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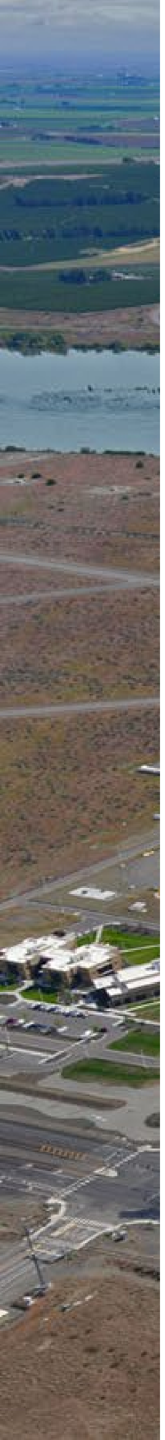

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Evaluation of Commercial Advanced NDE

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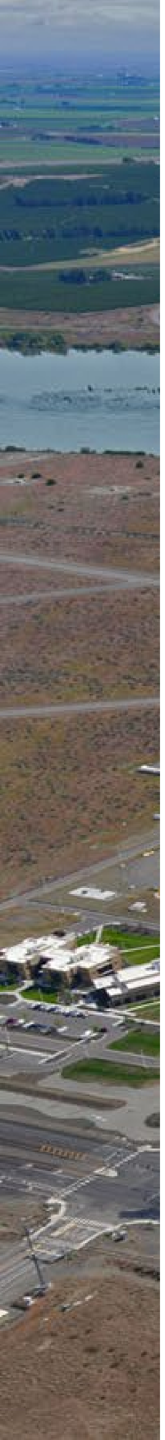
Abbreviations/Acronyms

- ASNT – American Society for Nondestructive Testing
- ATFM – adaptive total focusing method
- CASS – cast austenitic stainless steel
- DAS – delay and sum
- DMAS – delay, multiply, and sum
- DMW – dissimilar metal weld
- DoE – design of experiments
- EDM – electrical discharge machining
- EPRI – Electric Power Research Institute
- FMC – full matrix capture
- ID – inner diameter
- LOS – loss of signal
- NDE – nondestructive evaluation
- PA – phased array

PAUT – phased array ultrasonic testing
PCF – phase coherence factor
PCI – phase coherence imaging
PE – pulse echo
POD – probability of detection
PWI – plane wave imaging
RMSE – root mean square error
SNR – signal to noise ratio
TFC – thermal fatigue crack
TFM – total focusing method
TRL – transmit receive longitudinal
TW – through-wall
UT – ultrasonic testing
WCL – weld center line
WSS – wrought stainless steel

Motivation for Work

- The purpose of this task was to evaluate advanced PA techniques that are now commercially available to the nuclear industry and provide a framework for appropriate use of these methods
- Ultimately, the work will:
  - Define the impact of advanced PA techniques on probability of detection, especially for currently difficult examinations such as dissimilar metal welds and far-side exams
  - Assess whether these advanced techniques help clarify the significance of NDE findings



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Summary of Previous Work

- Report: “Evaluation of Advanced Phased-Array Techniques: Interim Results,” August 2023
  - ML23216A009, PNNL-34622
- Results showed that detection rate drops as microstructures/materials become more complex
  - Standard PAUT had the highest detection rates overall
  - FMC had the most accurate length sizing in the fine-grained WSS mockups
  - Detection rates in the CASS-CASS mockups were lowest overall. This was not unexpected due to the difficulty of CASS inspections and the small transmit aperture of FMC, where one element fires at a time
  - All methods struggled with length sizing in coarse-grained mockups due to sound field scatter and attenuation
- SNR for each UT method depended on specimen type
  - SNR was consistently highest with standard PAUT
  - SNR was consistently lowest with PWI
  - FMC performed best on fine-grained WSS
- Limited data compiled from the round robin resulted in weak statistical confidence for many analyses

Scope

- Evaluate flaw detectability with advanced UT techniques
  - FMC-TFM
  - PWI-TFM
- Compare results from commercially available equipment and software
  - Zetec (Eddyfi) Emerald
  - Eddyfi Panther
  - Sonatest Veo3
- Use a DoE to limit variables for statistical analysis
  - 2-MHz matrix array and linear array probes
  - DMW and WSS-WSS austenitic welds (no CASS)
  - Thermal fatigue cracks oriented circumferentially
- Focus conclusions on POD and sizing of flaws
  - Near-side and far-side exams
  - Length sizing and depth sizing
- Explore commercially available TFM data reconstruction algorithms
  - DAS, DMAS, PCF, PCI
- Look at upcoming techniques/algorithms that may not be commercially available yet
  - ATFM, Pulse Compression

Data Collection Plan

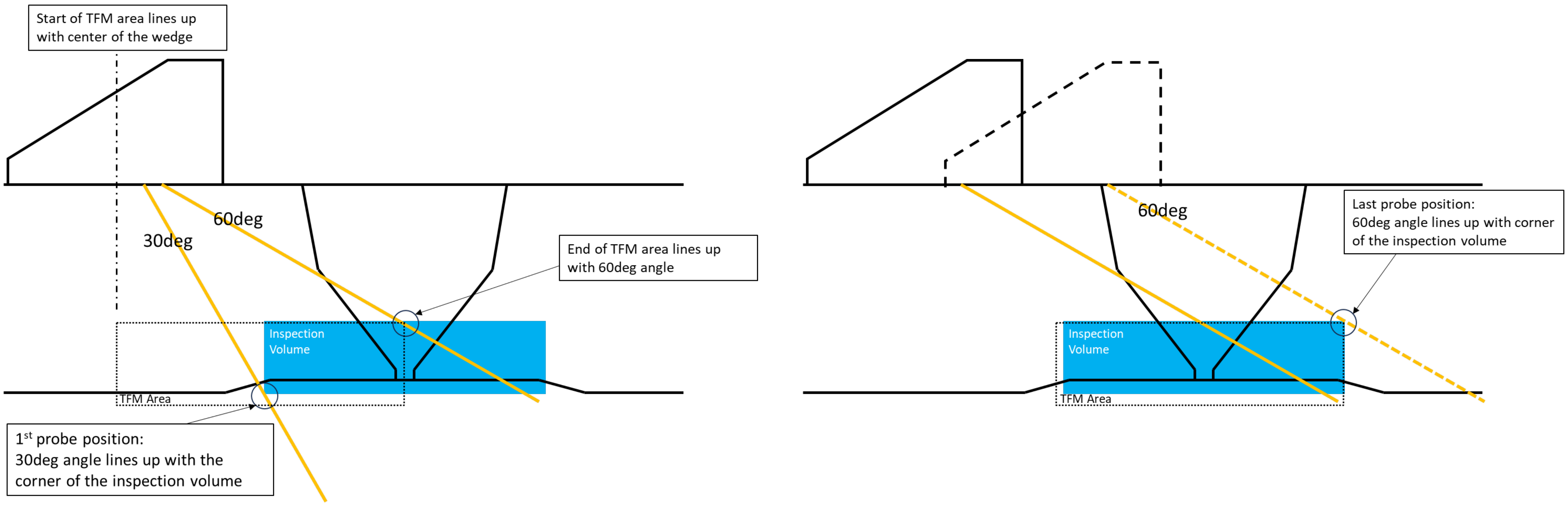
- LMT Advanced NDE Training Workshop
  - Held in 2023
  - Learned about vendor-developed methods for setting up and executing PWI scans for DMWs
  - These methods were followed throughout this phase of work for both FMC and PWI
- Data acquisition approach: Evaluate differences between commercially available hardware and software
  - Collect data with multiple commercially available instruments on same specimens using same probe frequency and scan parameters
  - Include only TFC, no machined notches
  - Include only circumferentially-oriented flaws (no axial flaws)
  - Limit materials to ≈1-2 inches thick
  - Limit material types to WSS and the carbon steel side of DMWs
  - Analyze data using a documented, systematic approach to ensure consistency

Data Collection Method

- Multi-line FMC scans were collected to cover the inspection volume
  - At least 4 line-scans on each specimen
  - Scan positions and TFM area were defined by information learned at LMT training course (shown in next slide)
  - Selected scan positions ensured a 30-60° PAUT angle sweep would be covered for inspections
  - All scans were collected using longitudinal wedges
- PA-UT probes
  - 2-MHz 10×5 matrix array, used with the Panther and Emerald
  - 2.25-MHz 20×1 linear array, used with the Veo3
- FMC data from each line scan were reconstructed using “Live TFM” (DAS) available for each system using direct mode longitudinal (L-L)

Data Collection Method: Multi-Line Scan Setup

- First and last line positions are defined based on inspection volume. Intermittent line positions are added to ensure full coverage of inspection volume
- A TFM area was defined based on maximum 60° angle and half the wedge footprint



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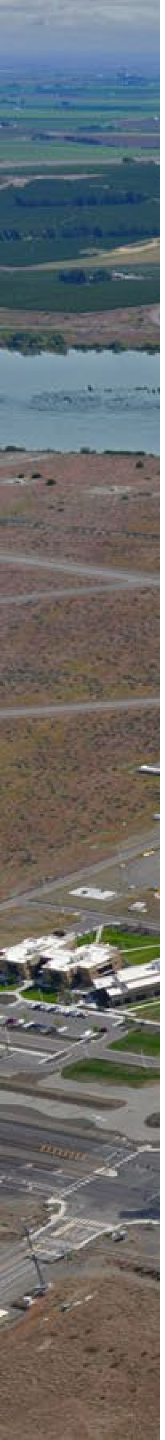
Data Collection: Hardware

- Three systems: Panther, Emerald, Veo3
  - Similar internal hardware
  - Variations in probe types supported and processing algorithms
  - Software used for collection and analysis
    - ✓ UltraVision 3 (Emerald)
    - ✓ Acquire/CIVA (Panther)
    - ✓ UT View (Veo3)
- Staff operating the equipment were trained on each instrument by the respective vendors

		Panther	Emerald	Veo3
Company		Eddyfi	Zetec (Eddyfi)	Sonatest
Operating Software		Acquire	UltraVision3	UT Studio
Max Elements		128	64	64
Frequency Bandwidth (MHz)		0.4-20	0.5-18	0.2-23
Scanning		Single Lines	Multi-line	Single Lines
Collection Method	FMC	x	x	only PE
	PWI	x	x	only PE
Processing	TFM (DAS)	x	x	x
	TFM (DMAS)		x	
	TFM (PCF)		x	
	TFMi™			x
	PCI		(future release)	x
	PAUT		x	

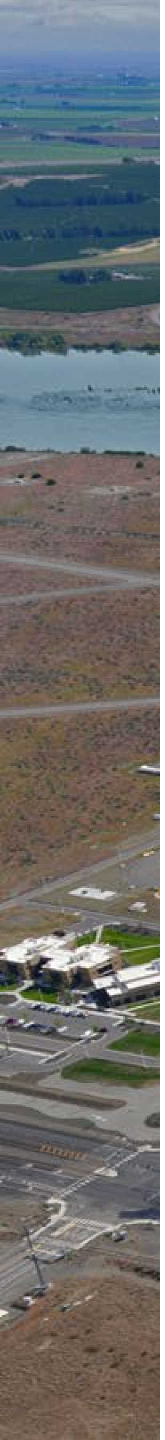


Data Collection: Scan Matrix

- These data were collected since the last report
  - Focusing on defined DoE parameters
- The Veo3 did not have TRL capabilities
  - All Veo3 scans were collected as PE
- PWI was performed in TRL configuration only
  - Veo3 does not have PWI option
- Color coding:
  - Red: Specimens not yet fabricated
  - Yellow: Specimen not scanned
  - White: Data collected, not yet analyzed
  - Green: Completed analysis

Specimen ID	Material Type	Scanner	Flaw Label	# Flaws	PAUT	FMC		PWI
					TRL	PE	TRL	TRL
02-24-15 s1	WSS	Emerald	A & B	2	(raster)		x	x
		Panther					x	x
		Veo3				x		
02-24-15 s2	WSS	Emerald	C	1	(raster)		x	x
		Panther					x	x
		Veo3				x		
21C-303-1	WSS	Emerald	1 & 2	2	(raster)		x	x
		Panther					x	x
		Veo3				x		
(NEW)-01	WSS	Emerald	all	5	(raster)		x	x
		Panther					x	x
		Veo3				x		
(NEW)-02	WSS	Emerald	all	5	(raster)		x	x
		Panther					x	x
		Veo3				x		

Specimen ID	Material Type	Scanner	Flaw Label	# Flaws	PAUT TRL	FMC PE	FMC TRL	PWI TRL
8C-036	DMW (CS-only)	Emerald	all (1-6)	6	(raster)		x	x
		Panther					x	x
		Veo3				x		
9C-023		Emerald	all (1-4)	4	(raster)		x	x
		Panther					x	x
		Veo3				x		
7C-059		Emerald	all (1-4)	4	(raster)		x	x
		Panther					x	x
		Veo3				x		
8C-032		Emerald	all (1-4)	4	(raster)		x	x
		Panther					x	x
		Veo3				x		
706-P1	DMW	Emerald	1 & 3	2	(raster)		x	x
		Panther					x	x
		Veo3				x		
706-P2	DMW	Emerald	1 & 3	2	(raster)		x	x
		Panther					x	x
		Veo3				x		
707-P1	DMW	Emerald	1 & 2	2	(raster)		x	x
		Panther					x	x
		Veo3				x		
707-P2	DMW	Emerald	2 & 3	2	(raster)		x	x
		Panther					x	x
		Veo3				x		



