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Status Update of NDE Research at PNNL – Modeling & Simulation

NRC-Industry Technical Information Exchange (TIE) Public Meeting

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V6323: Modeling and Simulation Update

Motivation

Without having to empirically generate NDE data, effective modeling and simulation allow us to evaluate:

- How a probe might behave under various conditions
- How sound fields may propagate in different materials or at boundaries within a material
- The ultrasonic signal response from a flaw
- Coverage issues and impingement angles, insonification effectiveness of targeted volumes of material, SNR, etc.

Modeling/simulation tools are only as good as:

- The algorithms and physics engines used for computations
- The inputs provided to the model
- The NDE experience level of the user

Caution: Models will never surpass empirical data

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V6323: Modeling and Simulation Update

Goal

- Determine if UT computational models adequately represent reality within their intended domain

Activities

- Conducted literature searches focused on NDE models and verification and validation concepts
- Created an inventory of relevant probes, mockups, flaw and reflector specifications, pertinent UT data, and UT instrumentation systems for use in collaborative studies with EPRI
- Developed processes and guidelines for acquisition of key performance parameters for ultrasonic probe characterization
  - To provide consistency and an appropriate level of scientific and engineering rigor for quantifying and characterizing the performance of all probes (conventional and phased array) used throughout this effort.
- Obtaining UT data on various mockups with machined reflectors and eventually various types of implanted and grown thermal fatigue cracks for empirical validation of modeling and simulation results
- Periodic teleconferences with EPRI NDE Center

V6323: Modeling and Simulation Update

Phased Approach

- Phase 1
  - Investigate simple geometrical reflectors and materials (machined notch defects in stainless steel plates)
- Phase 2
  - Investigate more realistic reflectors (implanted/grown fatigue cracks) in stainless steel plates
- Phase 3
  - Investigate realistic reflectors in coarse-grained, anisotropic materials (CASS)

Focus on CIVA

- Semi-analytical simulation with a user interface designed for UT applications
- Fast computational speed
- As compared to Wave 3000+ (finite difference time domain) on a simple configuration: 0.3 to 1435 minutes
- Hybrid Kirchhoff approximation and Geometric Theory of Diffraction (GTD) model for specular and tip diffraction signals

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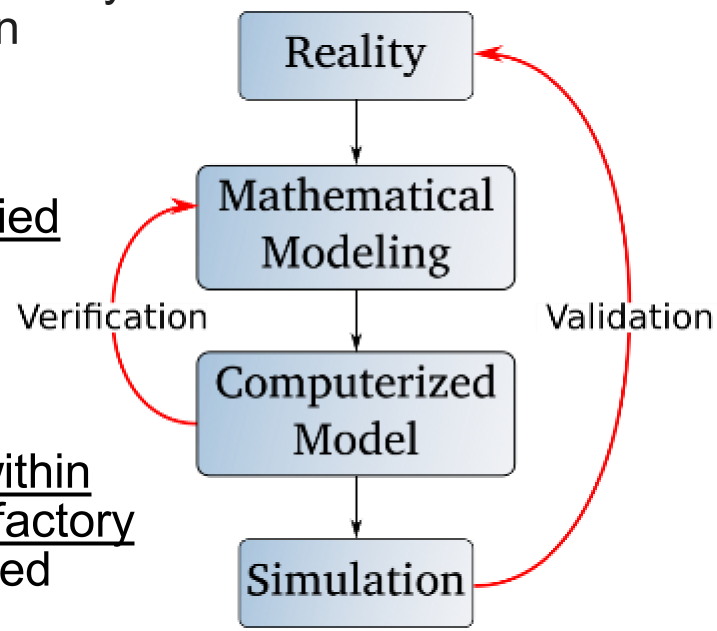
Background: Verification and Validation

- Goal
  - Determine if UT computational models adequately represent reality within their intended domain
- Verification
  - "substantiation that a computerized model represents a conceptual model within specified limits of accuracy" [1]
  - No code is bug-free
- Validation
  - "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" [1]
  - Error measurements (between a model's predicted and empirical observations) can identify discrepancies but don't show which is at fault – simulation or experiment



[1]Schlesinger S. 1979. "Terminology for Model Credibility." *SIMULATION* 32(3):103-104. DOI: 10.1177/003754977903200304.

