Ultrasonic beam mapping using Schlieren imaging

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NRC / Industry
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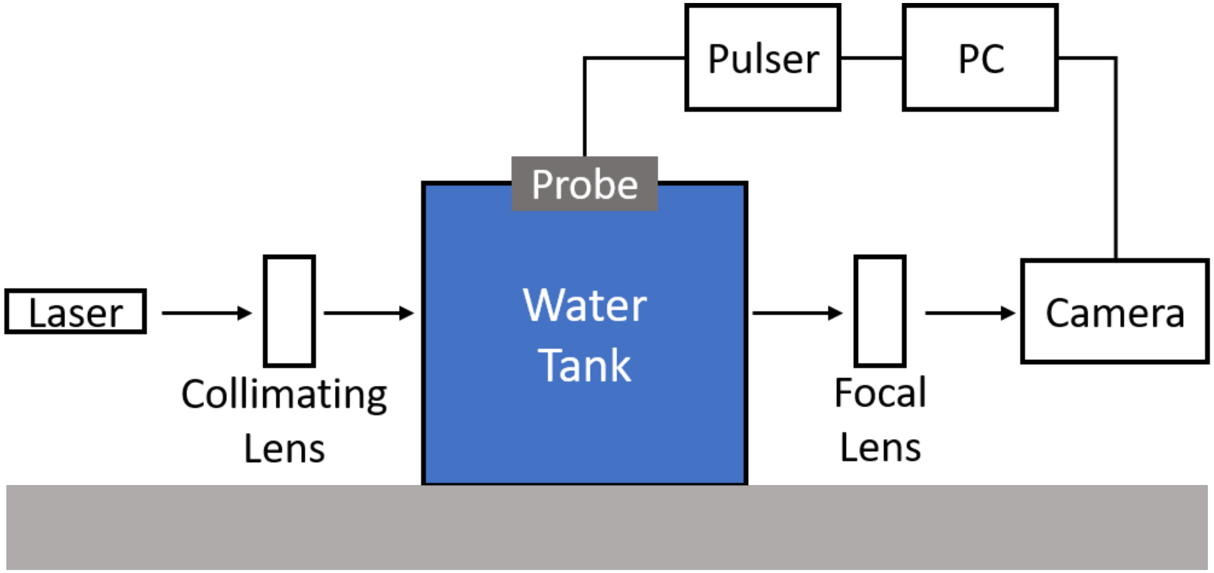
Presentation Outline

- Background
- Instrument
- Results
- Applications

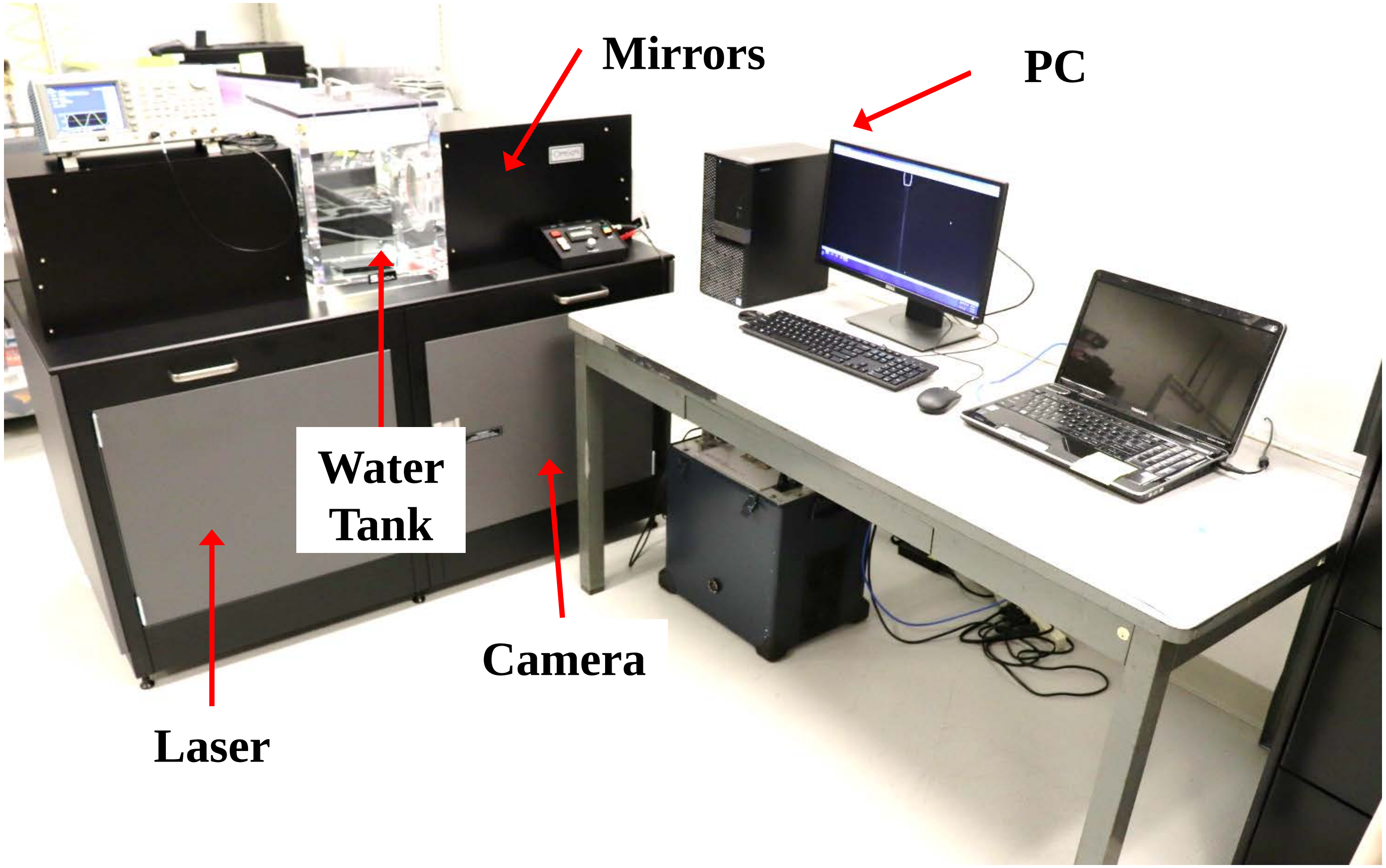
Schlieren Imaging

- Schlieren imaging provides a visualization of density variations in transparent media.
  - Ultrasonic pressure waves can be seen in water or, certain, transparent solids.
- To visualize an acoustic field with Schlieren imaging several basic elements are required:



Ultrasound Beam Analyzer

- ONDA's Optison is a self-contained system designed for generating Schlieren images of ultrasound waves.
  - Continuous and pulsed wave operations available.



Technical Specifications

- Tomography package for 3-dimensional measurements.

OptiSon S-12D

- High Resolution Digital Imaging
- Field of view : 9x12 cm to 3x4 cm (zoom 3:1)
- Image Definition: 1392 x 1040 pixels @ 12 bits
- Bandwidth : 1 to 100 MHz
- Spatial Resolution : Field of view/1390 or 50 µm, (whichever is larger)
- Time Resolution (Pulsed) : 150 ns
- Dynamic Range : 30 to 60 dB
- Power measurement accuracy : ± 2% between 5 mW and 100 mW
- Tank dimensions : 33cm(H) x 28cm(W) x 32cm(L)

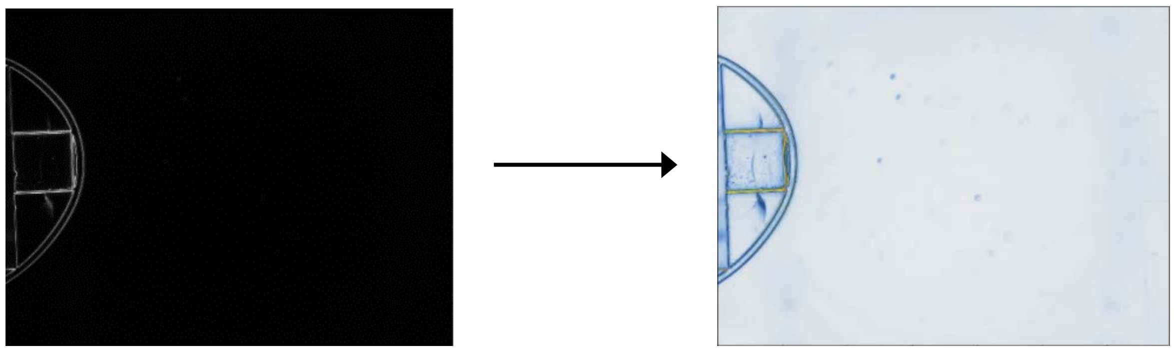
Further technical information is available at http://www.ondacorp.com/products_optison_specifications.shtml

Real-Time Imaging

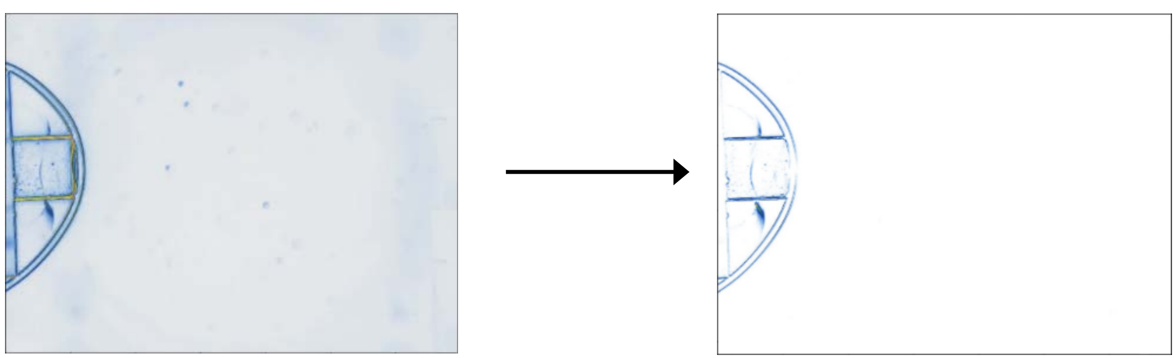
- The beam profile is seen in real-time.
  - Monochromatic images are saved by the system.

Image Processing

- From the raw monochromatic video output a color scale was applied to each frame and normalized.



- Mean is subtracted from each frame to remove coherent background noise.