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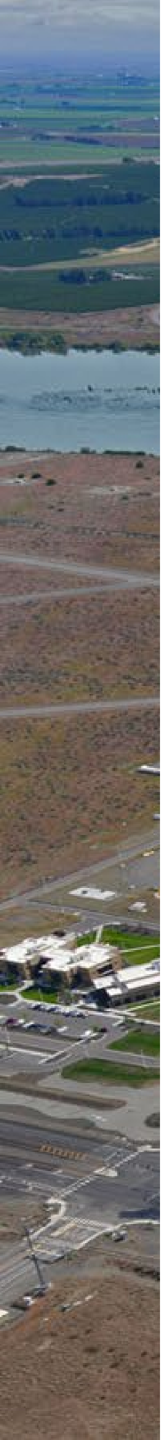
Analysis Approach

- Analysis procedure was documented to ensure consistent analysis across all data
  - Developed by a PDI Qualified ASNT UT Level III
- For a given specimen, each line scan was analyzed independently
- Detection
  - Analysis was not blind
  - Analysts looked for potential flaw signals where flaws were known to be
  - Unconvincing (low SNR) or obviously spurious signals were ignored
  - For specimens with multiple types of flaws, only TFCs were characterized
- Sizing
  - LOS sizing
    - ✓ Measure length of flaw at positions where signal reaches noise floor
    - ✓ Noise floor was estimated by the analyst using an echodynamic curve
- Two methods for depth sizing were used
  - Maximum tip signal (or maximum flaw signal if no tip was detected)
  - Tip “roll-off,” or location of approximately −6 dB decrease in tip signal
    - ✓ In our experience, this method is more accurate than measuring the location of the maximum tip signal
    - ✓ However, this method is more subjective, relying on analyst’s judgment

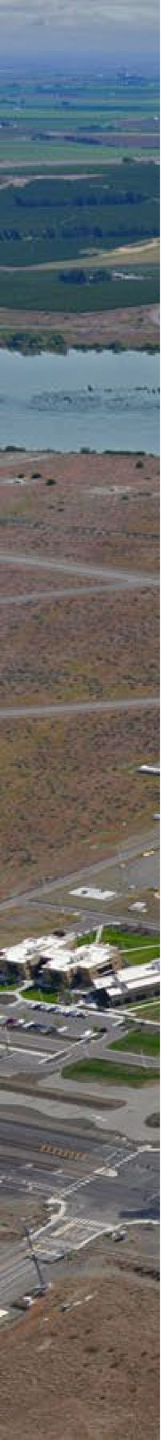


Notes on Analysis Software

- UltraVision 3 (Emerald data)
  - Proven and established industry standard software package for data acquisition and analysis
  - Analysis tools (e.g., gating, zooming, measurement cursors, echodynamic curves) are intuitive and easy to use
  - Gating/zooming quickly updates views once a file is loaded
  - Once a view is set up, another file can be opened to use the identical display settings (view windows, cursor/gate positions, etc.)
- CIVA (Panther data)
  - CIVA has analysis tools, and empirical data from multiple platforms (including the Panther) can be imported for analysis
  - As primarily a modeling and simulation platform, we found that CIVA was not as well designed for analysis as UltraVision, and the tools are not as intuitive as those in UltraVision
    - ✓ For example, gates have three different names: gates, section, and limitations, and there is a learning curve for when and how to use each
    - ✓ There was a lag in image updating whenever a gate was moved, so precisely adjusting gates was difficult and time consuming
    - ✓ Templates (with specific layouts/display settings) can be saved and loaded, but not all display parameters are saved
- UT View (Veo3 data)
  - No soft-gain setting, amplitudes are adjusted by the color bar
  - Cursors, gates, and measurement tools are straightforward to set
  - No echodynamic curves, so measuring LOS length sizing was more difficult
  - Percent-amplitude listed at cursor positions, but unable to measure mean amplitude region for SNR calculations

Notes about Statistical Analysis

- For a robust statistical data set, we estimate the total number of flaws scanned should be at least 60
  - 30 was the minimum where statistical conclusions can be drawn
- The WSS and DMW specimens were combined into one data set
  - 15 unique TFCs were collected and analyzed from the scan matrix
    - ✓ TFCs ranged from 15-77% TW
    - ✓ Documentation on specimen fabrication was used as true state
  - By combining all scans/skews for a given technique (PAUT, FMC, PWI), it was found that:
    - ✓ FMC had enough analyzed data for a meaningful statistical analysis (68)
    - ✓ PWI had nearly enough data for a meaningful statistical analysis (52)
    - ✓ Since PAUT was only collected with the Emerald (26), it could not be used to draw statistical conclusions on its own
- Note that full statistical analyses have not yet been performed on the data set



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Data Results: Detection

- For a given inspection (comprising a set of line scans), a detection in any one of the line scans was considered a successful detection of the flaw
  - Some flaws were detected on multiple line scans, and some flaws were seen in only one
- All flaws were detected from both skews using PA
- The detection rate was above 85% for both the Emerald and the Panther; the detection rate for the Veo3 was below 65%
  - Possible contributing factors to the lower detection rate for the Veo3 include smaller probe elements, fewer elements, and a slightly higher probe frequency
- PWI had the lowest detection rate of the three methods
- FMC-TFM for both the Emerald or the Panther had no missed detections when full coverage (both skews) was considered
- PWI-TFM for both Emerald and Panther missed one flaw each during full coverage exams, but not the same flaw
  - Emerald PWI missed 706-P2 Flaw 3; Panther PWI missed 707-P2 Flaw 3
- The most challenging flaw to detect across the advanced methods was 706-P2 Flaw 3
  - 21% TW, 10° tilt, 20 mm off the WCL in the buttering; see slide 20
  - This flaw was only detected from one skew for each instrument/method (Veo3 included)
  - Overall, the detection rate of this flaw was 40%

Percent Detection of Flaw Set

Scanning…	PAUT	FMC						PWI					
		Emerald		Panther		Veo3		Emerald		Panther		Veo3	
		sk90	sk270	sk90	sk270	sk90	sk270	sk90	sk270	sk90	sk270	sk90	sk270
From one skew	100%	100%	93%	93%	93%	13%*	63%*	93%	87%	87%	87%		
Full coverage		100%		100%		63%*		93%		93%			
By method		100%						100%					

*Due to time constraints, only the 8 EPRI flaws were scanned with the Veo3

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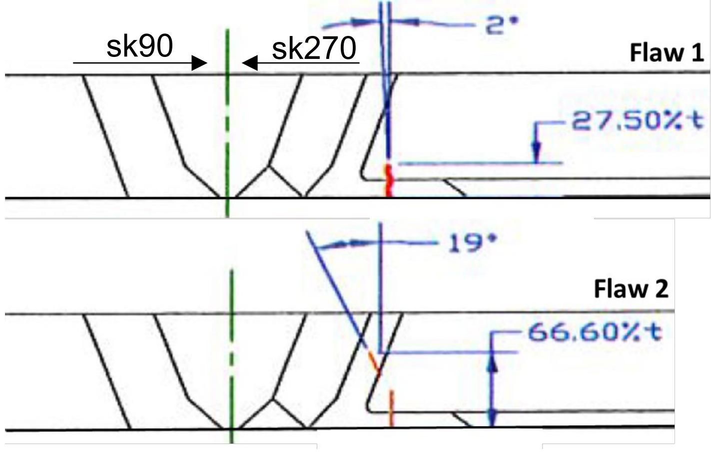
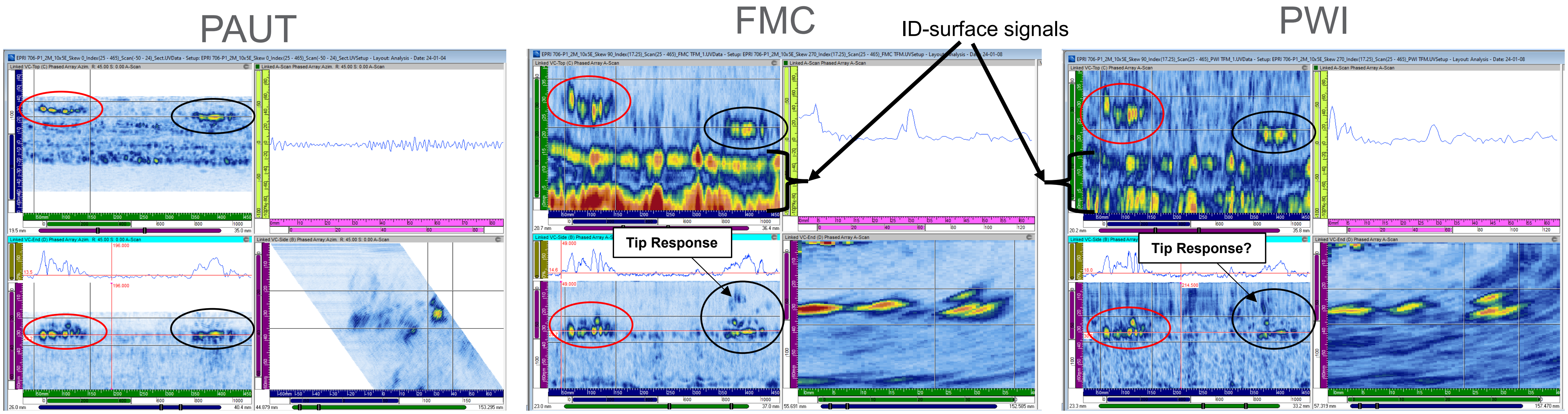
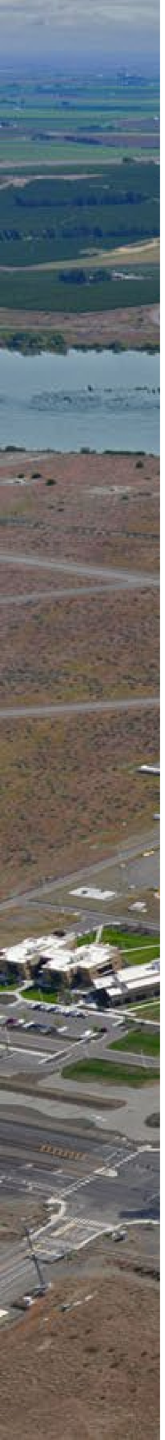
Example Scan Results: Detection

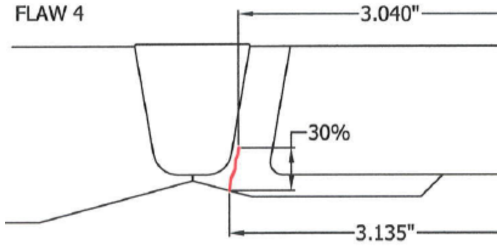


- General noise floor of PWI was higher than FMC or PAUT
  - FMC and PAUT were generally comparable
- FMC (and to a lesser extent PWI) can generate a large signal from the backwall
  - Adjustment of the TFM area can minimize the ID signal response
  - Raster scans can be hard to analyze since the ID signal can drown out the flaw corners
- The figures show two flaws detected in 706-P1 (DMW) and the surrounding background noise levels
  - Flaws 1 and 2 are circled in red and black, respectively

