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NATIONAL LABORATORY

Modeling and Simulation for Ultrasonic NDE

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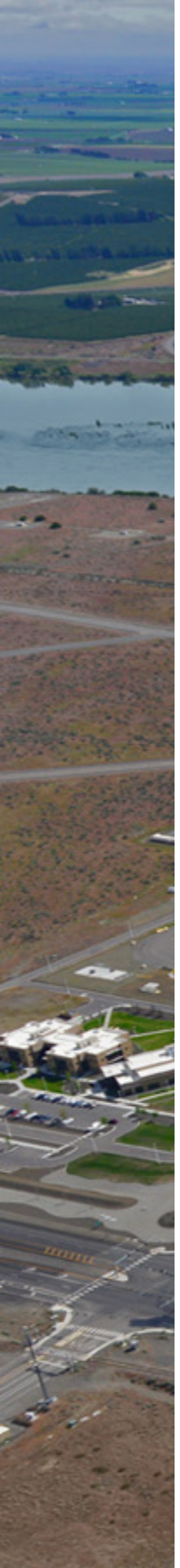

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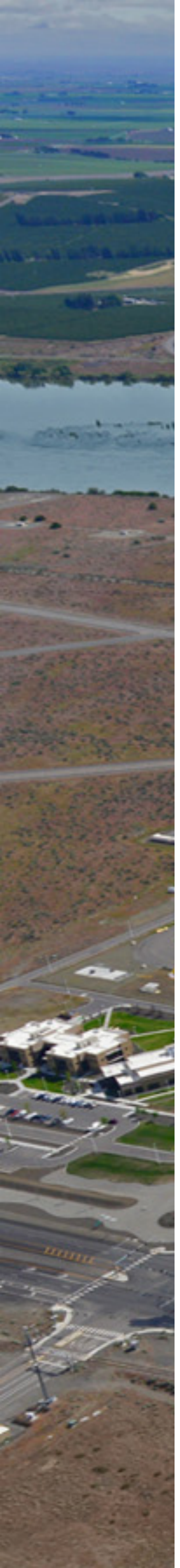
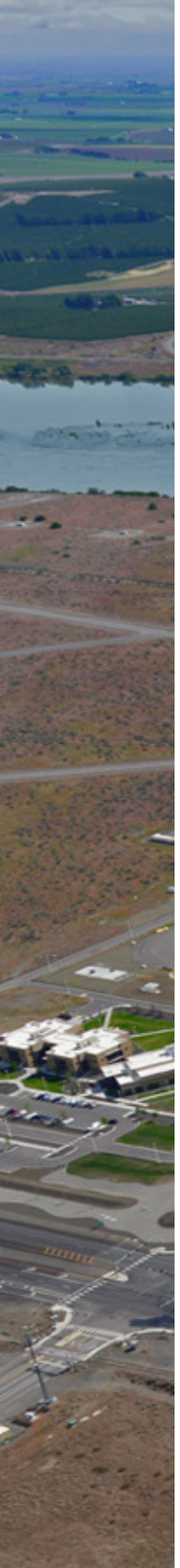


Purpose

Goal of this Research: Provide a solid technical basis for conducting, interpreting, and applying ultrasonic modeling to assess the effectiveness of inspections of NPP components.

This presentation will focus on PNNL's work to:

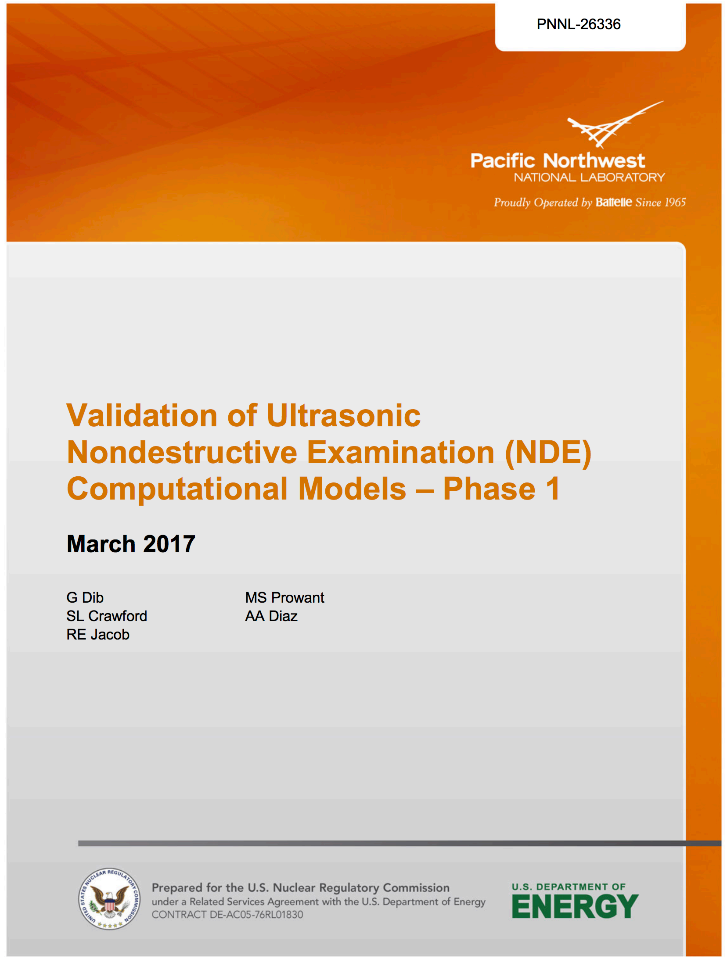
- Evaluate the usability of CIVA for predicting beam coverage in granular structures.
- Evaluate the effectiveness of models for predicting volumetric coverage and detecting flaws through austenitic welds.



Approach

- Thoroughly evaluate simulation tools (CIVA and UltraVision) and determine their potential usefulness for nuclear NDE.
  - Beam simulations
  - Flaw response simulations
  - Metamodels
  - Comparison with experimental data
- Create image similarity metrics for quantitatively comparing simulation results.
- Generate realistic models of austenitic welds and coarse-grain materials, including crystalline orientations.
- Evaluate the accuracy and usefulness of CIVA beam simulations and flaw response simulations through complex grain structures, such as:
  - Austenitic welds
  - Dissimilar metal welds
  - Coarse-grain CASS

Recent PNNL Reports on Modeling and Simulation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Validation of Ultrasonic Nondestructive Examination (NDE) Computational Models – Phase 1

March 2017

G Dib
SL Crawford
RE Jacob
MS Prowant
AA Diaz

Prepared for the U.S. Nuclear Regulatory Commission
under a Related Services Agreement with the U.S. Department of Energy
CONTRACT DE-AC05-76RL01830

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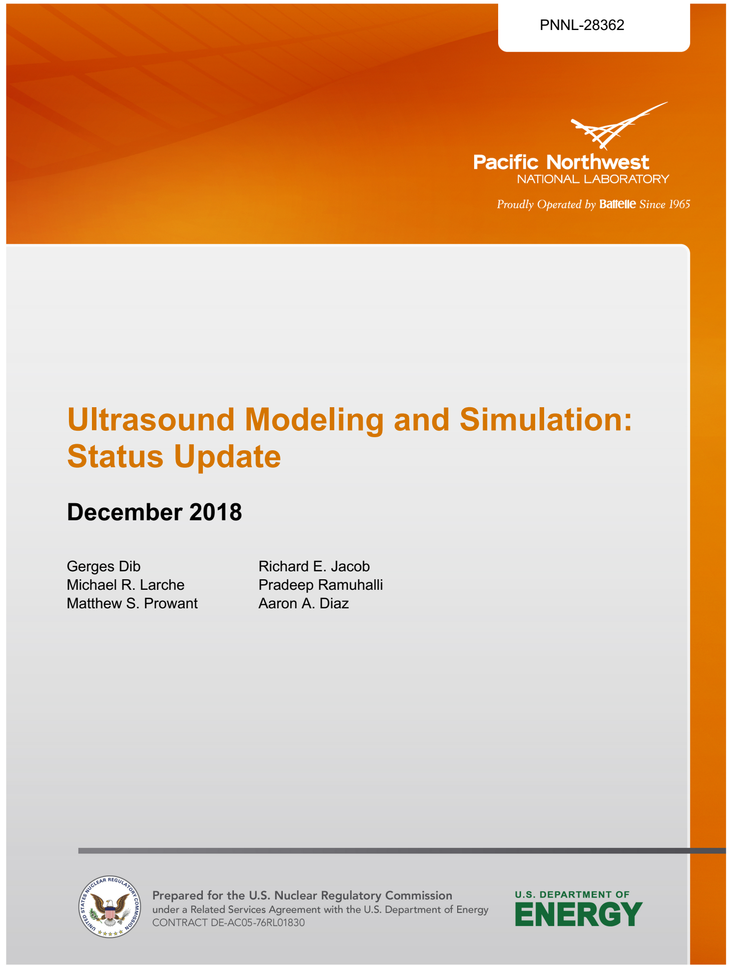
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Ultrasound Modeling and Simulation: Status Update

December 2018

Gerges Dib
Michael R. Larche
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Prepared for the U.S. Nuclear Regulatory Commission
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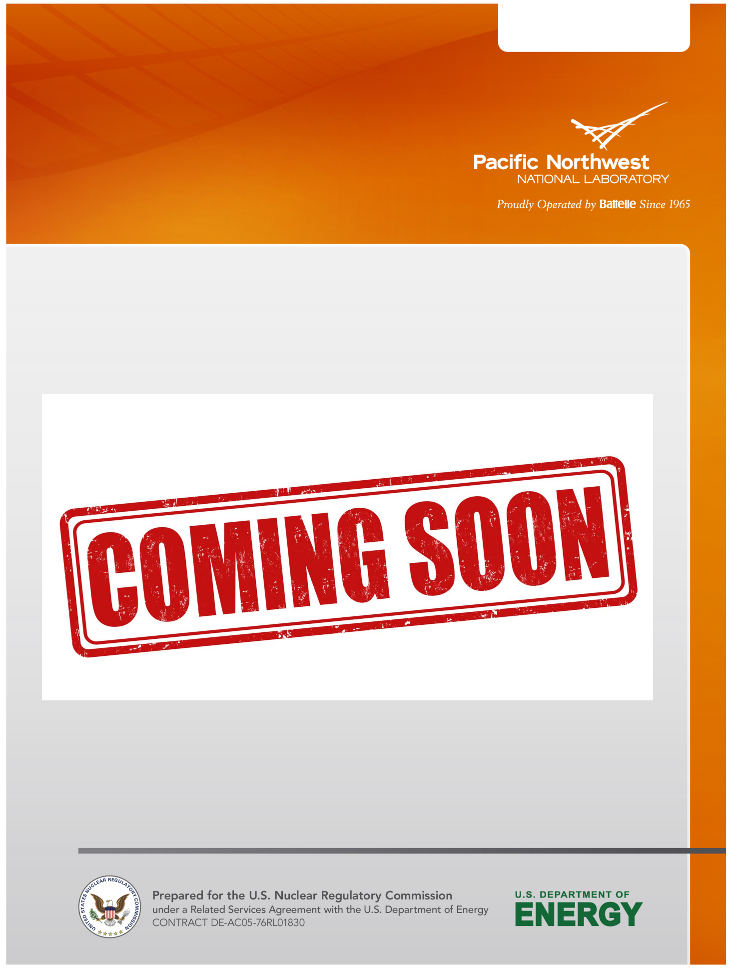
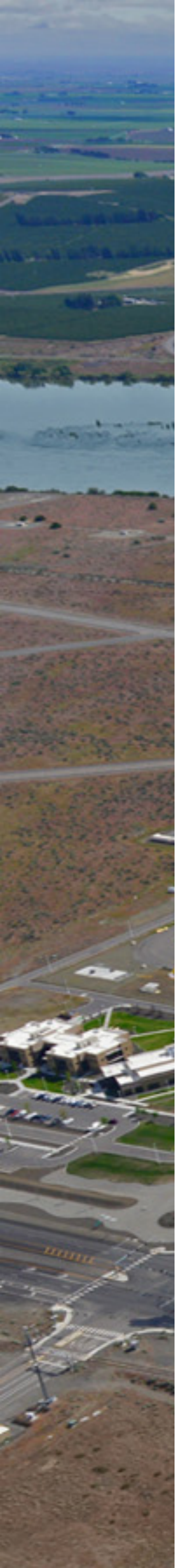


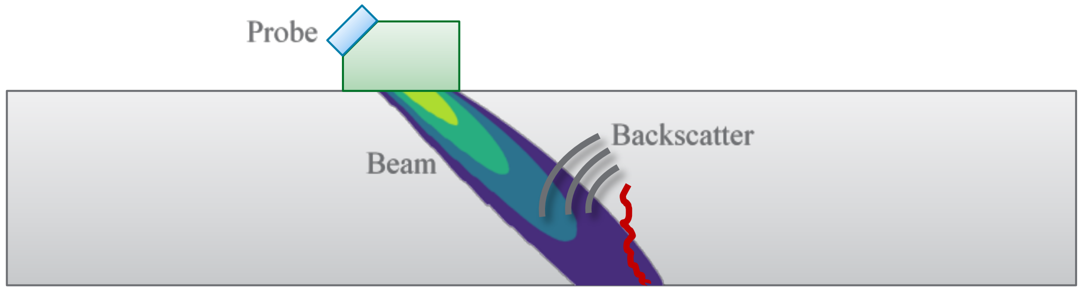
A new report is due to be published in spring of 2020



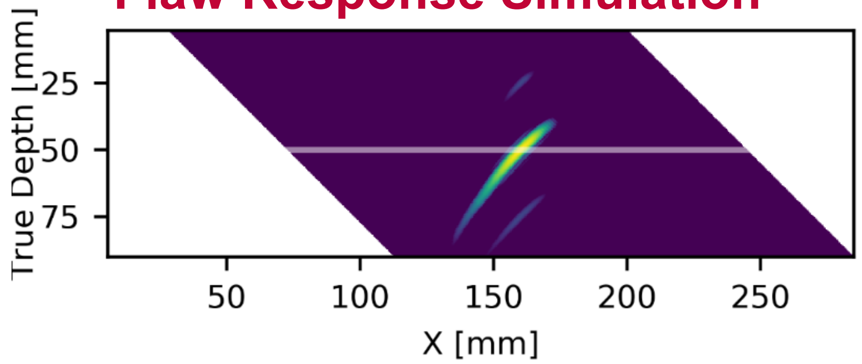
Key Concept Definitions

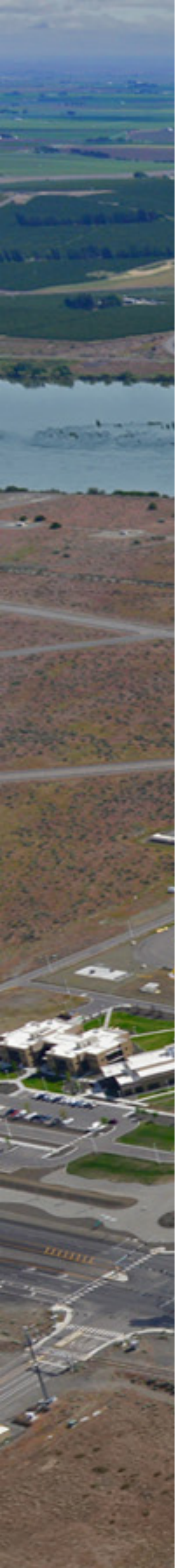
- Models are simplified approaches to approximating real-world outcomes.
- Models provide the framework for performing simulations.
- “Beam models” are used to simulate ultrasonic beam characteristics.
- “Flaw response models” are used to simulate the response from an insonified flaw.
- CIVA is a UT software package with both beam and flaw response models.
- UltraVision is a data acquisition and analysis tool that includes a beam model application.

Beam Simulation



Flaw Response Simulation

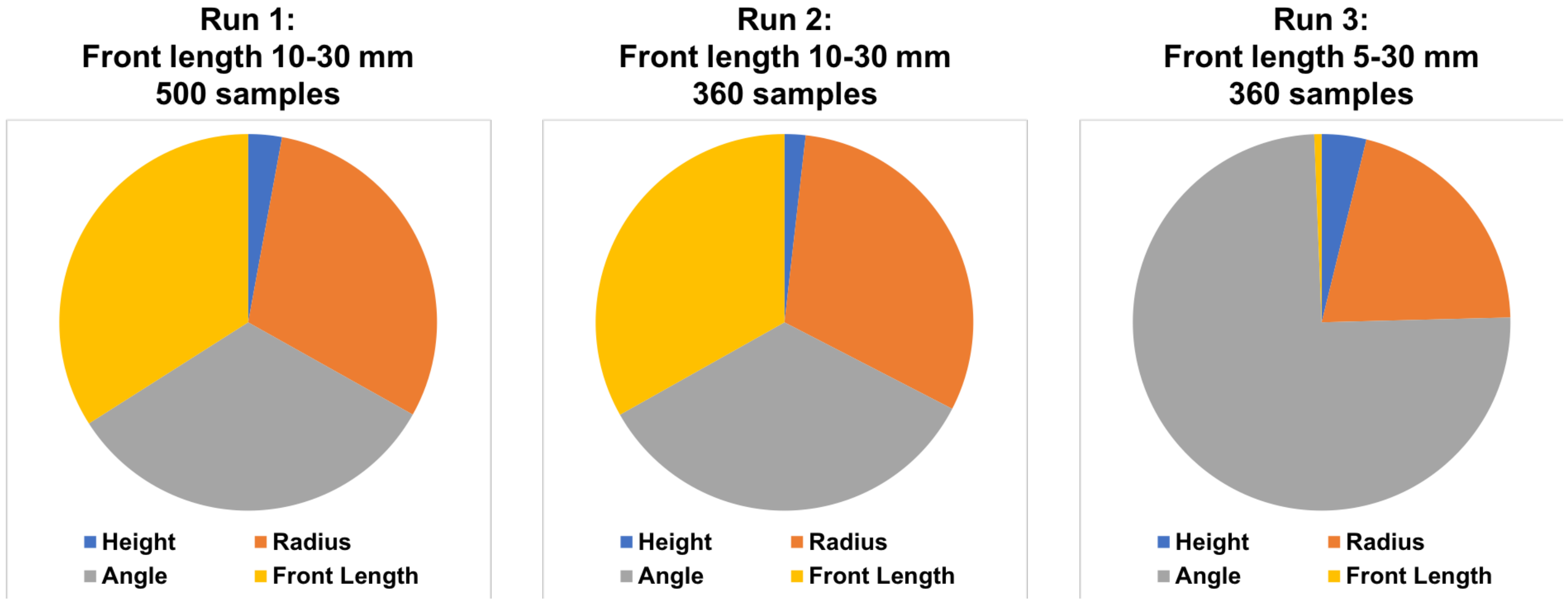


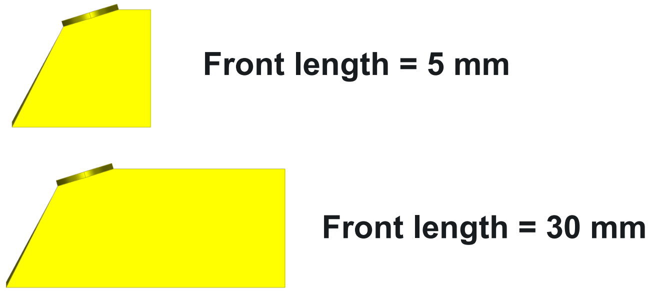


CIVA Metamodels

- CIVA provides a “metamodels” tool for rapid parametric studies and POD predictions.
- Small changes in input ranges can have a strong effect on resulting variable sensitivities.
- For example:
  - Wedge variables of height, angle, radius, and front length were variation parameters.
  - A small change in the front length range caused a huge change in results
- Metamodels should be used with caution. Use realistic input ranges and understand the effects of changing or adjusting parameters.