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Background: Sources of Errors[1]

- Parameter uncertainties
  - Inputs to the model not known, ex. probe dimensions, wedge angle….
- Experiment uncertainties
  - Probe coupling, noise
- Model inadequacy
  - Approximations to the wave equation
- Residual variability
  - Model can't adequately represent heterogeneous materials or fatigue crack with complex branching
- Coding and numerical errors
  - Bugs in the program, numerical methods are approximations to mathematical models

[1]Kennedy MC and A O'Hagan. 2001. "Bayesian Calibration of Computer Models." *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* 63(3):425-464. DOI: 10.1111/1467-9868.00294.
Oberkampf WL and CJ Roy. 2010. *Verification and Validation in Scientific Computing*, Cambridge University Press, United Kingdom.

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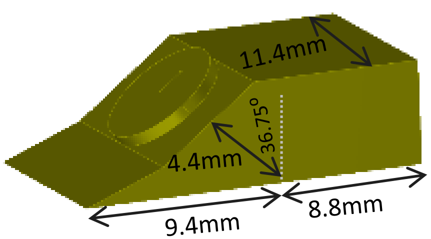
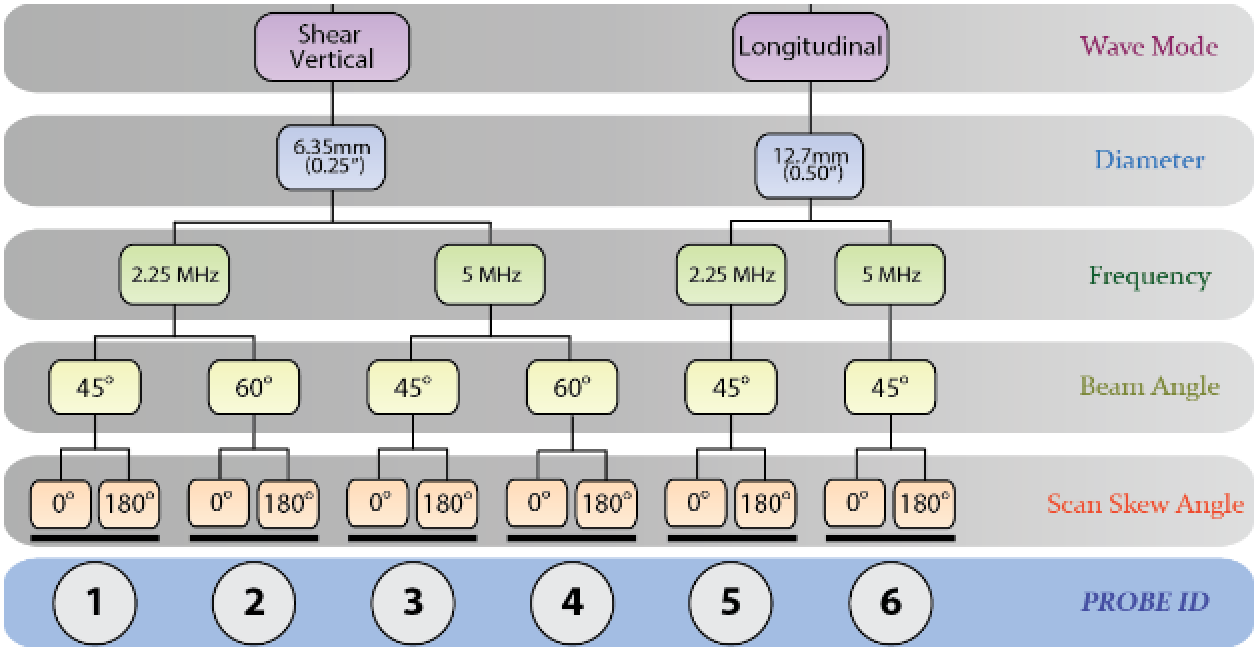
Phase 1 Specimens and Probes

- Measurements were conducted on three 304 SS plates:
  - Plate with 10 rectangular EDM notches varying in depth
  - Plate with 5 semi-elliptical saw cuts varying in length and depth
  - Plate with 14 rectangular EDM notches varying in orientation
- Six transducers
- Two scan directions
- 348 raster scans

