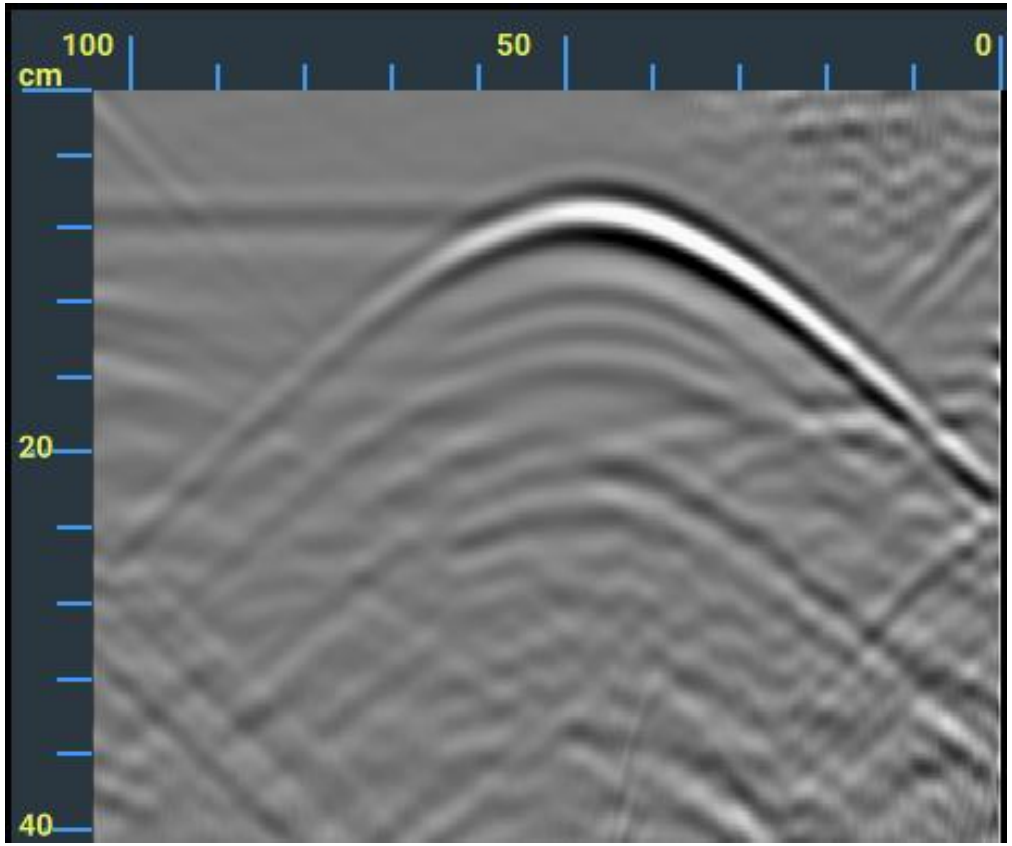
Embedded Target



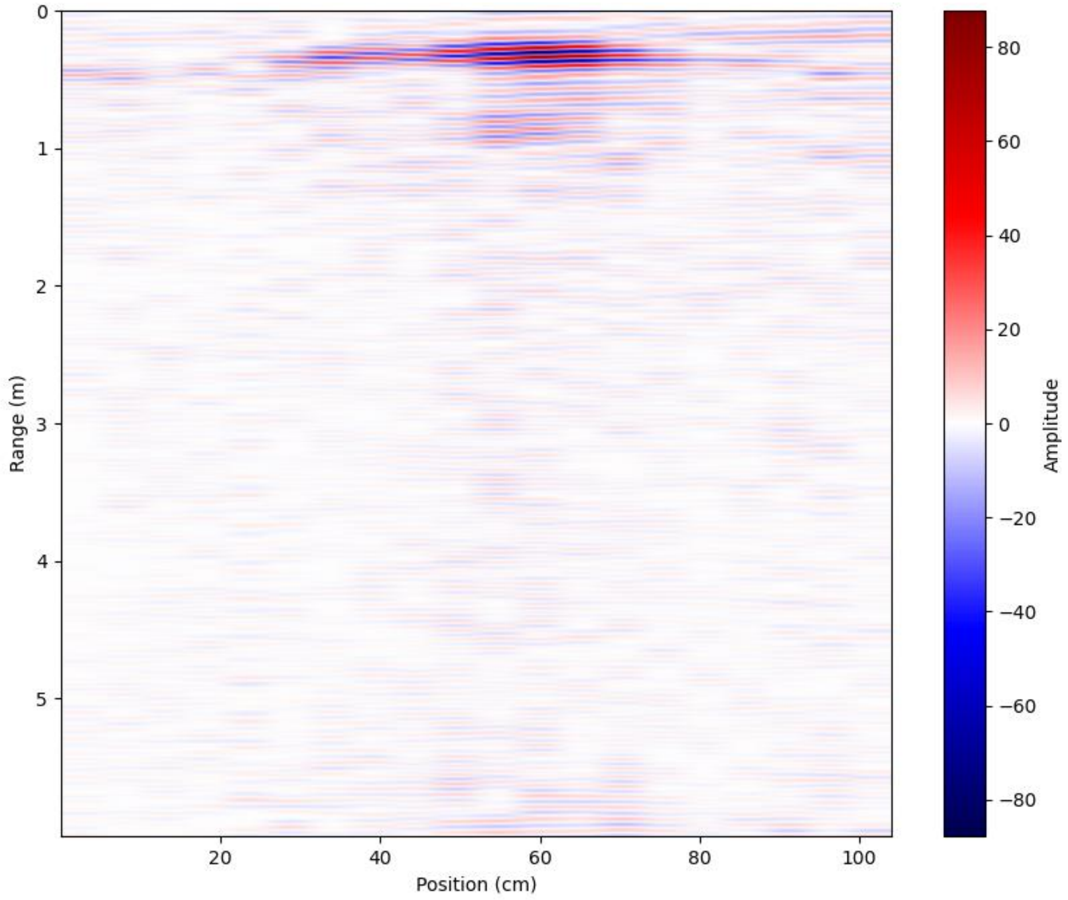
SD-GPR Test Environment

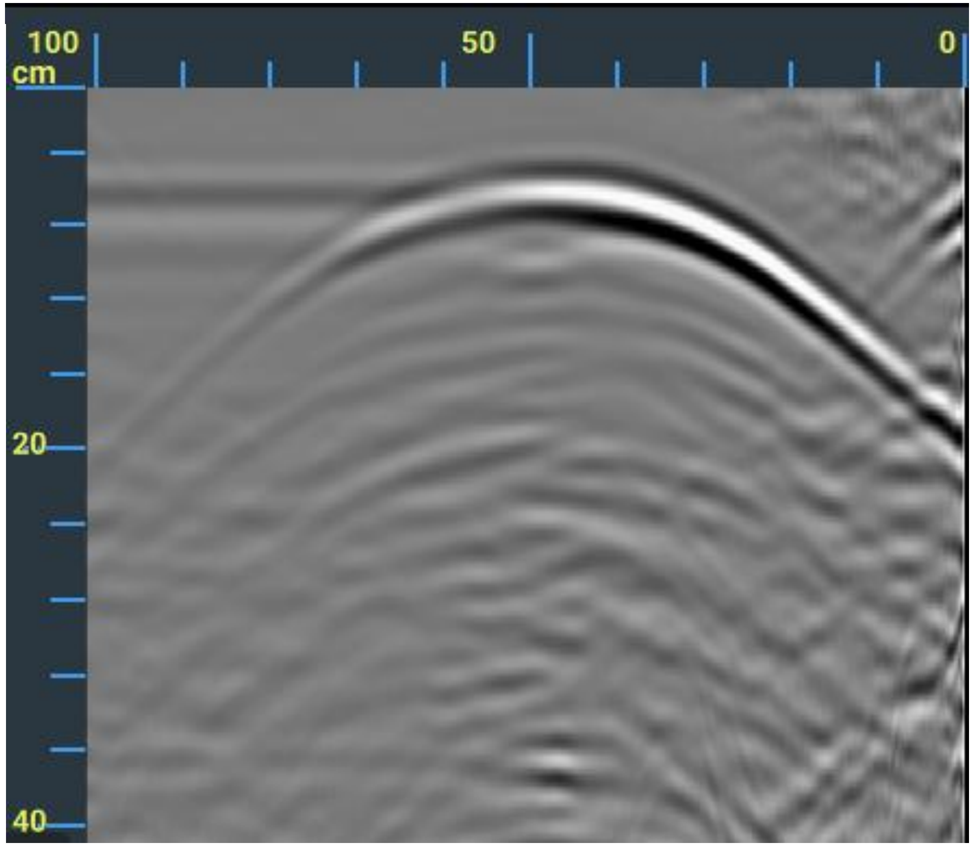
De-coupled Results – Soda Can



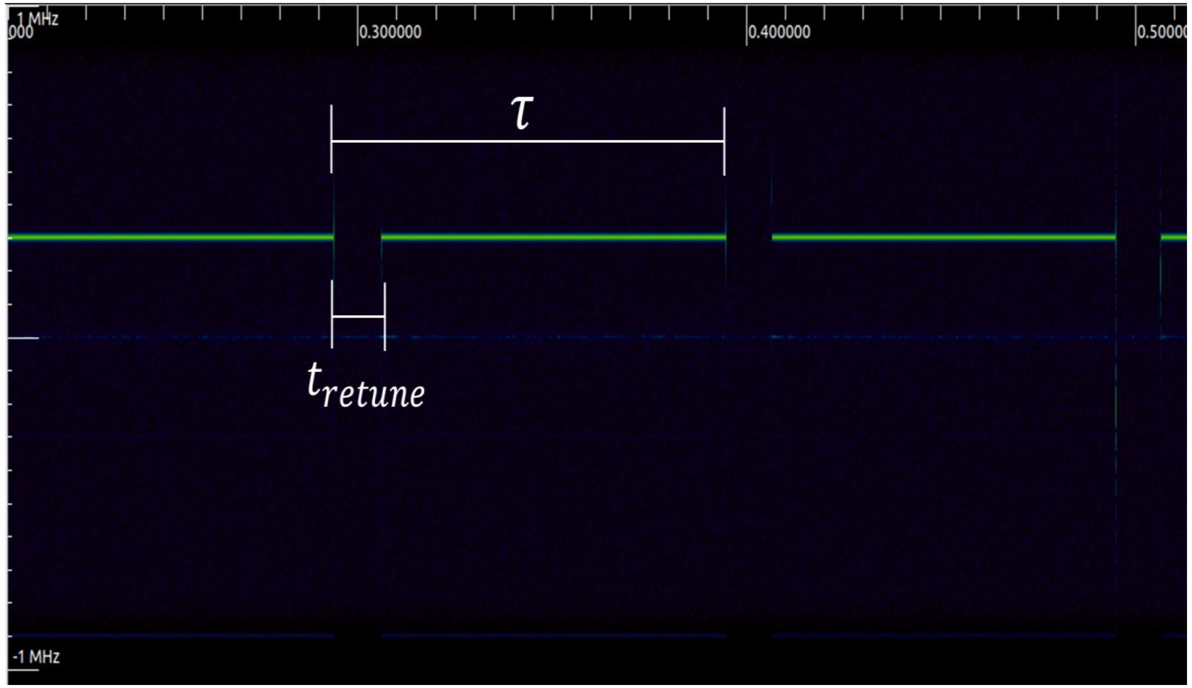


