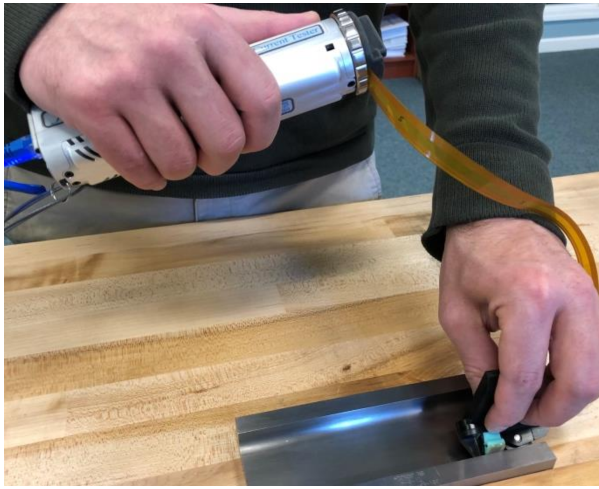
> 25 yrs
MWM-Array development
NEW < 1 pound
jET platform



On-Aircraft Engine Inspection, with Hand-Held Eddy Current Array Tester

PS&S

April 2018

Neil Goldfine, Todd Dunford, Mark Windoloski, Zachary Thomas

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jenteksensors.com

What is next for Eddy Current Testing of Engines?

- More ***accessible*** ET array tech
- More ***portable*** handhelds for arrays
- More ***adaptable*** by operators
- More ***predictable*** performance
- Plus
  - Reduced false indication rates
  - Less training requirements
  - Less surface preparation
  - Reduced automation costs
  - On-aircraft inspection in difficult to access areas
  - Support for complementary installed sensors
  - Inspection through coatings
  - Reliable inspection of shot peened and otherwise cold worked surfaces
  - Improved quality assessment for coatings, cold working, additive manufactured parts for porosity, metallurgical condition. geometric feature dimensions, and cracks
  - Real crack specimens with as manufactured conditions and curvatures.

Challenges that must be met

Presentation Outline for Hand-Held jET Applications

- Hand-held jET
  - jET configurations and end-effectors
  - MWM-Array sensors for jET
  - Compliant inserts for complex surface scanning
  - DOP Charts for varied drive-sense gap
  - Kits/Software for easy adaptation to new apps
  - **Introducing jAI (JENTEK A.I.)**
- Surface breaking and subsurface crack detection
  - Rescaling of crack response with variable liftoff, Grid Methods
  - Air calibration and Reference Calibration (per ASTM E2884)
  - Shaped filters used for improved POD and reduced false indications
  - Real-crack sample fabrication with as manufactured conditions
  - HyperLattices for subsurface crack detection with varying wall thickness
- Coatings and residual stresses
  - Thermal Spray coating and TBC coating characterization
  - Residual stress mapping for nickel alloys (no slides shown).
- Historical and ongoing case studies

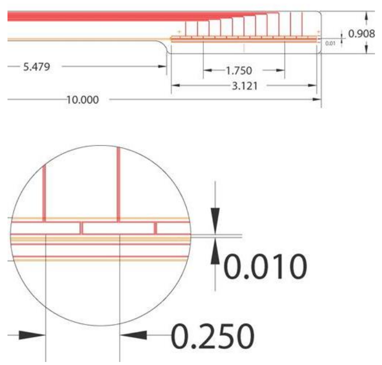
> 25 yrs
MWM-Array
development
NEW < 1 pound
jET platform

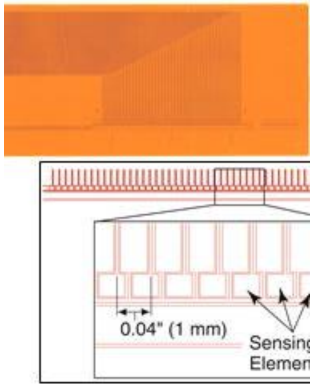
MWM-Array Technology Advantage: 4 key elements

JENTEK Sensors

1. Sensors: MR-MWM®-Arrays

- **Paradigm shift** in sensor design.
  First priority is predictable response based on physics-based modeling.





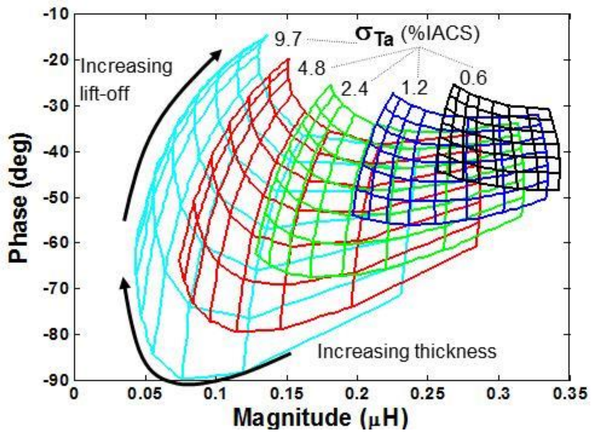
2. Next Generation® 8200α+ and jET™α Electronics

- **10x signal-to-noise improvement**
- **3 frequencies simultaneously**
- **Increased data rate up to 1,200 samples/sec.**
- **Reduced drift**

3. GridStation® Software using Hyperlattices™

- **Rapid, autonomous data analysis (with jAI)**

Performs multivariate inverse method (MIM) using precomputed databases to estimate multiple properties



Use signature libraries for rescaling and noise suppression

4. Cost & Convenience

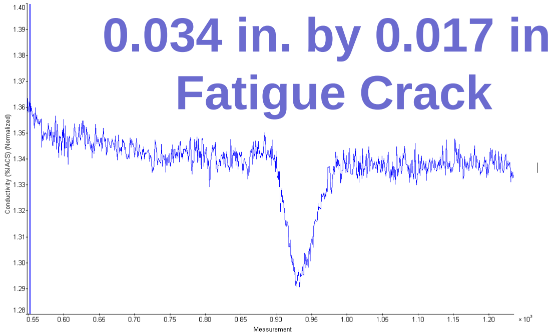
- **Cost competitive with conventional ET systems**
- **Reduced cost automation**
- **High performance manual scanning**
- **SHM fatigue gage support**
- **Easy adaptation by users to new applications**

Old vs New Instrumentation Performance

ensors

GS-IN7000β

- 10 kHz – 10 MHz operating frequency
- Used for all past MWM-Array engine component transitions
- Not available after 2014



0.034 in. by 0.017 in. Fatigue Crack

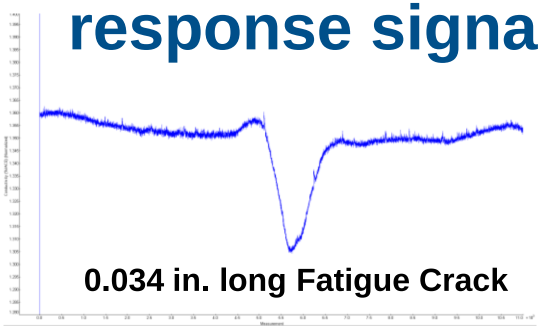
IN7000 taken at 100 Hz data rate

GS-8200α+

NEW < 1 pound
jET platform

- 2.5 Hz – 20 MHz operating frequency
- 100× faster data rate than IN7000
- 10× Improved signal-to-noise
- Now available **(GS39+, GS19 and jET 7 channels)**

Substantially improved crack response signal-to-noise



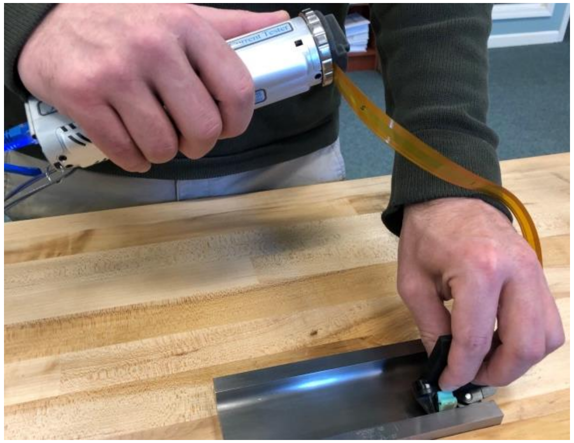
0.034 in. long Fatigue Crack

8200 taken at 1.3 kHz data rate

For complex parts

Advanced ET with Flexible Arrays: MWM-Array

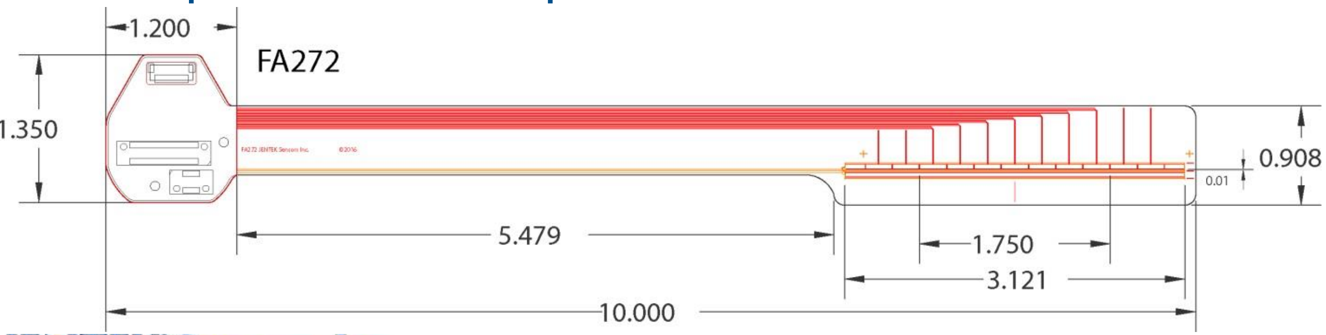
jET with GridStation MIMs



- Substantially **reduced** instrument noise
- **Simultaneous** complex impedance real and imaginary part measurement at three frequencies
- **Rescaling** of crack response for varied lift-off
- **Rescaling** for position of defect within array
- **Rapid** scanning

