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“Latest Developments in FMC/TFM Inspections”

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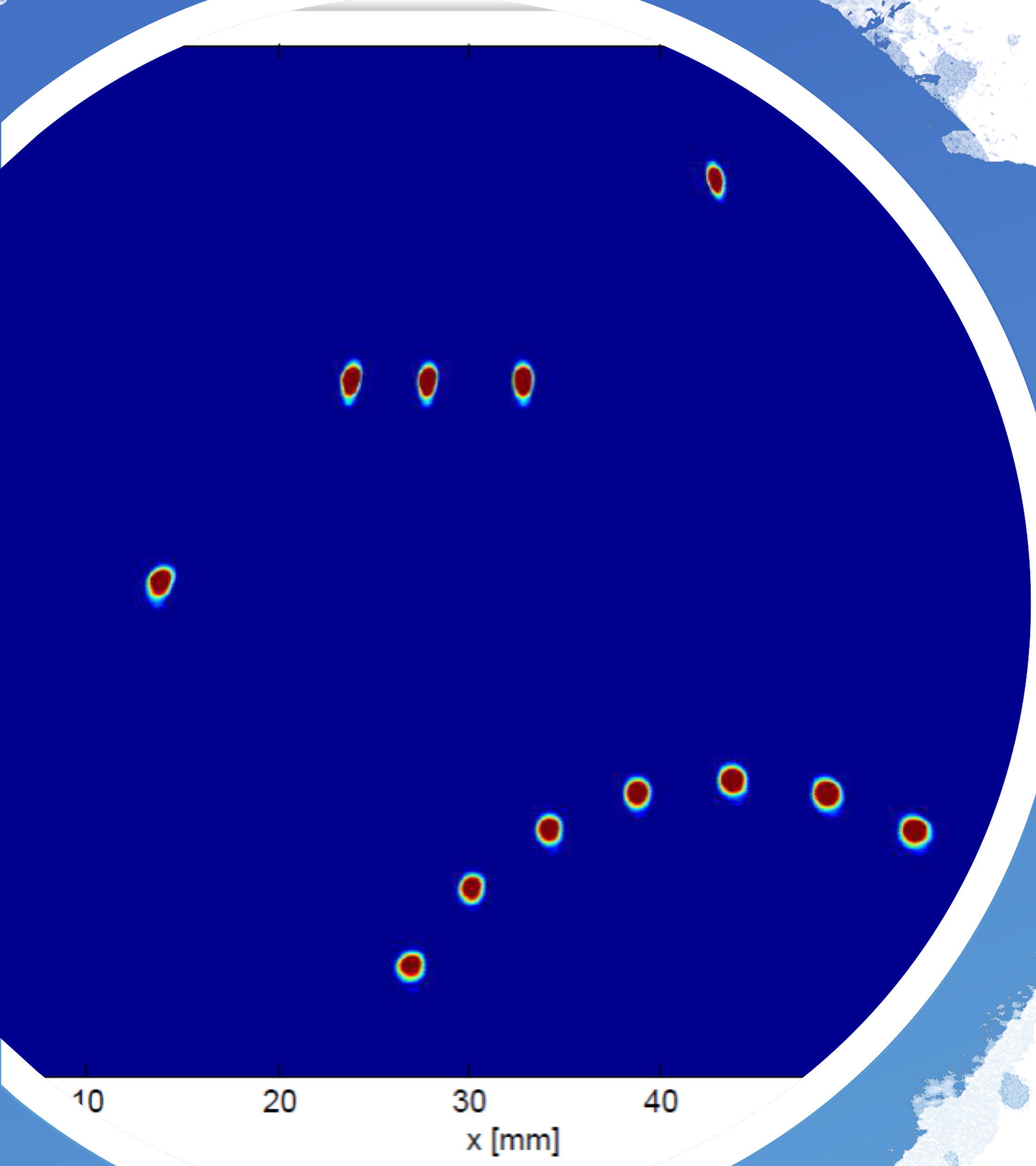
AOS and TPAC

Advanced OEM Solutions

TPAC



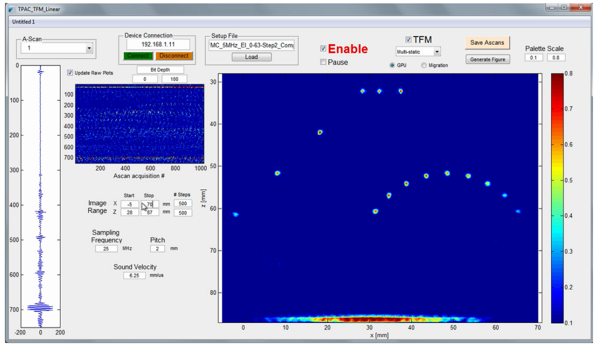
What is FMC/TFM?

What is FMC/TFM?

- FMC or Full Matrix Capture is a manner of acquiring Ultrasonic Testing (UT) data
- FMC describes a pulse/receive method implemented by data acquisition hardware
- In contrast to Phased Array UT (PAUT), there is no beam forming done in the hardware (no delay/focal laws).
- No specific focal spot/zone –
  - **<u>Focused Everywhere!</u>**
- Once the data is captured a signal processing or visualization algorithm is implemented
- One popular processing technique is the Total Focusing Method, or TFM
- FMC/TFM is FMC acquisition data imaged with the TFM algorithm

FMC/TFM – Important Distinction!

- (FMC) Full Matrix Capture = Data Acquisition
  - Performed via hardware
- (TFM) Total Focusing Method = Post-Processing Imaging of the FMC Data
  - Performed via software
  - A family of techniques

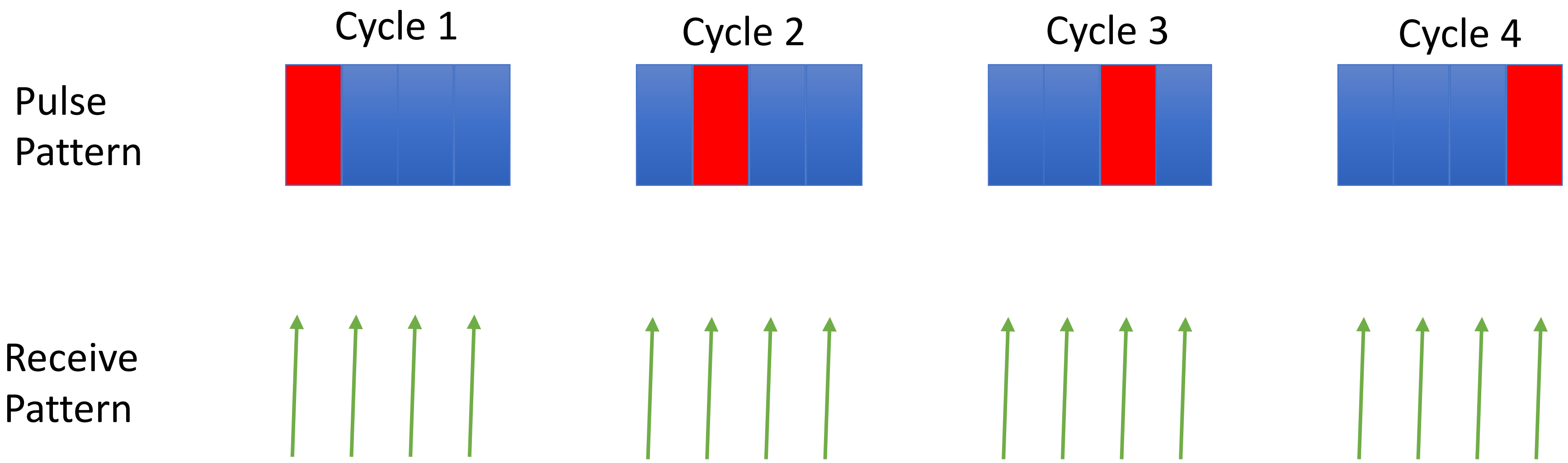


An Introduction to Full Matrix Capture (FMC)

Full Matrix Capture (FMC) Basics

- Transmit ONE, receive ALL
- The "standard" pulse/receive sequence is …
  - Transmit with element 1, then receive raw data (i.e. A-Scans) on all elements in the aperture
  - Then pulse with element 2, receive all, pulse 3, receive all … and so forth.
- In this case, one FMC acquisition cycle for a 64 element aperture is 64 x 64 = 4096 raw A-scans
  - As opposed to 64 with PAUT (N vs N^2)

