An Advanced Ultrasonic Spectroscopy Solution: Composite Damage Detection in Multi-Layered Materials

A4A NDT Forum, September 2025

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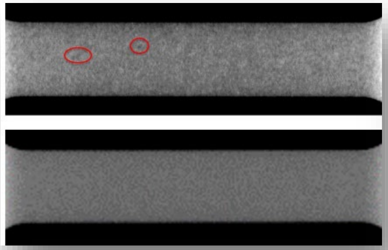
KRATOS: Advanced Materials Characterization

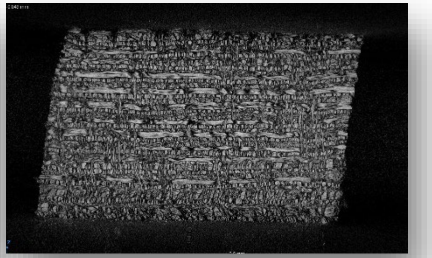
Nondestructive Solution Provider for Difficult Inspection Applications

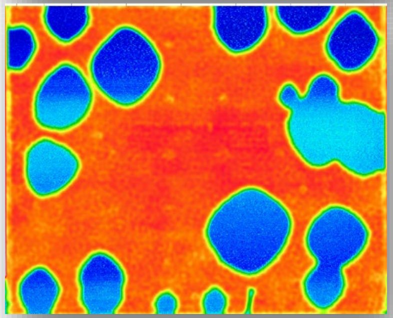
Traditional NDT/UT Methods

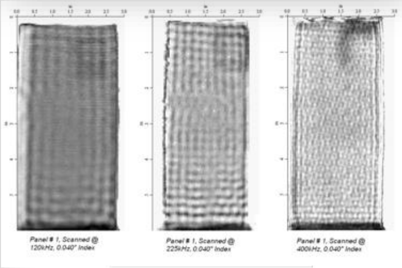
When use of traditional methods not possible or inconclusive

UltraSpec®









<u>Example Inspection Challenges:</u>

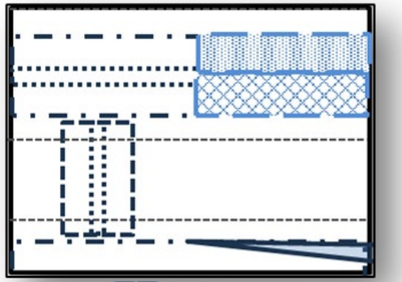
Highly attenuative materials

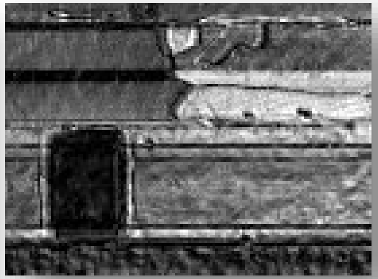
Highly variable material properties

Complex material structures

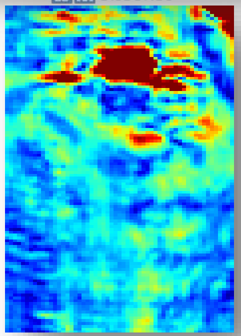
Multi-layered dissimilar materials

High depth of penetration requirement





DISBONDS



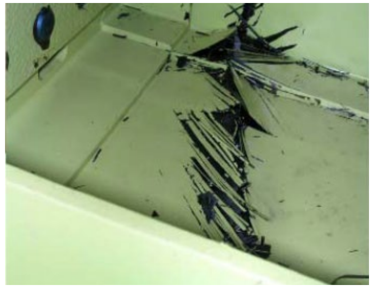
Area	Centroid	W x H	Approx. Area	Approx. Depth from TOP*
1	(1.9, 0.7)	1.0 x 0.5	0.3	20%
2	(4.5, 0.7)	0.8 x 0.4	0.2	21%
3	(1.5, 1.6)	0.7 x 0.8	0.4	33%
4	(3.0, 2.2)	0.6 x 0.6	0.3	40%

Inspection Challenge – Hidden Impact Damage with <u>Complexity</u>

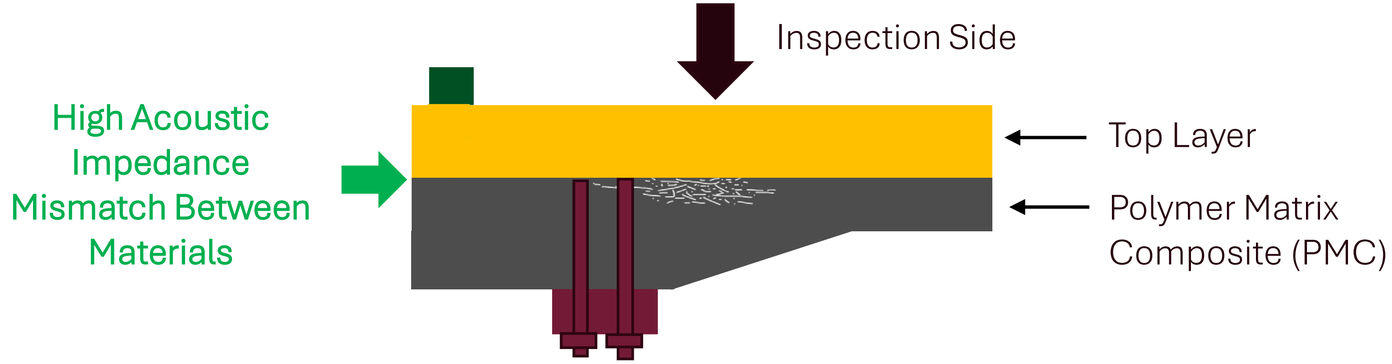
Carbon Laminate Damage: Can be more significant and widespread than what is visible at the area of impact as shown in the example below:

Extent of Visible Damage from Outside

Significant Internal Damage



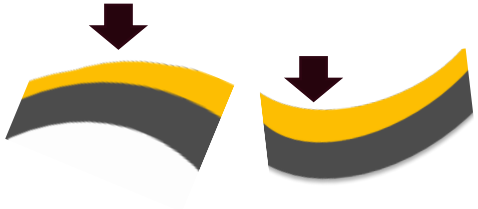
Imagine having another layer of material on the exterior of the carbon laminate;



AND imagine having tapered regions, thickness changes within the carbon laminate;

AND imagine having aluminum substructure and fasteners ...

...in CURVED structures.



Evolving an Advanced Ultrasonic Spectroscopy Technique for Composite Damage Detection Through Thick Specialty Coatings

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Computational Tools, Gurnee, IL

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Advanced Materials Research and Characterization

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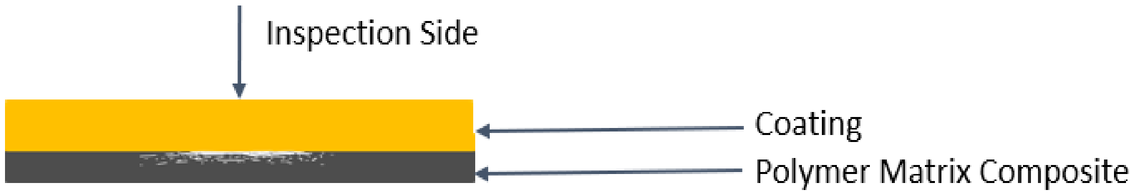
Outline

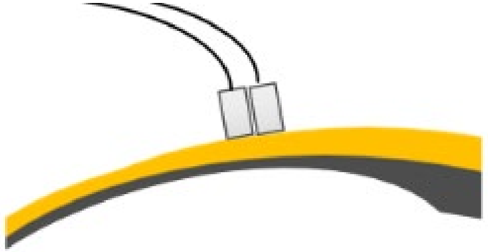
- Background
  - Motivation, Inspection Challenge
  - Initial Investigation Using UltraSpec^{TM}: Assess Impact-Damaged Panels
  - Background of UltraSpec
  - UltraSpec Data Reduction, Metrics, Model Development
  - Defect Samples, Results, Lessons Learned
- Transition to Realistic Structures – New Challenges
- Challenge #1 – THIN COMPOSITES at LOW FREQUENCIES
  - Example Case: Coating + PMC, Frequency Limitations
  - Physics Calculator, Modeling Results
- Challenge #2 – COATING PROPERTIES VARY
  - Self-Referencing Approach (In-Situ Inspection)
  - AIM: Analysis Advancements (ongoing)
- Challenge #3 – COMPRESSIVE SURFACE – “No Sliding”
  - Force Feedback, Perpendicularity to Surface (Curved), Complex Curvature Encoding
  - CobotScan
  - HandScan
- Results/Summary

Inspection Challenge

Problem: Thick outer coatings are applied to a polymer matrix composite (PMC) structure. The coatings are not designed to be disturbed or removed. Impact damage assessment of the PMC is needed.



Damage detection in PMC through coatings



Damage detection in curved and varying thickness PMC through coatings

The impedance mismatch between the materials is high, so significant energy is reflected at the coating-to-composite interface. The inspection solution must be able to achieve adequate penetration, signal-to-noise ratio, and sensitivity for multiple cases including curved surfaces and varying composite thicknesses as shown above.

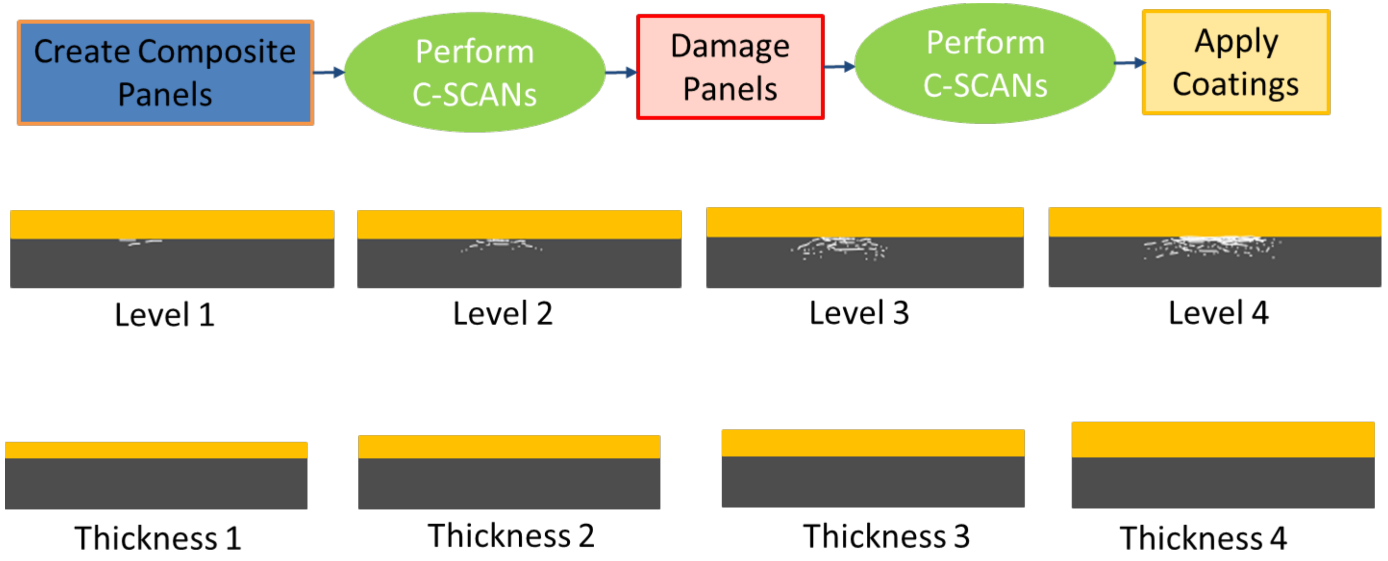
<u>Traditional UT and other NDE methods were attempted but were unsuccessful.</u>

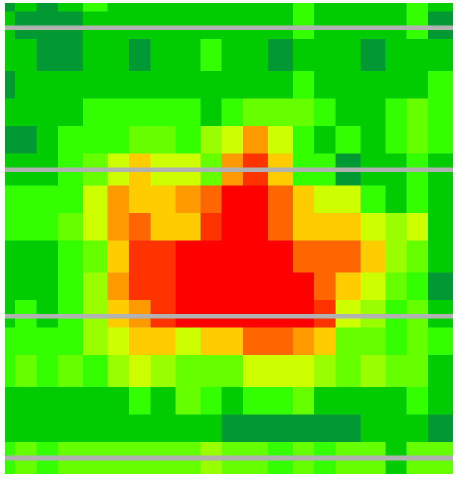
Initial Investigation Using UltraSpec™

Assess Impact-Damaged Panels

GOAL: Perform investigations on realistic, representative defect samples

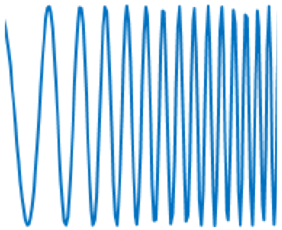
- **Tailor the technology for the application:** probes, parameters, scanning methods
- **Develop a model** to help understand material behavior and signature responses
- **Develop analysis strategies** to delineate from layer variations and substrate delaminations
  - Isolate and interpret individual layer signatures and variations
  - Perform inspections and generate colorized maps

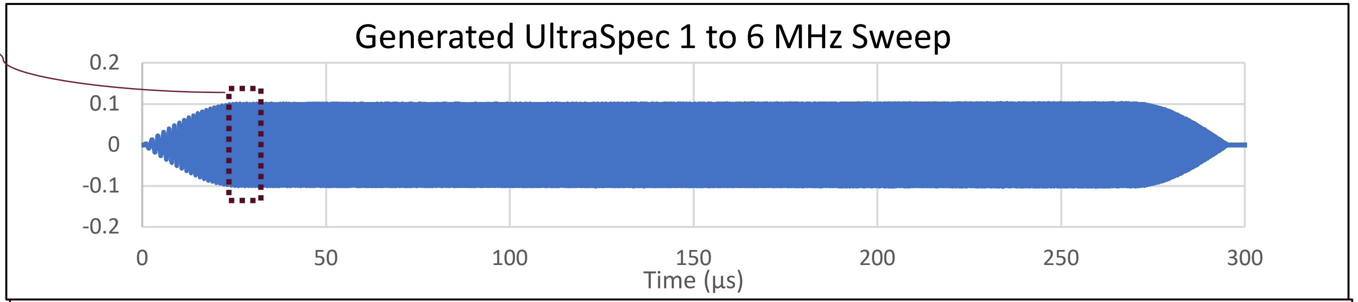




How UltraSpec™ is Different from Traditional UT

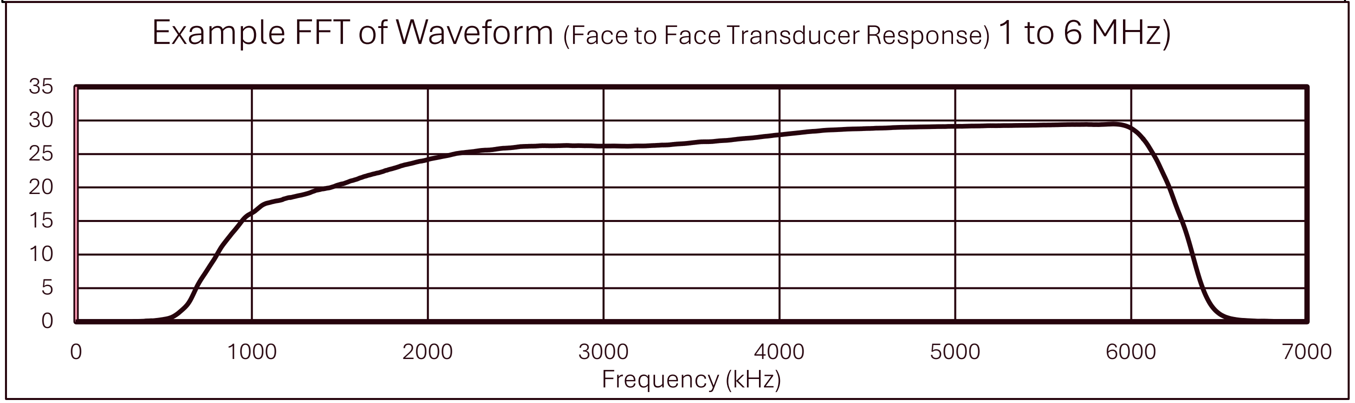
US Patent# 10605789





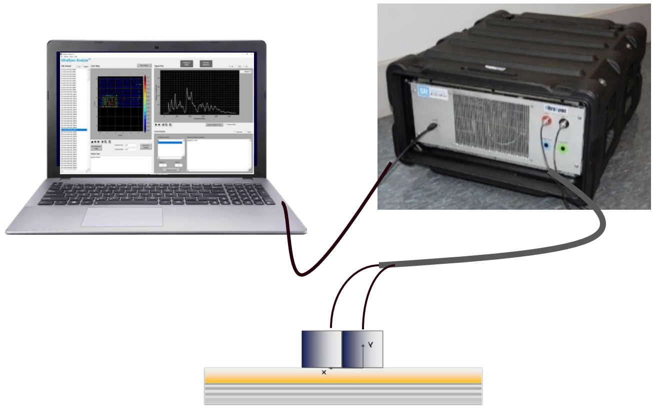
Long Duration Pulse

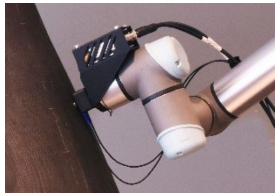
- User-defined frequency range
- Based on material
- Transducer performance can be key
- **MORE ENERGY** into and out of the material structure



