Exploring the Use of Surface Wave Ultrasonic Measurements for Near-Surface Rolling Contact Fatigue Depth Characterization

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Project Background

- This work is a collaborative effort between Simon Fraser University's Vehicle Track Interaction (VTI) Research Group in Vancouver Canada, and **Peak to Peak Measurement Solutions Ltd.** in Sheffield, UK.

- We are particularly grateful to **Henry Brunskill**, **Xiangwei Li**, **Harry Shackleton**, and **Roxie Rhodes** for their ongoing involvement and support.

PEAK TO PEAK Measurement Solutions

Project Background

- Physical rail samples used in this work are being collected in collaboration with the **National Research Council of Canada's** Automotive and Surface Transportation Centre (AST), through a joint industry request to support project work in measuring, quantifying, and mapping RCF in rails utilized under varying track operating conditions.

- We are particularly grateful to **Sylvie Chenier** and **Daniel Szablewski** for their collaborative efforts in this initiative.

National Research Council Canada   Conseil national de recherches Canada

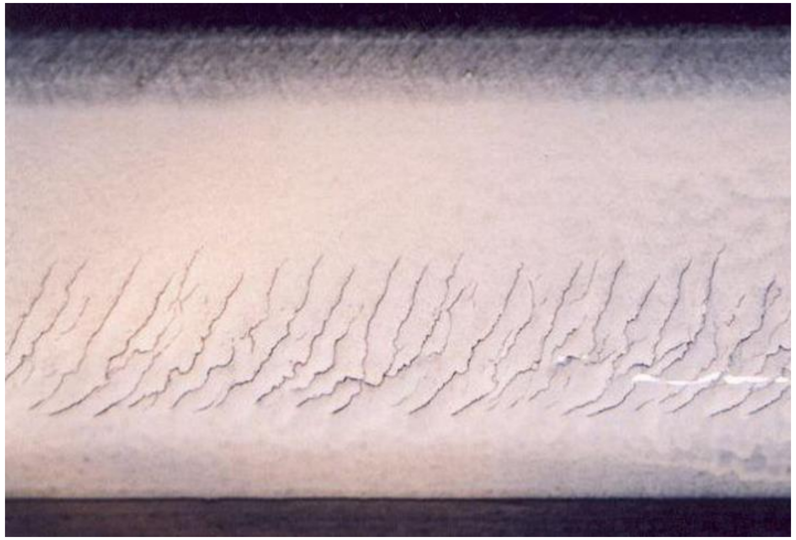
Overview

- Background and Motivation
- Experimental Setup (proof of concept phase)
- Challenge #1: Optimizing Electrical and Mechanical Parameters
  - Proof of concept results (signal energy)
- Challenge #2: Decoupling depth estimates from coupling conditions
  - Proof of concept results (reflection & transmission coefficients)
- Conclusions and Future Work

Background and Motivation

Rolling Contact Fatigue (RCF) is a critical issue in modern railways due to increased operational demands, causing significant **safety risks** and **economic losses**.

- **Preventive grinding** is a widely used strategy for mitigating **early-stage shallow** RCF cracks and extending asset life, but its effectiveness, closely tied to optimal grinding depth, depends on **accurate and precise characterization of crack depth**.



Sources [2]

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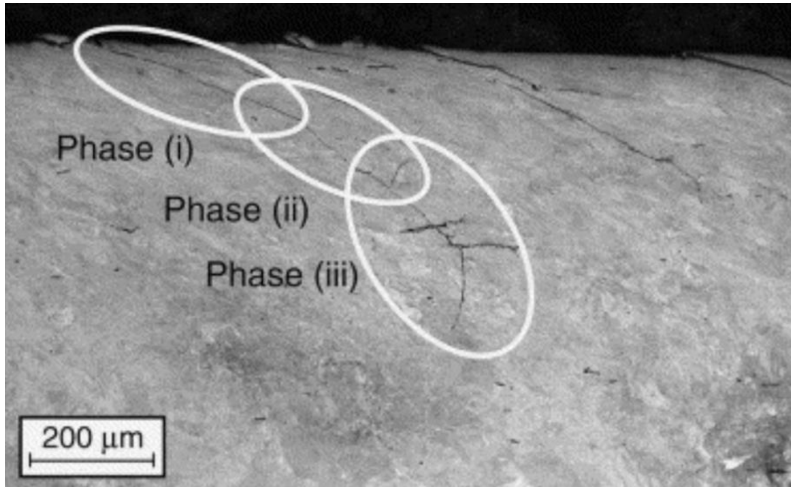


Sources [3]

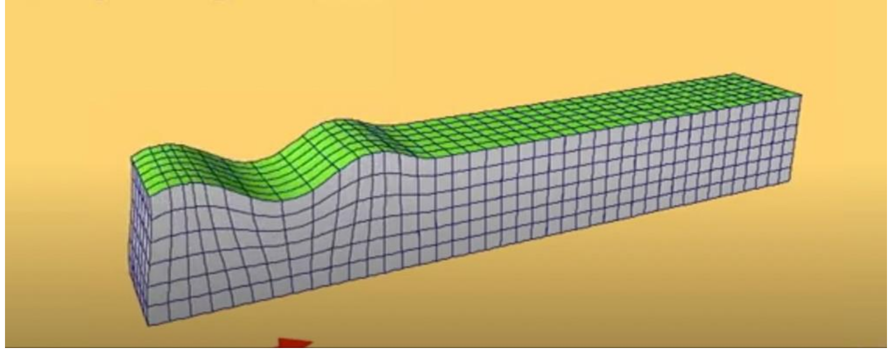
Background and Motivation

- However, **existing non-destructive testing methods** have limitations in detecting and measuring the depth of **near-surface RCF cracks**.

Eddy Current Inspection (EC)	Magnetic Flux Leakage Inspection (MFL)	Conventional Body Wave Ultrasonic Inspection (UT)	Visual Inspection and Automated Visual Inspection (VT)
• **Limitations in accurate depth estimation** due to length (vs depth) measurement of surface-breaking cracks, combined with uncertain/unpredictable crack angles, especially in branching cracks. • Challenges in correctly determining full depth of defects due to limited penetration depth, especially if the density of small RCF cracks on the surface is high.	• Challenges in evaluating **crack depth** or surface shape of the cracks. • Challenges in detecting non-transverse to flux cracks and those are close to search coils.	• Downward propagation makes vertical cracks hard to detect; probes must be fixed, limiting speed, range, and in-field efficiency. • **Challenges in detecting surface and near-surface defects** Affected by grease/films and "dead zone" issues, missing cracks shallower than 3 mm using manual UT and 5mm using vehicle mounted UT.	• Near-surface RCF cracks can be closed surface cracks without crack mouth, thus are **invisible** to the **eye or high-speed cameras**. • For visible cracks, the **crack depth cannot be reliably estimated** from visible surface length alone.

Background and Motivation

- Recent studies suggest that **surface wave ultrasonics**, which travel along and stay near the surface of a solid material, is a promising alternative for enhancing near-surface RCF crack detection and depth characterization.



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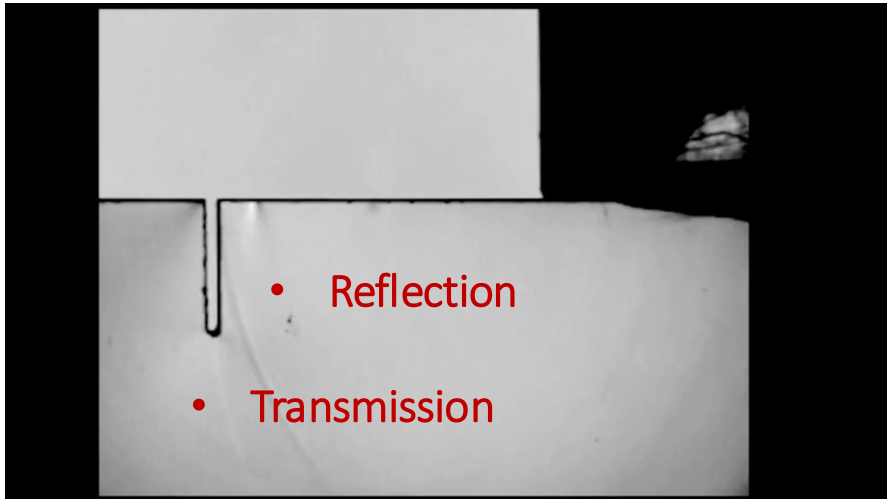

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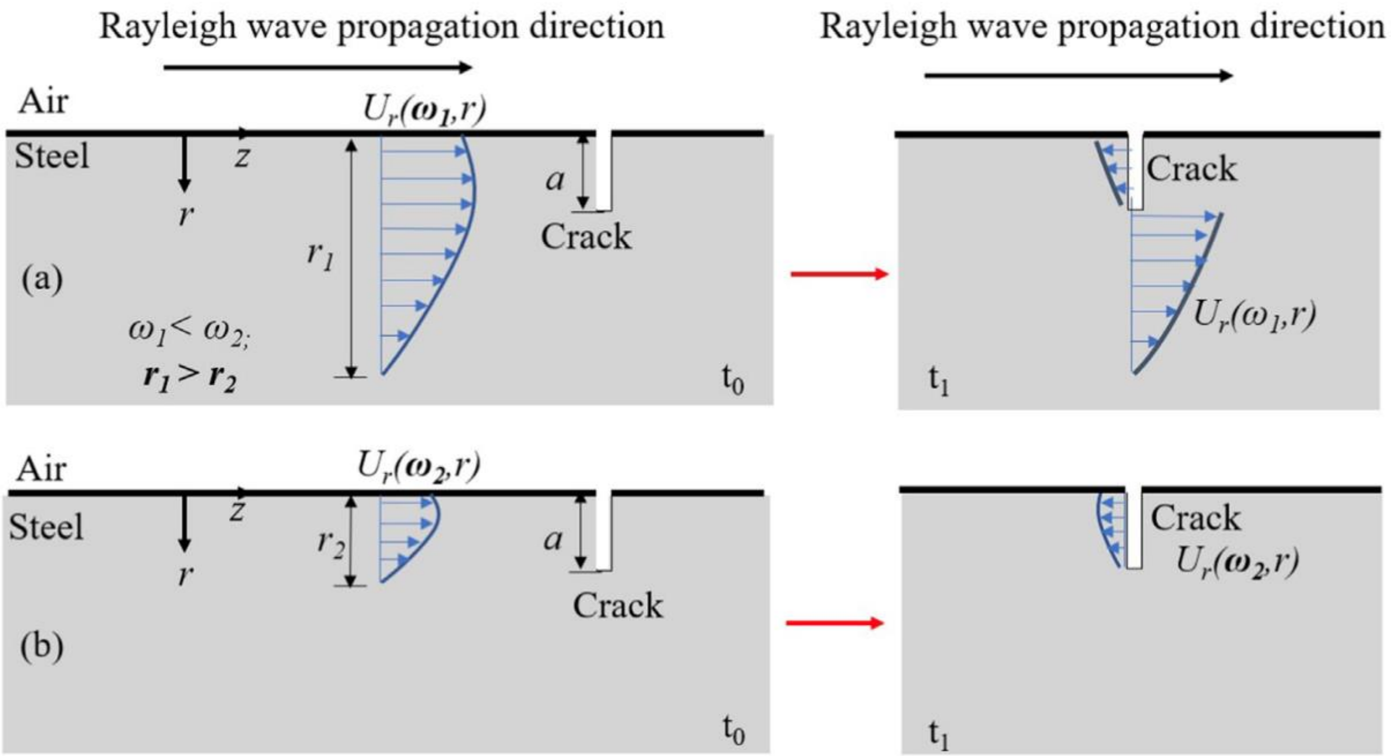