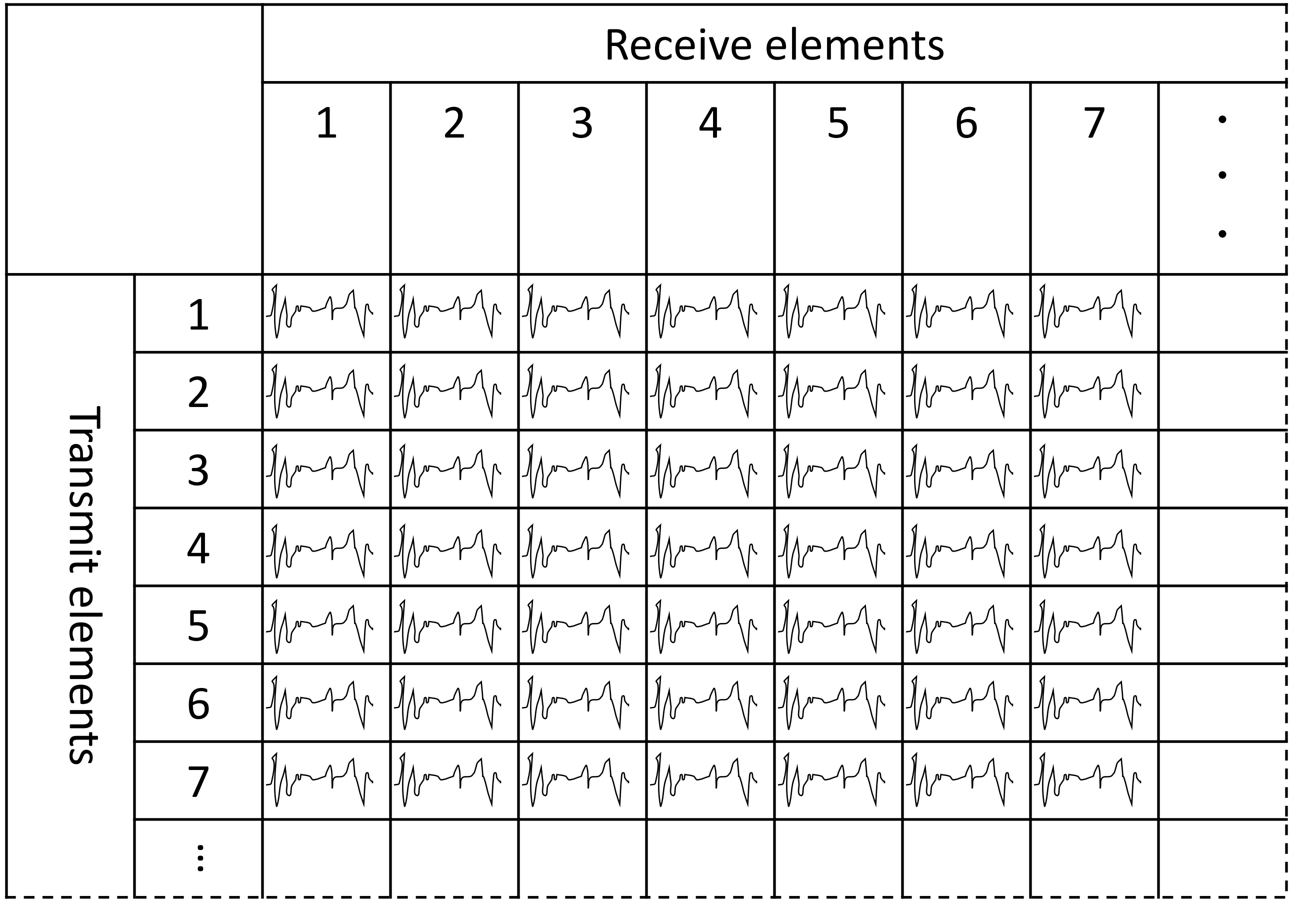
Full Matrix Capture (FMC) Basics



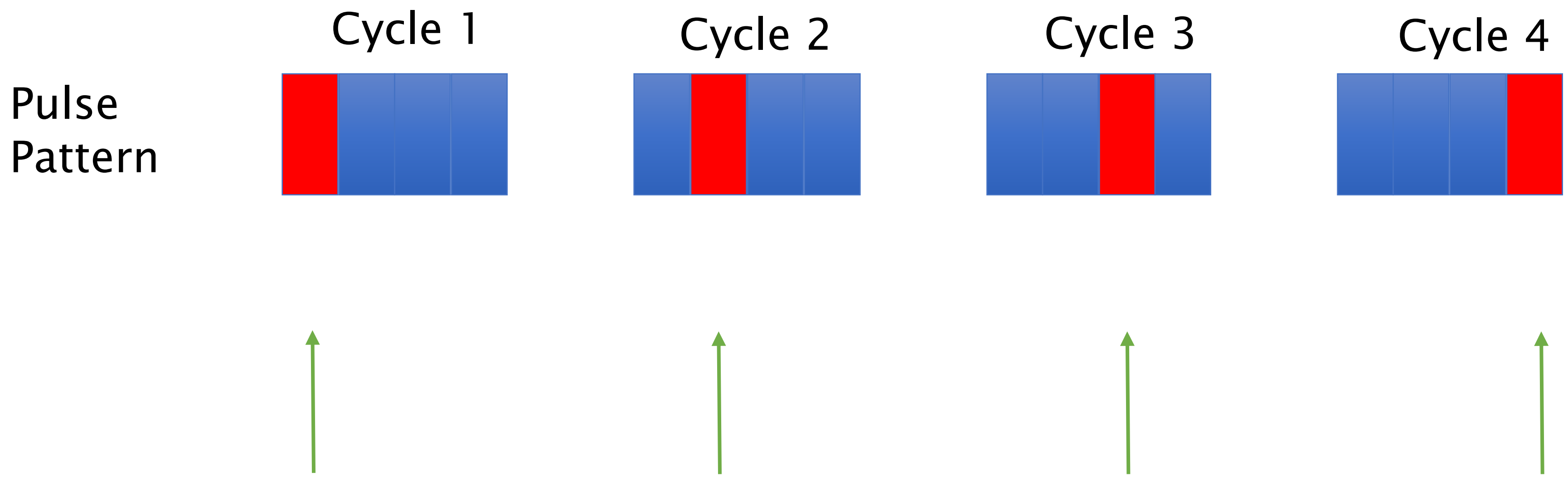
In this example, we have 4 elements…

4 x 4 = 16 raw A-scans

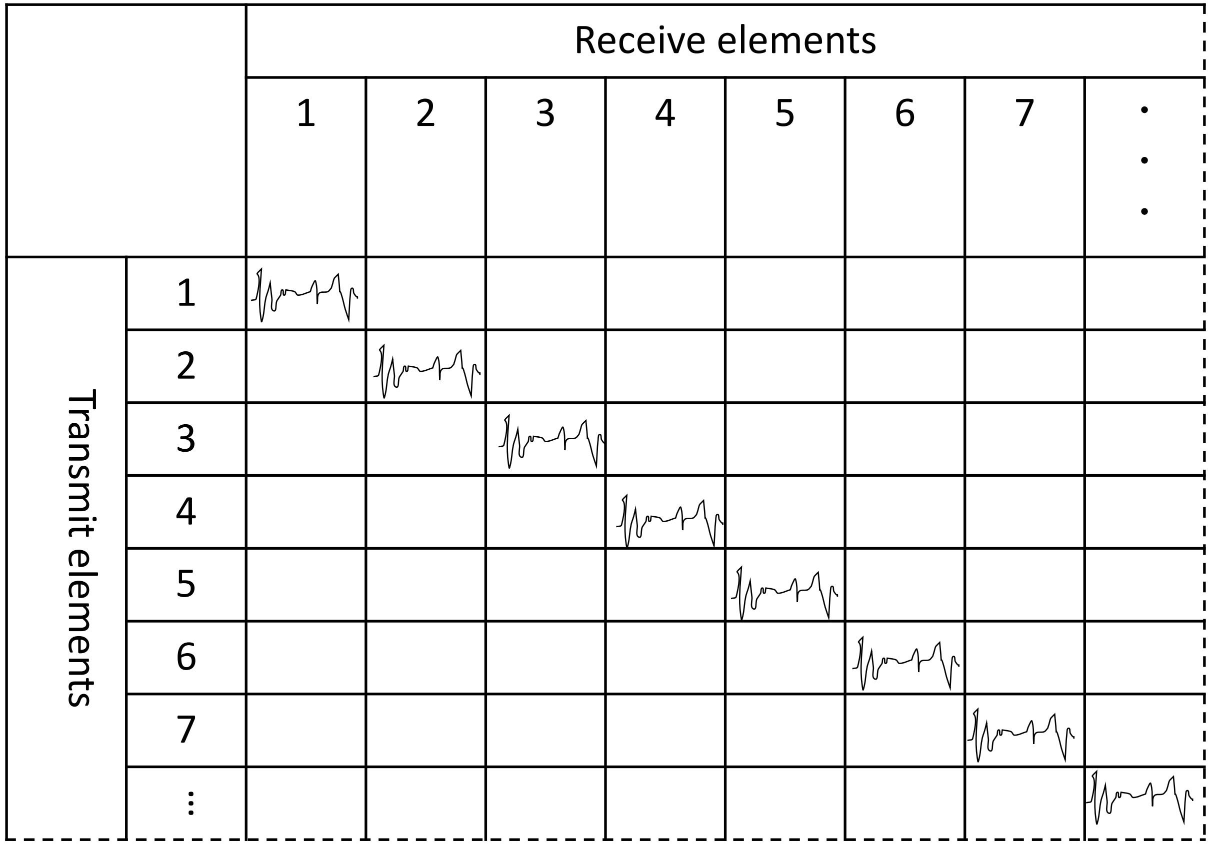
Full Matrix Capture (FMC) Basics



Synthetic Aperture Focusing Technique (SAFT)

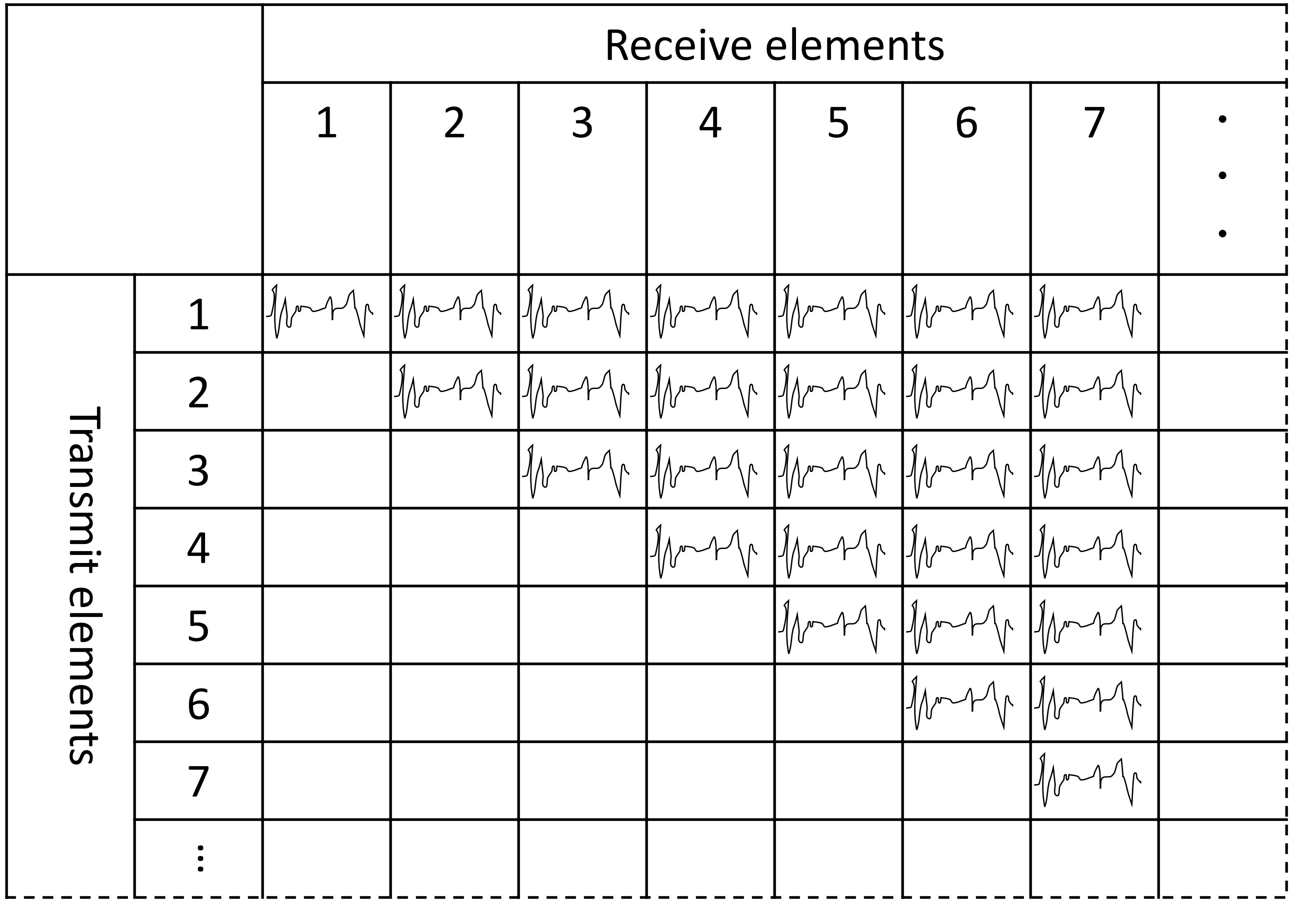


Synthetic Aperture Focusing Technique (SAFT)

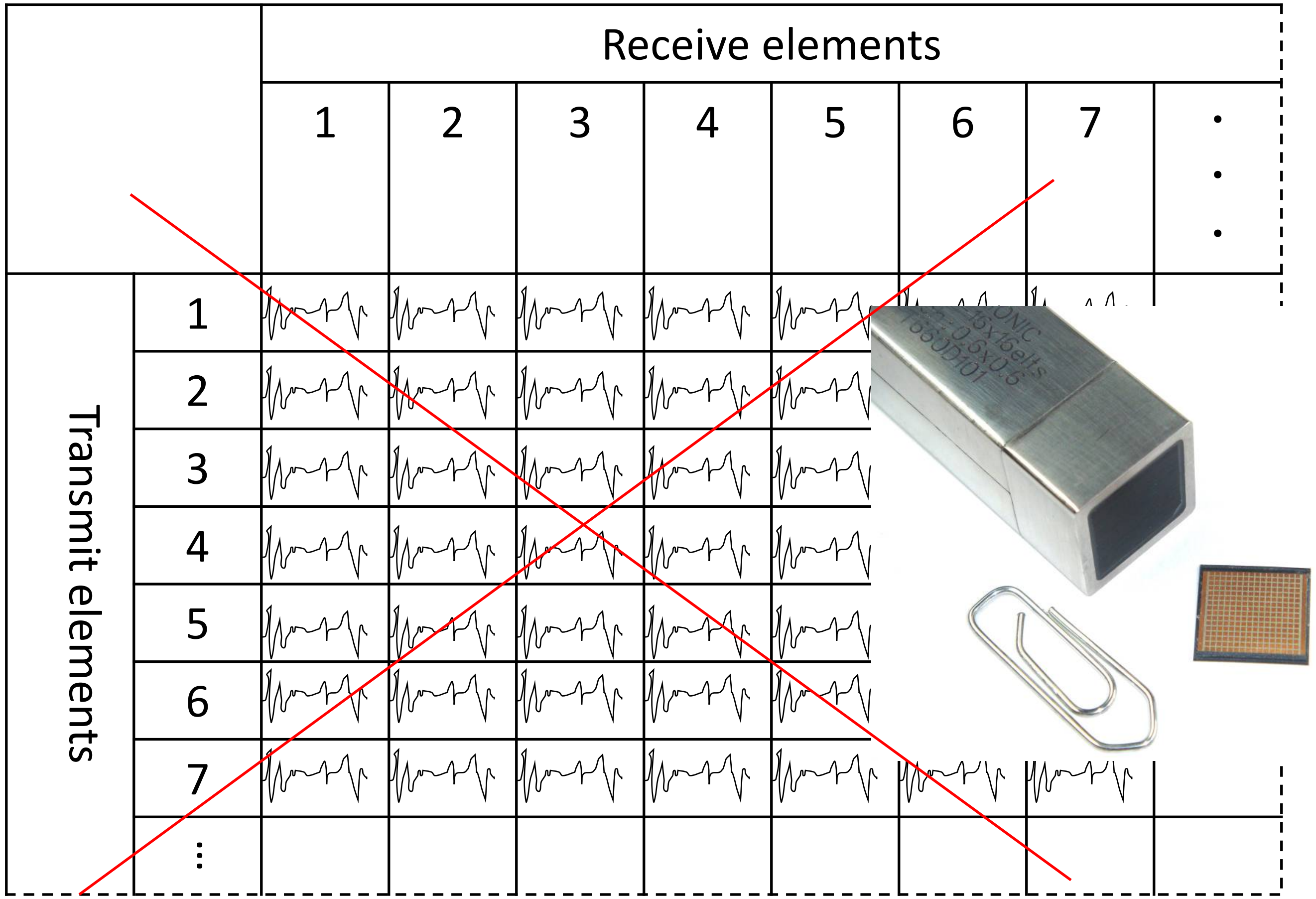


Half Matrix Capture (HMC)

***Assumes symmetricity of data**

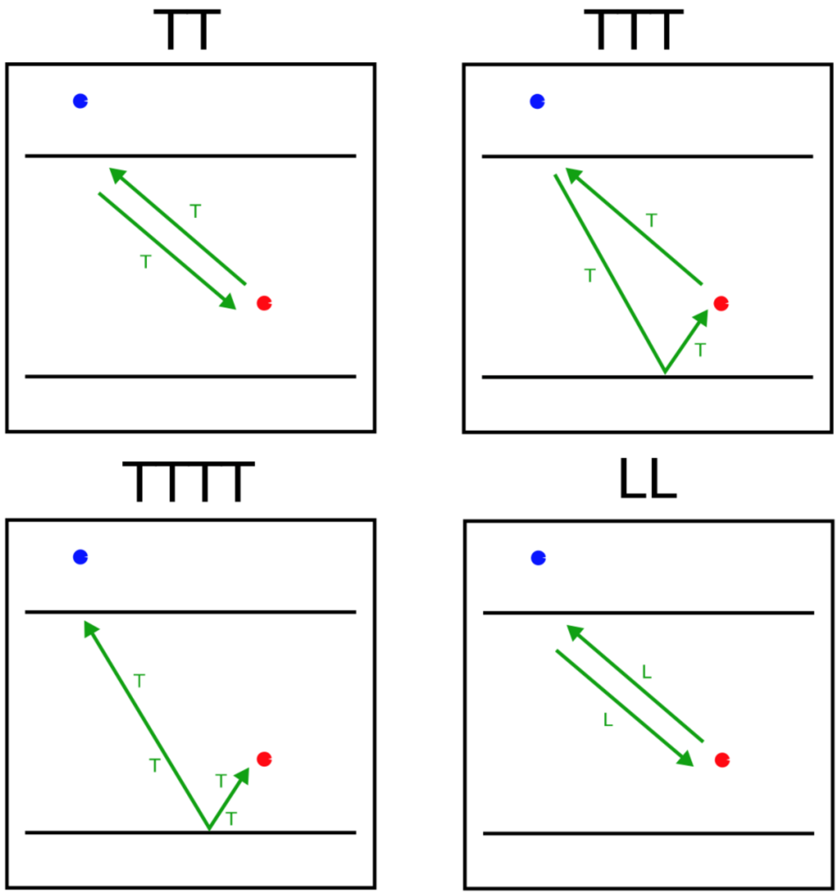


Full Matrix Capture ≠ Matrix Phased Array

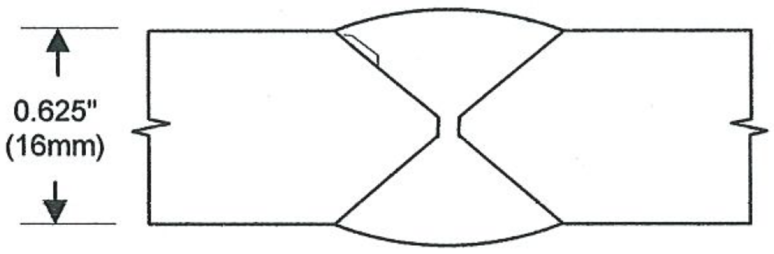


FMC/TFM Wave Modes

- A benefit of FMC/TFM is the ability to image a data set in multiple wave modes
- This can be dependent on equipment
  - Multiple acquisitions required?
- Snell's law should be considered to optimize SNR

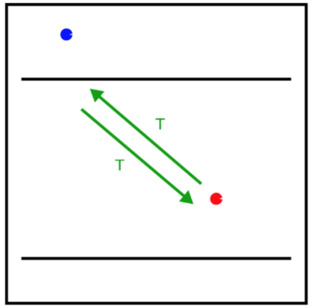


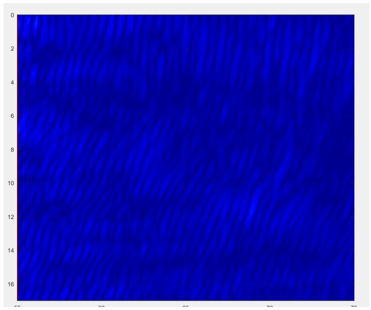
FMC/TFM Wave Modes



52. Lack of Fusion in Double Vee,
(sub surface) UT

TT





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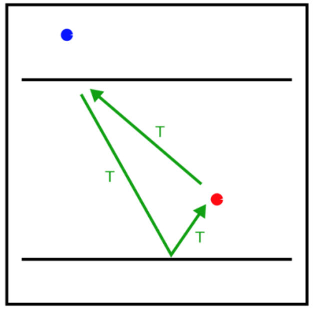
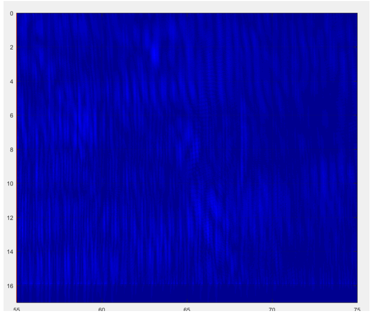
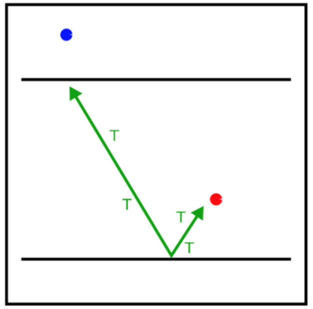
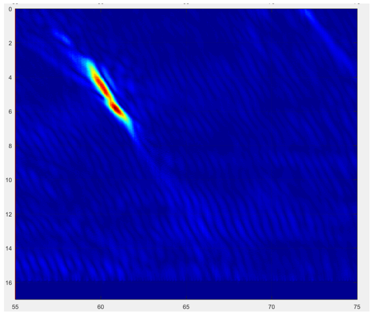