THREE CLASSES OF DATA

- Spectral Behavior
- Resonance Behavior
- Pulse Compression

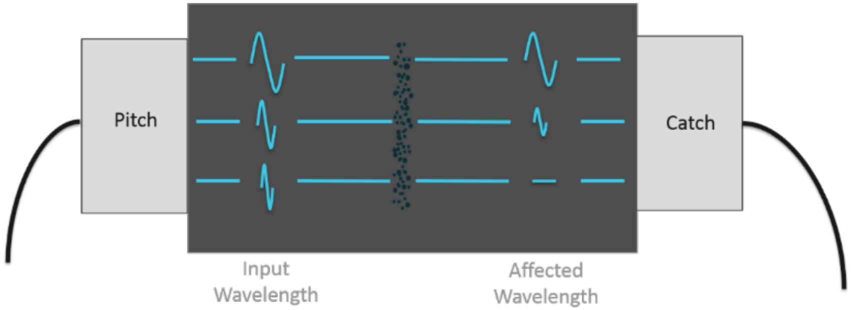


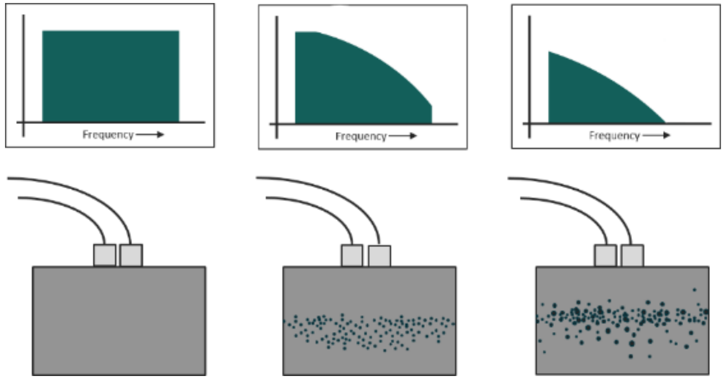


Ultrasonic Spectroscopy: Spectral Behavior

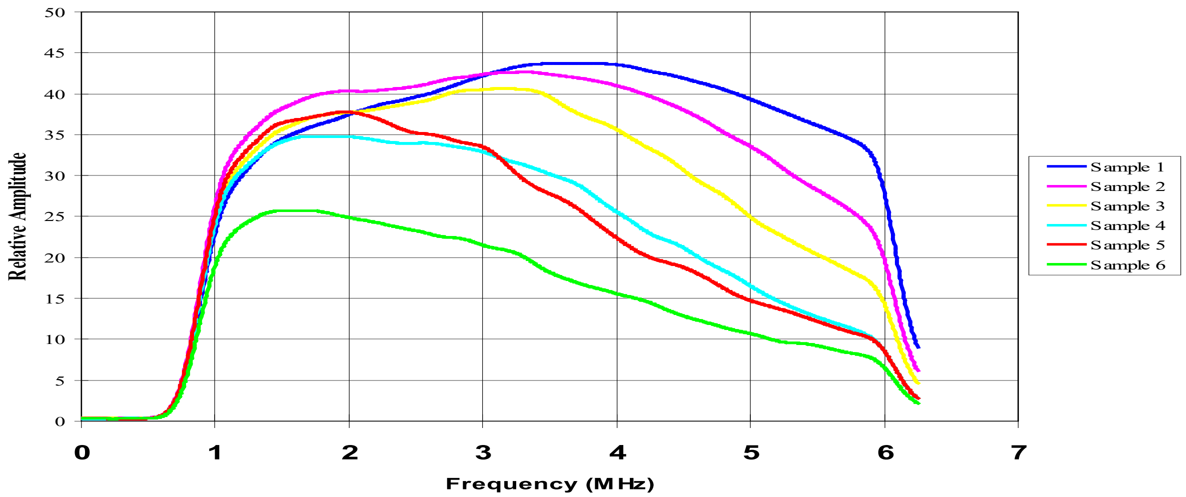
Attenuation as a Function of Frequency

Smaller wavelengths will be more sensitive to a given size porosity or defect





UltraSpecTM Spectral Response: Transmission Through Aluminum Samples with Varying Size Porosity



Ultrasonic Spectroscopy: Resonance Behavior

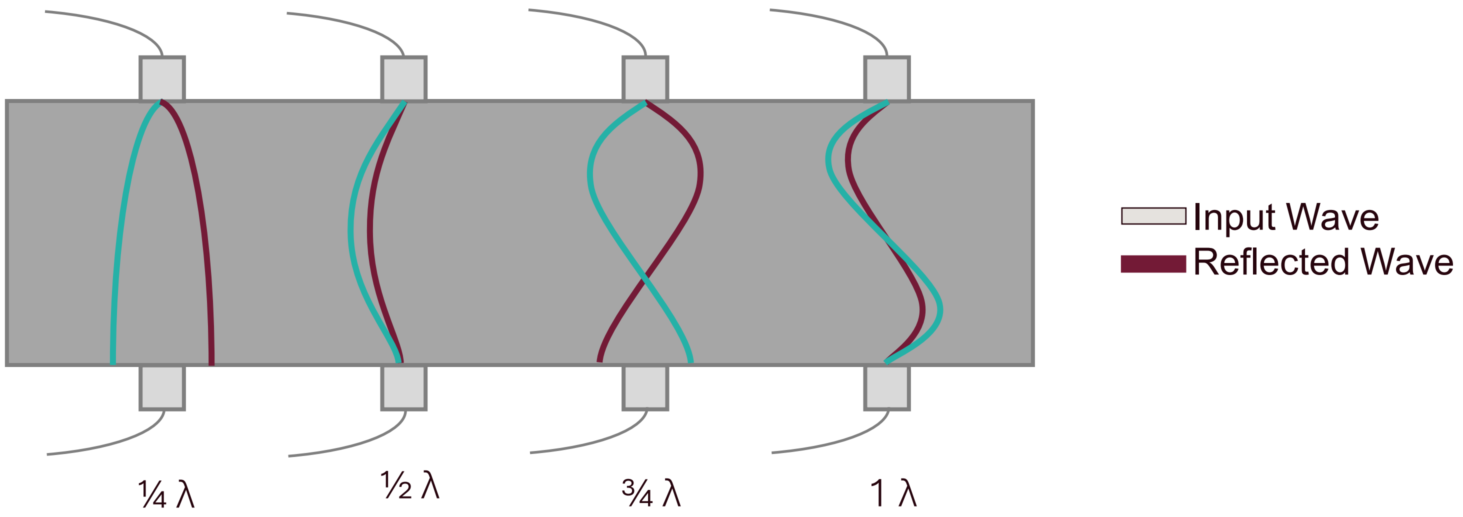
The Physics of Resonance

- Resonance Determined by Thickness and Velocity
- Integer Half Wavelengths Resonate
- Odd Quarter Wavelengths Cancel
- Harmonics are Multiples of a Fundamental Frequency

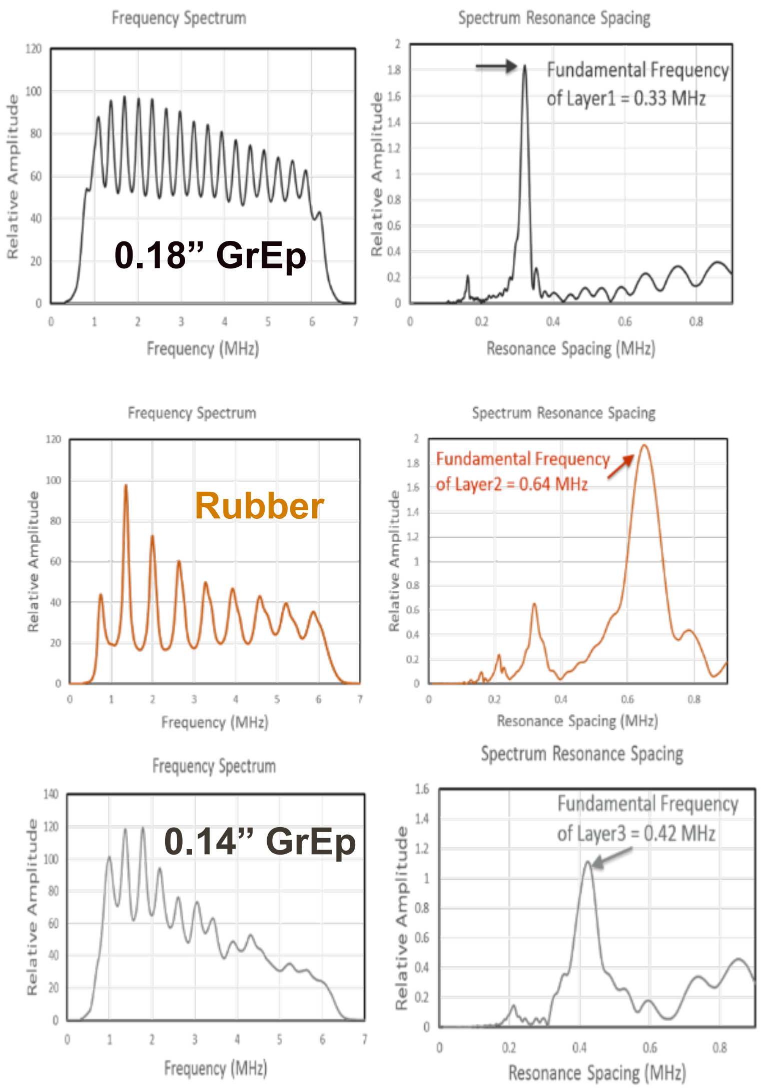
Resonance Intensity

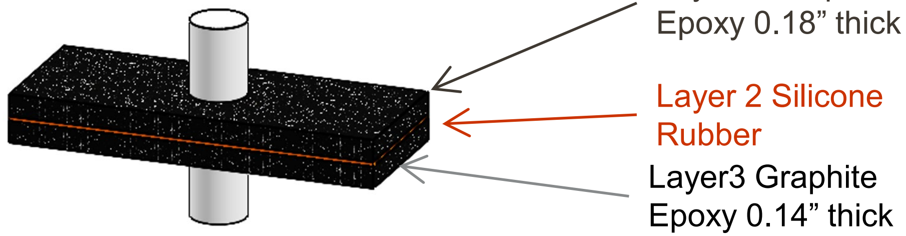
- Affected by Impedance Mismatch
- Affected by Surface Condition
- Affected by Internal Damping

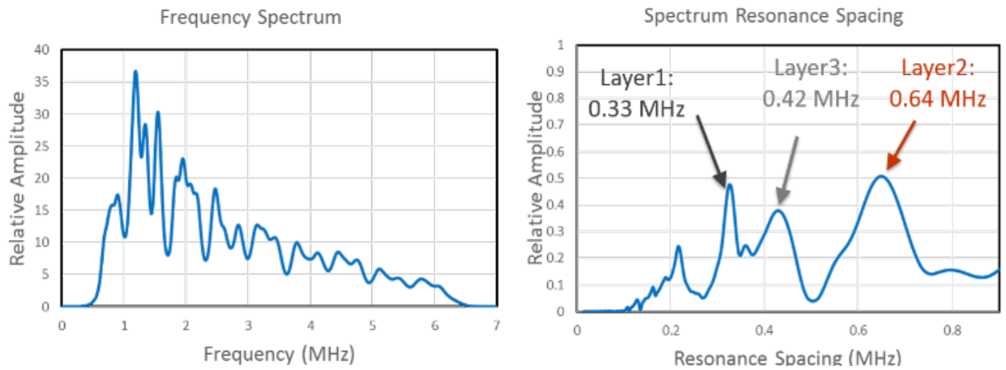
$$\text{Resonant Frequency} = \frac{velocity}{2 * thickness}$$



Resonance Multi-Layer Example





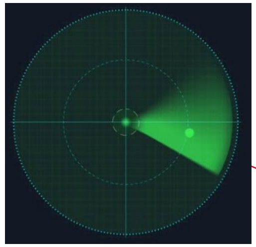


Resonance of all 3 layers are represented in the spectrum information.

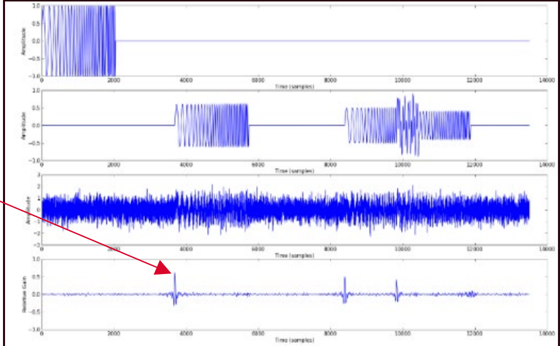
Ultrasonic Spectroscopy: Pulse Compression

Time Delay of Interface-Reflections

Radar



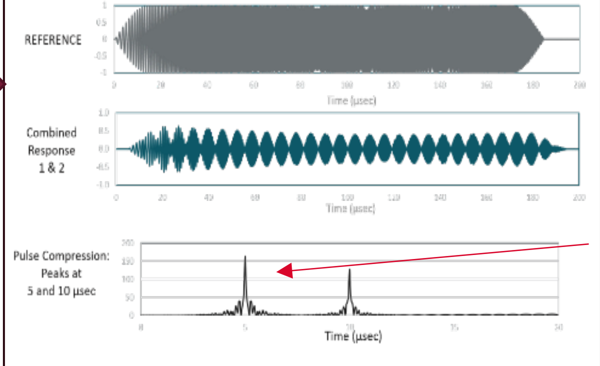
"Blips" on RADAR Screen

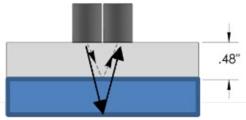


http://marksinclair.wikidot.com/radar

Utilize similar algorithm with UltraSpec response.

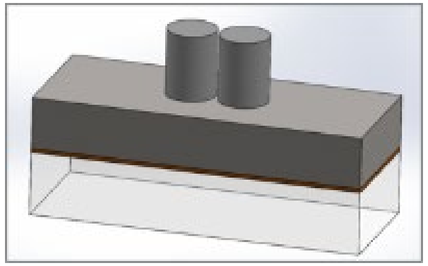
UltraSpec™

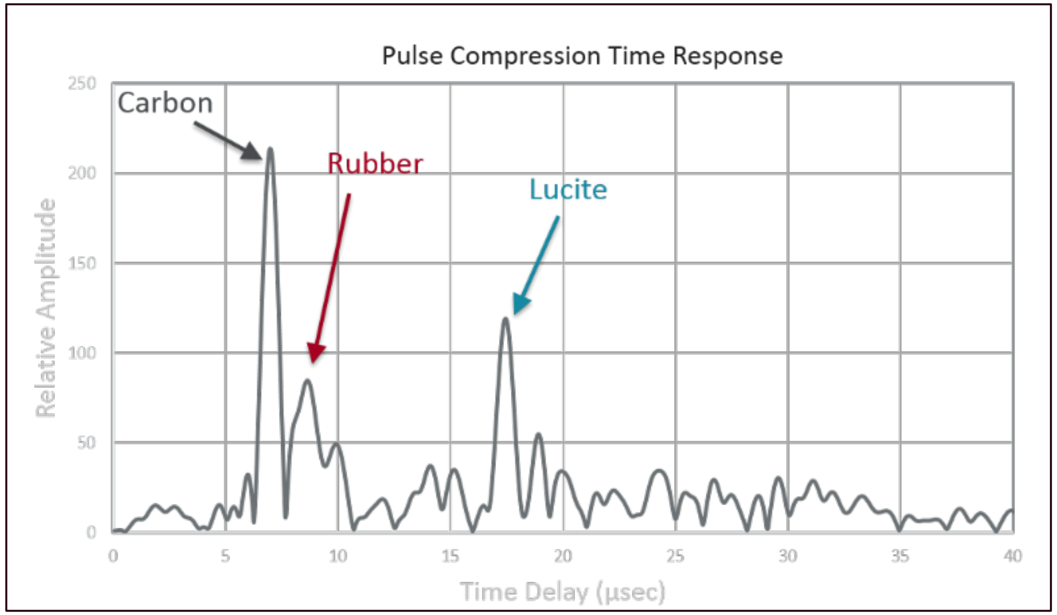




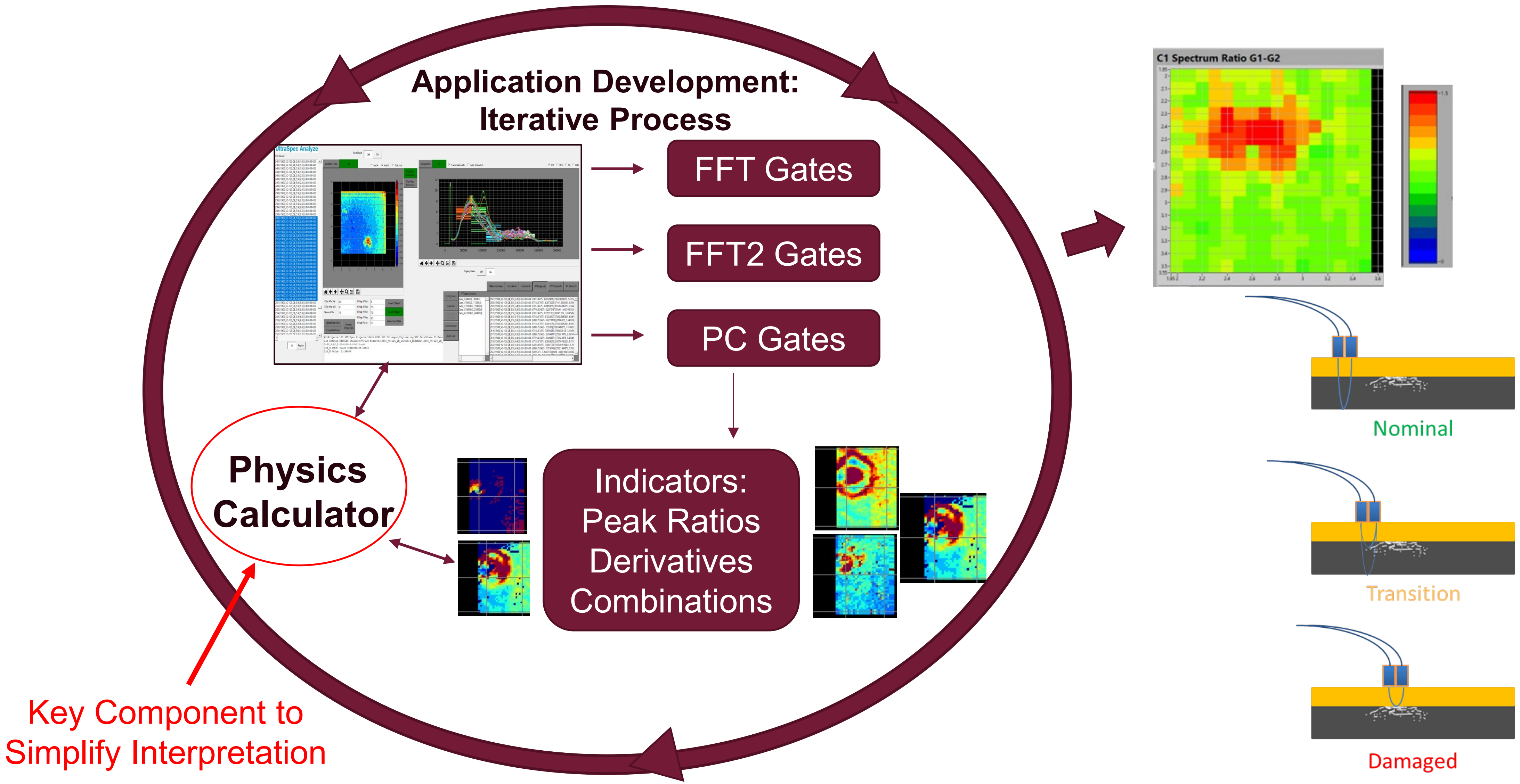
Interface reflections in Material Structure