MWM-Array

- Linear drive (**no crosstalk**, **increased crack response**)
- Flexible arrays to limit lift-off
- Simple lines and squares enable MIMs



ASTM Standard E2884-13

Designation: E2884 – 13

Standard Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays[1]

This standard is issued under the fixed designation E2884; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the use of conformable eddy current sensor arrays for nondestructive examination of electrically conducting materials for discontinuities and material quality. The discontinuities include surface breaking and subsurface cracks and pitting as well as near-surface and hidden-surface material loss. The material quality includes coating thickness, electrical conductivity, magnetic permeability, surface roughness and other properties that vary with the electrical conductivity or magnetic permeability.

1.2 This guide is intended for use on nonmagnetic and magnetic metals as well as composite materials with an electrically conducting component, such as reinforced carbon-carbon composite or polymer matrix composites with carbon fibers.

1.3 This guide applies to planar as well as non-planar materials with and without insulating coating layers.

1.4 *Units*—The values stated in SI units are to be regarded as standard. The values given in parentheses are mathematical conversions to inch-pound units that are provided for information only and are not considered standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

E2238 Guide for Evacuation Route Diagrams

2.2 *ASNT Documents:*[3]

SNT-TC-1A Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing

ANSI/ASNT-CP-189 Standard for Qualification and Certification of NDT Personnel

2.3 *AIA Standard:*

NAS 410 Certification and Qualification of Nondestructive Testing Personnel[4]

2.4 *Department of Defense Handbook:*

MIL-HDBK–1823A Nondestructive Evaluation System Reliability Assessment

3. Terminology

3.1 *Definitions*—For definitions of terms relating to this guide refer to Terminology E1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *B-Scan*—a method of data presentation utilizing a horizontal base line that indicates distance along the surface of a material and a vertical deflection that represents a measurement response for the material being examined.

3.2.2 *C-Scan*—a method of data presentation which provides measurement responses for the material being examined in two-dimensions over the surface of the material.

3.2.3 *conformable*—refers to an ability of sensors or sensor arrays to conform to non-planar surfaces without significant

Introducing jAI (JENTEK Artificial Intelligence)

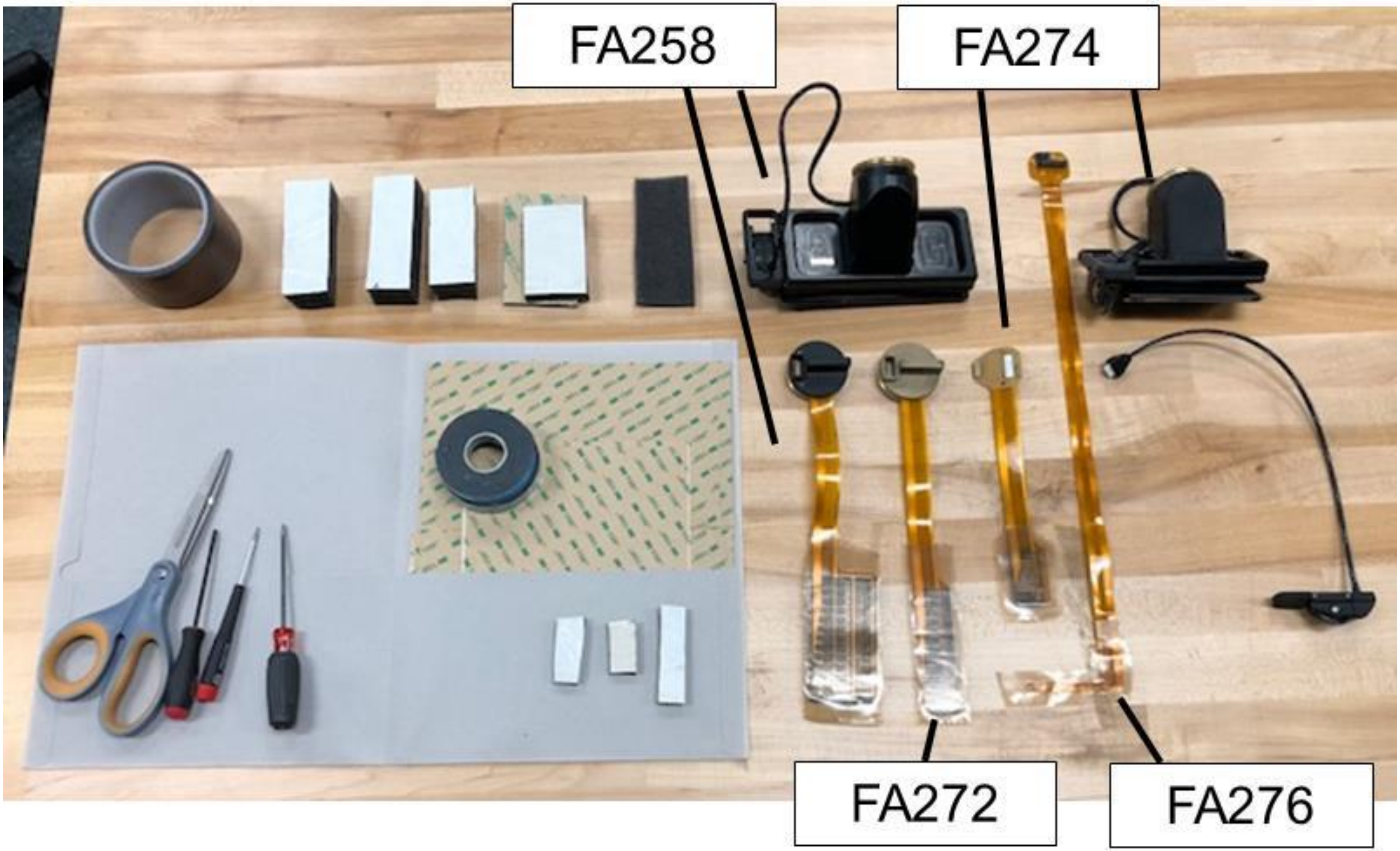
Modeled Deterministic Part

- Sensor design for predictable response using iterative model-based optimization
- Precomputed sensor response databases for model based Multi-variate Inverse Methods (MIMs)
- Instruments, such as the jET, designed to deliver data that is suitable for MIMs:
  - Simultaneous frequencies
  - Simultaneous Real and Imaginary transimpedance parts
  - Parallel channels
  - Accurate transimpedance with very low signal to noise
  - High data rates for rapid scanning
- Very rapid data analysis