Sources [6]

Background and Motivation

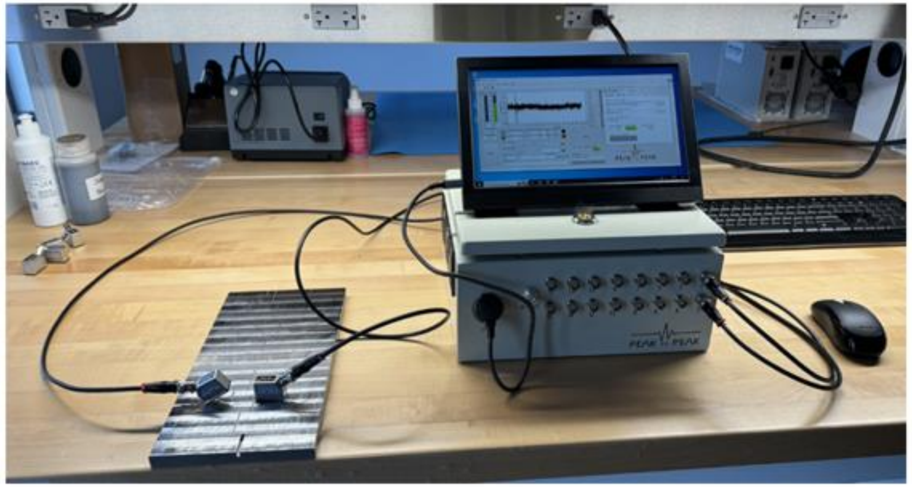
- Recent studies suggest that **surface wave ultrasonics**, which travel along and stay near the surface of a solid material, is a promising alternative for enhancing near-surface RCF crack detection and depth characterization.

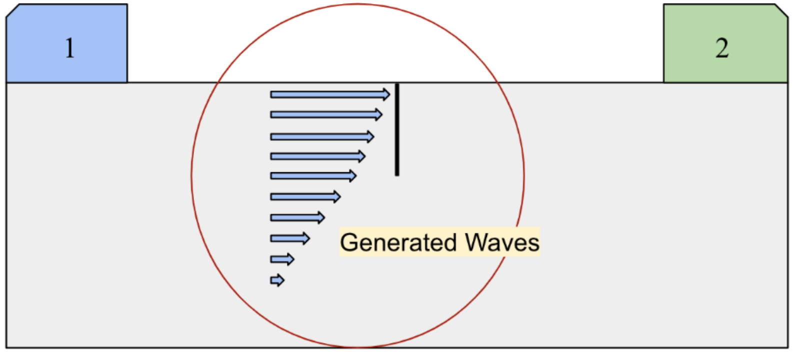
Specific advantages of surface waves:

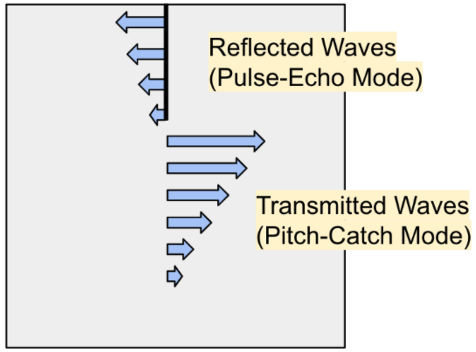
- Low attenuation along the rail surface: long coverage and efficient inspection from a single position;
- Flexible: measurement depth adjustable by changing transducer frequency;
- Low sensitivity to surface roughness or imperfections;
- High sensitivity to surface defects: strong signal-to-noise ratio, especially for defects on/near the running surface;
- Focused on critical cracks among a cluster of cracks: suitable for determining optimal grinding depth;
- Practical advantages:
    - simple data interpretation;
    - robust and portable, easily integrated with handheld or train-mounted inspection systems.

This research aims to **investigate and evaluate** the **feasibility and performance** of surface wave ultrasonic inspection as a potential solution.

Experimental Equipment and Setup (proof of concept phase)



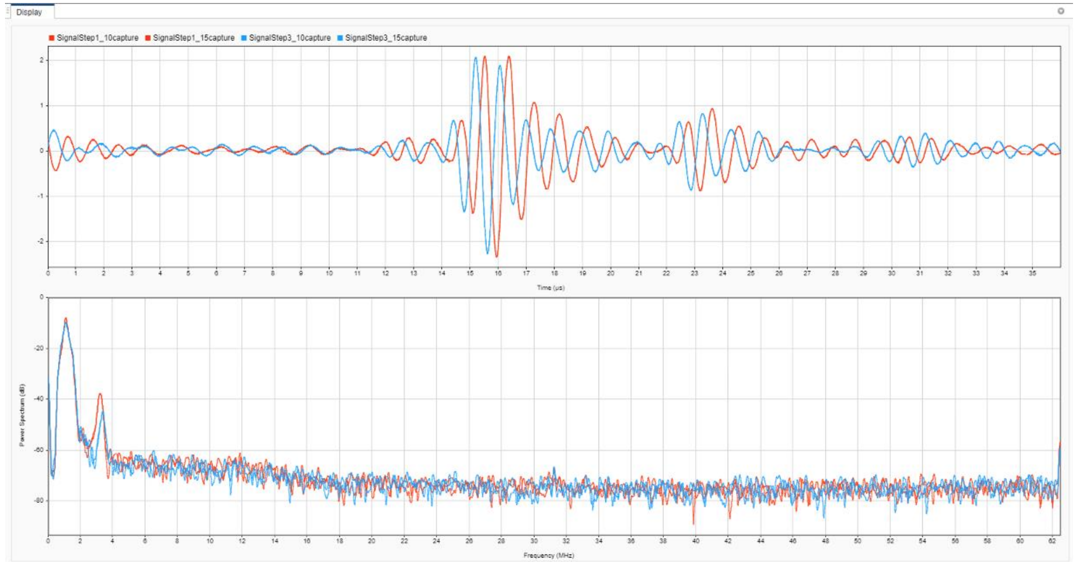



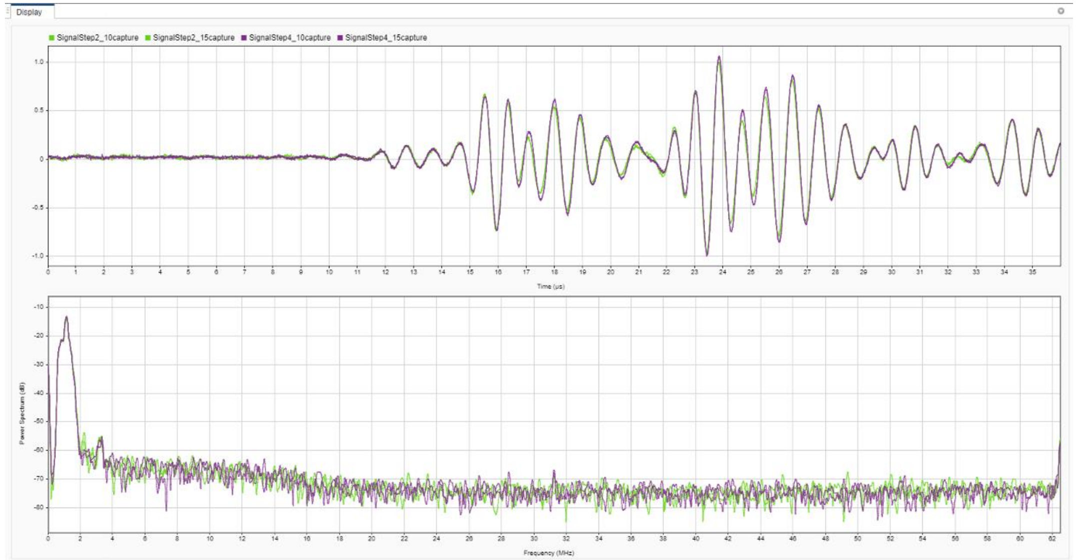


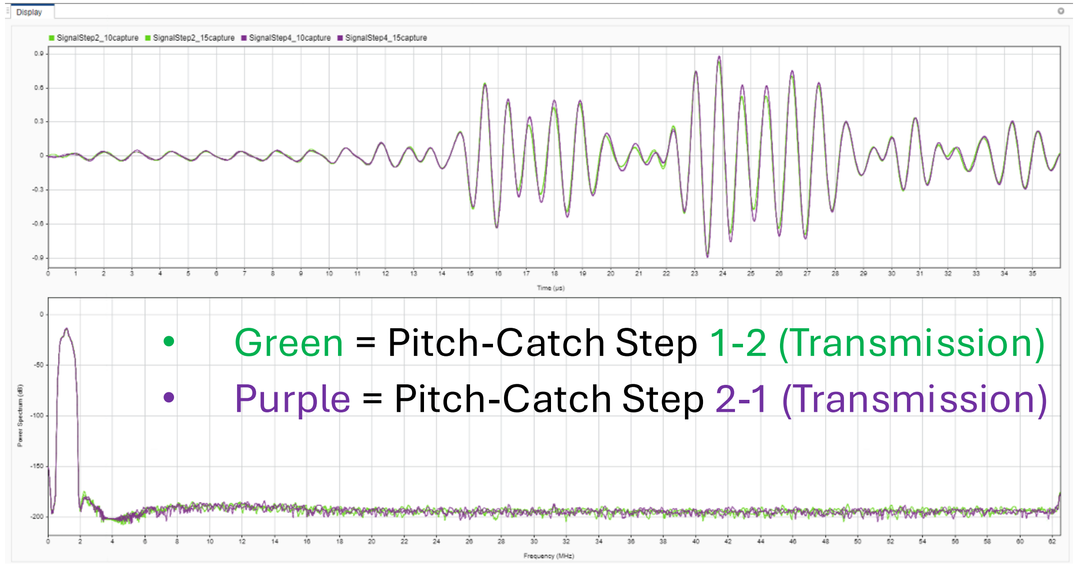
Measuring Modes:

- **Pulse-Echo** Mode (**Reflection**)
  - Step 1-1 (signal send & receive: Probe 1)
  - Step 2-2 (signal send & receive: Probe 2)
- **Pitch-Catch** Mode (**Transmission**)
  - Step 1-2 (signal send: Probe 1; receive: Probe 2)
  - Step 2-1 (signal send Probe 2; receive: Probe 1)

Signal Processing







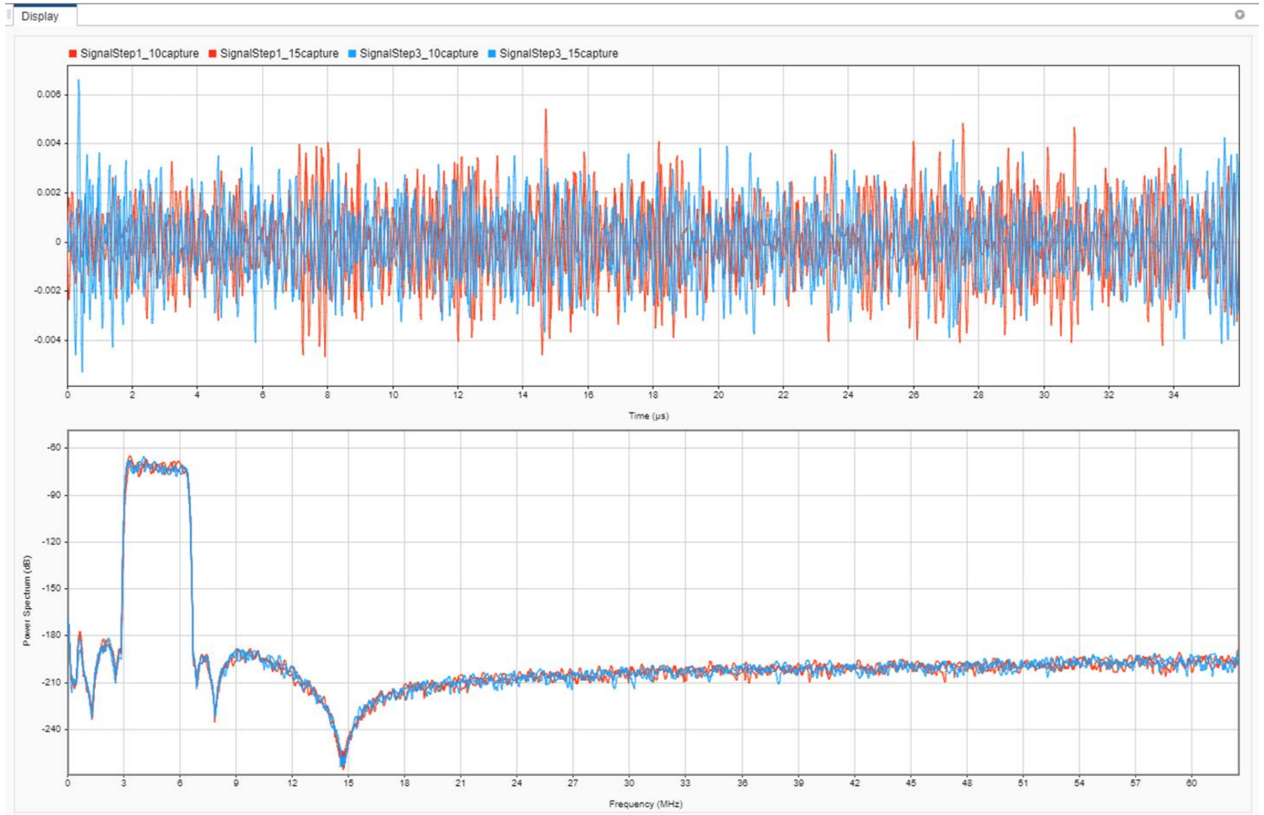
Challenge #1: Optimizing Electrical and Mechanical Parameters

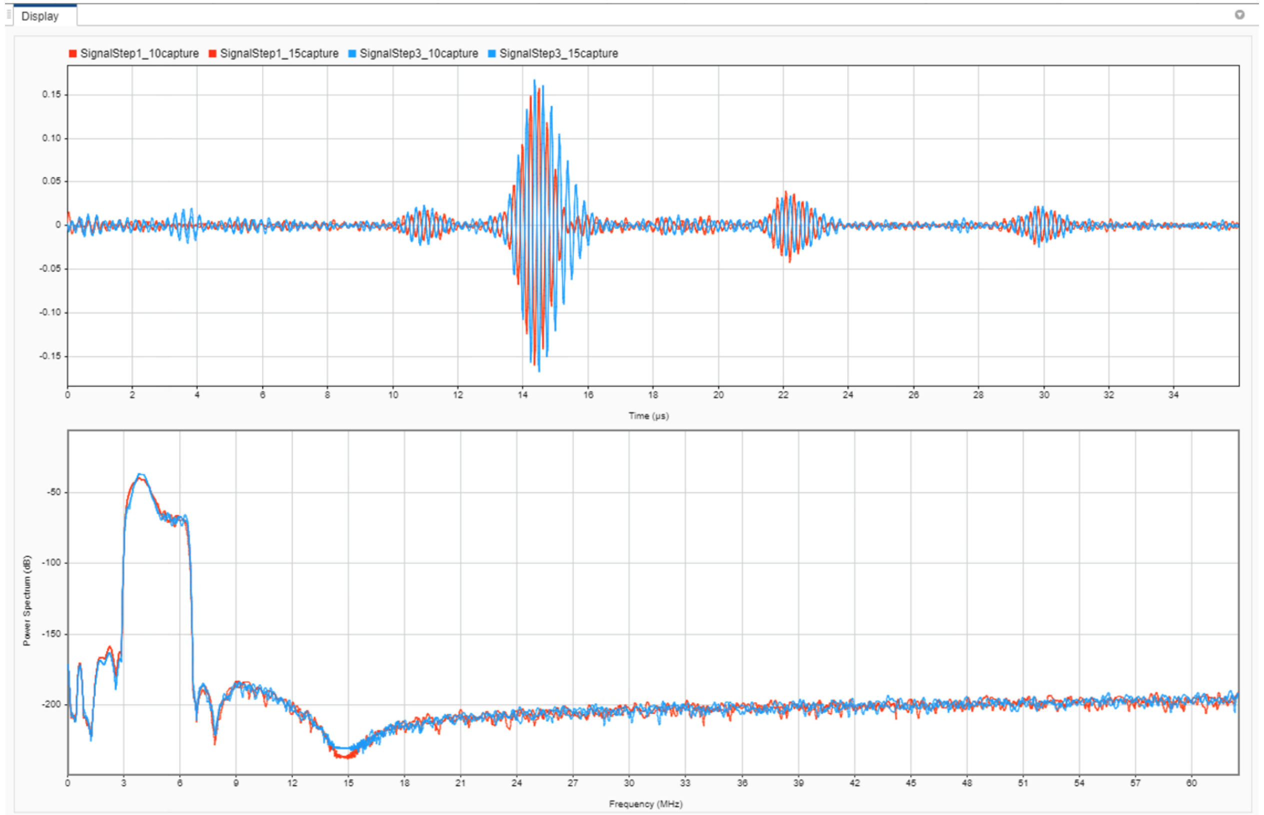
- **Electrical & Digital Configuration Optimization:**
  - ✓ Choose best **data collection mode** and pulse repetition frequency (**PRF**);
  - ✓ Adjust **attenuation** and **gain** for the best signal quality;
  - ✓ Set optimal **charge** (pulse width) to shape excitation pulse and control signal energy;
  - ✓ Apply effective **digital bandpass filters** for signal processing.

- **Mechanical Configuration Optimization:**
  - ✓ Test **probe frequencies** and identify which carry useful information;
  - ✓ Select optimal probe **built-in bandpass filter**;
  - ✓ Select optimal pulsing **channel**, **probe**, and signal **direction**;
  - ✓ Optimize **probe positioning** and **spacing**;
  - ✓ Determine best **coupling medium** and **pressure**.