Experiment De-coupled Results – Pie Tin

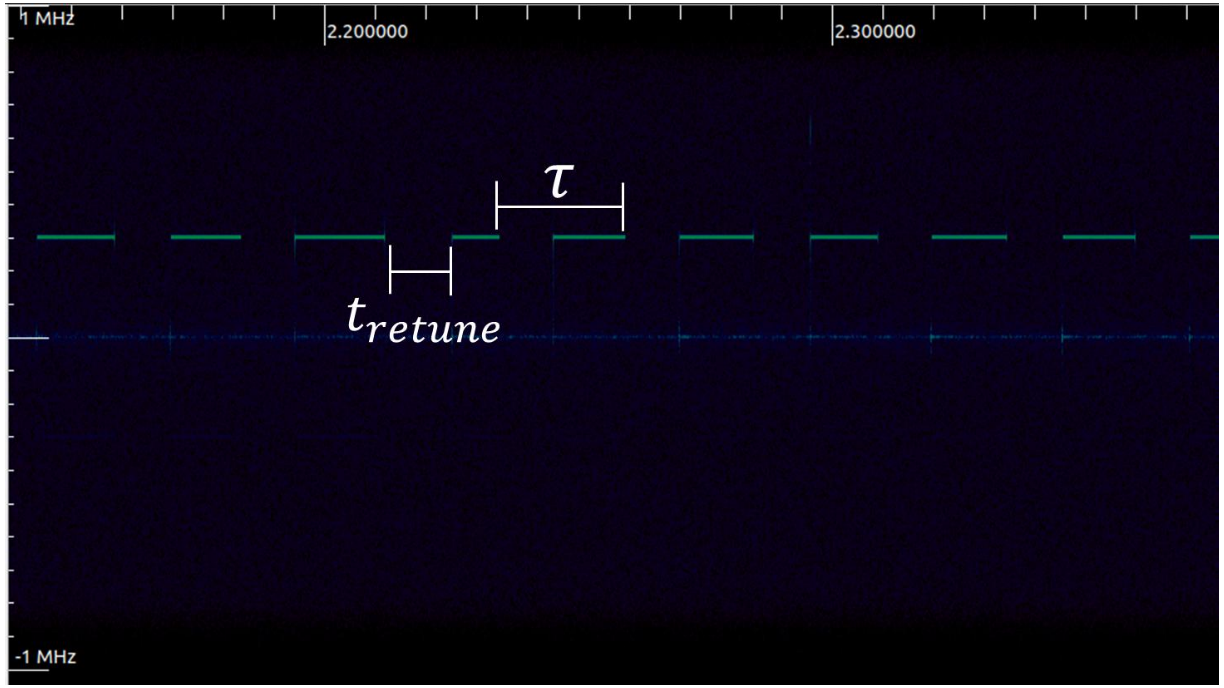




Transmit Time Analysis

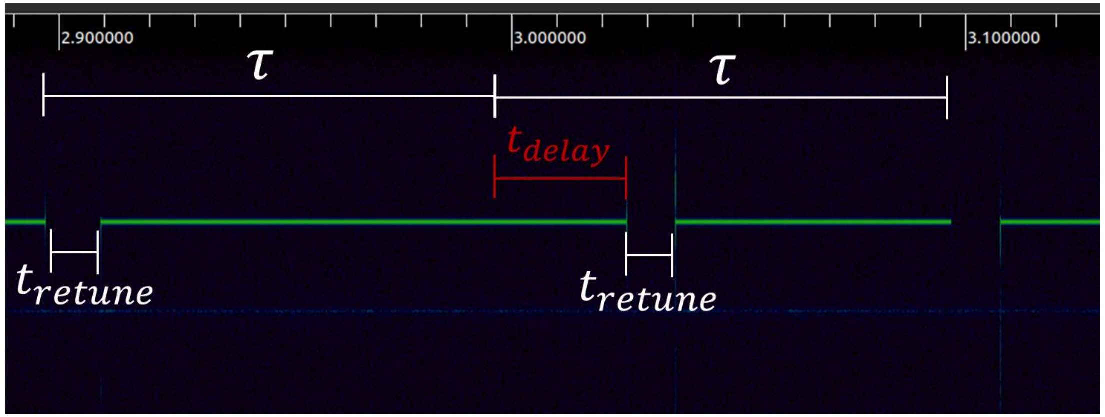


100 ms Transmit Time

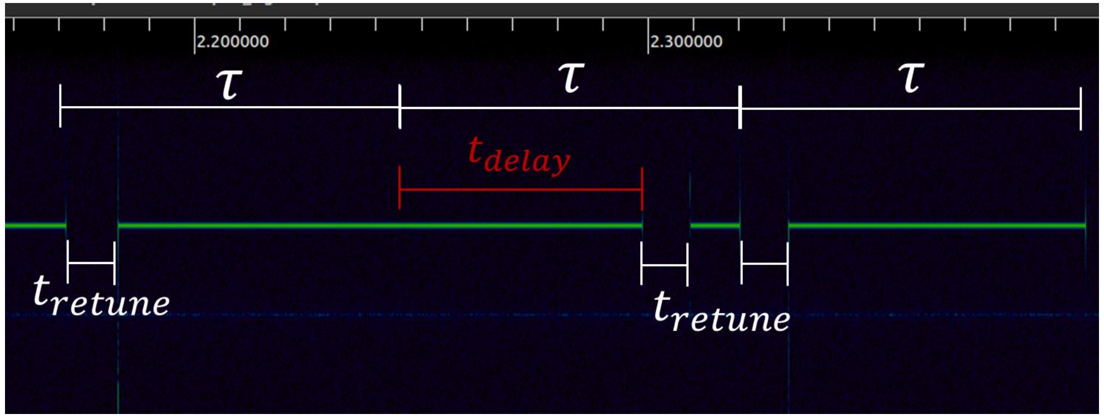