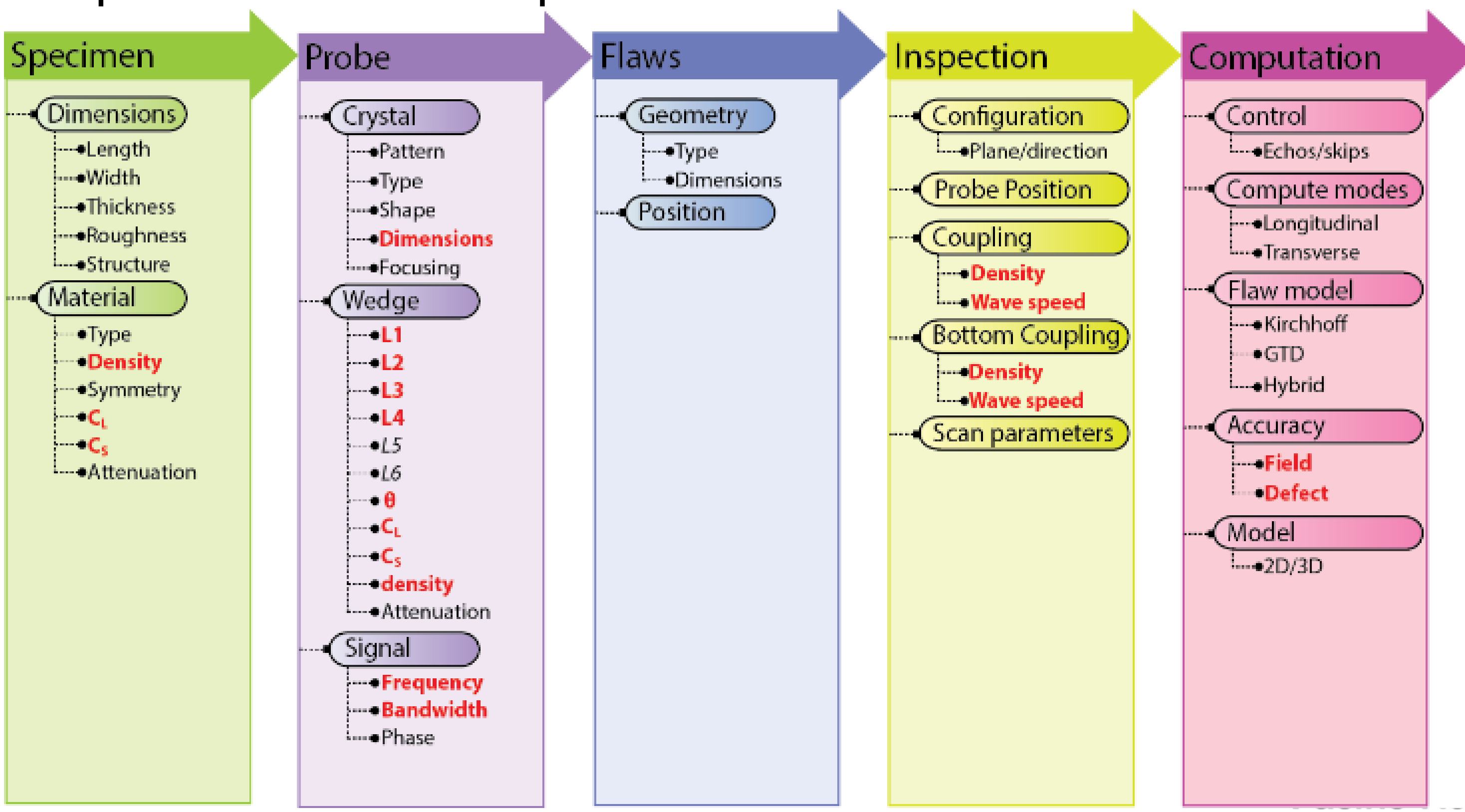
5 MHz, 45^{o}, quarter inch





Parameter Inputs for CIVA

- Specifying parameters for a conventional UT scan in CIVA.
- For proper evaluation of CIVA computation:
  - Specimen, transducer and flaw parameters should match their experimental counterparts.