Three Layer PC Example: 0.4" PMC, Rubber, 0.5" Lucite





Data Does Not Equal Information → Parse Data for Critical Information



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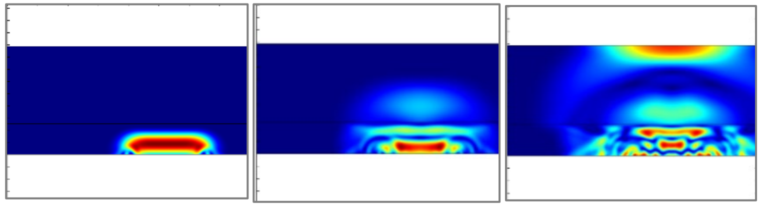
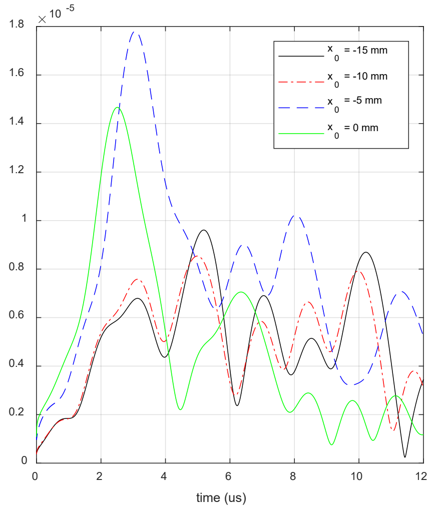
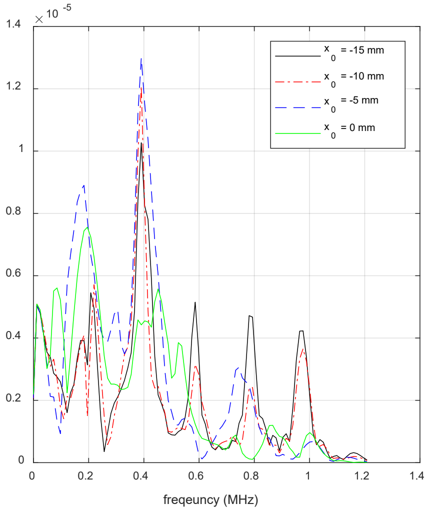
UltraSpec™ Finite Element Model Development & Studies







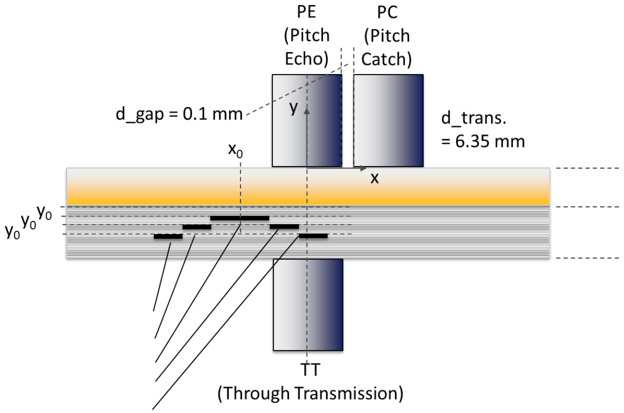
Computational Tools

Dr. John Aldrin

pogo.

- UltraSpec™ model
    - Pogo solver, MATLAB interface
- Performed sensitivity studies
- Examined three modes of UltraSpec - Spectral Response, Resonance Response, and Pulse Compression Reflections → ***multiple metrics for the varying responses should be used*** to cover full range of specimen conditions and damage detection

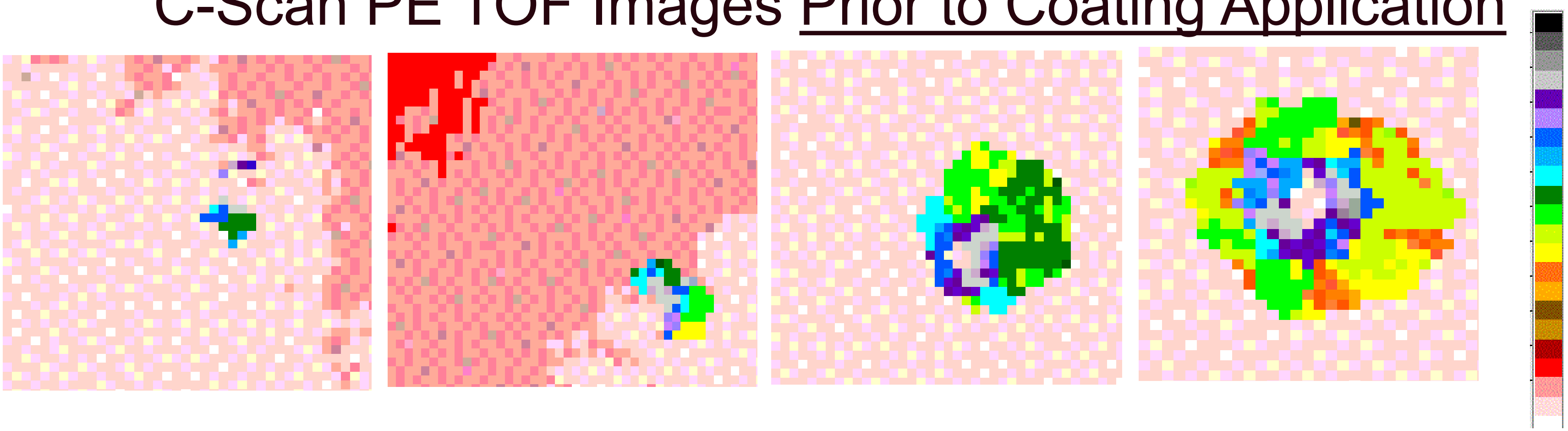
Complex Damage Profiles:



Initial Investigation Results: Varying Impact Damage Energies

Low → High

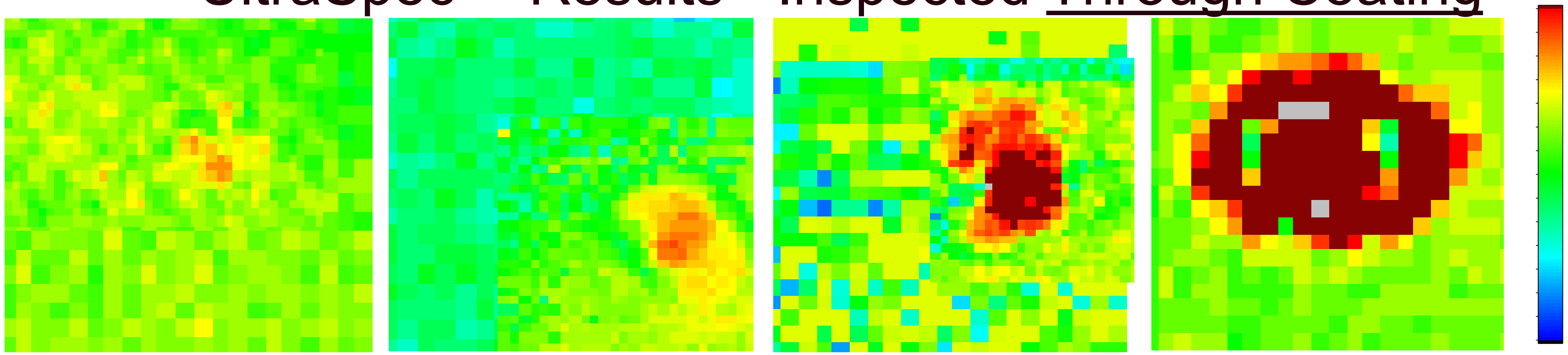
C-Scan PE TOF Images Prior to Coating Application



Traditional C-Scan Attempted AFTER COATING APPLIED – No signal beyond front face.

UltraSpec™ Results - Inspected Through Coating

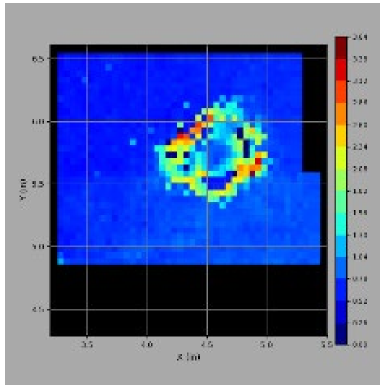
Each square is ~2"x2"

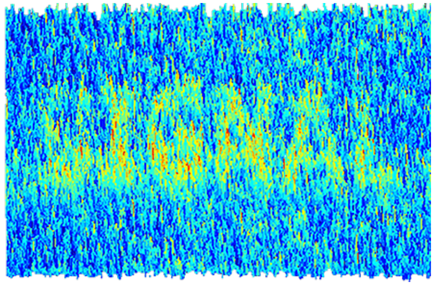


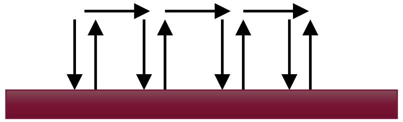
Lowest Impact Energy | Moderately Low Impact Energy | Moderate Impact Energy | Moderately High Impact Energy

Initial Investigations: Summary of Lessons Learned

- Success on panels is only the first “baby” step
  - Fairly flat (they were bowed slightly)
  - Thicker PMC layer (thicker is better for UltraSpec™)
  - Nice, round impact damage – is this realistic?
  - How to assess variations in coating?
- Signals are at/near the noise floor
  - Reduce electrical and acoustic cross-talk
  - Denoising signal strategies need to be addressed – everything matters
- Must have perpendicular pitch-catch probe contact/approach
  - Appropriate probe fixturing, especially for uneven and curved surfaces
  - Compressive nature of the coating means **“no sliding”** during scans
  - Force feedback needed in probe design





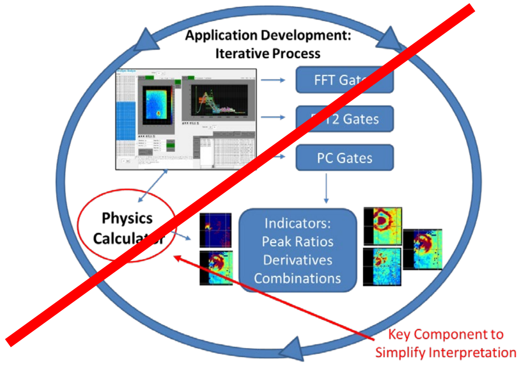


Discrete Point Acquistion
“Push-Acquire-Release”
With Consistent Force

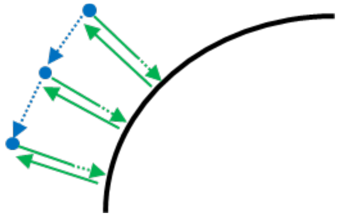
Transition to Realistic Structures

Reality is MUCH more complex than defect samples…

- **Challenge #1:** PMC thicknesses are thinner - 0.1” or less
- **Challenge #2:** Coating state varies with each structure that will require inspection
- **Challenge #3:** Complex curvatures



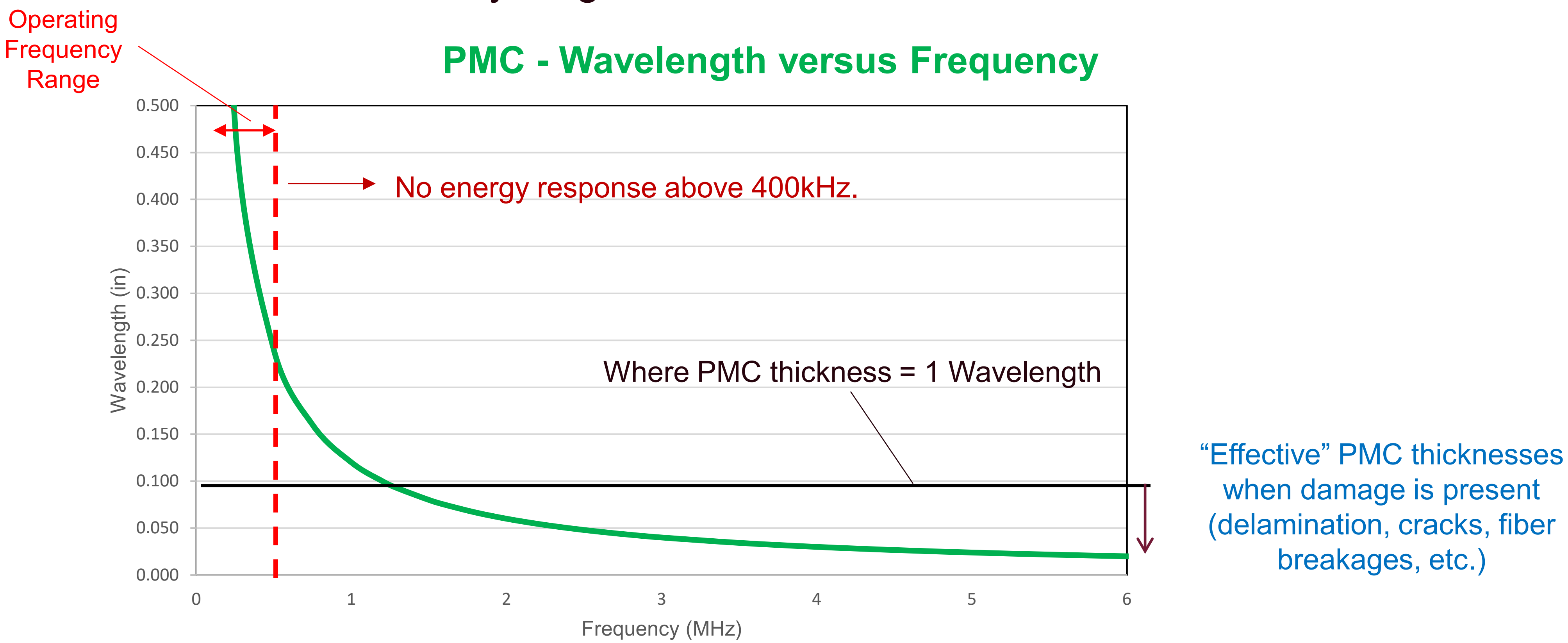
Unable to Perform with ALL POSSIBLE COATING STATES



CHALLENGE #1

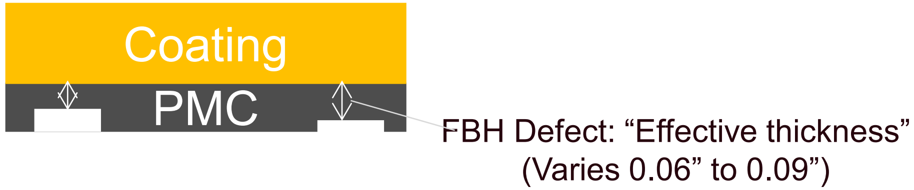
The coated composite field articles have thin regions of interest (<0.1”)

The samples generated for the initial investigation had PMC thicknesses >0.2”. Balancing adequate penetration while still achieving sensitivity changes in thin composite structures is very challenging. Rules of thumb would necessitate 2 MHz or 5 MHz frequency selection. The coating attenuates everything above ~400 kHz.



Physics Calculator Comparison

Example Case with Flat Bottom Holes (FBH)



Coating resonances are dominant (first layer, high impedance mis-match at Coating to PMC interface.

All PMC layer resonant frequencies are far above the maximum frequency (400kHz).

Layer(s)	Res. Freq. (kHz)	2nd Harm. (kHz)	3rd Harm. (kHz)	4th Harm. (kHz)	5th Harm. (kHz)
Coating x.x" thick	100	200	300	400	500
PMC 0.12" thick	500				
PMC 0.09" thick	667				
PMC 0.08" thick	750				
PMC 0.07" thick	857				
PMC 0.06" thick	1000				
Coating + PMC 0.12" thick	83	167	250	333	417
Coating + PMC 0.09" thick	87	174	261	348	435
Coating + PMC 0.08" thick	88	176	265	353	441
Coating + PMC 0.07" thick	90	179	269	358	448
Coating + PMC 0.06" thick	91	182	273	364	455

*Note: Not all peaks are present in experimental data.