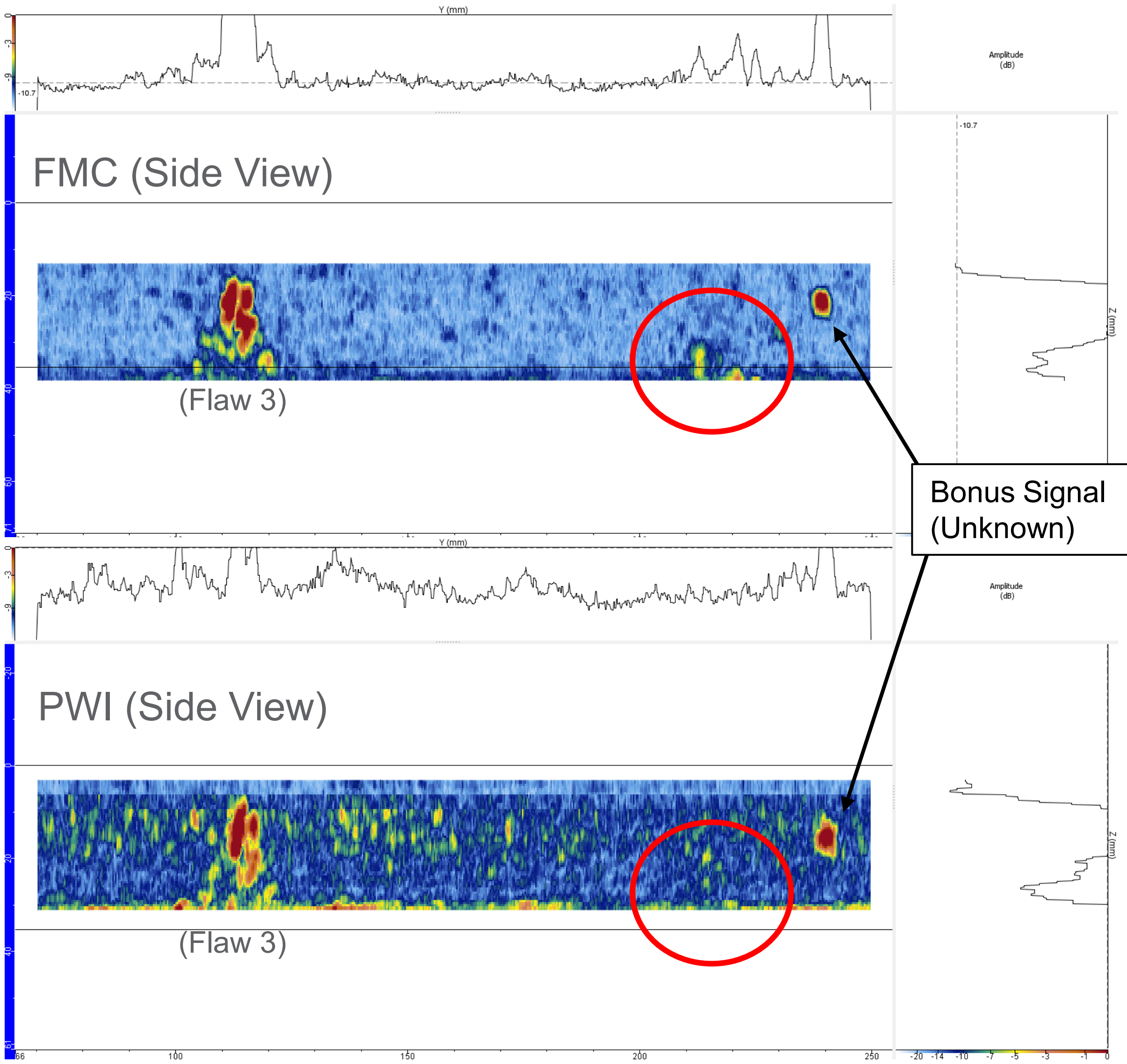




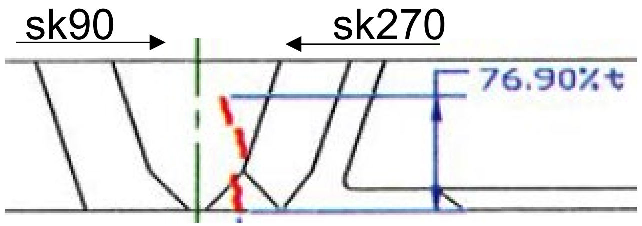
Example Scan Results: Missed Detection



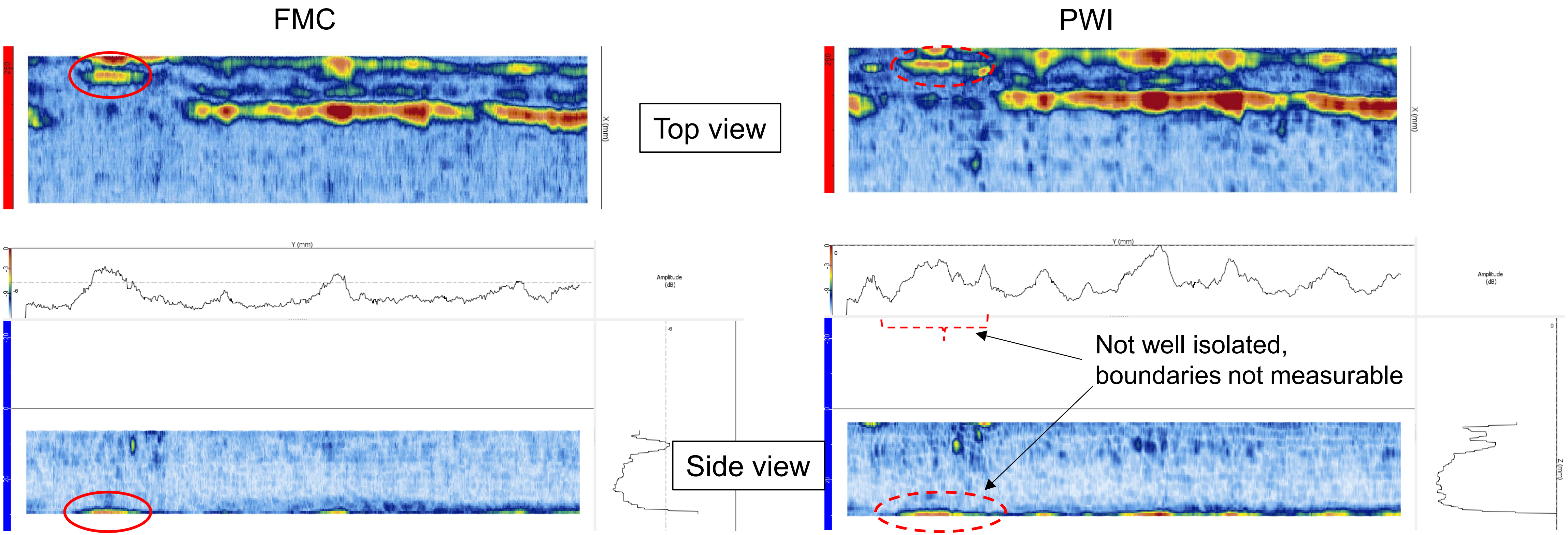
- Flaw was visible in FMC data but not in PWI data (circled in red)
  - Higher noise background in PWI scan made this flaw undetectable
  - Mockup 8C-032 Flaw 4 (DMW)
    - ✓ 30% TW TFC
  - An unknown signal appeared in both scans, possibly a weld fabrication defect



Example Scan Results: Detected but Not Sized

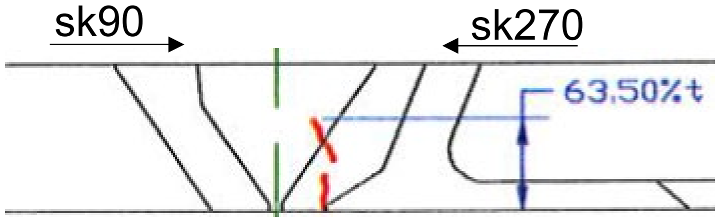


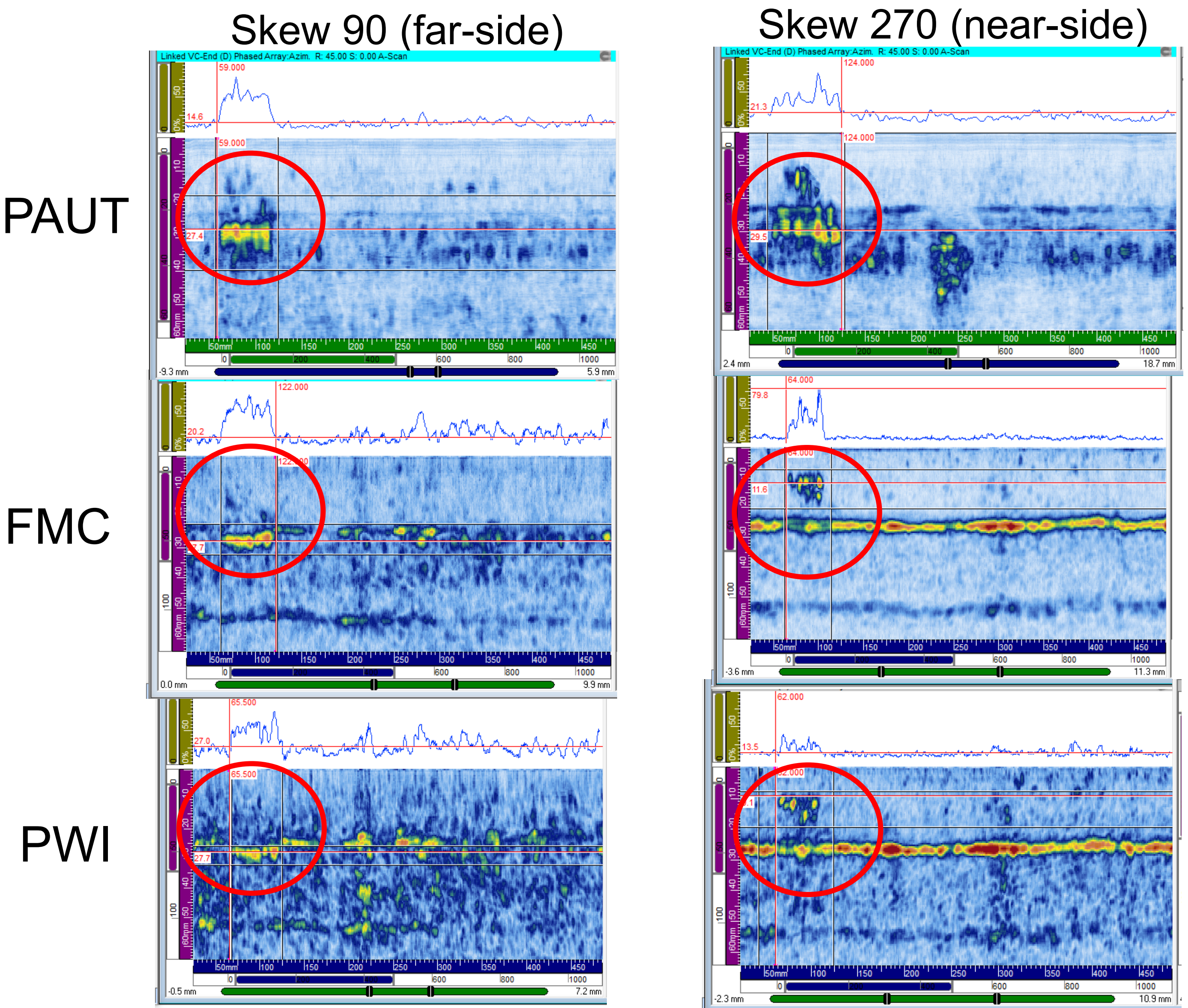
- A flaw appeared in both FMC and PWI scans (circled in red)
  - Flaw could not be length-sized in PWI scan (dashed circle) due to background signals from specimen ID
  - Flaw was easier to isolate in FMC scan, although it was still challenging to gate out the relevant signal
  - Mockup 706-P2 Flaw 1 (DMW)

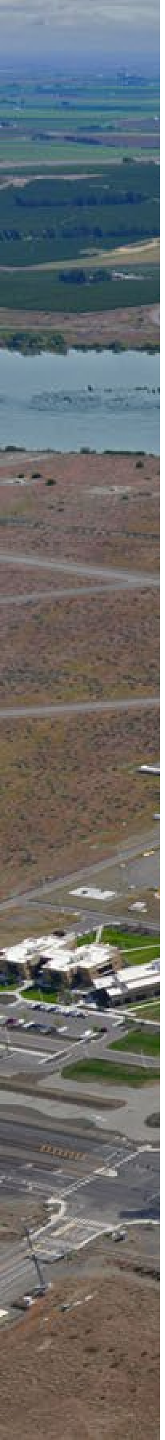


Example Scan Result: Different Methods

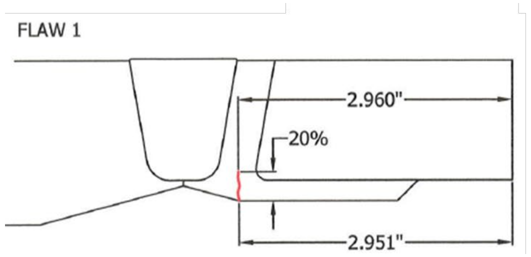
- 707-P1, Flaw 1 (DMW)
  - Multi-segment flaw in the buttering and on the weld fusion line
  - Top of the flaw was tilted in favor of a near-side (skew 270) inspection
- Skew 90 had lower SNR than skew 270 for all methods
  - Corner of the flaw was difficult to detect from skew 270 in the advanced methods due to backwall response
- PWI showed the highest overall noise background
  - PWI was expected to outperform FMC when inspecting through an austenitic weld