Experimental Settings Optimization

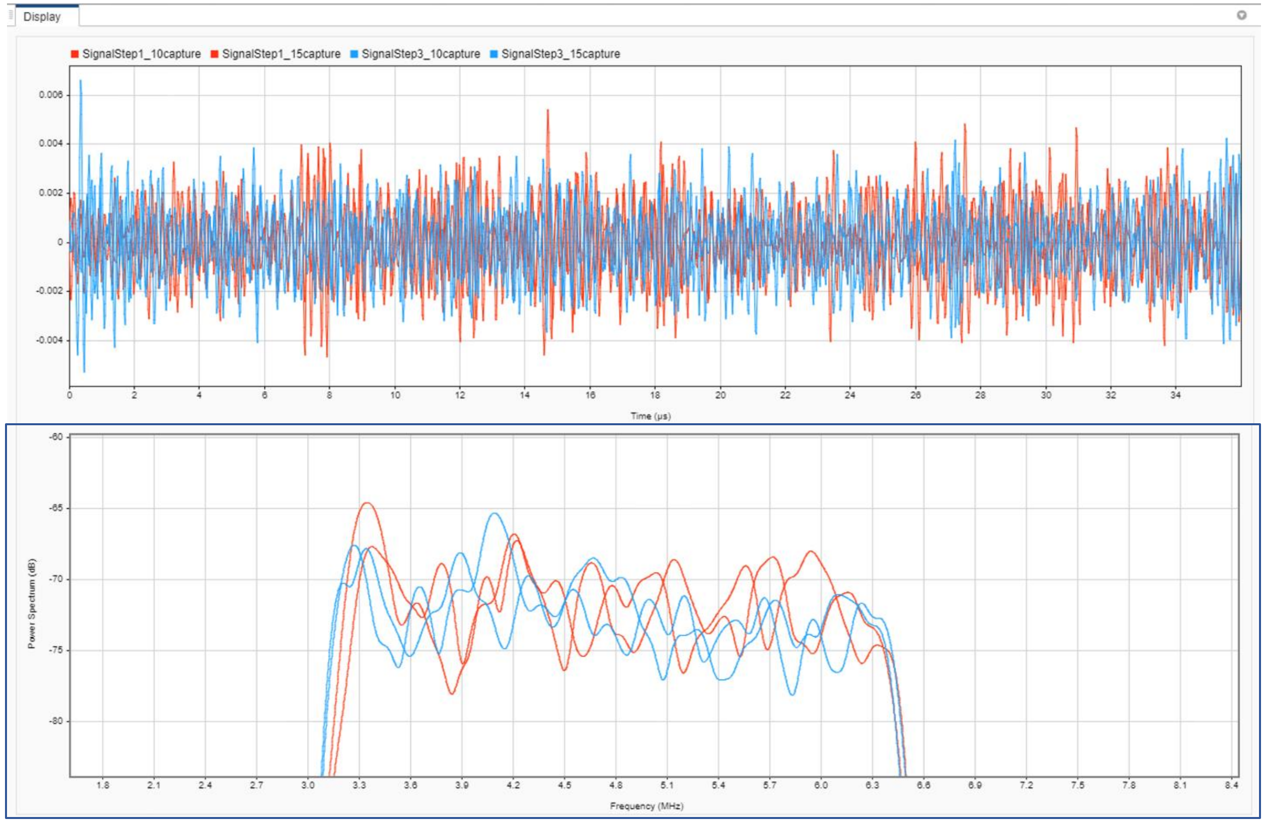
- **4 MHz Filtered Reflection Signal Sample – Before (left) vs. After (right) Settings Optimization:**
  - ➢ **Time Domain** Signal Amplitude and **Frequency Domain** Power Spectrum

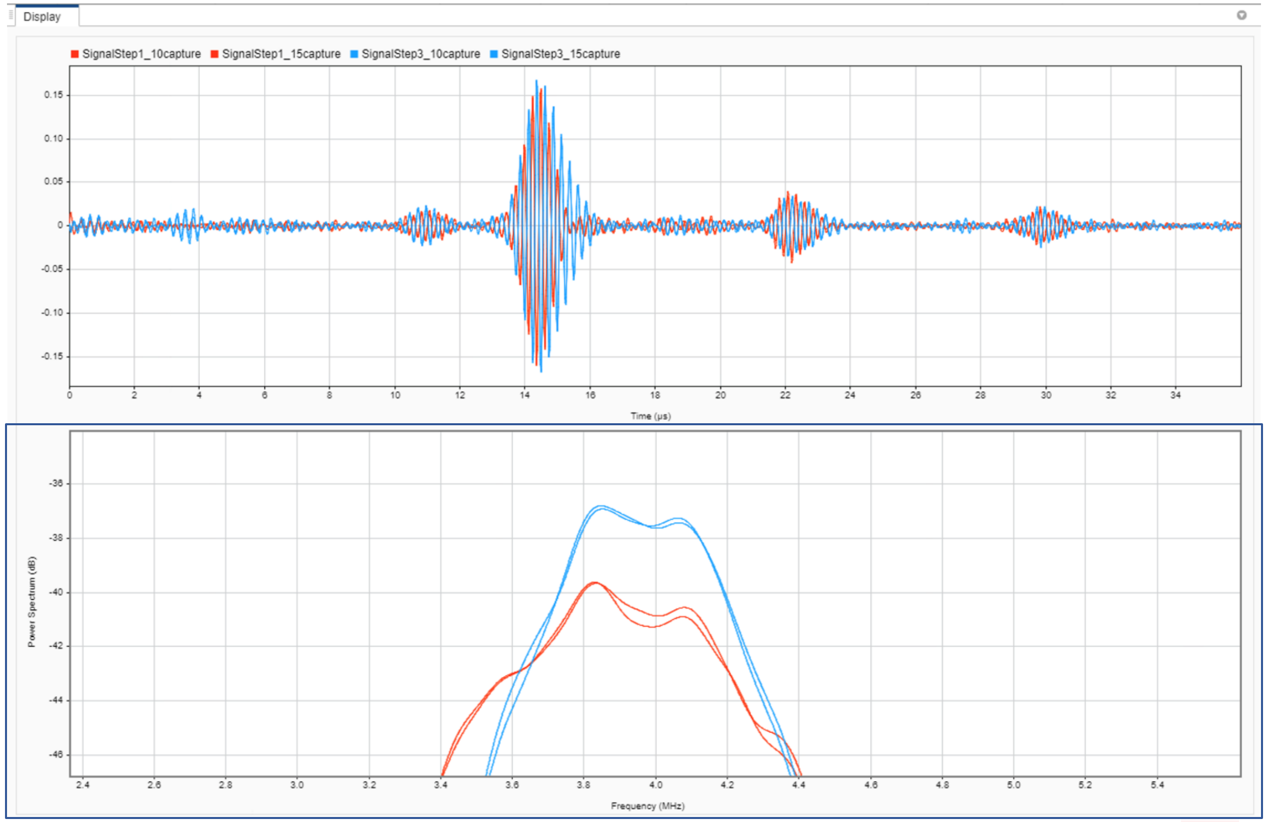




Experimental Settings Optimization

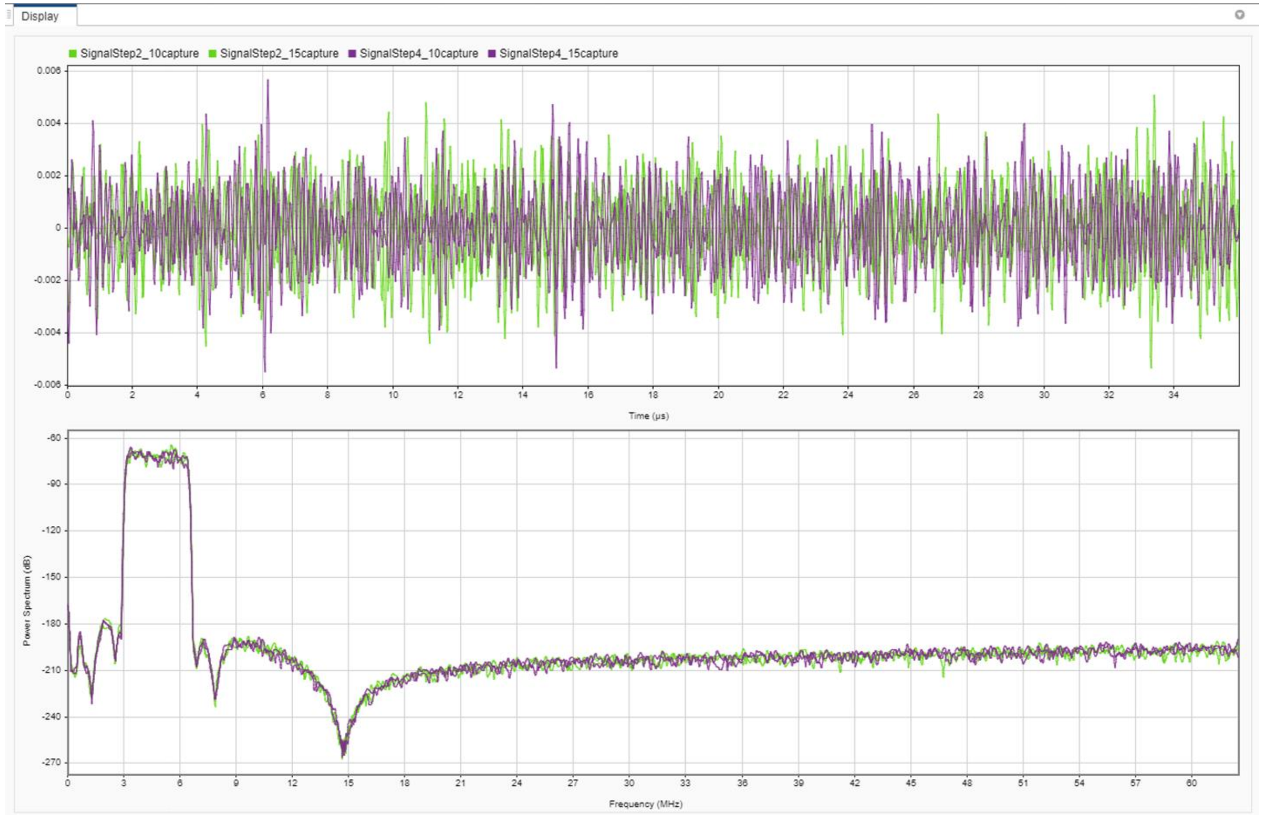
- **4 MHz Filtered Reflection Signal Sample – Before (left) vs. After (right) Settings Optimization:**
  - ➢ **Time Domain** Signal Amplitude and **Frequency Domain** Power Spectrum