Even though the coating and PMC have dramatically different acoustic impedances, they still <u>resonate as a full thickness</u> at these low frequencies. Watching for a change in the “full” resonances may provide a way to assess for damage in the thin PMCs. (**VERY SMALL CHANGES** <8kHz.)

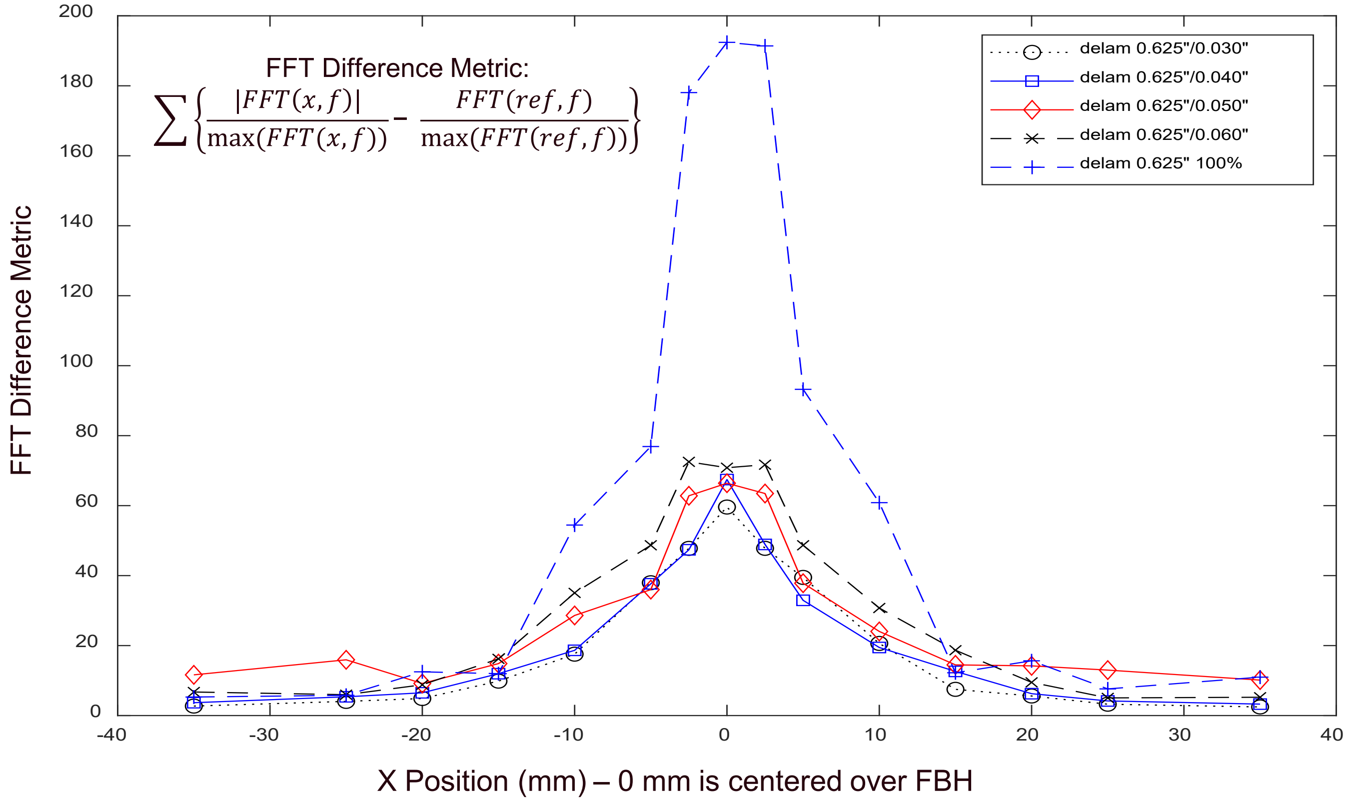
Similarly – watching for changes in the pulse compression back wall reflection may provide an alternative method - are also **VERY SMALL CHANGES** (<1 μs).

Modeling Studies: Differences in Spectral Signatures

Example Case with Flat Bottom Holes (FBH)

FBH Defect: “Effective thickness”
(Varies 0.06” to 0.09”)

Modeling Results: FFT Difference Metric Versus Position Over 0.625” Diameter FBH

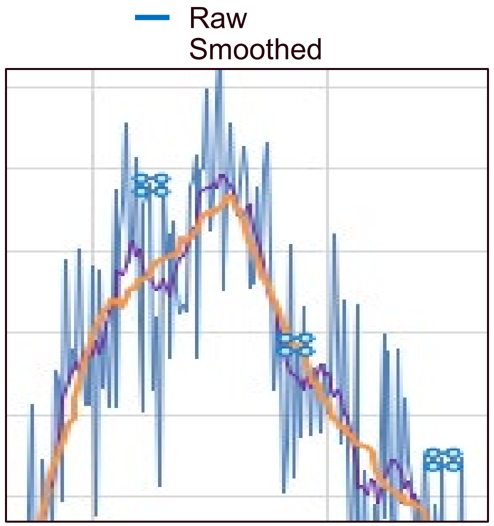


Modeling Results There is ***<u>very little change near the edges of the holes</u>*** (-10mm, 10mm) and the most spectral changes are when the probe is aligned over the center of the hole.

Modeling and experimental data show the resonance changes associated with damage in thin composites are generally ***<u>very subtle</u>***.

Denoising Strategies

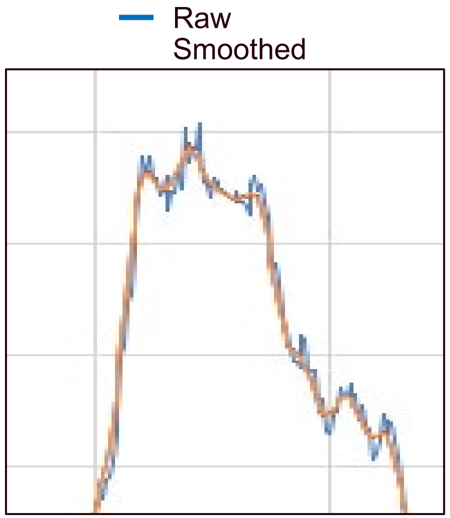
Under-smoothing: Track Noise Peaks/Valleys
Over-smoothing: Lose Subtle “Real” Peaks/Valleys
“Just Right” smoothing: Signal, Not Noise



High Smoothing

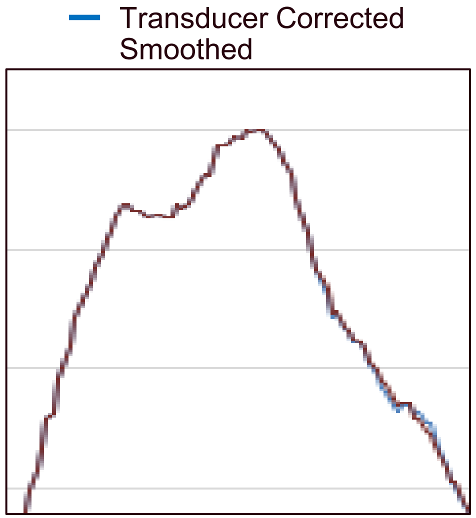
UltraSpec Acquire: LabView → Python

Acquisition Point Averaging (APA)



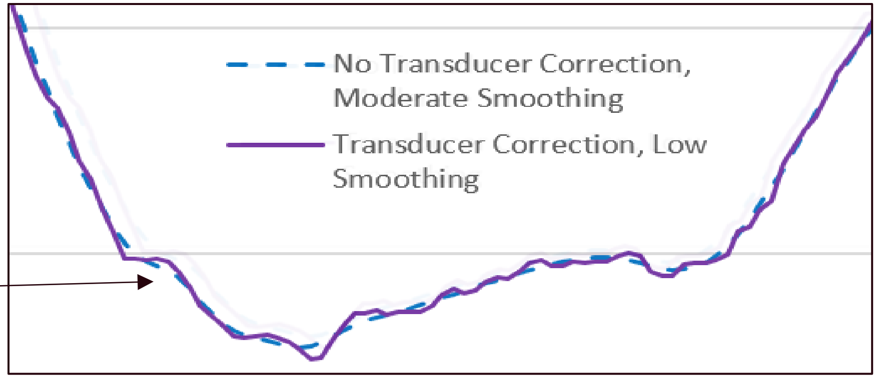
Moderate Smoothing

Transducer Response Corrections



Low Smoothing

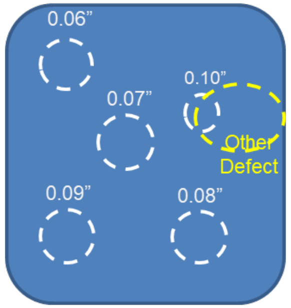
Subtle differences in kHz range of interest.



Denoising strategies dramatically improved the consistency and quality of the data:

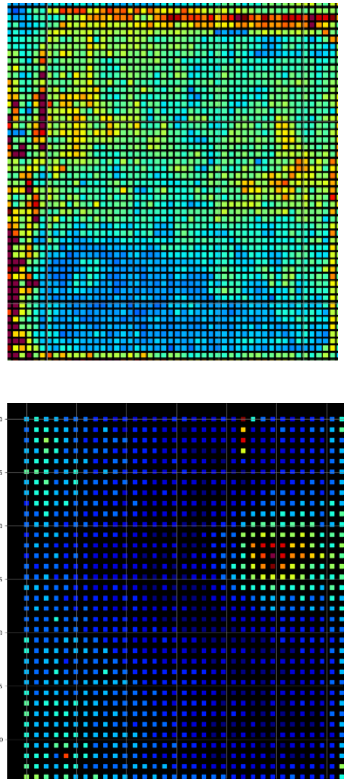
Improvement to Results

Flat Bottom Holes (FBH)

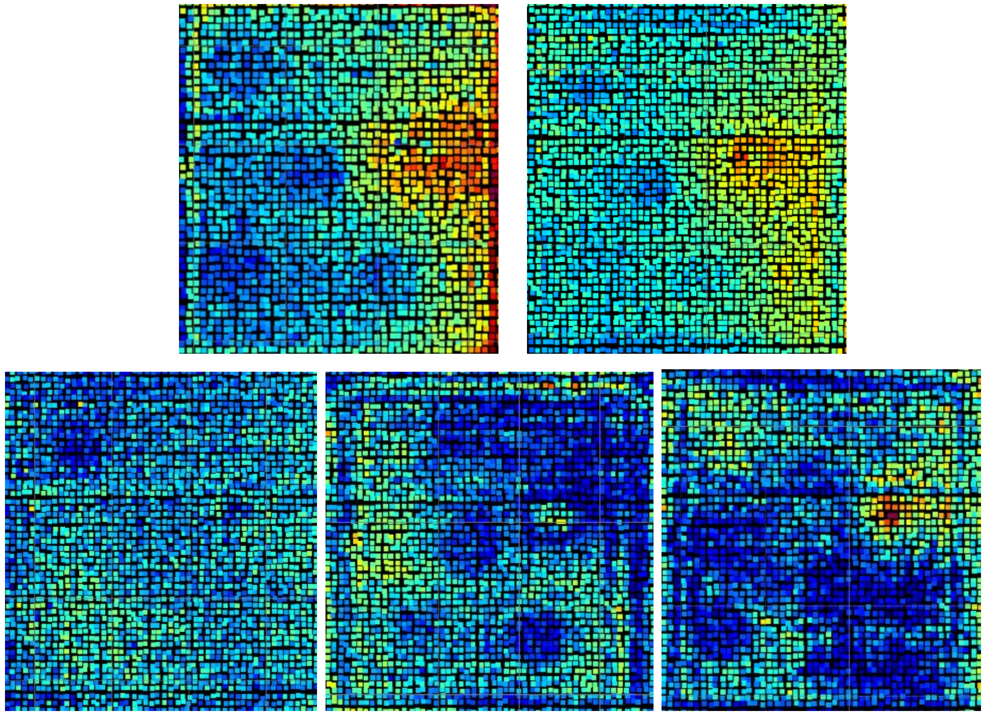


Panel FBH Layout

Results Prior to Recent Improvements



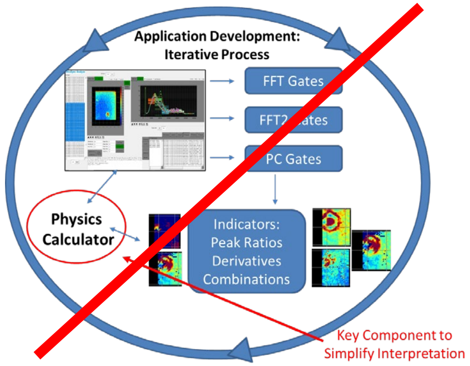
Results After Recent Improvements



CHALLENGE #2

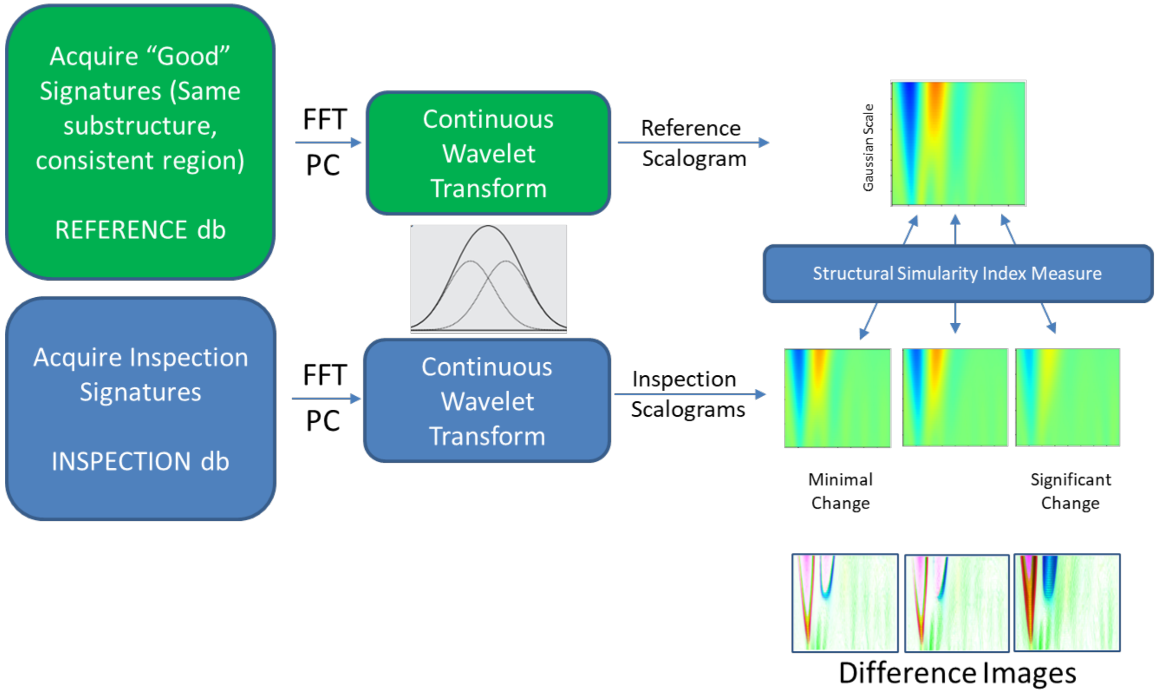
Coating state is different on potentially every structure that will require inspection

- No way to have predefined knowledge of coating state (ultrasonic response, material properties)
- No way to evaluate for predefined gating or signatures
- Need to determine method for human-assisted interpretation (novice user)
- No way to have full set of "reference standards" for every case



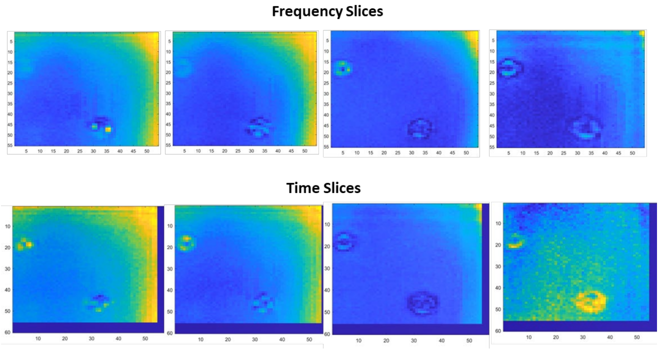
Unable to Perform with ALL POSSIBLE COATING STATES

Generic Self Referencing Approach (SRA)

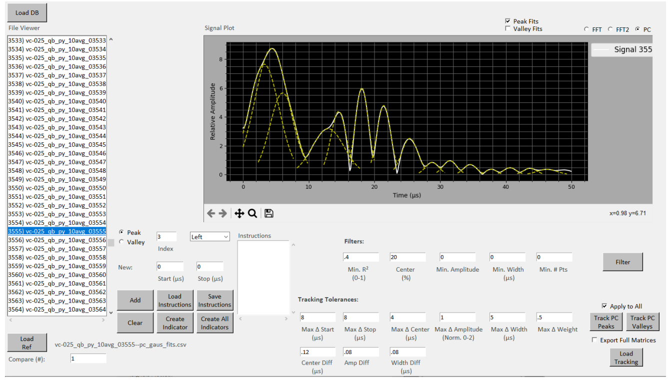


Advanced Interpretation Module (AIM)