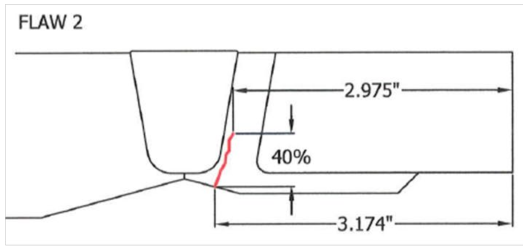




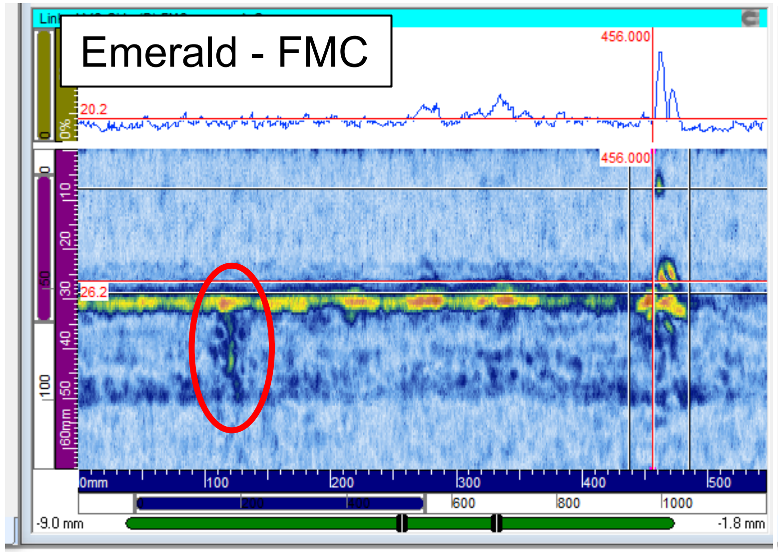


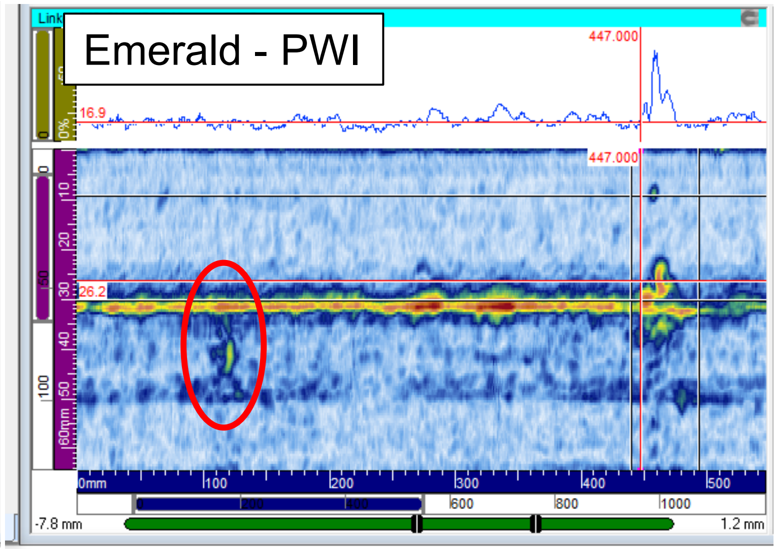
Example Scan Results: Different Hardware

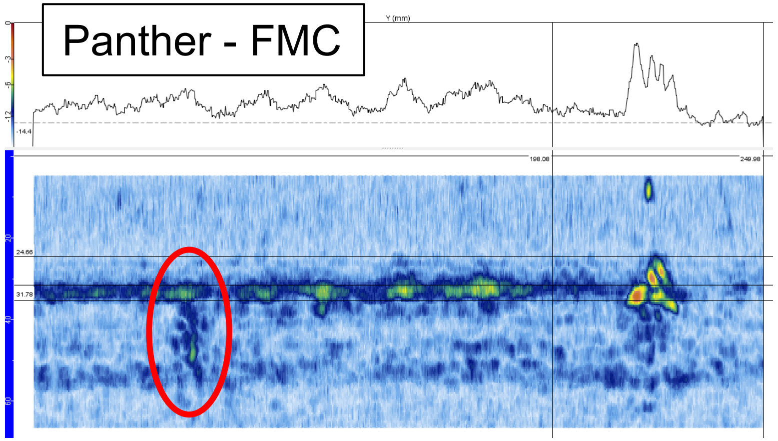


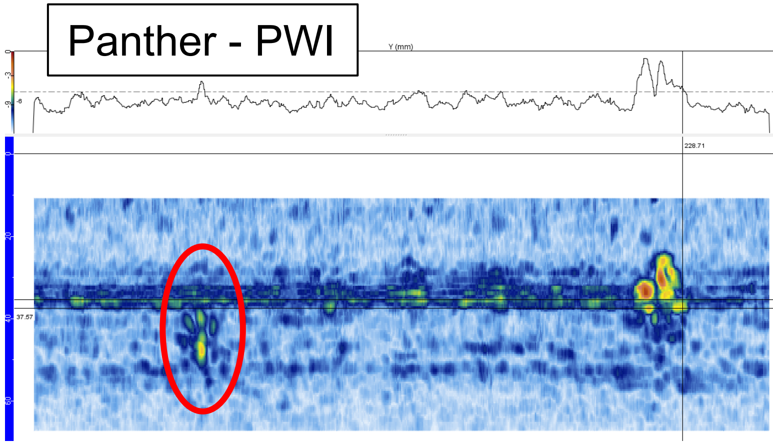


- The same probe/wedge was used with both instruments
  - 2 MHz 10×5 TRL
- Emerald (top) vs. Panther (bottom)
  - Same line scan collected
  - 8C-032 (DMW), skew 270
  - Flaws 1 and 2
- FMC (left) and PWI (right)
  - Both flaws were detected
  - Flaw 1 (red circle) was detected on a full-V bounce
- Similar results for the data
  - Emerald has brighter geometric response
  - Noise and flaw response are similar SNR

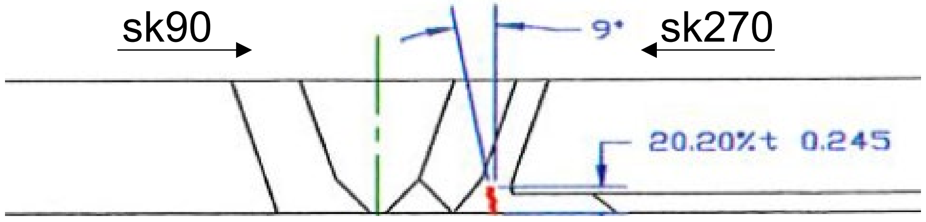






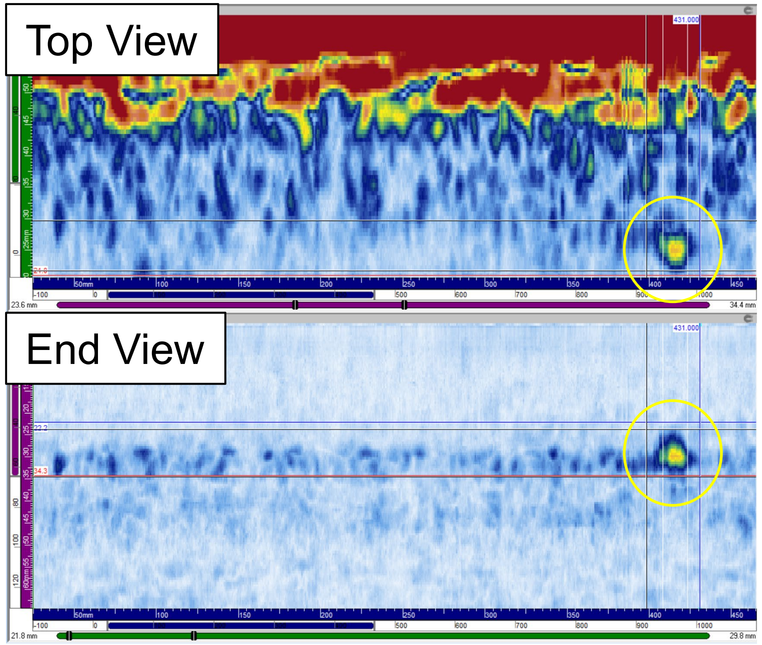


Example Scan Result: Limited Detection

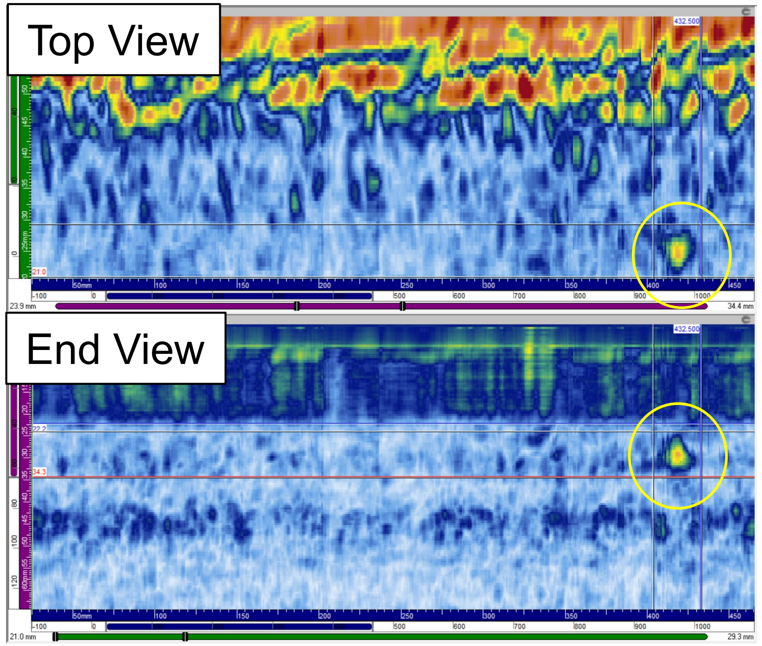


- 706-P2 Flaw 3 (DMW) – Circled in yellow
  - 20% TW flaw located in the buttering
- Only seen with skew 270 (near side) from one line (39 mm)
  - PAUT did not see the backwall noise under the probe
  - PWI experienced noise that interfered with the end-view when the flaws were near the edge of the TFM area

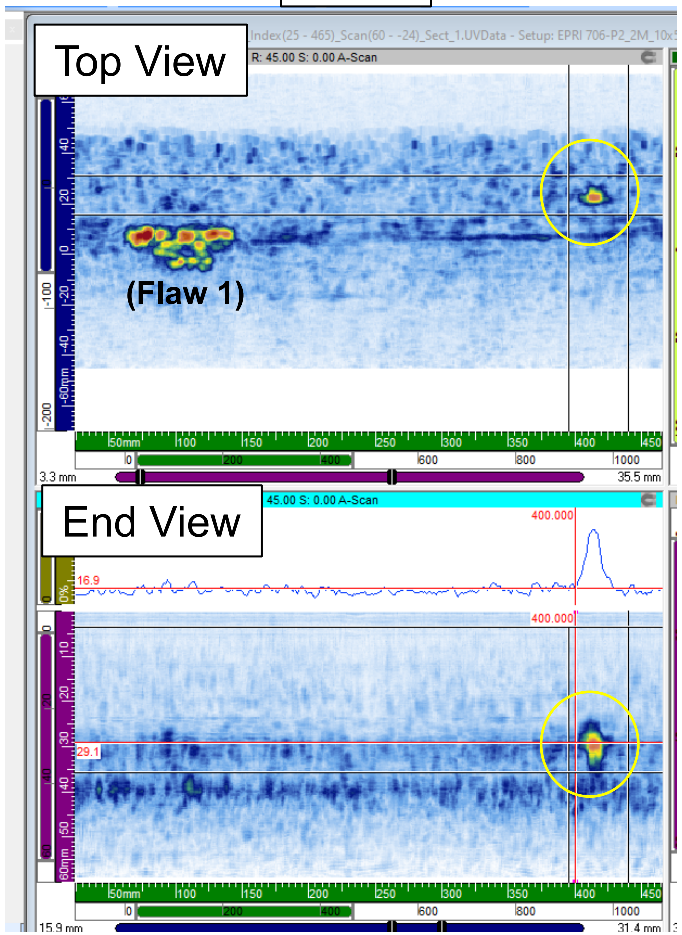
FMC



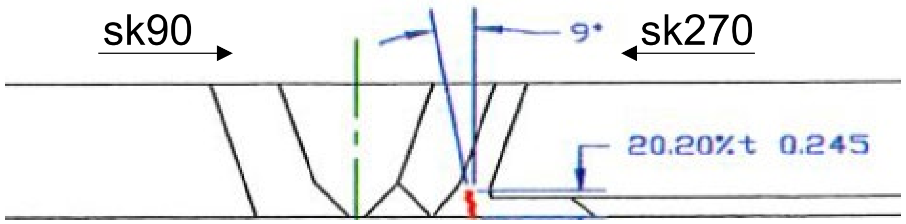
PWI



PAUT

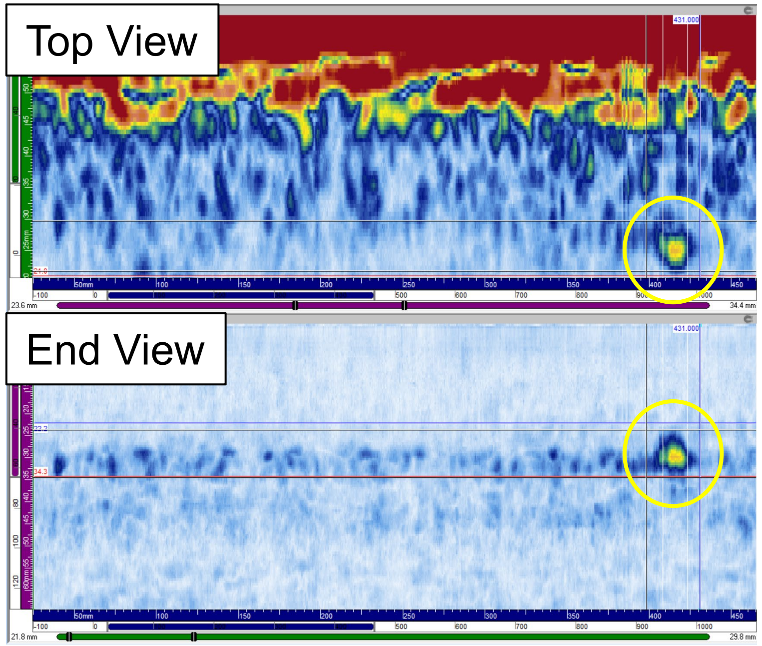


Example Scan Result: Limited Detection (cont.)