Unmodeled Deterministic &Stochastic Part

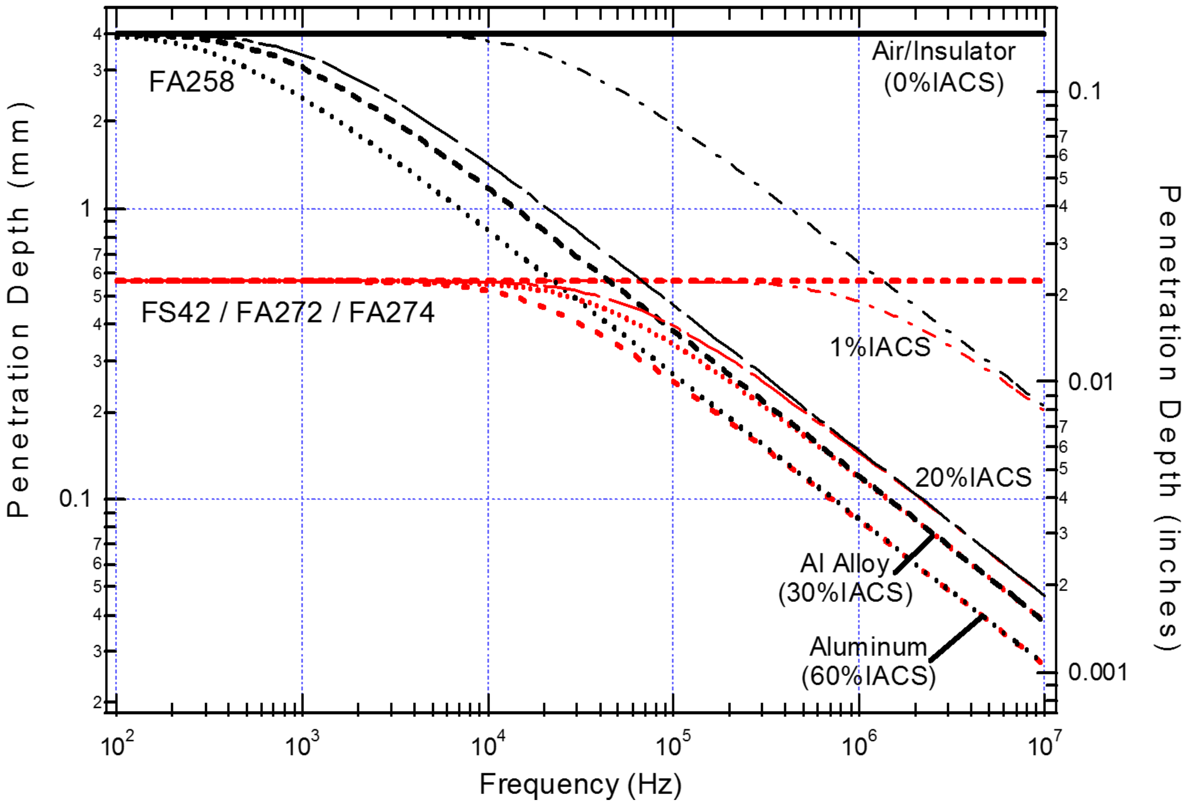
- After removal of deterministic part (using model based MIMs), remaining data can be more appropriately processed using traditional AI pattern recognition or filtering methods.
- Shape filters (like wavelet analysis)
- Libraries of signatures for selective shape filtering based on apriori or logically determined metadata/information.
- Other pattern recognition, that takes advantage of
  - Simultaneous frequencies
  - Simultaneous Real and Imaginary transimpedance parts
  - Parallel channels
- **User AI guidance for new apps (in early development)**

Sensor Kits for adaptation to new applications

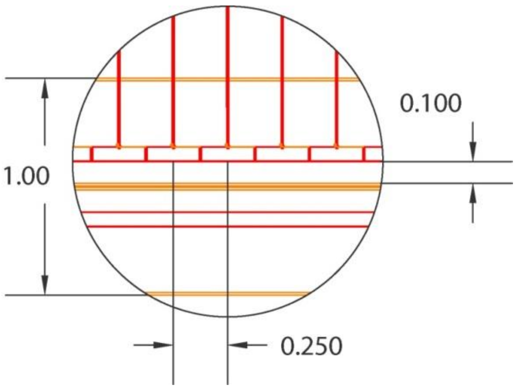


Depth of penetration comparison

Single Rectangle drive: FA272/274 enable small surface breaking crack detection. **Dual Rectangle drive:** FA258 can provide improved sensitivity to subsurface flaws in the Ti-6Al-4V alloys compared to FA272/FA274 due to larger drive sense gap.



FA258 for subsurface crack detection

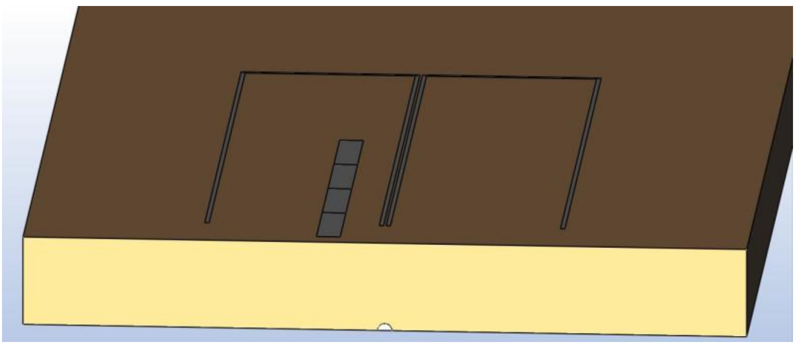


FA278 for surface crack detection

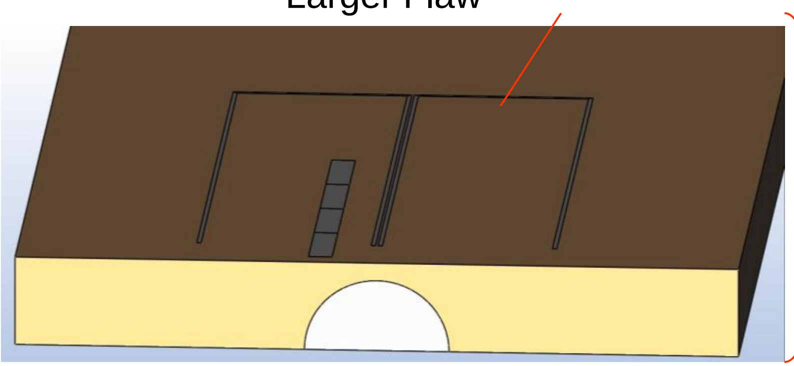
Subsurface crack modeling option

- Standard 2D models for sensor response
  - Use JENTEK Grid Methods to obtain conductivity values for several frequencies
  - Higher frequencies will provide a measure of near surface region conductivity
  - Lower frequencies provide higher sensitivity to subsurface cracks
- 3D models to better correlate scan information to crack dimensions
  - Example: FA258 over a 0.25 in. plate with small and large cracks (for 1%IACS)

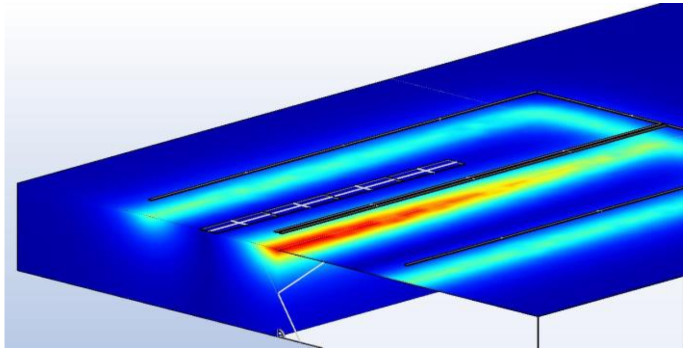
Smaller Flaw

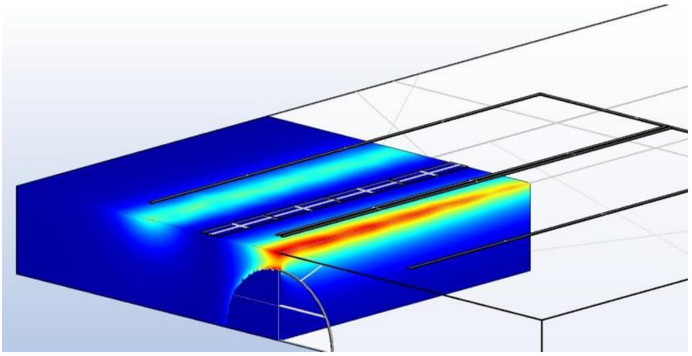


Larger Flaw



½ of physical geometry (using symmetry)





Induced current density contour plots [100 kHz; 0.05 in. lift-off; 0.4 in. long larger notch]