Data Cubes
Amplitude "Slices"
Structure/Feature

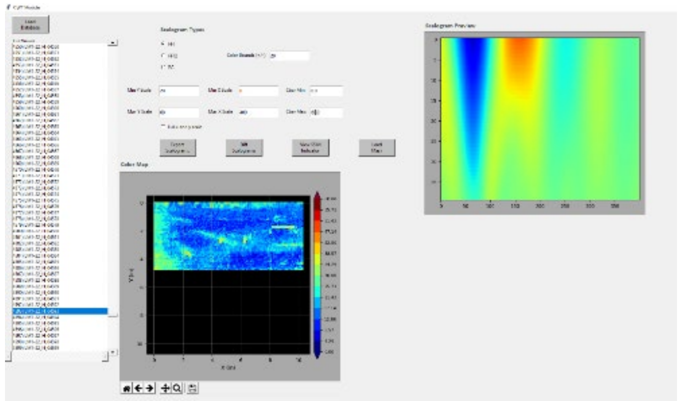


Peak/Valley Fits
Peak/Valley Tracking (PVT)

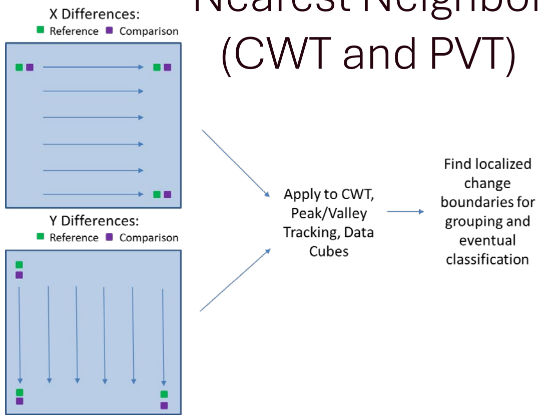


Physics Calculator: Changes in Resonances & Time Reflections

Continuous Wavelet Transforms (CWT)
(Self-Referencing Algorithm)



Spatial Comparisons
Nearest Neighbor
(CWT and PVT)

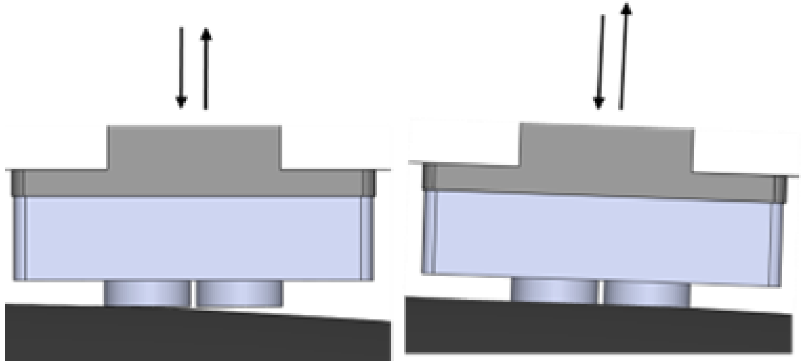


CHALLENGE #3

The coating is compressive and requires adequate probe pressure for discrete point acquisition.

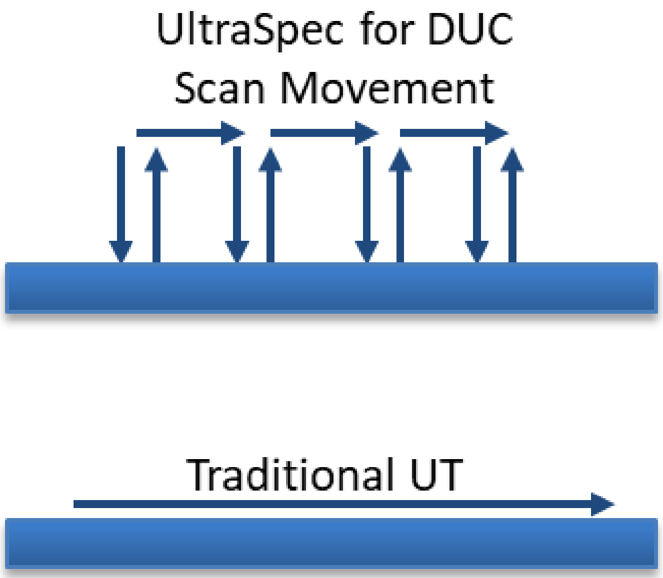
Analytics: Garbage IN, Garbage OUT
How to ensure the user takes GOOD DATA?

Dry Couplant, Compressive Material:
Force Required,
Perpendicular to Surface

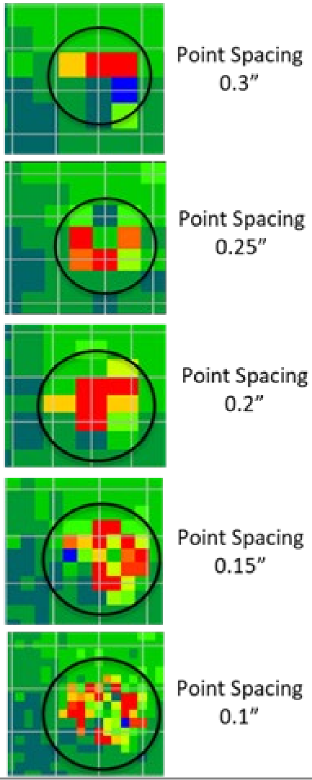


Flat surfaces +/- 2°
Curved surfaces TBD

Unable to SLIDE Probe Across Surface
Push-Acquire-Release

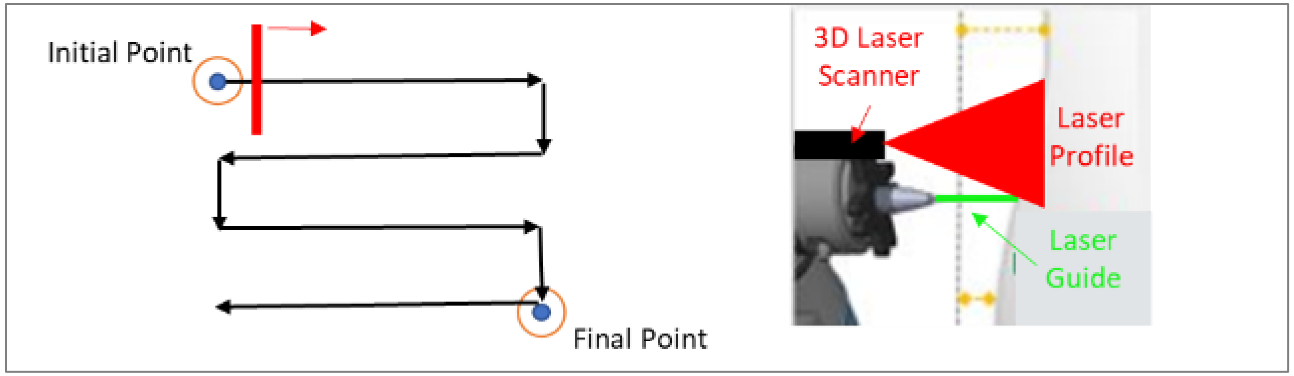


Discrete Point Acquisition:
Resolution Preferred for Defect Detection and Sizing
≤0.2” Point Spacing

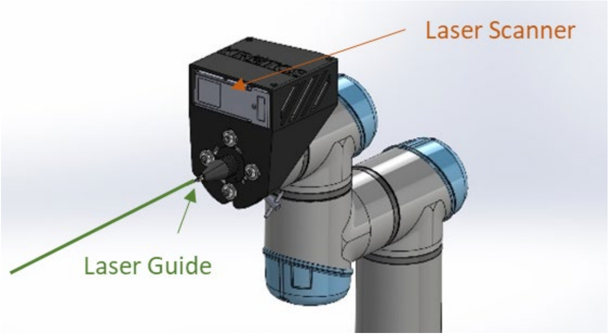


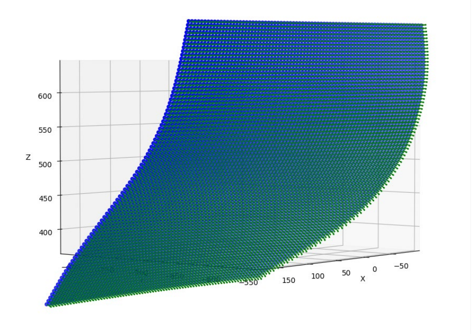
CobotScan Automated Solution

Built-in Force Feedback, Full 3D Control

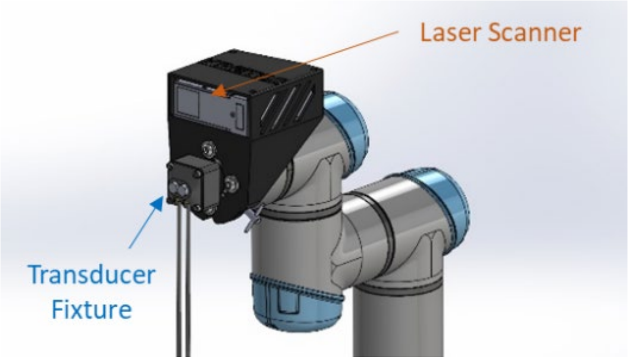


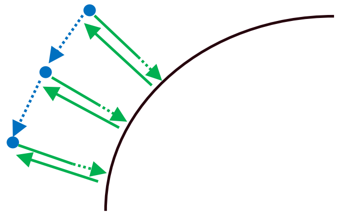
With 3D laser scanner head:
Perform automated measurements for 3D surface in order to generate cobot positional points (blue) and normal vectors (green).





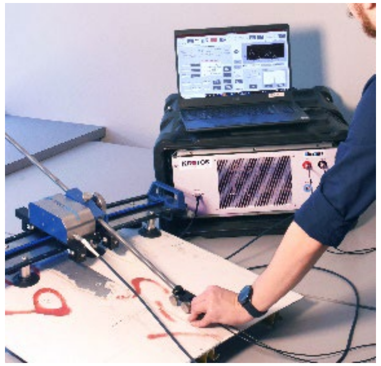
With UltraSpec head:
Take data with force feedback using set of points with directionality normal to the surface.





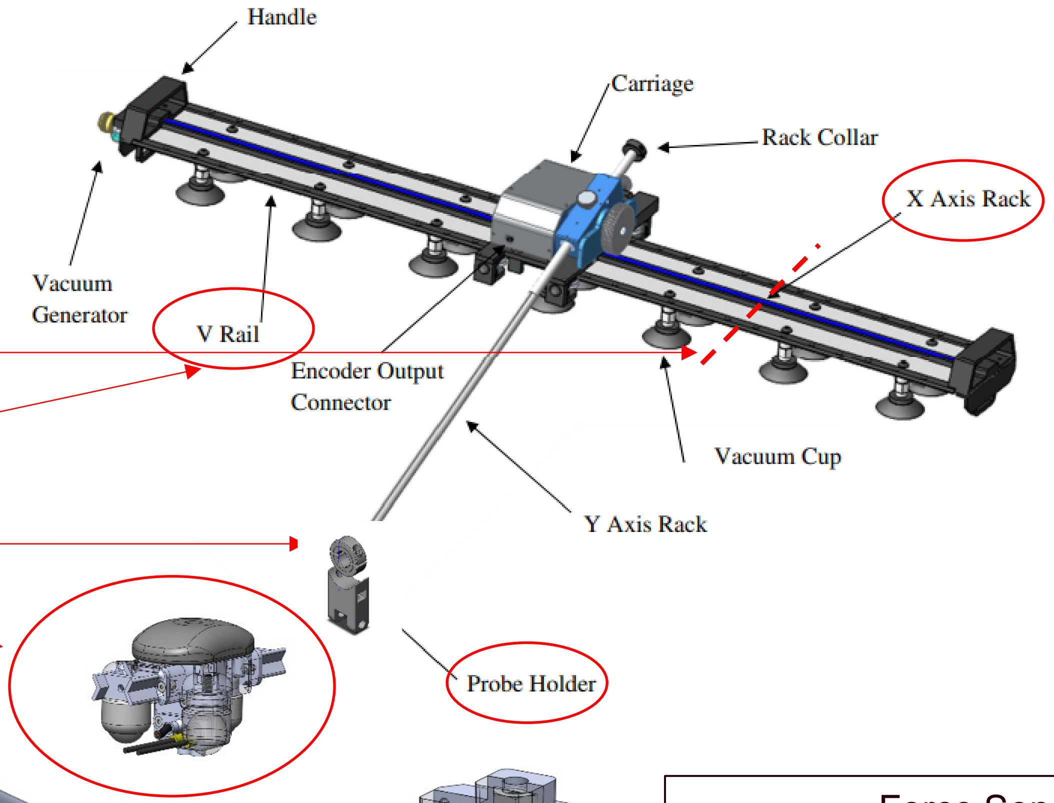
HandScan Field Solution

Built-in Force Feedback, Complex Curvature Encoding



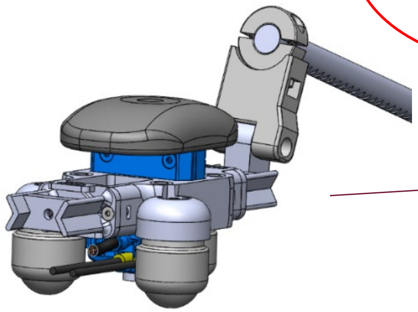
TecScan's TecFlex Scanner
MODIFICATIONS:

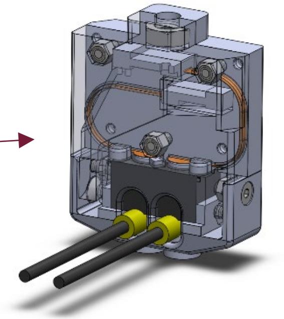
- Shortened length of x-axis track
- Added flexibility to the x-axis track:
  - 3D printed V Rail (Edge) Material (Thermoplastic Polyurethane TPU)
- Designed probe adapters of varying reach
- Designed probe attachment (trike)



Probe Assembly
"Trike"

Designed to rotate in 2 axes (repeatably) in order to seat all three wheels on complex curved surfaces. Once in position, the user pushes on the top to engage the transducers until adequate force/pressure at the surface is achieved.



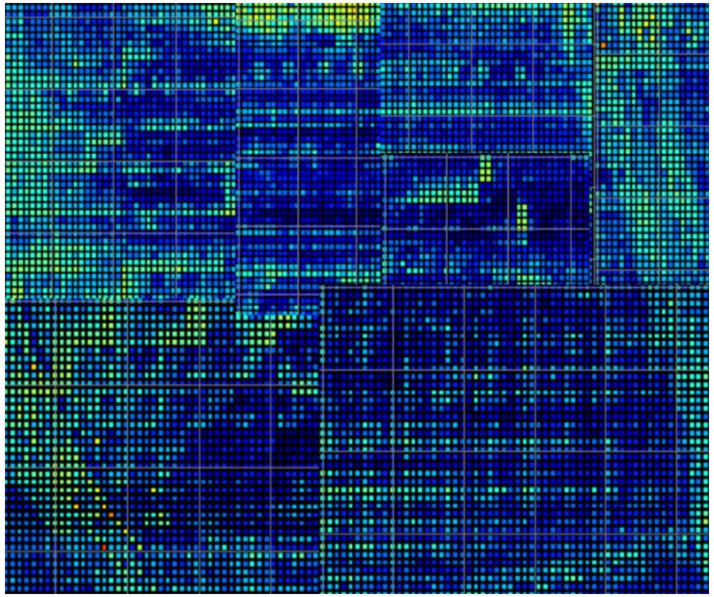


Force Sensor Kit
2 Capacitive Force Sensors

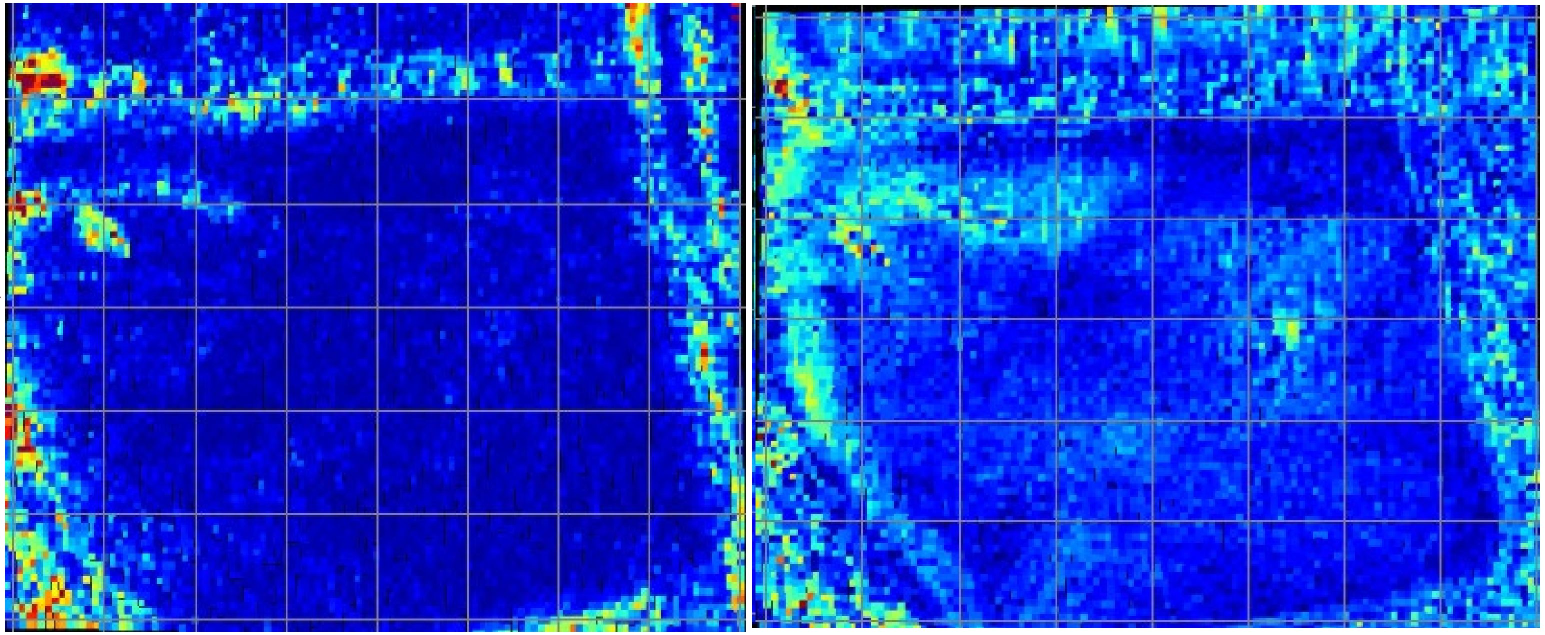
While taking data - after both sensors are above threshold, data is automatically collected (beep sounds).

