# Improving Bondline Time of Flight Predictions Utilizing Machine Learning and Hardware Improvements

Finnian Day

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Advanced Materials and Processing Branch
NASA Langley Research Center

STRUCTURES AND MATERIALS
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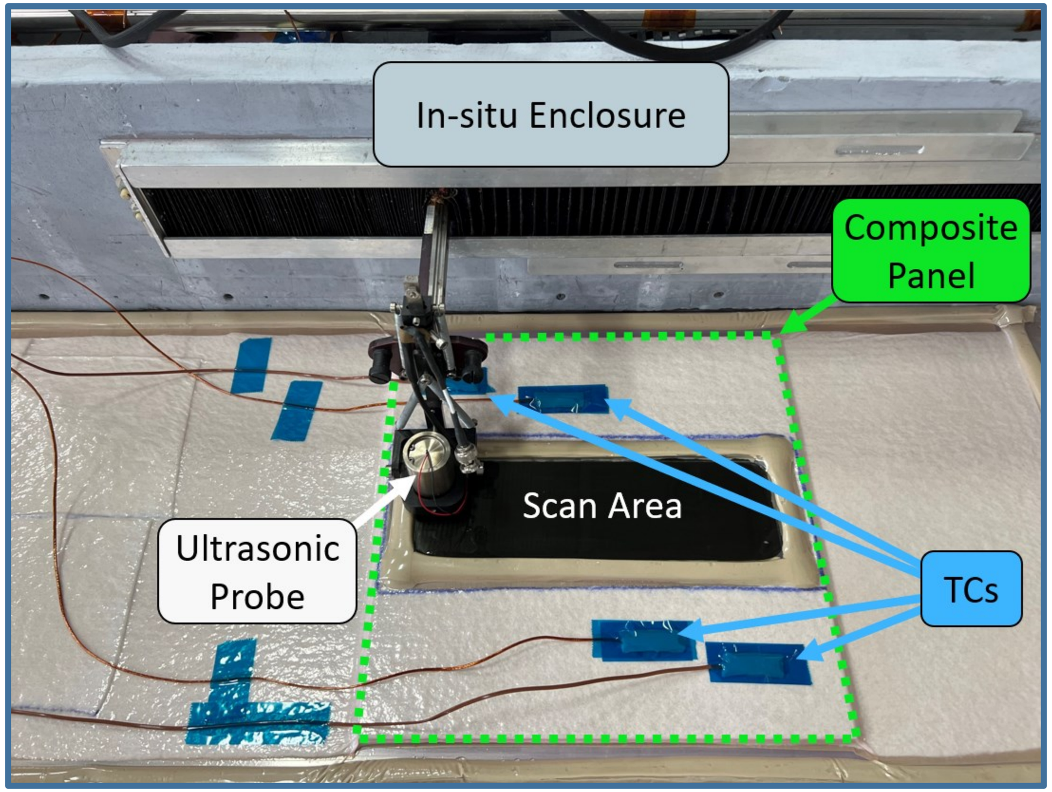
# Background

- **T**ransformational **T**ools and **T**echnologies (TTT) project aims to develop computational and experimental ways to help predict future aircraft performance
    - TTT bonded composites team develops tools and methods to analyze and qualify bonded composite joints
        - Process monitoring subgroup utilizes ultrasonic non-destructive evaluation (NDE) methods to *investigate bonded composite joints during cure cycles*

# Approach

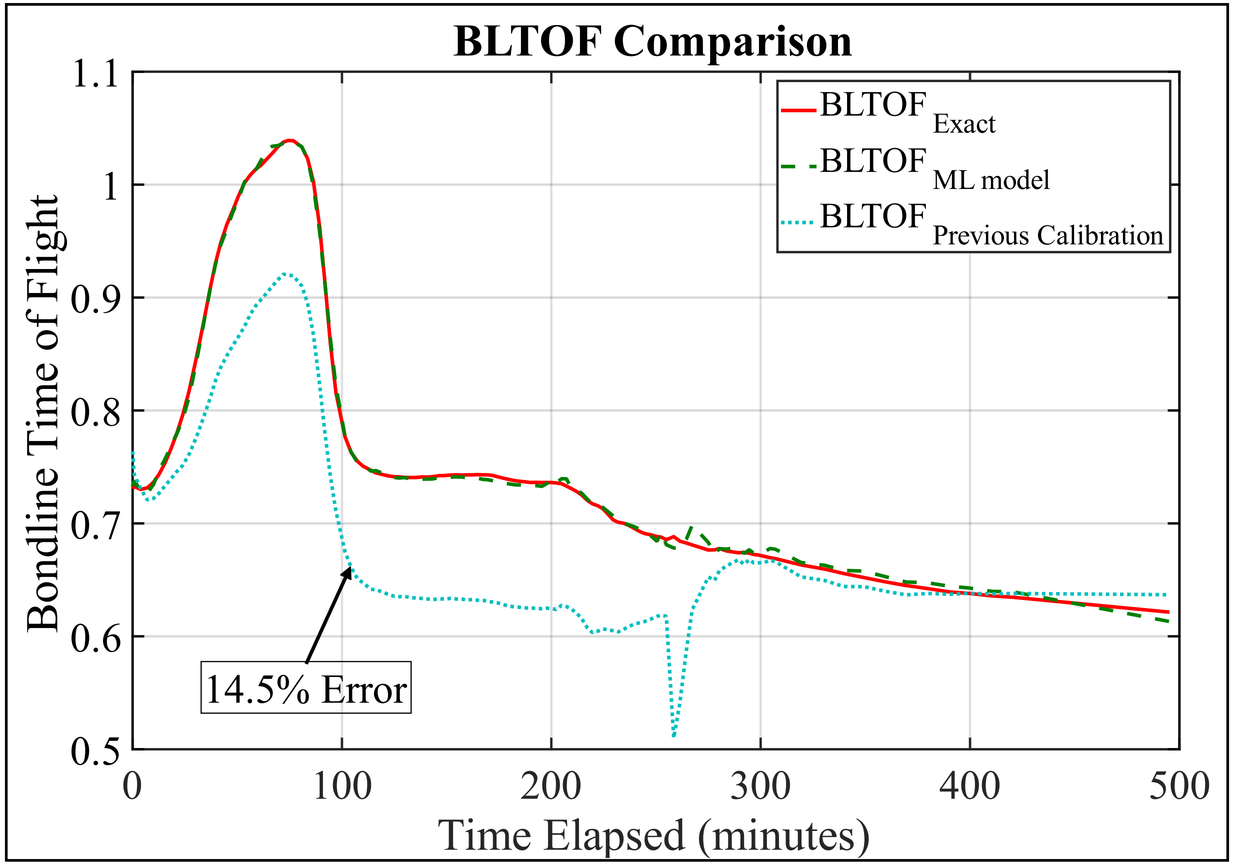
- ❖Goal: Measure bondline thickness in composite joints
  - ❖Strength of bonded joints are related to the thickness of the joint
- ❖Methods:
  - ❖In-situ autoclave ultrasonic scanner
    - ❖2.25 MHz contact transducer
    - ❖10 MHz immersion transducer
  - ❖Machine learning predictions
- ❖Challenge:
  - ❖No commercial system capable of measuring bondline thickness during cure
  - ❖Measurement error more pronounced in thin materials