25 ms Transmit Time

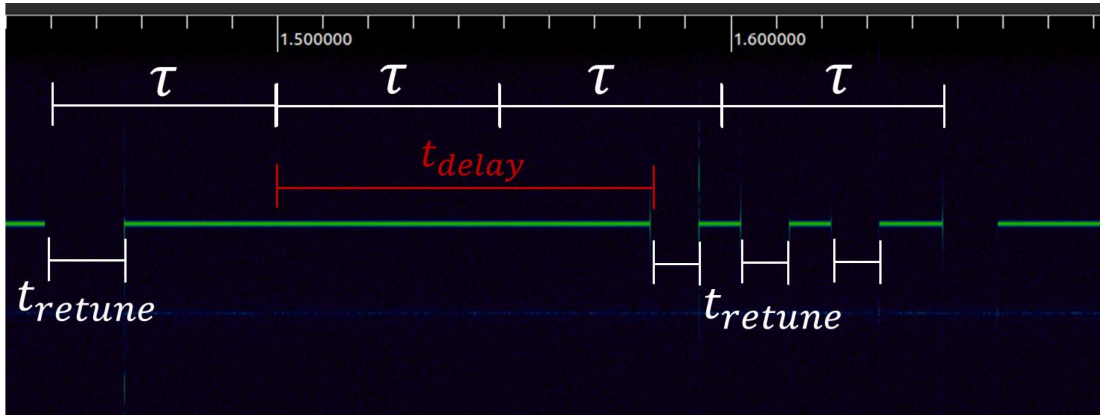
1.35 GHz Boundary



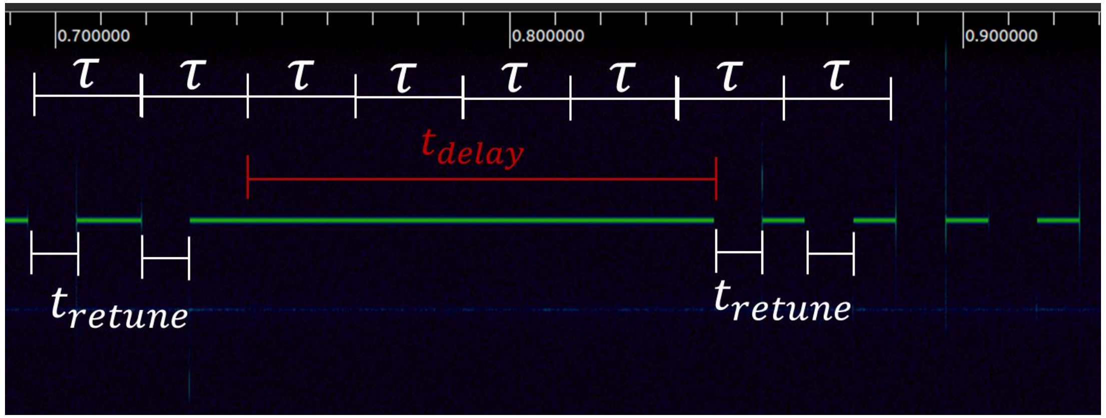
100 ms Transmit Time



75 ms Transmit Time



50 ms Transmit Time



25 ms Transmit Time

Conclusion

- Proposed SD-GPR Delivers Comparable Performance to COTS GPR

- SDR Shows Promise as an Alternative
  - Cost Effective
  - Flexible

- Future Work:
  - Addressing Retune Issues
  - Refine Static Clutter Removal
  - Real-Time Display
  - Wireless Interface

GPR	Target	Lateral	Depth	e_d	$\overline{e_d}$
COTS	Pie Tin	42 cm	5 cm	13 cm	11.5 cm
	Soda Can	46 cm	6 cm	10 cm	
SD-GPR	Pie Tin	55 cm	25 cm	11 cm	9 cm
	Soda Can	55 cm	20 cm	7 cm	