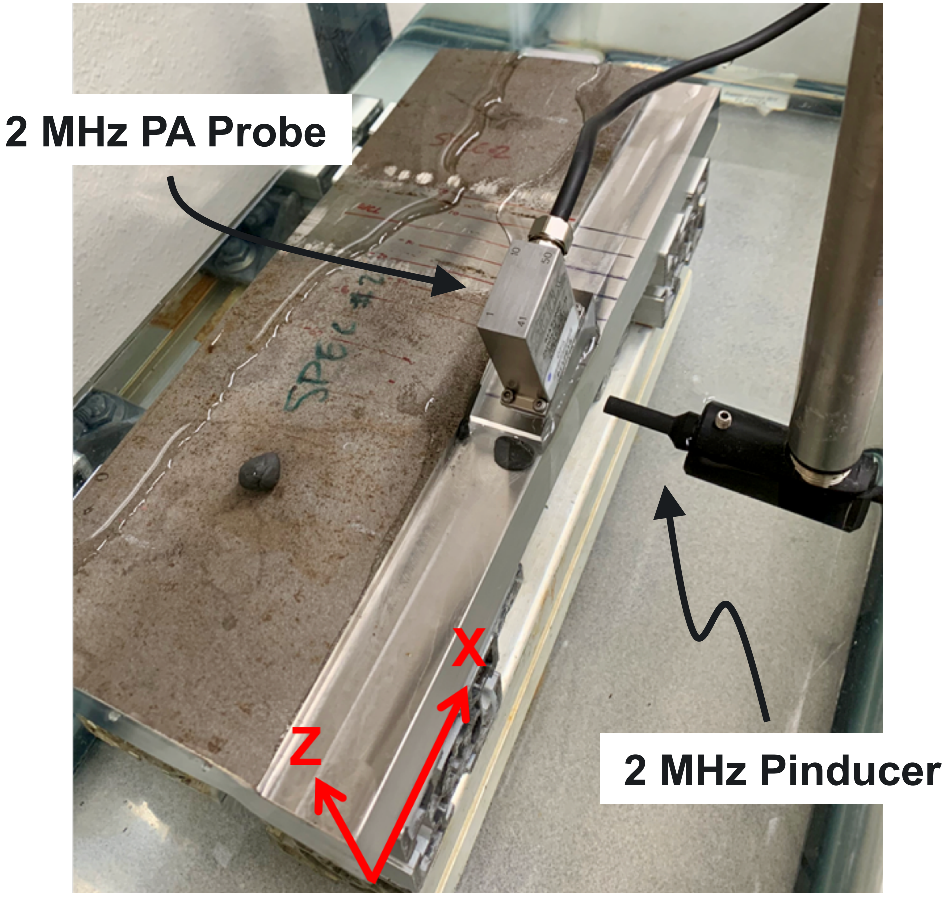
CIVA pie charts show the relative sensitivity of flaw response to each parameter

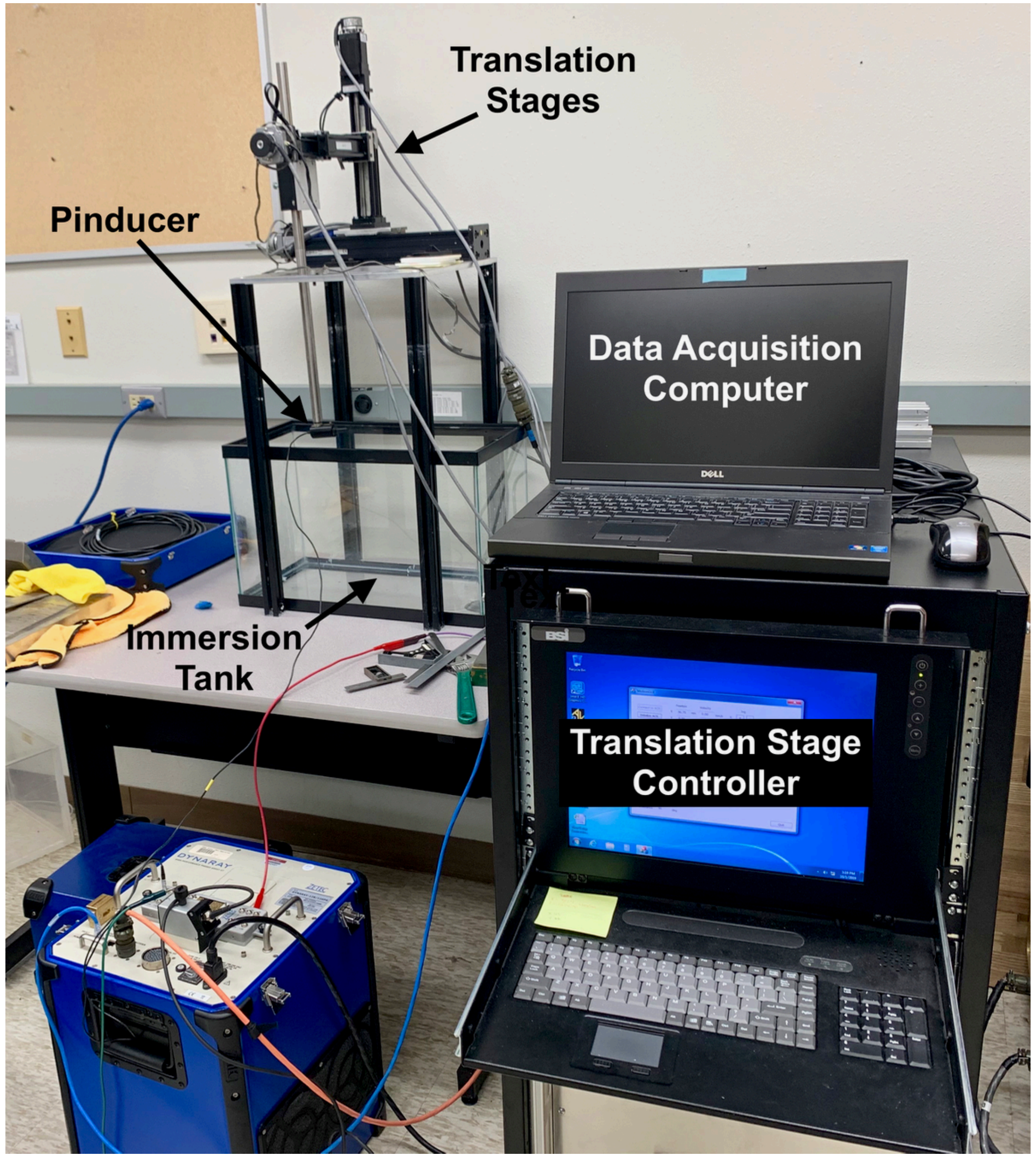




Effects of Weld Microstructure on Beam Simulations: Experimental Validation

- Measurements were taken on three weld specimens.
- A pencil probe, or pinducer, was used with water coupling to measure the side profile longitudinal sound fields from a 2 MHz 10x5 matrix phased array probe (transmit only).

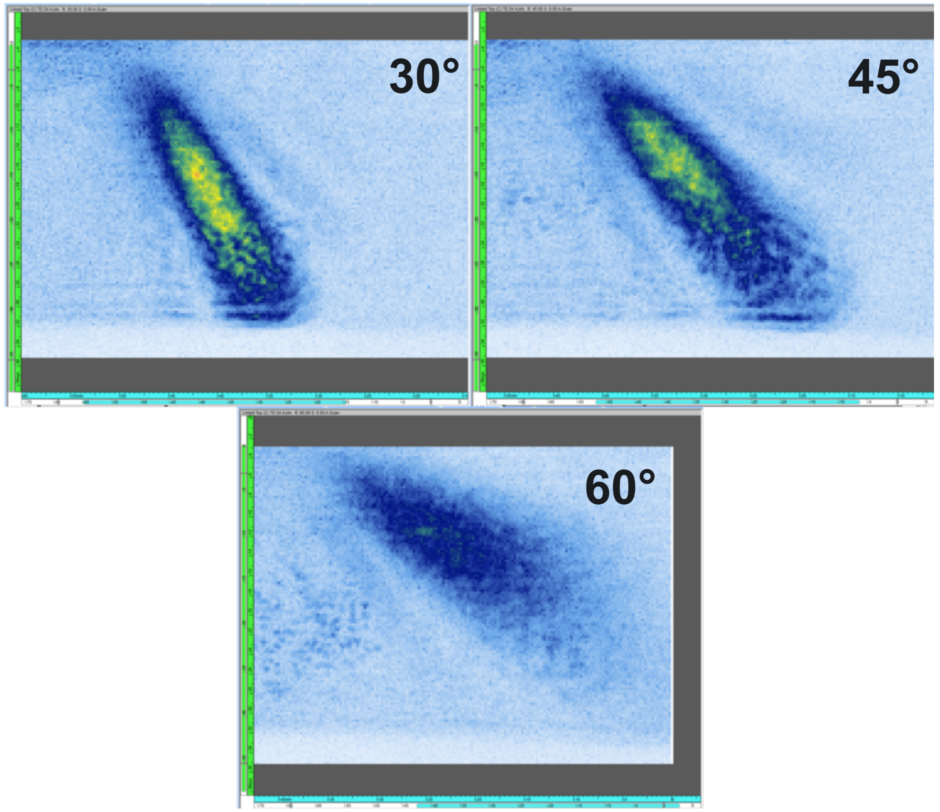


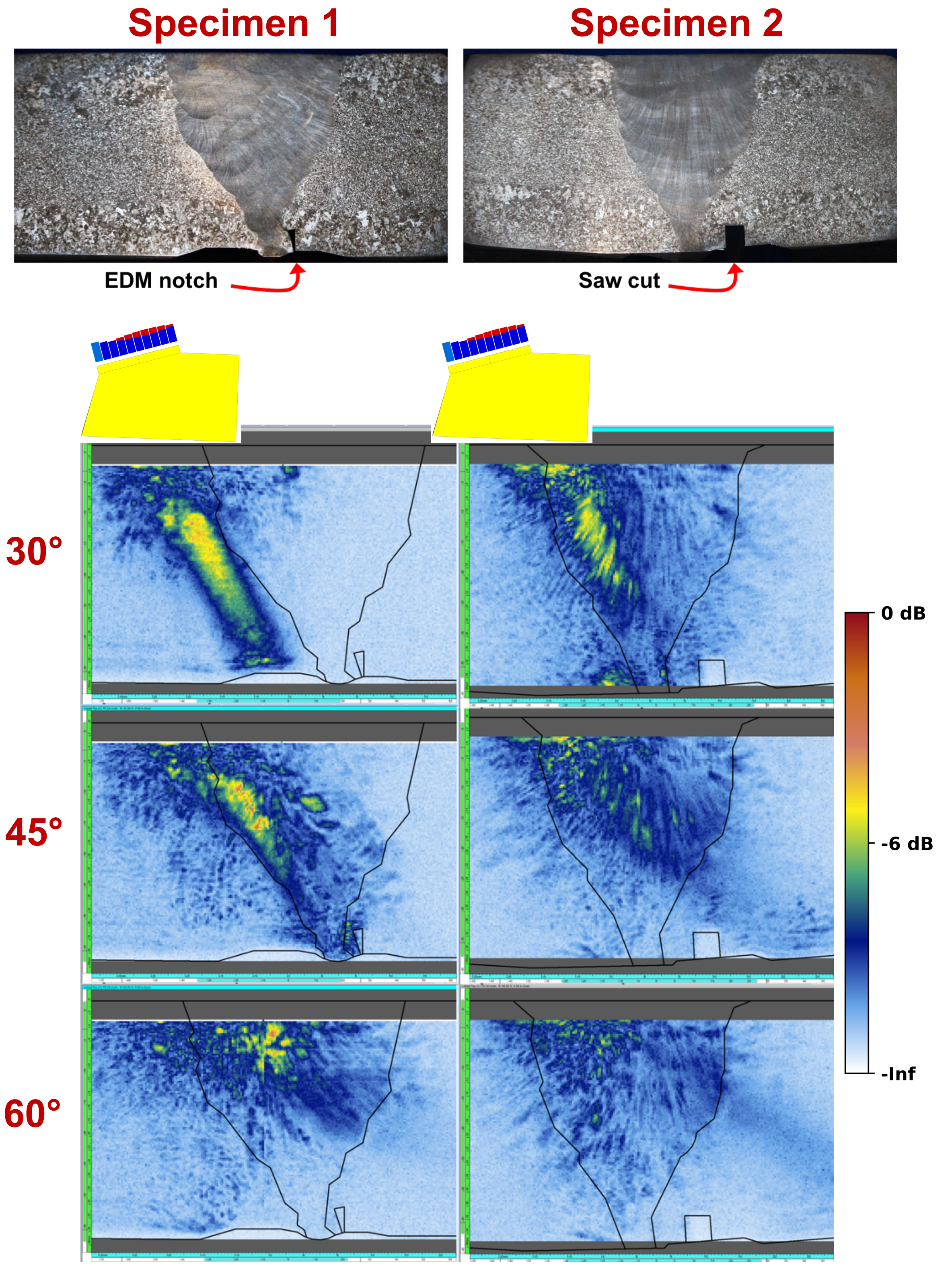


WSS-WSS Beam Maps

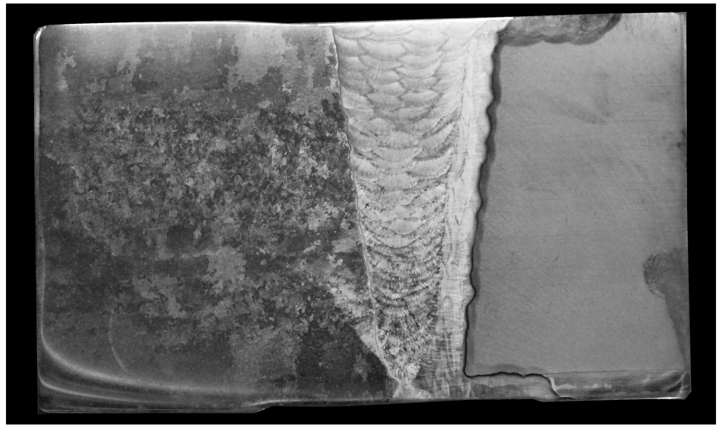
- WSS-WSS specimens, 36 mm thick
- 2 MHz PA probe with 24 mm true-depth focus
- 30°, 45°, and 60° focal laws

Parent Material Beam Maps



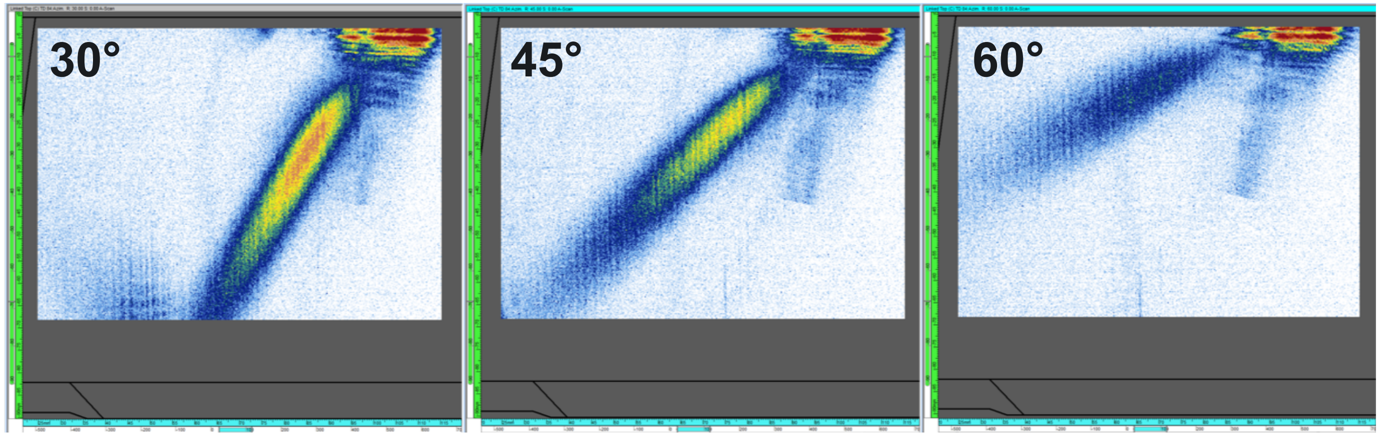


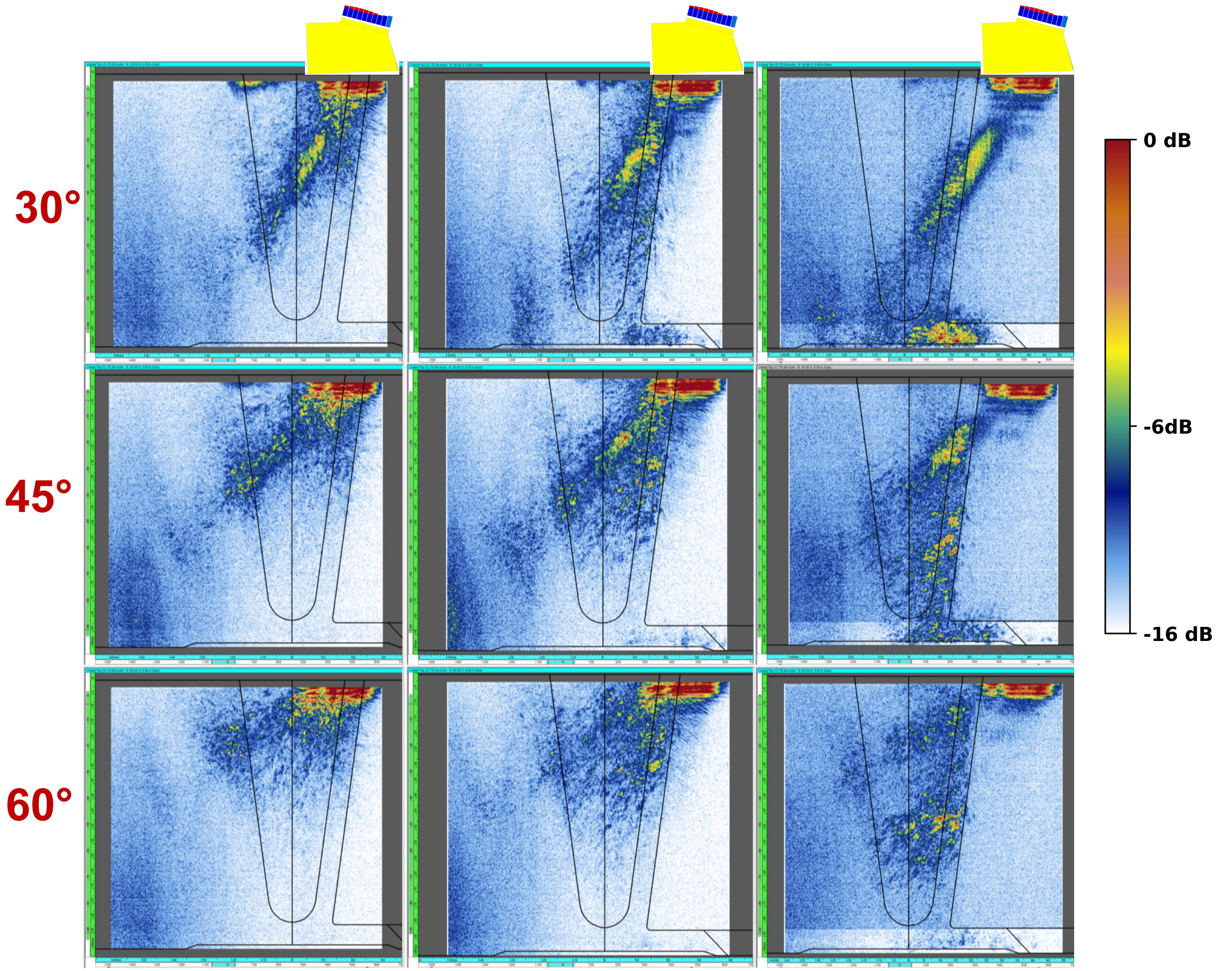
DMW Beam Maps



- CASS-CS specimens, 84 mm thick
- 2 MHz PA probe with 84 mm true-depth focus
- Probe placed on the CS side
- 30°, 45°, and 60° focal laws