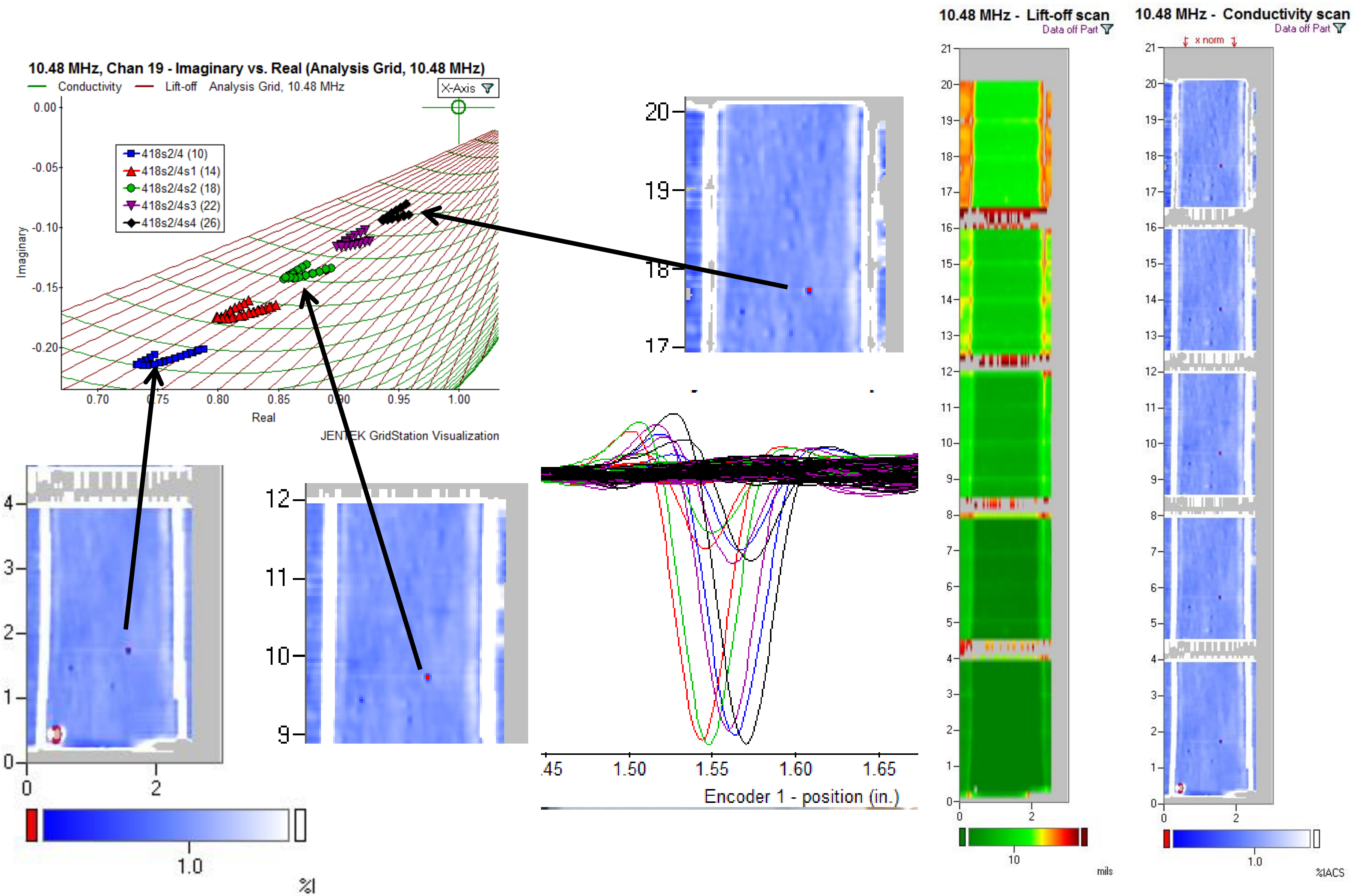
HyperLattice Multivariate Inverse Methods (MIMs)

This is part of the NEW JENTEK jAI environment

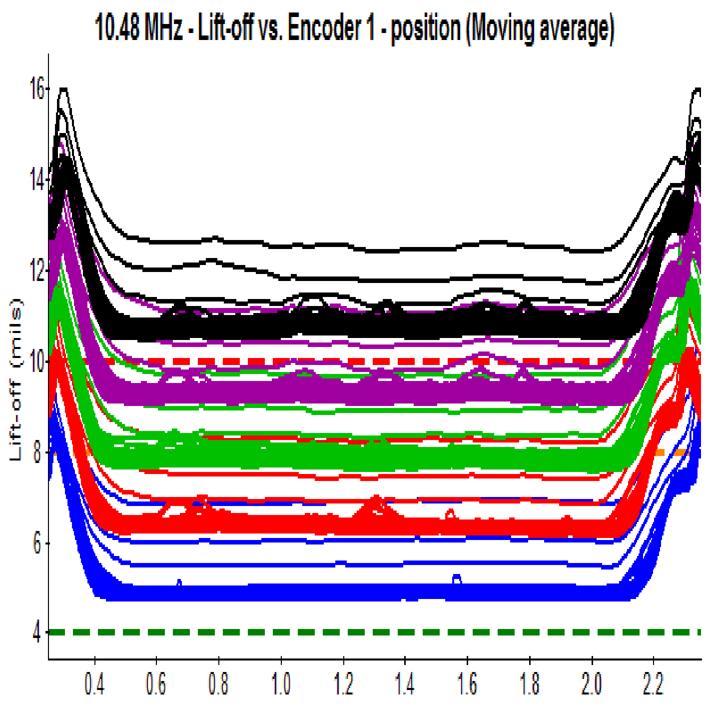
- **Surface breaking flaws** – Two unknown Grid Method for conductivity/liftoff at single frequency
  - Rescaling of crack response with variable liftoff
  - Enables air calibration
  - Modified reference calibration used to tune air-cal for improved crack detection and surface anomaly suppression
  - Shaped filters used for improved POD performance and false alarm suppression
- **Subsurface crack detection** – HyperLattice Multivariate Inverse Method (MIM). Need Lattices for three unknown method to correct for variable layer thickness. (see AA&S 2018 presentation for discussion of subsurface flaws)

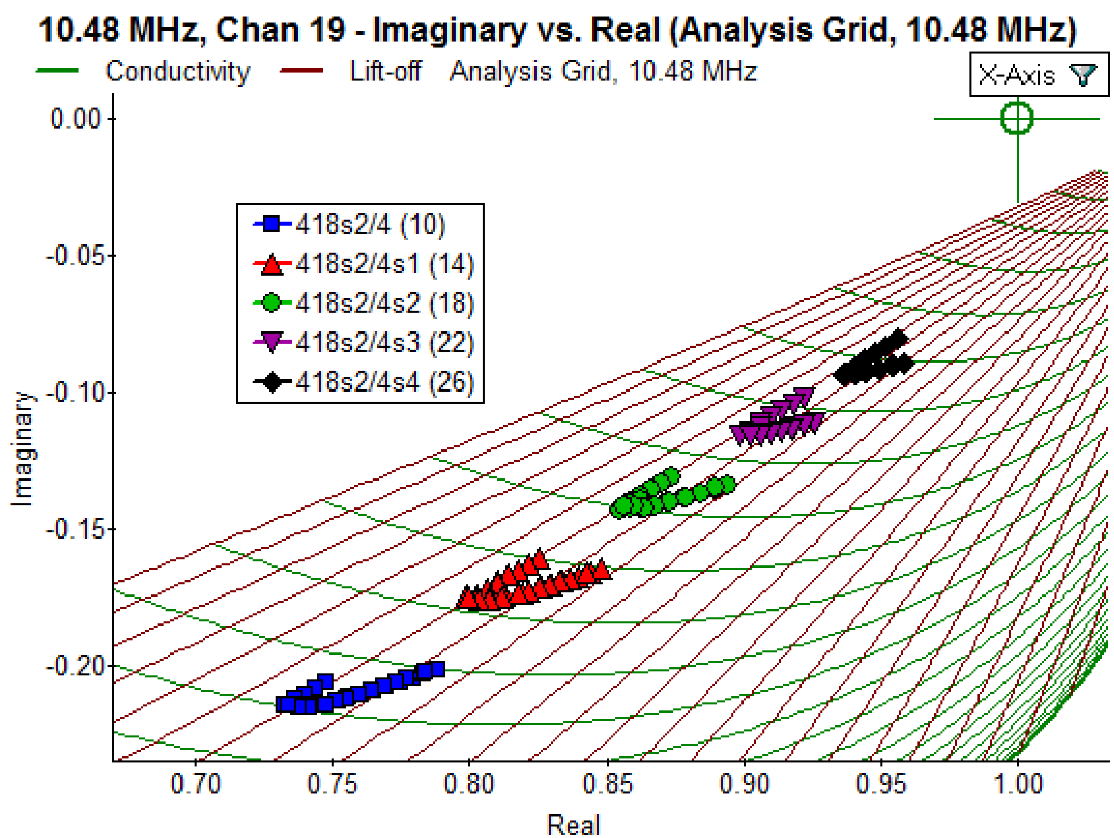
Surface Cracks: Rescaling of Conductivity Response (evolving jAI)

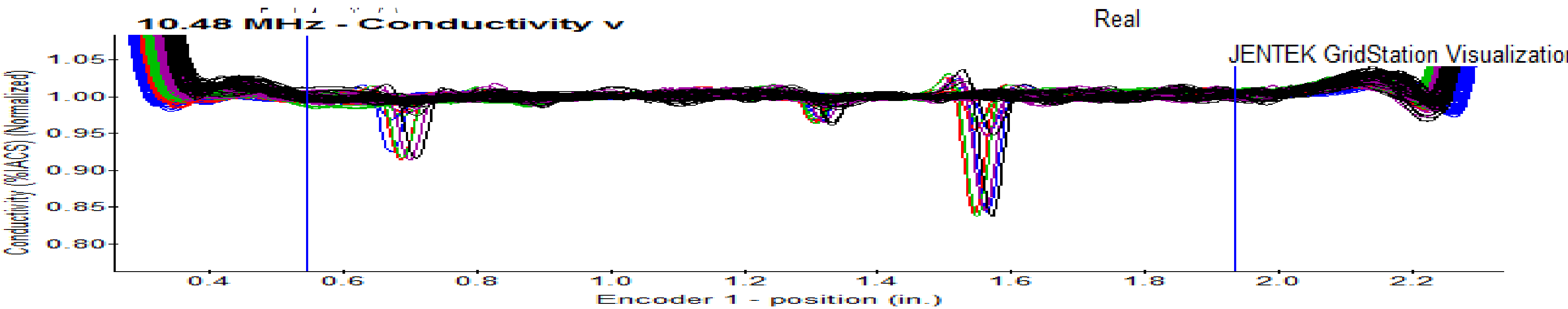
JENTEK Sensors



Surface Cracks: Rescaling of Conductivity Response (evolving jAI)