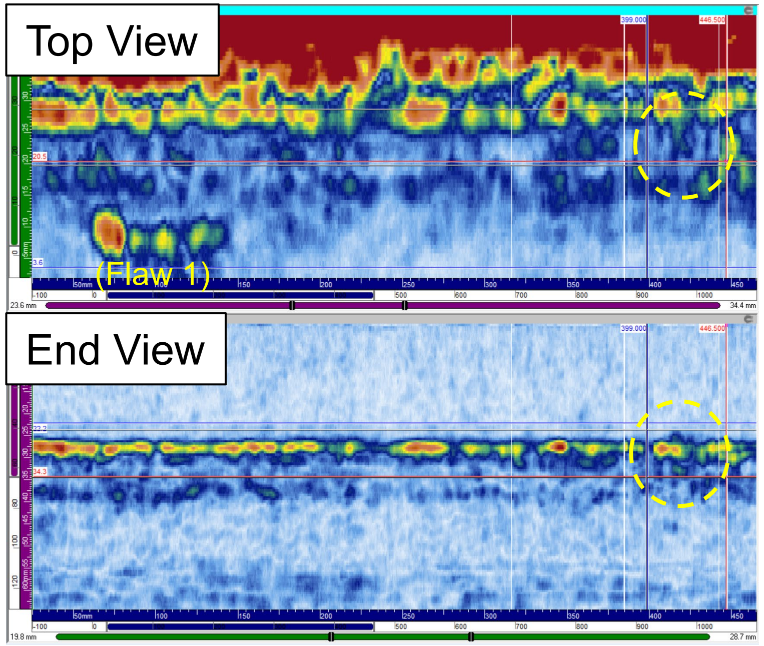


- Examples of additional FMC line scans with Flaw 3 (circled in yellow) or the lack of response where it should be (dashed circle)

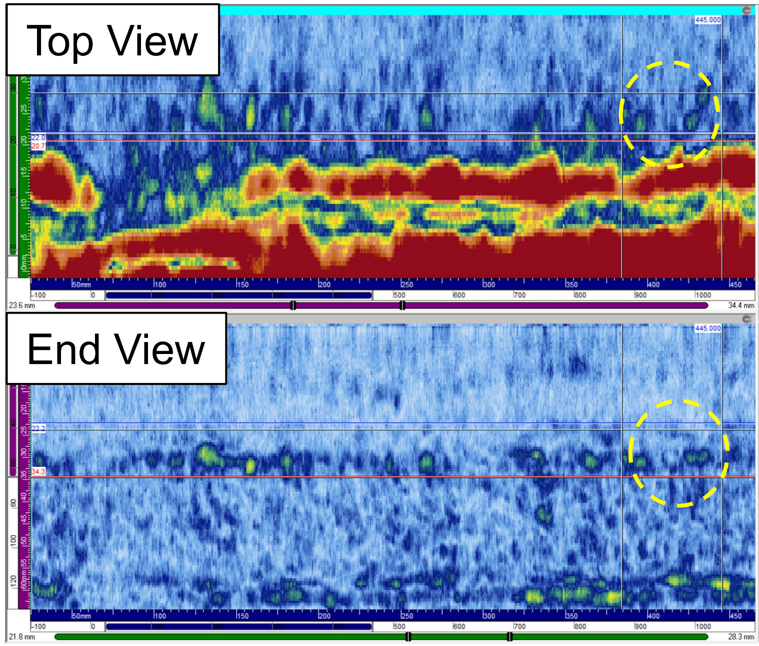
Skew 270 (39 mm index)
Detection

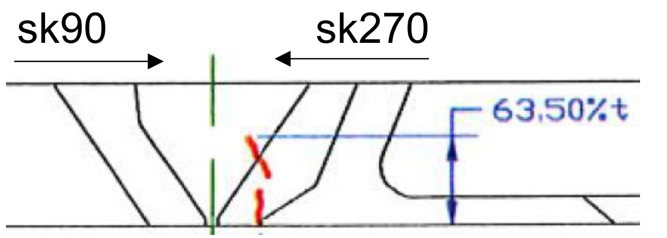


Skew 270 (20.25 mm index)



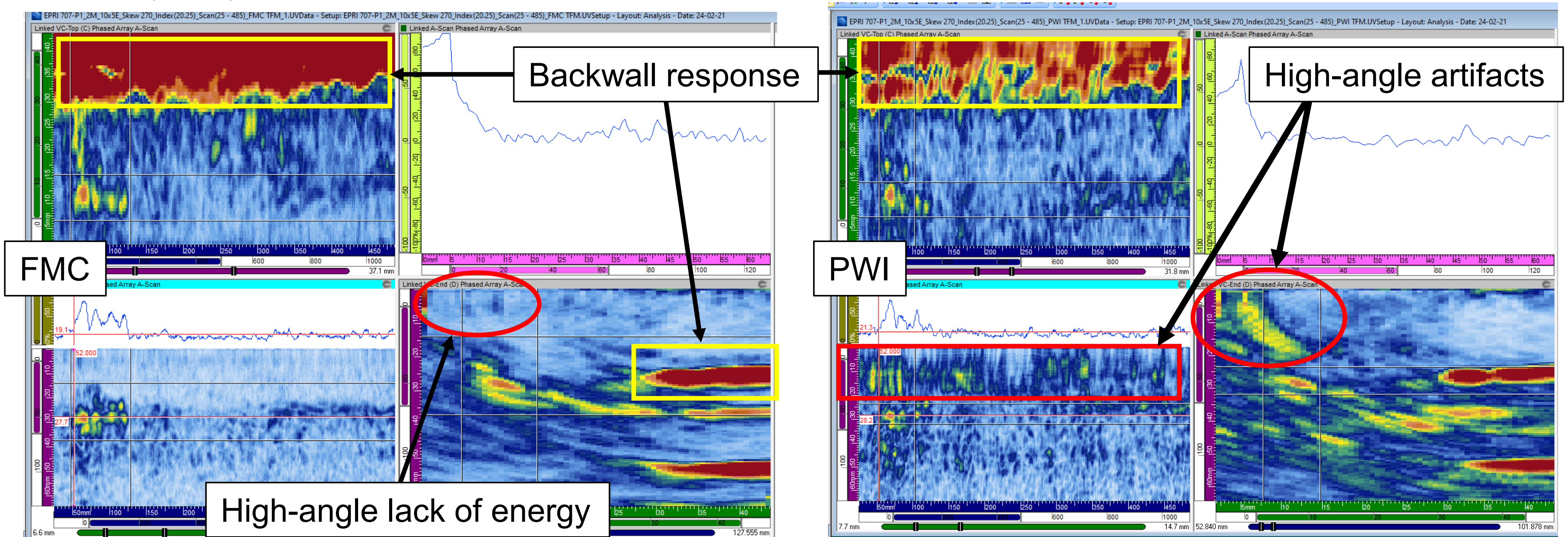
Skew 90 (17.25 mm index)



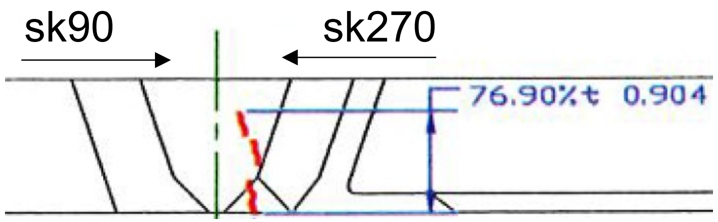


TFM Processing Artifacts

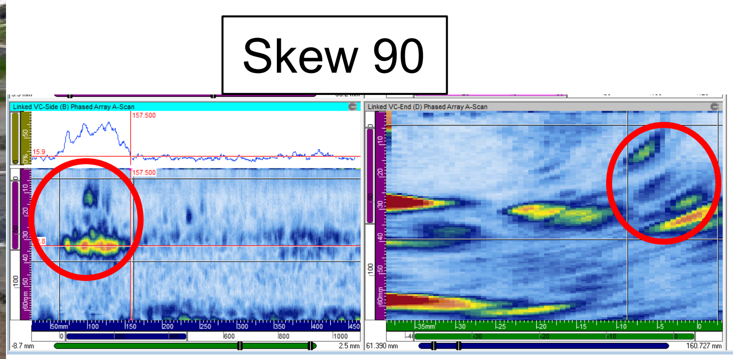
- Both FMC-TFM and PWI-TFM created strong ID backwall responses directly under the probe
  - Backwall responses were higher in FMC than PWI
  - PWI was bulk-waves at prescribed angles, whereas FMC was a spherical wave front
- The top corner of the TFM area was not insonified by the probe and therefore did not contain useful information
  - The top corner would have to be insonified by sound energy emitted at 80+ degrees from the probe wedge for standard PAUT
  - A PAUT probe and wedge will not generate sufficient sound energy at that high of an inspection angle
  - Calculation of PWI tends to create an artificial noise-band in the high-angle region of the TFM area
- 707-P1 Flaw 1 (DMW) is shown