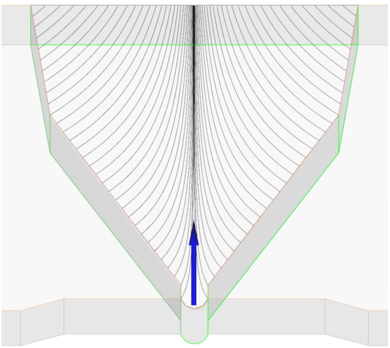
CS Parent Material Beam Maps



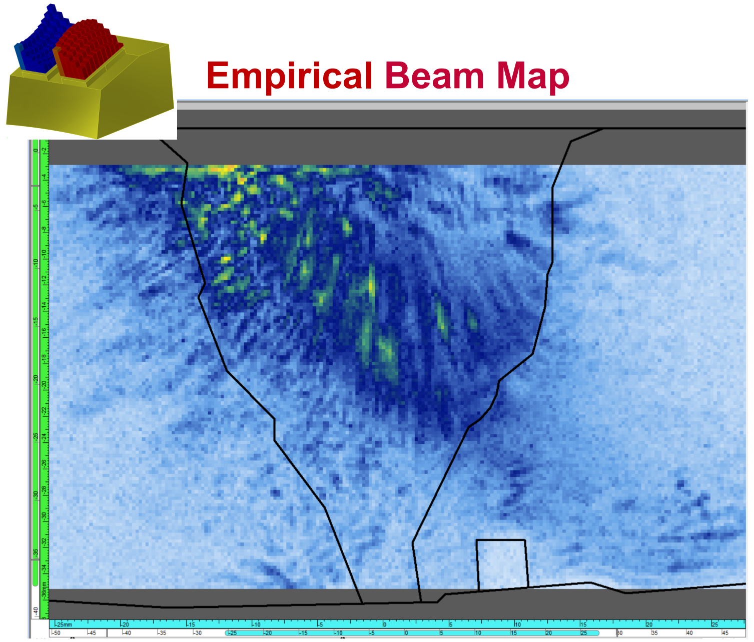


The Ogilvy Weld Model for Austenitic Beam Simulations

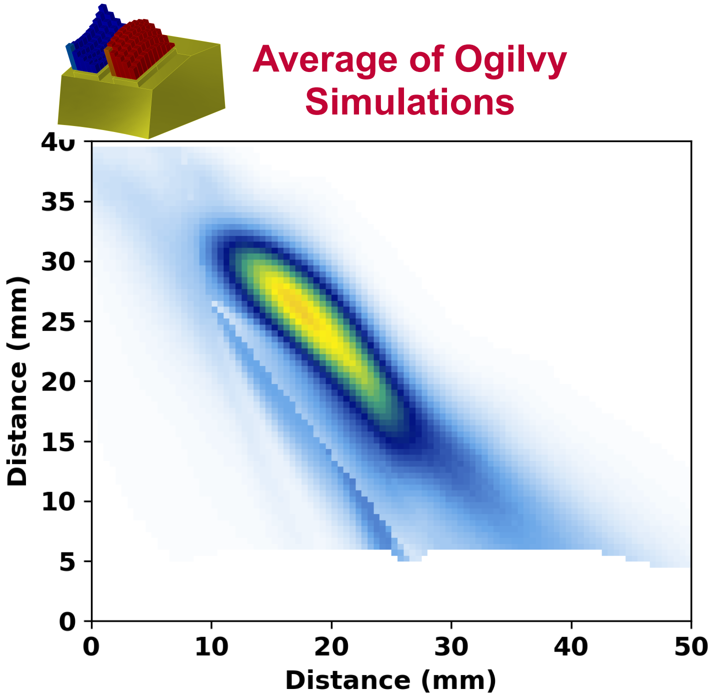
- The Ogilvy model is commonly used to approximate grain structures in austenitic welds because it is easy to implement and simulates some beam redirection.
- However, the Ogilvy model generates grains with continuously varying crystalline orientations.
- Seven simulations were run with the same Ogilvy model but using different stiffness matrix values from the literature.
- The Ogilvy model does not result in beam scatter and still allows for beam focusing – attributes not observed experimentally.



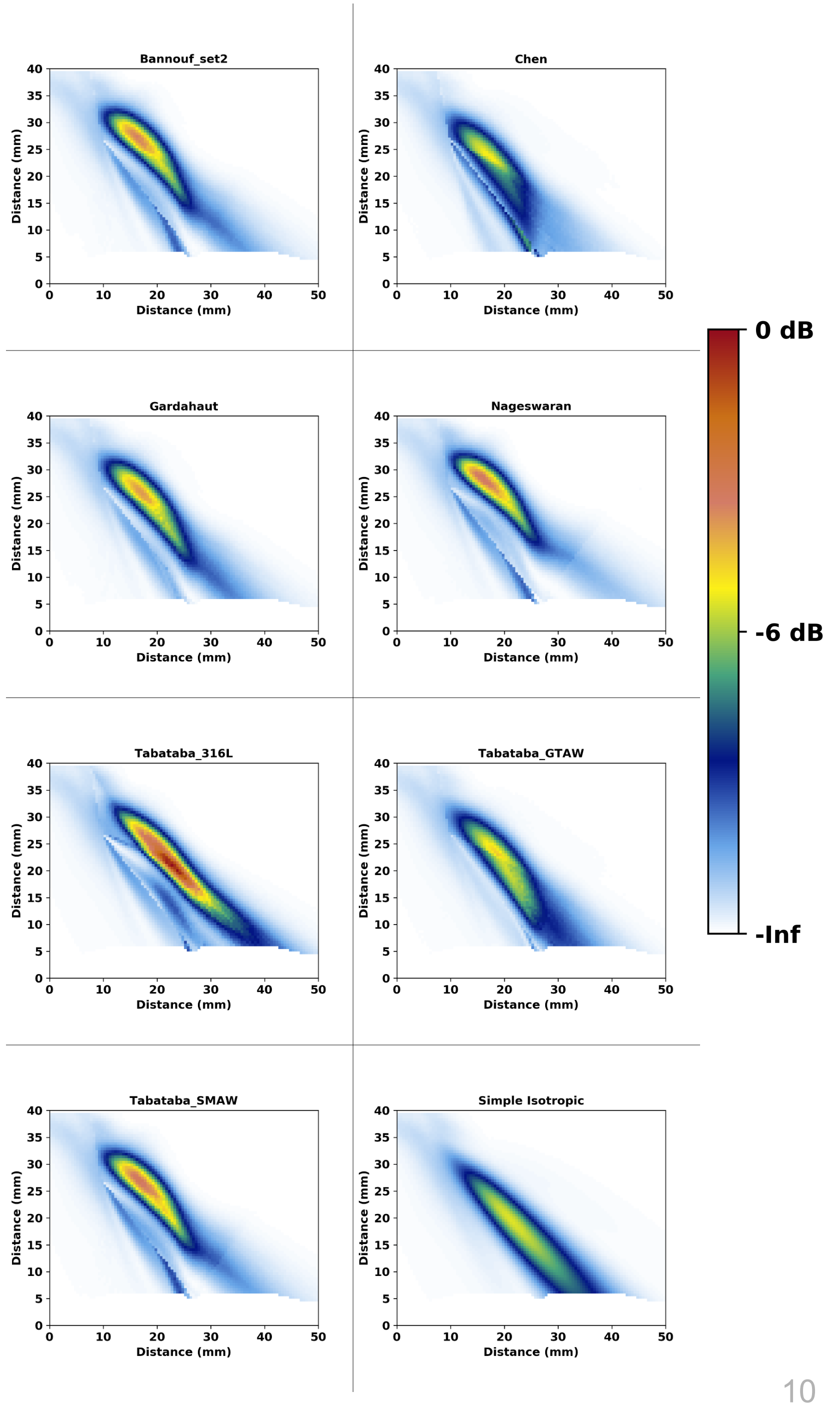
The Ogilvy model used for simulations

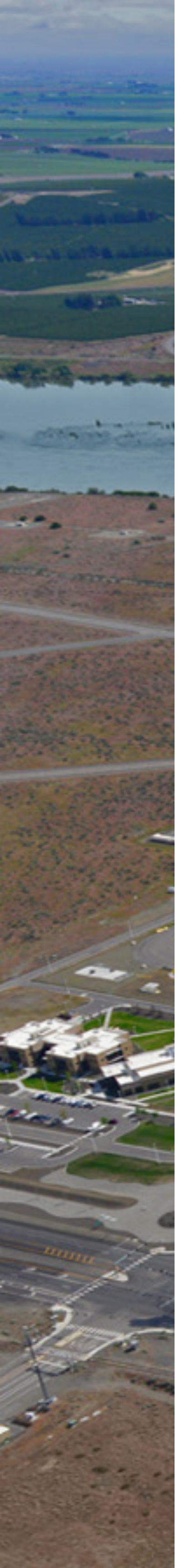


Empirical Beam Map



Average of Ogilvy Simulations

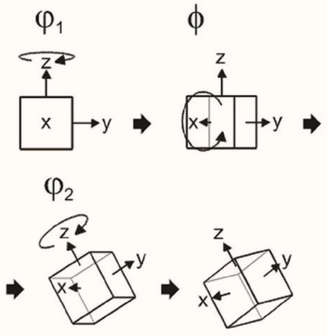




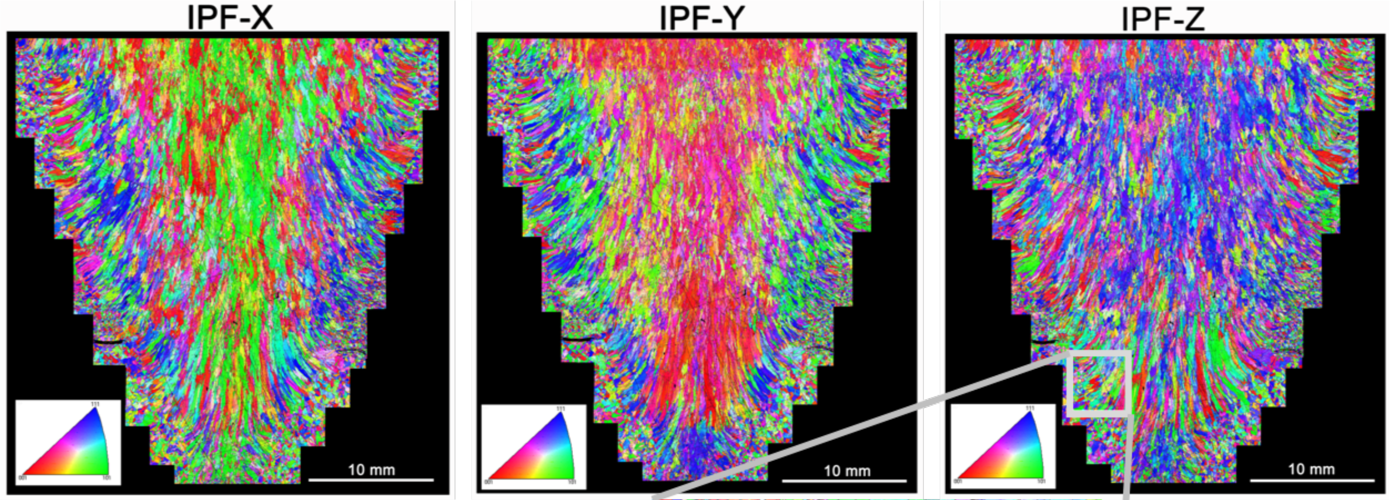
Weld Microstructure Characterization

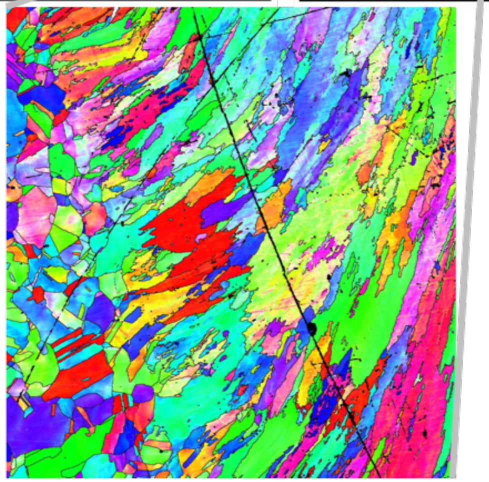
- A more realistic representation of weld microstructure was needed to provide a basis, or true-state, for modeling inputs.
- An austenitic weld sample was polished and etched to characterize the weld microstructure.
- Electron backscatter diffraction (EBSD) was employed to measure grain size and orientation.
  - The grain sizes were measured to 4 μm (0.00016 in.) resolution.
  - Grain crystal orientations (Euler angles) were also measured.

Euler angles are used to define grain orientations



Electron Backscatter Diffraction Results



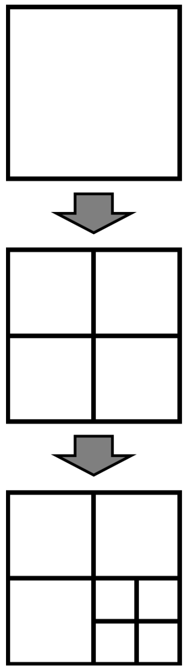


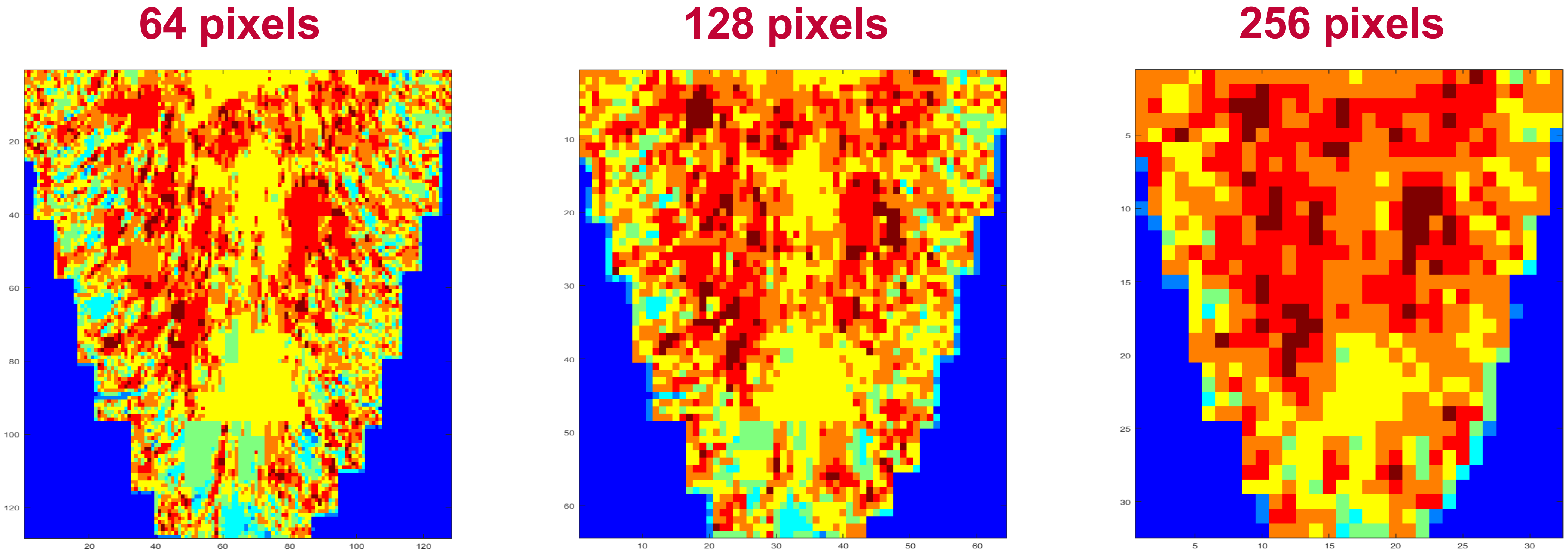
Each color represents a different grain orientation

Weld Photograph

Weld Microstructure Downsampling

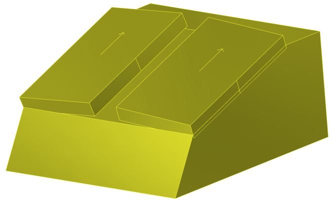
- What grain resolution is required to simulate the weld microstructure with sufficient accuracy while balancing simulation runtime?
- To test this, a quadtree decomposition was implemented to downsample the microstructure to varying levels of resolution: 256 pixels (≈ 40% λ at 2 MHz), 128 pixels (≈ 20% λ), and 64 pixels (64 pixels ≈ 10% λ).
- To further reduce complexity, Euler angles were grouped into discrete bins.
- Several weld cartograms of varying resolution were generated to test simulation sensitivity to weld microstructure parameters.