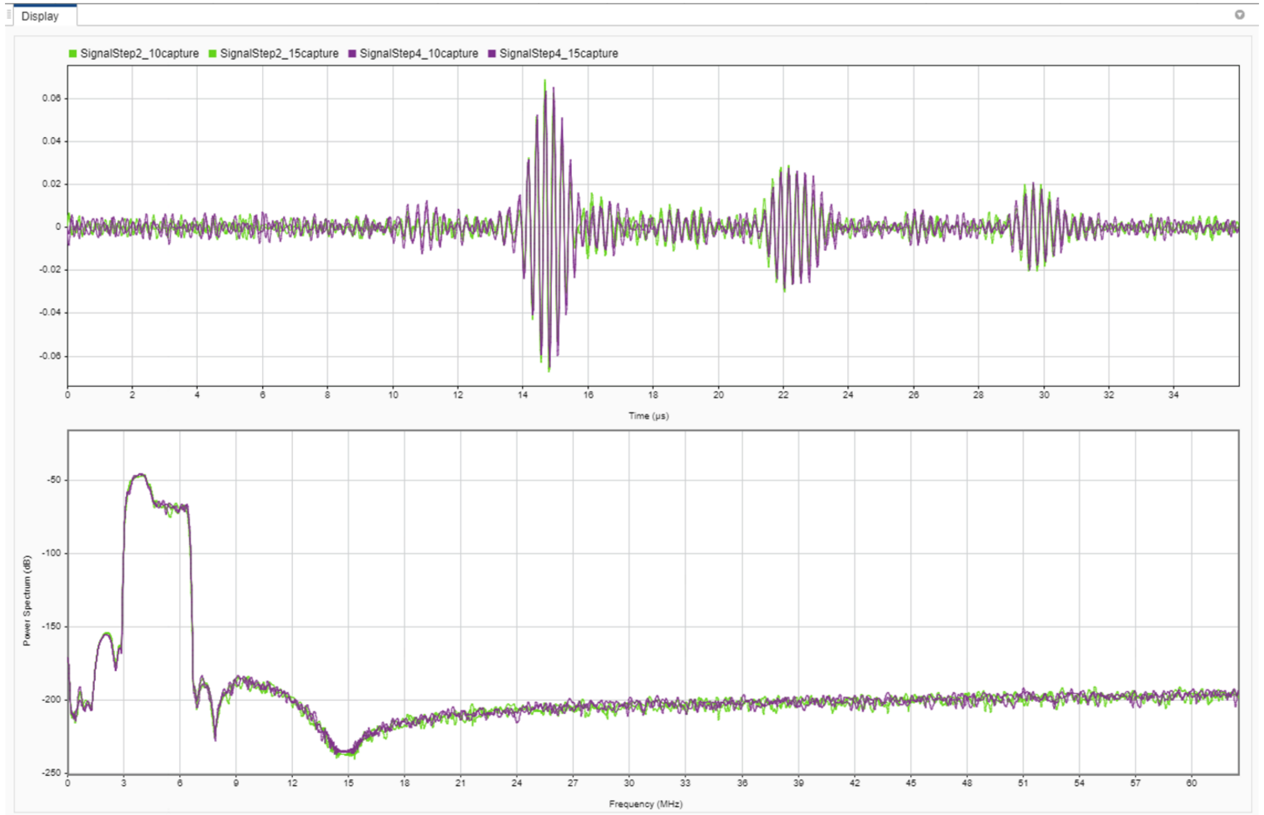




Experimental Settings Optimization

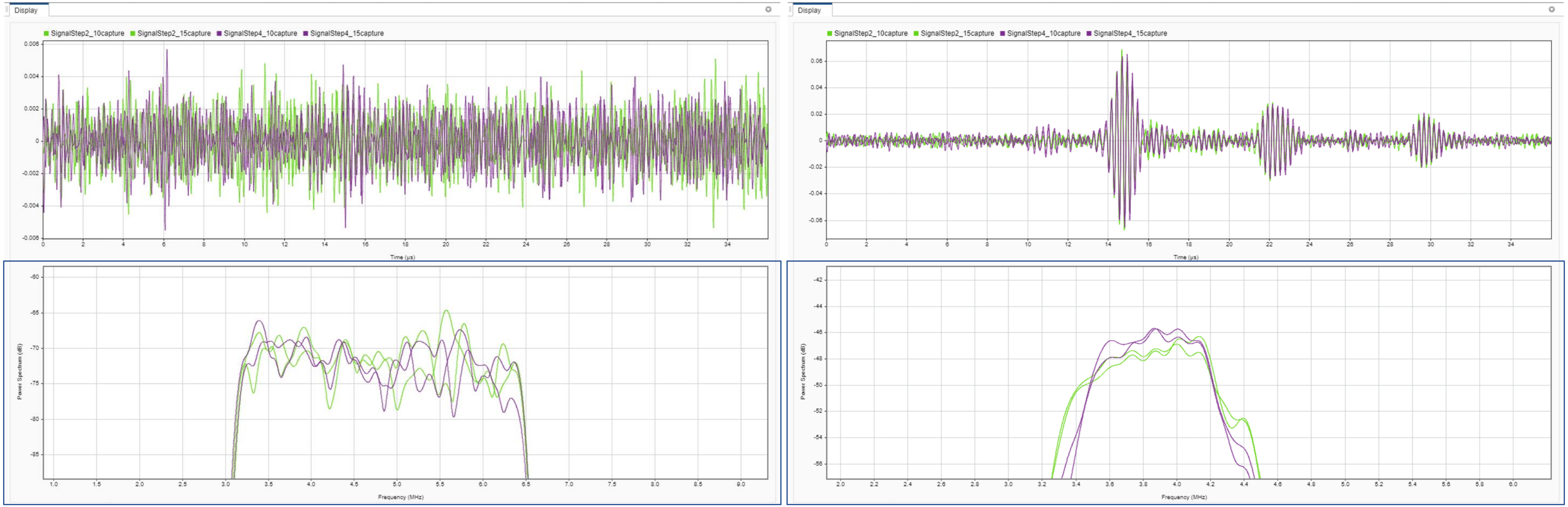
- **4 MHz Filtered Transmission Signal Sample – Before vs. After Settings Optimization:**
  - **Time Domain** Signal Amplitude and **Frequency Domain** Power Spectrum





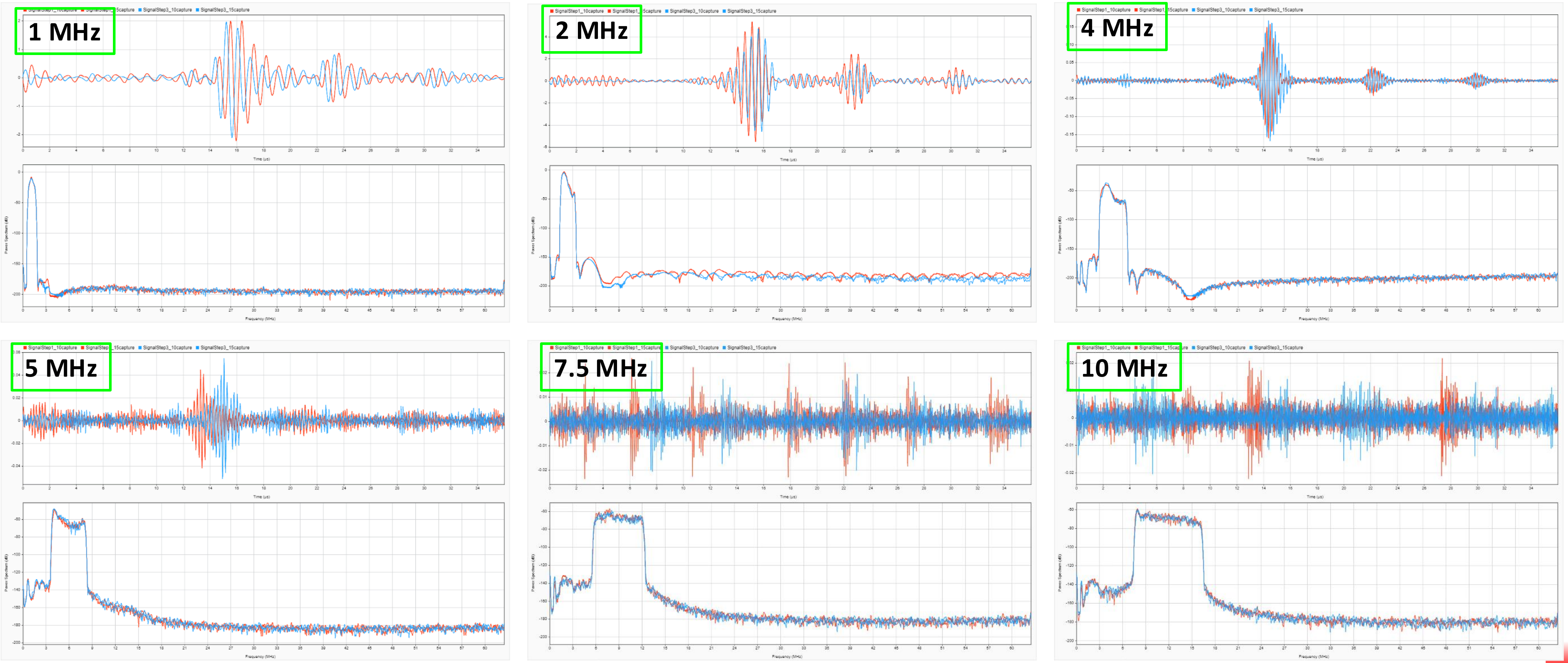
Experimental Settings Optimization

- **4 MHz Filtered Transmission Signal Sample – Before vs. After Settings Optimization:**
  - **Time Domain** Signal Amplitude and **Frequency Domain** Power Spectrum



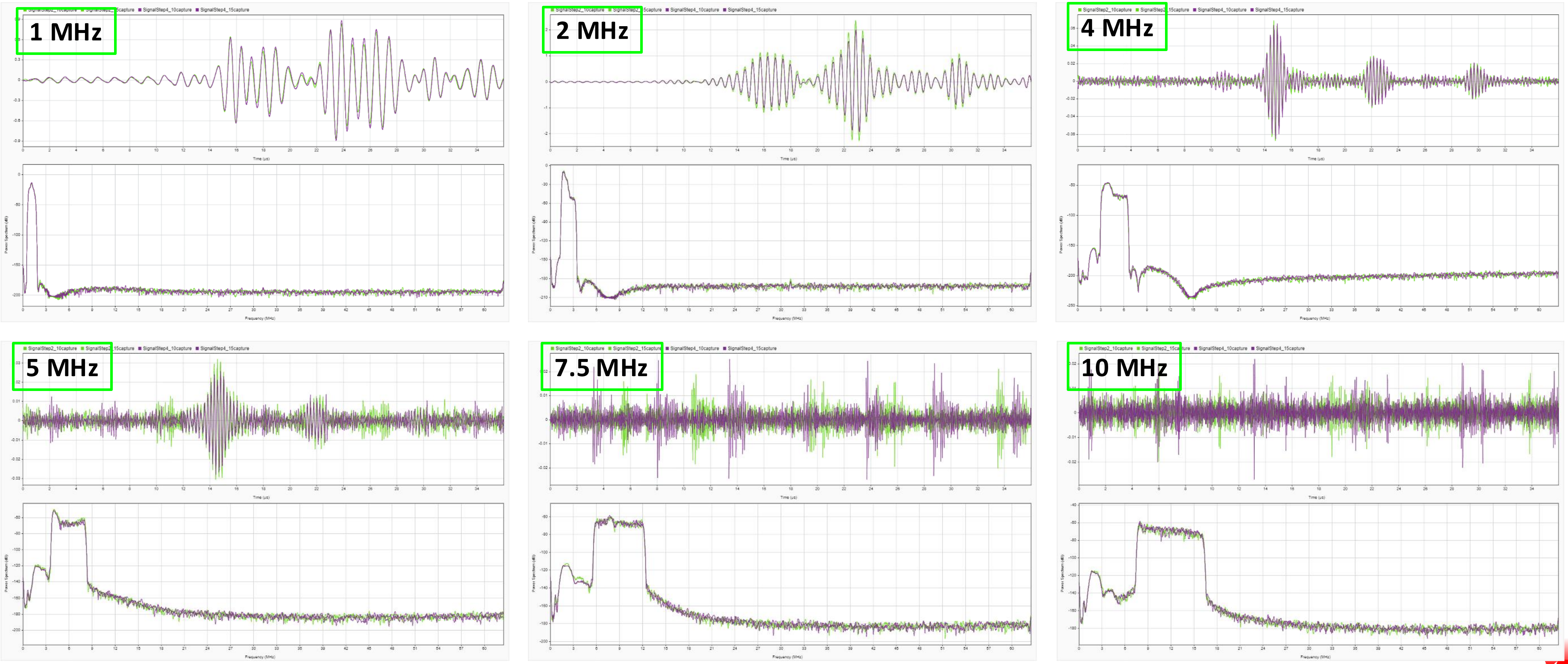
Probe Frequencies and Useful Information