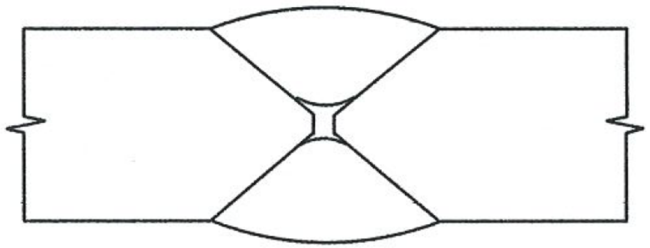


TTTT



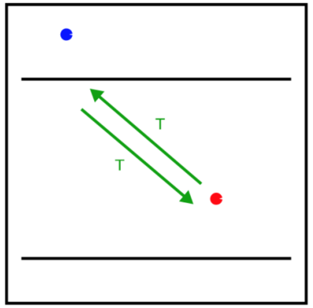


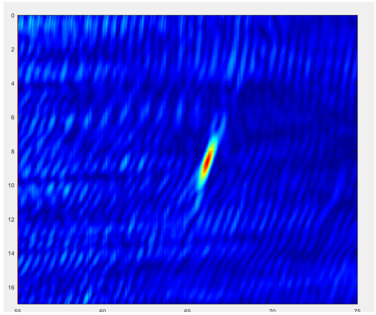
FMC/TFM Wave Modes



57. Incomplete Root Penetration in
Double Vee, UT, RT

TT





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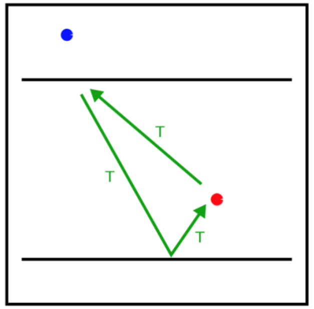

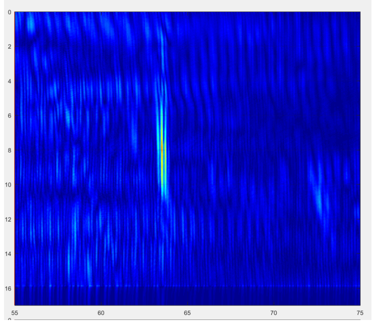

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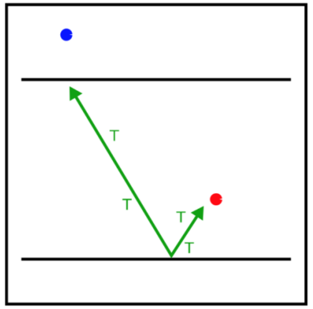
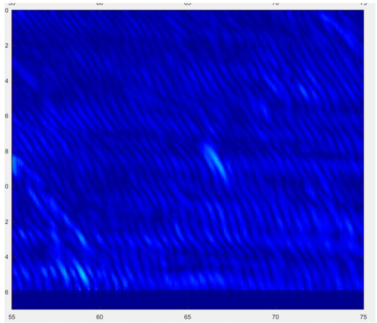
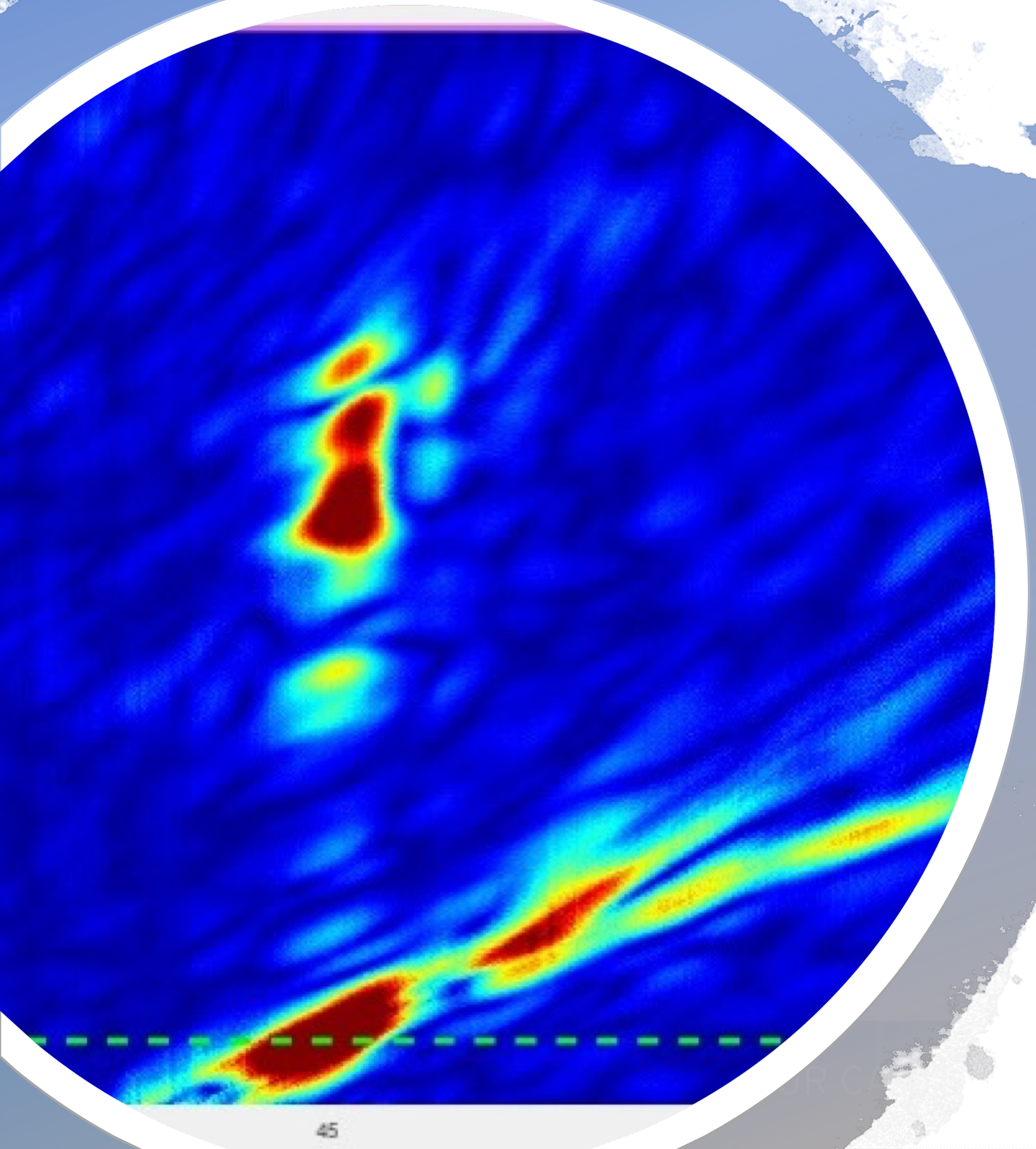




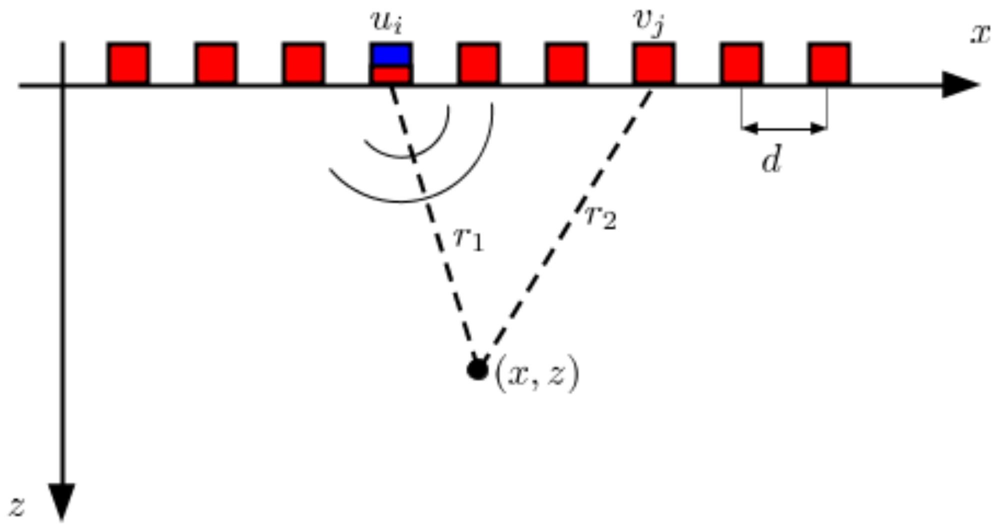


An Introduction to Total Focusing Method(TFM)

Total Focusing Method (TFM) Basics

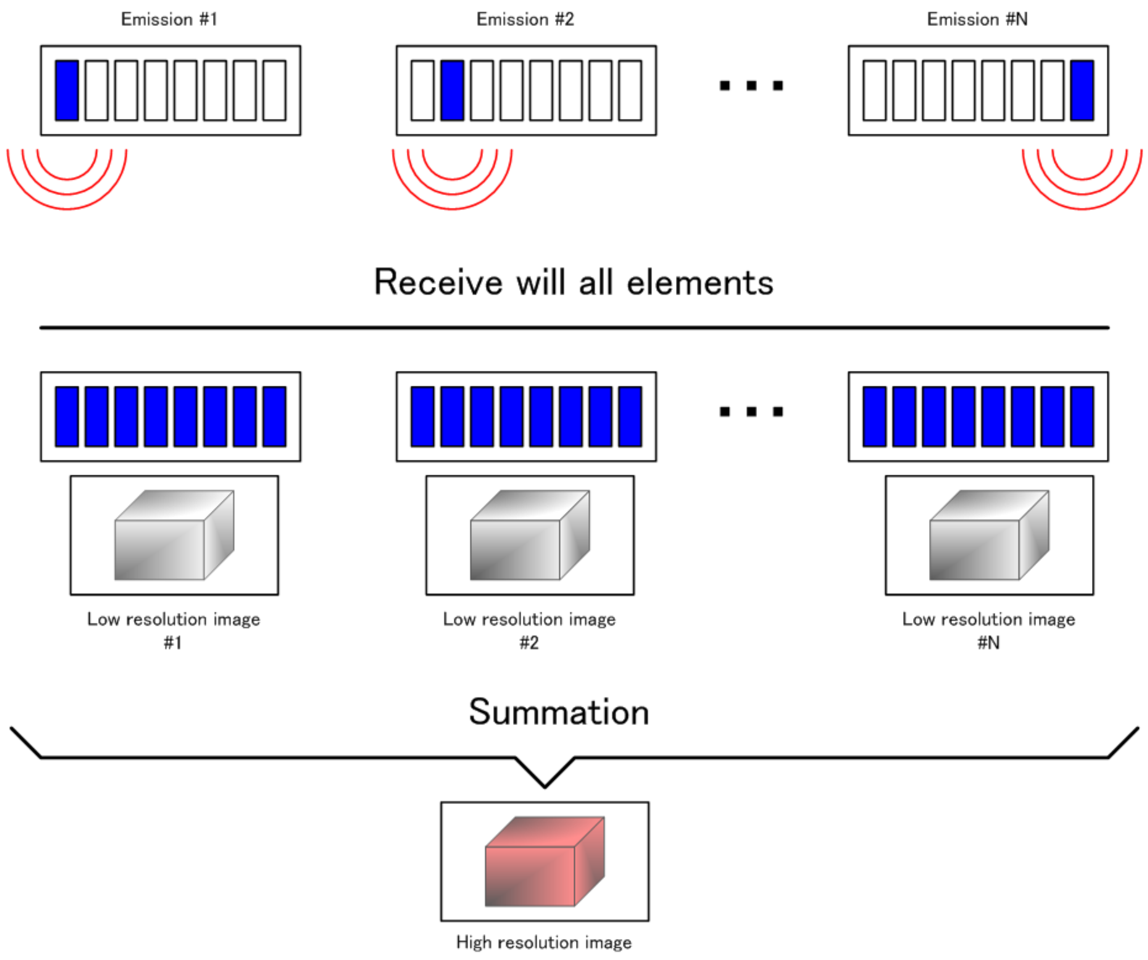
- TFM is an advanced image reconstruction technique, performed via software "post"-processing
- By applying the TFM algorithm to FMC data, the inspection can be focused at all points within the focusable range of the probe (near field).

Total Focusing Method (TFM) Basics



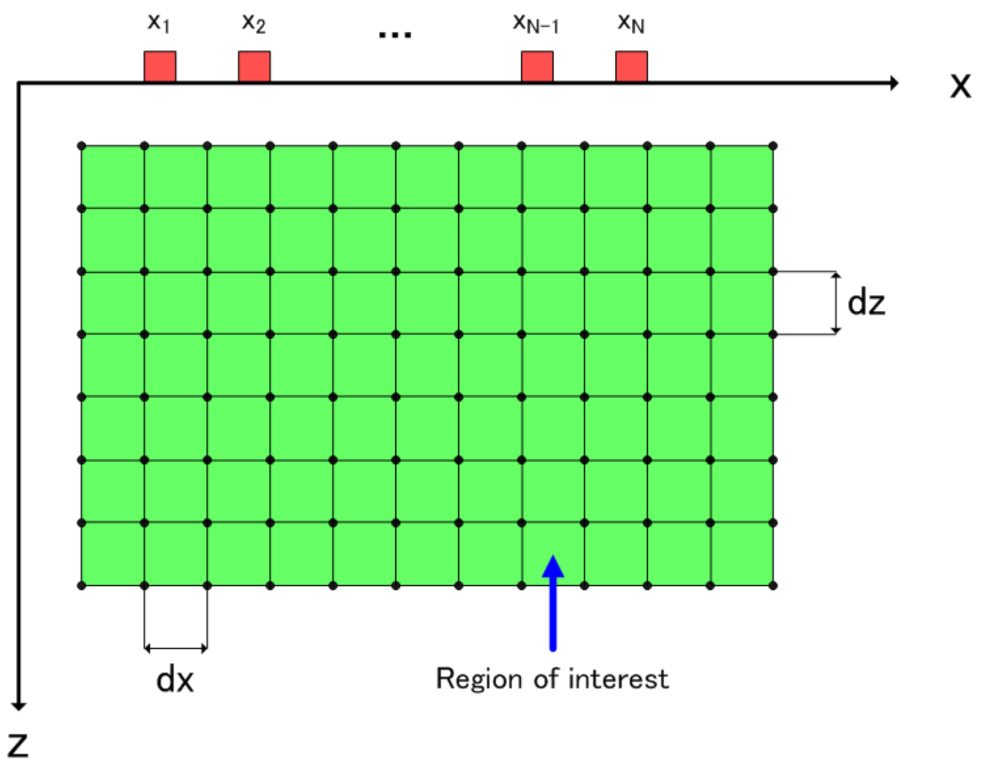
$$o(x,z) = \sum_{i=1}^{N} \sum_{j=1}^{N} y\left(\frac{r_1 + r_2}{c}, u_i, v_j\right)$$