TCs: Thermocouples

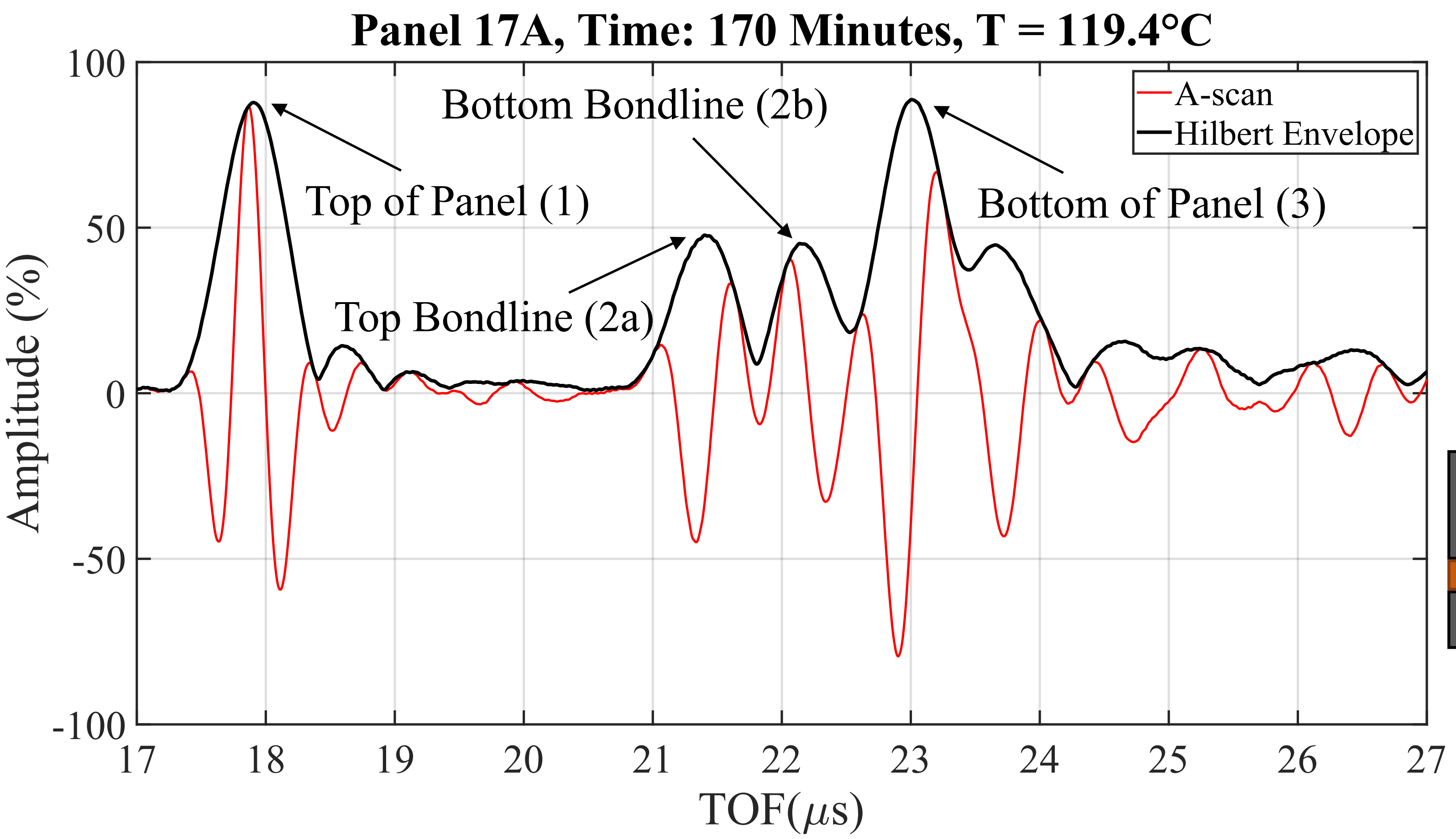
# Significance

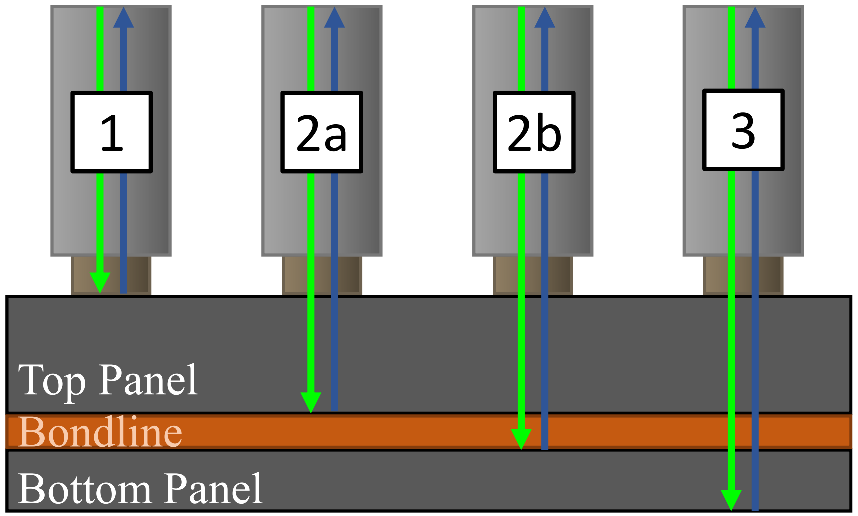
- ❖Bondline measured to be about 0.683mm
  - ❖14.5% error is roughly 0.1mm
- ❖0.1mm error is much more significant with films as thin as the bondline
  - ❖Less significant for measurements of greater magnitudes