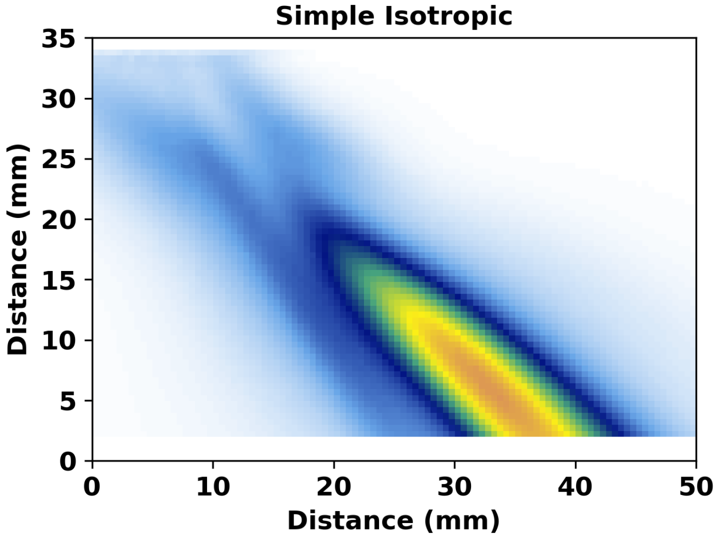


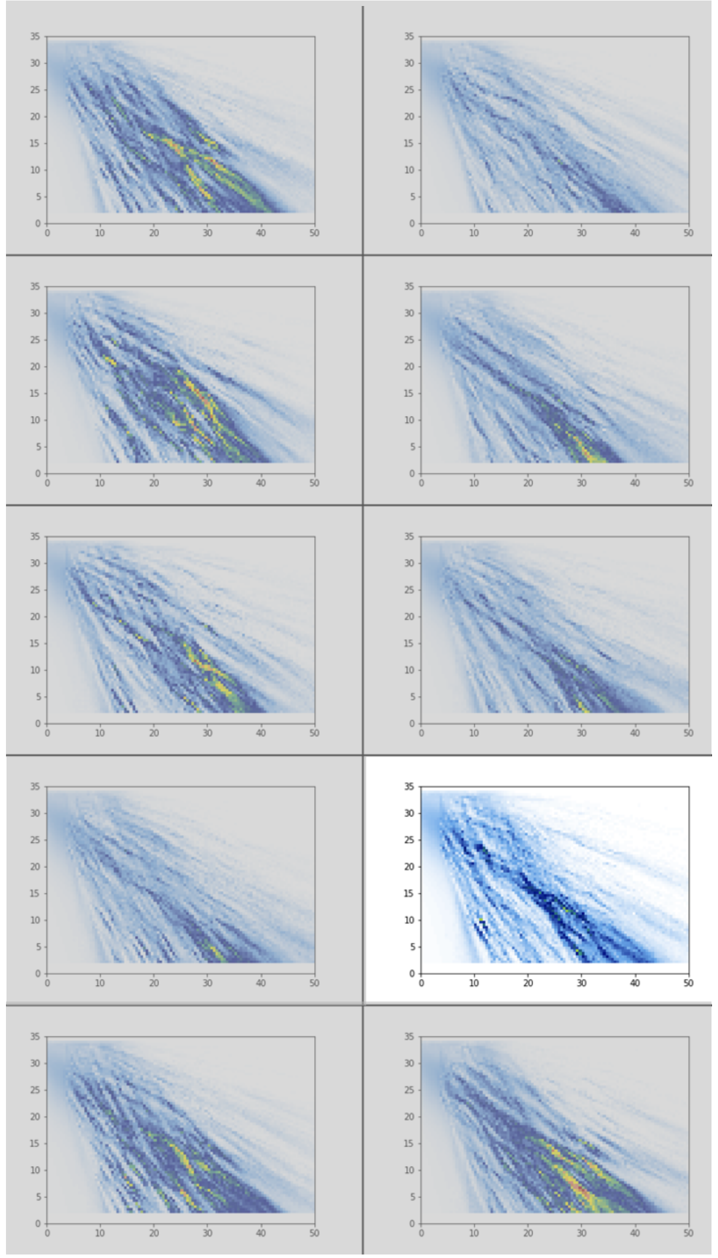


Through-weld Beam Simulations – TRL Probe

- Dual-element, 2 MHz TRL probe at 45°, 36 mm focal depth.
- To test beam variability with different grain orientations, 10 simulations were run with the same geometry but different Euler angles.
- Results were compared to the overall average by using image similarity metrics to determine the “most typical” case.
- The most typical case was then used in future simulations to represent a “typical” austenitic weld.







Average of 10 Simulations

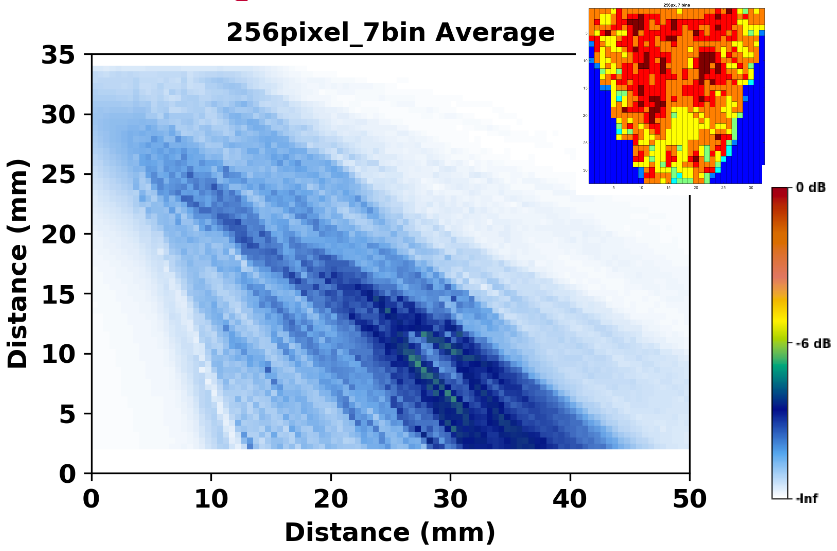
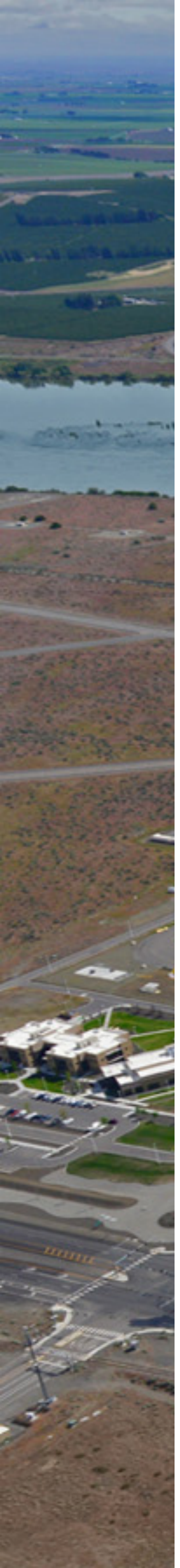


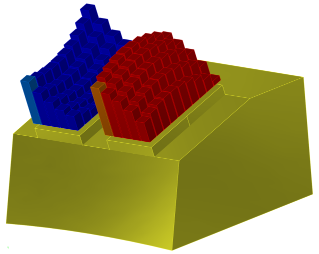
Image Similarity Metrics Compared to Average

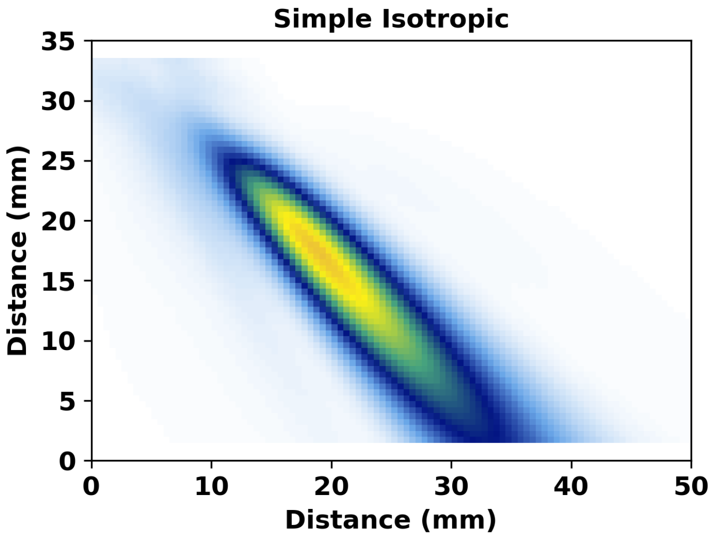
Case	ssim	mse	corrcoef
Average	1.000	0.000	1.000
isotropic	0.488	38.25	0.907
01	0.446	12.35	0.829
02	0.499	14.25	0.897
03	0.505	20.87	0.921
04	0.445	11.52	0.854
05	0.430	26.27	0.846
06	0.463	11.55	0.843
07	0.429	14.76	0.836
08	0.511	7.61	0.888
09	0.510	9.12	0.870
10	0.505	19.65	0.883

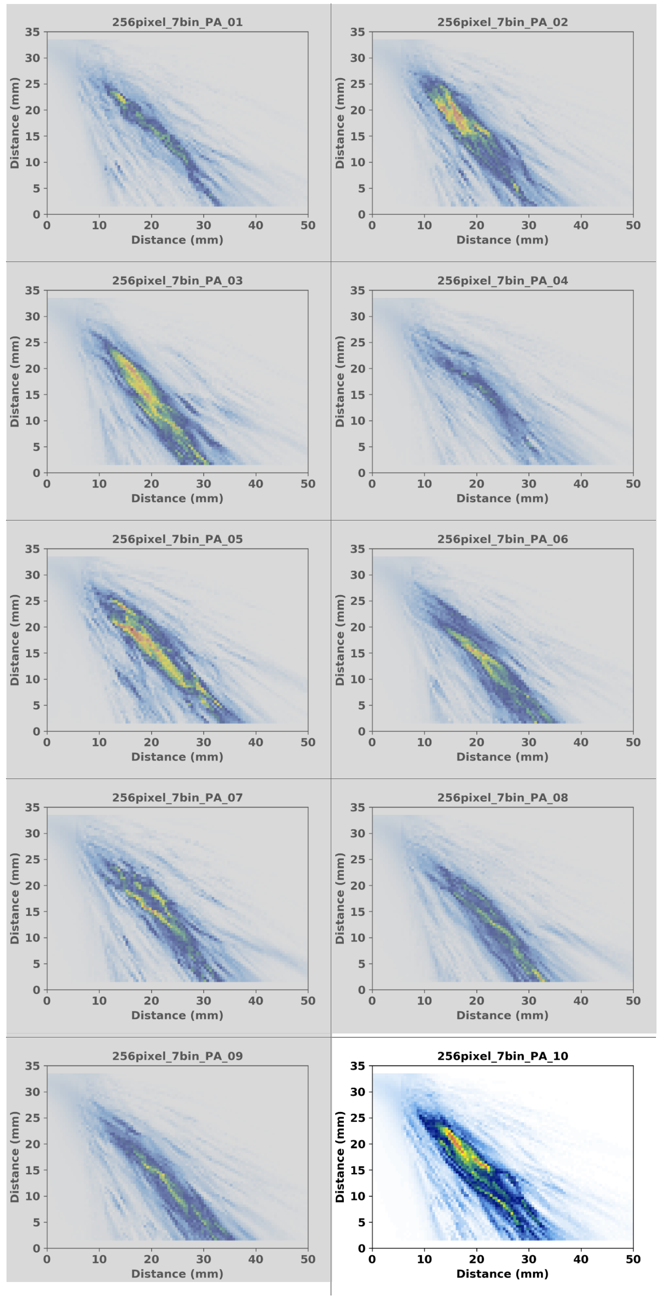


Through-weld Beam Simulations – PA Probe

- Dual-element, 2 MHz PA probe at 45°, 24 mm focal depth.
- 10 simulations, each with a set of 7 Euler angles.
- Results were quantitatively compared to the overall average to determine a nominal case.







Average of 10 Simulations

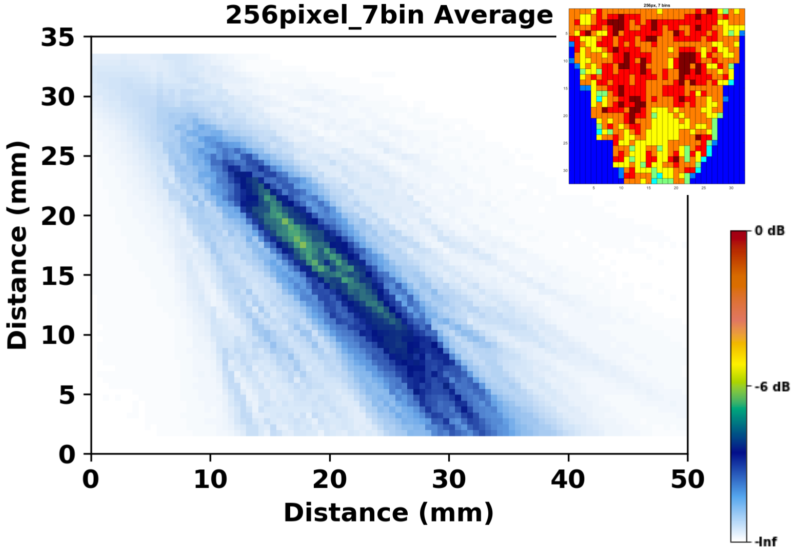
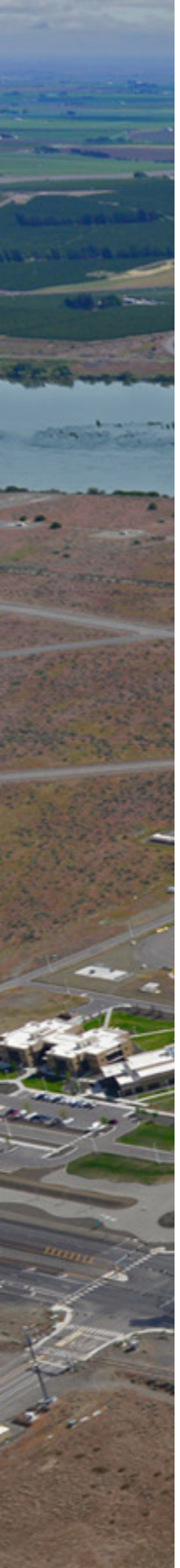


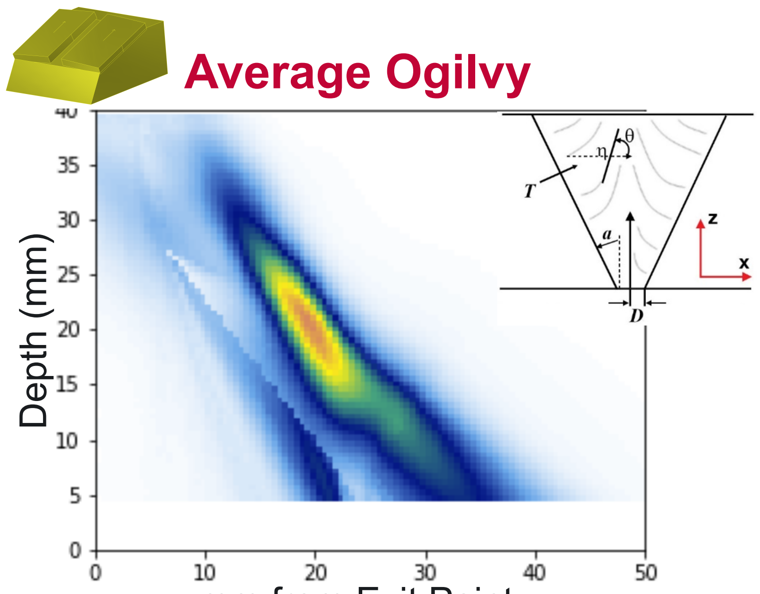
Image Similarity Metrics Compared to Average

Case	ssim	mse	corrcoef
Average	1.000	0.00	1.000
isotropic	0.648	3.24	0.967
01	0.588	1.93	0.871
02	0.639	2.35	0.920
03	0.592	3.54	0.890
04	0.613	1.90	0.892
05	0.543	3.37	0.919
06	0.618	1.34	0.932
07	0.606	1.53	0.917
08	0.642	1.20	0.923
09	0.638	1.02	0.934
10	0.658	1.62	0.943

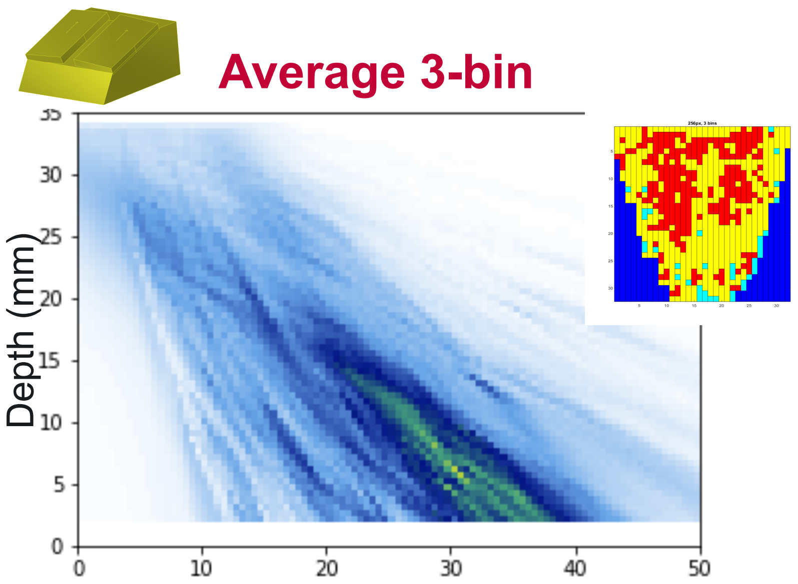


Comparing Beam Simulation Results

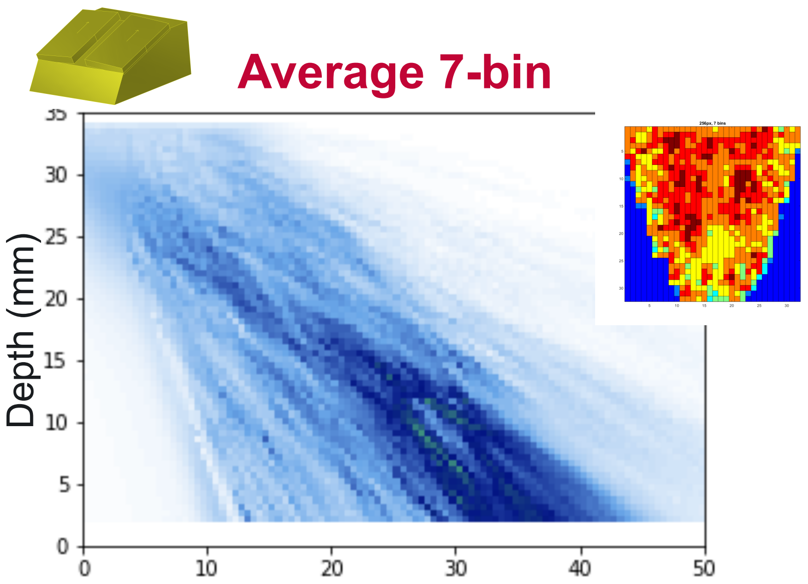
- Ogilvy models show little beam scatter and good beam formation.
- Overall, the 3-bin and 7-bin results showed significant beam scatter and poor beam formation.
- The 7-bin results show less simulation-to-simulation variation in the beam pattern, which means the beam is being scattered more across the scan region.
- The 3-bin results show better beam formation, which means less scatter and more beam redirection.