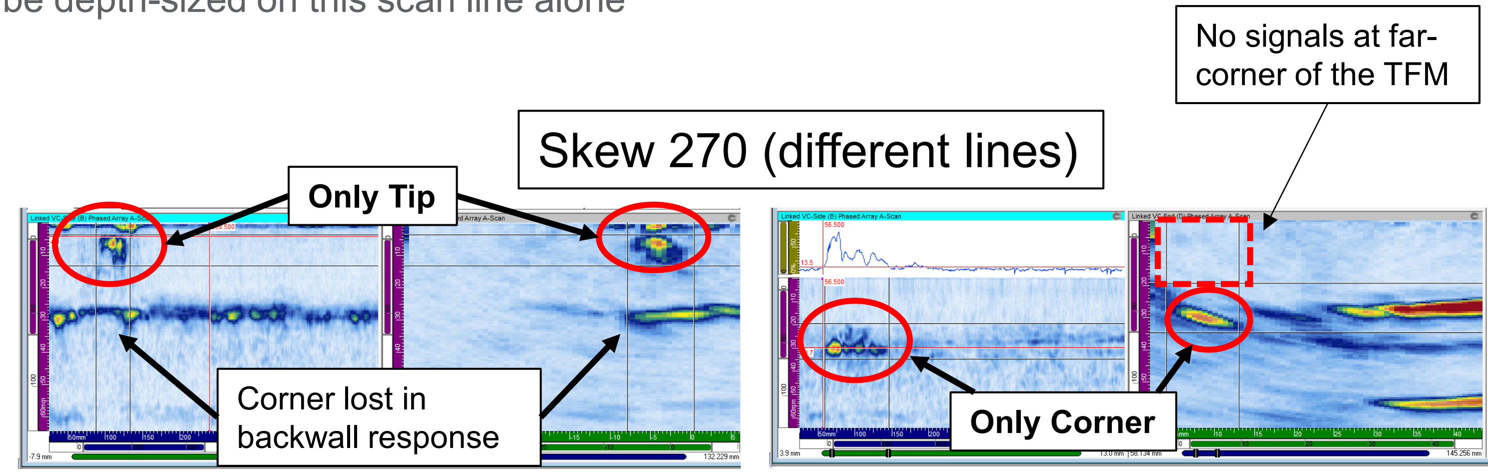


Example Scan Result: TFM Artifact Interference



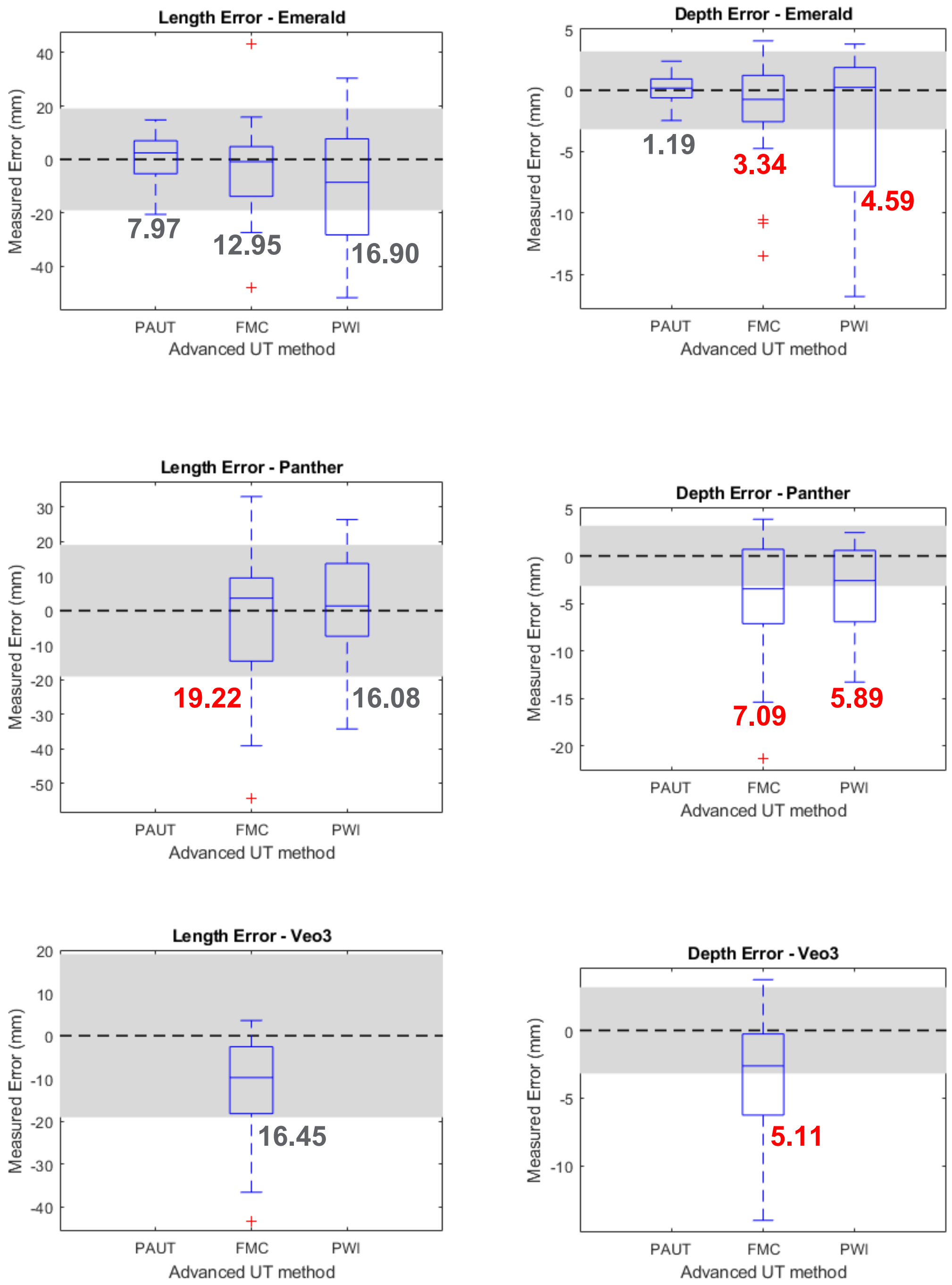
- 706-P2, Flaw 1 (DMW)
  - Multi-faceted flaw near the weld fusion line
  - FMC-TFM
- Skew 90 captured the entire flaw profile, including a tip response
- Skew 270 captured the corner **or** tip, depending on which line was being analyzed
  - Corner was obscured by backwall-response when the tip was insonified
    - ✓ Due to TFM reprocessing capturing normal-beam reflection
  - The tip was not insonified in the next line scan position
    - ✓ The flaw was detected but could not be depth-sized on this scan line alone





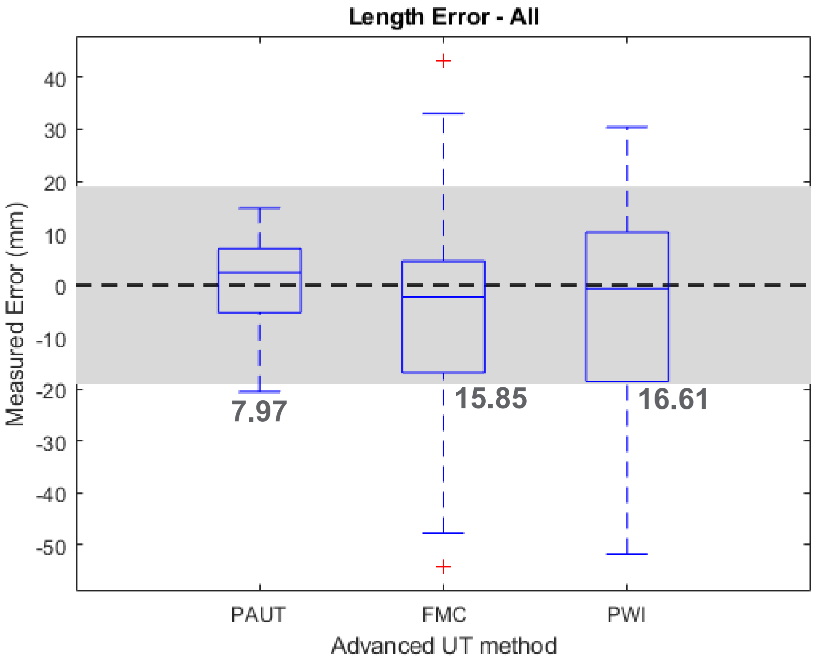
Data Results: Sizing by Acquisition System

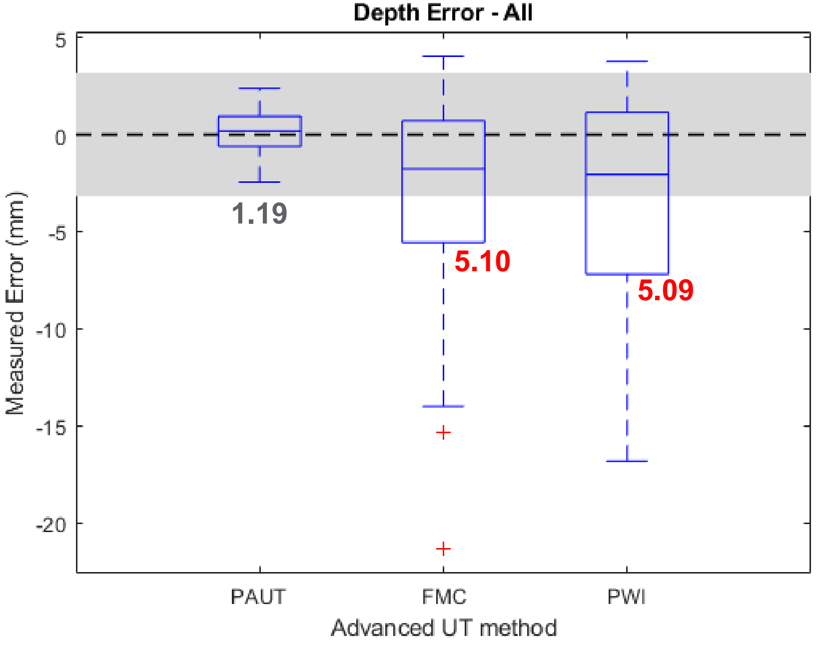
- Box-and-whisker plots show range of length and depth-sizing results for each data acquisition system
- Veo3 consistently undersized both length and depth for FMC (the only mode available)
- PWI depth sizing was biased toward undersizing in depth measurements
- Grey regions on plots depict the RMSE acceptable limits from ASME Code Section XI, Appendix VIII (Performance Demonstration for Ultrasonic Examination Systems)
  - Length: 19.05 mm (3/4 in.)
  - Depth: 3.18 mm (1/8 in.)
- Numbers on plots represent RMSE for each data set
  - Black numbers are within Appendix VIII limits, red numbers exceed those limits
  - All advanced depth-sizing was outside Appendix VIII limits
  - Almost all length RMSEs were within Appendix VIII limits



Data Results: Sizing Overall

- Box-and-whisker plots show combined data for length and depth sizing, comparing different data acquisition methods
- Median length and depth measurements were within 4 mm of true state values for all methods
    - Medians are represented on the plots by horizontal lines within the boxes
    - Black numbers are within Appendix VIII limits, red numbers exceed those limits
    - Length RMSE for all three methods are within Appendix VIII requirements
    - Only PAUT depth-sized within Appendix VIII requirements
- Both advanced techniques had similar length and depth RMSEs



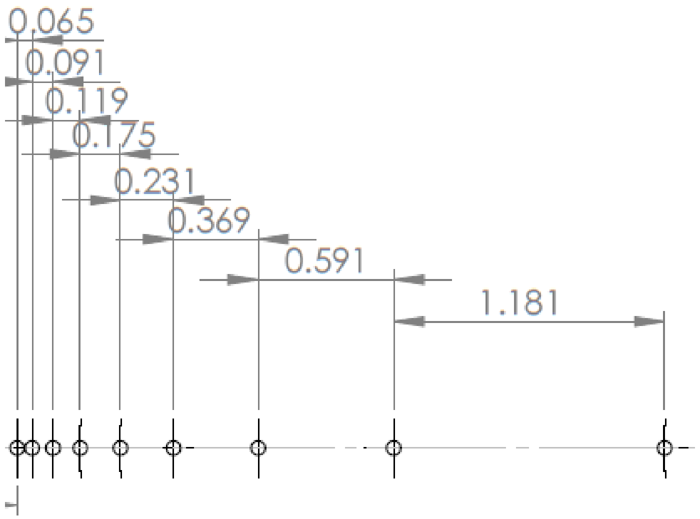


Data Results: Sizing Summary

- PA was able to length size and depth size the flaws within the RMSE limits
- Length sizing of the advanced methods was within or nearly within the RMSE limits for the individual instruments, but depth sizing was not
- None of the advanced methods depth-sized adequately. We found this surprising, especially for FMC, because the advanced methods were expected to be more sensitive
- The material types and weld microstructures in these mockups were probably key factors. The benefits of FMC are often demonstrated on carbon steel, but the flaws in this study were in/near austenitic welds
- The results, which are consistent with the first phase of our work, suggest that the small transmit aperture and low amount of sound energy for each FMC pulse may make it unsuitable for other than the finest grained materials

Results: Resolution Holes

- A specimen with arrays of holes of various spacing was designed to compare imaging resolution of PAUT and FMC.
- Nine holes (not quite flat bottom) were drilled into flat plate mockup 19C-358-2 (WSS) away from the weld
  - WSS base material
  - 1/16-in.-diameter holes
  - Holes were 50%TW (1.25-in.-thick specimen)
  - Holes were drilled with increasing spacing
- Holes were scanned with 2-MHz TRL probe
  - 10×5 elements in each array
- Data were collected as PAUT and FMC



Hole spacing for resolution mockup. Units are in inches.

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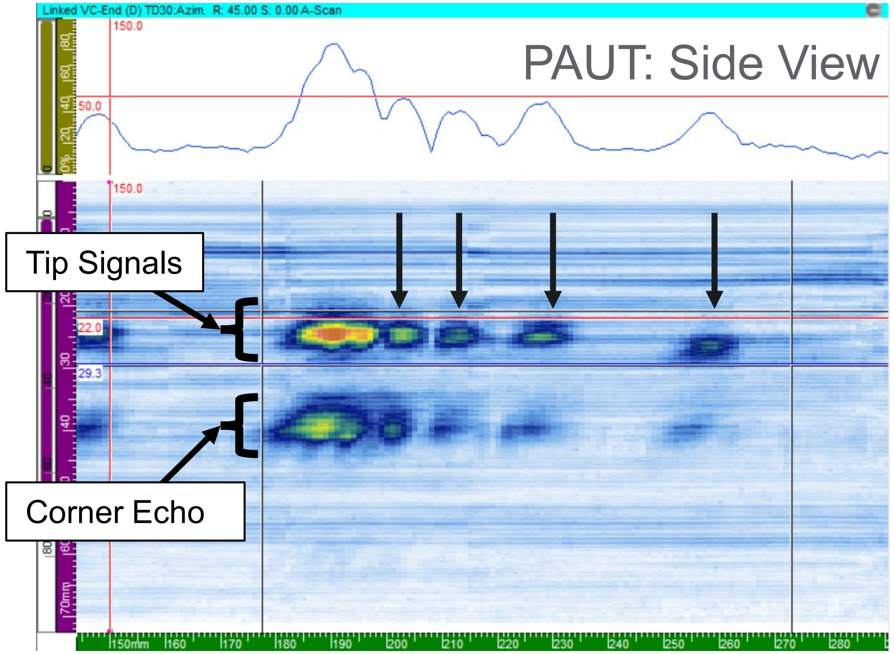
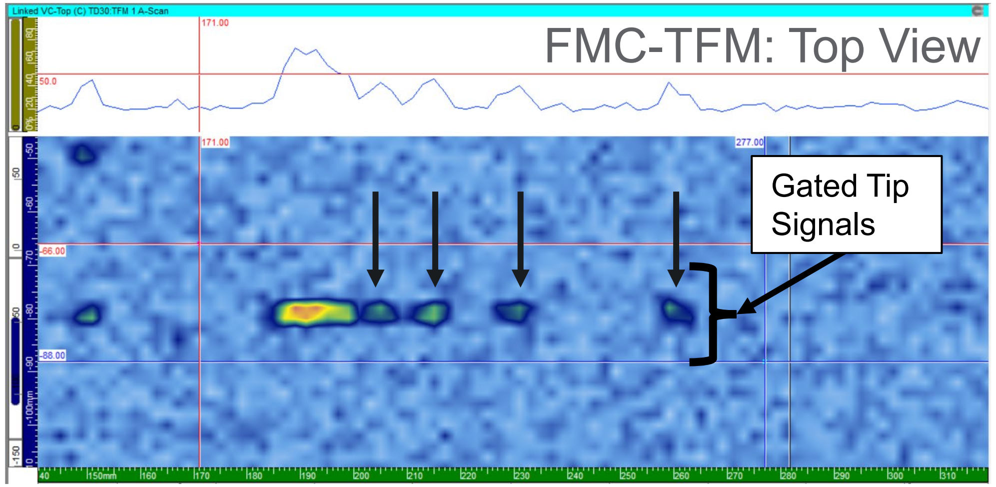
Resolution Holes: Empirical Data