Total Focusing Method (TFM) Basics



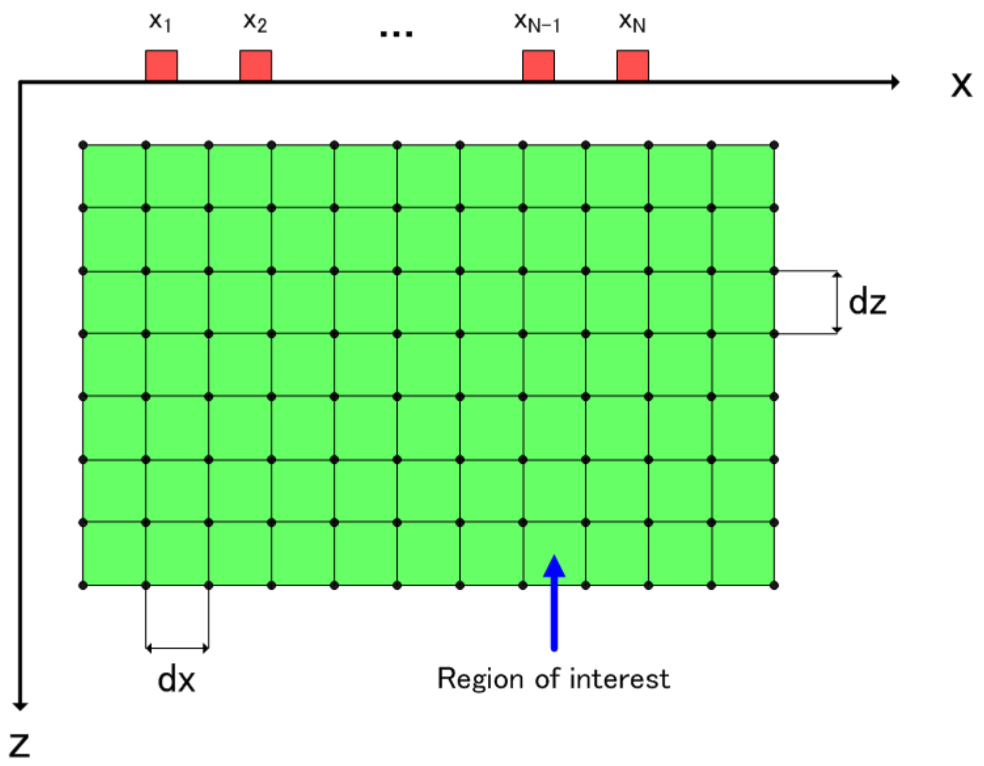
Total Focusing Method (TFM) Basics

- User specifies inspection range, pixel resolution, and offset of reconstruction points.
- TFM calculation performed for each reconstruction point
- No limit to resolution (with TPAC software)

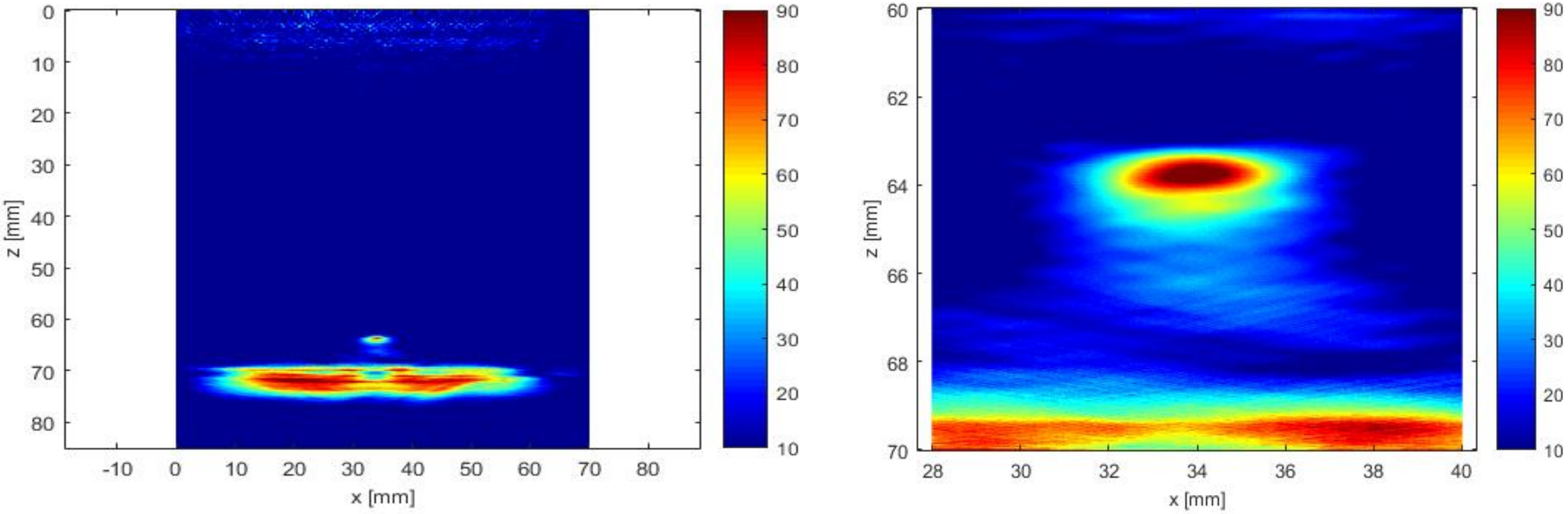


Total Focusing Method (TFM) Basics

- The reconstruction is (can be) “flexible,” meaning when “zooming” into the inspection area to view an area of interest, the reconstruction applies the same number of specified pixels, thus, no resolution is lost

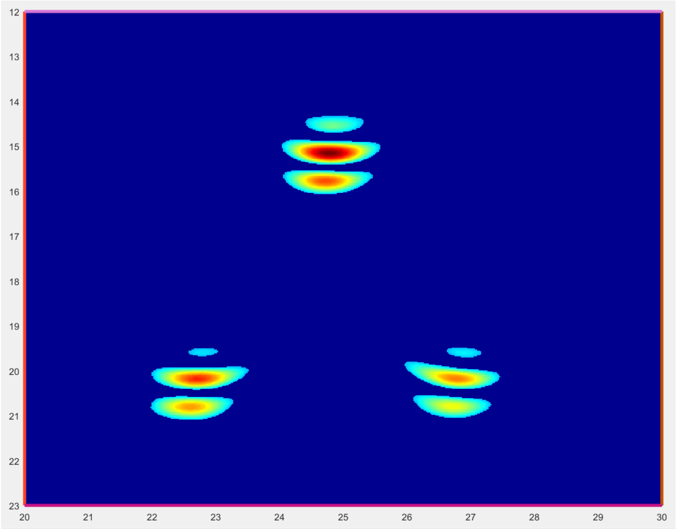


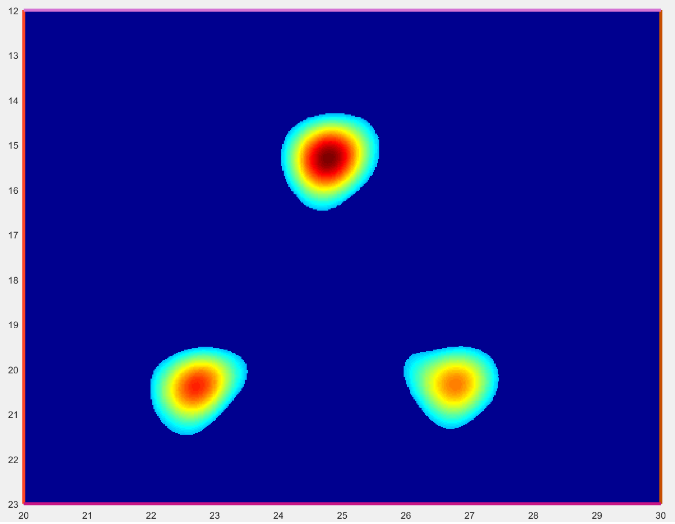
Total Focusing Method (TFM) Basics



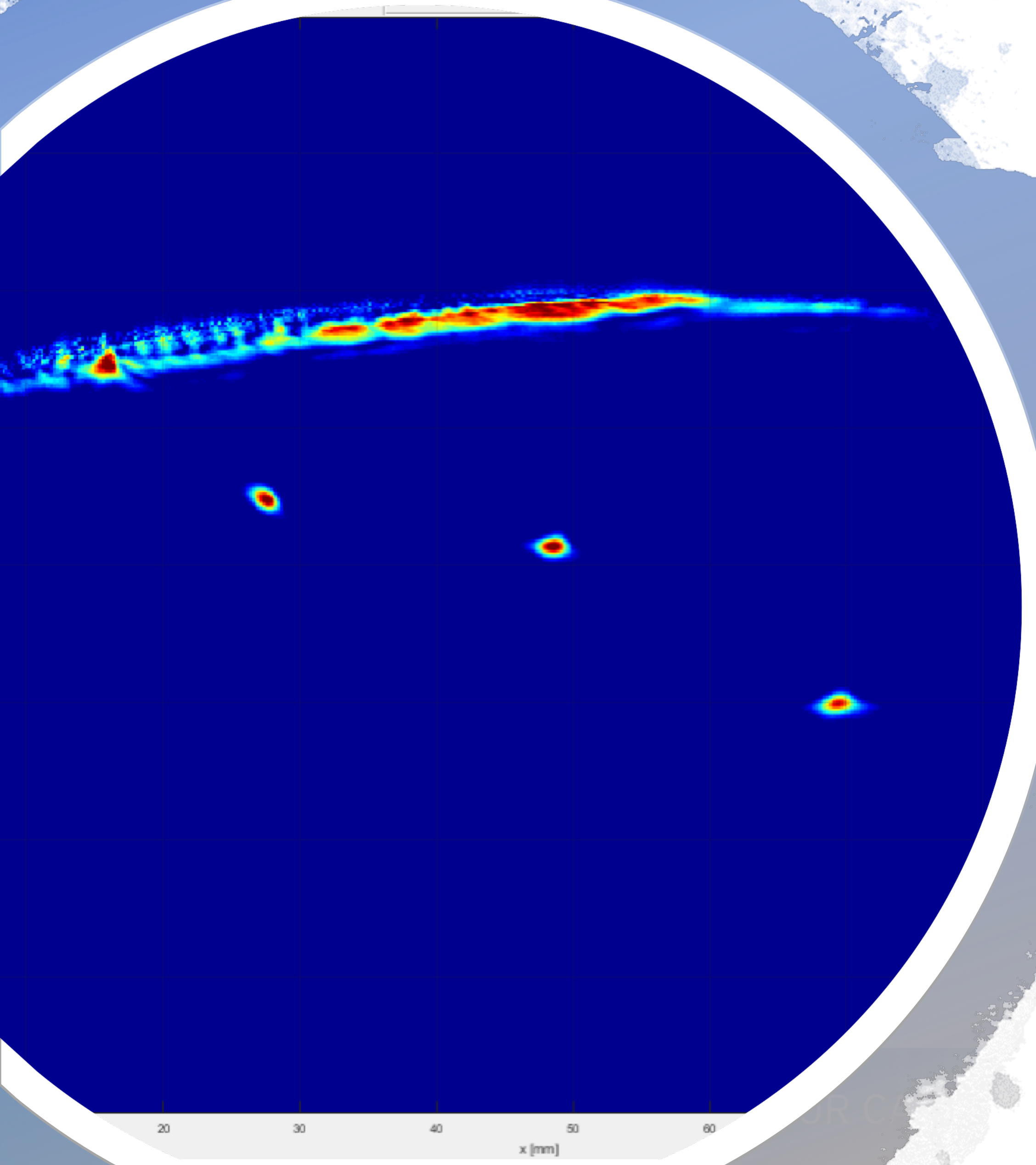
Example of saved FMC data with TFM algorithm (re)applied to a specific area of interest

TFM Image – Envelope vs Absolute





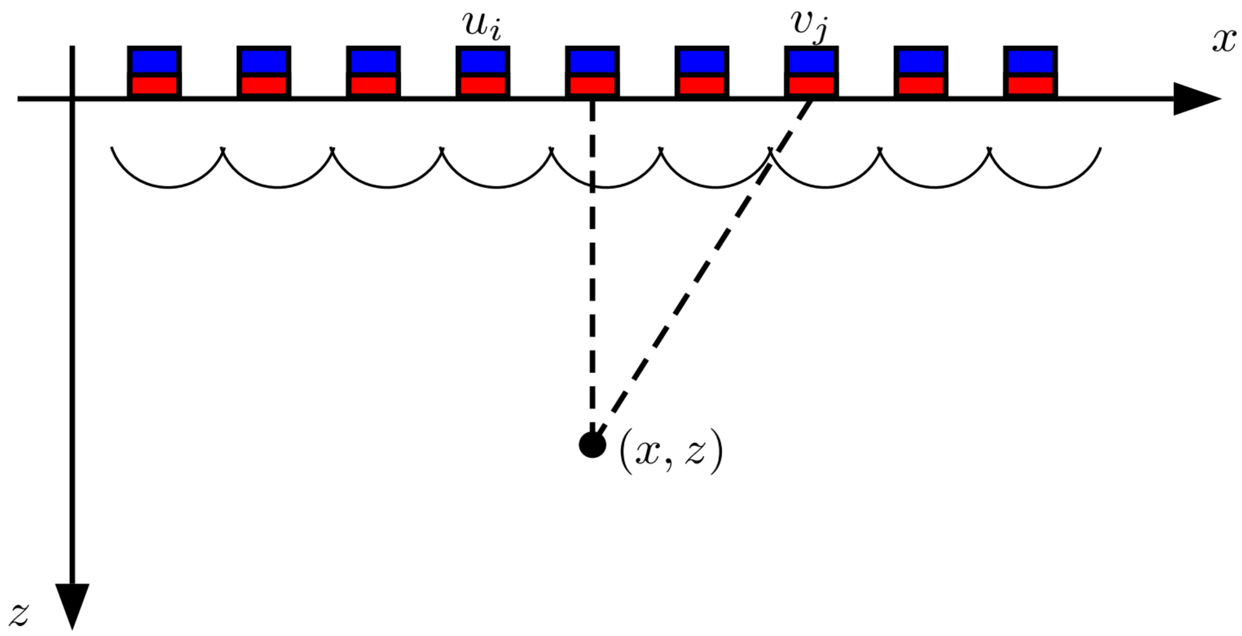
In a general sense, we can compare application of an envelope to the TFM data as a form of smoothing. It can be more visually appealing, just make sure that it doesn't affect your specific application negatively.



Advancements in Total Focusing Method(TFM)

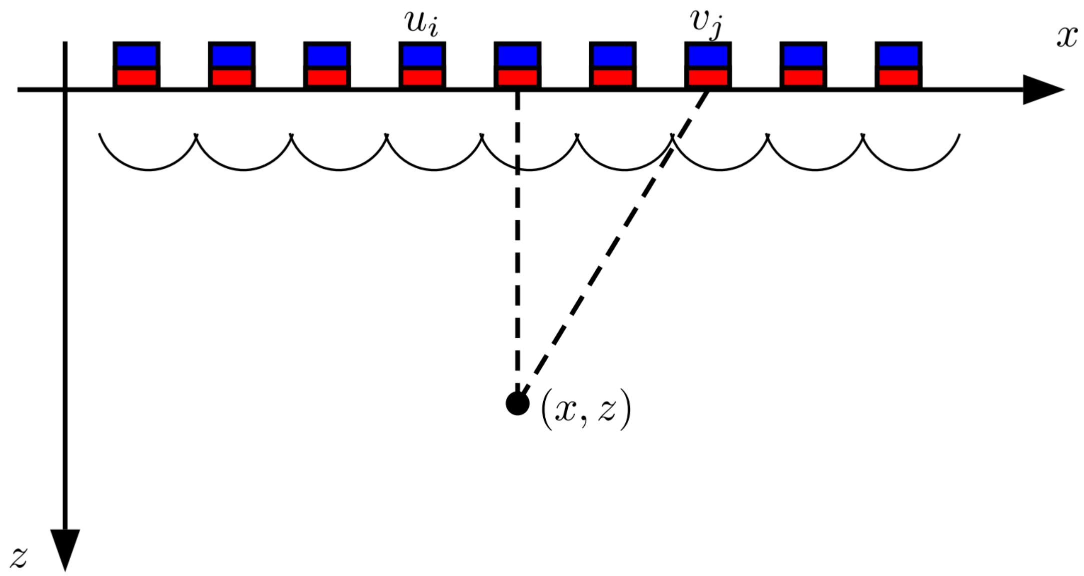
PWI (Plane Wave Imaging)

- PWI (… PWI/TFM) utilizes a larger transmitting aperture than FMC/TFM, but with the proper algorithmic image processing, the data set can still be used to create a TFM image.