BLTOF: Bondline Time of Flight

# Example Waveform: Glassy State at Cure Temperature



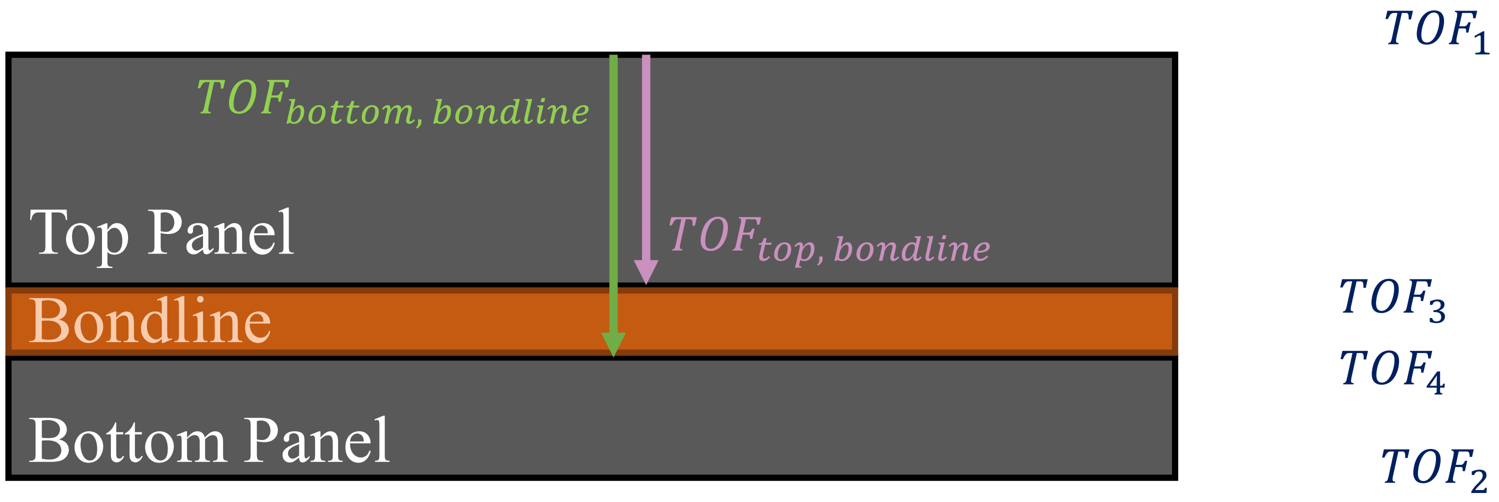


TOF: Time of Flight

# TOF: Direct Method

$$TOF_{bondline} = TOF_{bottom,\,bondline} - TOF_{top,bondline}$$
$$TOF_{bondline} = TOF_4 - TOF_3$$

- Provides the most accurate BLTOF measurement
- Easiest method with clear pulses
  - More difficult/impossible with thin bondlines
  - Uncertain top/bottom of bondline



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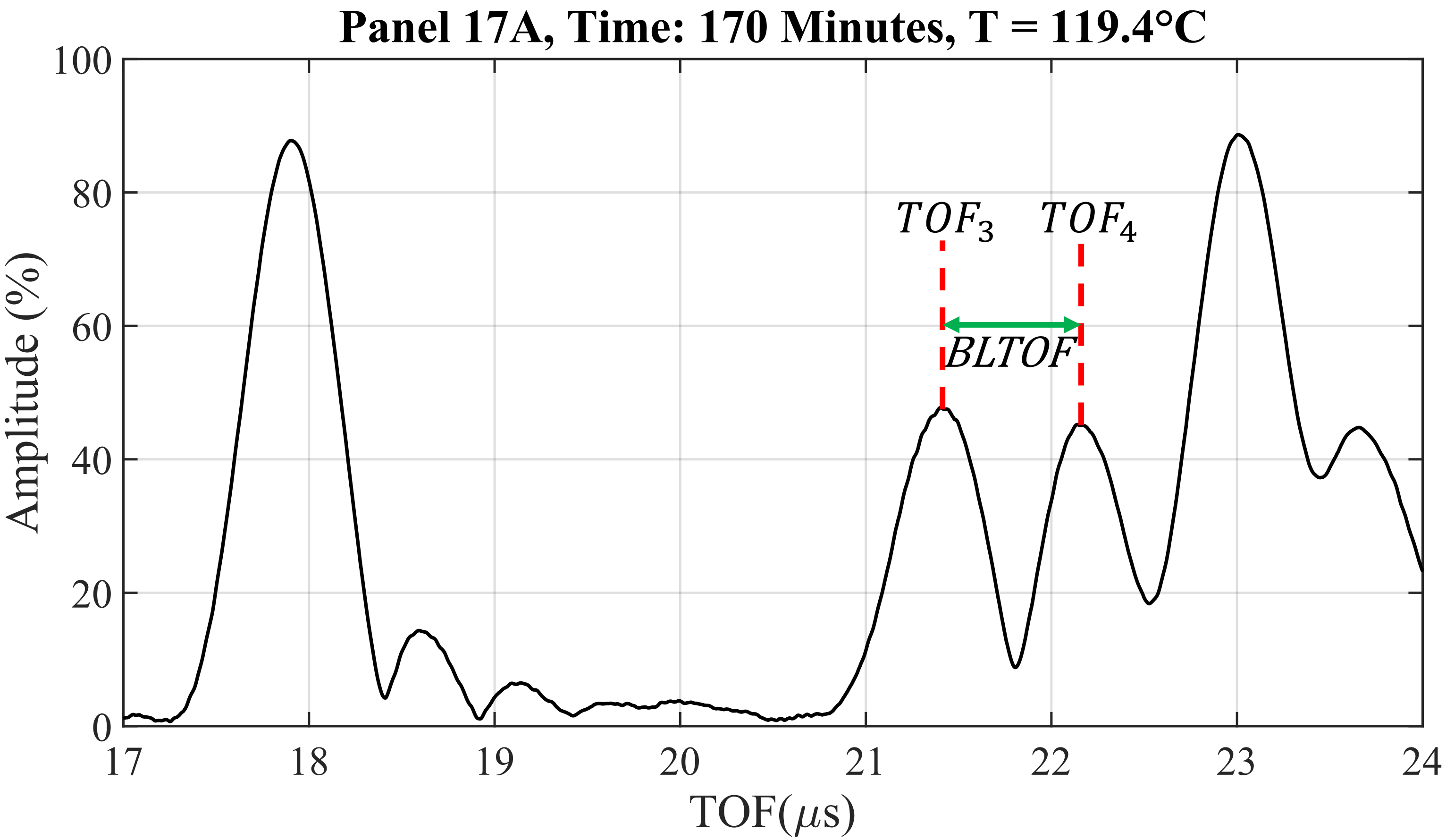
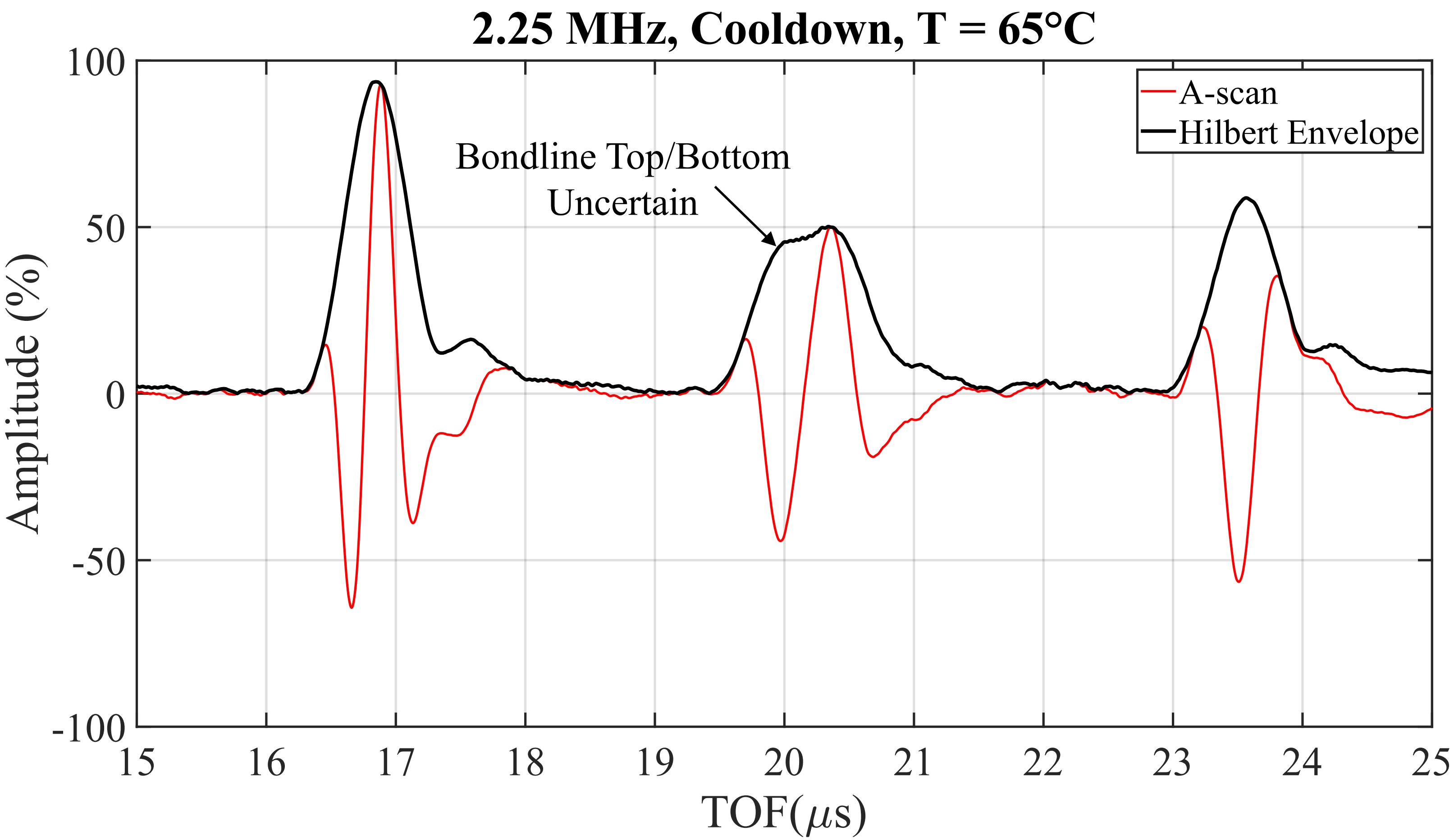