- 1, 2, 4, 5, 7.5, 10 MHz Probe Frequencies (Reflection):



Probe Frequencies and Useful Information

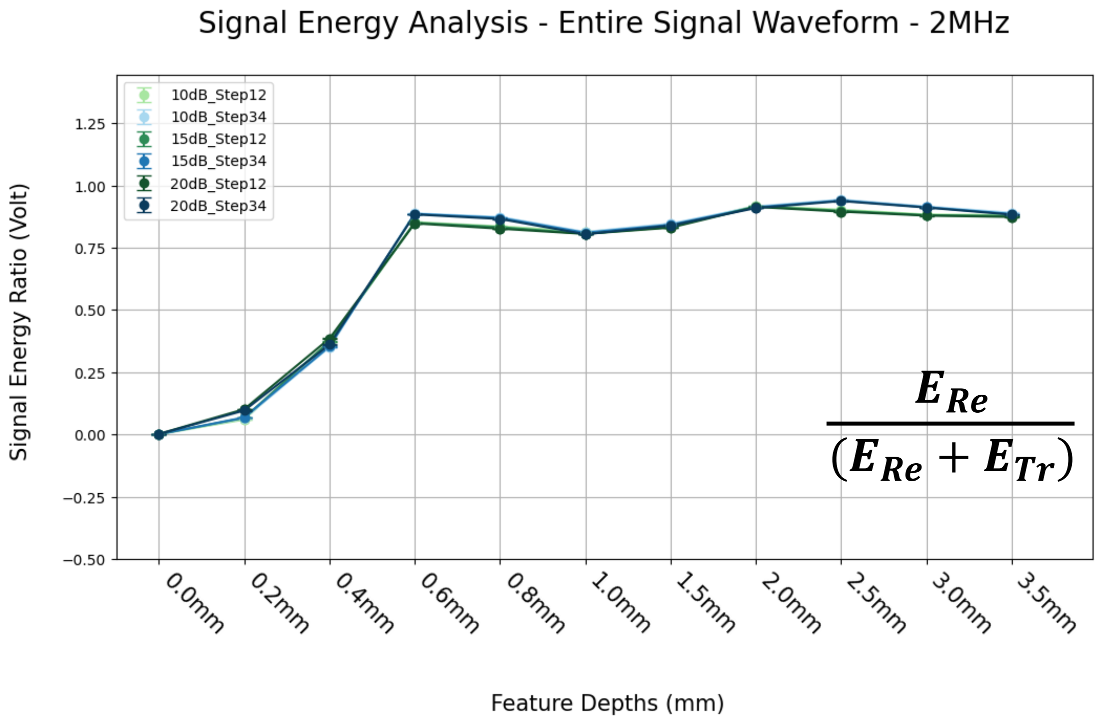
- **1, 2, 4, 5, 7.5, 10 MHz Probe Frequencies (Transmission):**

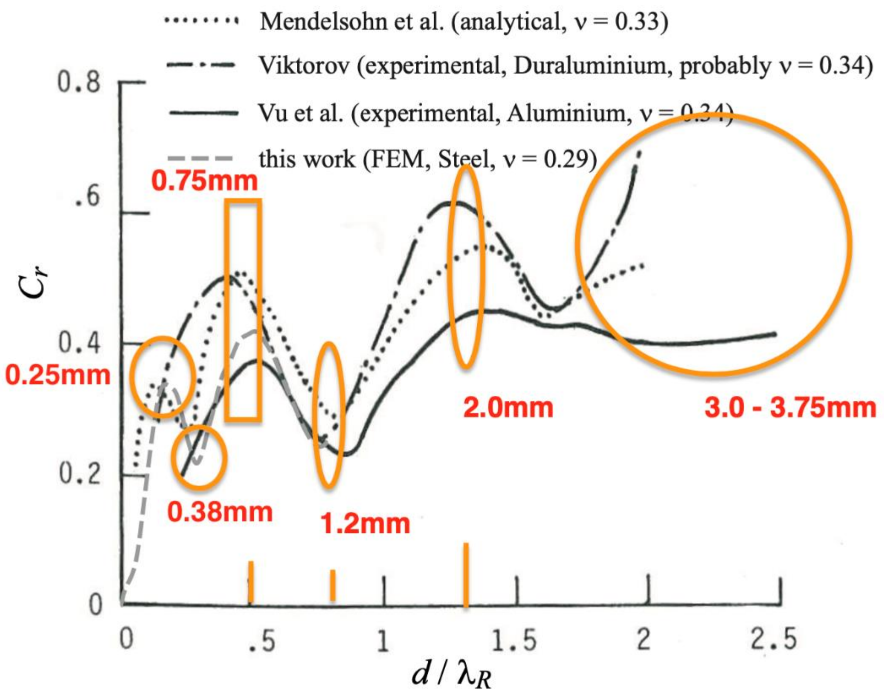


Proof of Concept – Signal Energy

- **Proof of Concept:** Surface wave ultrasonic signals, measured with **proper combinations of frequencies, modes, and settings,** demonstrate a statistically significant, meaningful, and predictable **correlation** with both the measured feature **depths** and **locations**.

- **Signal Energy Ratio vs. Feature Depth: Comparison with Literature Reflection Coefficients :**





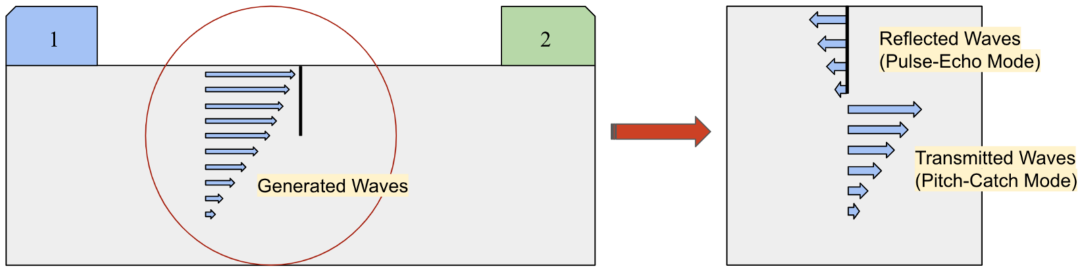
Sources [7]

Challenge #2: Decoupling Depth Estimates from Coupling Conditions

- The challenge: signal amplitudes (both induced and measured) at each probe depend on detailed coupling conditions, particularly at higher frequencies. i.e:

  - **Reflected** Signal (Probe 1) = f_{11}*(notch depth, probe 1 coupling)*
  - **Reflected** Signal (Probe 2) = f_{22} *(notch depth, probe 2 coupling)*
  - **Transmitted** Signal (Probe 1) = f_{21}*(notch depth, probe 1 coupling, probe 2 coupling)*
  - **Transmitted** Signal (Probe 2) = f_{12}*(notch depth, probe 2 coupling, probe 1 coupling)*

- As a result, precise and careful control of couplant and probe pressures was required to get repeatable results for signal energy ratios.



Measuring Modes:

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  - Step 2-1 (signal send Probe 2; receive: Probe 1)

Challenge #2: Decoupling Depth Estimates from Coupling Conditions

- To overcome this, a methodology was developed to estimate normalized **reflection and transmission coefficients** (independent of coupling conditions) such that:
  - **Reflection** Coefficient (Probe 1) = f_{11}*(Reflected Signal (Probe 1), Reflected Signal (Probe 2), Transmitted Signal (Probe 1), Transmitted Signal (Probe 2))*
  - **Reflection** Coefficient (Probe 2) = f_{22}*(Reflected Signal (Probe 1), Reflected Signal (Probe 2), Transmitted Signal (Probe 1), Transmitted Signal (Probe 2))*
  - **Transmission** Coefficient (Probe 1) = f_{21}*(Reflected Signal (Probe 1), Reflected Signal (Probe 2), Transmitted Signal (Probe 1), Transmitted Signal (Probe 2))*
  - **Transmission** Coefficient (Probe 2) = f_{12}*(Reflected Signal (Probe 1), Reflected Signal (Probe 2), Transmitted Signal (Probe 1), Transmitted Signal (Probe 2))*
- Did it work?...

Proof of Concept – Decoupling Feature Depth Estimation from Coupling Conditions

- **Enhance result reliability** by normalizing **couplant effects** and establishing **reflection** and **transmission coefficients**, which is especially important at **higher frequencies** due to their **shorter wavelengths** relative to couplant thickness/unevenness and **increased sensitivity** to surface variations.
- **Multiple Linear Regression:** Demonstrates **effective decoupling** of feature depth estimation from **exact coupling conditions**.