PWI (Plane Wave Imaging)

- As seen in the image below, several elements are transmitting at once, but the image reconstruction still considers each elemental transmit/receive pair, as in “standard” FMC/TFM.



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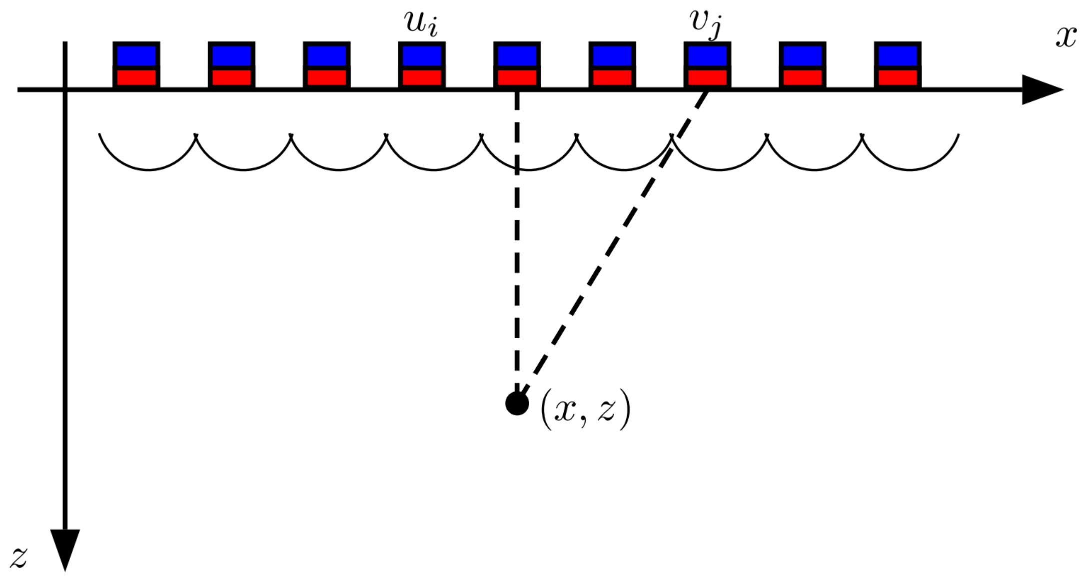
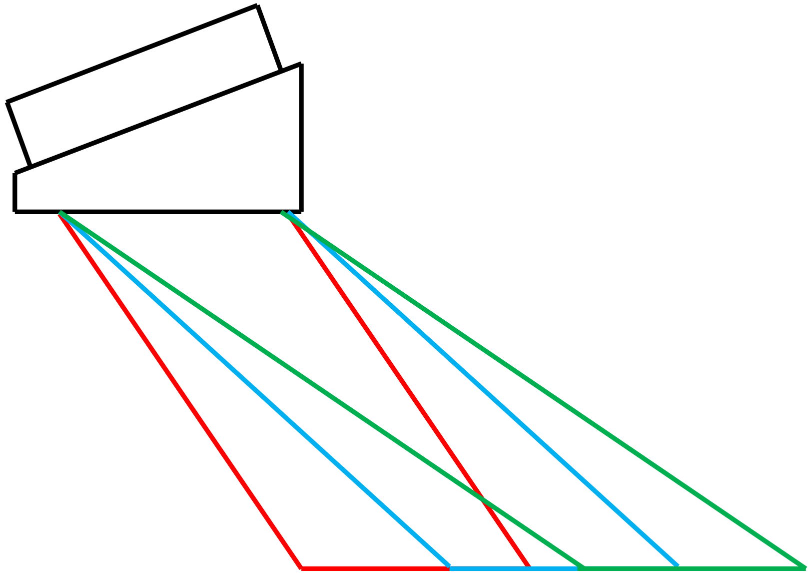
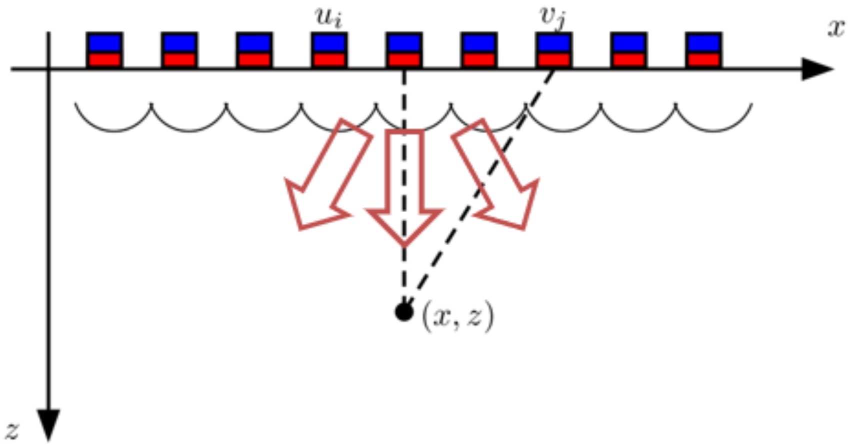
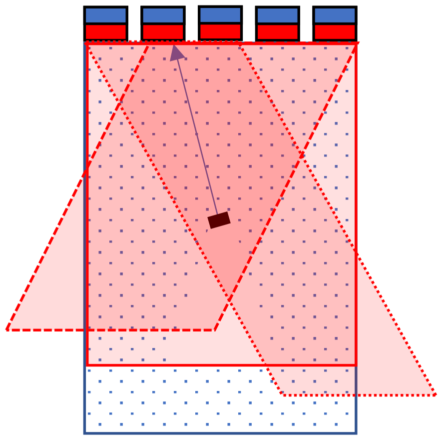


PWI Angular Propagation

PWI can be angularly propagated with and without a wedge. A common approach for weld inspection will be to propagate in a way that mimics a PAUT sectorial scan. For example, plane waves from 40 to 70 degrees, with an angular resolution of 5 degrees.

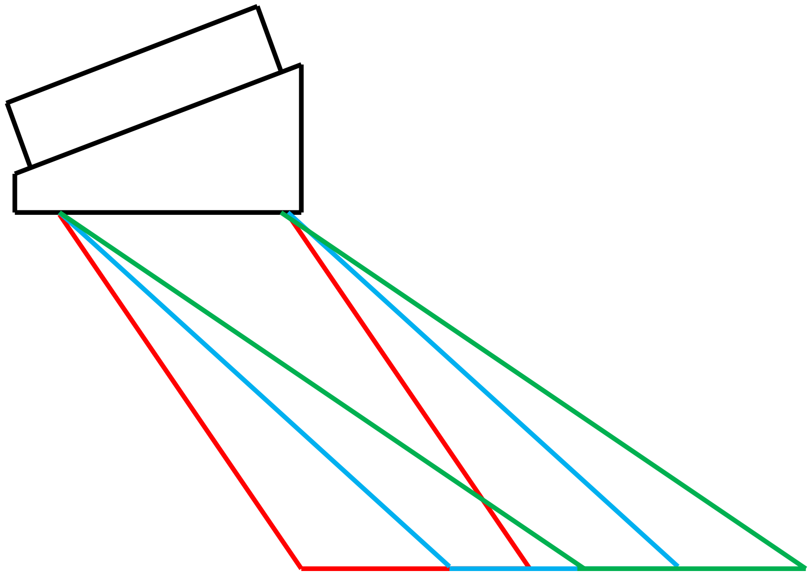


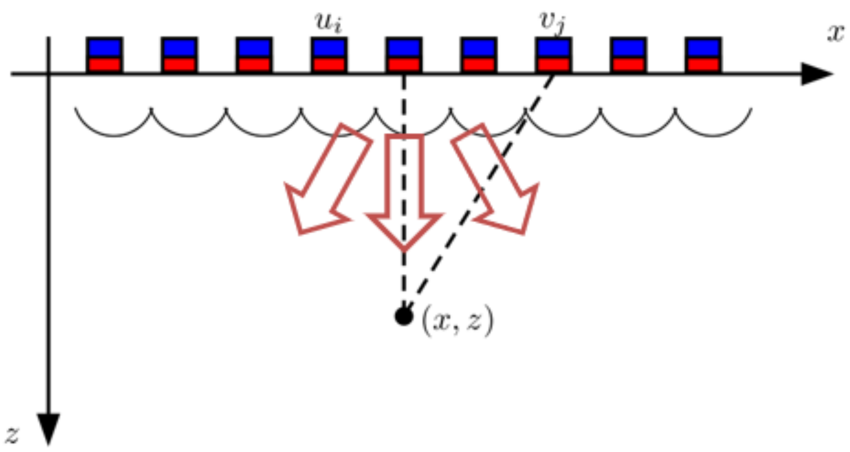




PWI Angular Propagation

The file size and inspection speed will be directly correlated to the number of propagated plane waves.
More angles/plane waves will reduce inspection speed and increase file size.