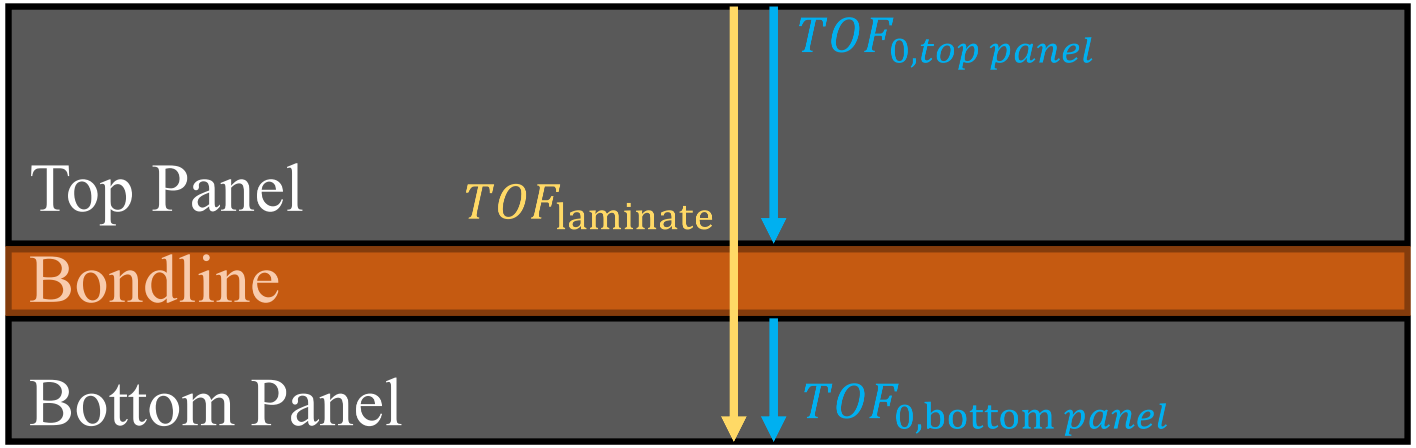
# Uncertain Bondline



# TOF: Subtraction Method

$$TOF_{bondline} = TOF_{laminate} - \boldsymbol{TTCF} \times (TOF_{0,top\ panel} + TOF_{0,bottom\ panel})$$

- Top and bottom panels scanned individually without adhesive
- Subtracted from TOF through entire laminate
- Temperature directly influences the speed of sound through the half panels
  - Needs to be corrected for TOF calculations during cure → ***TTCF***



$TOF_1$

$TOF_3$

$TOF_4$

$TOF_2$

# TOF Temperature Correction Factor

- Originally estimated by scanning a cured half panel during full autoclave cycle
  - Found a “multiplier:” $TTCF = \frac{TOF}{TOF_0}$
  - $TTCF(T, P, \dot{T})$ determined using basic regression analysis (i.e., piece-wise curve fitting)

- “Exact” calculation combines the direct and subtraction methods
  - $TOF_4 - TOF_3 \approx TOF_{laminate} - \boldsymbol{TTCF} \times \left(TOF_{0,top\ panel} + TOF_{0,bottom\ panel}\right)$
  - $\boldsymbol{TTCF} = \frac{(TOF_2 - TOF_1) - (TOF_4 - TOF_3)}{(TOF_{0,\ top\ panel} + TOF_{0,bottom\ panel})}$
  - Machine learning model fits data to find $TTCF(T, P, \dot{T})$
    - Model chosen: Support vector machine (SVM) model with fine Gaussian kernel

$T$: Temperature [°C]
$P$: Pressure [kPa]
$\dot{T}$: Ramp Rate [°C/min]