Model Validation

- Qualitative
  - Visual assessment based on A-, B- and C-scans
  - Presence of expected responses: specular, tip, mode converted
  - Echo shape and location
  - Relative amplitudes
- Quantitative
  - Since POD is of primary importance a single amplitude-based metric derived from the line scan through the lengthwise center of the flaw (B-scan image) was computed
  - A parametric study on the 19 input parameter to the simulation was conducted to provide an estimate of the simulation uncertainty

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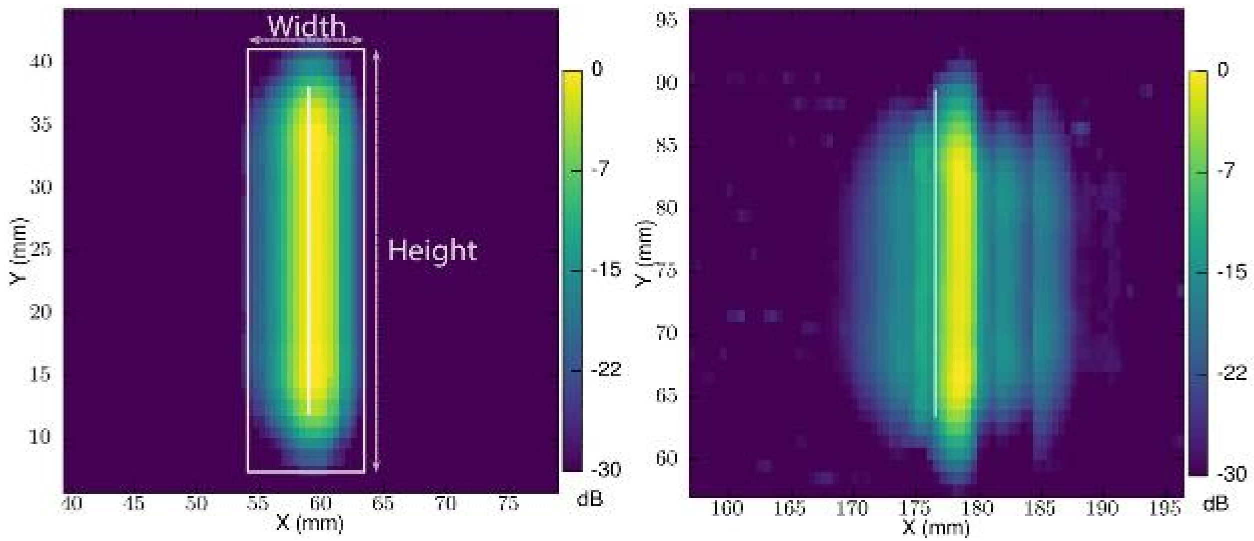
Qualitative Comparison

- A-scan
  - Pulse shape difference
  - Pulse arrival time near or less than one pulse cycle (expected due to error in phase angle in simulation input)
  - Amplitude differences and tip-diffracted echo relative to specular echo smaller in predictions
- C-scan
  - Predicted responses had wider responses than observations
  - Response height (flaw length) were equal in predicted and observed data



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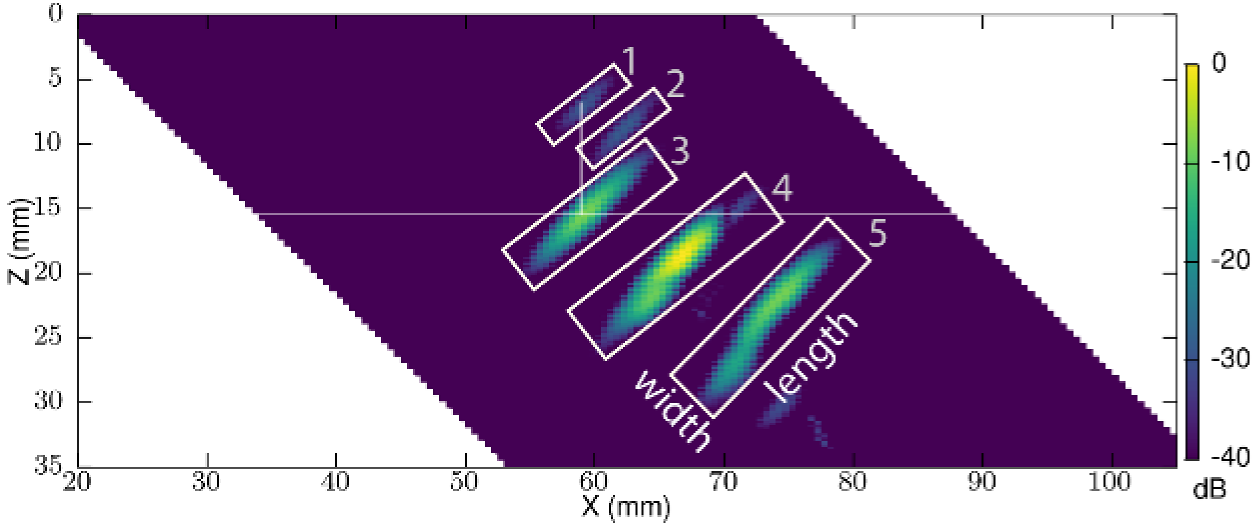
Qualitative Comparison