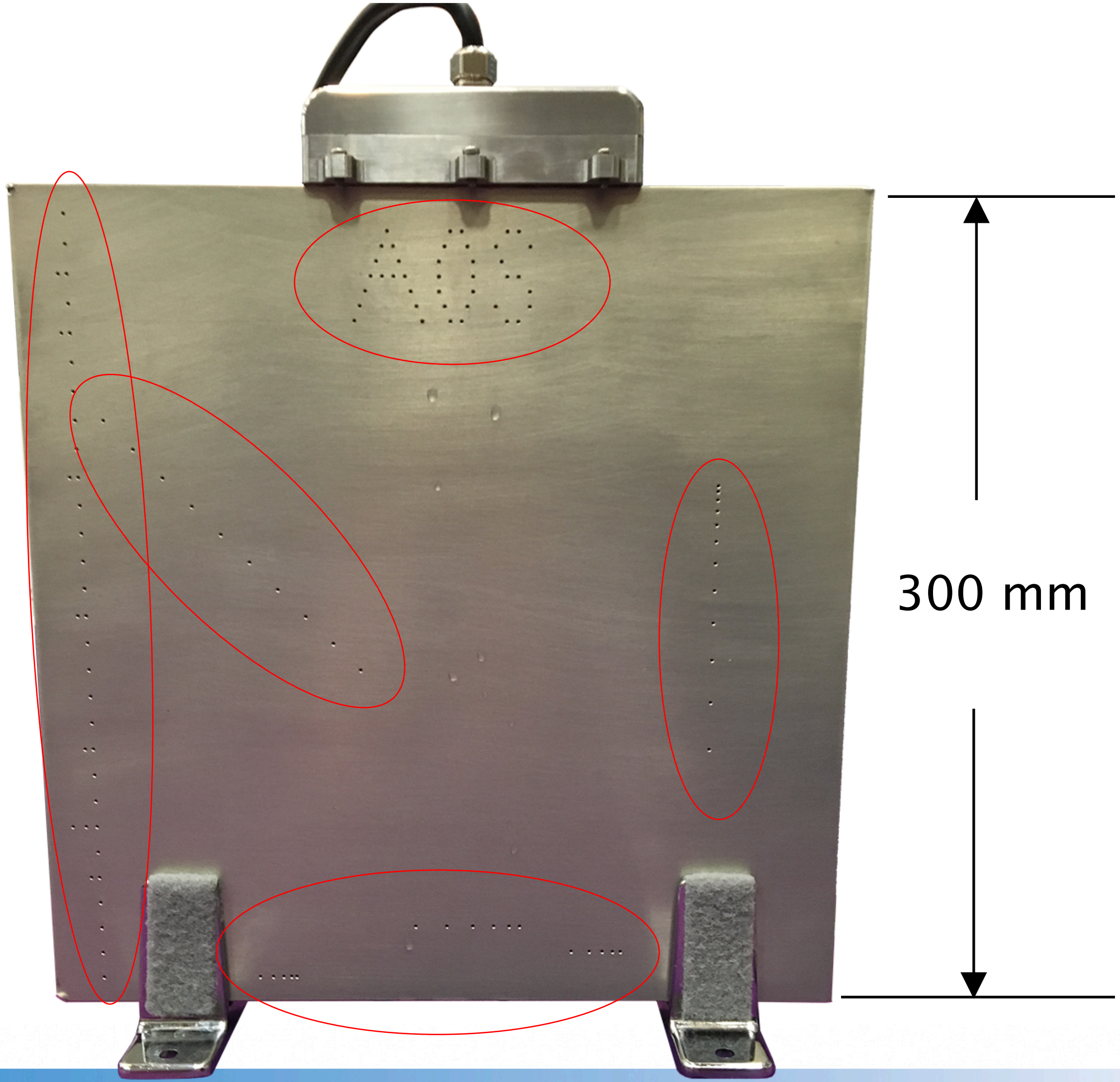




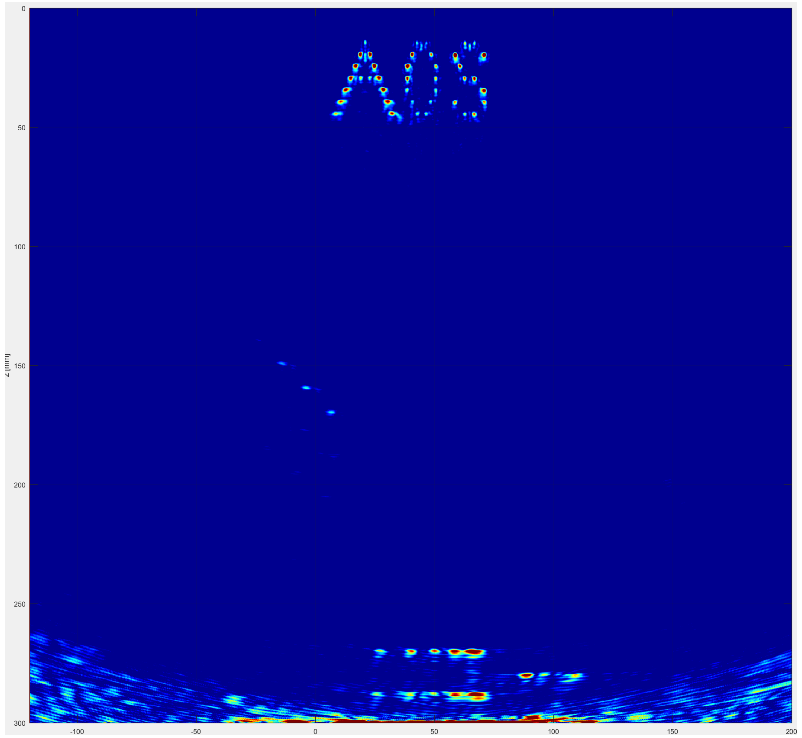
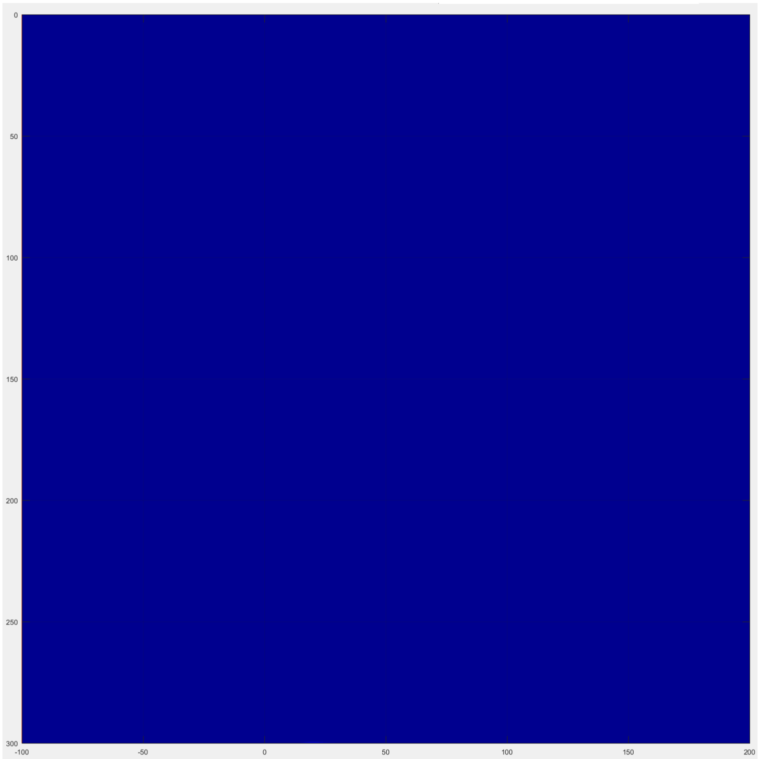
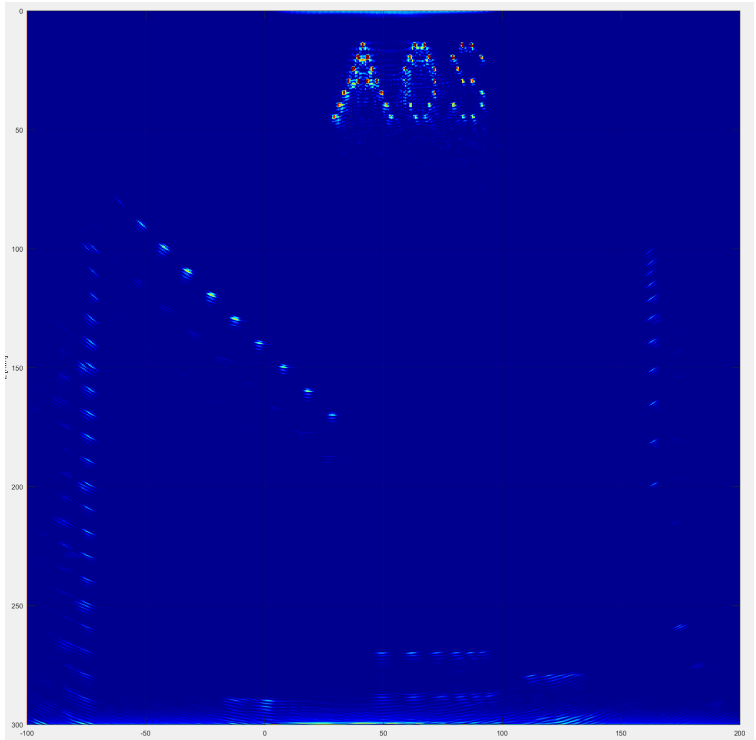
Benefits of PWI (Plane Wave Imaging)

- PWI acquisition with TFM image processing = PWI/TFM
- Represents an optimization of both FMC data set acquisition and TFM image post-processing
- As a general rule, much faster than traditional FMC/TFM
- Provides greater relative sensitivity than FMC/TFM (higher reflector amplitude at same gain levels)
- Good penetration/SNR for attenuative materials (Ti, Inconel, etc.)
- Smaller file sizes

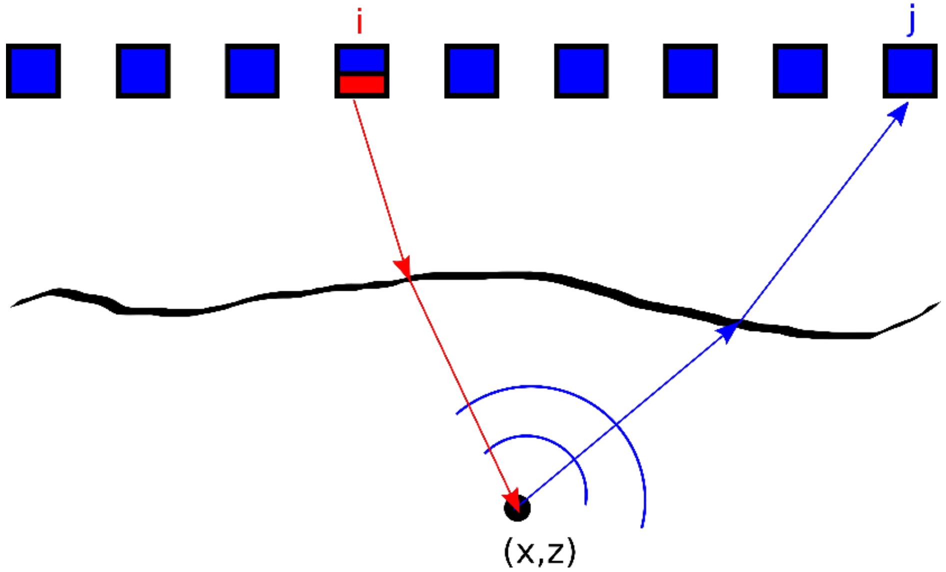
Comparison of PWI vs “Traditional” FMC/TFM



Comparison of PWI vs "Traditional" FMC/TFM

PWI	FMC/TFM (same dB)	FMC/TFM (+30dB)
		

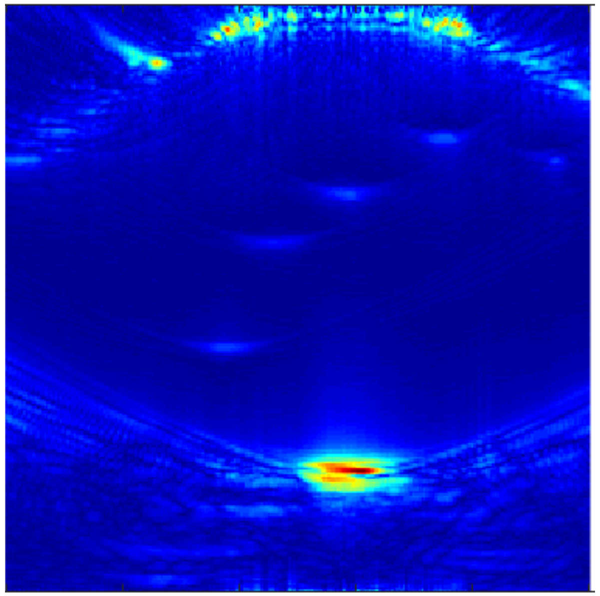
Adaptive FMC/TFM



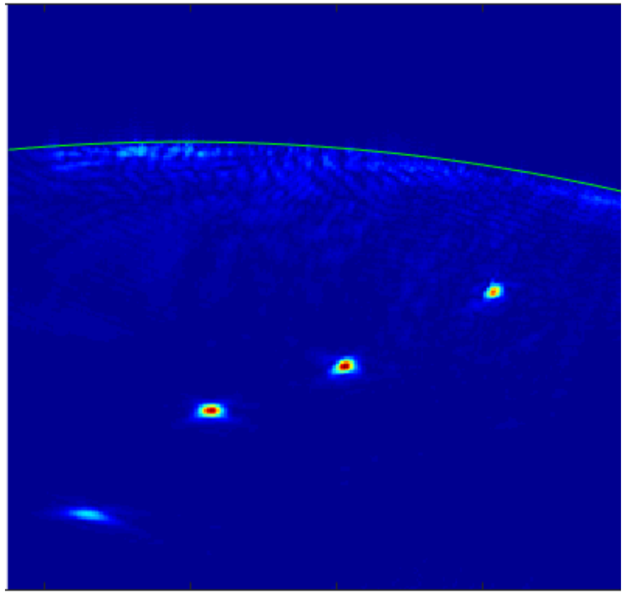
- When the surface of the sample is not flat (curved or completely irregular), it affects Time of Flight computations of the TFM algorithm.
- The first step is to perform a **surface estimation**, using the interface echoes received by all elements.
- Then **using the same FMC data set,** the TFM algorithm is run, considering estimated surface.
- Can be utilized with both FMC/TFM (ATFM) and PWI/TFM (APWI)

Adaptive FMC/TFM

Standard TFM



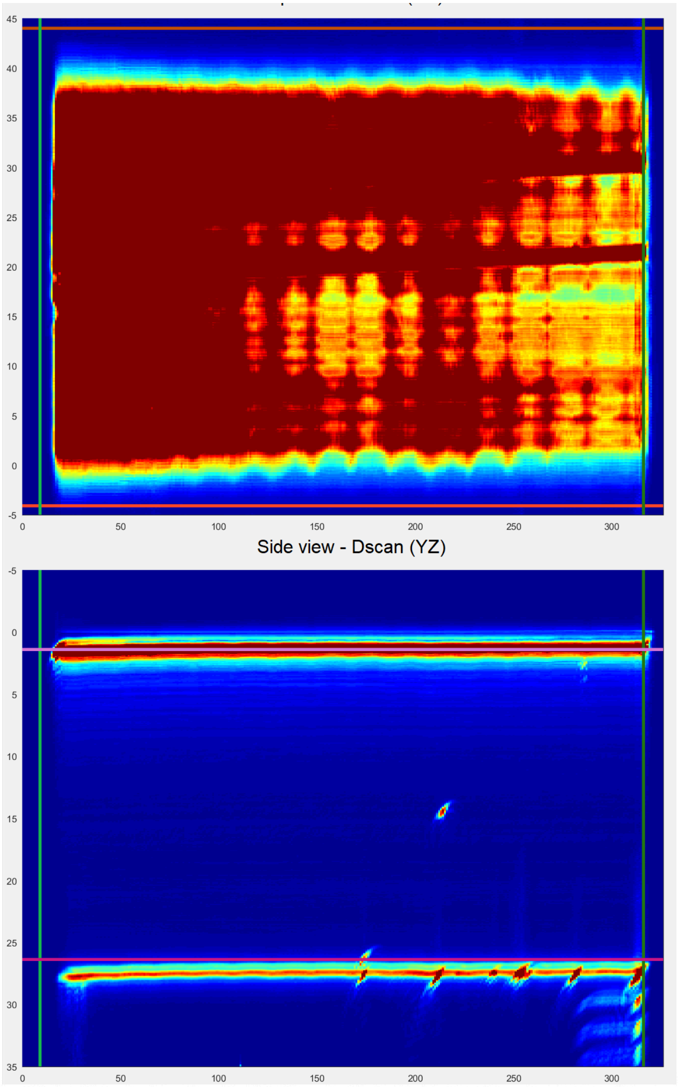
Adaptive TFM



Can remove or limit the need for extensive (and expensive) motion control!

Adaptive FMC/TFM

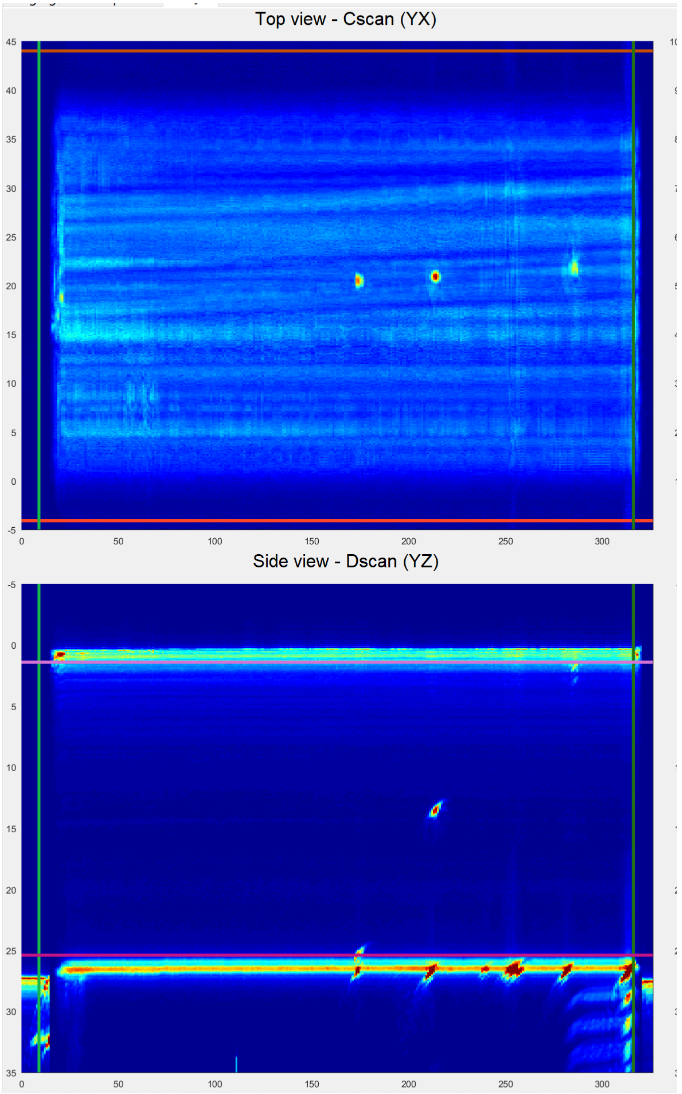
Standard TFM imaging of a rough surface part with C-scan image completely obstructed due to surface irregularity.