# Machine Learning Model Selection

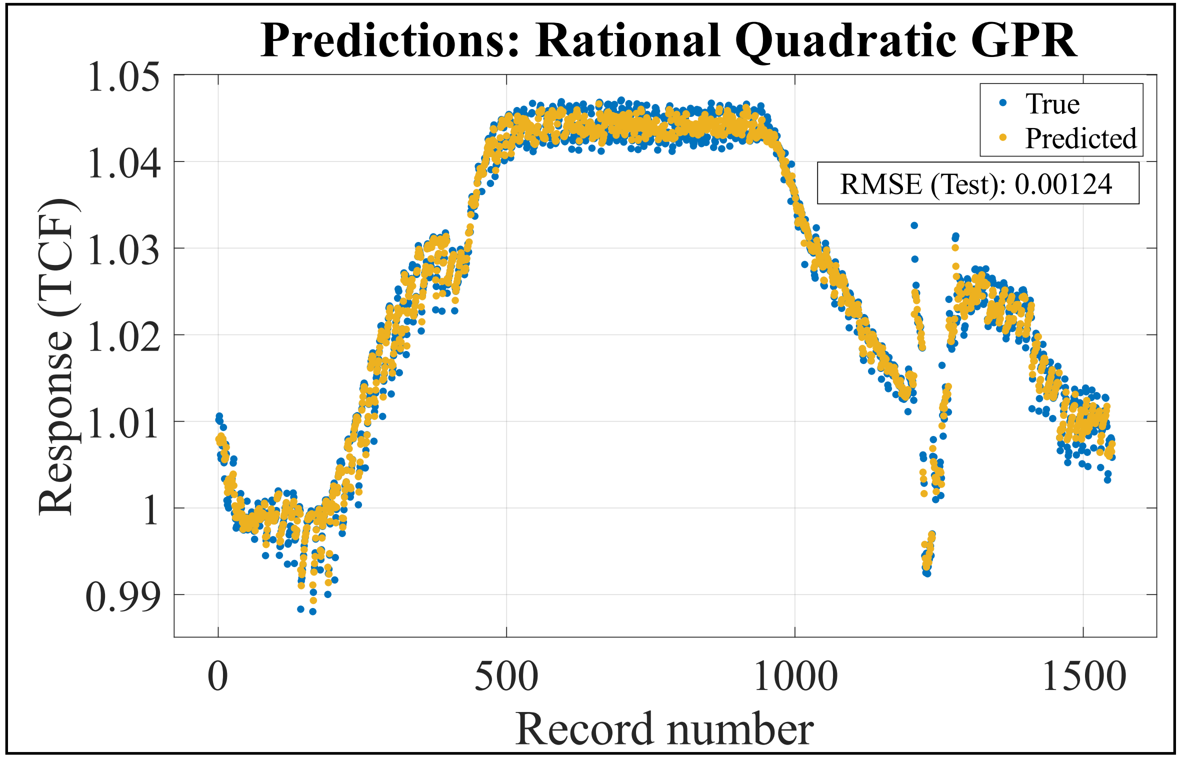
| | **Model Type** | **RMSE (Test)** |
|---|---|---|
| **1** | Gaussian Process Regression<br>*(Exponential GPR)* | 0.00124 |
| **2** | Gaussian Process Regression<br>*(Rational Quadratic GPR)* | 0.00124 |
| **3** | Gaussian Process Regression<br>*(Matern 5/2 GPR)* | 0.00162 |
| **4** | Tree<br>*(Fine Tree)* | 0.00169 |
| **5** | Gaussian Process Regression<br>*(Squared Exponential GPR)* | 0.00173 |
| **6** | Ensemble<br>*(Bagged Trees)* | 0.00188 |
| **7** | Neural Network<br>*(Wide Neural Network)* | 0.00211 |
| **8** | Tree<br>*(Medium Tree)* | 0.00219 |
| **9** | Neural Network<br>*(Medium Neural Network)* | 0.00230 |
| **10** | Neural Network<br>*(Trilayered Neural Network)* | 0.00232 |
| **11** | Support Vector Machine<br>*(Fine Gaussian SVM)* | 0.00233 |
| **12** | Neural Network<br>*(Bilayered Neural Network)* | 0.00233 |
| **13** | Tree<br>*(Coarse Tree)* | 0.00283 |
| **14** | SVM<br>*(Medium Gaussian SVM)* | 0.00317 |

| | **Model Type** | **RMSE (Test)** |
|---|---|---|
| **15** | Neural Network<br>*(Narrow Neural Network)* | 0.00428 |
| **16** | SVM<br>*(Coarse Gaussian SVM)* | 0.00461 |
| **17** | Kernel<br>*(Least Squares Regression Kernel)* | 0.00545 |
| **18** | Kernel<br>*(SVM Kernal)* | 0.00579 |
| **19** | Linear Regression<br>*(Interactions Linear)* | 0.00595 |
| **20** | Stepwise Linear Regression<br>*(Stepwise Linear)* | 0.00596 |
| **21** | Linear Regression<br>*(Linear)* | 0.00620 |
| **22** | SVM<br>*(Linear SVM)* | 0.00626 |
| **23** | Linear Regression<br>*(Robust Linear)* | 0.00634 |
| **24** | SVM<br>*(Quadratic SVM)* | 0.00760 |
| **25** | Efficient Linear<br>*(Efficient Linear Least Squares)* | 0.01591 |
| **26** | Efficient Linear<br>*(Efficient Linear SVM)* | 0.01822 |
| **27** | Ensemble<br>*(Boosted Trees)* | 0.04358 |
| **28** | SVM<br>*(Cubic SVM)* | 0.93369 |

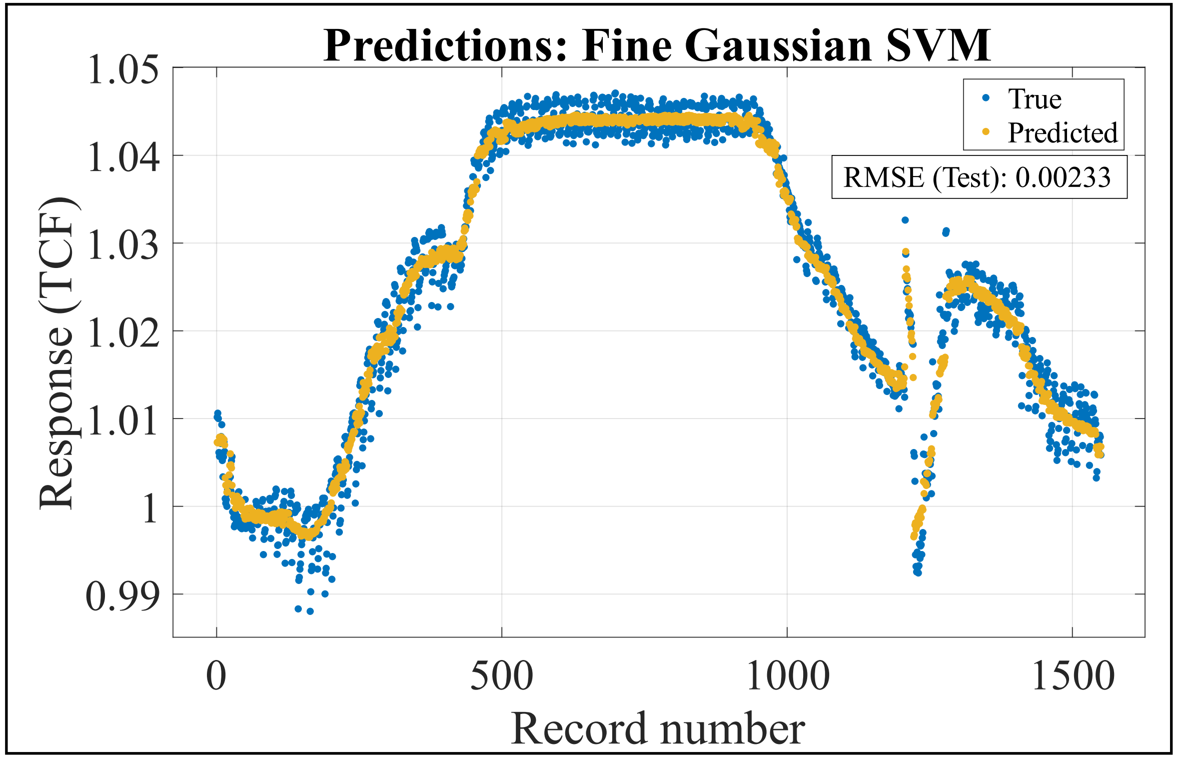
RMSE: Root Mean Squared Error

# ML Model Response Plots

Overfit model example



Selected model



# TTCF Comparison

$$TOF_{bondline} = TOF_{laminate} - \mathbf{TTCF} \times \left(TOF_{0,top\ panel} + TOF_{0,bottom\ panel}\right)$$