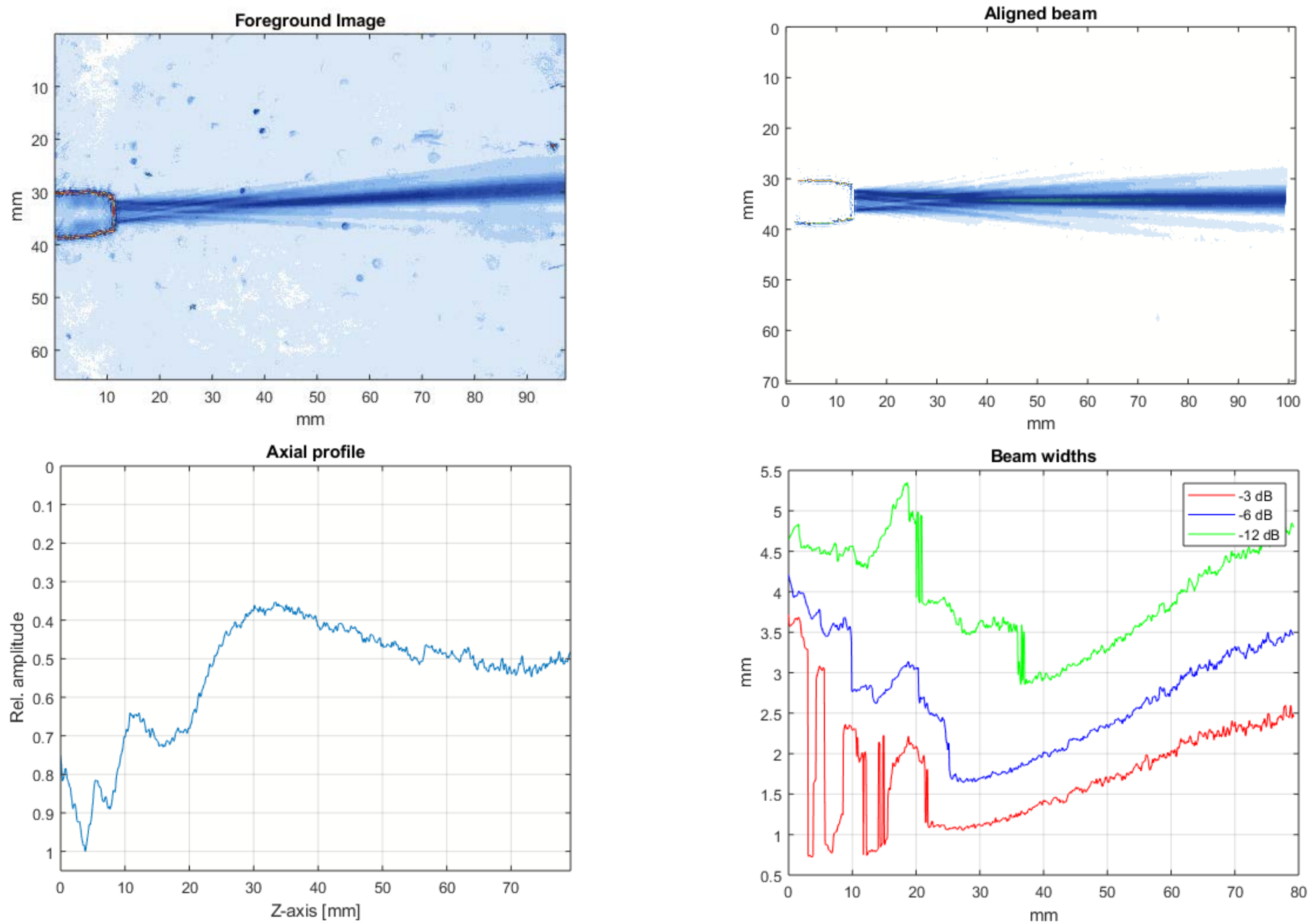
Results

- Three results will be shown:
  1. Beam width measurements.
  2. Phased array ultrasonic (PAUT) wave propagation inside an acrylic specimen with a 0.5 inch diameter side drilled hole (SDH).
  3. Acoustic wave interacting with a wavy metallic surface.
- This presentation places an emphasis on a qualitative assessment of results to showcase NDE opportunities and applications.
  - Quantitative results can be extracted from the results shown.

Note: All the results shown in this presentation are preliminary and have not been peer reviewed.

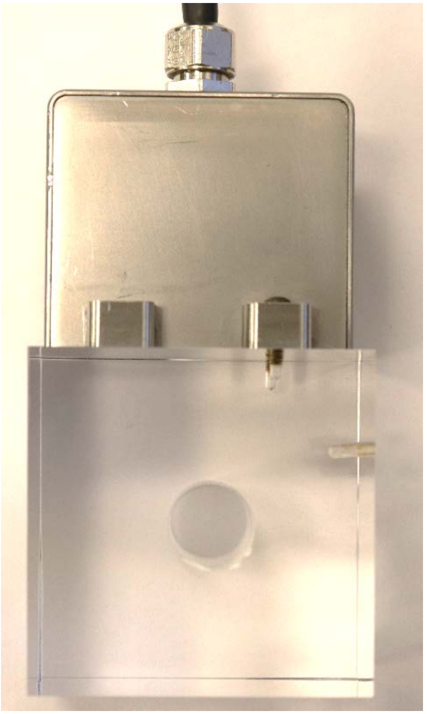
Beam Intensity and Width Measurements

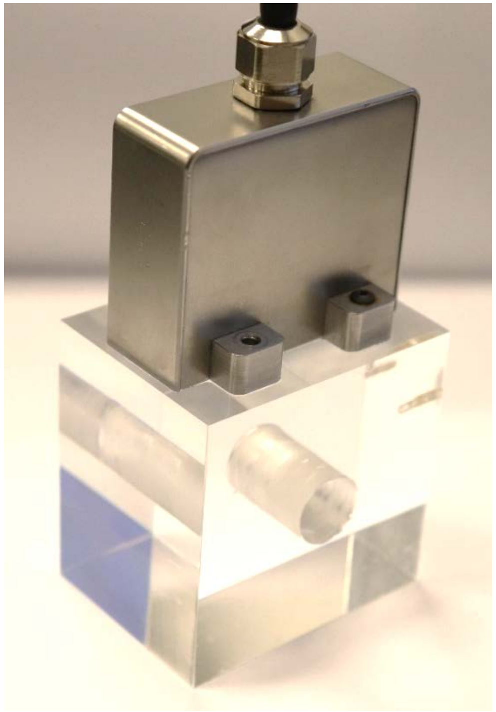
- A high spatial resolution image provides quantitative beam intensity and size measurements for transducers.
  - The below is a generic example of beam measurements from images.



PAUT in Acrylic – Experimental Setup

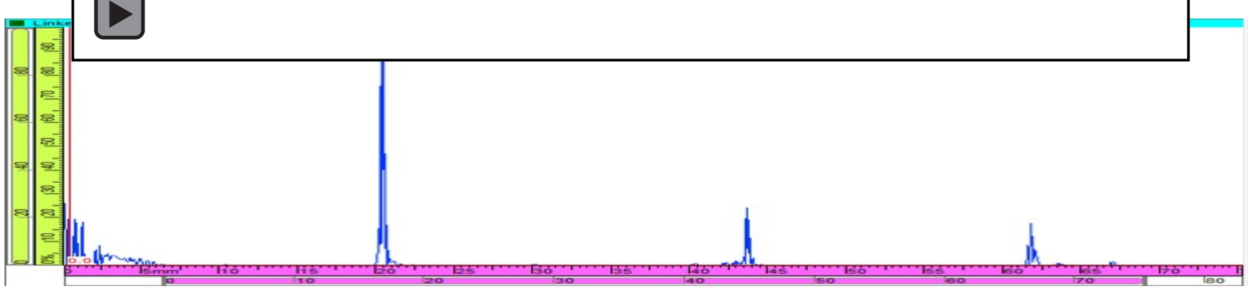
- Imasonic, 5MHz, 64 elements.
- Zetec Dynaray and UltraVision were used to control the transducer.
- Transducer was mounted on acrylic and custom fixturing was used to support in the water tank.
- Acrylic sheet is 2 inch x 2 inch and 1.5 inch thick (into the page)





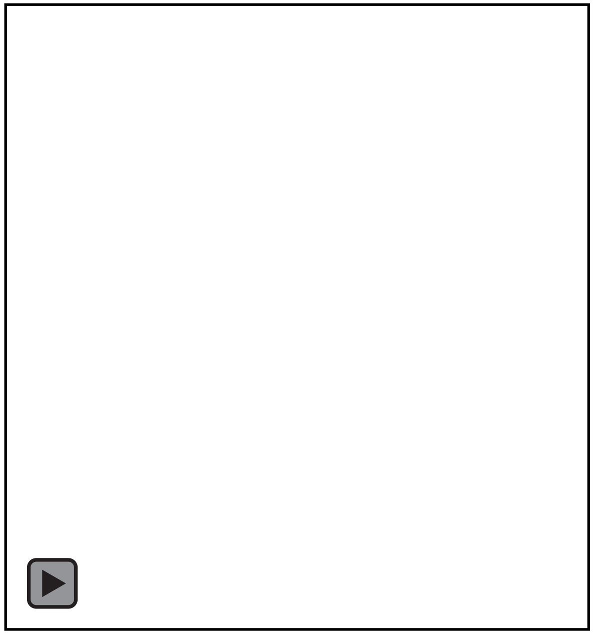
PAUT in Acrylic, 0.5 inch SDH – First Case

- Sound beam focused at the top of the SDH.



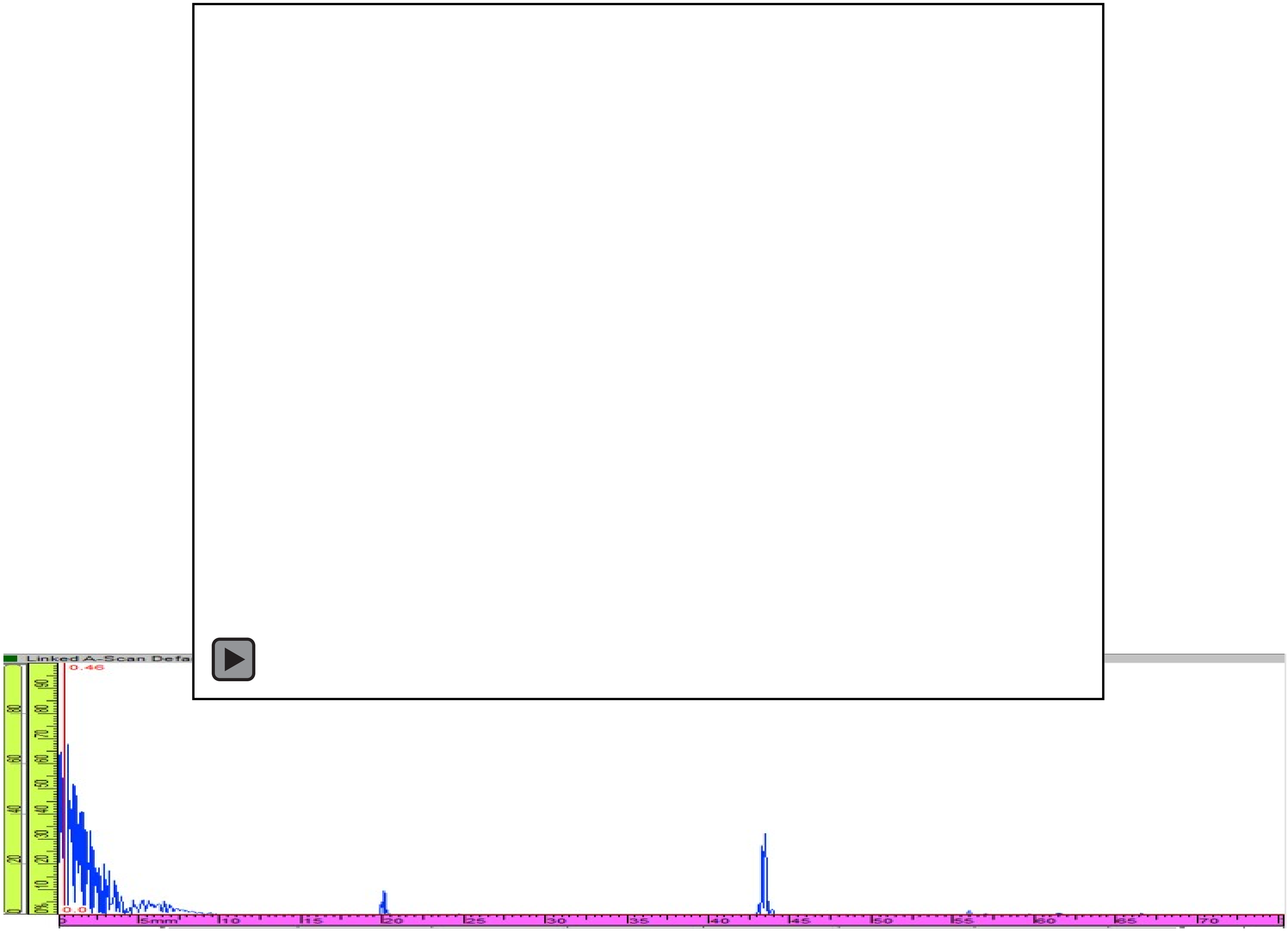
PAUT in Acrylic, 0.5 inch SDH – First Case

- Experimental and simulated data can be used together to aid in the development of ultrasonic models.
- Beam intensity and size measurements can be taken from the experimental and simulated images.
  - Allows a detailed refinement of modeling input parameters.