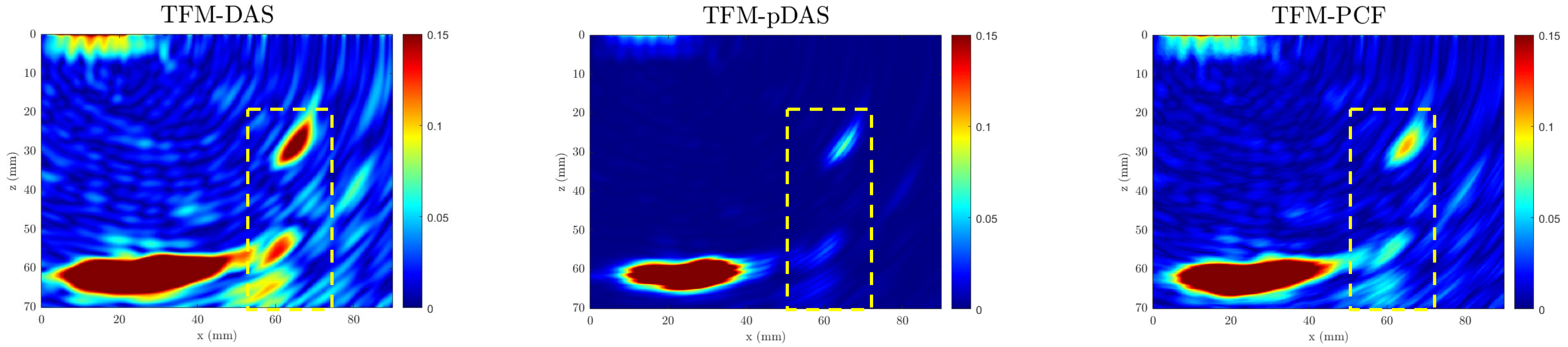
- Empirical scans at 2 MHz using TRL PAUT resolved four holes (indicated by arrows) and showed some corner echoes, although the tip responses were stronger
  - Tips were direct echoes, not tip diffracted signals
- Empirical FMC-TFM also resolved four holes
  - Noise level was high due to WSS material microstructure
  - Tip signals were prominent, but corner echoes were lost in surface reflections
- Overall, both PAUT and FMC performed comparably; however, our expectation that FMC would resolve more holes than PAUT was not met





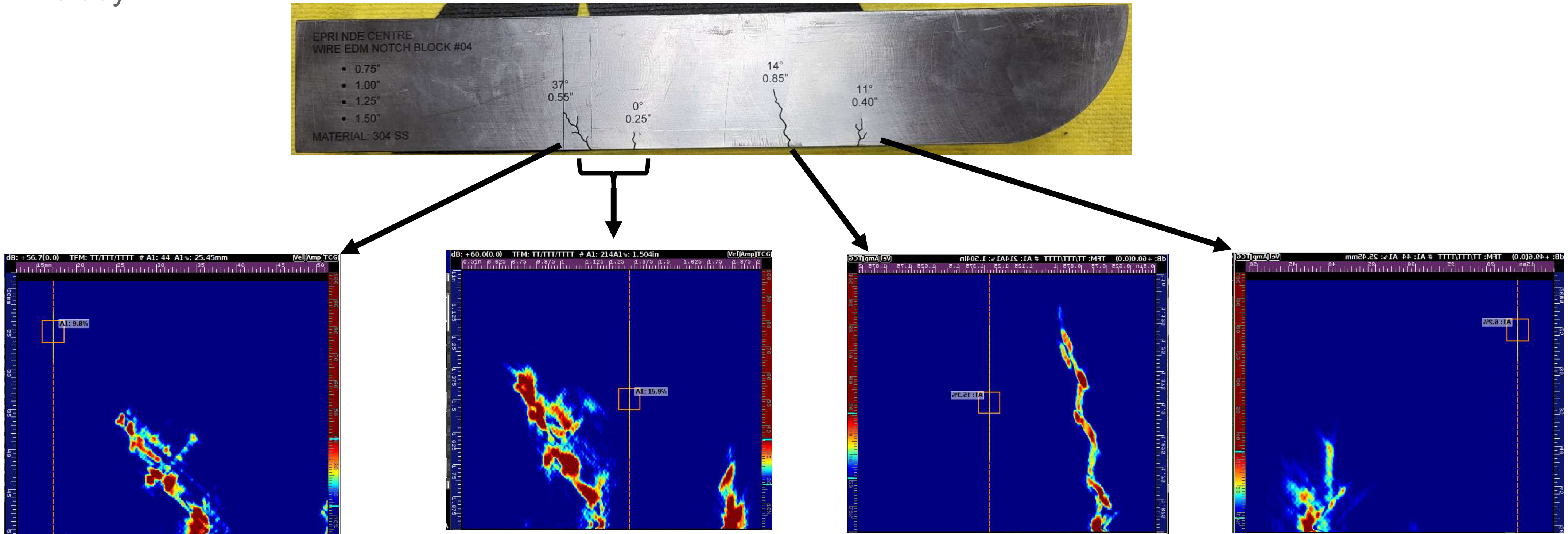
External Data: AOS/TPAC Visit

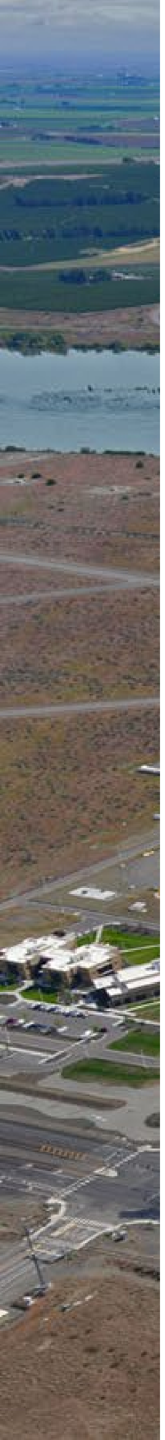
- A series of fixed-position data sets were collected using the Pioneer (TPAC's advanced UT instrument) and TRL transducers (0.5-1 MHz) on coarse-grained CASS samples at PNNL
- PNNL was provided example images of data that were collected. Qualitative differences can be observed from the different processing approaches
  - Differences in post-processing algorithms highlight strengths of collecting raw FMC data that can be reprocessed with different TFM algorithms
  - Flaw responses for B504 Flaw 1 are shown below (dashed yellow box)
- The pDAS method had the lowest noise floor, but it also had the lowest signal intensity. Determining the superior processing method was subjective



External Data: Sonatest TFMi™ with the Veo3

- A series of fixed-position scans were collected on a wire EDM Notch Block on loan to PNNL from EPRI
  - 2-in.-thick, fine-grain WSS
  - Wire EDM “cracks” spanning the entire width of the specimen
- Data were collected using a 5-MHz 32×1 linear array on a shear wedge
  - TFMi reconstruction using TT, 3T, 4T (and sometimes TTL) modes
- Results of this test were impressive. Scans from single probe positions visualized the full flaw geometries, including branches and facets. However, results did not translate well to mockup scans and actual cracks in this study





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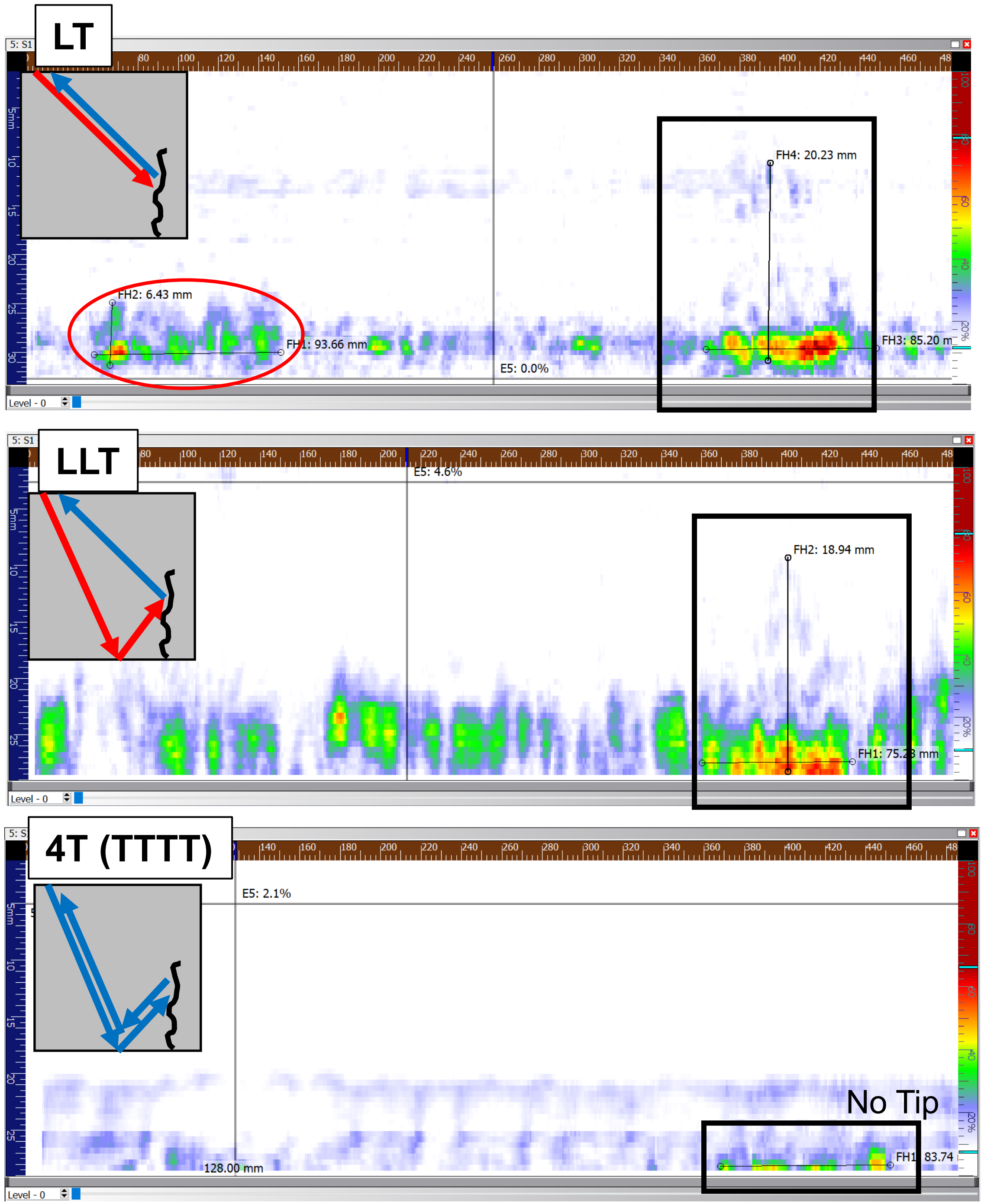
Intro to TFMi™: Alternate Processing Modes

- TFMi uses multiple modes and mode conversions to generate an image
  - By combining different TFM processing modes/algorithms, spurious noise signals can be greatly reduced
- Most systems default to a single direct mode (usually LL or TT) for Live-TFM processing
  - Such modes only give direct signal responses from the flaw with no specimen bounces
- Commercial options are becoming available for some hardware to define which wave path to process
  - Indirect bounces as well as mode-conversions can be used as the travel time calculation for the TFM grid
  - Bouncing limits the TFM area to the ID of the specimen as defined
- The figure shows 706-P1 Flaw 2 (black box) with different mode processing
  - Flaw 1 also detected/sized in LT (circled in red)



TFMi™: Overview

- Technique where FMC data collected are processed in TFM using multiple beam paths
  - TT, LL, LT, TTT, etc.
- These processed TFM results are combined into one final image
  - Algorithm involves multiplying these processed results
  - All modes are processed and combined in real time, so modes cannot be separated, added, or removed in post-processing
- Amplitude of final image decreases dramatically, but inconsistent signals (such as noise) become zero
  - TFMi greatly reduces or removes signals that do not appear across all processed modes
    - ✓ Processing modes that do not detect the flaw will likely remove flaw signals from the final processed image
  - Selection of which modes to use becomes **<u>very</u>** critical
    - ✓ Difficult to determine which methods are needed beforehand