OLS Regression Results

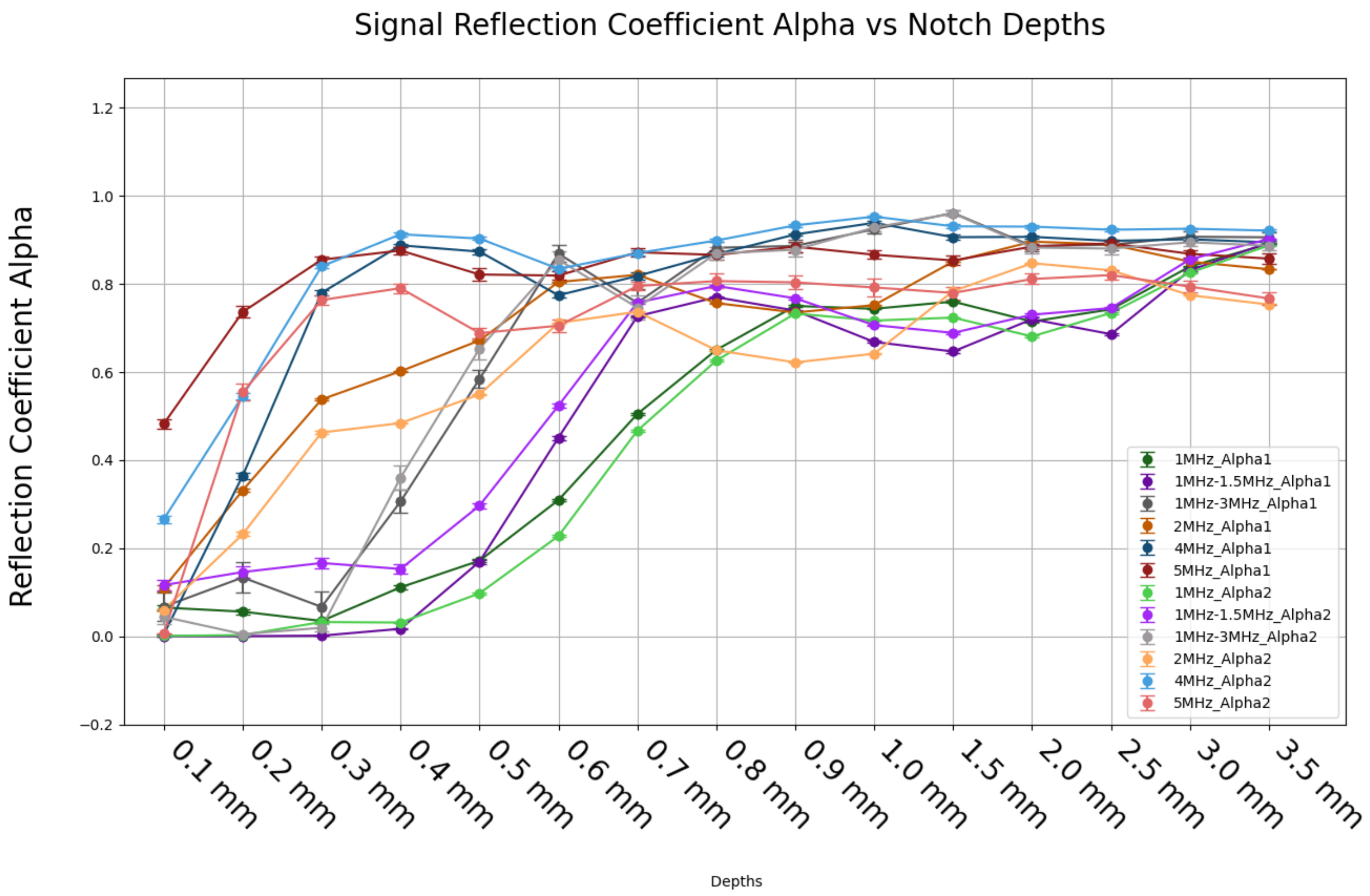
Dep. Variable:	Alpha_1	R-squared:	0.955
Model:	OLS	Adj. R-squared:	0.954
Method:	Least Squares	F-statistic:	3768.
Date:	Fri, 11 Jul 2025	Prob (F-statistic):	0.00
Time:	22:56:11	Log-Likelihood:	635.05
No. Observations:	540	AIC:	-1262.
Df Residuals:	536	BIC:	-1245.
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
Intercept	-0.2639	0.040	-6.530	0.000	-0.343	-0.184
Probe1_Force_F1_N	2.323e-05	0.000	0.156	0.876	-0.000	0.000
Probe2_Force_F2_N	3.234e-06	0.000	0.020	0.984	-0.000	0.000
Notch_Depth_d_mm	3.0662	0.029	106.320	0.000	3.010	3.123

Omnibus:	221.342	Durbin-Watson:	0.026
Prob(Omnibus):	0.000	Jarque-Bera (JB):	59.485
Skew:	0.595	Prob(JB):	1.21e-13
Kurtosis:	1.893	Cond. No.	3.56e+03

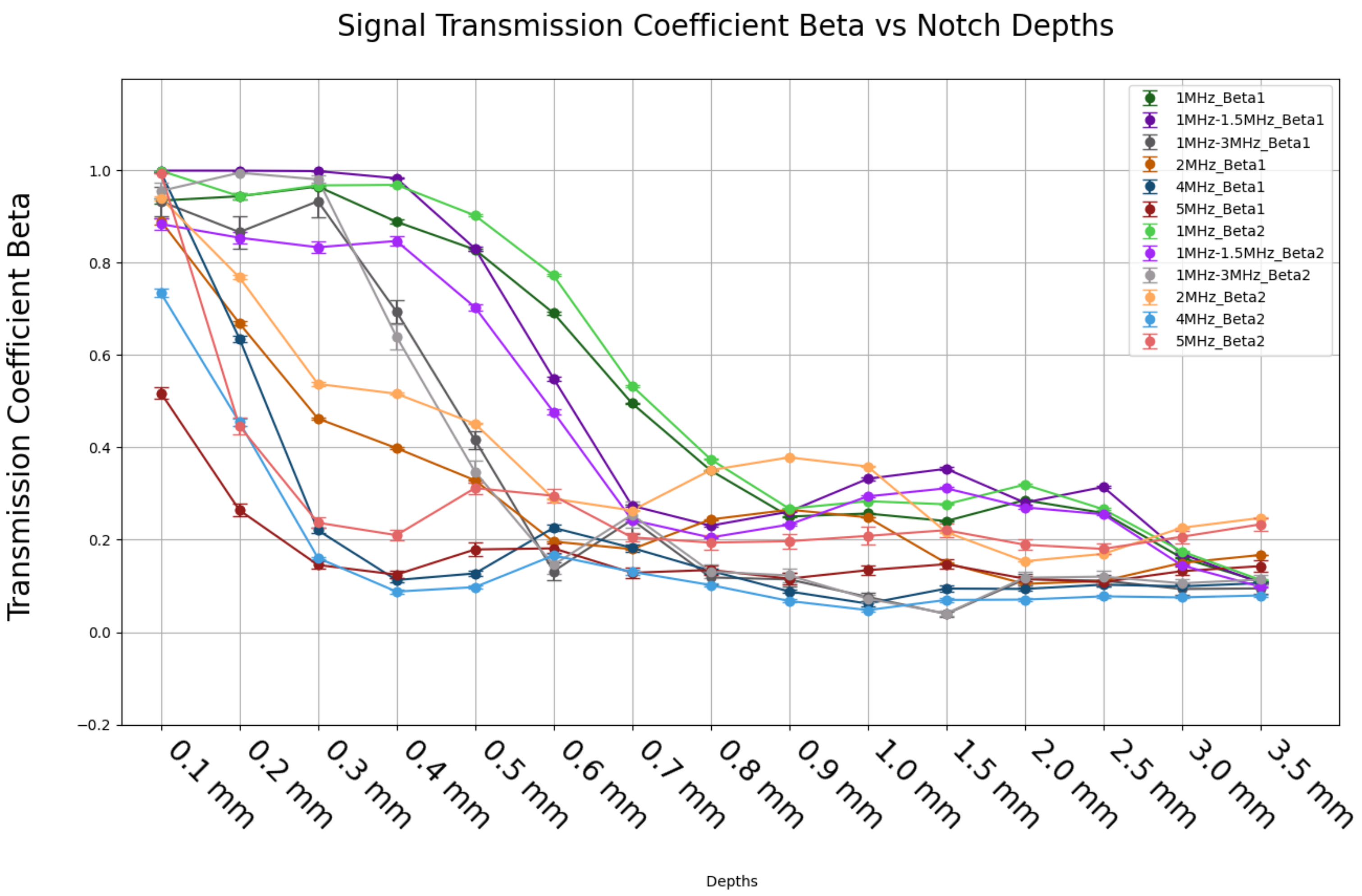
Proof of Concept – Reflection & Transmission Coefficient