- Scan 62, Time: 170 Minutes, Temperature: 119.4°C

$TOF_{laminate} = 5.103\mu s$
$TOF_{0,\ top\ panel} = 3.340\mu s$
$TOF_{0,\ bottom\ panel} = 0.832\mu s$

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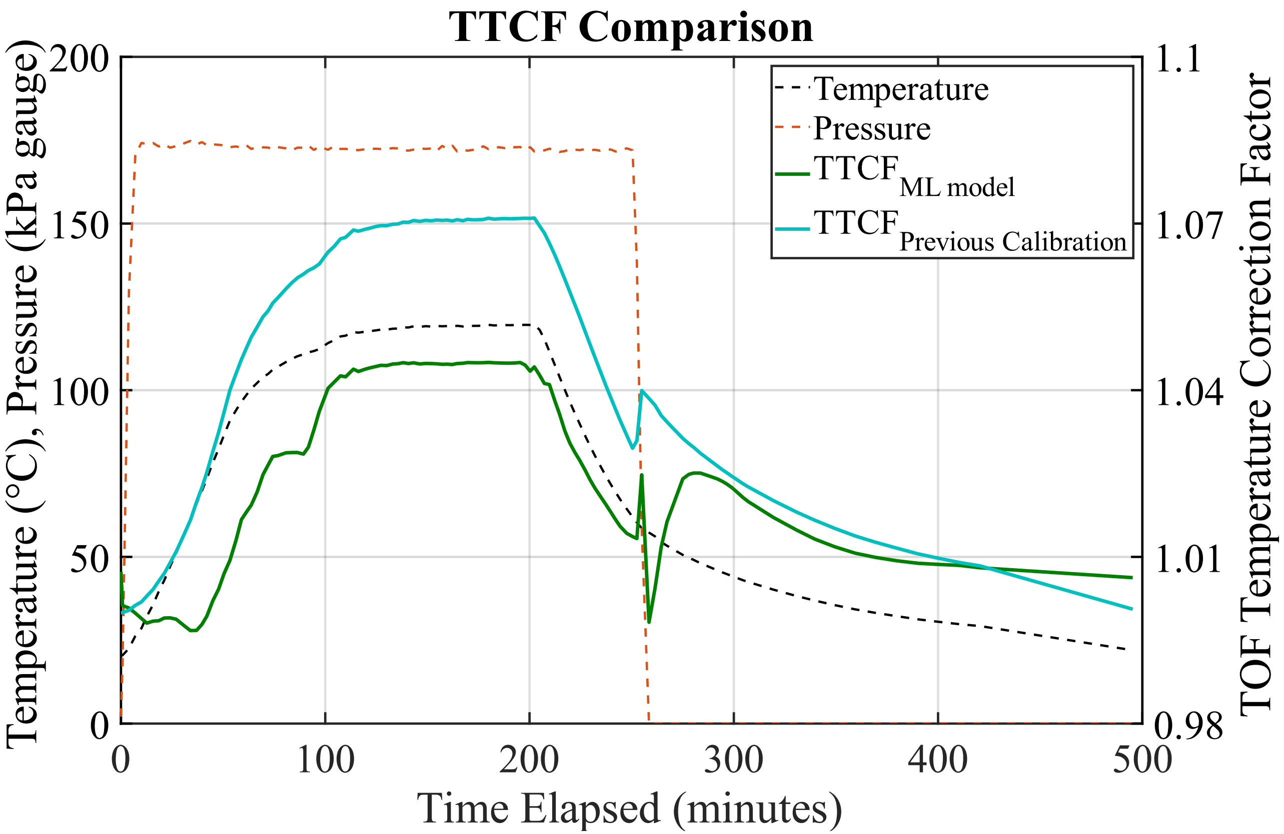
$TTCF_{Previous\ Calibration} = 1.071$
$TTCF_{ML\ model} = 1.045$
$\%_{error,\ TTCF} = 2.47\%$

$TOF_{bondline,\ previous} = 0.6364\mu s$
$TOF_{bondline,\ ML} = 0.7440\mu s$
$\%_{error,\ TOF} = 14.46\%$



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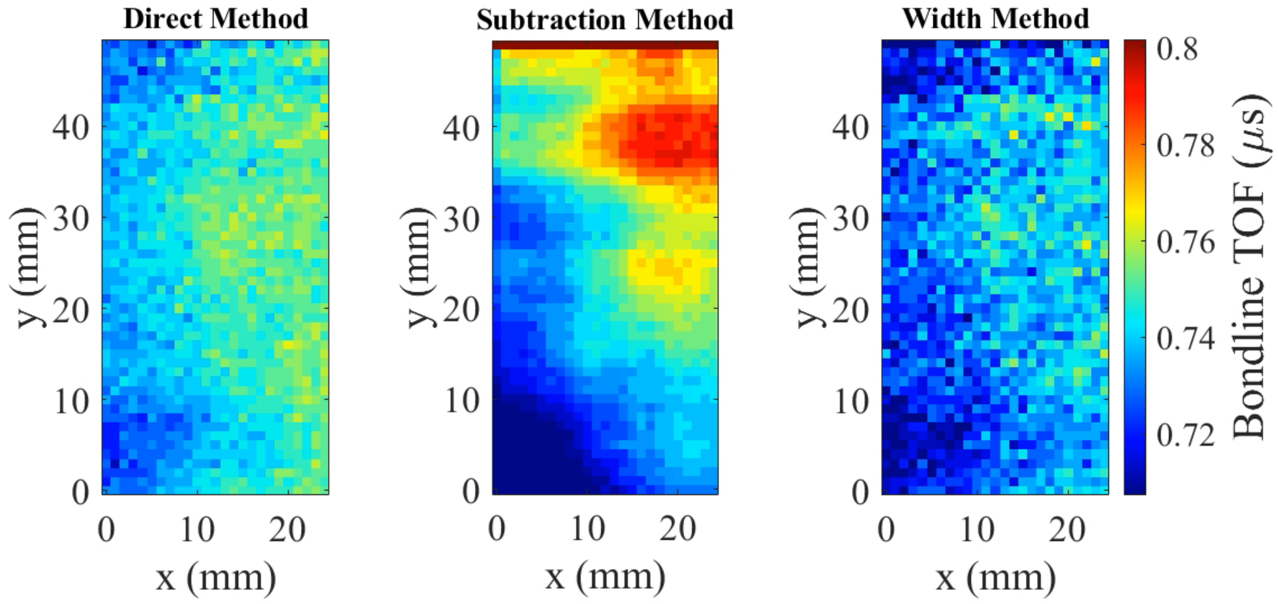
Scan: 50, Time: 137.5-138.8 minutes, Temperature: 118.8-118.9°C