PAUT in Acrylic, 0.5 inch SDH – Second Case

- 10 degree plane wave passing through the SDH.



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Metallic Specimen with a Wavy Surface

- Imasonic, 5MHz, 64 elements.
- Aluminum block with simplistic geometry - weld root and counterbore.
  - Representative of an inside surface examination in immersion.
- Acoustic waves can be seen reflecting off the surface and after passing through the specimen.
  - Visualization is not possible inside metallics.

Metallic Specimen with a Wavy Surface

- An angled plane wave is transmitted from the probe.
- In the video notice the:
  - Upper surface reflections from the wavy surface.
  - Acoustic wave exiting the backwall of the specimen.
- Applications such as this can be used to:
  - Determine reflection and transmission energy transfer due to multiple layers.
  - Observe surface reflections from complex surface profiles, pitting/corrosion, grinding marks, etc.

Applications

- Acoustic sound fields can be investigated without being distorted by a measuring probe.
  - Hydrophones are typically used to quantify a sound field in water, but they cannot be applied to solids.

- Characterize ultrasound probes and look for any irregularities in the beam-profile.
  - Irregularities could be due to manufacturing or damage after production.

- Study wave propagation in certain solid transparent medium.
  - Investigate transducer and procedure design, sound interaction with defects, modeling and simulation validation, etc.

- Training
  - Visualize the sound field and its interaction with defects.
  - Correlate the visualization to instrument readings.

discussion

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Recommended practices for ultrasonic modeling of coarse-grained materials

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- Research Objective
- Proposed Workflow
- Results
- Conclusions

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Ultrasonic Modeling and Simulation of Cast Austenitic Stainless Steel: Technical Update. EPRI, Palo Alto, CA: 2018. 3002013160.

Free and Publicly Available

Background

- Ultrasonic testing (UT) of Cast Austenitic Stainless Steel (CASS) is challenging due to the coarse-grained anisotropic and inhomogeneous nature of the material.
- Ultrasonic wave interaction within the material structure is subject to scattering and attenuation.
- Results in reduced signal-to-noise ratios (SNR) and challenging analysis and interpretation of results.

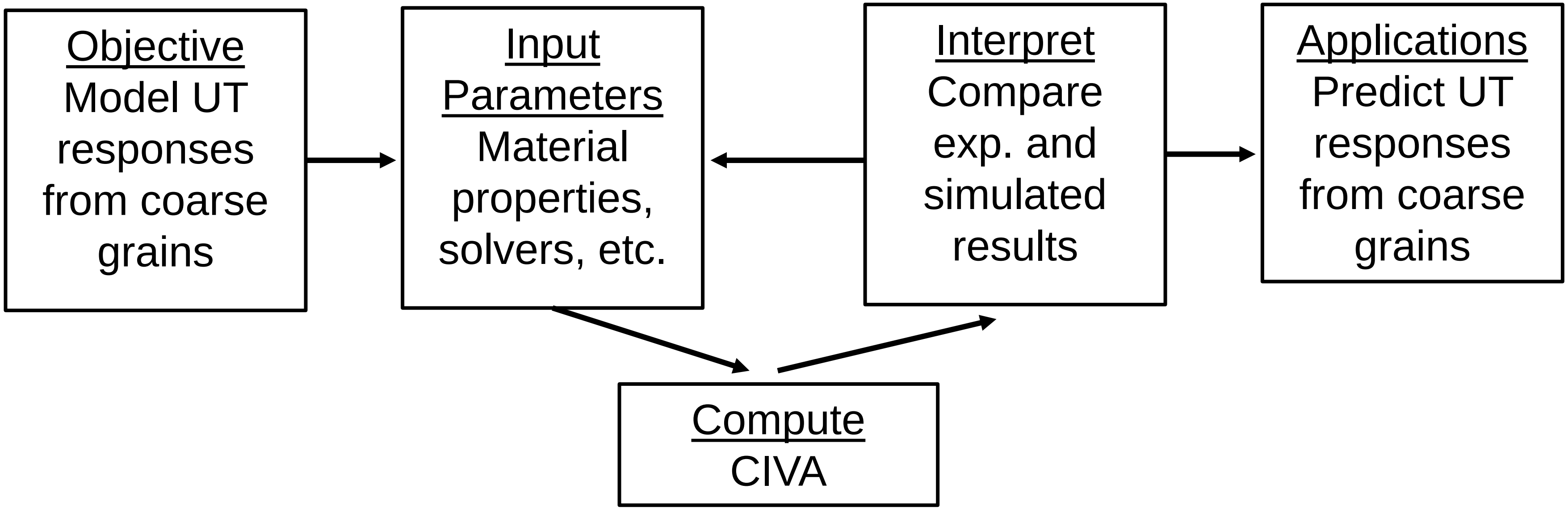
Research Purpose

- This research proposes an experimental based strategy to setup ultrasonic models and simulations aiming at accurately simulating Ultrasonic Testing (UT) in a coarse grain material such as Cass Austenitic Stainless Steel (CASS).

- The software used for this study was the French Alternative Energies and Atomic Energy Commission's (CEA's) CIVA.
  - CIVA is a commercially available software package focused on the modeling and simulation of Nondestructive Evaluation (NDE) techniques.
  - Minimal research has been conducted on nuclear industry CASS materials using this software package.

Applications

- Accurate models can be used to support the investigation of ultrasonic techniques for CASS. Mathematical modeling lifecycle:



- N-824 Ultrasonic Examination of Cast Austenitic Piping Welds from the Outside Surface
- N-711-1 Alternative Examination Coverage Requirements for Examination Category B-F, B-J, C-F-1, C-F-2, and R-A Piping Welds, Section XI, Division 1
- Investigate ultrasonic responses from different grain types (equiaxed, columnar, mixed).

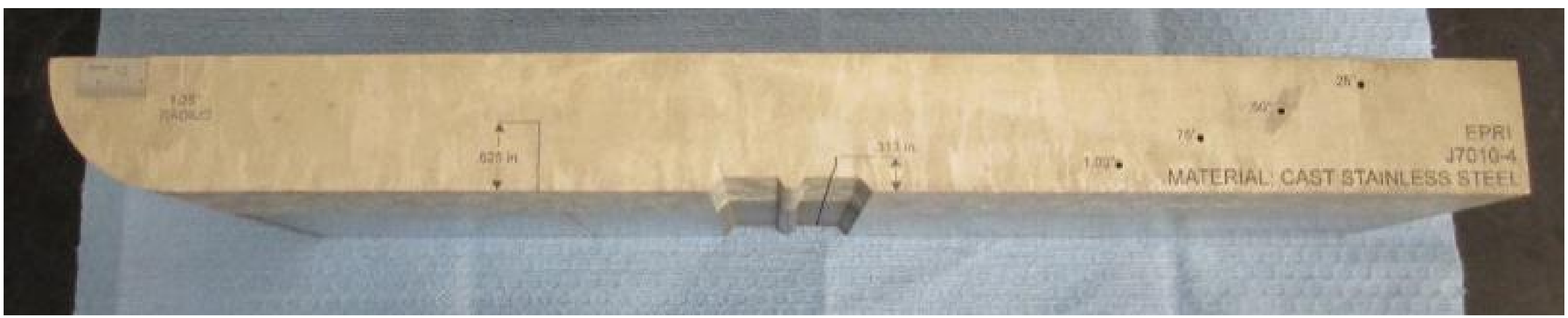
Proposed Workflow

- The proposed workflow was performed on a single specimen. Further research will be conducted on additional specimens to help confirm its generalization.
- The workflow consisted of the following:
  - Experimental UT measurements:
    - Probe characterization
    - Material characterization
    - Angle beam longitudinal wave (LW) contact measurements
  - Grain size measurements from macrographs
  - CIVA UT simulations:
    - Parametric study of CIVA input parameters (grain characteristics and material velocities)
    - Model development for immersion and contact measurements
  - Comparison of results between experimental and simulated measurements

Test Specimen

- CASS specimen 1.25” (31.75 mm) thick, with known electro-discharge machining (EDM) defects, was selected for the study:
  - Weld root, counterbore, radius, side drilled holes (SDHs), and cracks

- Experimental studies on this specimen consisted of :
  - Material characterization - 0° immersion LW with 0.5, 1.0, and 2.25MHz
  - 45° LW contact for defect response using a 1.0MHz transmit/receive (T/R) probe



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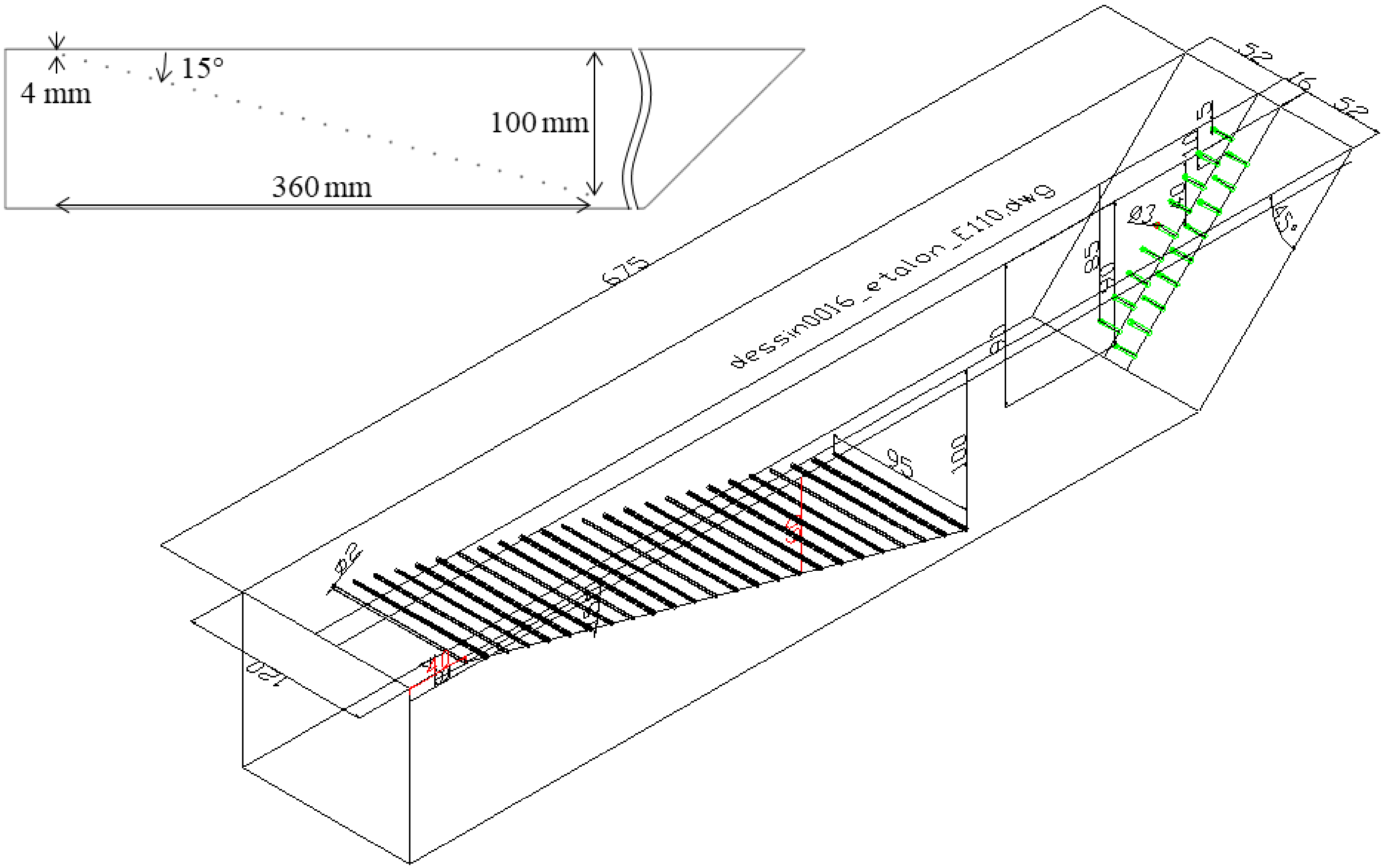
Reference Specimen

- Carbon steel specimen with a series of SDHs was used to help characterize probe parameters and provide reference measurements for amplitude comparison between experimental and simulated data.