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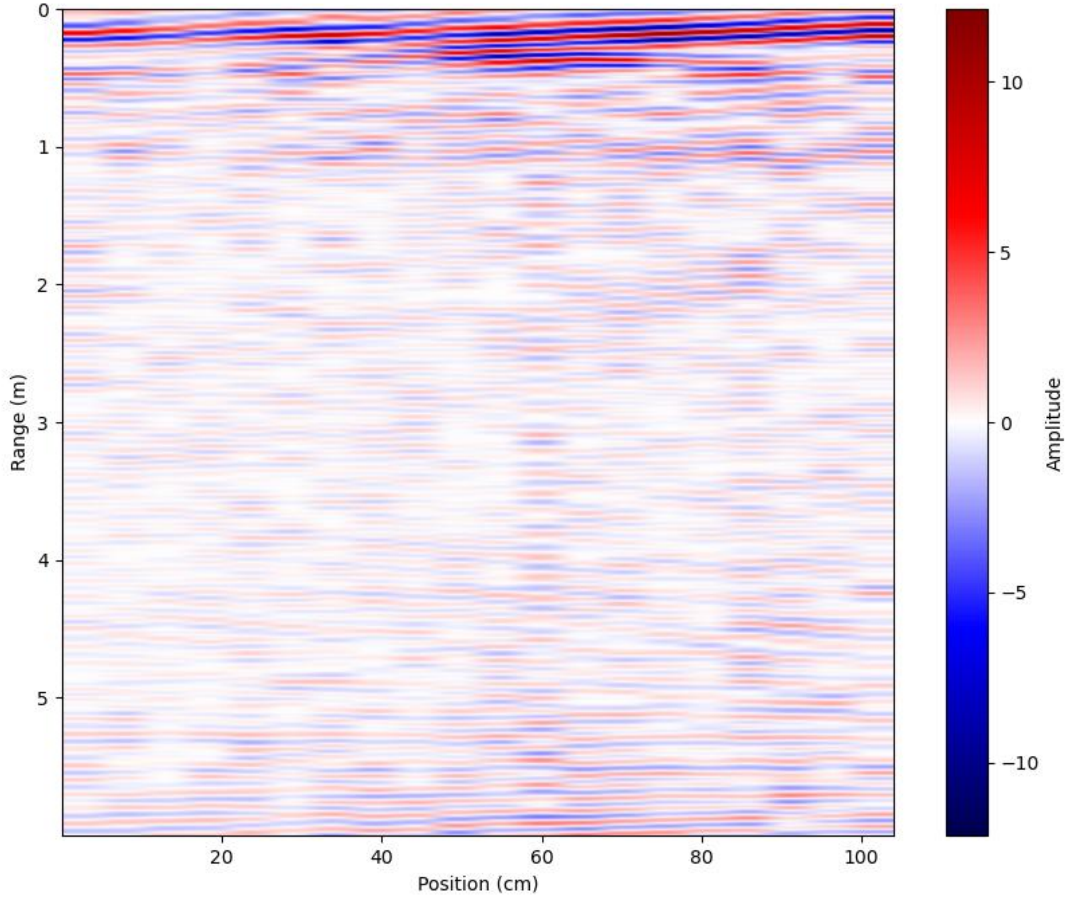