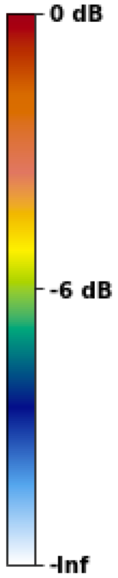
Average of 8 Simulations



Average of 10 Simulations

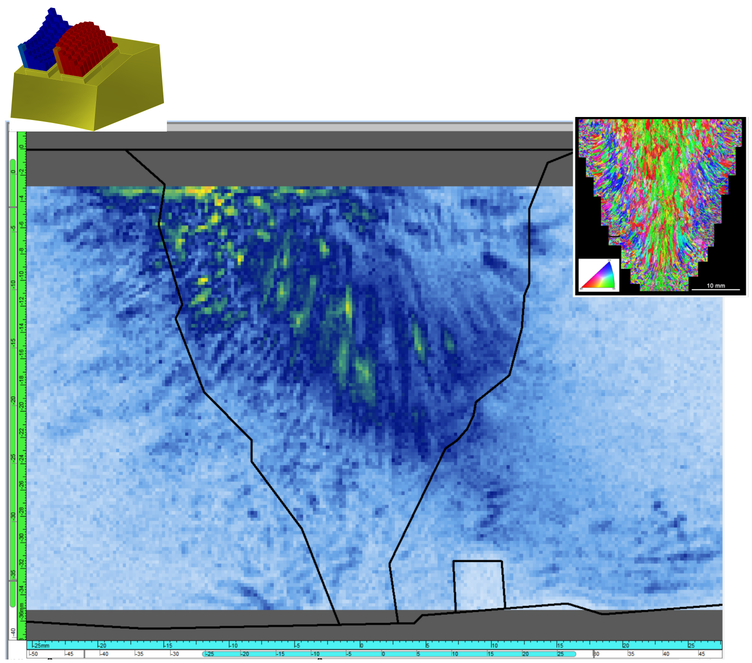


Average of 10 Simulations

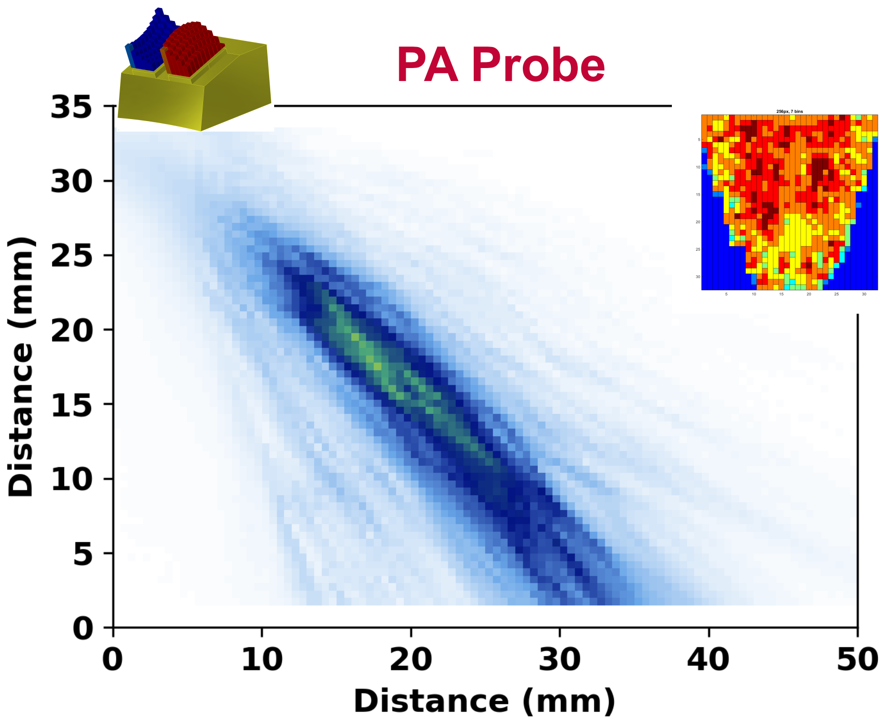


Comparing Beam Simulation Results

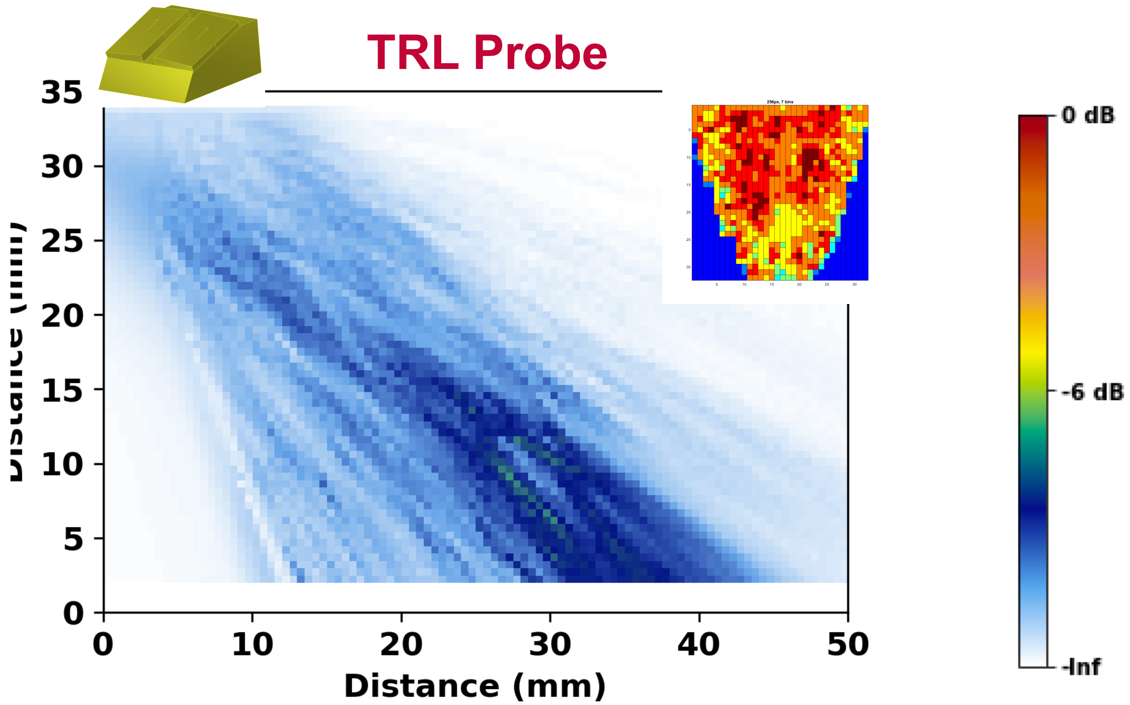
- The simulations show unrealistically high levels of beam formation and sound penetration through the weld.
- The empirical beam shows almost no far-side backwall insonification, little insonification of the inner 1/3 volume, and much more near-OD scatter.
- Model shortcomings include:
  - Lack of attenuation
  - Grain sizes too large
  - Limited number of Euler angles
  - No mode conversions or interface interactions



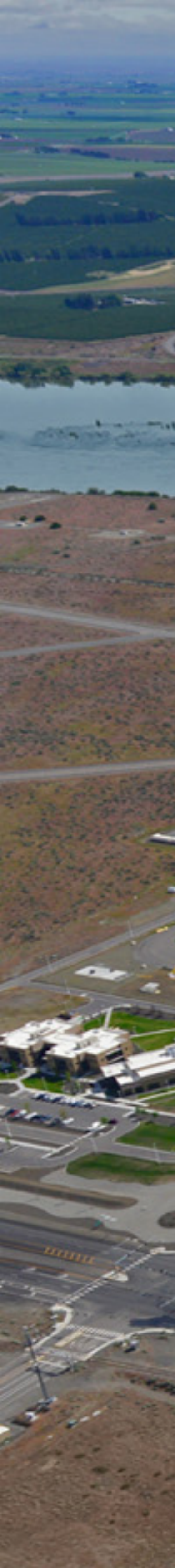
Empirical Sscan, 45°



Average of 10 Simulations

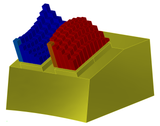


Average of 10 Simulations



Attenuation

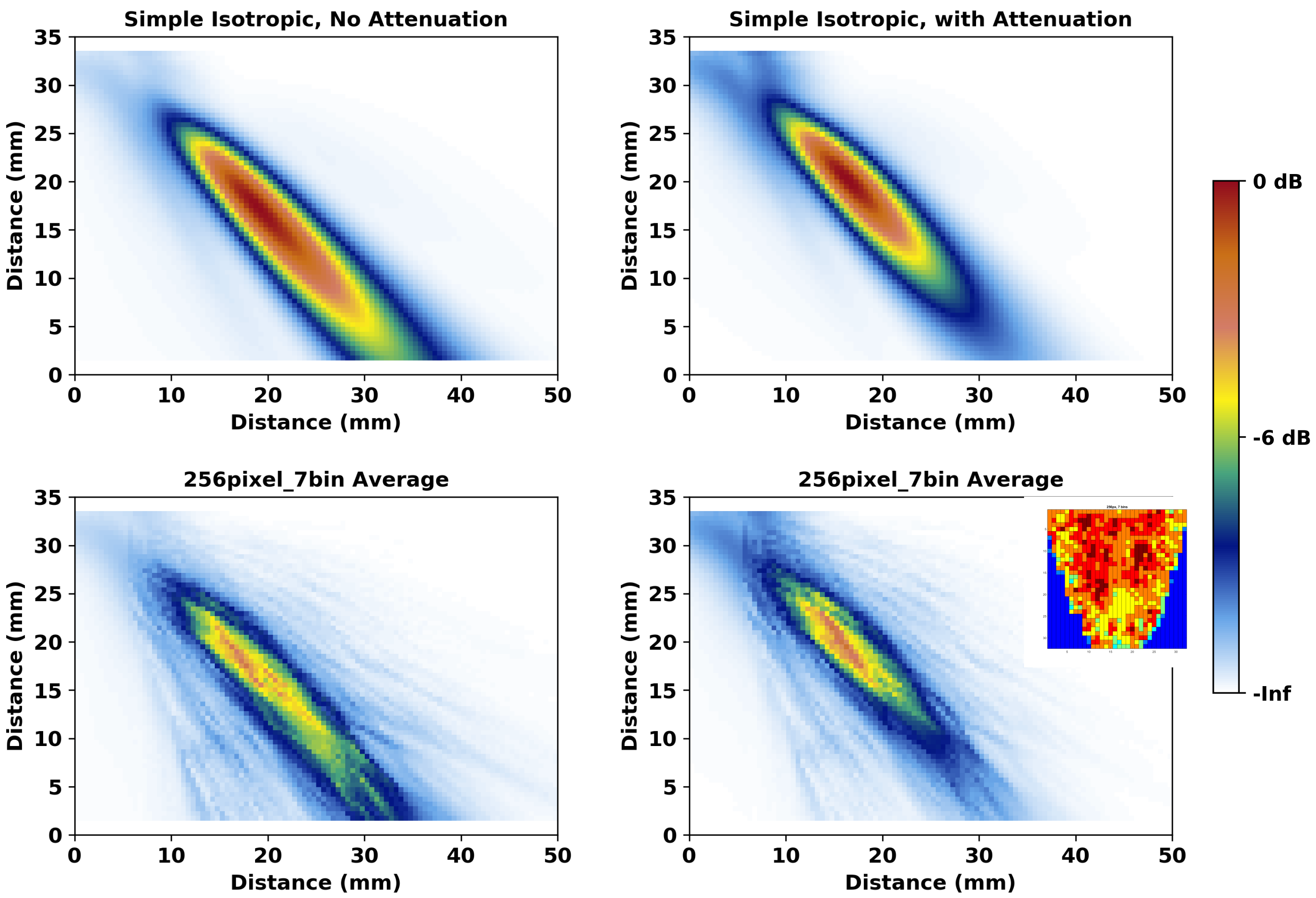
- Adding attenuation to the models helps bring results more in line with empirical data
- 2 MHz PA probe, WSS-WSS Specimen.



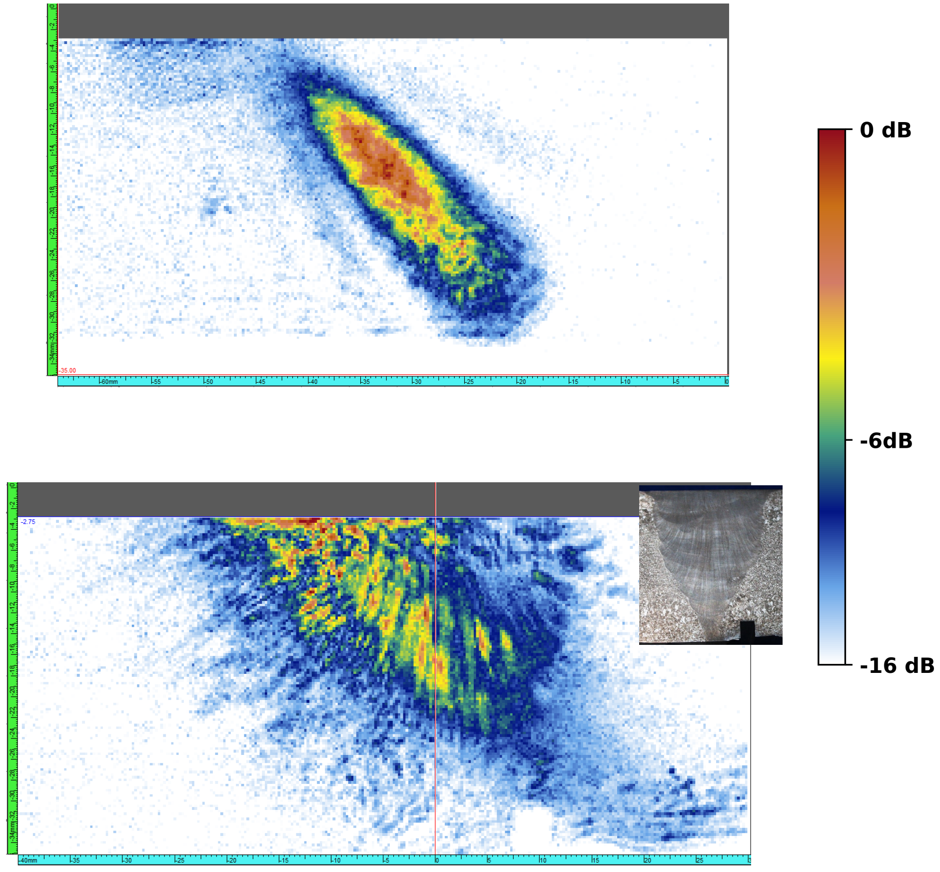
No Attenuation | **0.2 dB/mm Attenuation**

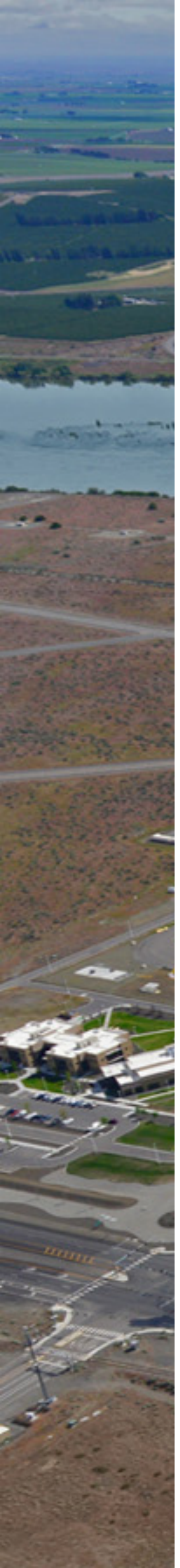
Isotropic

Through-weld



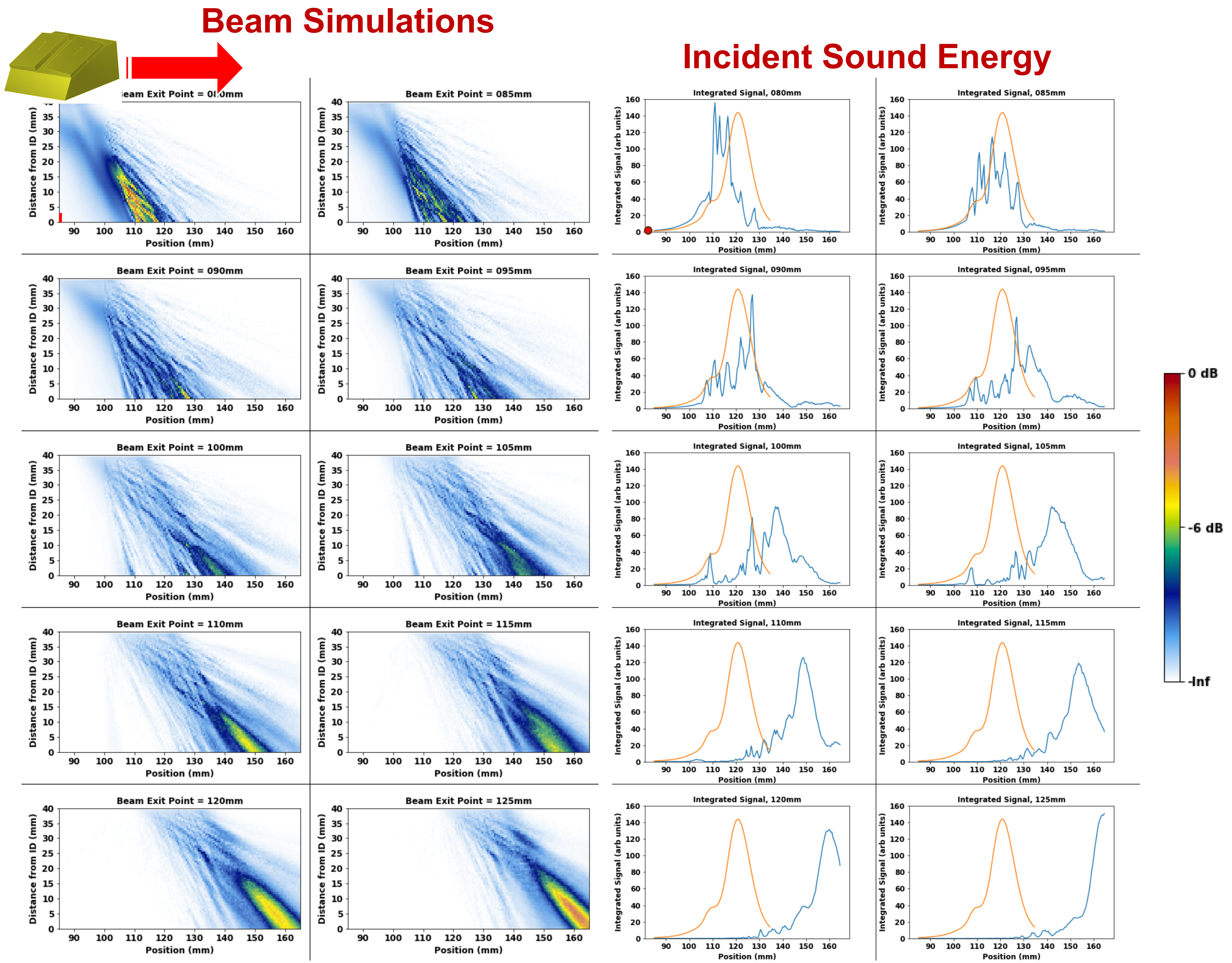
Beam Maps

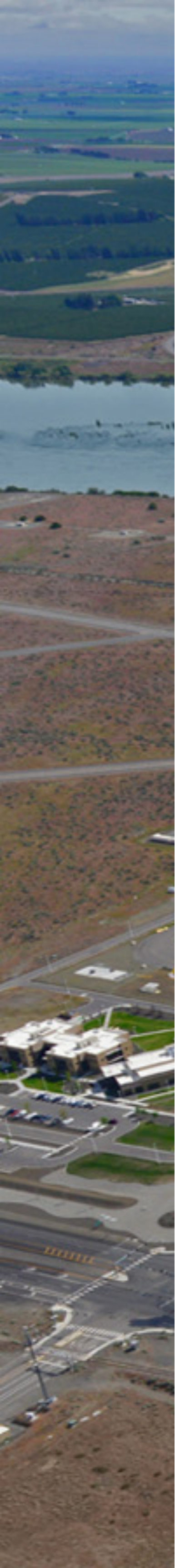




Beam Simulations to Predict Flaw Response

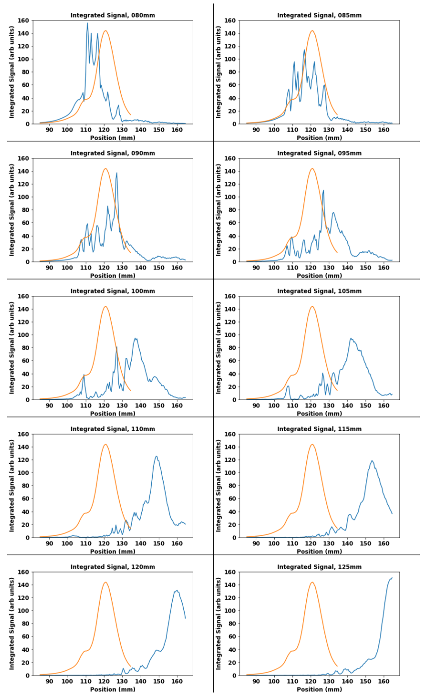
- Beam simulations of a 2 MHz TRL probe scanning across the weld with 5 mm steps
- Sound energy hitting a 3 mm flaw across the entire ID was measured to simulate a corner response
- Graphs of sound energy hitting the flaw were made for each probe position
- Blue lines show the weld simulations, orange lines show the isotropic case
- Local peaks in sound energy indicate localized beam focusing