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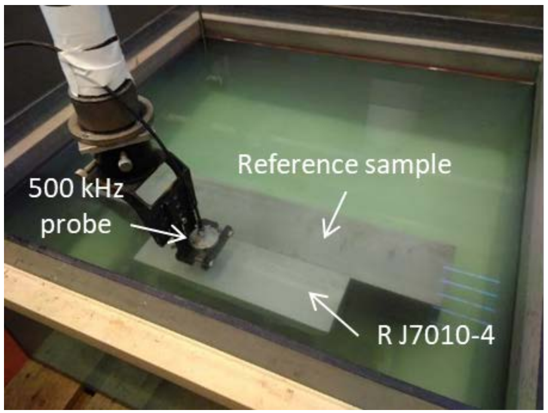
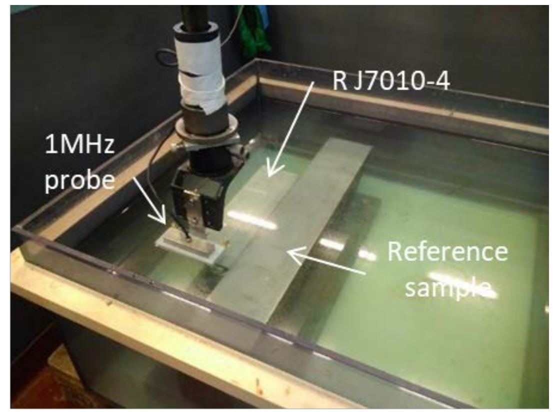
Experimental Setup

- Immersion scanning for reference and test specimen. Data was collected with a MultiX 128 channel system.

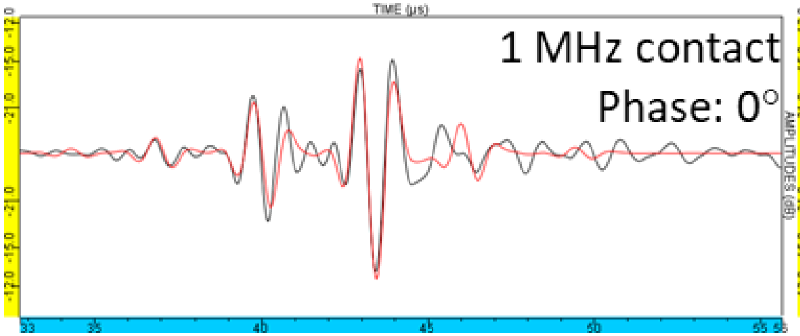


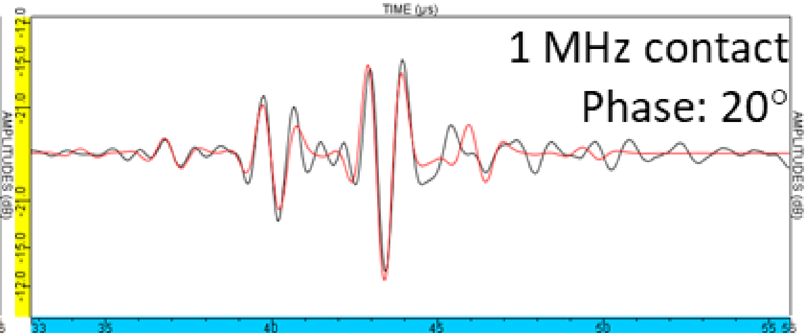


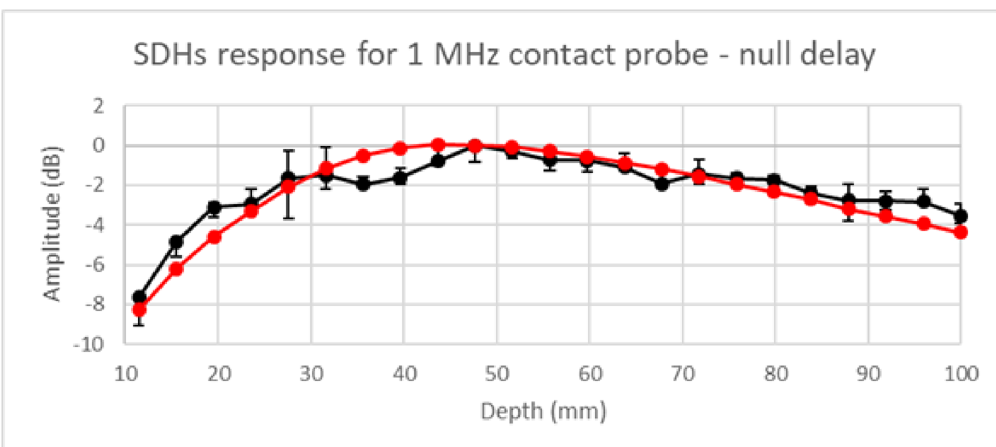
- Immersion probes for material characterization and T/R probe for defect response.

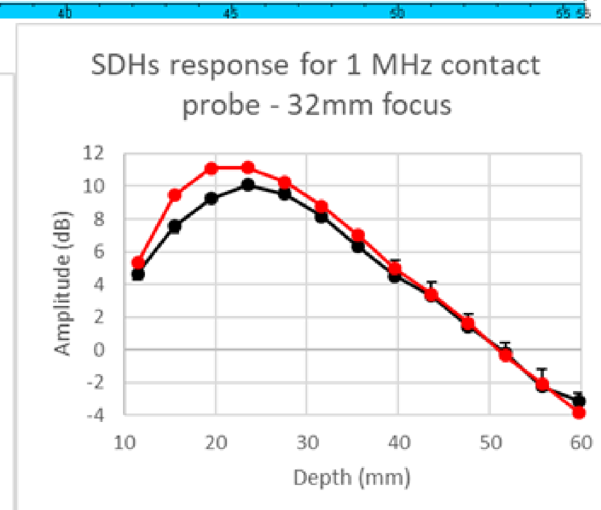
Probe Characterization

- Experimental UT data was taken on the reference sample and this information was used to determine probe phase angle, as well as probe and wedge dimensions.









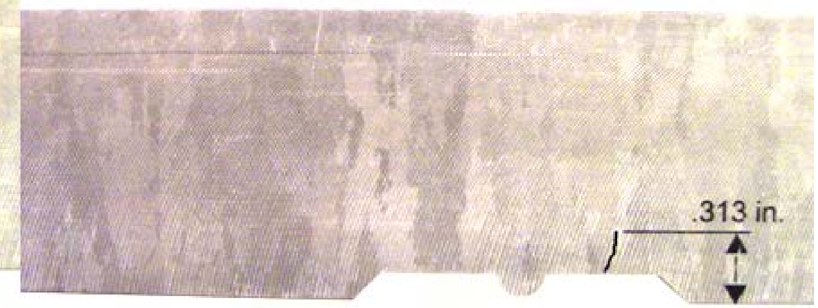
Note: Black = experimental, red = simulated

Grain Sizing – 1 of 3

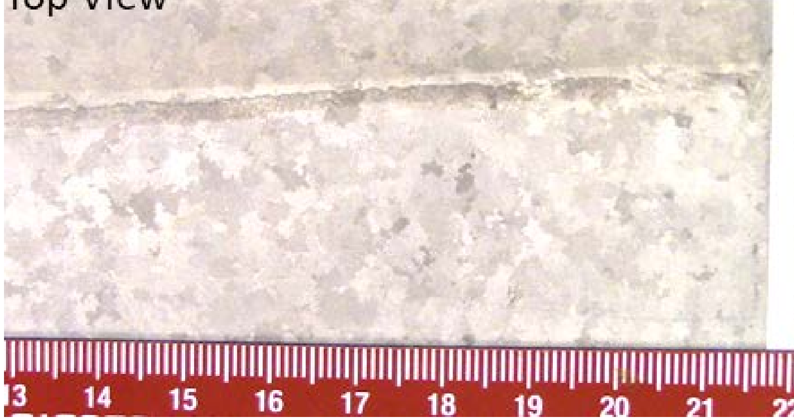
- Macrograph images were taken from the top and side views of the test specimen.
  - Columnar grain structure.