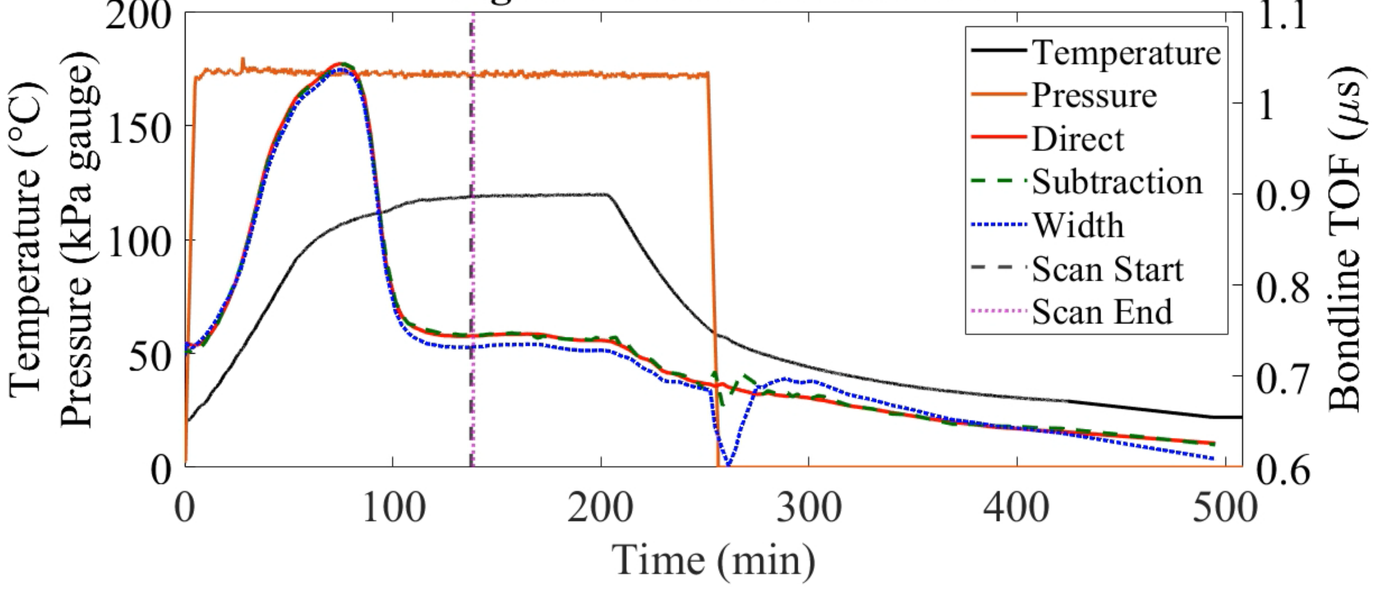


Direct Method

Subtraction Method

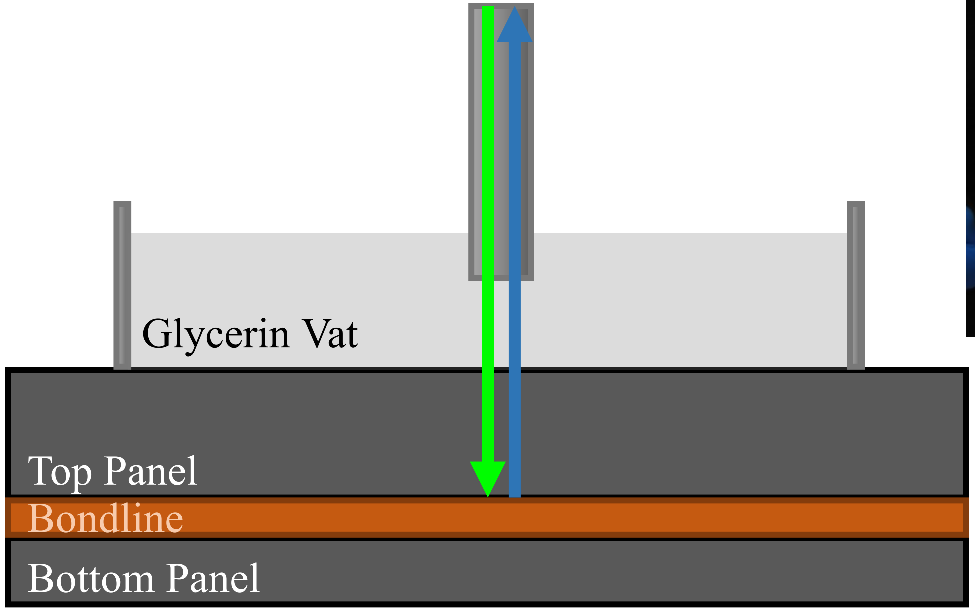
Width Method

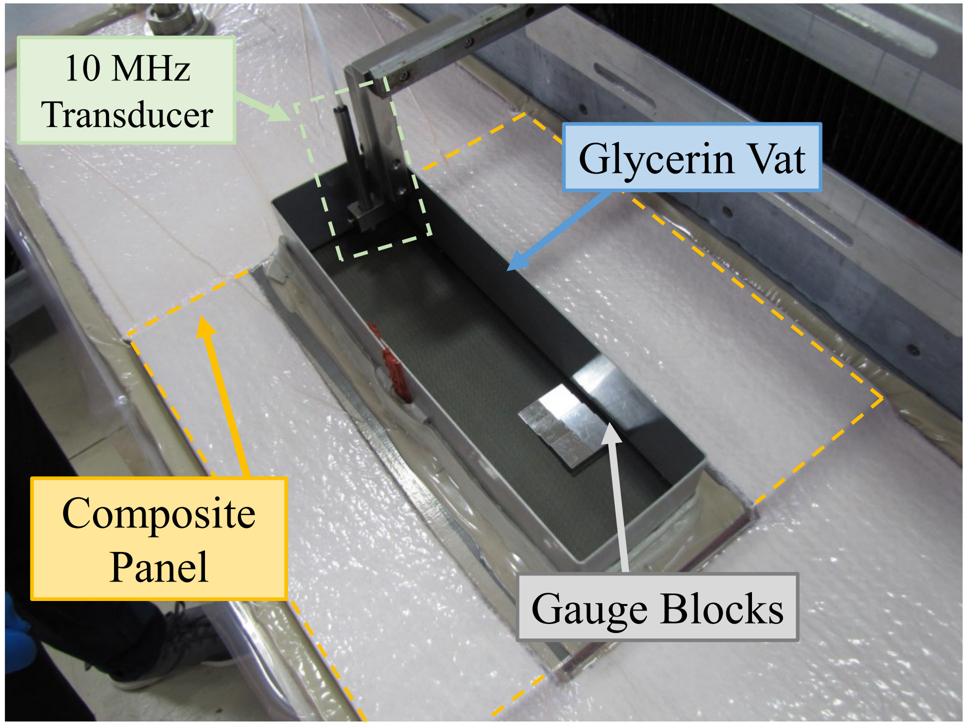
Avg. Bondline TOF Per Scan



# 10 MHz Transducer Upgrade

- 10 MHz immersion probe installed replacing 2.25 MHz contact probe
- Allows for the direct method on thinner bondlines
  - Previously limited by the 2.25 MHz probe