- B-scan
  - Echo width and relative location consistent between predictions and observations
  - Echo length larger in observations than predictions (matching same observation in C-scan width)
  - Peak amplitudes of tip-diffracted echo relative to the specular echo is smaller in predictions than observations



- Summary
  - Noted differences likely due to inaccuracies in the input parameters and/or experimental variables

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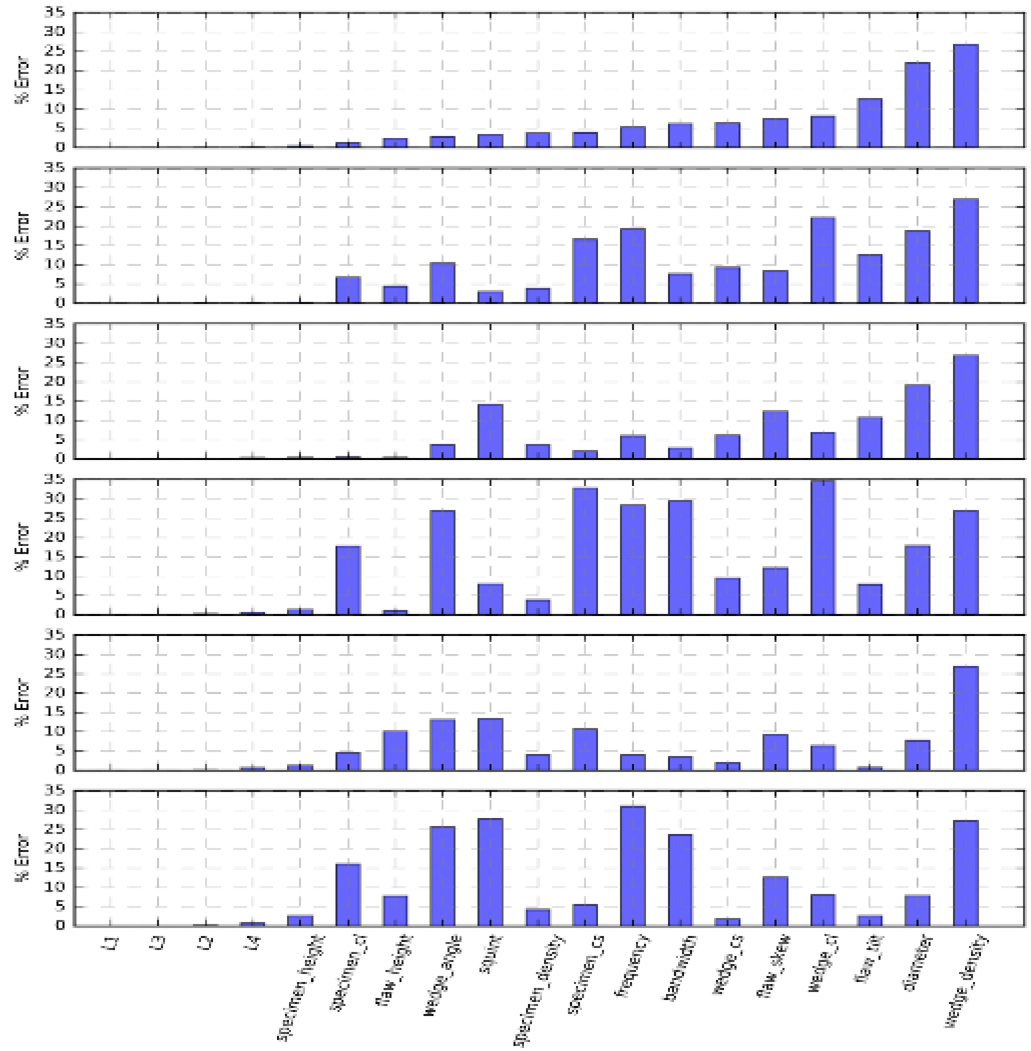
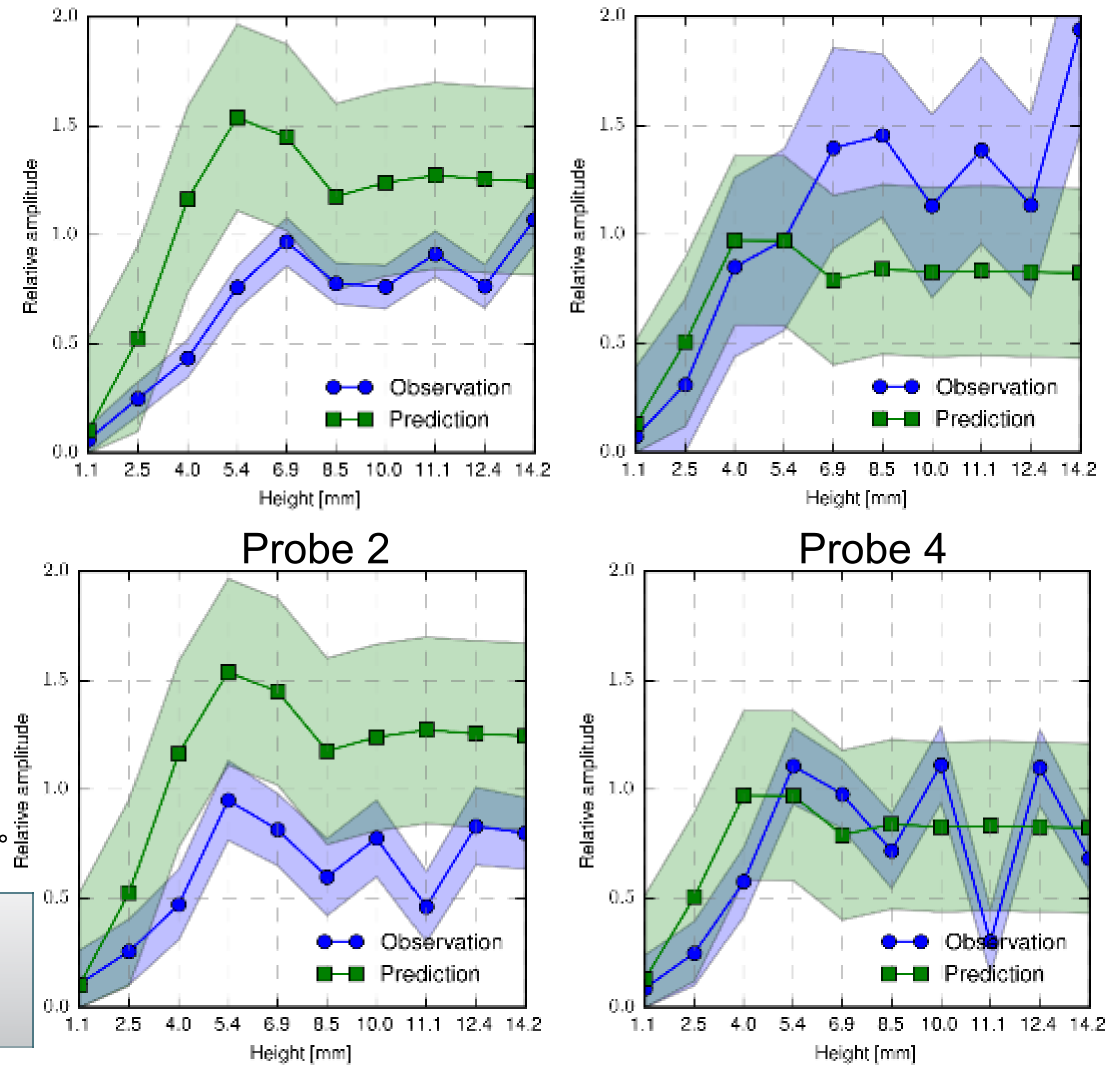
Quantitative Comparison