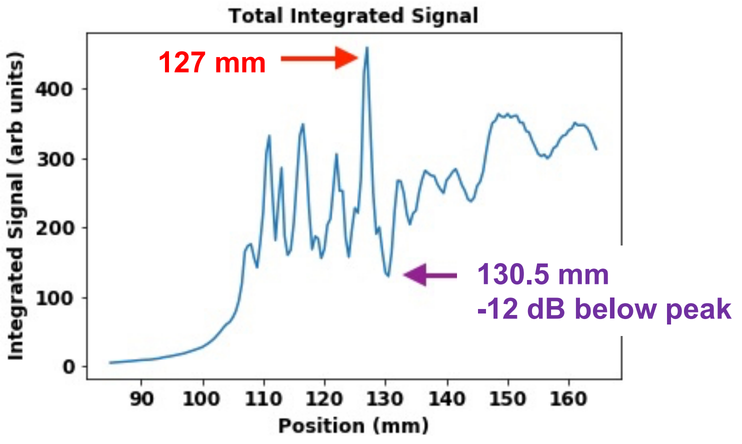
Beam Simulations vs Flaw Response Simulations

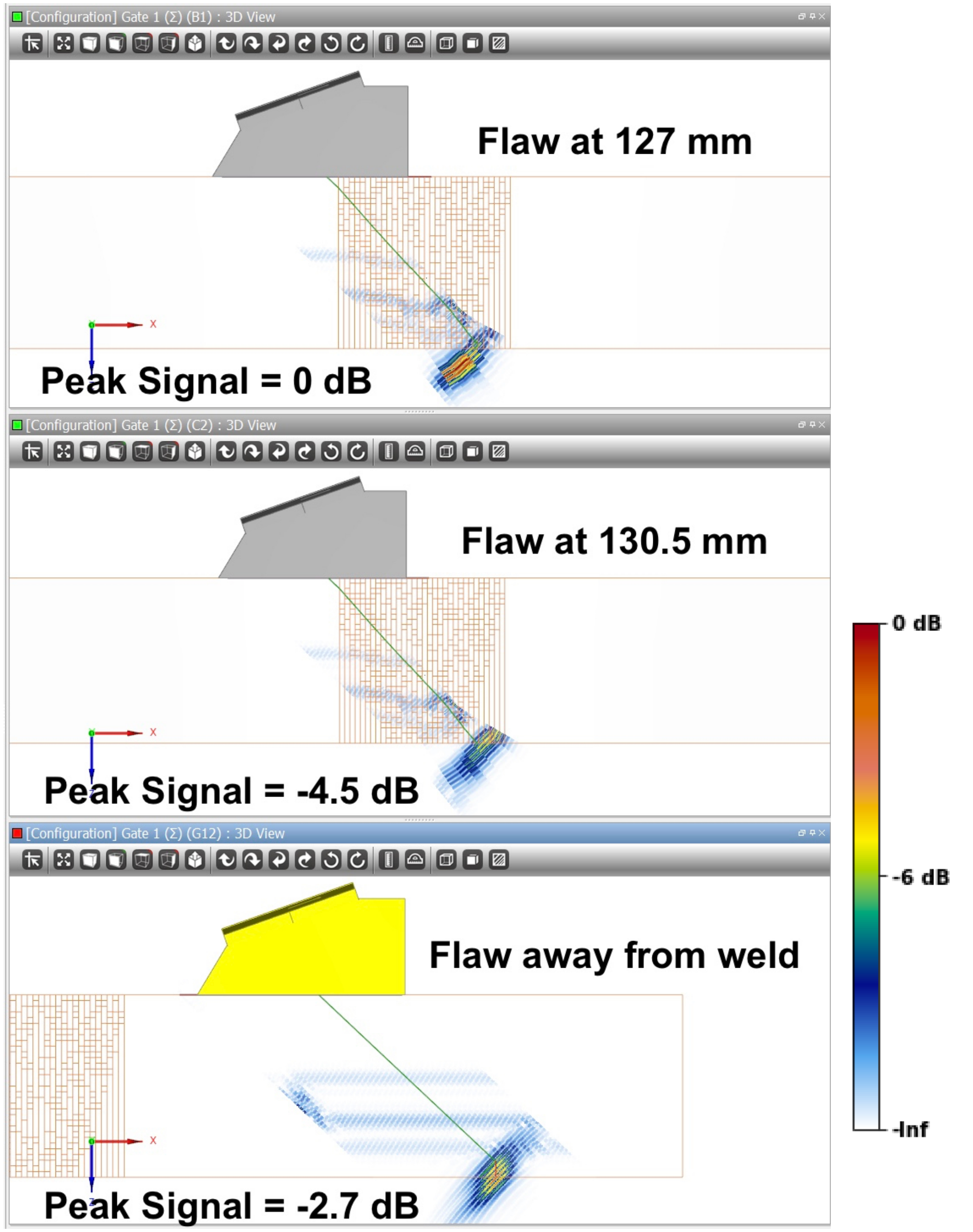
- All the blue lines were added to get a total sound incident on the ”flaw”.
- A local peak and trough were identified 3.5 mm from one another.
- Flaw response simulations were run with a 3 mm “flaw” at the two locations.
- Results show a higher flaw response at the peak position than at either the trough position or the control (isotropic) position.
- The flaw position can make a big difference in signal response based only on what the weld region is doing to the sound beam.



Add these up…

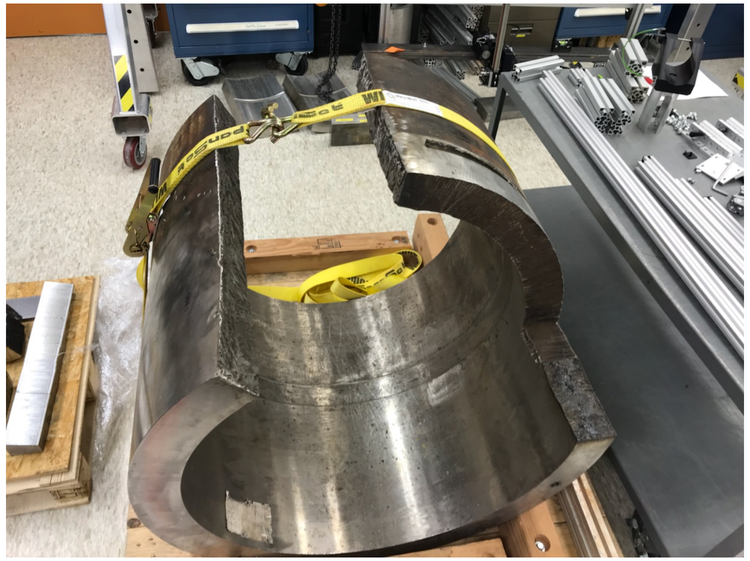
…to get this:





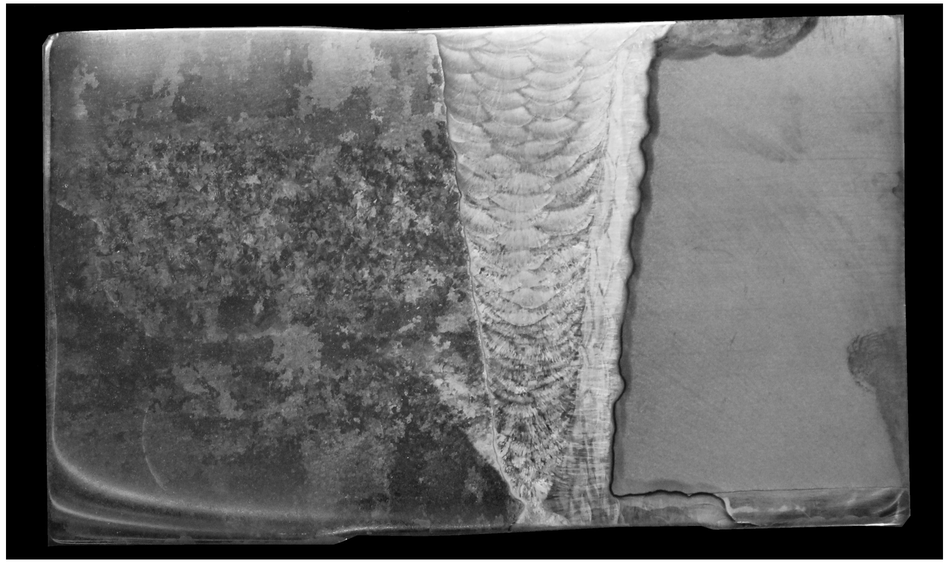
DMW Model

- Thick-wall CASS-CS DMW mockup
- A coarse-grain weld model was developed for initial simulations using a polished section.
- Substituted WSS for CASS to work around a limitation in CIVA for defining grains in the CASS side.
- 10 sets of Euler angles were randomly assigned to the different grains.

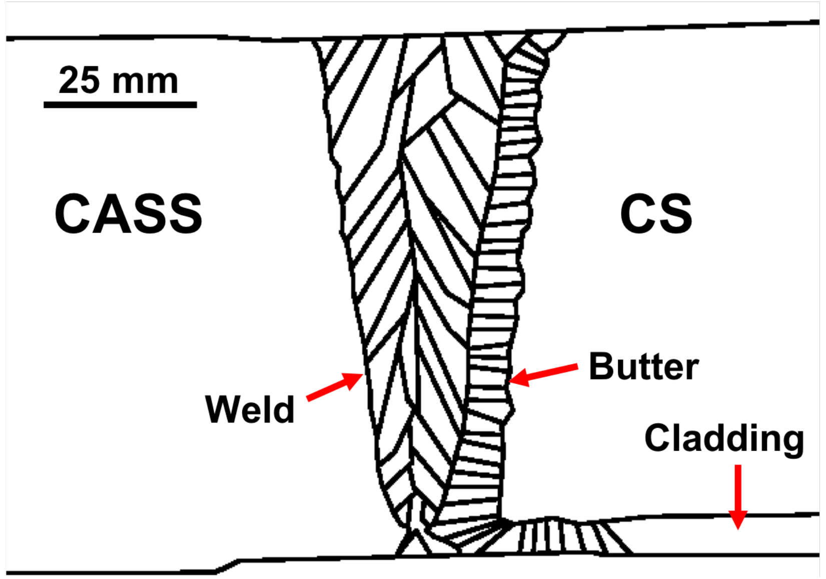


Thick-wall DMW mockup

See ML19255J814



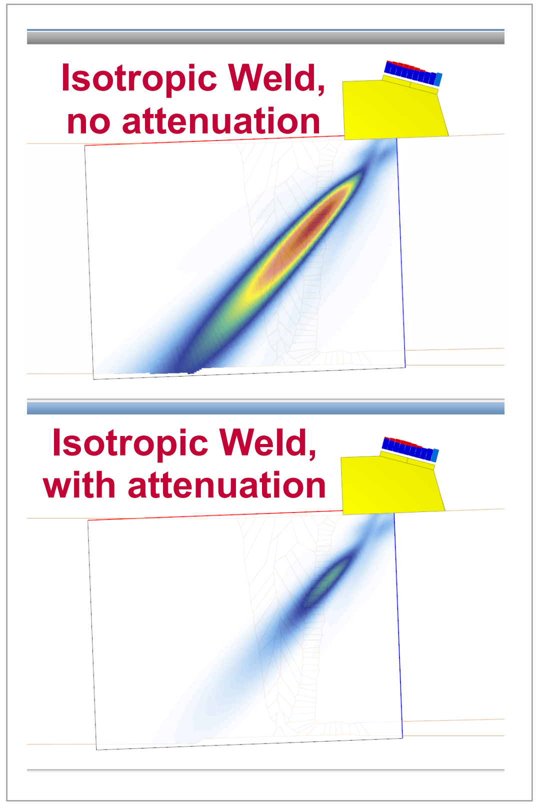
Polished and etched weld region

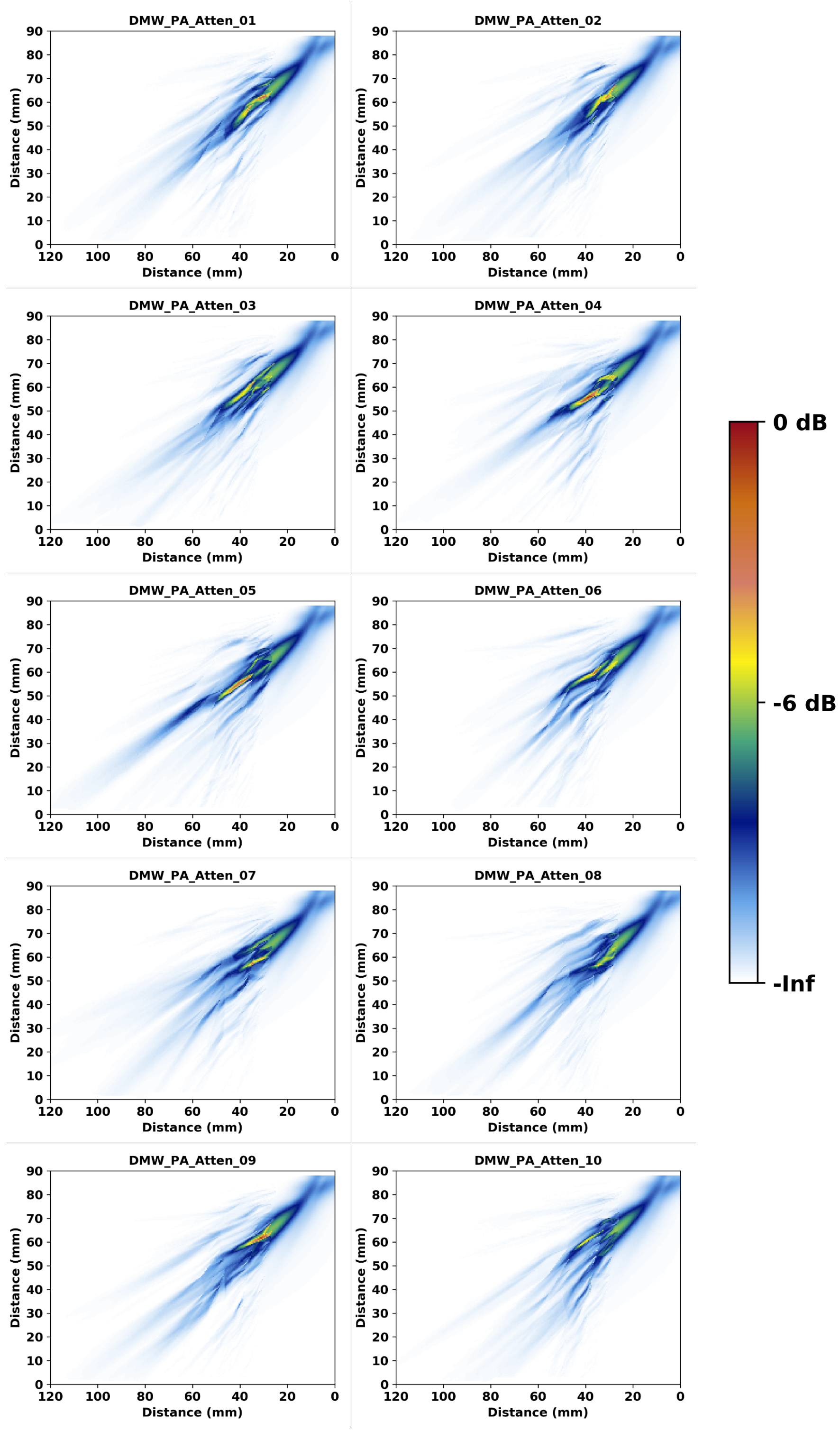


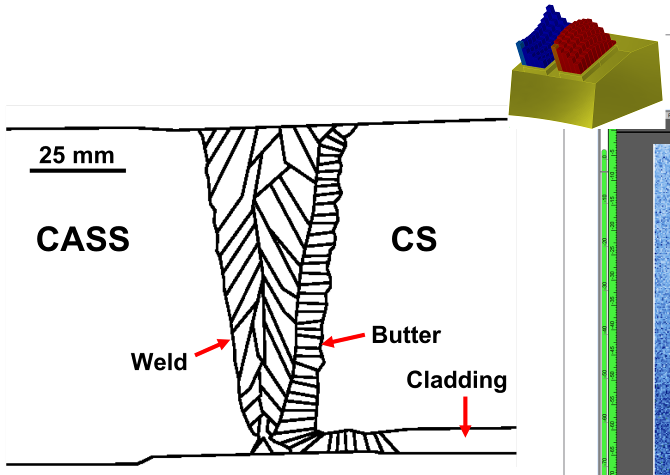
Sketch of weld region to define grain boundaries

DMW Simulation Results

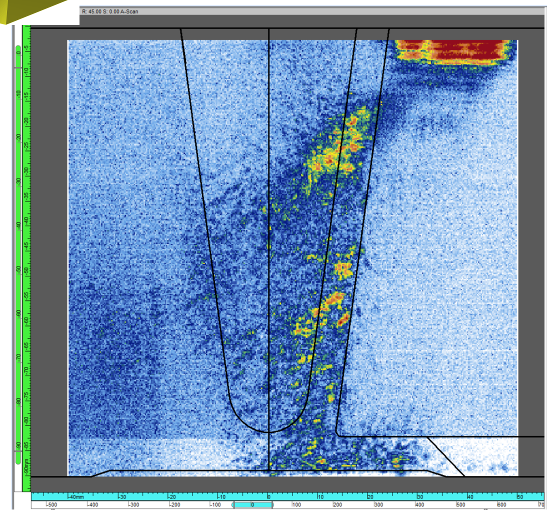
- 2 MHz PA probe with 84 mm focal depth and 0.1 dB/mm attenuation.
- Simulated scatter does not reflect beam maps.
- Stochastic and geometric scattering predominated in simulation results.
- The model grains are too large to provide realistic beam scatter.