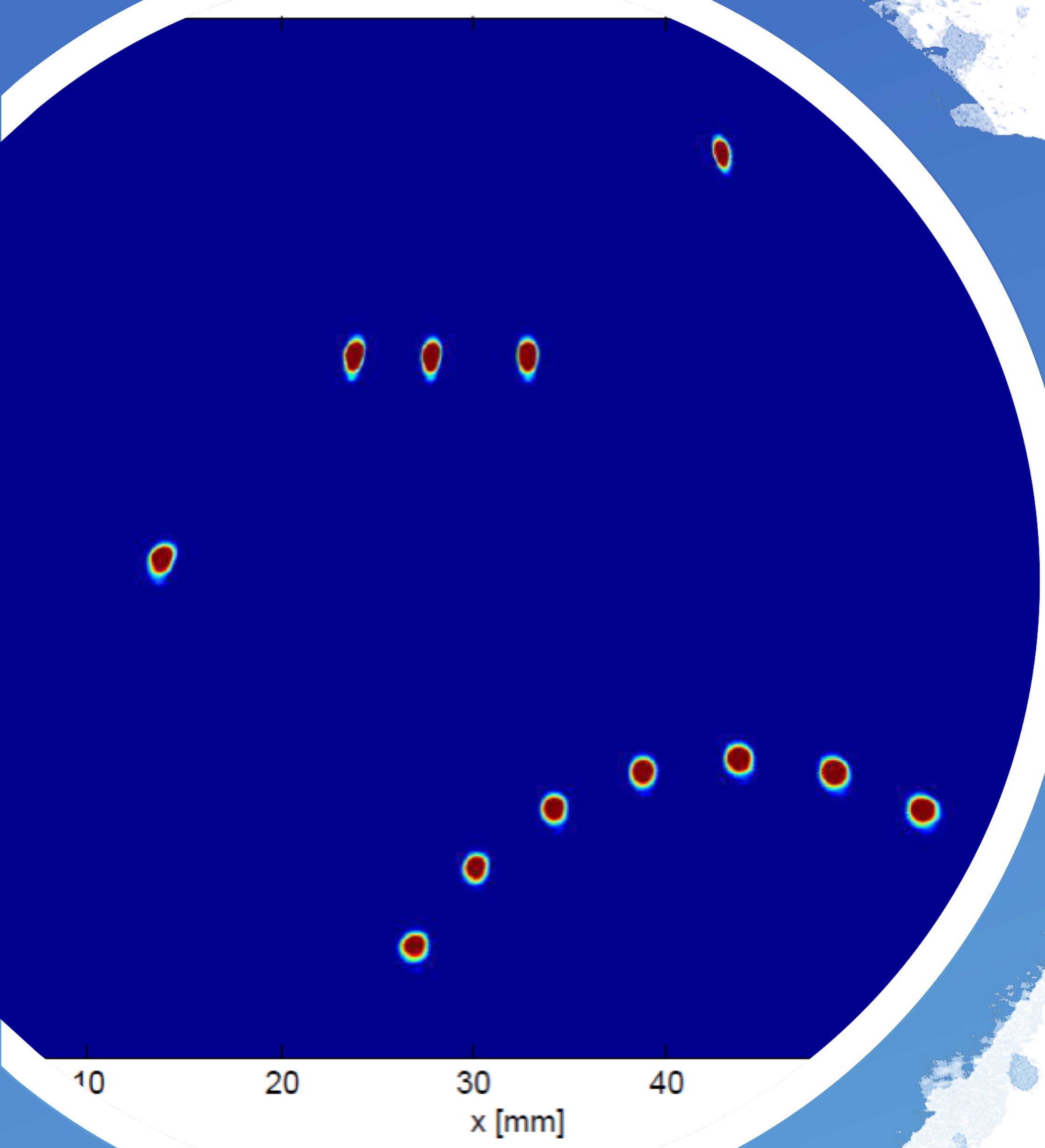


Adaptive FMC/TFM

The exact same part and FMC data with adaptive algorithm applied in post-processing – all targeted FBH are now visible.

In some cases, the data can be acquired with non-Adaptive approach with the Adaptive signal processing applied in analysis





Historical Constraints

FMC/TFM Historical Constraints

- **Too Slow!**
  - The volume of data (i.e., A-scans) generated by FMC/TFM is much larger than PAUT (n vs. n^2) = greater processing time = slower inspection speeds.
- **Current Industry Solutions:**
  - **Short-Term Workarounds**
    - TFM shortcuts (e.g. sparse – less transmit elements) = less resolution/worsened SNR
    - Reduced frame size/TFM reconstruction points = losing some benefits of FMC/TFM (increased coverage)
  - **AOS/TPAC Method**
    - Separate acquisition unit from processing unit (laptop).
      - Using GPU to offload massive parallel computation requirement onto PC, not reliant on limited CPU capacity.

FMC/TFM Historical Constraints

- **Too Much Data!**
  - The volume of data (i.e. A-Scans) generated by FMC/TFM is much larger (n vs. n^2) = much larger file size.
- Current Industry Solutions:
  - **Short-Term workarounds**
    - External SSD connected to unit (bulky, limited capacity).
    - Daily data transfer (connection and technician reliant).
  - **AOS/TPAC Method**
    - Separate acquisition unit from processing unit (laptop).
      - You can have an acquisition laptop with multiple TB capacity.

Important Equipment Considerations

Instrument Configuration

- 16 vs. 32 vs. 64 vs. 128 vs. ?
- The greater the number of available parallel channels, the larger your focused inspection grid (range) can be.
  - As in PAUT, this is still a function of the near field of the probe:

$$N = \frac{D^2}{4\lambda} \quad \text{or} \quad N = \frac{D^2 F}{4V}$$

Instrument Configuration

- Configuration focusing ability comparison ($\mathcal{L}$ waves in steel):

Probe Frequency	Element Pitch	Parallel Channels	Range of Focus in Z (w/o *k* factor)
2.25MHz	0.5mm	16	~6mm
2.25MHz	0.5mm	32	~24mm
2.25MHz	0.5mm	64	~98mm
2.25MHz	0.5mm	128	~391mm

- Also applicable to standard PAUT.

TFM Reconstruction Points

- The number of available reconstruction points in TFM image reconstruction is analogous to pixel count on your television – the more available reconstruction points = the better your inspection image!

TFM Frame/Grid Size	Total TFM Reconstruction Points
128 x 128	~16,000
256 x 256	~65,000
512 x 512	~262,000
1000 x 1000	~1,000,000

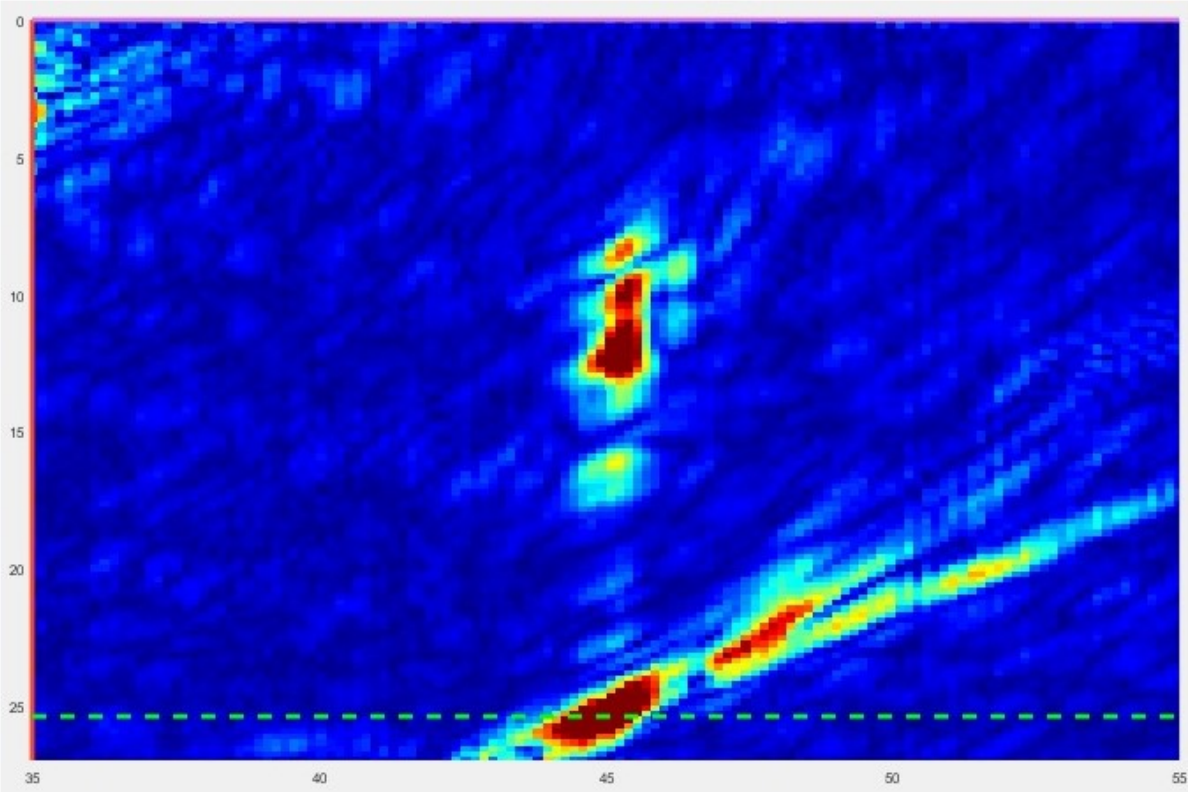
TFM Reconstruction Points

- We can also view this as available points per wavelength, which we can then correlate to minimum flaw size detection, sizing accuracy, resolution, etc.

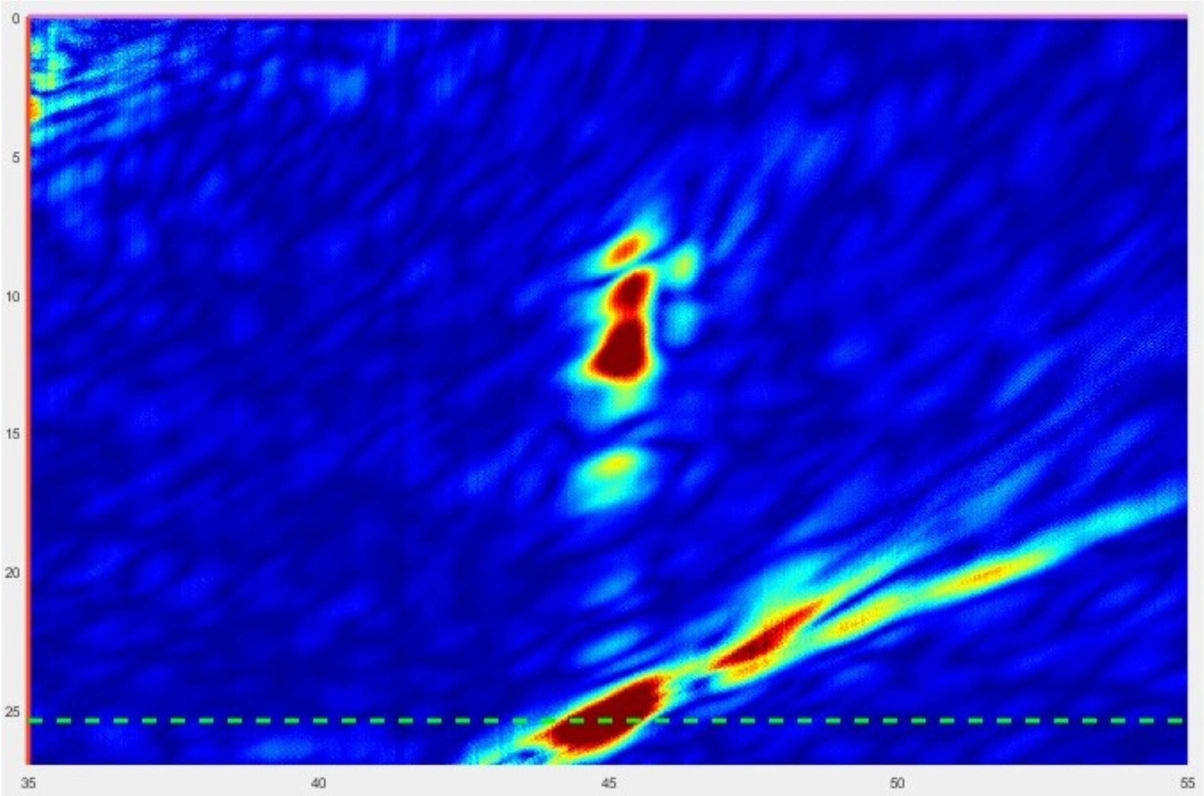
TFM Frame/Grid Size	Total TFM Reconstruction Points	~TFM Reconstruction Points per (L)Wavelength, along Z, in 3"T Steel		
		2.25 MHz	5 MHz	10 MHz
128 x 128	~16,000	4	2	1
256 x 256	~65,000	9	4	2
512 x 512	~262,000	17	8	4
1000 x 1000	~1,000,000	34	15	8

TFM Reconstruction Points

128 x 128 (16K TFM Points)

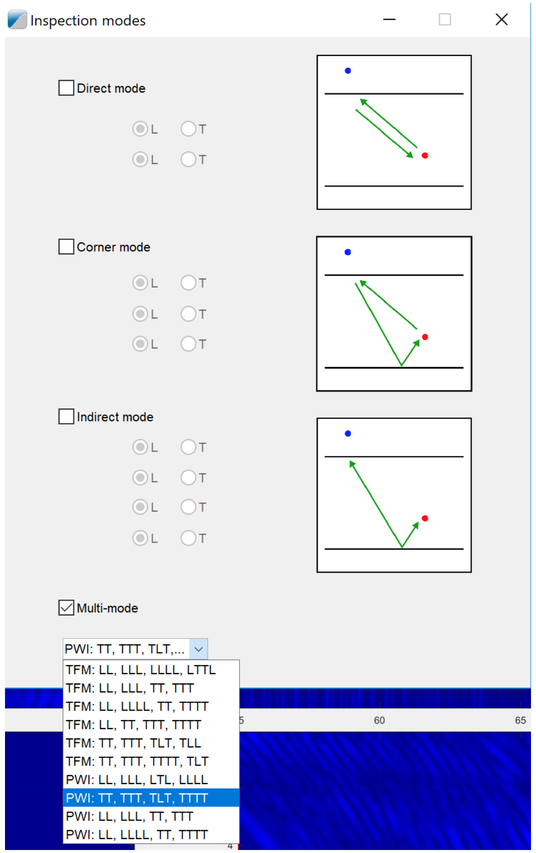


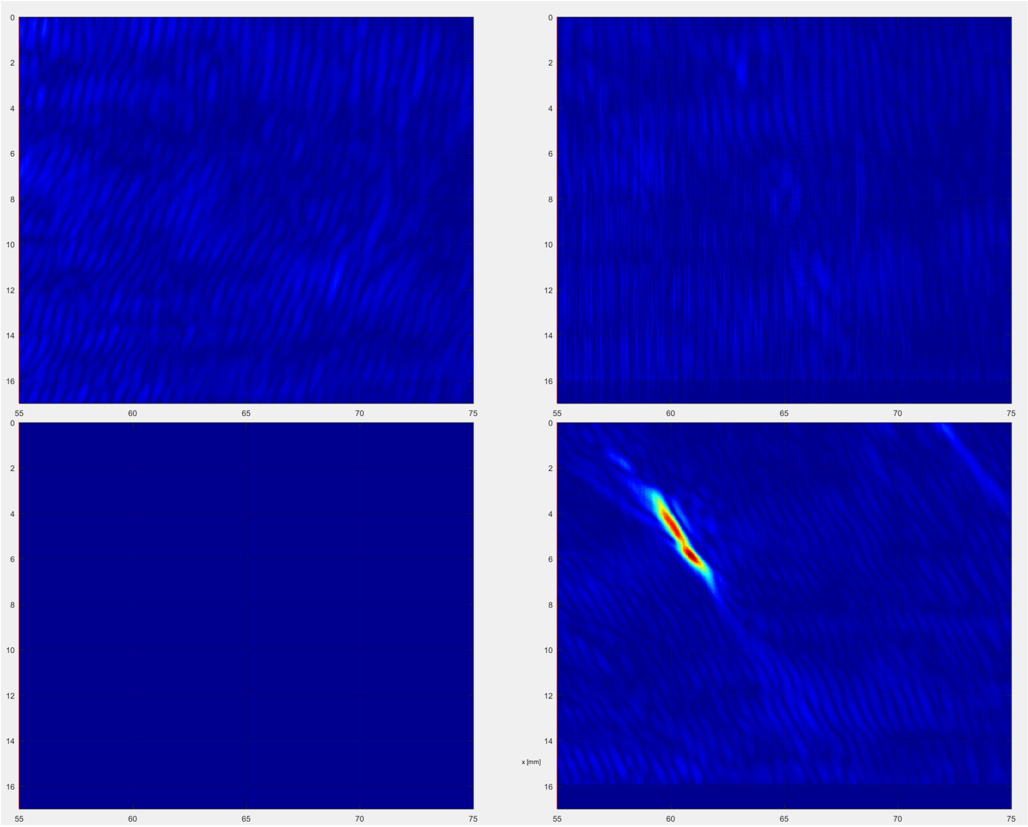
1000 x 1000 (1M TFM Points)