RESULTS Before/After ALL Recent Improvements

Results Prior to Recent Improvements



Results After Recent Improvements



Representative composite aircraft structure.

Summary

Several challenges related to a field inspection need to inspect damage in composite materials through thick specialty coatings were discussed along with solutions to overcome those challenges.

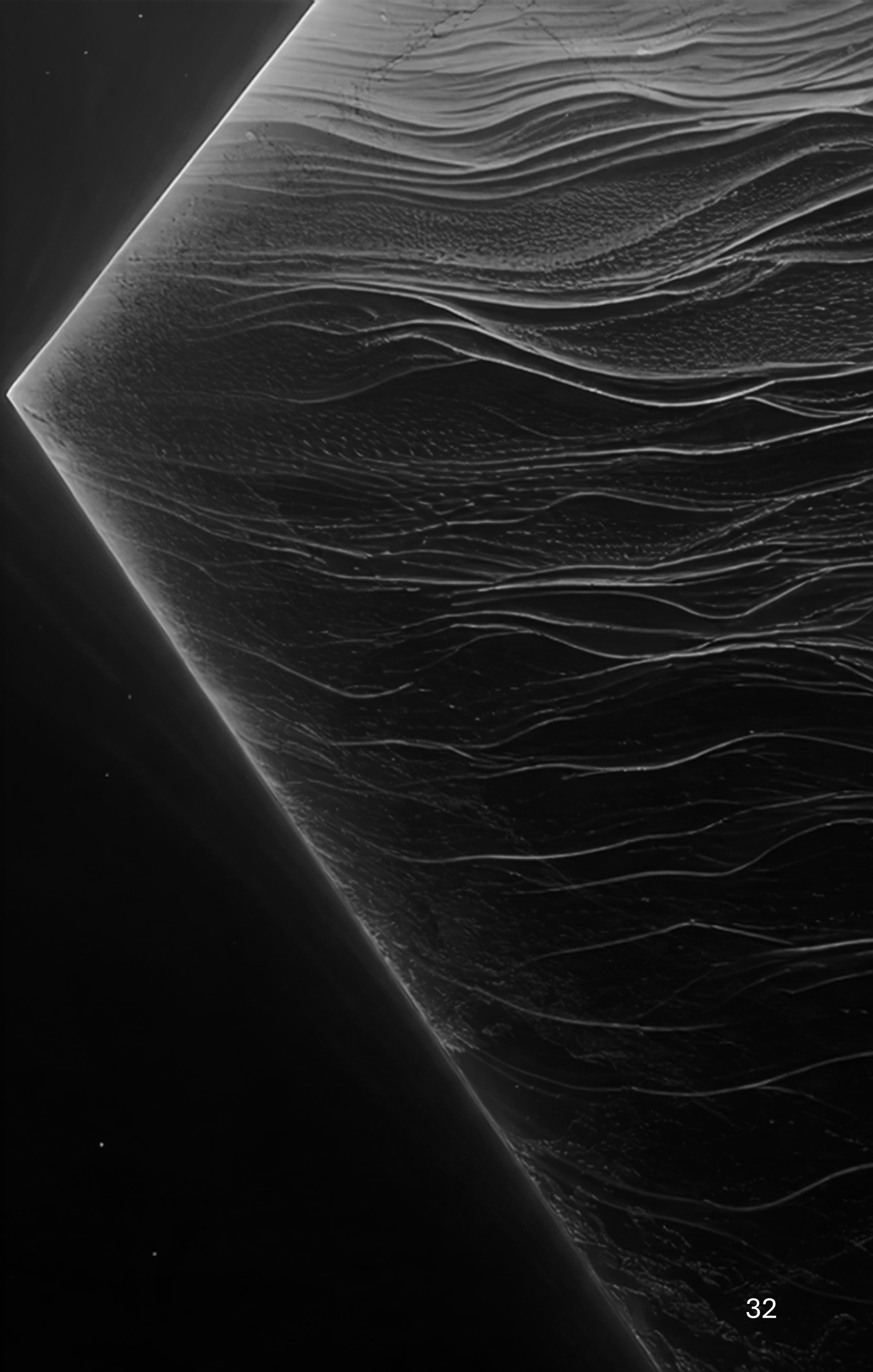
- Utilizing low frequency ultrasound to assess damage in thin PMCs that would normally require 2-5 MHz:
    - At low frequencies (long wavelengths), even dissimilar materials (impedance change is high) still tend to resonate as one full thickness.
    - Modeling and experimental data show that individual resonance peak changes as well as overall spectral changes are very small and challenging to track.
    - Tracking the “subtle changes” in resonance behavior was not possible until advanced denoising strategies were successfully employed.

- Because every inspection occurrence has potentially different coating properties, generic self-referencing methods must be employed. In response to that, ongoing work to expand advanced algorithms (within AIM) show promise and utilize a multitude of methods that are applied to each class of UltraSpec data.

- Implementing designs for probe fixturing for CobotScan and HandScan methods were done to ensure perpendicularity to curved, compressive surfaces with force feedback in order to acquire clean, consistent data and to mitigate the uncertainty of improper data collection.

Questions?

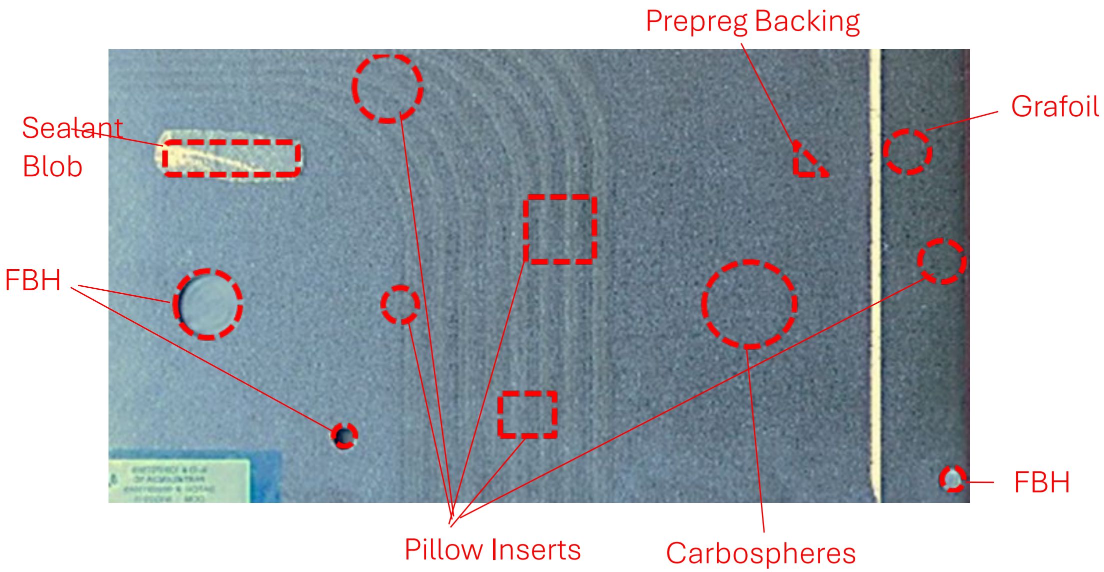
Supplementary Slides on FAA Laminate Samples: UltraSpec® Advanced Interpretation Module (AIM)



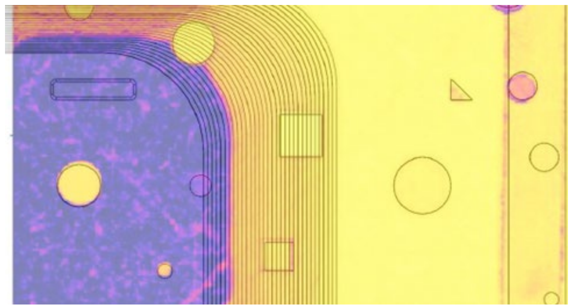
AIM: Data Cube Movies

Time Data Cube Movie:
Watch for "white" defects → early reflections at differing depths as movie progresses from top surface to backwall.

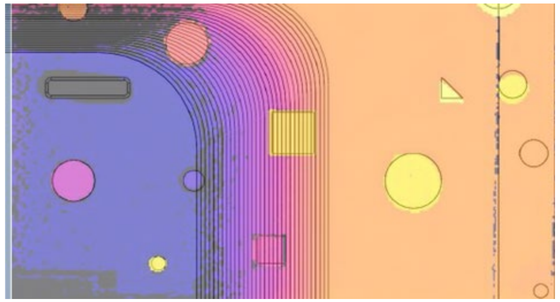
Inverted Image to Match Front



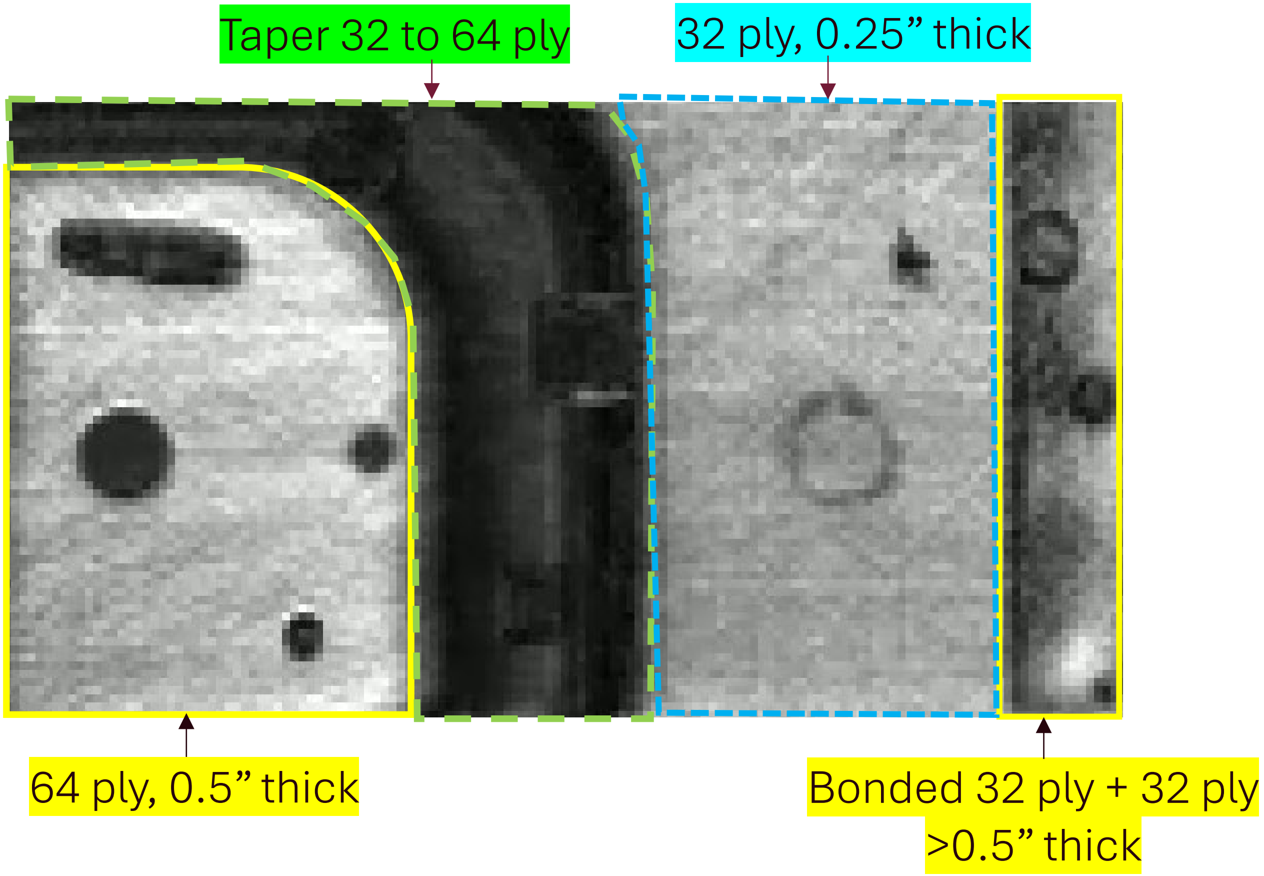
Ability to Extract/Size Features with Depth Information



Traditional UT: Amplitude



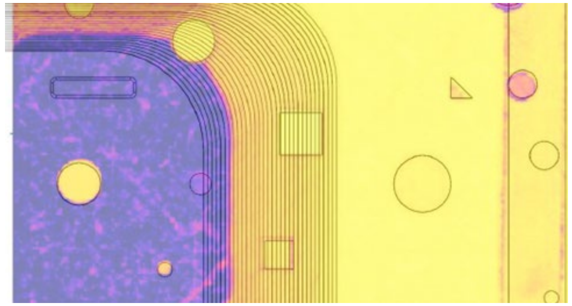
Traditional UT: Time of Flight (TOF)



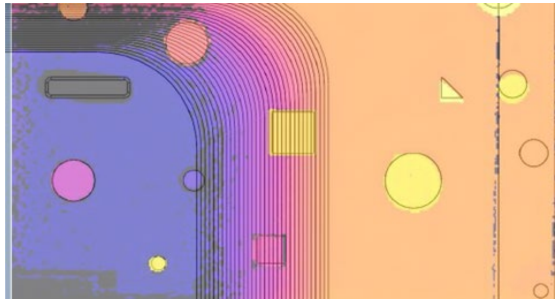
FAA-AANC NDI Test Specimen Library Sample

ULTRASPEC®

AIM: Example Results

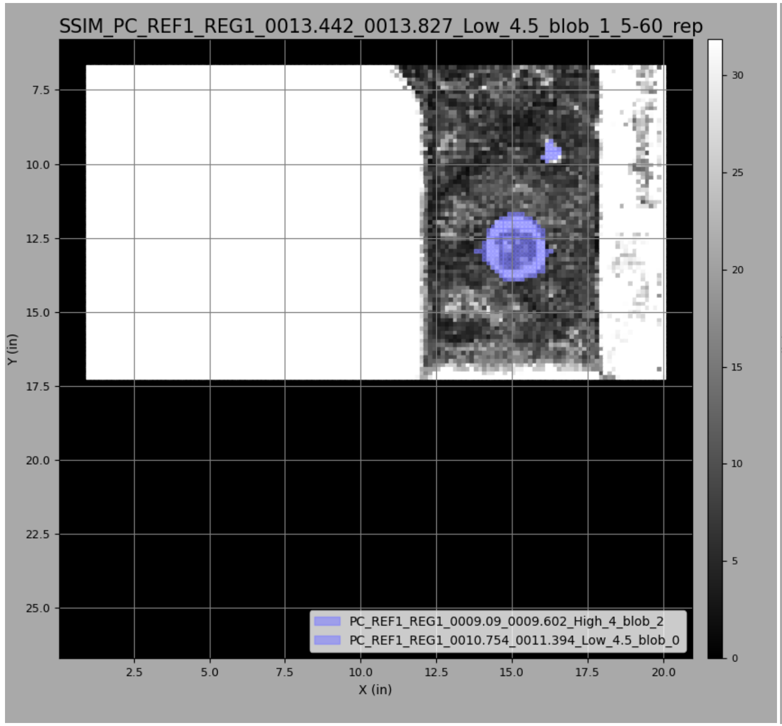


Traditional UT:
Amplitude

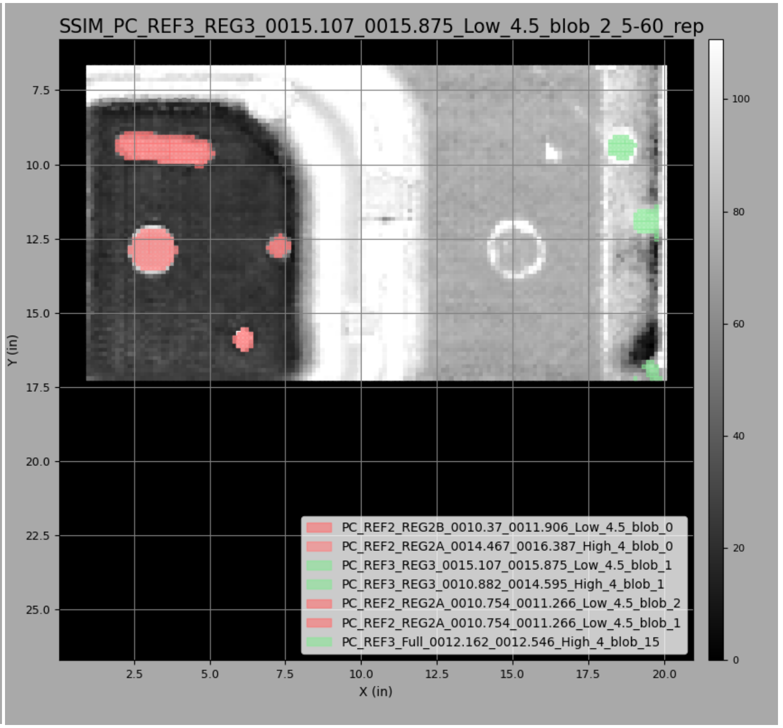


Traditional UT:
Time of Flight (TOF)