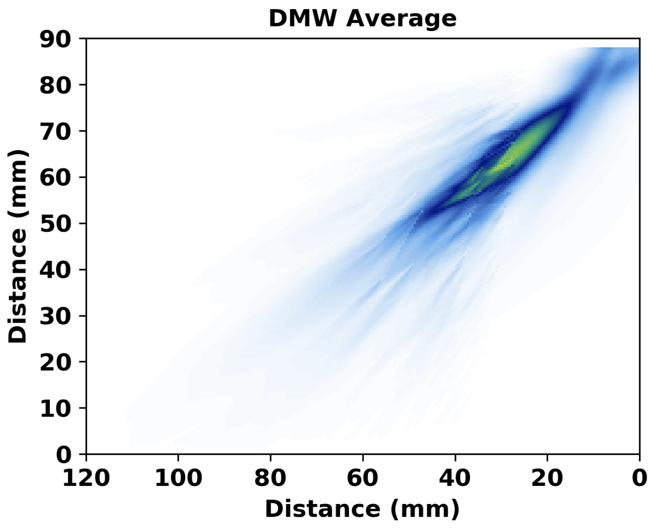




Empirical scan, 45°



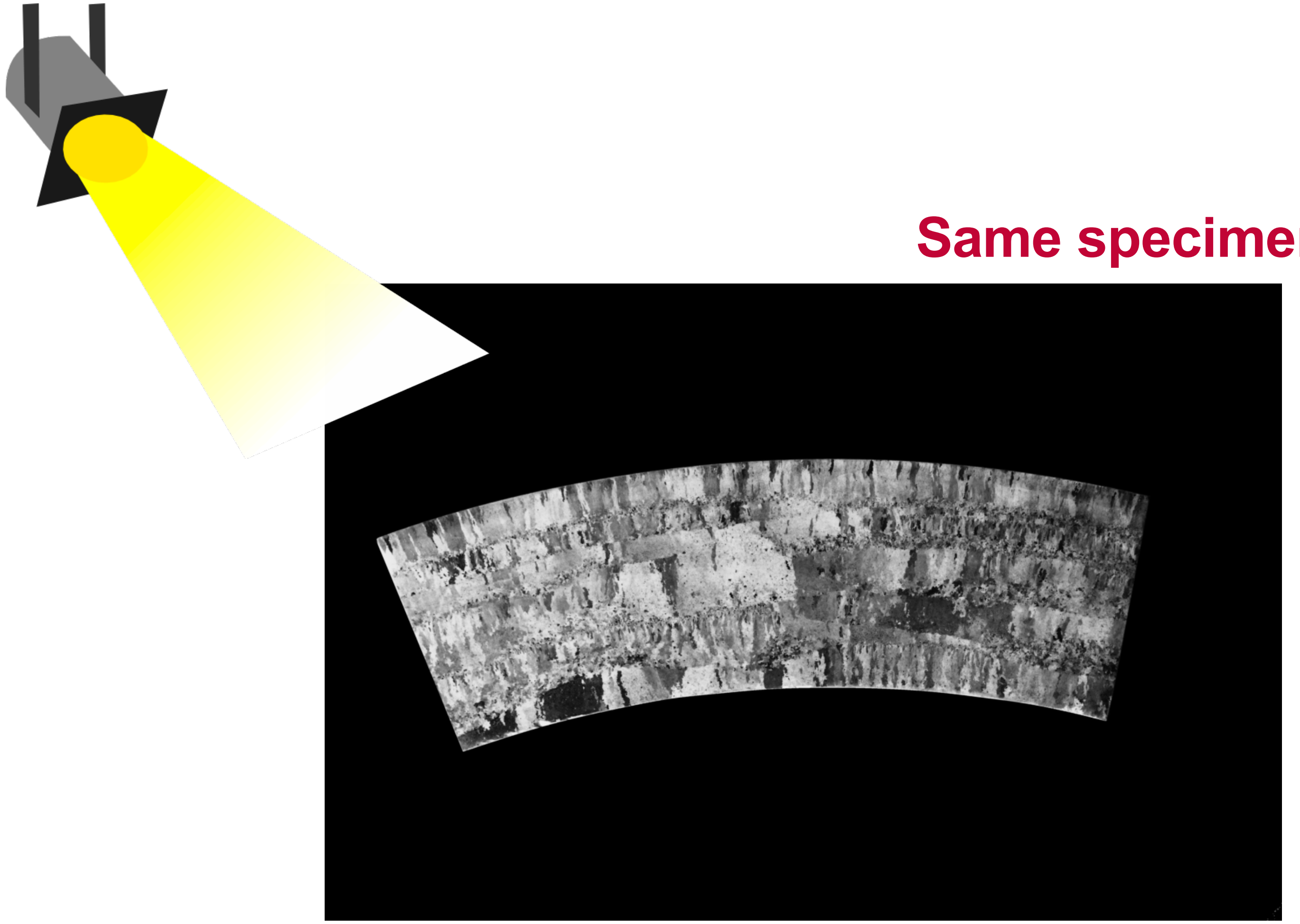
Average of 10 Simulations

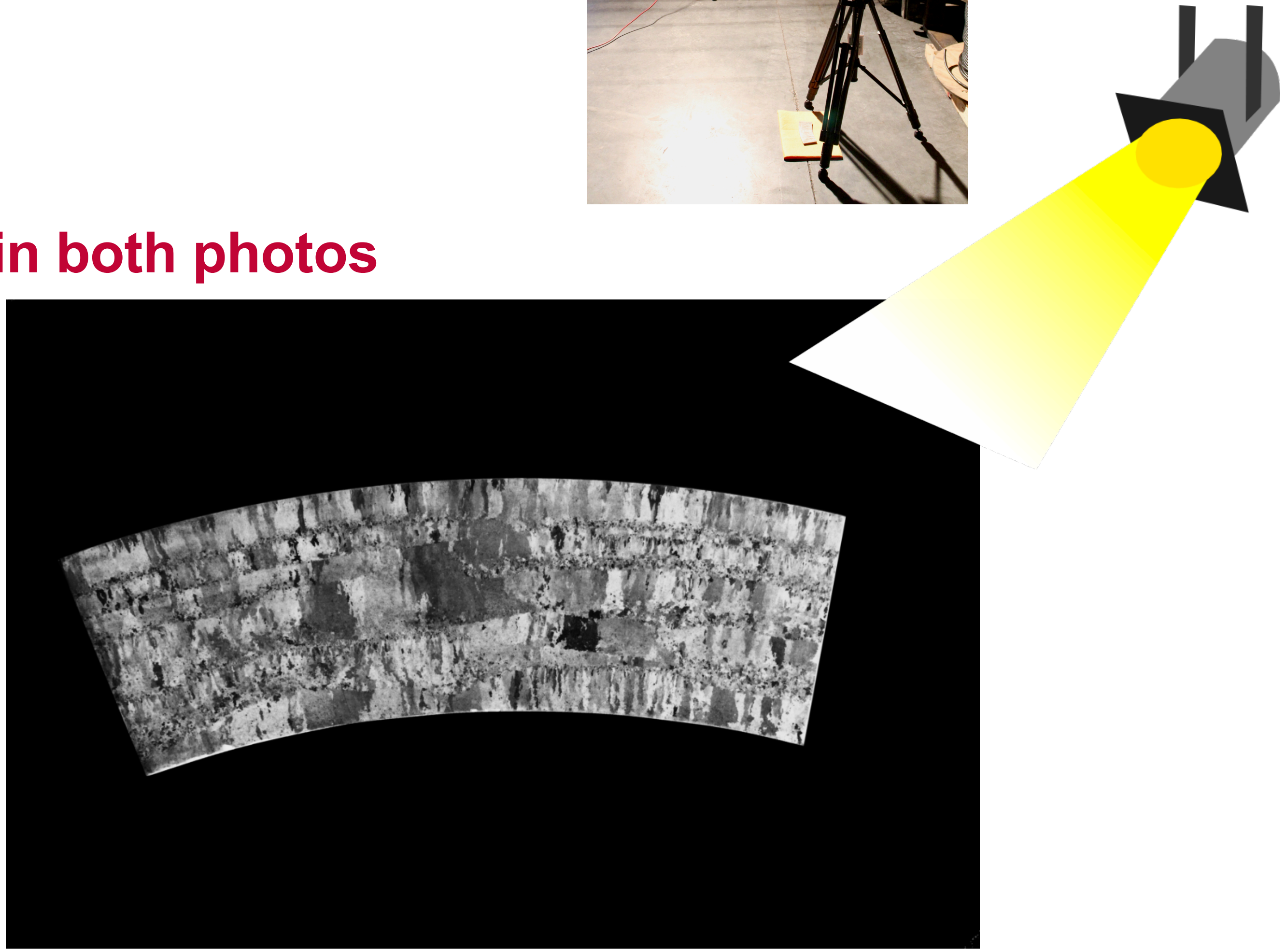


Simulations with Realistic Grain Boundaries

- Simulations in coarse-grained CASS materials require grain boundary definitions
- Photographs from multiple illumination angles capture the grain boundaries of polished and etched sections
- Appearance of grain reflections depends on incident light angle

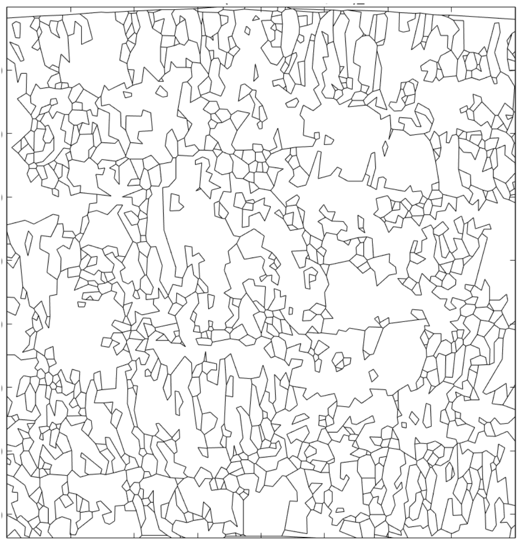
Same specimen in both photos



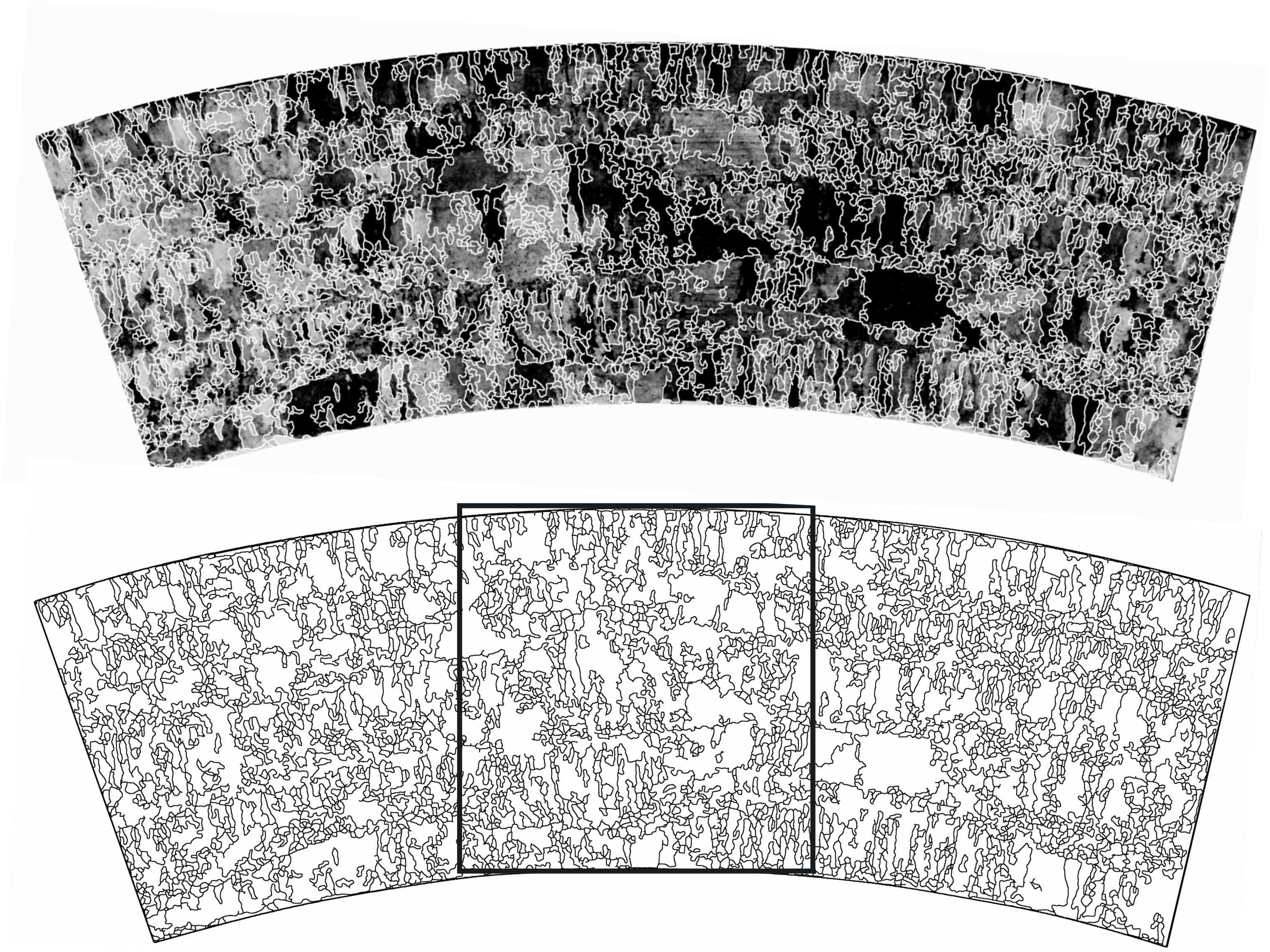


Identify and Outline the Grain Boundaries

- Photos were processed and filtered to highlight and outline grain boundaries.
- Grains smaller than ~1/10 the sound wavelength at 1 MHz were removed.
- Curved grain boundary outlines were made into straight line segments to generate a CAD file.
- The CAD file can be imported into CIVA.



Subsection of specimen with straight line segments used in simulations

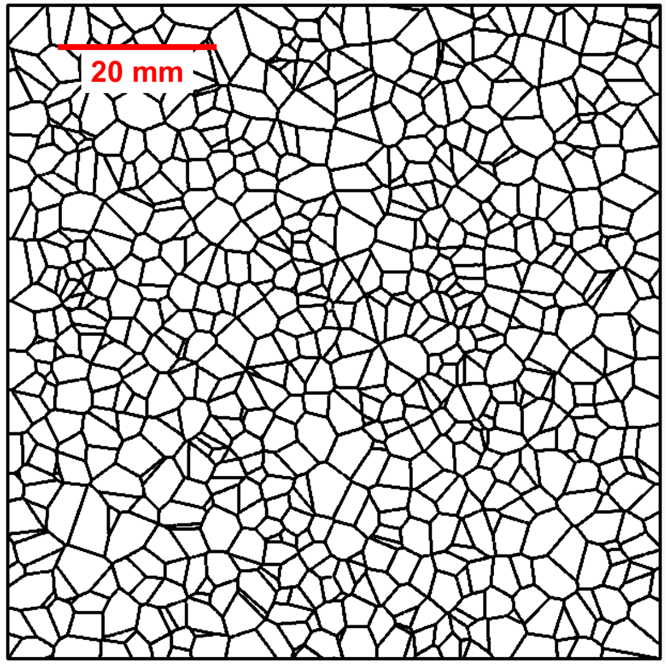


Average size: ≈7 mm^2 (0.01 in^2)
Median size: ≈2 mm^2 (0.003 in^2)

Realistic Geometries vs CIVA-generated Models

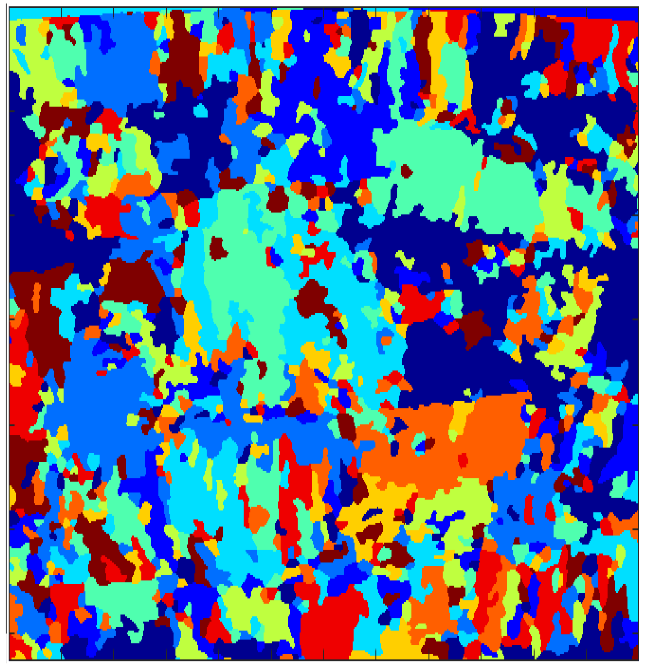
- CIVA can automatically generate random Voronoi regions to imitate coarse-grained geometries. To compare simulation results, the number of Voronoi regions and course-grained regions was the same.
- For the coarse-grained model, 10 Euler angles were assigned at random, and stiffness matrix values were taken from the literature.
- CIVA does not assign Euler angles to the Voronoi regions; instead it assigns different propagation velocities.

Voronoi, Equiaxed



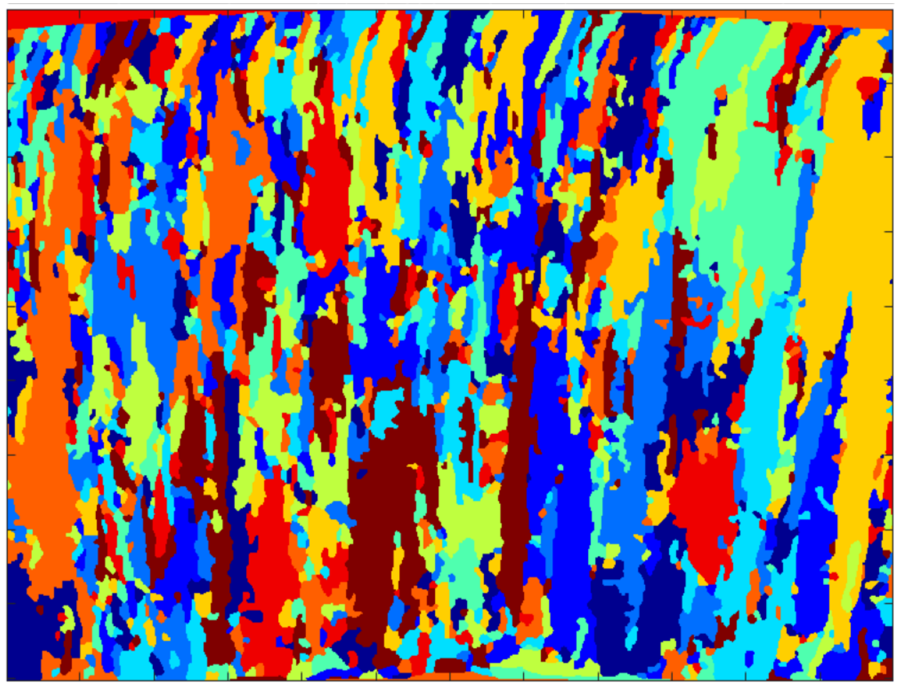
Voronoi:
- **810 regions**
- **7 mm^2 avg.**
- **26 mm^2 max.**

Coarse-grain Equiaxed



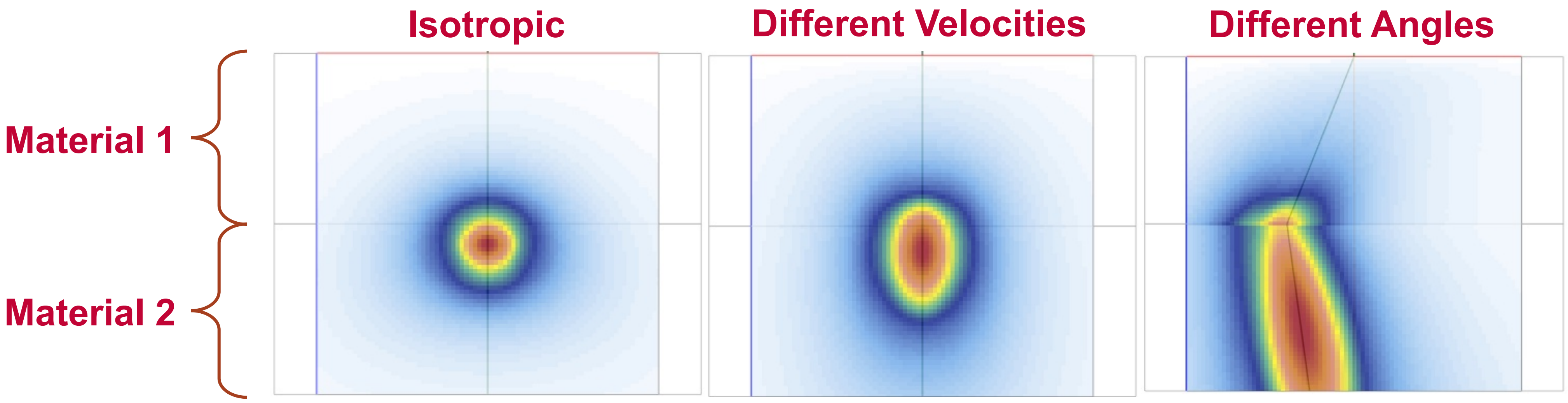
Coarse grain:
- **810 regions**
- **7 mm^2 avg.**
- **430 mm^2 max.**