Advanced approach > Low resolution/point density ispection with high resolution analysis

Imaging in Multiple Wave Modes



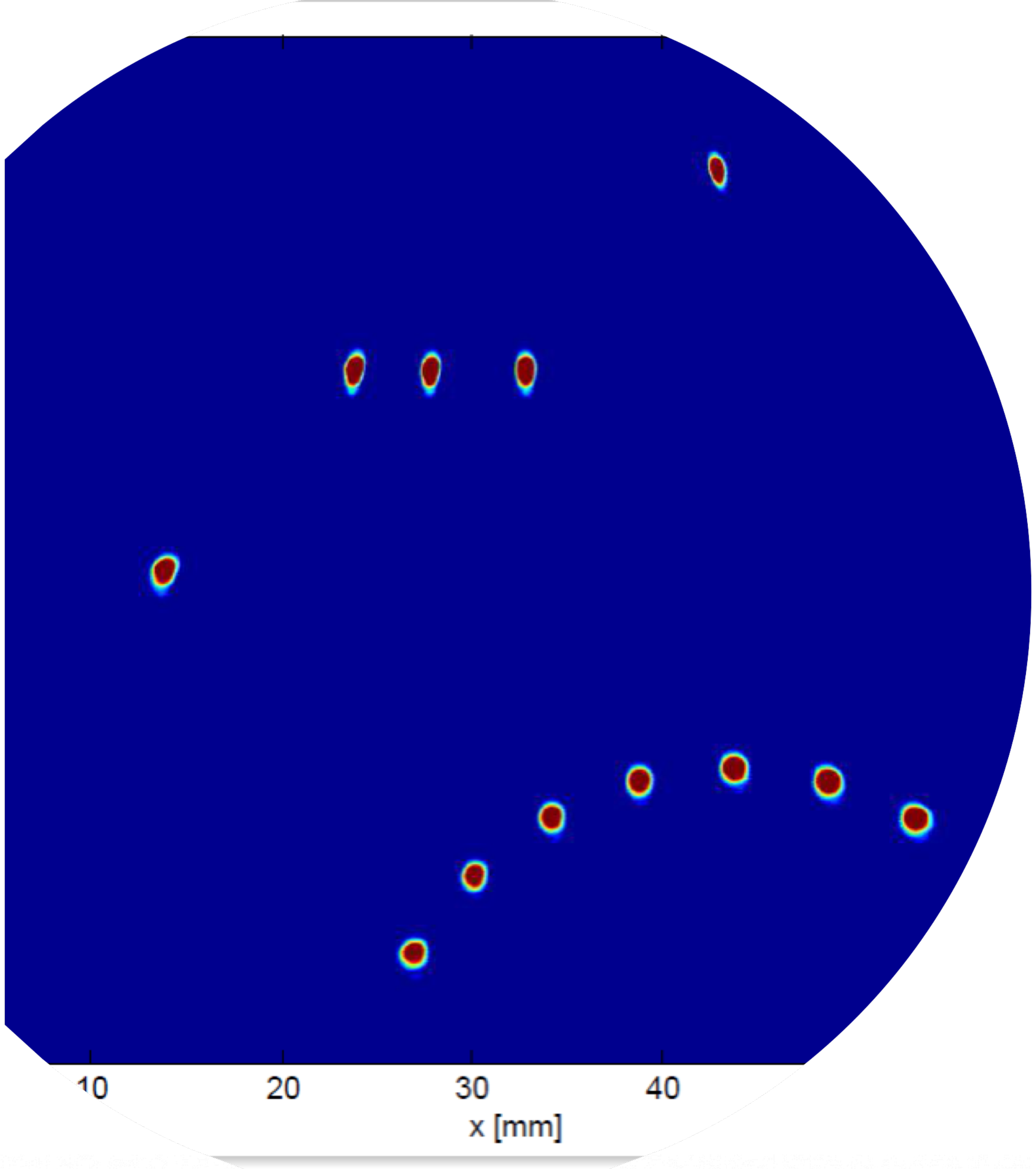


Saving the FMC Data Set

- Two questions can be asked regarding the FMC/TFM data saving capabilities:
  - Do you have the ability to save the <u>FULL</u> FMC data set?
    - Technician-selected TFM (i.e. processed) images are an inadequate substitute.
  - What modifications can be made in post-processing/analysis mode?
    - Setup (pitch/frequency)
    - Signal processing (filtering/additional algorithms)
    - Physical (TFM point density/frame)

Benefits of Saving the FMC Data Set

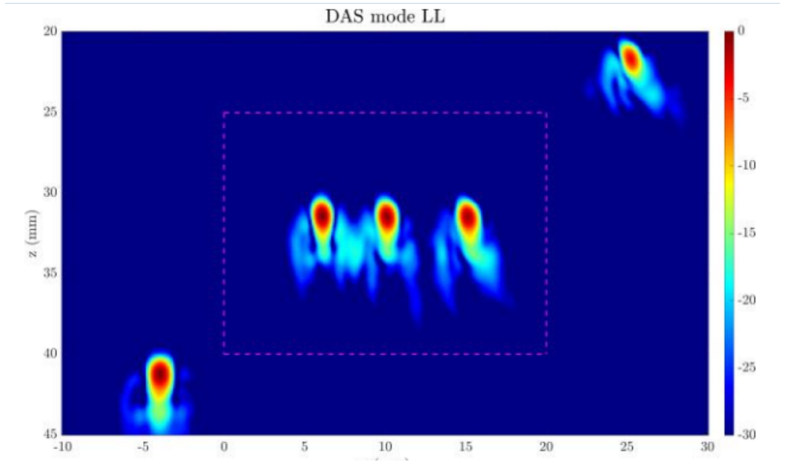
- Some possibilities when acquiring the full data set
  - Increased inspection speed via low-resolution acquisition and high-resolution analysis
  - No need for successive acquisitions for multiple wave mode analysis
  - The ability to apply additional algorithms (e.g. adaptive to non-adaptive, enhanced TFM)
  - Historical record of inspection data

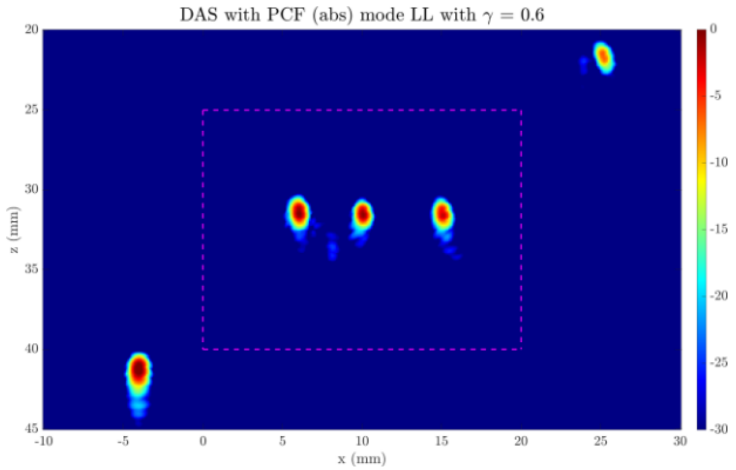


Latest Developments and Future Advancements

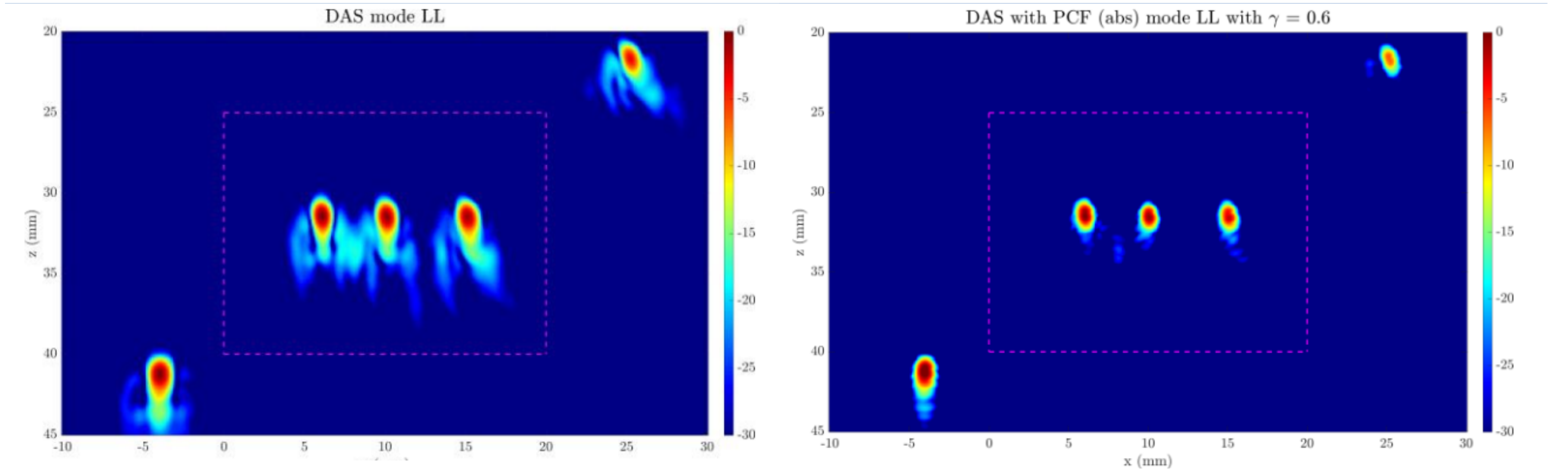
What's New?

- **New Signal Processing Approaches**
  - Virtual Source Aperture
  - Phase and Signal Coherence
  - "Multi-Surface Adaptive
  - Proprietary/New Signal Processing Algorithms (e.g. XWI)
  - Removed Limitations on Probe Usage (MPA) and Propagation (e.g., DMA)



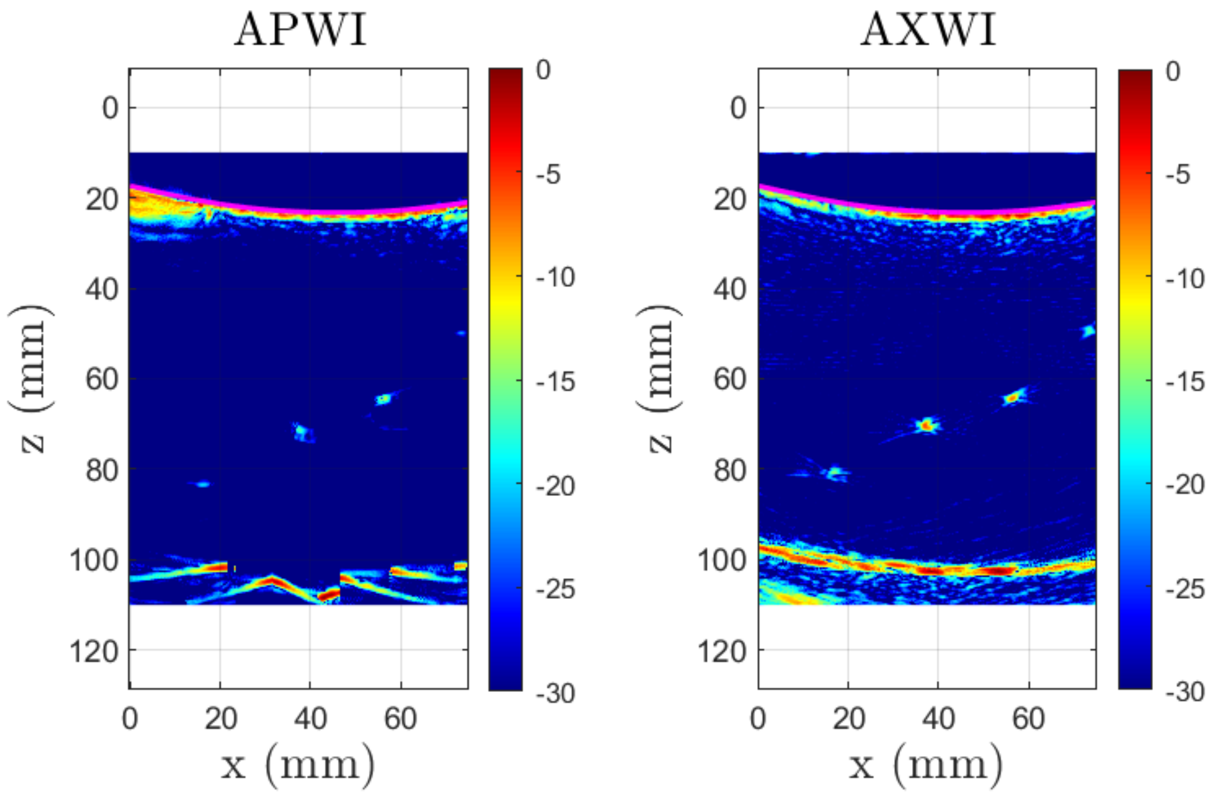


FMC Signal Processing Example – Phase Coherence



Weights contribution of transmitting element to a specific pixel or TFM data point based on the amount the FMC data, or A-Scans, are in-phase

FMC Signal Processing Example – XWI

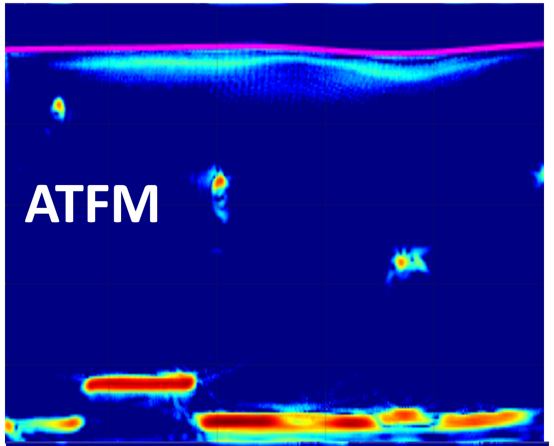


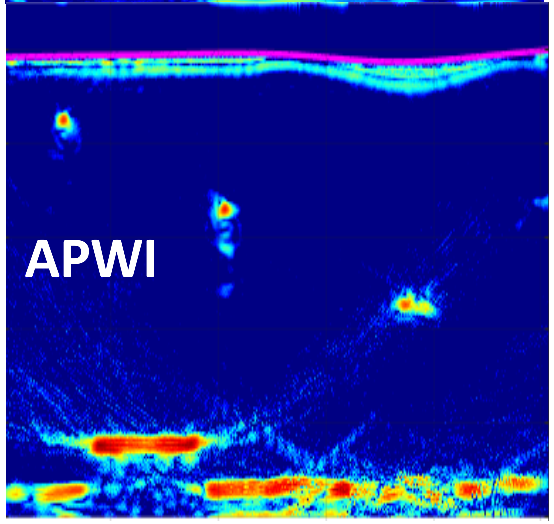
A refined Adaptive approach where the surface is generally known. Provides faster inspection and image reconstruction times.

PAUT vs FMC/TM vs PWI/TFM

Some General Case Comparisons

	PAUT	FMC/TFM	PWI/TFM
SPEED	✓		✓
PENETRATION	✓	✓	
RESOLUTION		✓	✓
SPECIFIC FOCUSING	✓		
SNR		✓	✓
NSR		✓	





THANK YOU!

Questions?
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Thank you for participating!

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