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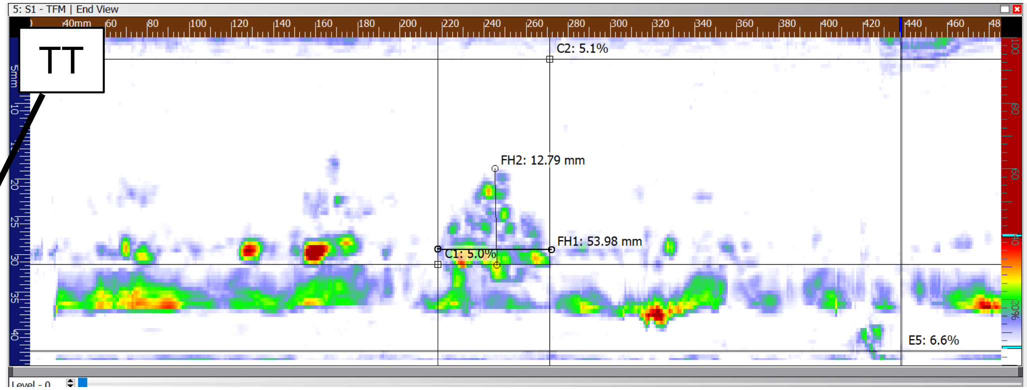
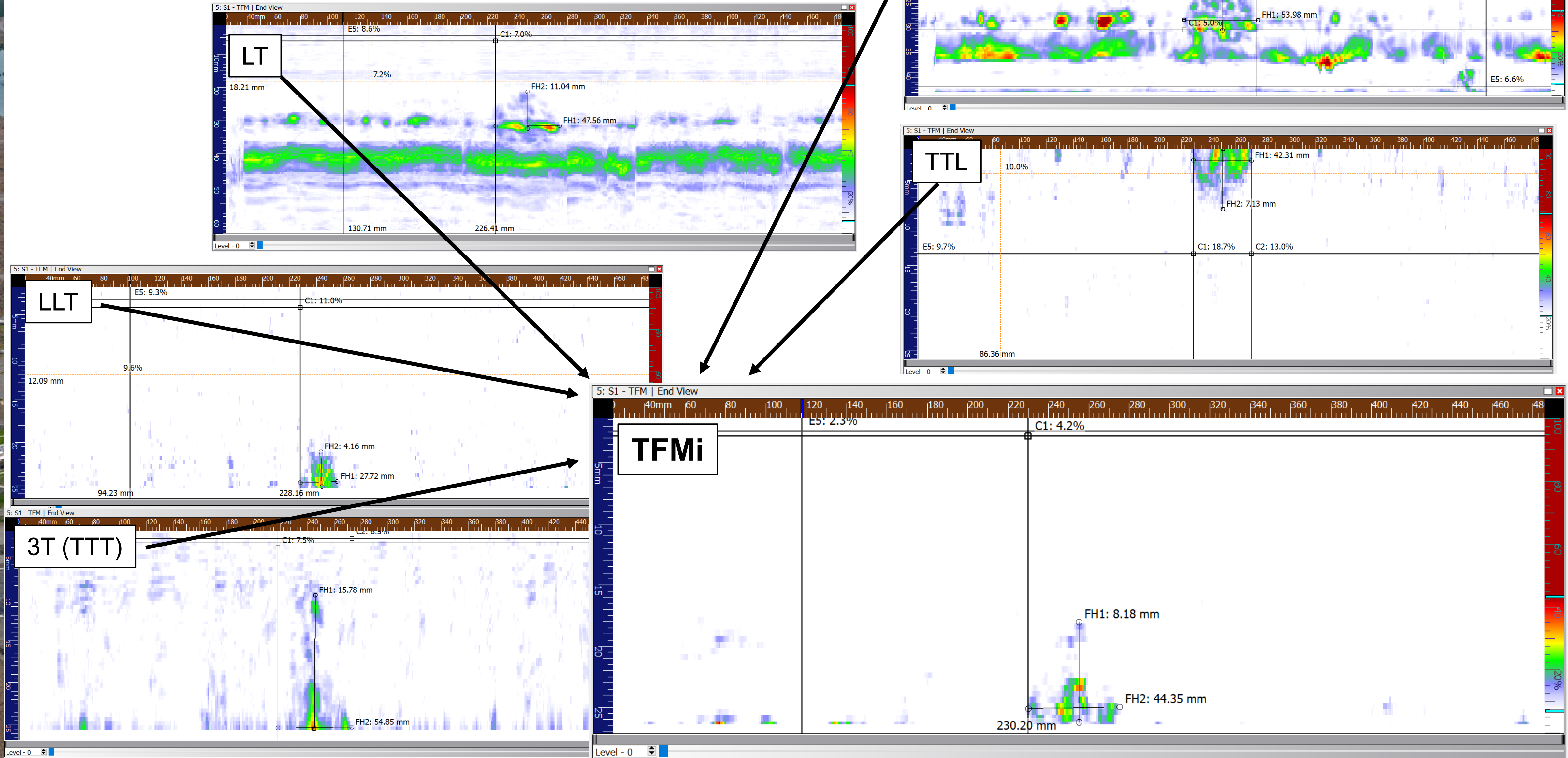
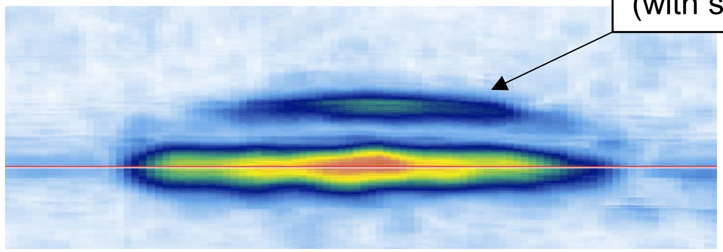
TFMi™: Example



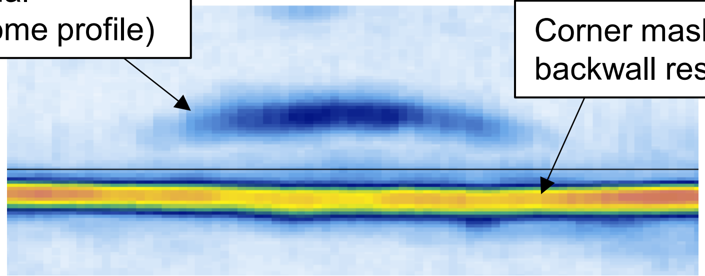


Notes on TFM Reprocessing (post-processing)

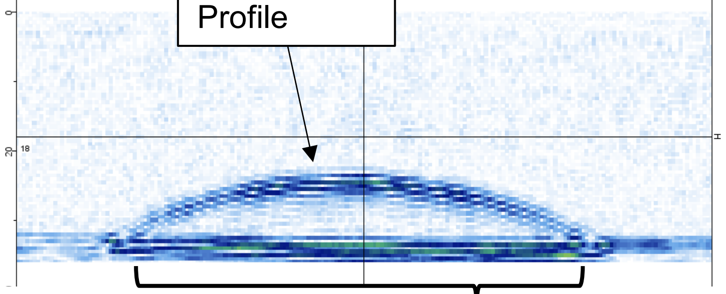
- Systems typically default to "Live TFM" (DAS) for reconstruction due to less-intensive calculation (less speed constraints while scanning), and raw A-scan data are discarded
  - To allow for additional post processing, raw A-scan data must be stored
  - Collecting all the raw A-scans slows down scanning significantly and results in very large file sizes
- Post-processing of raw data allows for different algorithms to be evaluated on the data set to best highlight regions of interest
  - Different algorithms have positive and/or negative impacts on flaw signals and background noise
  - Multiple iterations can be required to get the correct parameters and reconstruction volume
  - Results can improve flaw characterization
  - Due to extra time in setting up and executing the reconstructions, post-processing is not suitable for routine detection
- Example below shows standard PAUT (left) and FMC-TFM (center) scans of an EDM notch (WSS). In the CIVA-reconstruction of the raw FMC data (right), the entire notch profile and corner response was easily characterized (length, depth, profile)
  - Both PAUT and FMC-TFM detect the tip
  - Corner was not visible in Live-TFM due to backwall response
  - Shows positive impact of reprocessing on the ability to characterize flaws



PAUT



FMC-TFM
("Live TFM")



FMC data
reprocessed in CIVA

Data Summary

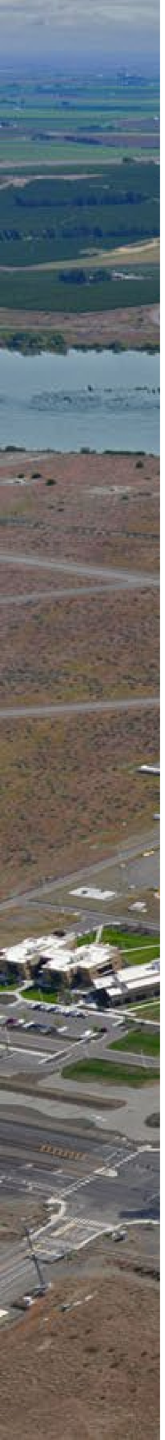
- The only method with 100% flaw detection from single-sided access was PAUT
  - PAUT was only performed with the Emerald and analyzed with UltraVision3, so it is unclear if the other instruments/software would give the same result
- FMC had a 93%+ detection rate with the TRL transducer when considering scans from only one side of the weld
  - At least 14 of the 15 flaws were detected from one side of the weld
  - For dual-sided exams, detection was 100%
  - The Veo3 did not perform as well, but it also was limited to the use of a single linear array
- PWI missed detection of no more than two flaws with the TRL probe from one side of the weld
  - The Emerald had 100% detection when combining scans from both sides of the weld
  - The Panther had 93% detection when combining scans, one flaw was missed in both
  - PWI was not an available data collection mode on the Veo3
- Every flaw was detected at least once with the advanced methods
  - Combining FMC or PWI results across all three instruments resulted in 100% detection
- Length-sizing RMSE was generally within Section XI Appendix VIII limits
  - Only FMC with the Panther was outside the 19.05-mm limit (calculated 19.22 mm)
- Only PAUT was within the RMSE limit for depth sizing
  - Both PWI and FMC tended to undersize the depth of the flaw

Discussion

- Planning out the size of the TFM box (especially the distance extending in front of the probe) is crucial
  - Much like standard PAUT, signals cannot be received from uninsonified regions
  - LMT’s definitions for inspection setup help set controls to ensure reasonable processing volume
  - It is good practice to simulate a sweep of PAUT angles to determine the region insonified by the probe/wedge combination
- No common software exists to analyze the data acquired with the three instruments
  - Each analyst had experience with a different software package (UltraVision3, CIVA, UT View)
  - Human factors (analyst experience, software usability) make comparing results across the three instruments/software difficult
    - ✓ These differences, albeit minimized through the analysis procedure, create confounding variables that limit direct comparisons
  - PAUT was only collected with the Emerald, not with the other two systems
- Length sizing for all methods was within or close to acceptable RMSE limits
  - Overall, PAUT outperformed FMC and PWI for both length and depth sizing
  - Looking across all acquisition systems combined, both FMC and PWI performed similarly
- More time would be needed to look at SNR and the advantages of reprocessing the data using other TFM algorithms
  - Using just DAS does not show significant improvement over PAUT for detection or sizing
  - Post-processing techniques (such as provided by the TPAC data) appear to reduce noise signals but may also reduce flaw response amplitudes

Key Takeaways

- Advanced UT methods did not outperform PAUT for flaw detection or sizing of flaws in the specimens scanned in this study
  - PAUT detection rates were as high as or higher than those of PWI or FMC
  - PAUT length and depth sizing were more accurate than FMC or PWI and were within the RMSE limits of Section XI Appendix VIII
- Spatial resolution observed with PAUT was not improved with FMC
- Any benefits realized from advanced methods are likely not worth the higher costs of implementing such methods
  - Potential benefits stem from the variety of data processing available both currently and in the future (reprocessing of data)
  - Added costs include equipment, probes, protocol development and performance demonstration, analyst performance demonstration, additional scan time, and additional computation time
- Results of this study suggest that there is no compelling driver to replace existing inspection methods with advanced PAUT in routine inspections in U.S. nuclear power plants (for examining materials of the type, size, and thickness used in this study)



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Potential Follow-on Work

- Evaluate emerging advanced techniques for improved flaw detection and sizing
  - Are certain materials or flaw types better suited for advanced UT than others?
  - Frequency-modulated AWG (pulse compression)
    - ✓ Unique pulse allows for increased resolution (aka sharper peaks from coherent responses)
  - Modified PWI
    - ✓ Adds more energy into coarse-grained components while allowing post processing signal analysis
  - Adaptive TFM (ATFM)
    - ✓ Inputs complex geometry/materials of the part when performing reconstruction
    - ✓ Accounts for sound redirection during propagation for improved image quality
- Test advanced signal processing algorithms
  - Can advanced algorithms improve detection and/or characterization?
  - Evaluate the different types of post-processing methods available (DMAS, PCI, PCF, etc.)
  - Impacts on SNR during analysis, especially in noisy materials
  - Investigate the impacts on resolution and flaw sizing of different algorithms for TFM reconstruction in different materials or inspection scenarios
- Expand analysis of challenging flaw or material geometries
  - Limited coverage scenarios where flaws cannot be completely insonified
  - CASS
  - Surface curvature or roughness (such as wire arc additive manufacturing)