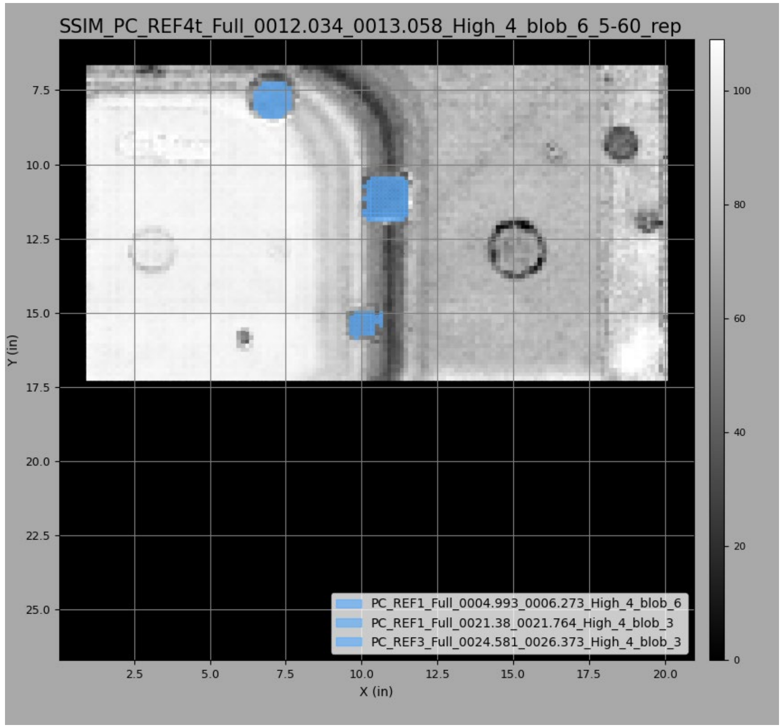
Defects in 32 Ply Thickness

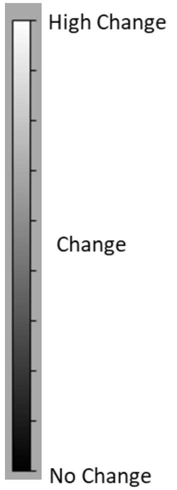


Defects in 64 Ply Thickness



Defects in Tapered Thicknesses

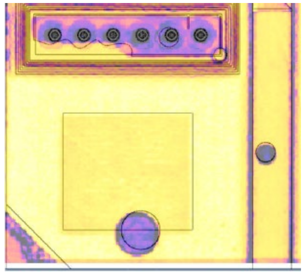




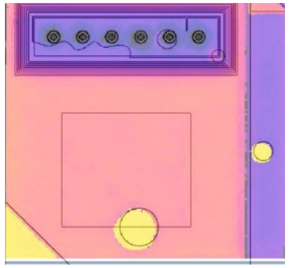
FAA-AANC NDI Test Specimen Library Sample

AIM: Data Cube Movies

Time Data Cube Movie:
Watch for "white" defects → early reflections at differing depths as movie progresses from top surface to backwall.

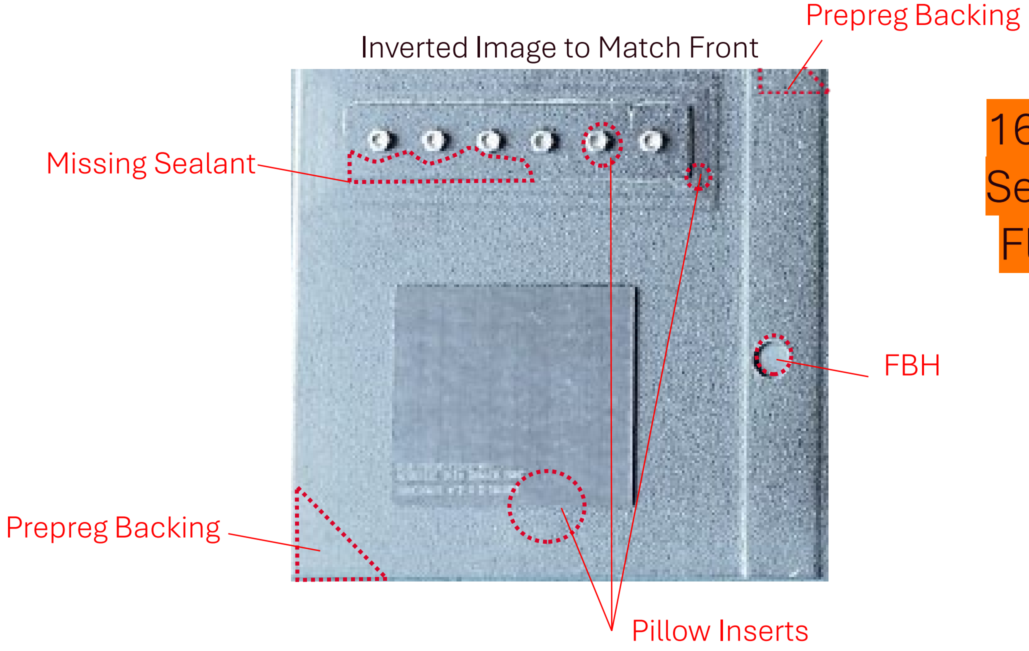


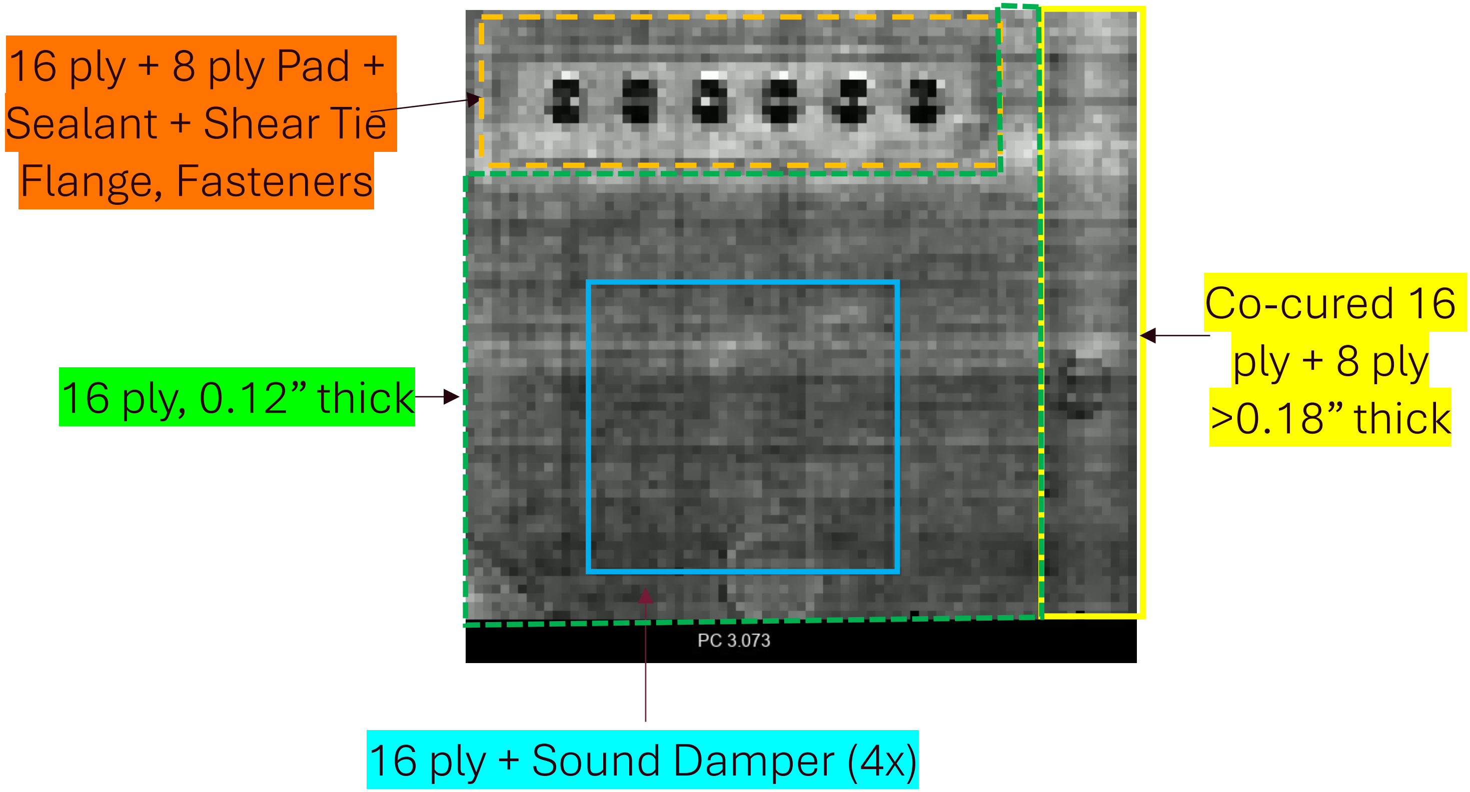
Traditional UT: Amplitude



Traditional UT: Time of Flight (TOF)

Inverted Image to Match Front

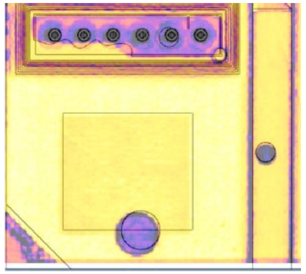




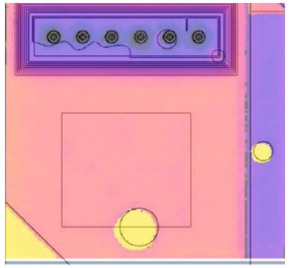
FAA-AANC NDI Test Specimen Library Sample

ULTRASPEC®

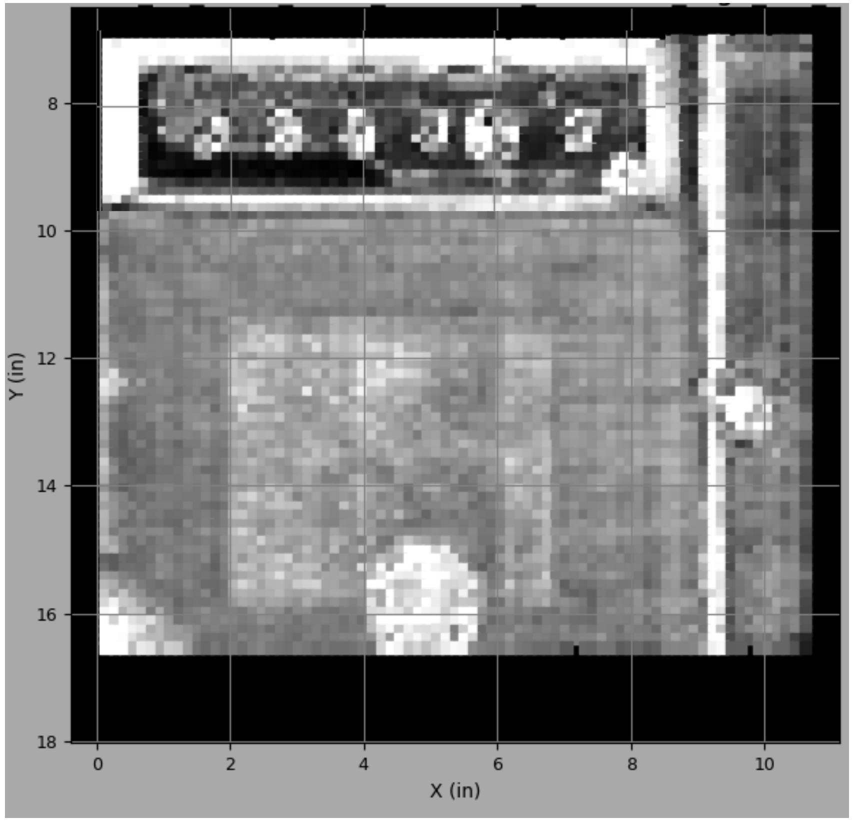
AIM: Example Results

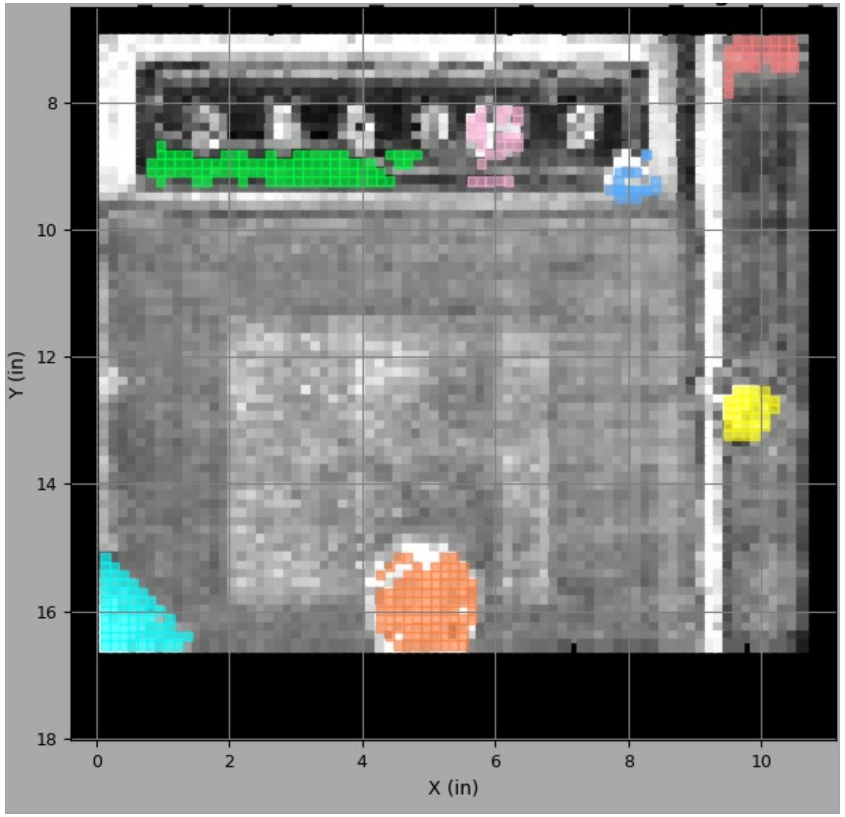


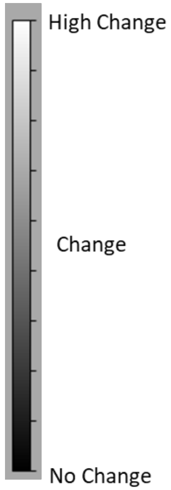
Traditional UT:
Amplitude



Traditional UT:
Time of Flight (TOF)





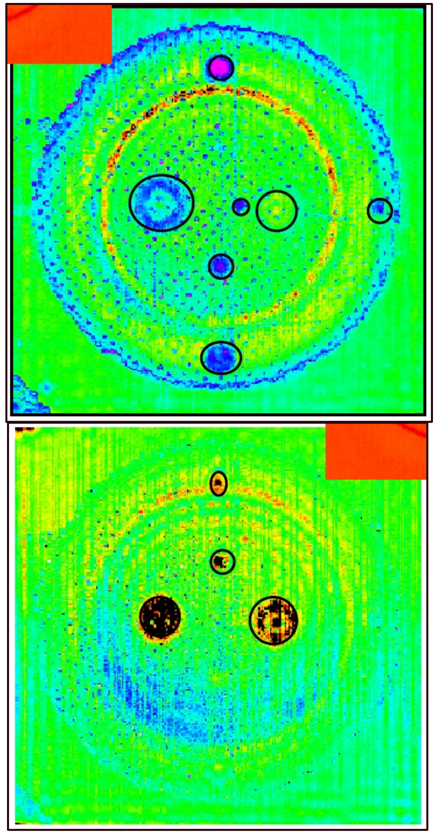


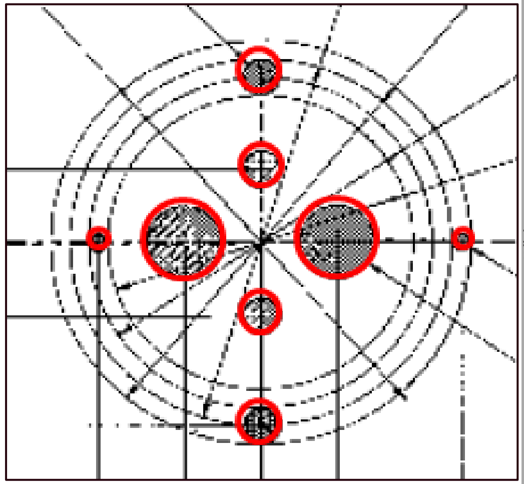
FAA-AANC NDI Test Specimen Library Sample