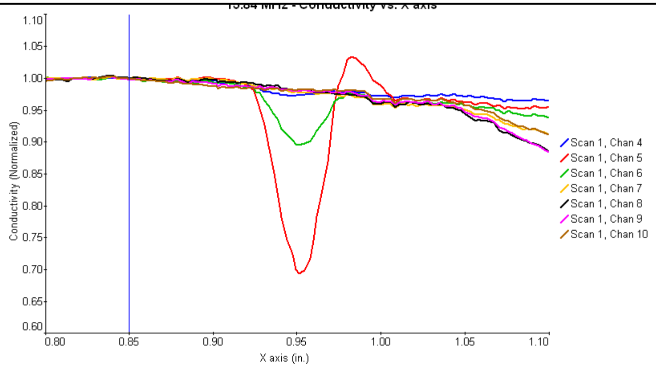


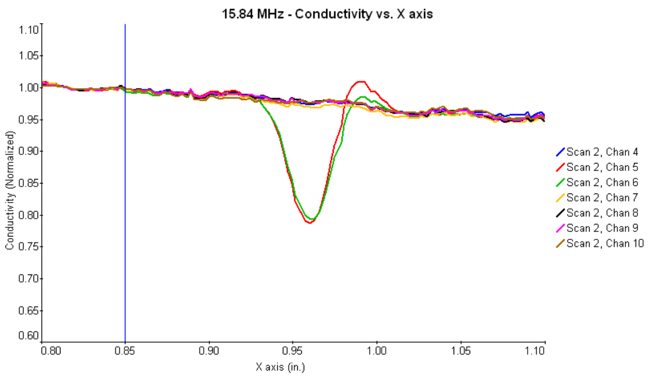
Shape Filtering to suppress false indications (evolving jAI)

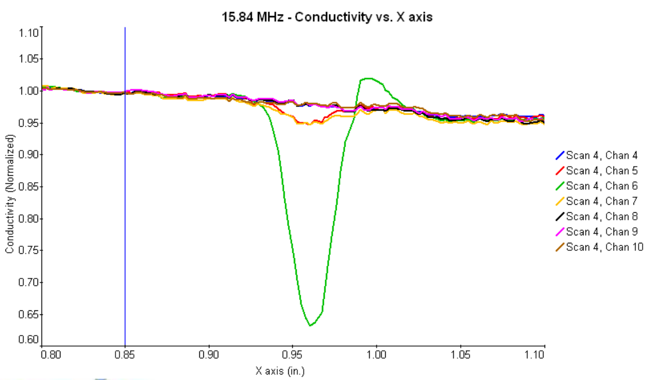
JENTEK Sensors

Varying Transverse Position of crack

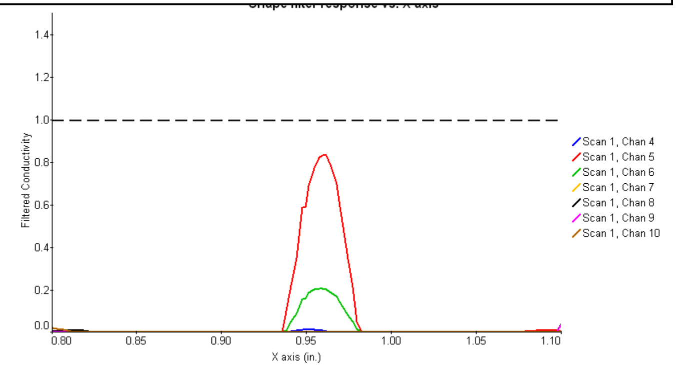
Unfiltered Crack Response

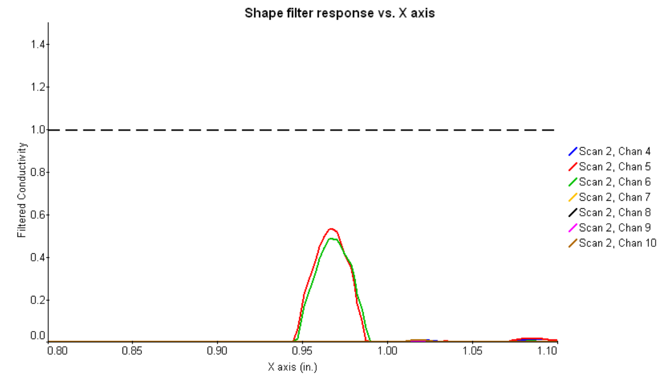


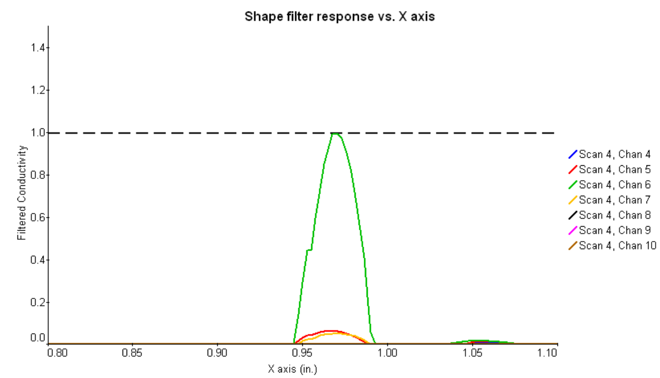




Filtered Crack Response



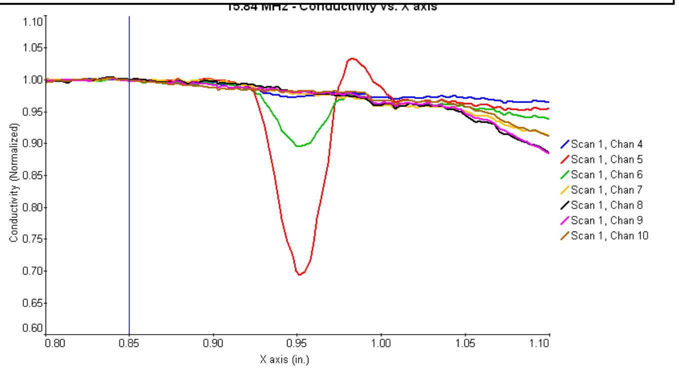


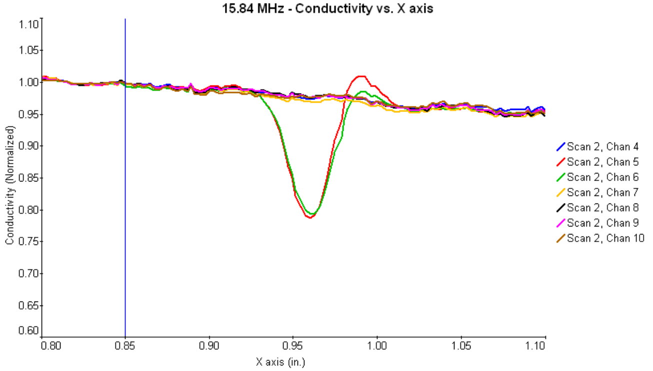


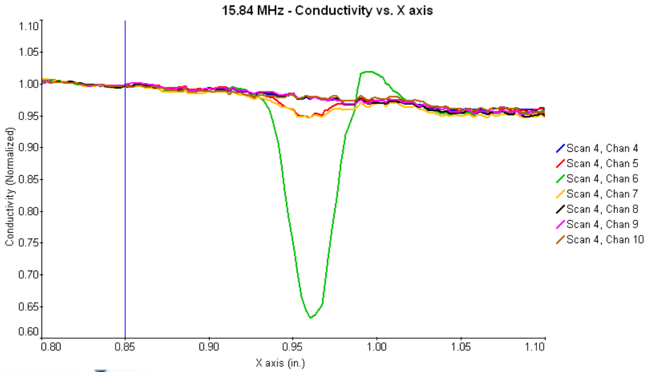
Shape Filtering Libraries rescale for crack position (evolving jAI)