Side View A

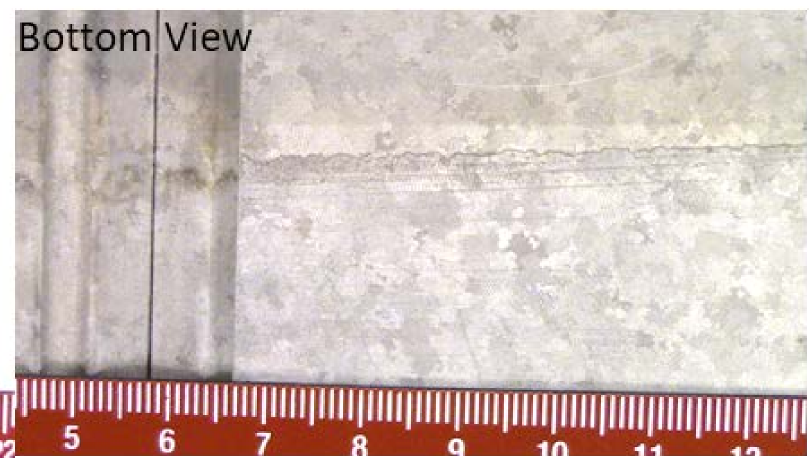
Side view B



Top View

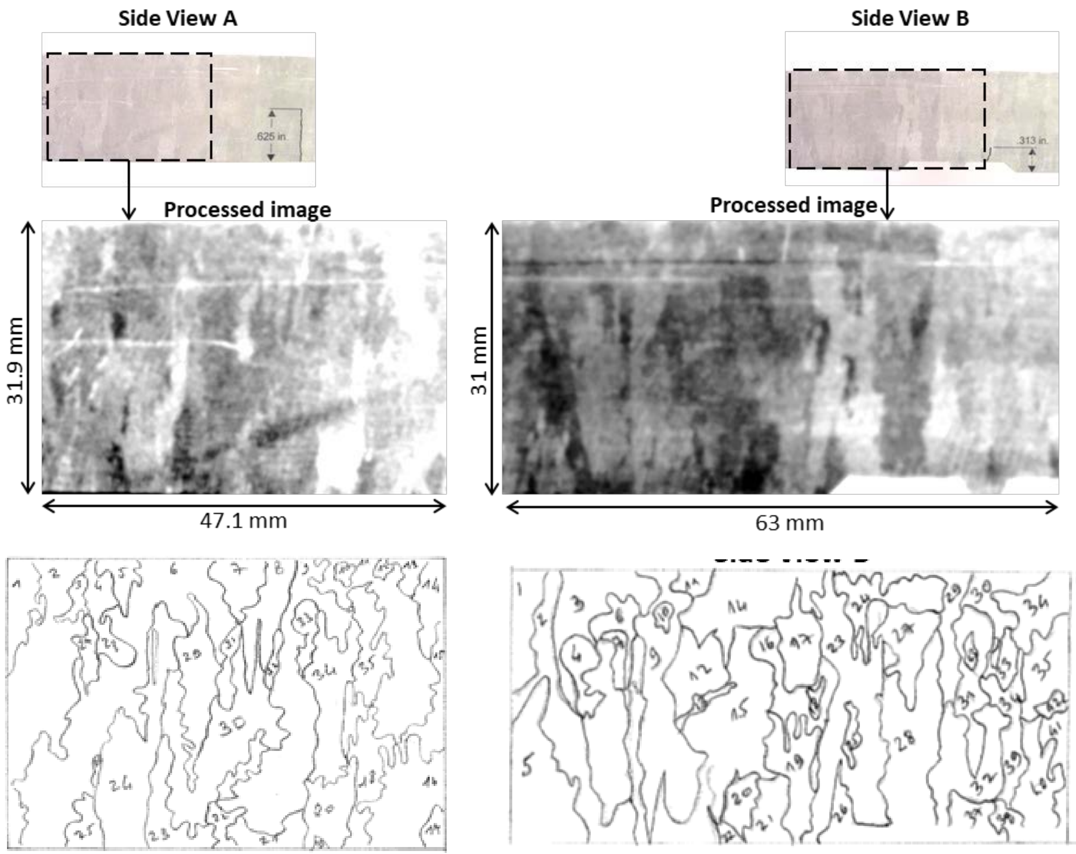


Bottom View



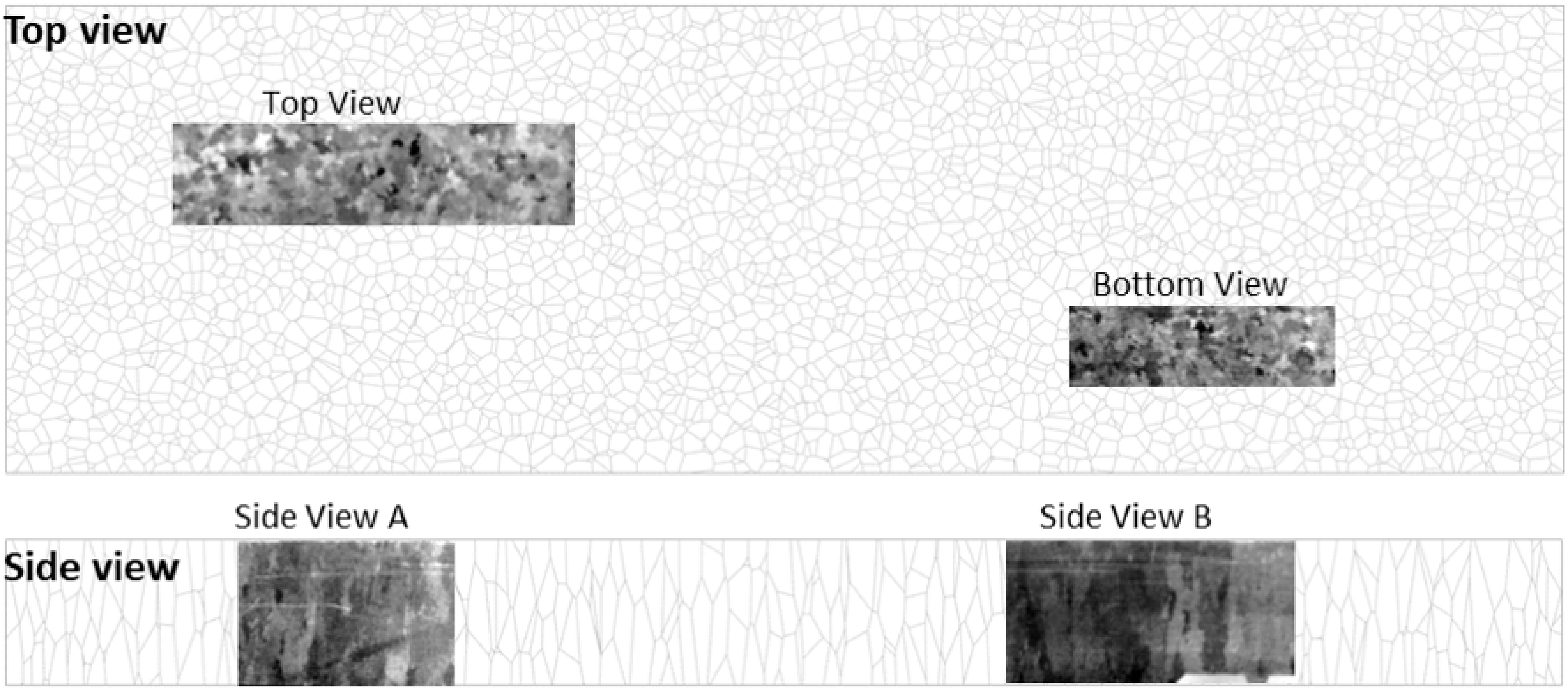
Grain Sizing – 2 of 3

- Image processing was applied to the macrograph images so the individual grains could be counted and sized.



Grain Sizing – 3 of 3

- Grains sizes from the macrograph estimated a size of 3.5 mm (wide) by 12.25 mm (tall).
- CIVA models with Voronoï cells were initially sized based on the macrograph measurements.

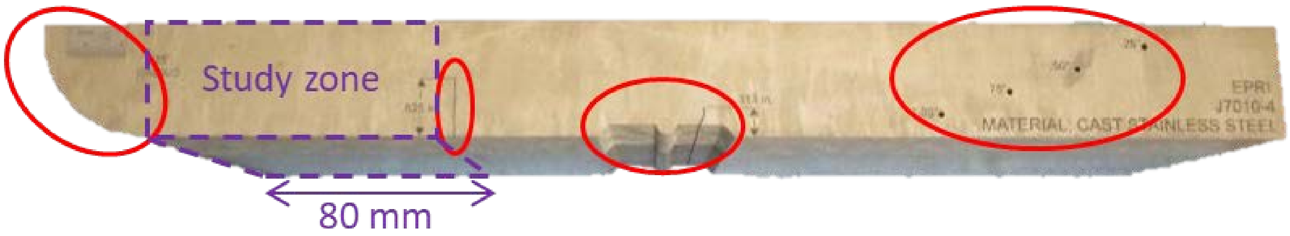


Material Characterization – Immersion Testing

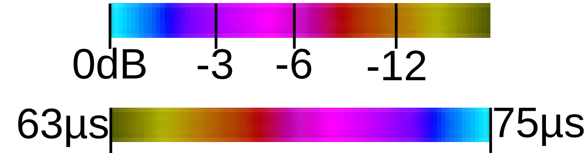
- The objective of the material characterization was to define the nominal grain velocity and its distribution.

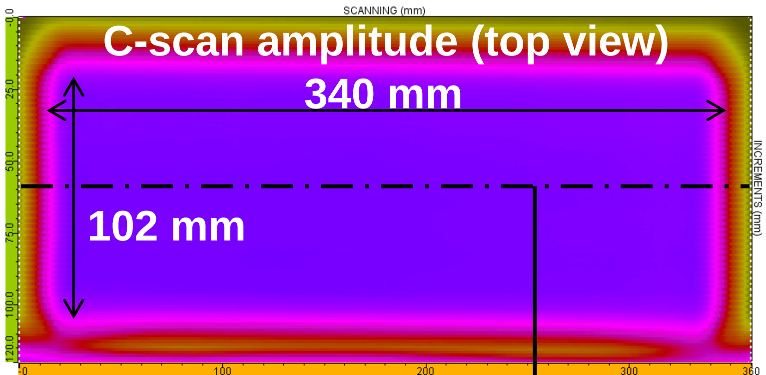
- A study zone 80 mm x 102 mm was define in a flat region of the specimen which was free from geometric and defect influence.
  - The study zone allowed the study of grain influence on UT signal amplitude and time-of-flight (TOF).

- A 0°LW was used for material characterization to avoid mode conversion.
  - 0.5, 1.0, and 2.25 MHz probes

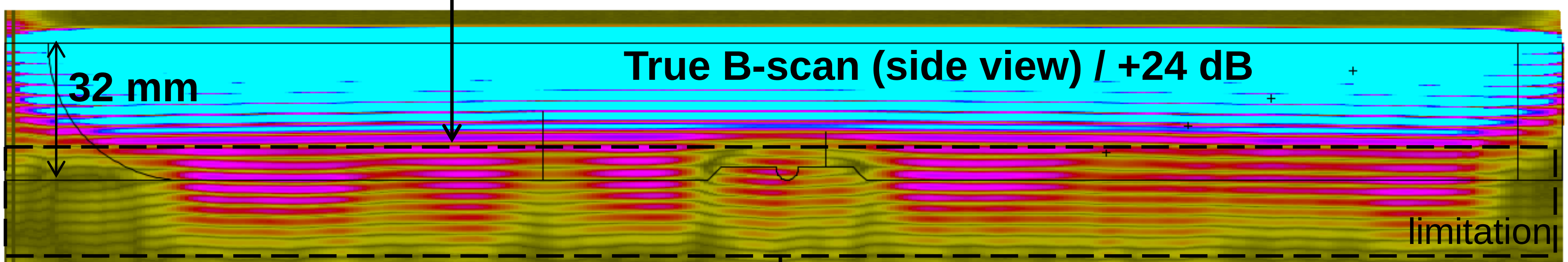


500 KHz probe





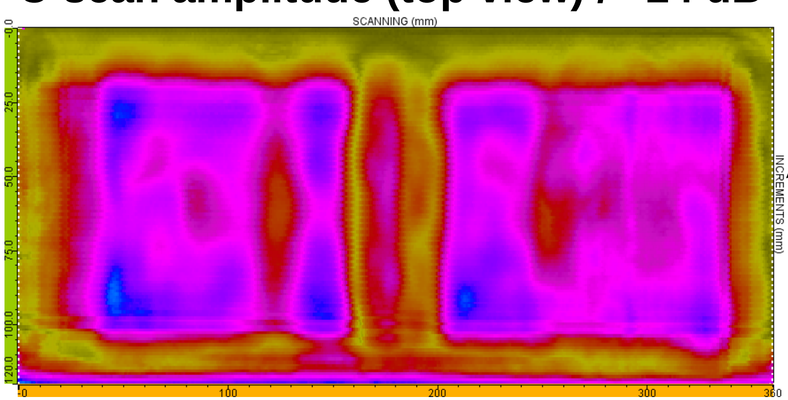
- Scan resolution : 1 mm (both axis)
- Part material used for display: Stainless Steel 302 (V_L: 5660 m/s)
- Very large echoes due to low freq.

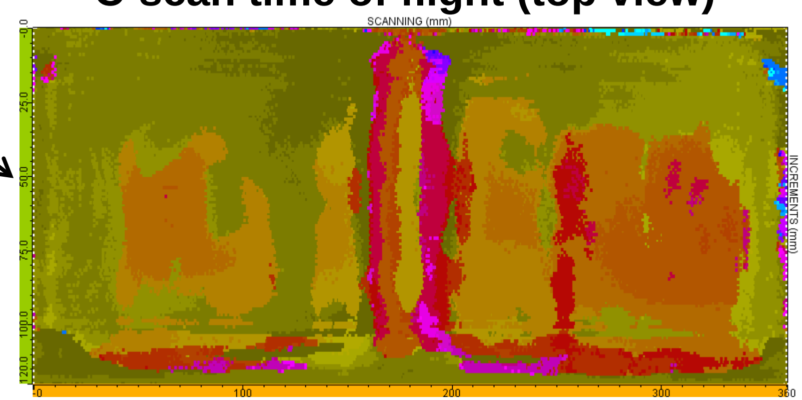


C-scan amplitude (top view) / +24 dB

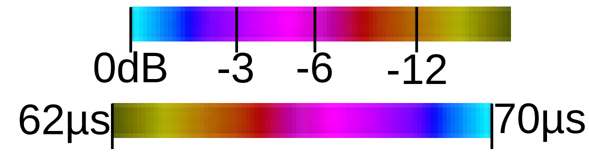
C-scan time of flight (top view)