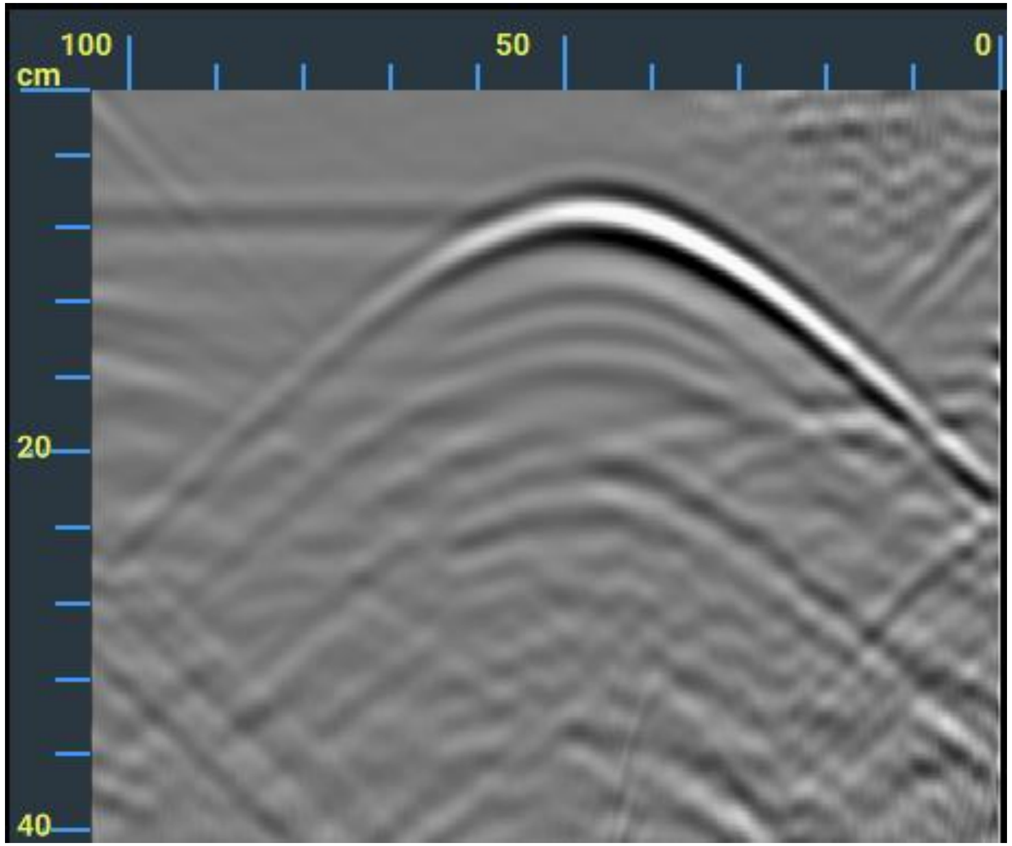
Initial Results – Soda Can





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