Varying Transverse Position

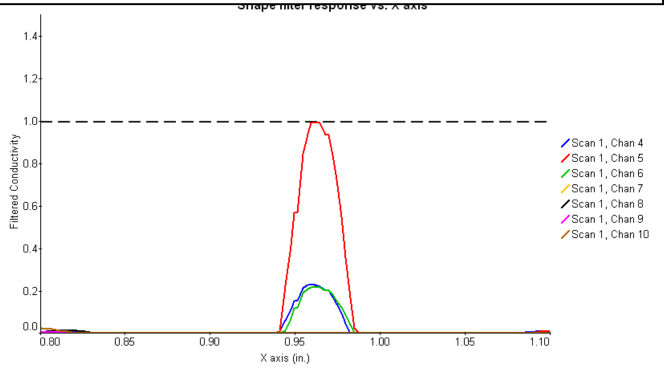
Unfiltered Crack Response

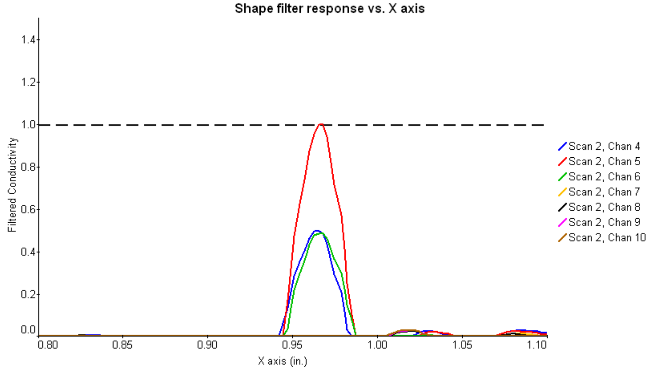


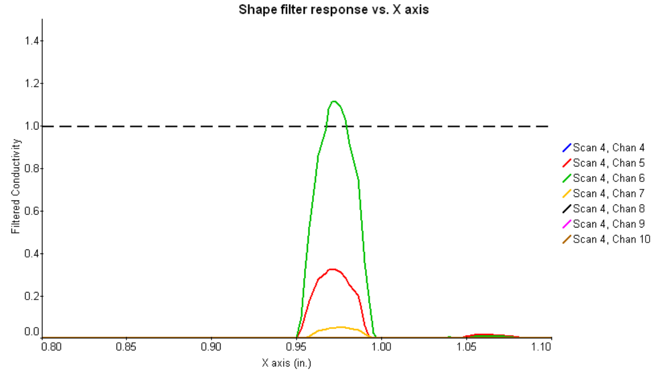




Filtered Crack Response



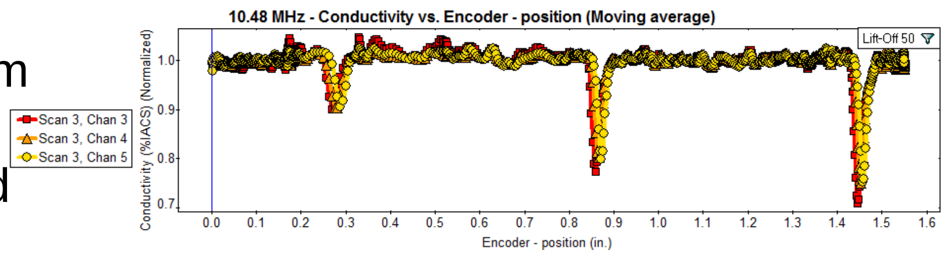


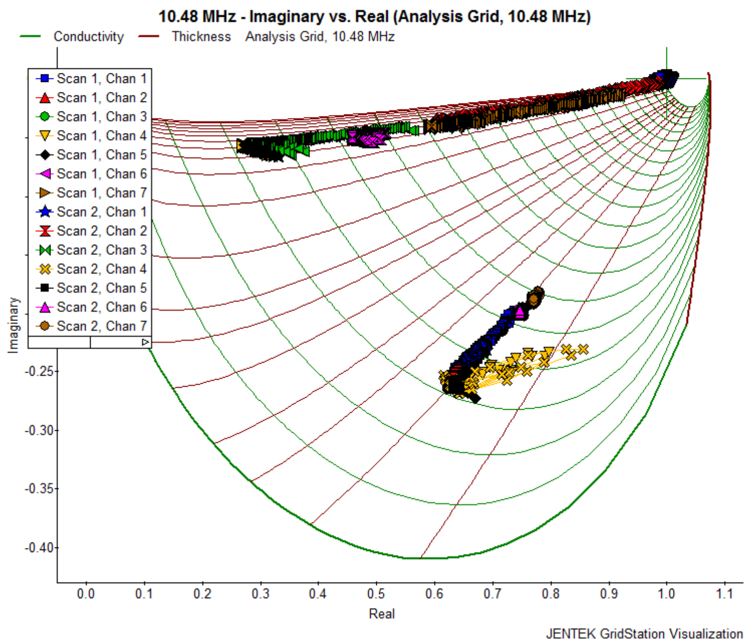


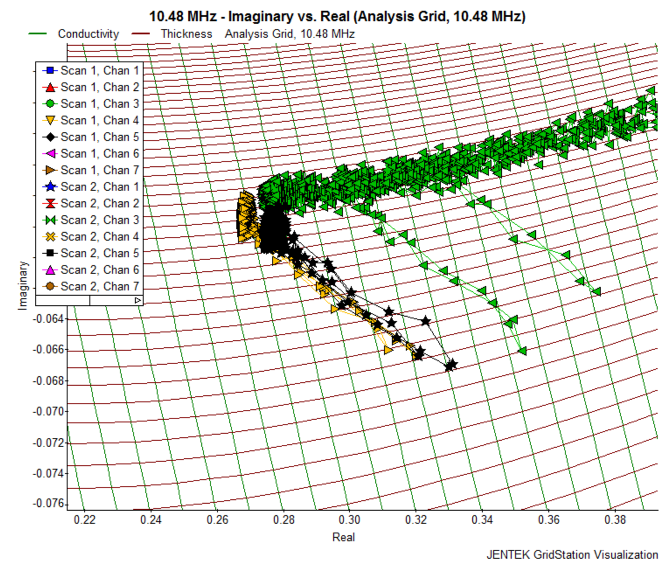
Titanium and Aluminum Alloy Inspection after Air Calibration, Using GridStation Software