Inspection of Repairs in Honeycomb Composite Structures
Scarf Repair SK 12595-R1

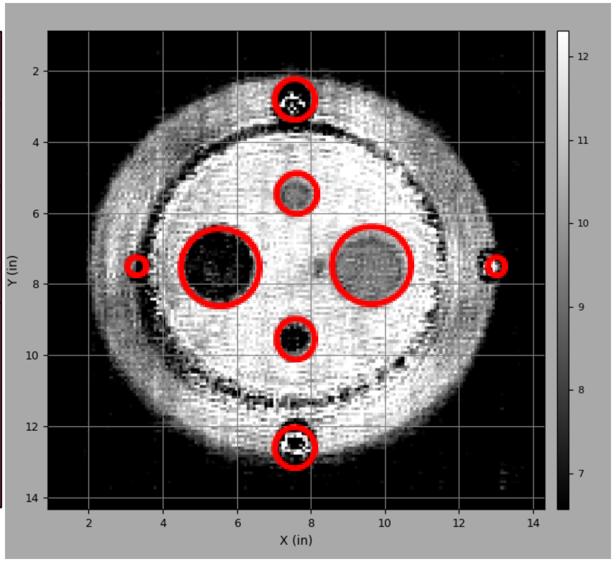
UltraSpec® Spectral Amplitude Movie

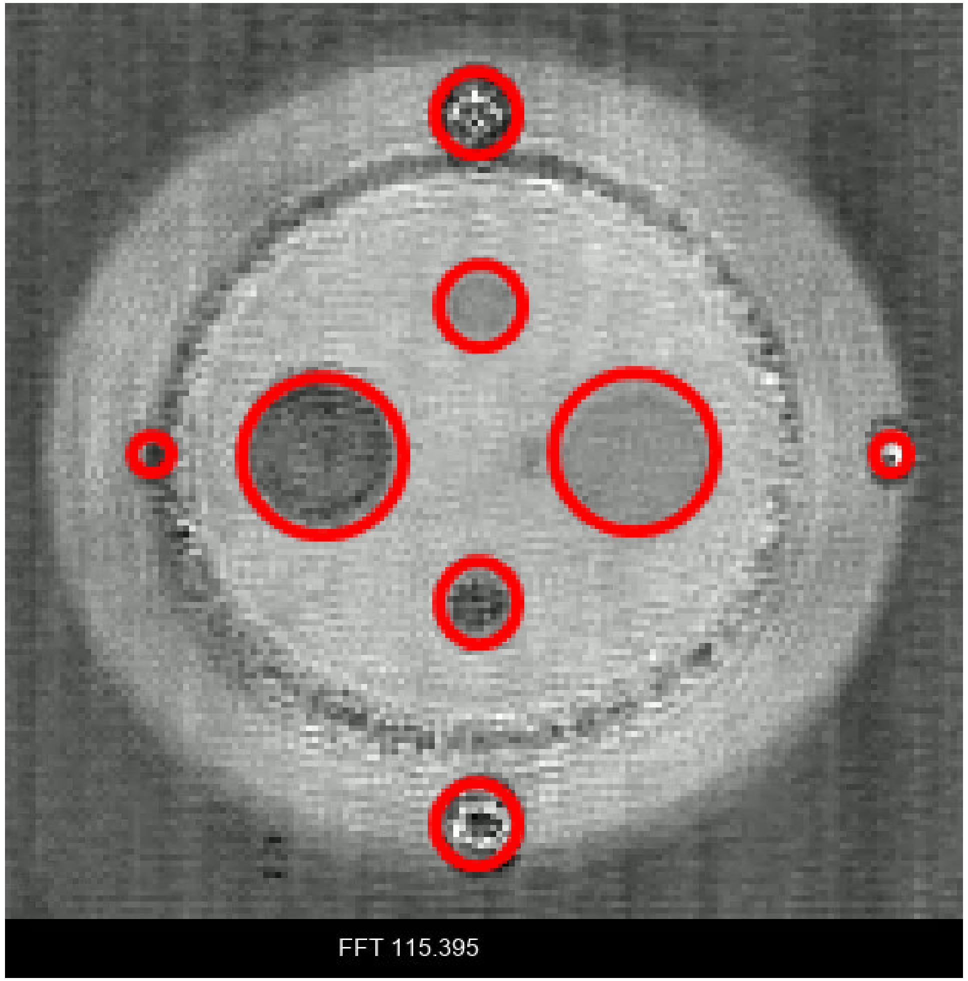
Traditional NDE
Results: MIA



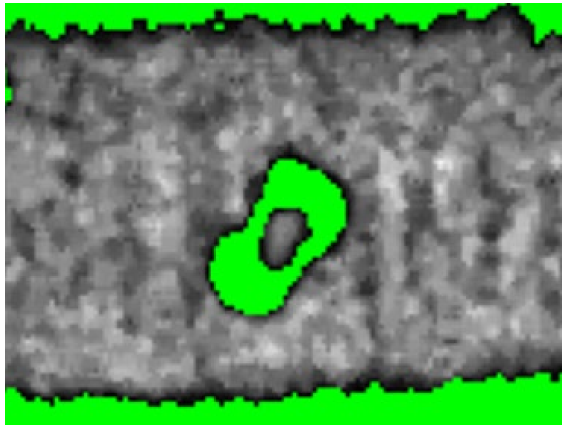


UltraSpec® Results
116kHz

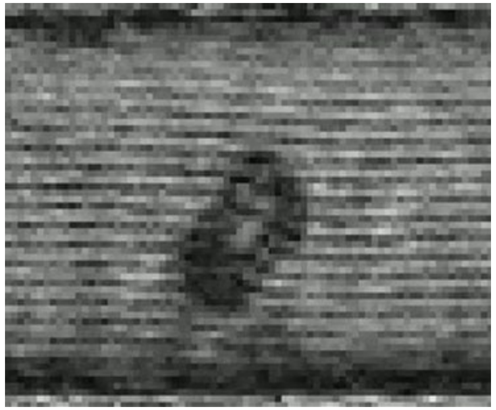




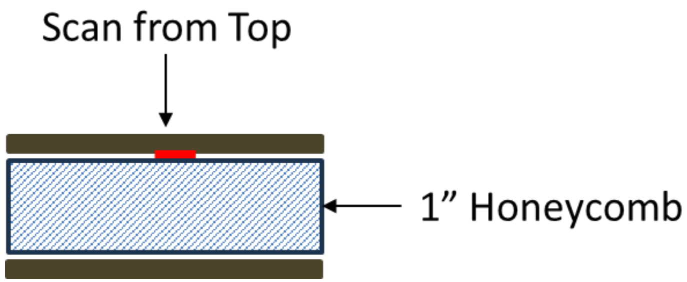
UltraSpec®: Other Relevant Application Examples
Honeycomb Sandwich with Embedded Disbond

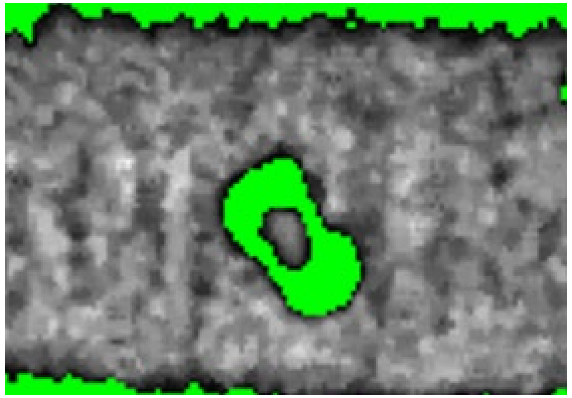


Potted edges, Immersion TT UT

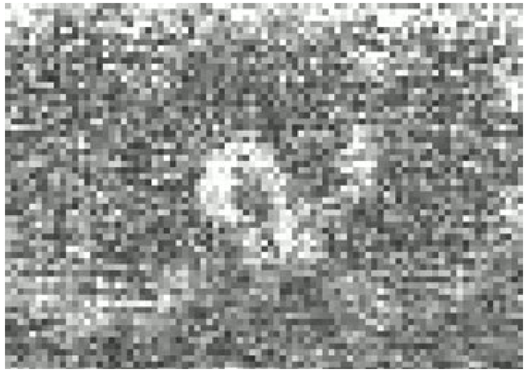


UltraSpec Scan Results
Pitch-Catch from TOP

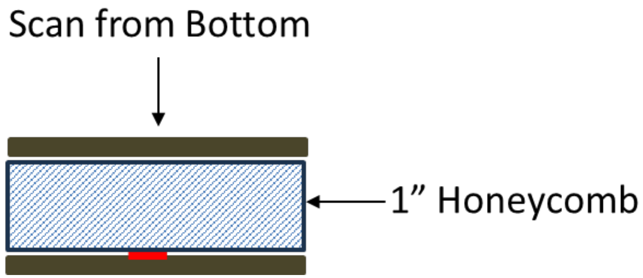




Potted edges, Immersion TT UT



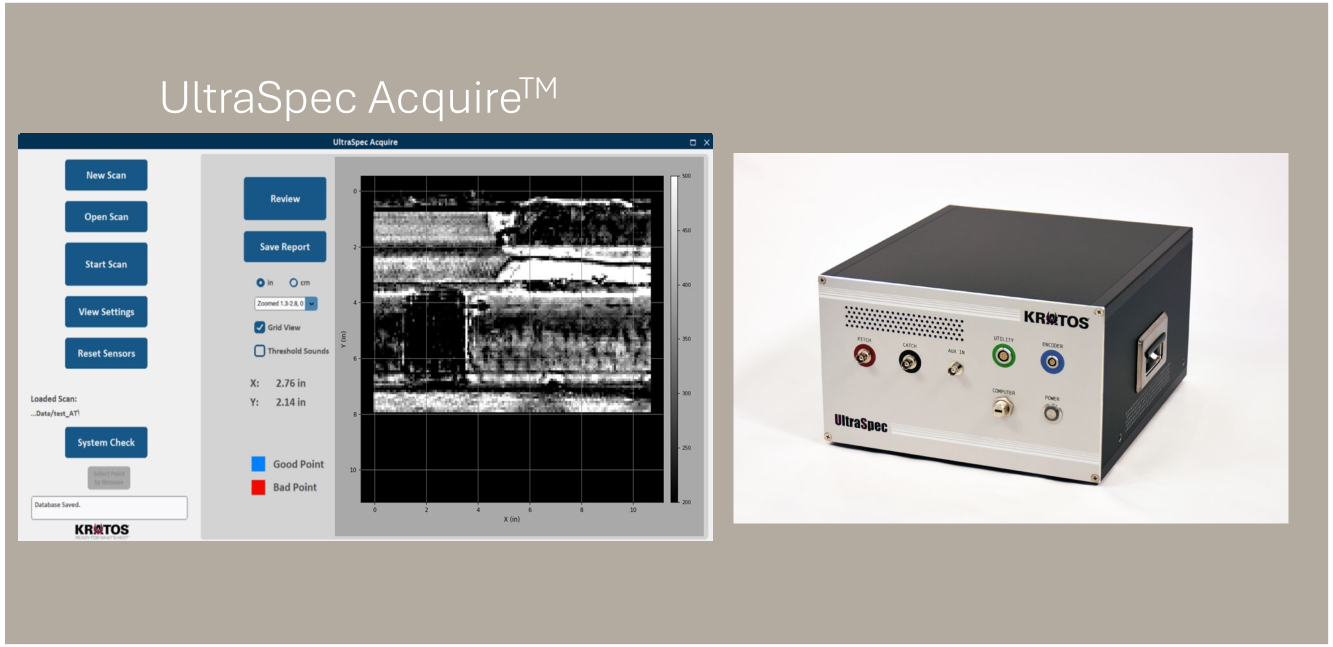
UltraSpec Scan Results
Pitch-Catch from BOTTOM



ULTRASPEC®

Adaptability for New Applications

Configuration File, Meta Data

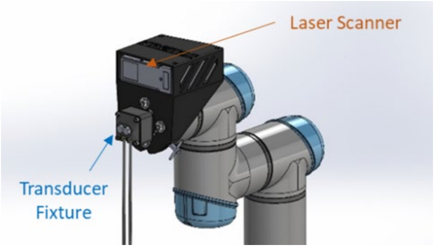


AIM Recipe

Reporting

- ➢ Laminate thicknesses up to 2” thick, tapered regions, aluminum substructure
- ➢ Complex composite bonded structures (i.e. “pi joints”)
- ➢ Complex sandwich structures
  - Depth of penetration – can see disbonds on opposite side of 1” honeycomb
  - Composite or aluminum
- ➢ Complex multi-material bonded structures

Scan Options: Collaborative Robot, XY Encoding

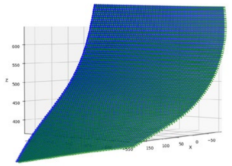


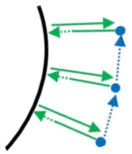
Portable OPTIONS

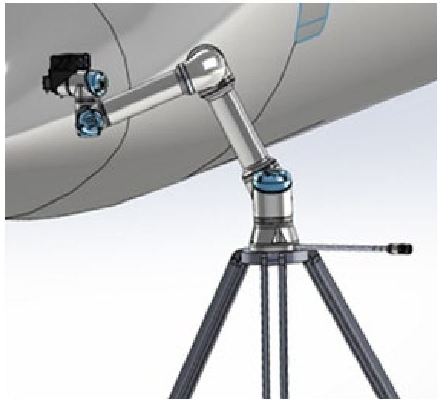
*Controlled, repeatable positions/rotations
*Consistent couplant

Automated, Semi-Portable

Laser Profile Surface Capture
Discrete Positioning
(Complex Curvatures)
Dry-Coupled

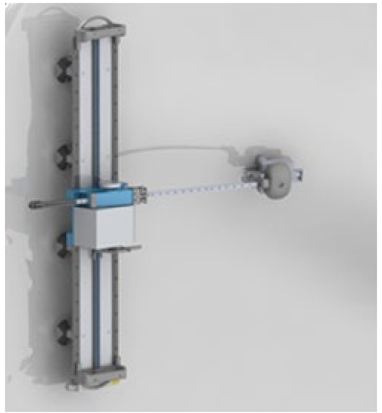






Manual, Portable

Customized Probe Fixture
Vertical Aircraft Mounting
(Complex Curvatures)
Dry-Coupled



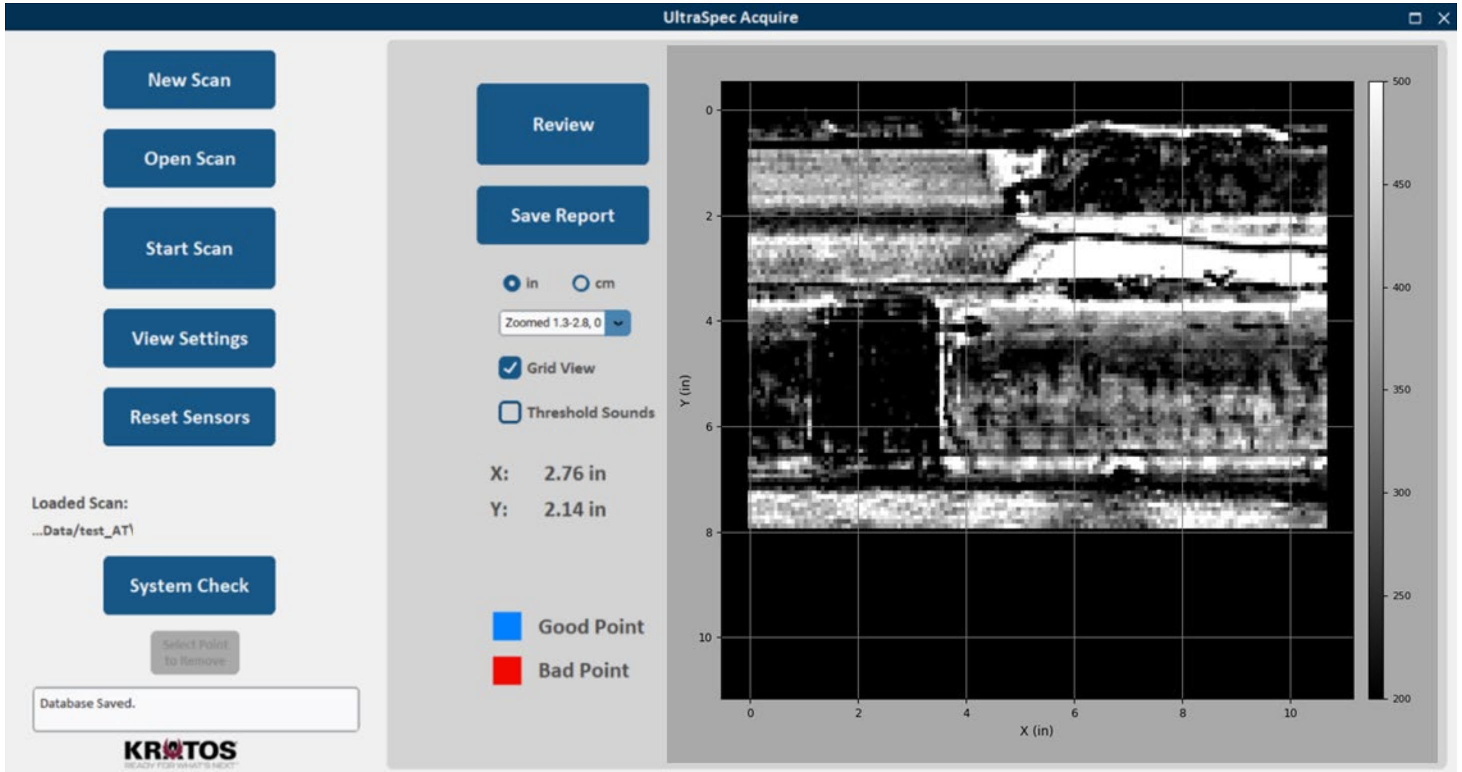
Automated, Portable

Customized Probe Fixture
(Slight Curvatures)
Dry-Coupled or Water Couplant

ULTRASPEC®

UltraSpec® SYSTEM

Guided Software: UltraSpec Acquire



- Provides Step-by-Step Guide through setup and scanning activities
- Designed for novice user with minimal training
- AIM Recipe can output data cube movies, AIM results or raw data when necessary

Thank you!

Email: janellechambers@kratosdefense.com

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Can we help with your inspection challenges?

- Kratos is available for demonstrations.
- If you have difficult inspection challenges, send us a sample! We can perform a quick assessment.