Bottom Face

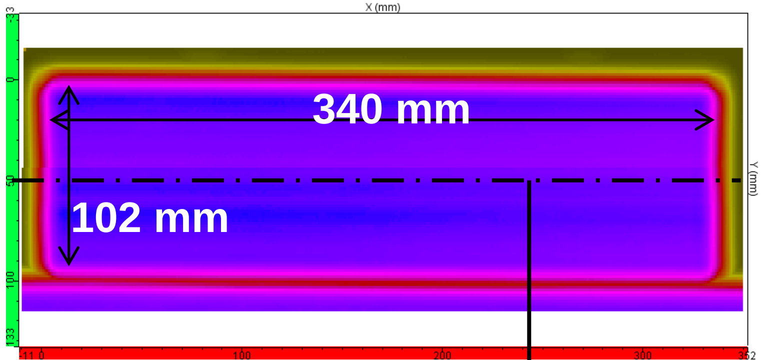




1 MHz probe

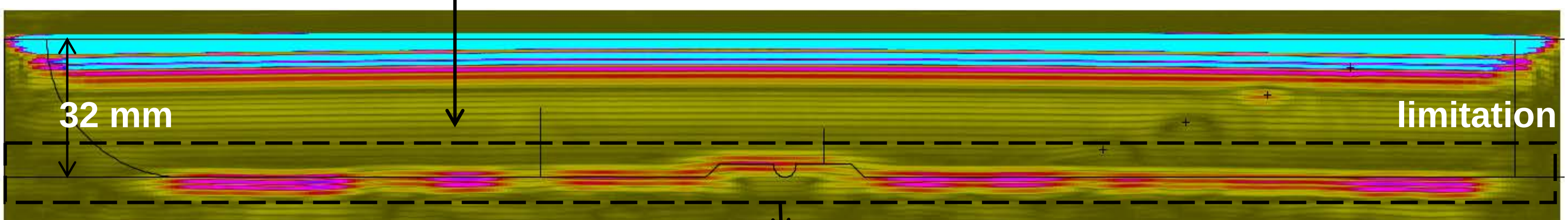


C-scan amplitude (top view)



- Scan resolution : 1 x 1.4 mm
- Part material used for display: Stainless Steel 302 (V_L: 5660m/s)

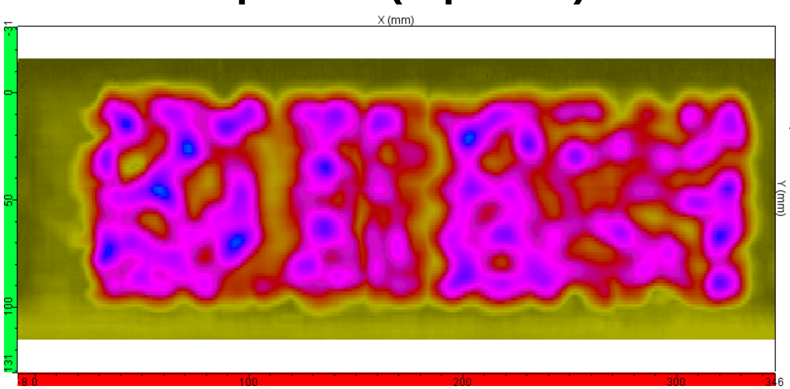
True B-scan (side view) / +27 dB



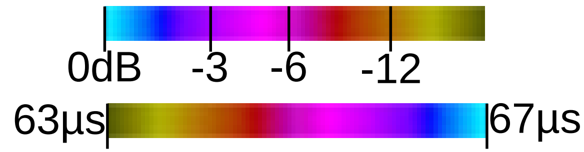
C-scan amplitude (top view) / +27 dB

Bottom Face

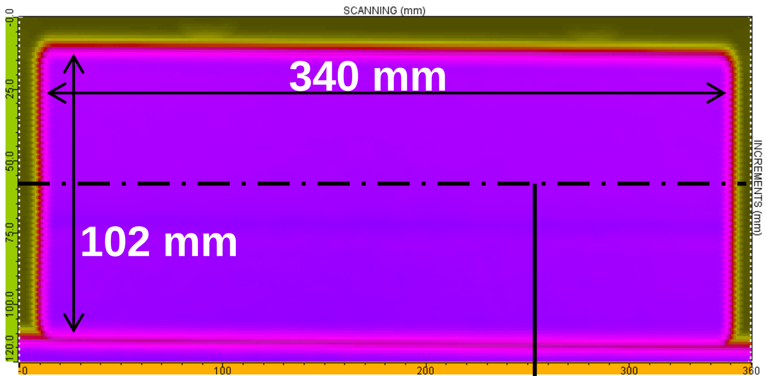
C-scan time of flight (top view)



2.25 MHz probe

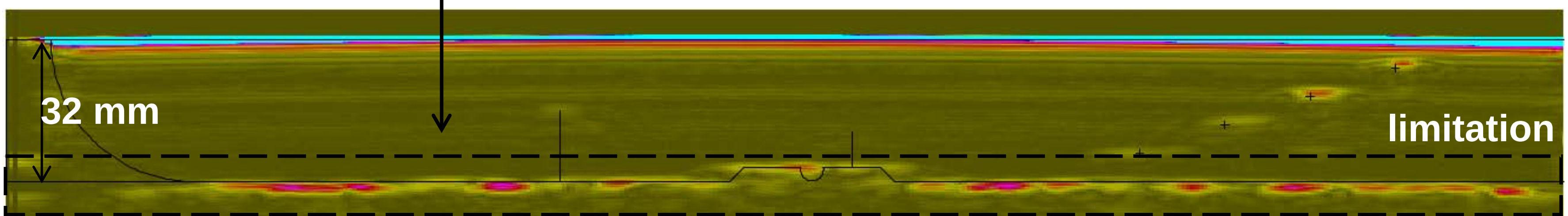


C-scan amplitude (top view)



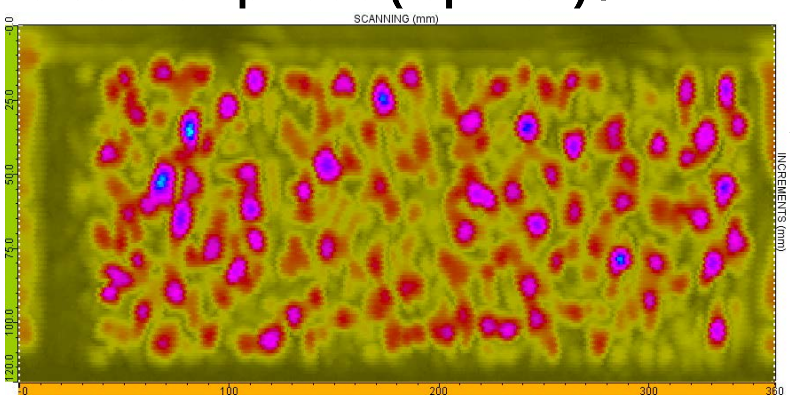
- Scan resolution : 1 mm (both axis)
- Part material used for display: Stainless Steel 302 (V_L: 5660m/s)

True B-scan (side view) / +27 dB

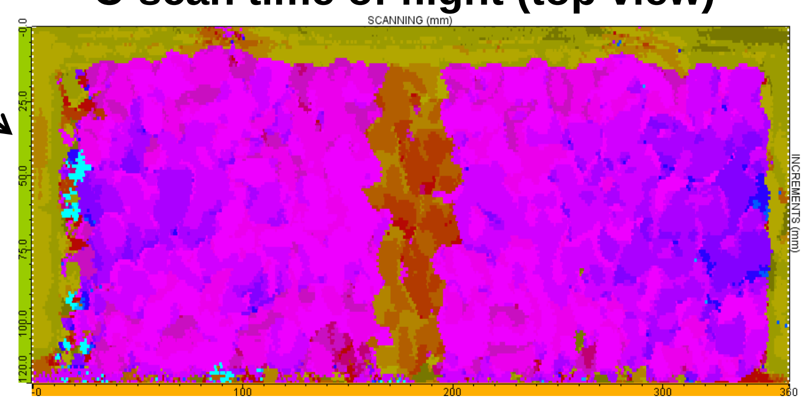


Bottom Face

C-scan amplitude (top view) / +27 dB

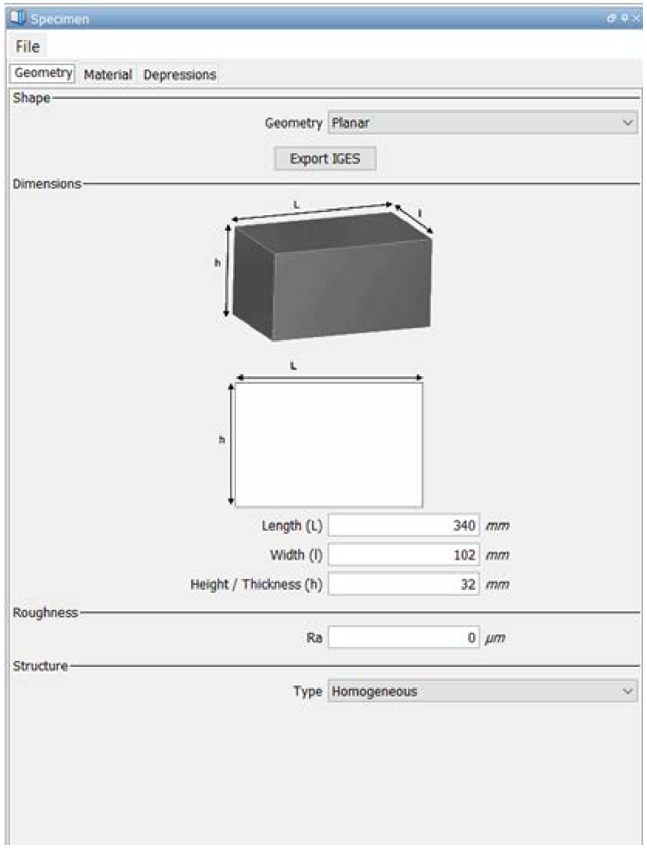


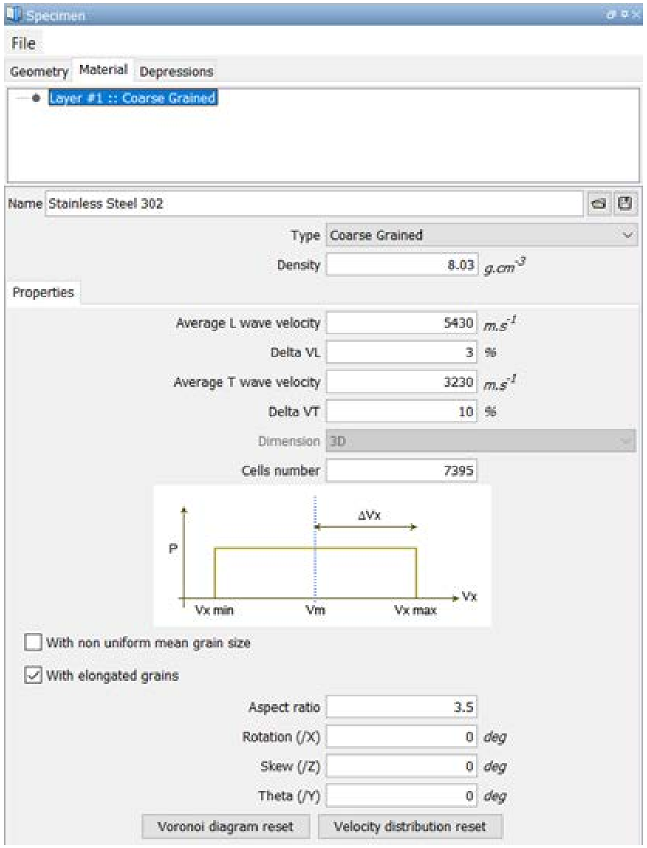
C-scan time of flight (top view)



Developing CIVA Models

- CIVA models were developed using Voronoï cells.
  - Models with Voronoï cells are limited to flat plates and cylinders.
  - A detailed description of the relevant CIVA input parameters for coarse grain materials are given in the report (EPRI Product ID # 3002013160).