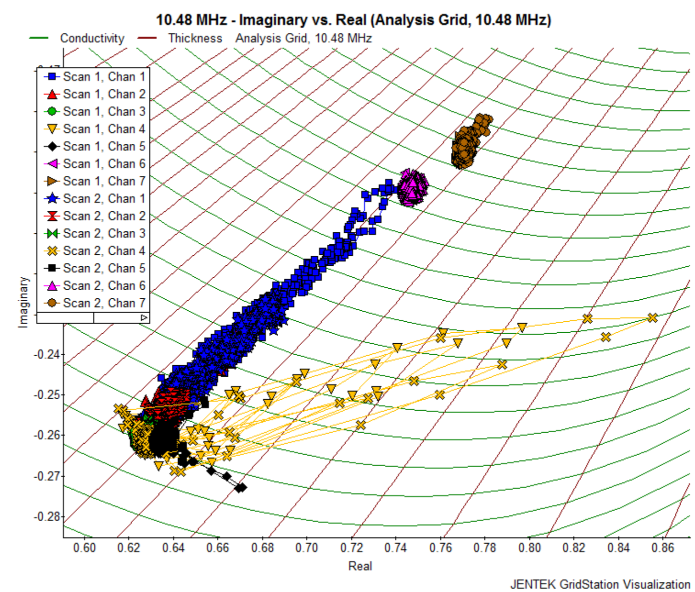
JENTEK Sensors

Aluminum Alloy Standard

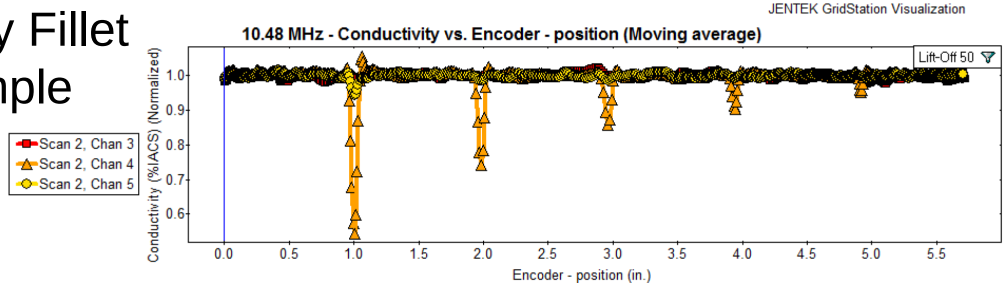






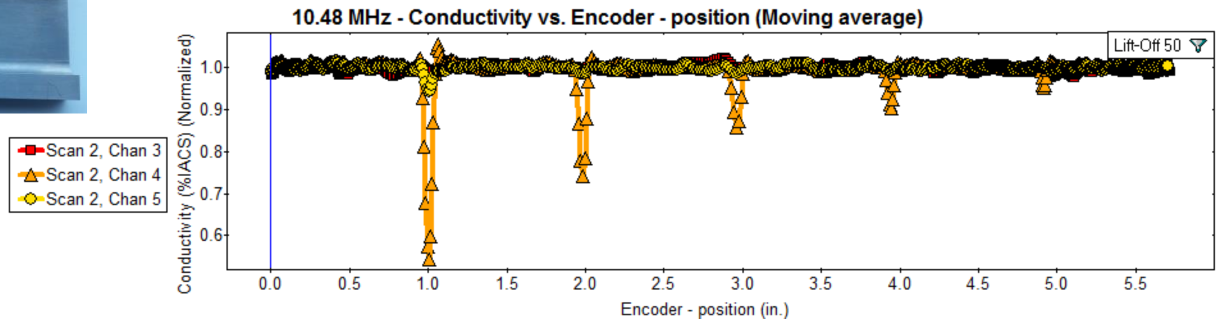


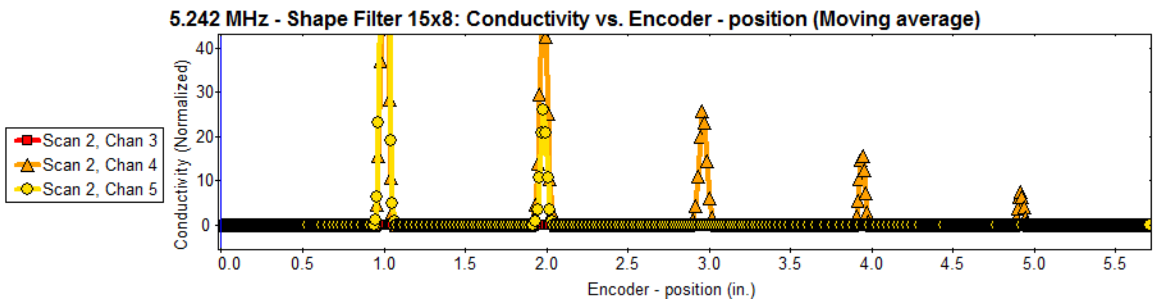
Titanium Alloy Fillet Sample

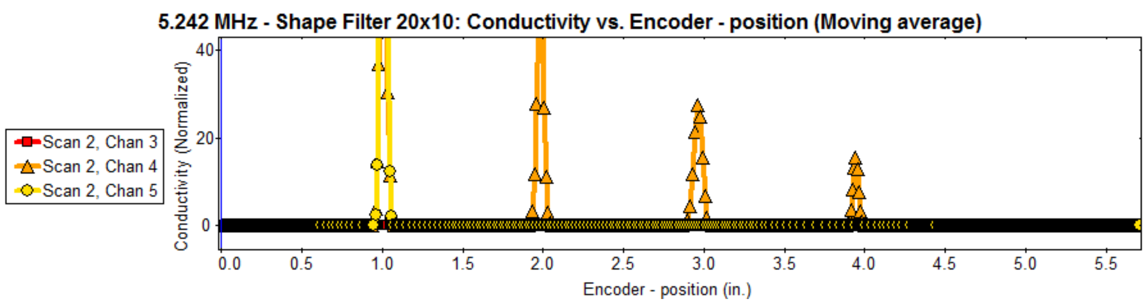


Titanium Alloy Unfiltered and Shape Filtered Results

EDM Notch Sizes:						
	length	0.06	0.04	0.03	0.02	0.015
	depth	x0.03	x0.02	x0.015	x0.01	x0.0075



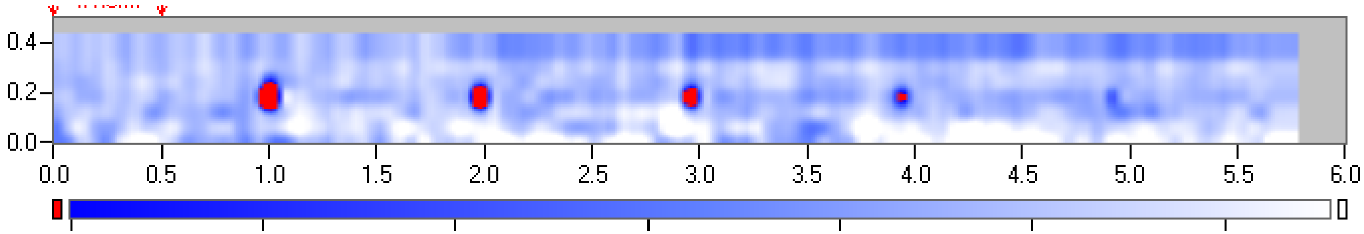




Titanium Alloy Unfiltered and Shape Filtered Results

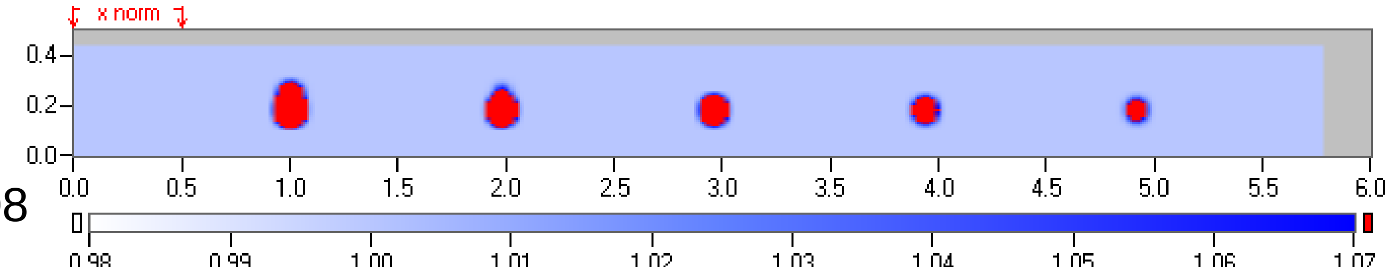
EDM Notch Sizes: length 0.06 0.04 0.03 0.02 0.015
depth x0.03 x0.02 x0.015 x0.01 x0.0075

Unfiltered
5.2MHz
Conductivity



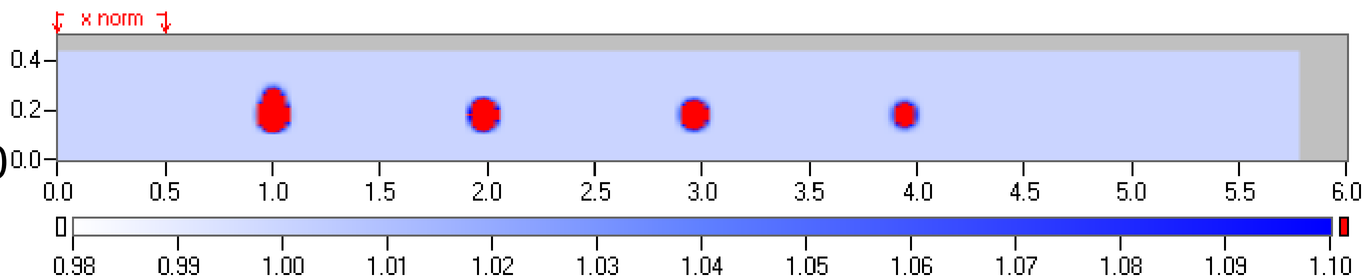
5.242 MHz - Shape Filter 15x8 Conductivity scan - Set 2

Shape
Filtered
0.015 x 0.008

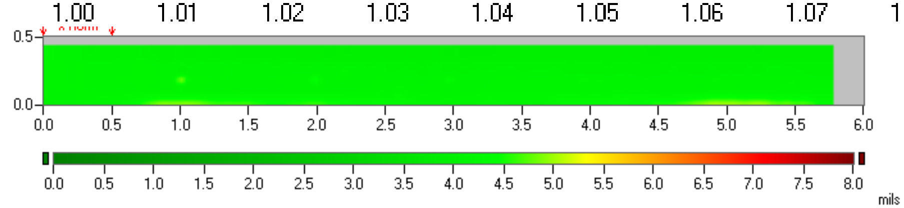


5.242 MHz - Shape Filter 20x10 Conductivity scan - Set 2

Shape
Filtered
0.020 x 0.010



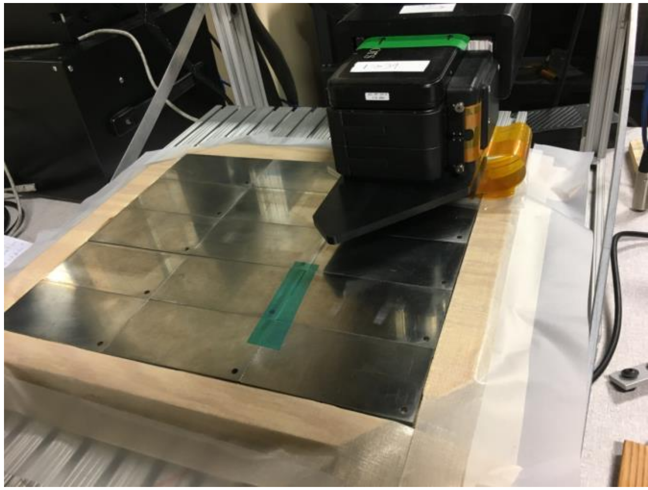
Lift-off
Verification



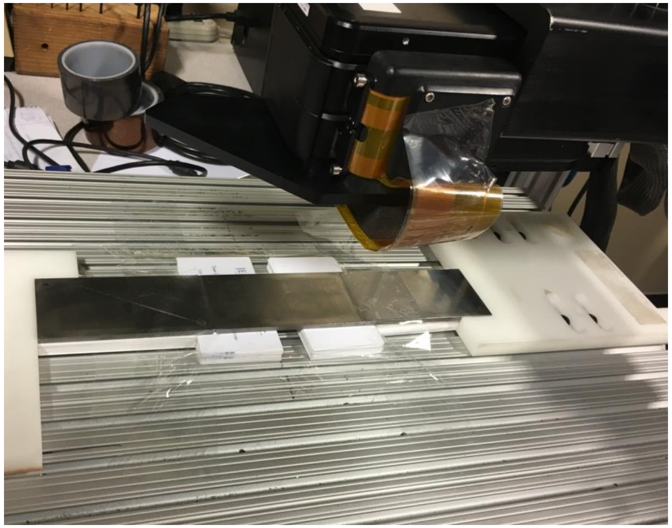
High Frequency ET Surface Crack Detection for Titanium Alloys