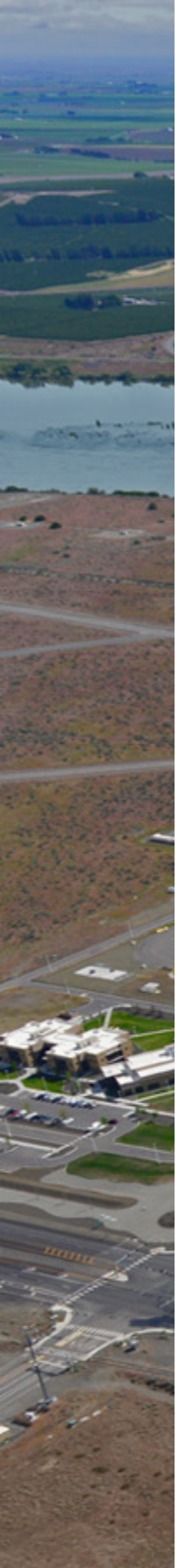
Columnar



The Effect of Euler Angles on Beam Propagation

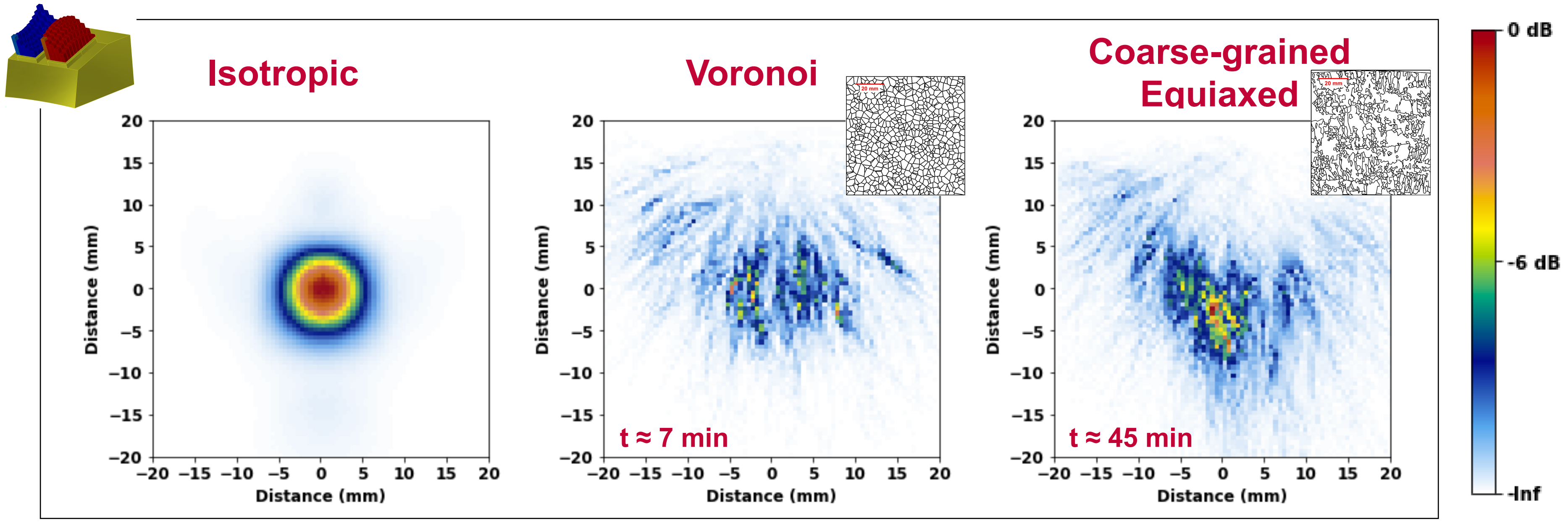
- CIVA uses velocity differences in the Voronoi model to simulate grain-to-grain changes in sound propagation.
- In the coarse-grained model (and real specimens), Euler angles affect the direction of preferred sound propagation by changing the crystalline orientation, but not the sound velocity.
- With hundreds of grains, the problem is essentially reduced to a “random walk” diffusion. Does the distinction still matter?

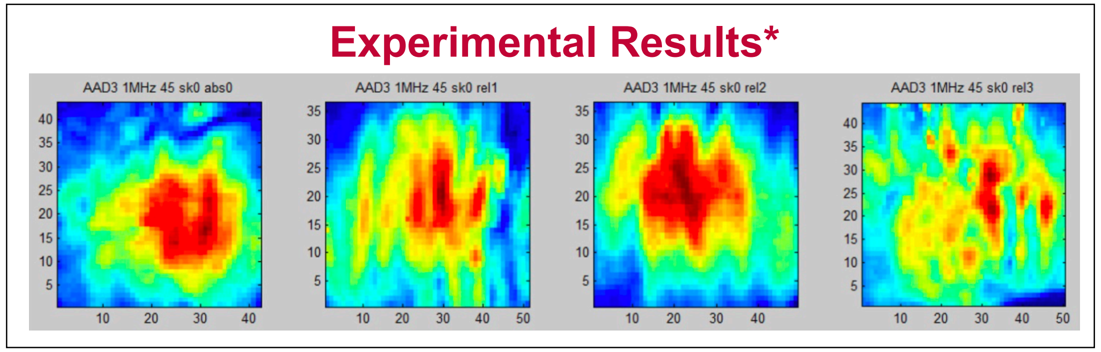




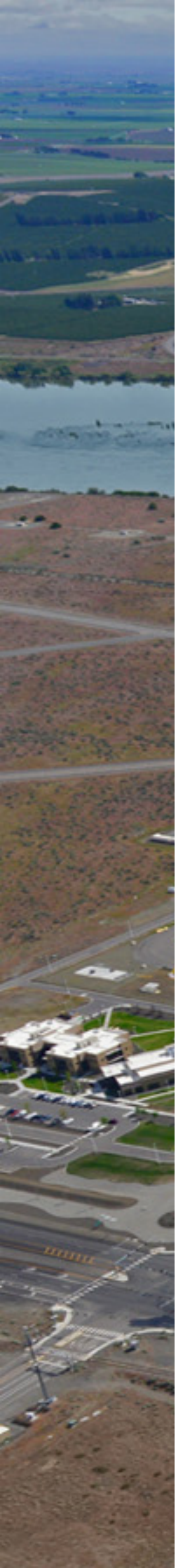
Coarse-grained Beam Simulation Results

- CIVA simulations were run with a 1 MHz phased-array probe and a 45° refraction angle. The beam was focused in the simulation plane to be consistent with experimental setup.
- Results show significant beam scatter in both coarse-grained scenarios.
- Beam scatter in the Voronoi case is qualitatively similar to that in the coarse-grain case.
- Simulation results are consistent with experimental results on the same specimen.





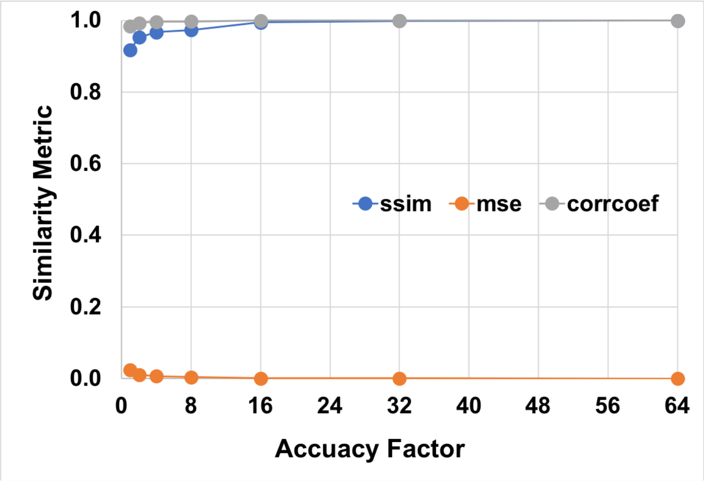
*From Crawford, et al., "Phased Array Ultrasonic Field Mapping in Cast Austenitic Stainless Steel." ML14155A165. 2014. Figure B.46.



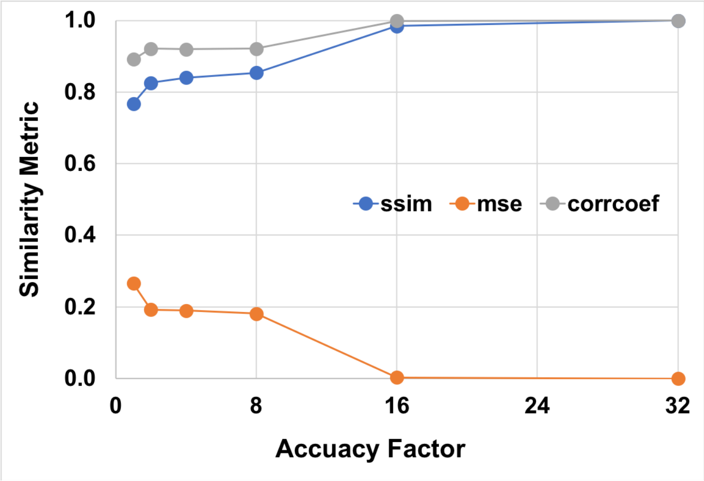
CIVA Accuracy Factor

- Image similarity metrics can help determine the CIVA accuracy factor needed for optimal simulations.
- The accuracy factor determines the level of meshing and has a strong affect on simulation time.
- Simulations were compared to the “ideal” case – the one with the highest accuracy factor.
- Voronoi regions need a relatively low accuracy factor. Realistic grains need a high accuracy factor, which translates to longer simulation times (many hours).

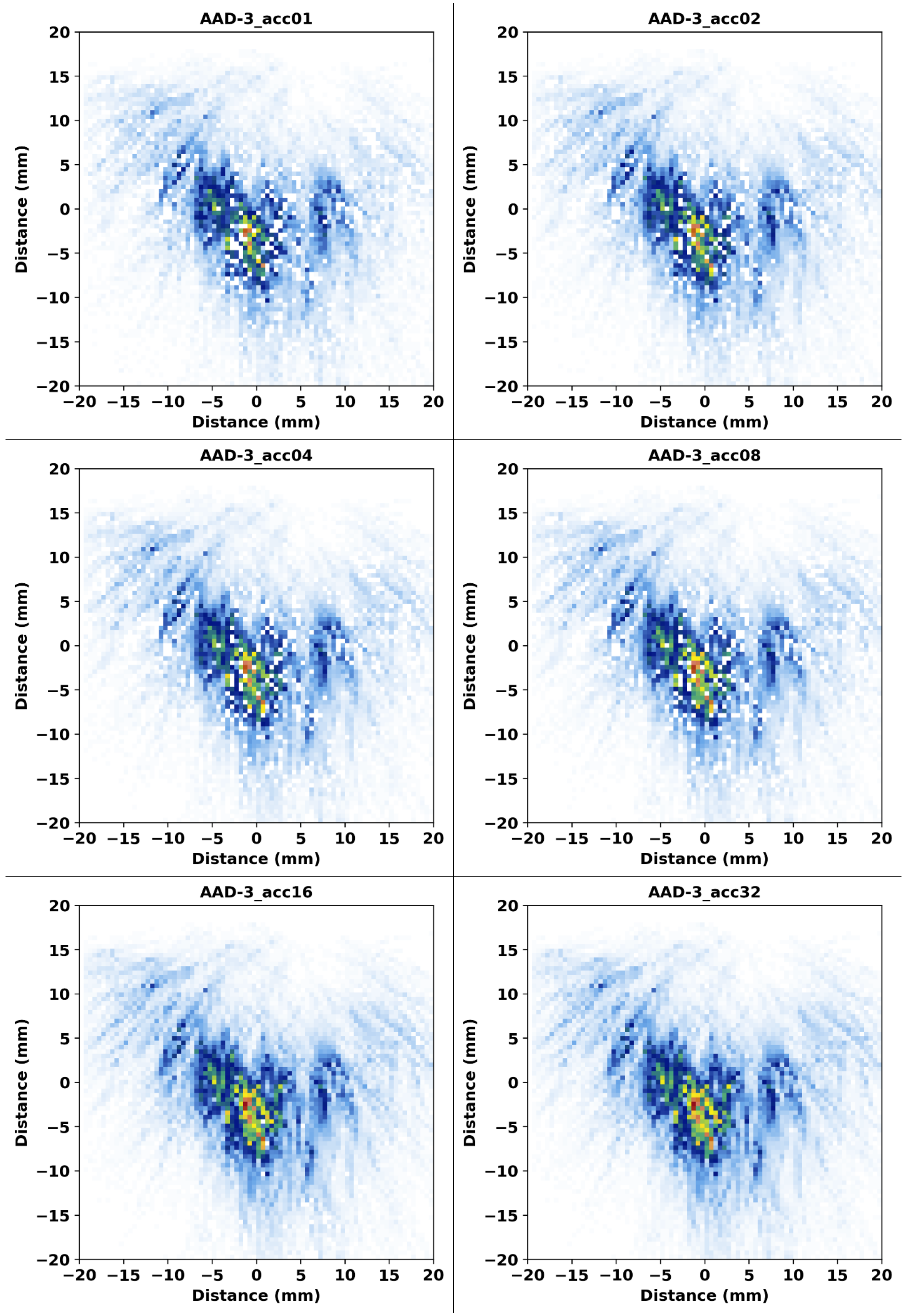
Voronoi



CASS

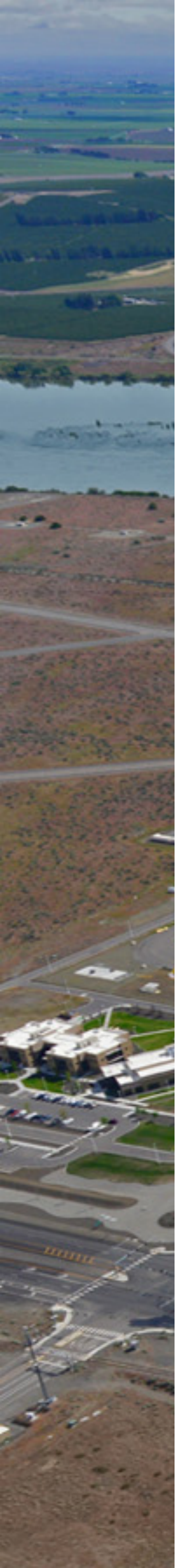


CASS



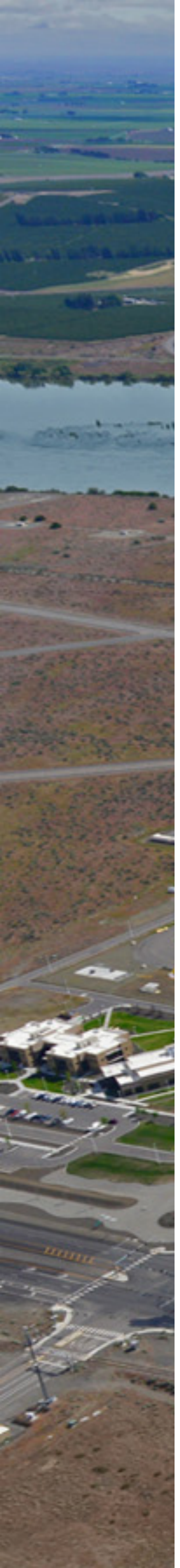
Conclusions

- Model approximations and limitations should be well understood prior to estimating detection capability. Realistic value ranges should be used with metamodels, and results should be considered critically.
- Empirical beam maps suggest that idealized weld geometries (e.g., Ogilvy) do not realistically represent beam scatter and beam formation through weld microstructure.
- Realistic weld geometries and microstructures can be created and loaded into CIVA. However, CIVA struggles to handle specimen definitions that have a large number of interface boundaries.
- Simulated beam profiles through realistic welds are qualitatively in agreement with experiments, showing scatter, reduced beam formation, and poor penetration through the weld. However, experimental scans show more scatter, less beam formation, and less sound penetration.
- It is unclear how accurately the weld properties need to be defined to minimize simulation uncertainty.



Conclusions (continued)

- Attenuation in models is needed for simulations to better agree with experiment.
- Simulated flaw responses through welds are challenged by long computation times and uncertainties in weld properties. It is even more time consuming to include specimen frontwall/backwall/interface interactions, mode conversions, and noise, but it may be necessary to enhance realism.
- Simulations with low computational effort may be limited in their ability to estimate true flaw detection capability in the vicinity of welds or specimen geometry.
- Beam simulations can be predictive of flaw response, but they should not be used as surrogates for flaw response simulations.
- Voronoi-generated coarse-grained geometries may be a suitable and efficient representation of beam scatter through bulk CASS material, although there are limitations to CIVA's ability to implement them.
- Modeling provides a valuable tool for predicting potential beam coverage and flaw detection, but results should be validated with empirical studies when possible.



Ongoing Research: Modeling & Simulation

- Integrate “true-state” austenitic weld microstructure information into simulations at different levels of detail.
  - At what resolution do results converge?
  - What is the simplest geometry that will give sufficiently realistic results?
- Establish the practical limitations of running beam and flaw response simulations with realistic microstructures.
- Continue to investigate how well beam simulations using realistic microstructures agree with experimental beam maps made on the same geometries. Determine which simulation parameters should be adjusted to improve agreement with experimental scans.
- Increase flaw response simulation realism:
  - Include specimen frontwall, backwall, and interface reflections.
  - Add mode conversions and attenuation.
  - Mimic realistic cracks by adding flaw morphology.
  - Determine appropriate levels and types of noise.
- Evaluate the new release of CIVA 2020 and other relevant commercial software platforms, as needed.
- Determine a standard method to evaluate UT simulation results from commercial software platforms used by industry.

How You Can Help

- We need information on industry planned use cases for modeling and simulation.
  - Helps focus efforts, should result in better targeted guidance documents based on NRC and industry research in this area
- What are the relevant inspection geometries and materials?
- Provide feedback with your experiences with model development and running simulations.
  - Success stories
  - Frustrations or concerns

Contact:
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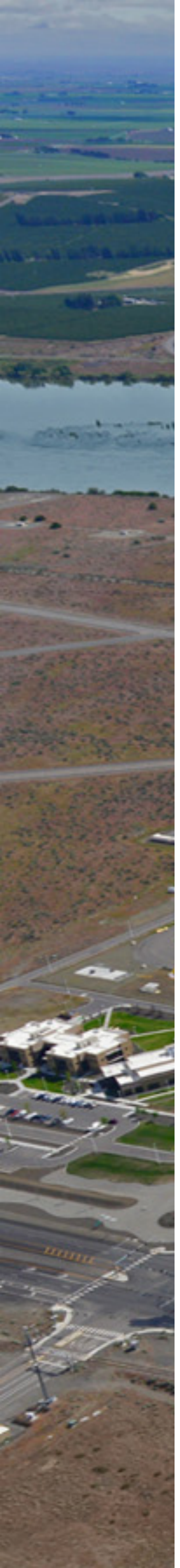

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Thank you