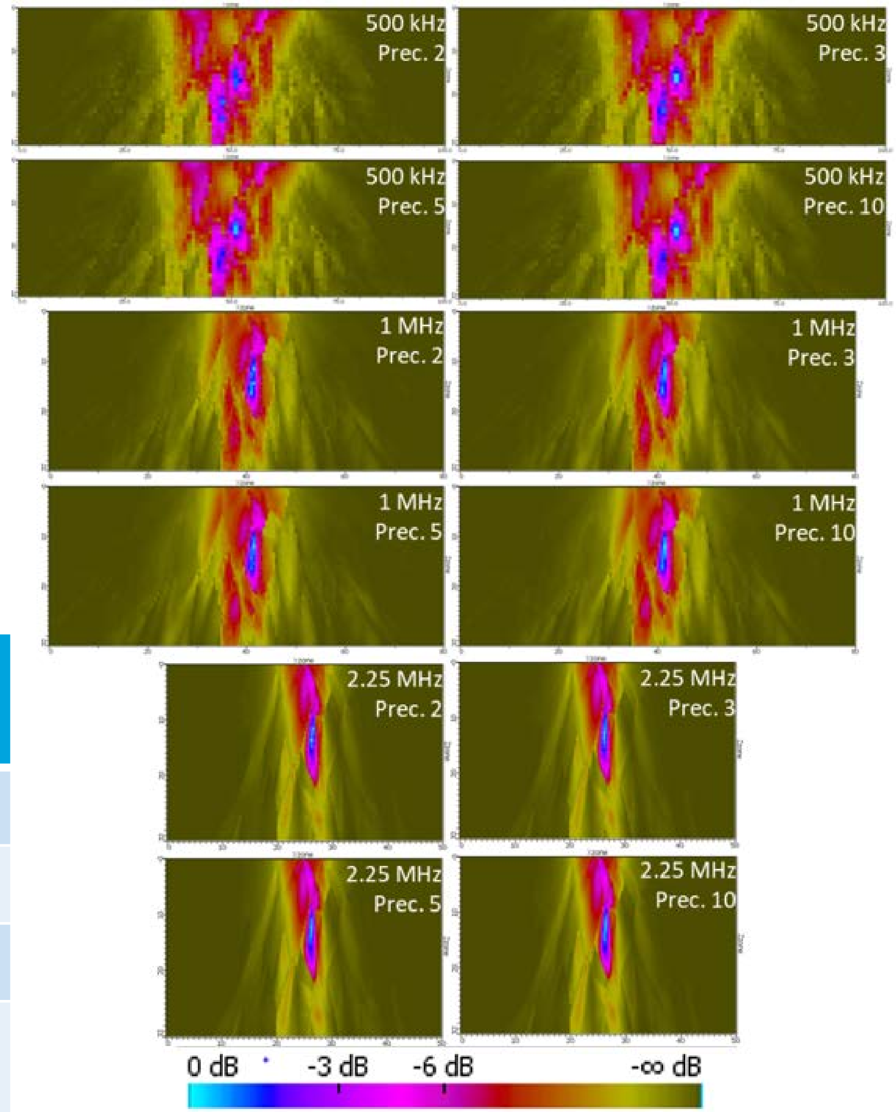


Computation Parameter Study

- Field and defect precision values were studied and determined based on a convergence of response echoes.
- These values can be overlooked and are critical for accurate simulations.

Probe [MHz]	Field Precision*	Defect Precision*
0.5	3	10
1.0	3	5
2.25	3	3

*Increasing these parameters increase computation time

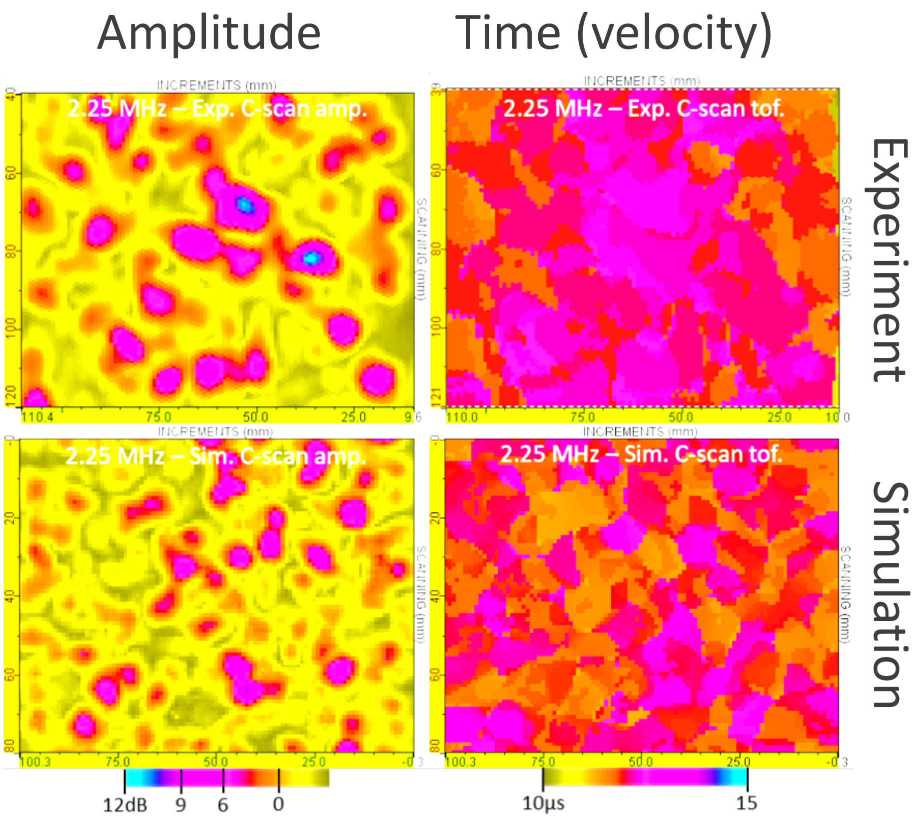


Final CIVA Settings - Immersion Evaluation

- A manual parametric study was conducted on CIVA input parameters to determine a final set of input values for critical parameters.
  - Nominal material velocity and its distribution
  - Grain size and elongation

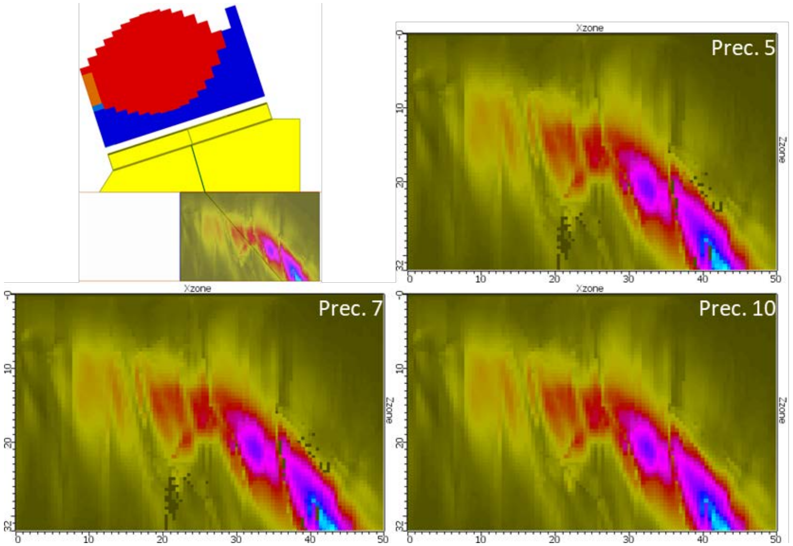
- The parametric study was evaluated based on amplitude and TOF measurements from the study zone.

- Refer to the report for extensive details on the parametric study.

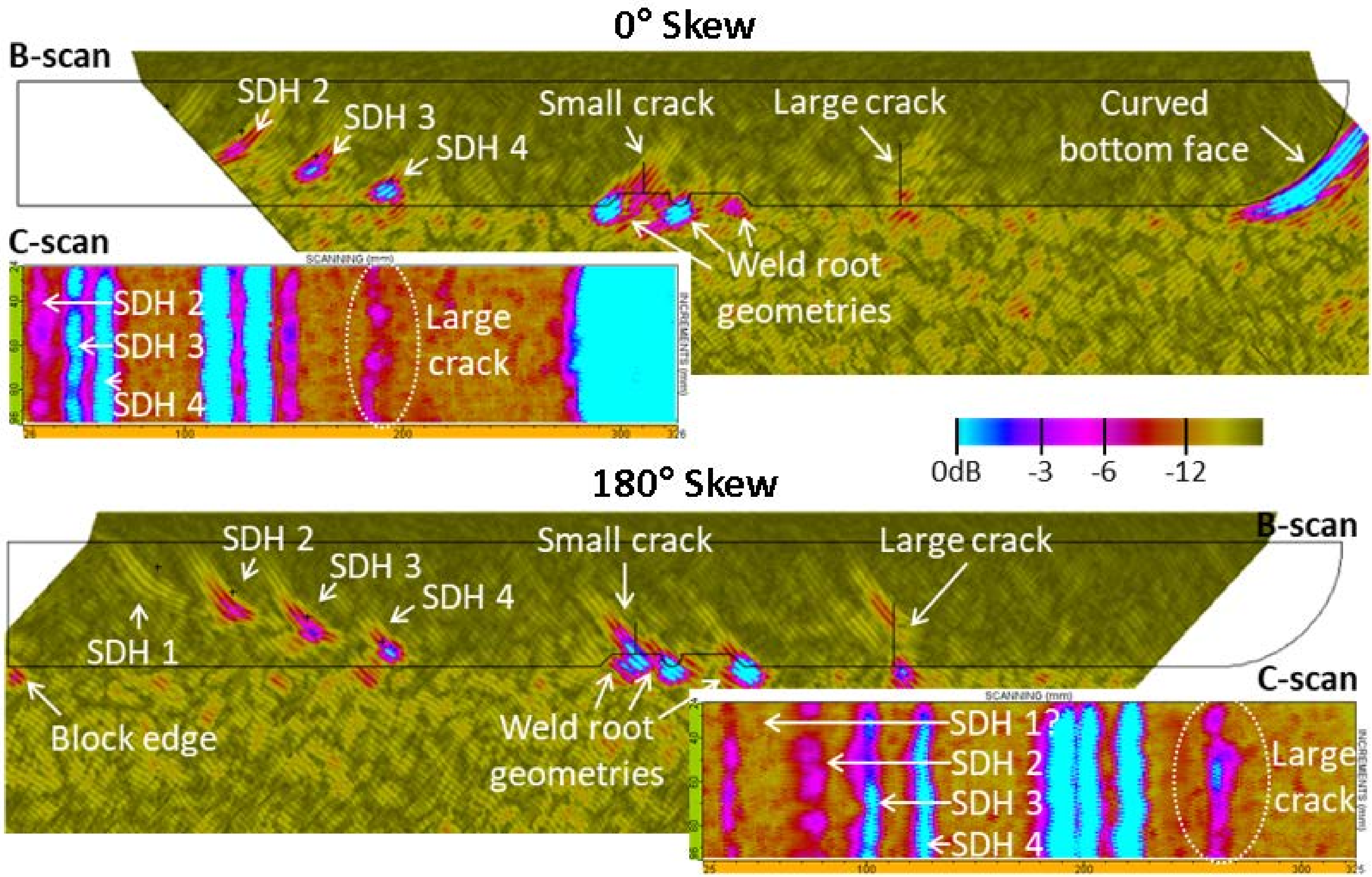


Contact Probe Evaluation

- CIVA simulations were conducted using the models built from the probe and material characterization work.
- A 45°LW, 1MHz contact phased array T/R probe was scanned in both the 0° and 180° skew directions.
- A field precision value of 10 was used for the contact probe simulations.