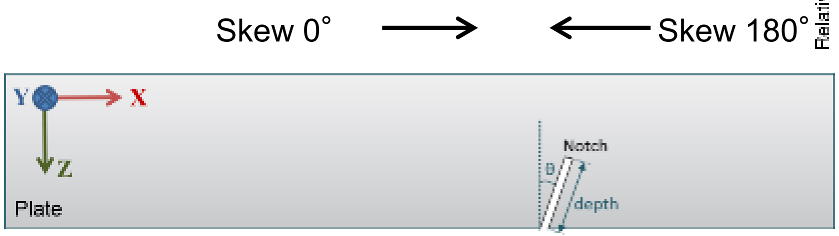
- Parametric Study (to estimate simulation uncertainty)
  - 19 input parameters and 6 probes
  - Assume normal distribution for input parameters
  - Parameters varied by ±3σ
- Results
  - Probe wedge dimensions (L_1 – L_4) had little effect
  - Wedge density had the largest effect in Probe 4 with 35% error
  - Variability between probes



Quantitative Comparison

- Computed amplitude-based metric with confidence bands
- Example: Plate 1 (skew 0°, top, and 180°, bottom), differences up to 7 dB
- Difficult to draw overall conclusions





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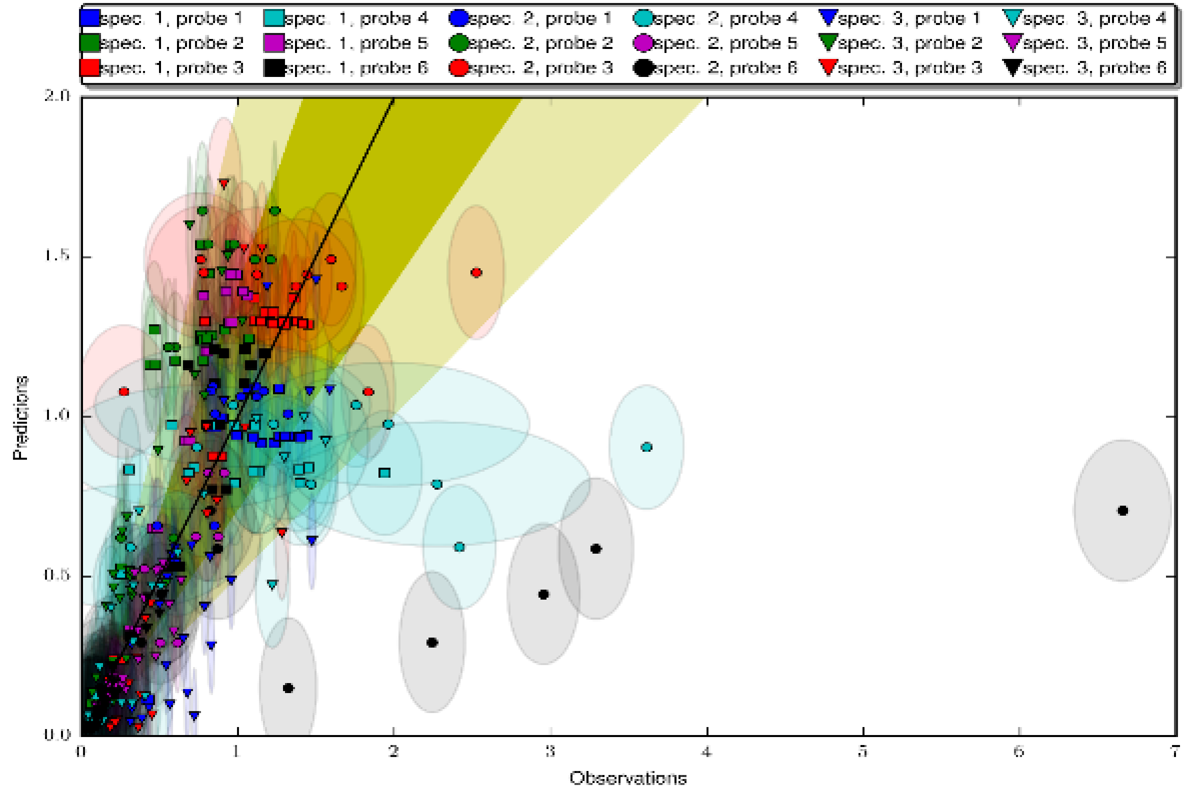
Quantitative Comparison