- **Signal Reflection Coefficient VS. Feature Depth (Single Notch):**



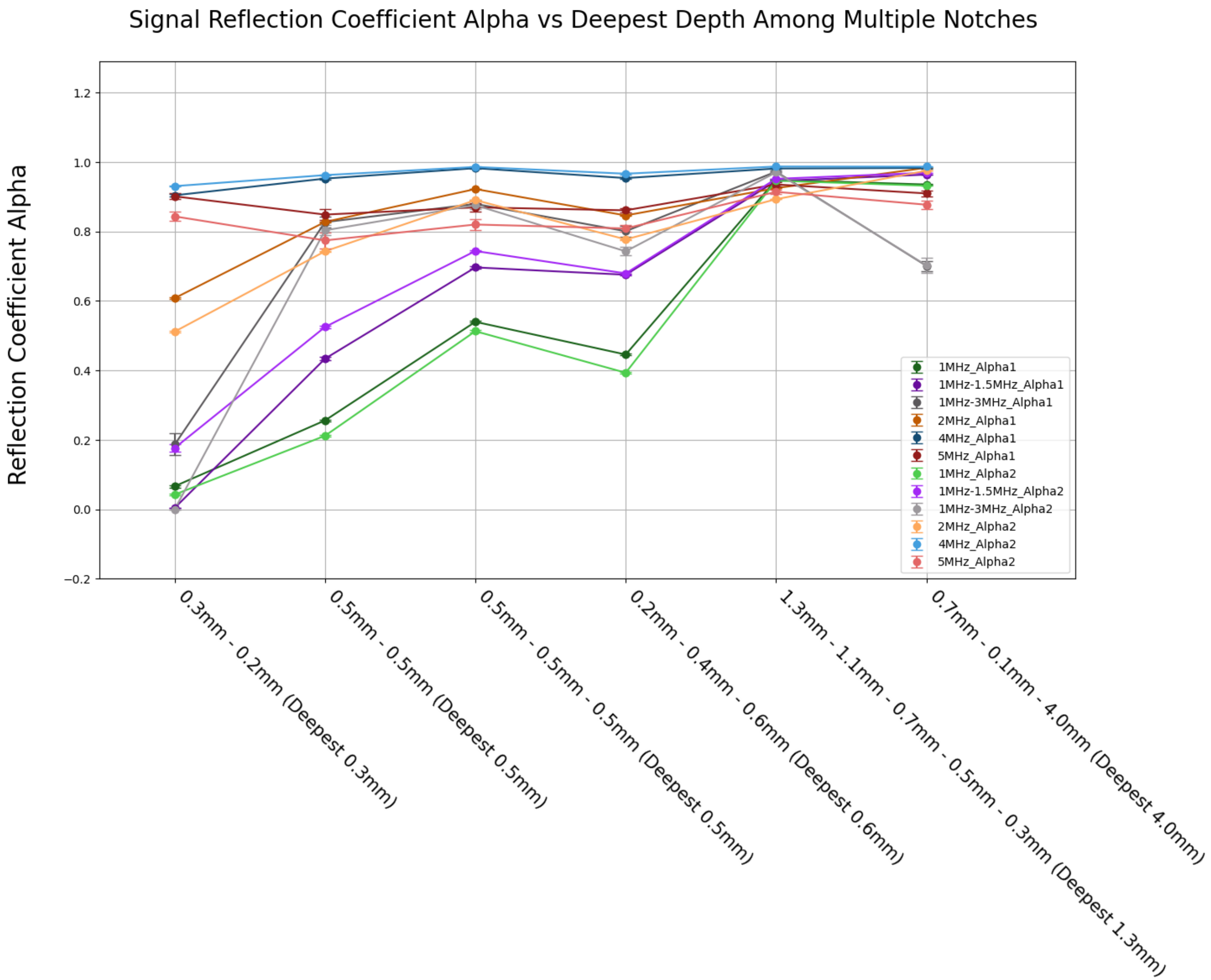
Proof of Concept – Reflection & Transmission Coefficient

- **Signal Transmission Coefficient VS. Feature Depth (Single Notch):**



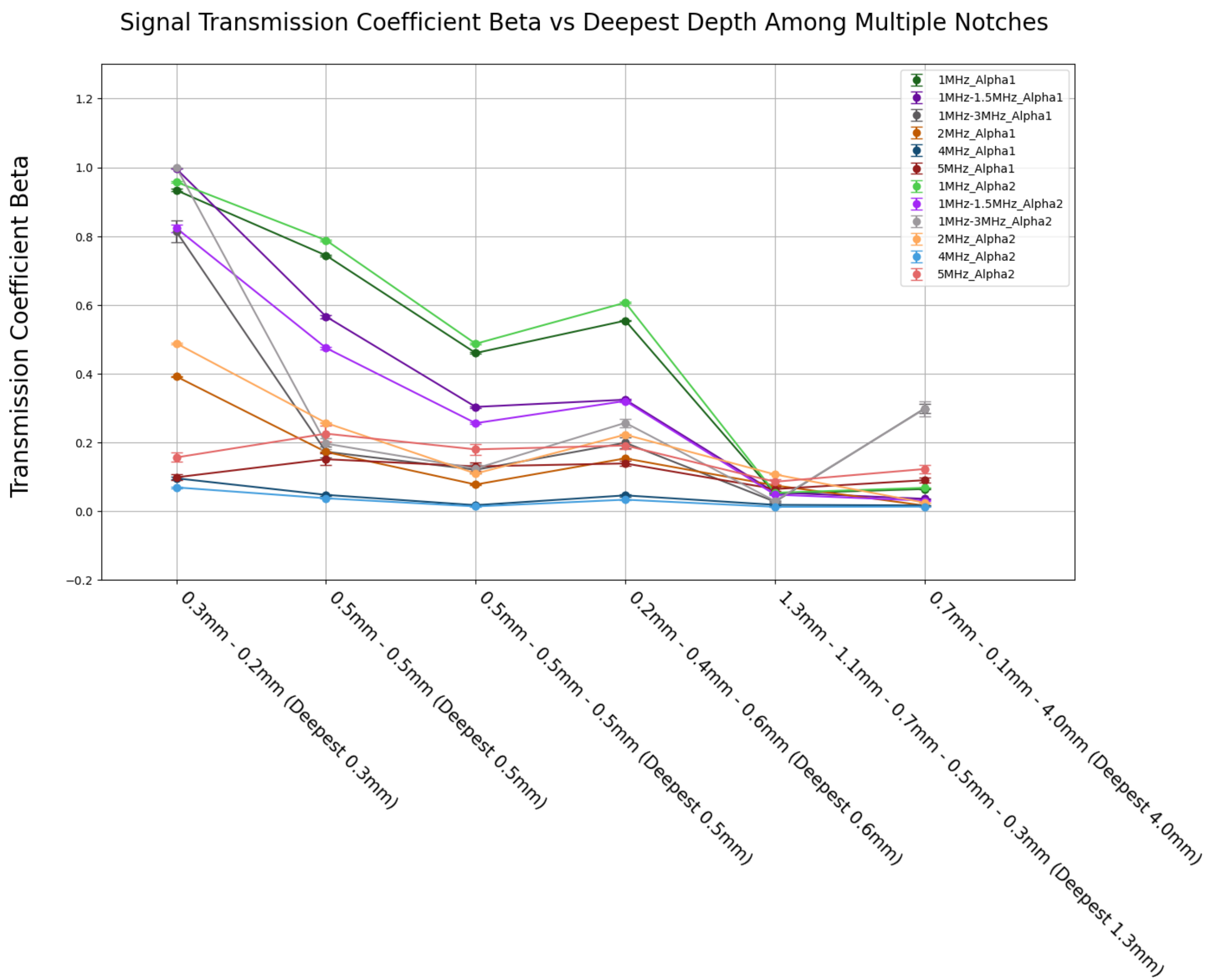
Proof of Concept – Reflection & Transmission Coefficient

- **Signal Reflection Coefficient VS. Feature Depth (Multiple Notches – Deepest/Most Significant Notch):**



Proof of Concept – Reflection & Transmission Coefficient

- **Signal Transmission Coefficient VS. Feature Depth (Multiple Notches – Deepest/Most Significant Notch):**

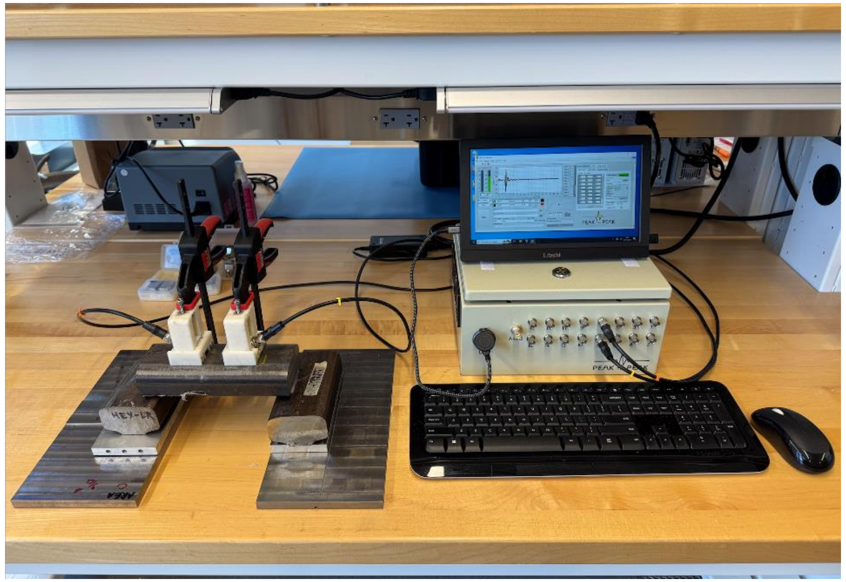


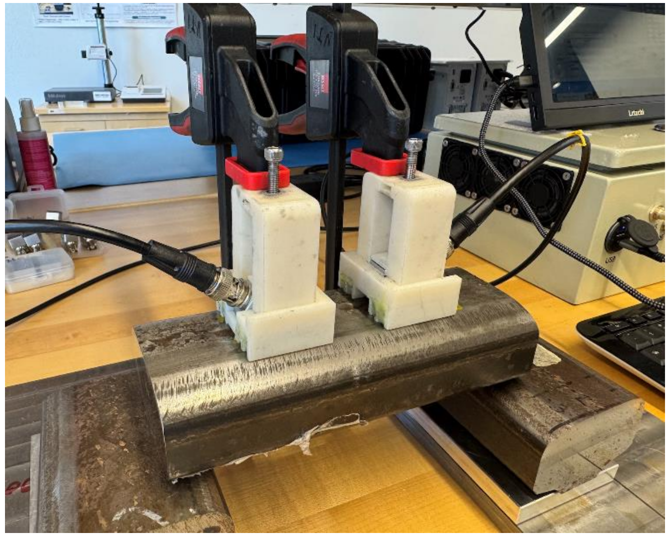
Conclusions

- Surface wave ultrasonic measurement appears to hold **promise** for **characterizing** feature **depths** within the relevant range.
- With optimized electrical and mechanical settings, probe signal frequencies ranging from 1 to 5 MHz carry and provide **useful information**.
- Signal **strength** decreases with increasing **frequency** due to increased **wave attenuation**.
- **Higher-frequency** signals, with smaller wavelength and shallower penetration depth, are more influenced by **coupling conditions**.
- A methodology to calculate **reflection and transmission coefficients** that are independent of coupling conditions has been developed, and appears to be effective.

Future Work

- The next **major phase of work** will involve testing on rail samples collected from the field, with varying types and depths of RCF damage. This will include:
  - Identifying **optimal ultrasonic couplant(s)** for curved and rough rail field samples.
  - Developing **new clamps** to ensure stable and reliable probe mounting on rail samples.
  - **Collecting ultrasonic data** from **rail samples**, then performing **destructive metallurgical analysis**.
  - Exploring **correlations** between **measured signals** and **observed crack depths**, to identify potential features for reliable crack depth estimation.





Project Funding

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Canada Foundation for Innovation (CFI)
[John R. Evans Leaders Fund project number Project number 41998]

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Thank you!