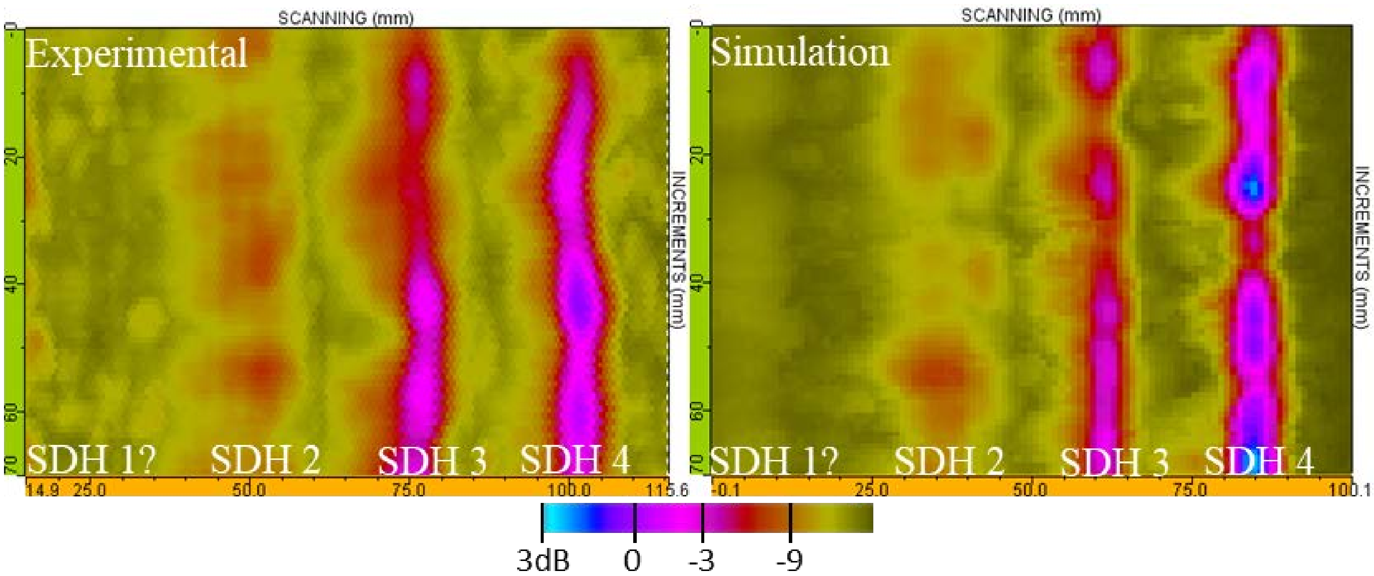


Experimental Results



Comparison of SDHs

- Experimental and simulated results were qualitatively and quantitatively in good agreement for 180° skew.

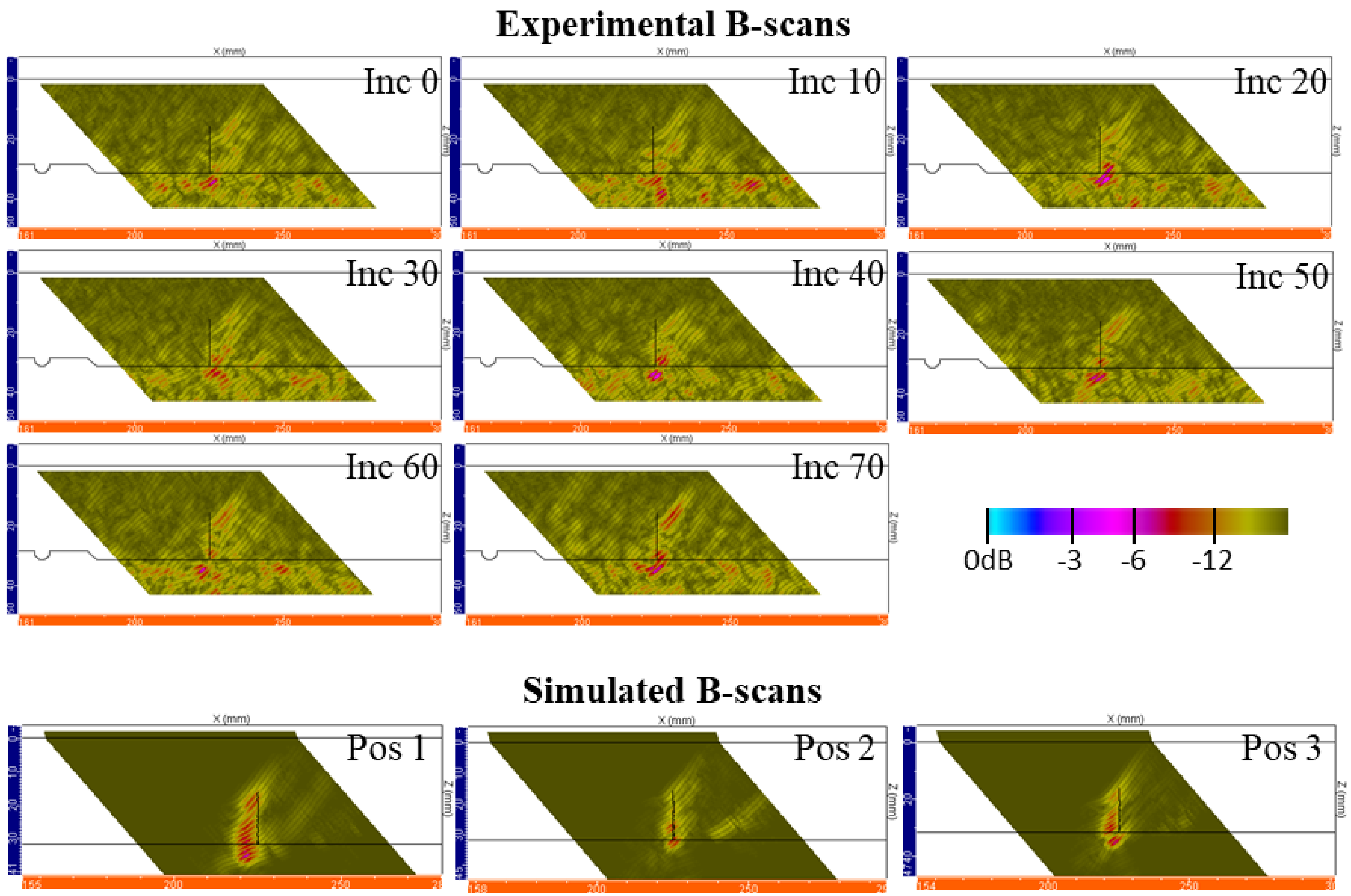


Flaw	Min amplitude* (dB)	Max amplitude* (dB)
SDH 1	−20.4 (−5)	−14.2 (−3)
SDH 2	−11.3 (−1.6)	−3.5 (−0.1)
SDH 3	−4.8 (−0.2)	1.1 (−0.7)
SDH 4	−2.4 (+4.6)	5.6 (+2)

***Simulation (simulation - experimental)**

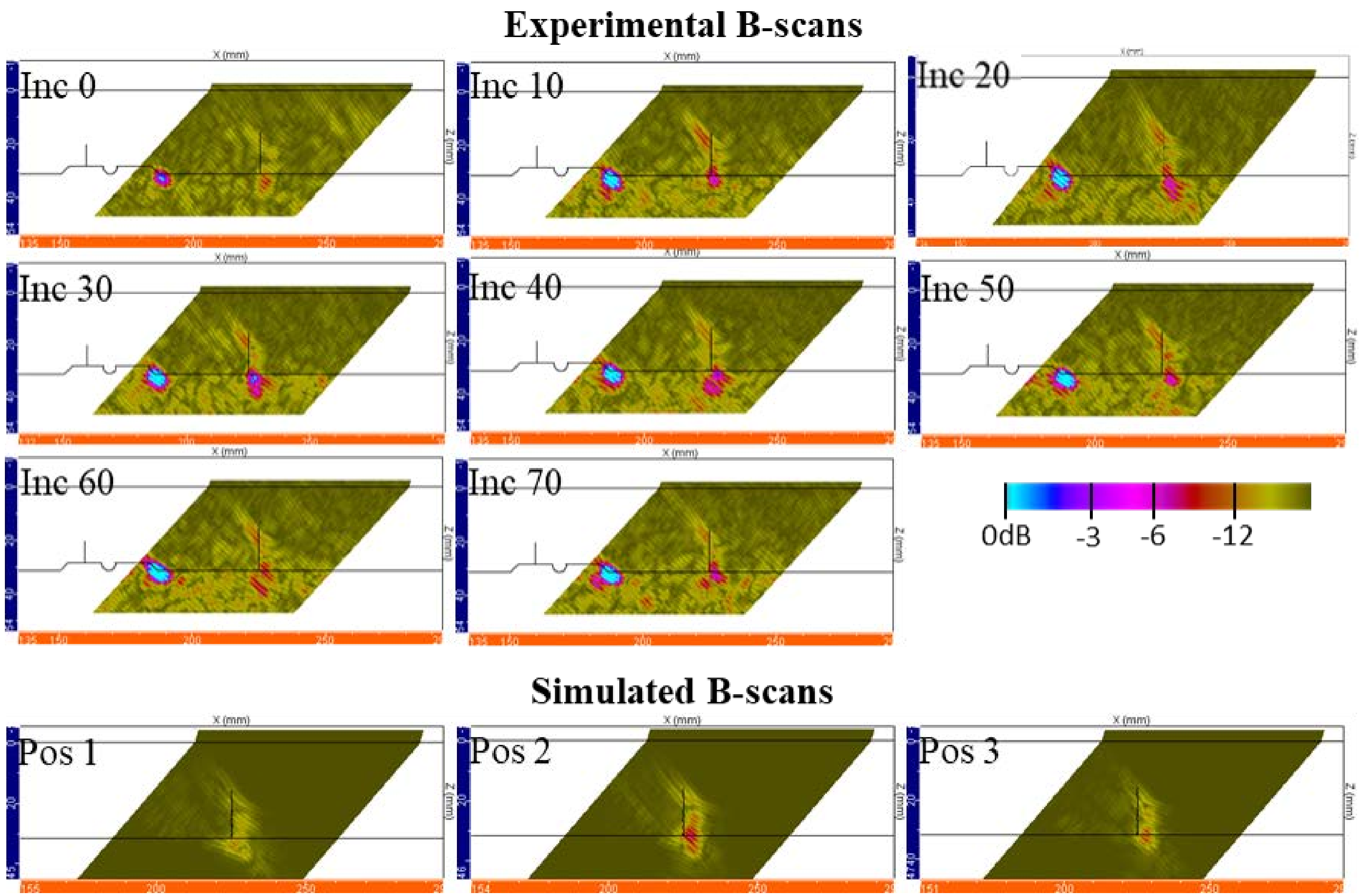
Comparison of Large Crack – 0° Skew

- Experimental and simulated results were quantitatively similar in amplitude response but it is recognized that signal-to-noise ratio (SNR) needs improvement. Noise needs to be incorporated into the models.



Comparison of Large Crack – 180° Skew

- Experimental and simulated results were quantitatively similar in amplitude response but it is recognized that signal-to-noise ratio (SNR) needs improvement. Noise needs to be incorporated into the models.



Computation Times

- Simulation times vary significantly depending on the model's complexity.
  - Results shown are for 1MHz.

Immersion

Computer Specs: Intel i7-7700HQ, processor 2.8/3.8 GHz, 16Gb RAM, Windows 10, CIVA 2017 SP1

Beam/Echo	Details	Time
Beam	Homogenous /bottom	33s
Beam	Coarse grain/ prec. 5	19m 1s
Echo	Field prec. 3/ Defect prec. 5	3h 21m 21s

Contact

Computer Specs: Intel i7-4770, processor 3.4/3.9 GHz, 16Gb RAM, Windows 7, CIVA 2017 SP1

Beam/Echo	Details	Time
Beam	Field Precision 1	6m 52s
Beam	Field Precision 10	1h 3m 24s
Echo	J7010-4 large crack, front, 1	137h 12m 30s

Conclusions

- Prior to coarse grain simulations an effort was placed on properly characterizing ultrasonic probes by using a homogeneous well-known material to define CIVA probe settings, amplitude references, and to evaluate experimental error and uncertainty.

- The report provides an introduction to developing and setting up CIVA coarse grain models with detailed descriptions of the primary modeling inputs. Computation time for each simulation is presented in an appendix and modeling limitations are presented.

- A comparison is made between experimental and simulation results for a 45°LW, 1MHz contact dual matrix phased array probe. The results showcase both qualitative data and amplitude responses from known features such as side drilled holes and a large crack.

- Future work can focus on aspects such as efficient techniques for incorporating noise into the simulations, reducing computation times, and large grain materials with welds.

discussion

Together…Shaping the Future of Electricity