- All data together with uncertainty represented by ellipses
- Yellow bands: differences between observations and predictions at -3 and -6 dB levels
- 5 Outliers: Probe 6, specimen 2, skew 0°; but skew 180° data are within -6 dB band



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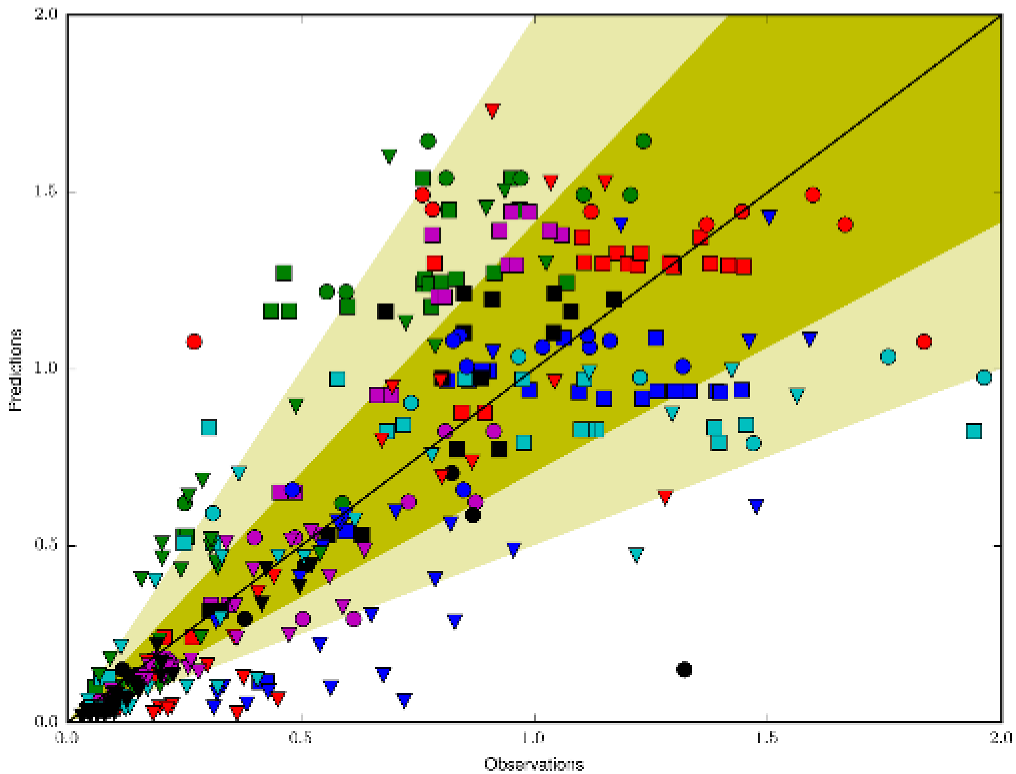
Quantitative Comparison

- Enlarged view
- 20% of data (71 points) lie outside -6 dB region
- 49% of data lie outside -3 dB region
- Of the 71 outliers
  - 20 are above slope = 1 line, predictions > observations
  - 51 are below slope = 1 line, predictions < observations



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Conclusions

- Best-case scenario: homogeneous material and machined notches
- A qualitative assessment shows some differences between observations and predictions but also many similarities
- Quantitatively, although models are useful for providing insight and visualizing wave fields, there is no evidence that models can be used to replace experiments in applications that require an assessment of amplitude
- Experimental and model input uncertainties must be taken into account
- Acceptable levels of discrepancies need to be defined

Future Work

- Phase 2 has been initiated
- Future work scope is evolving with Phase 2 (complex flaws) and Phase 3 (heterogeneous materials) likely to be combined
- A beam coverage assessment is expected to be included

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