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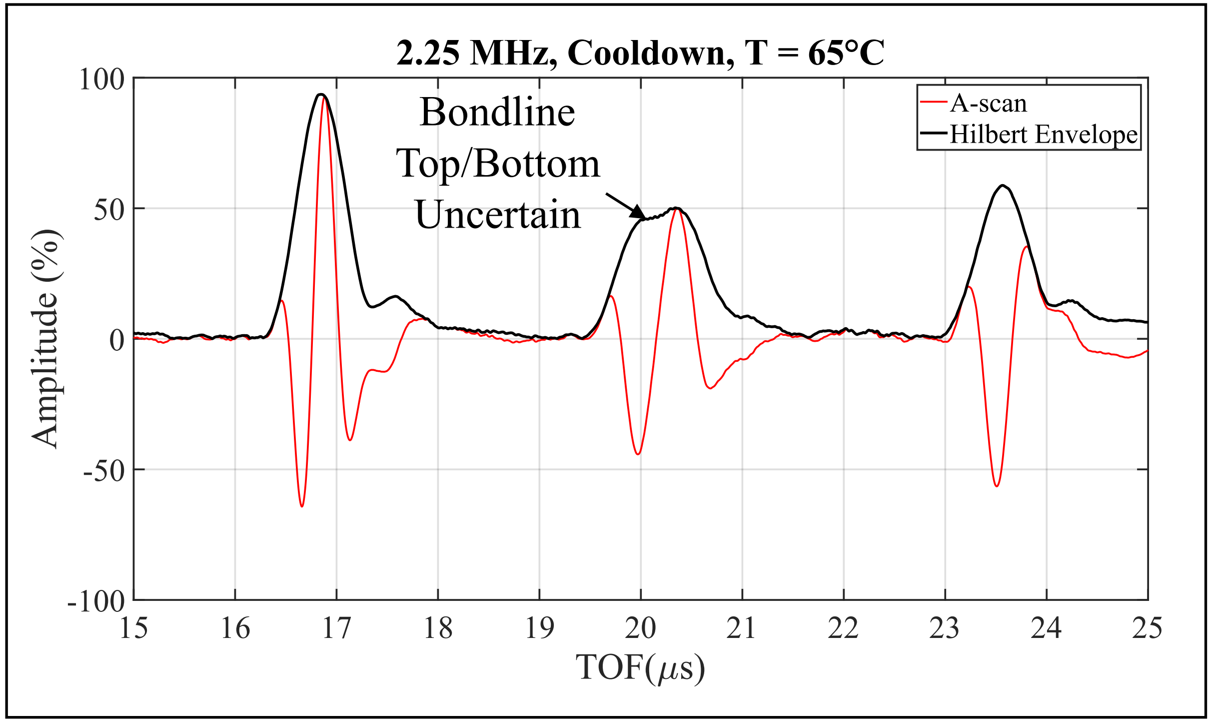

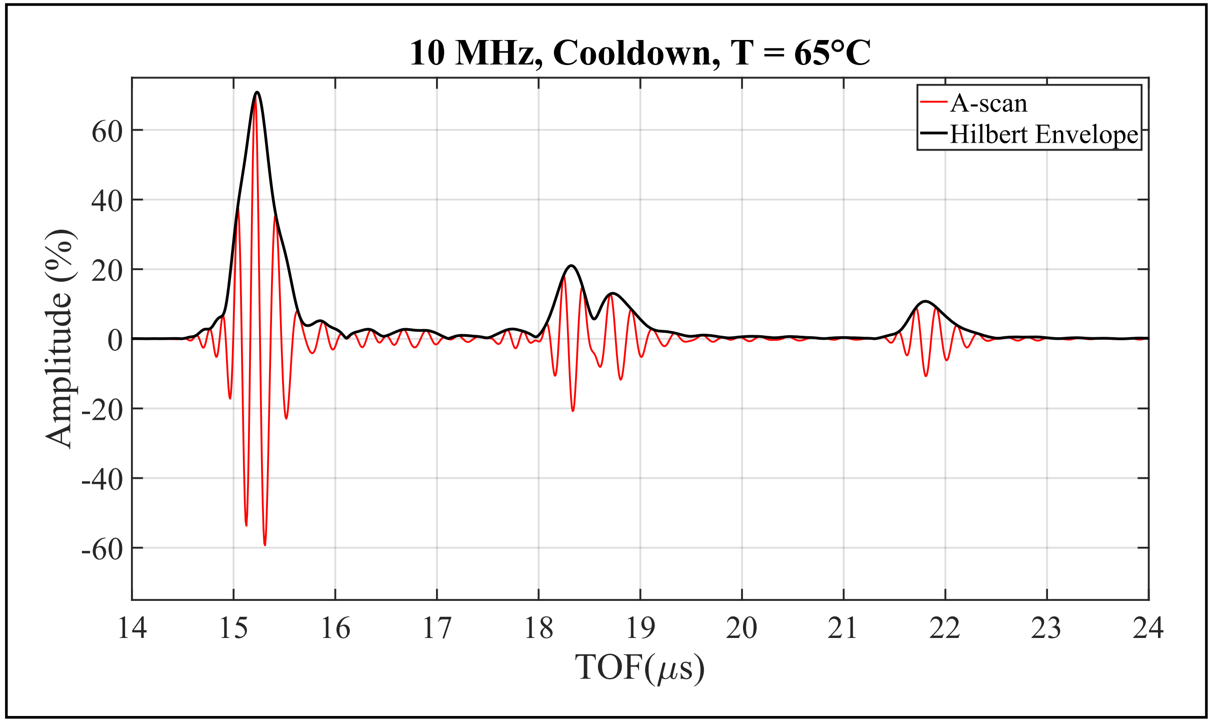

# Summary

| | Direct Method | Subtraction Method | Width Method |
|---|---|---|---|
| **Pros** | • No calibration required<br>• Only dependent on top/bottom of bondline peaks | • Does not require bondline peaks<br>• Easiest peak detection (top/bottom of panel) | • No calibration required<br>• Available without bondline peaks |
| **Cons** | • Requires clear top/bottom of bondline peaks<br>  • Needs higher frequency transducer for thinner bondlines | • TTCF calibration required | • Requires clean front wall peak<br>• Ignores wave dispersion<br>  • Over prediction<br>• Top/bottom of bondline need relatively same magnitude |

# Acknowledgements

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