New set of 29 titanium plates accessed

- training set of 4 plates
- Using GS39 system
- POD samples provided by aerospace OEM
- Real cracks (Trueflaw and OEM sizing provided (significant variation in real crack sizing)
- **NOTE: Multiple POD studies completed for MWM-Arrays for surface breaking cracks**



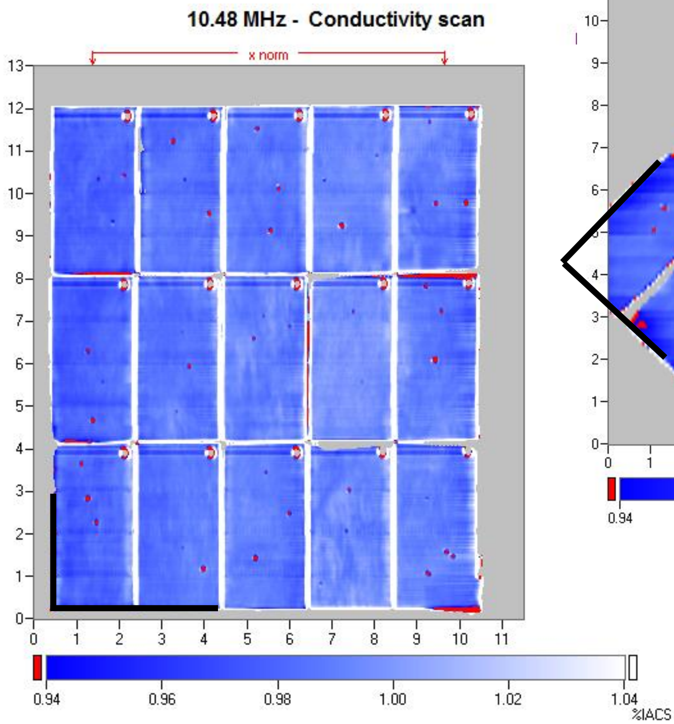
Crack	Angle	Crack Size (mm)	Crack Size (")	Keyence Measurement (mm)	Keyence Measurement (")	Trueflaw ID	Test Piece	Difference (%)
7	**90**	0.80	**0.032**	0.77	**0.031**	019BHB4368	W1403	-3%
8	**90**	0.40	**0.016**	0.53	**0.021**	020BHB4374	W1403	32%
9	90	0.30	0.012	0.73	0.029	020BHB4380	W1403	144%
34	**90**	0.60	**0.024**	0.52	**0.021**	025BHB4411	W1418	-13%
35	**90**	0.60	**0.024**	0.71	**0.028**	025BHB4417	W1418	18%
36	**90**	1.00	**0.040**	0.90	**0.036**	026BHB4423	W1418	-10%
85	90	0.50	0.020	0.52	0.021	037BHB4516	W1454	5%
86	40	0.60	0.024	0.35	0.014	037BHB4523	W1454	-41%
87	90	2.20	0.088	1.96	0.078	037BHB4528	W1454	-11%
19	45	1.70	0.068	1.26	0.050	021BHB4391	W1410	-26%
20	90	1.10	0.044	0.89	0.035	022BHB4396	W1410	-19%
21	0	1.30	0.052	1.48	0.059	023BHB4401	W1410	14%

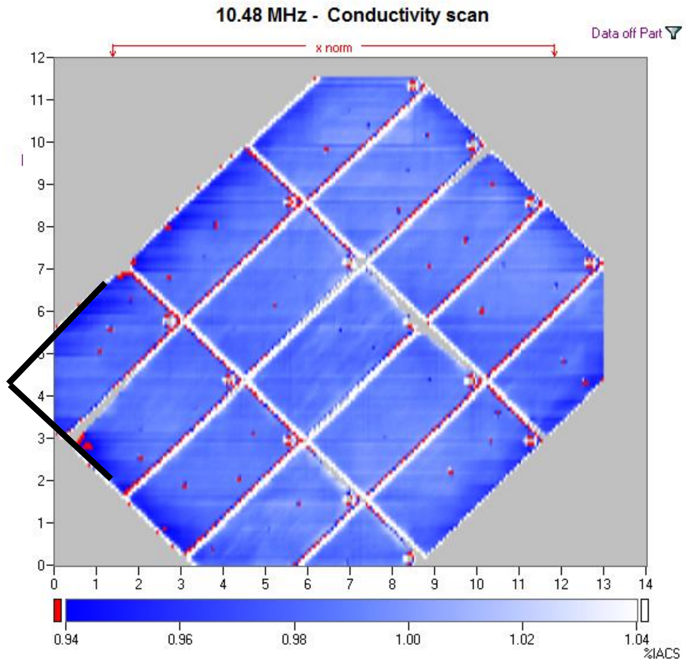


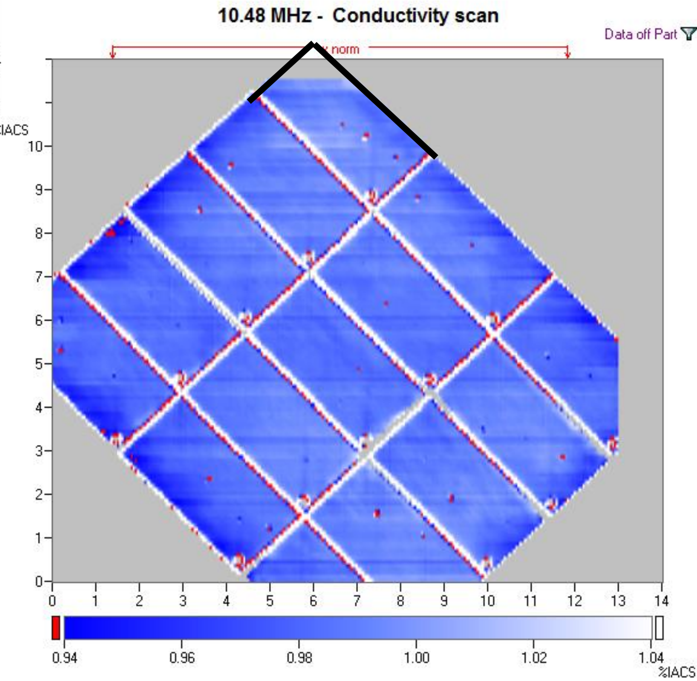
Continued HF Flat Plate Data (Conductivity)

JENTEK Sensors

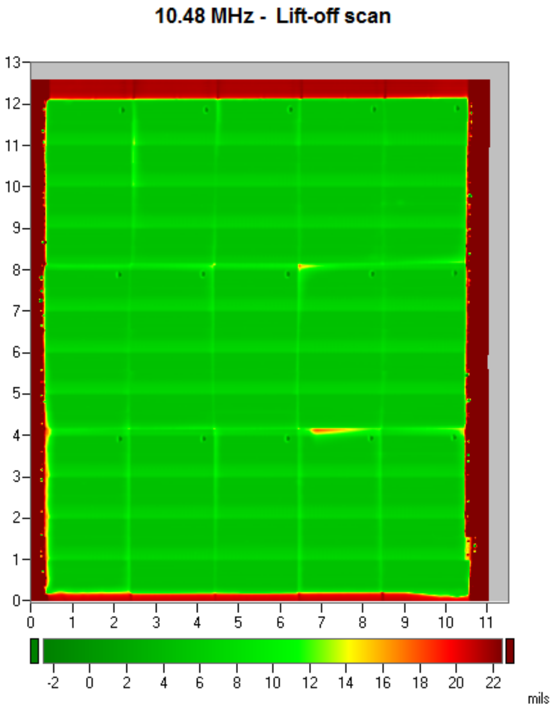
(not shape filtered)

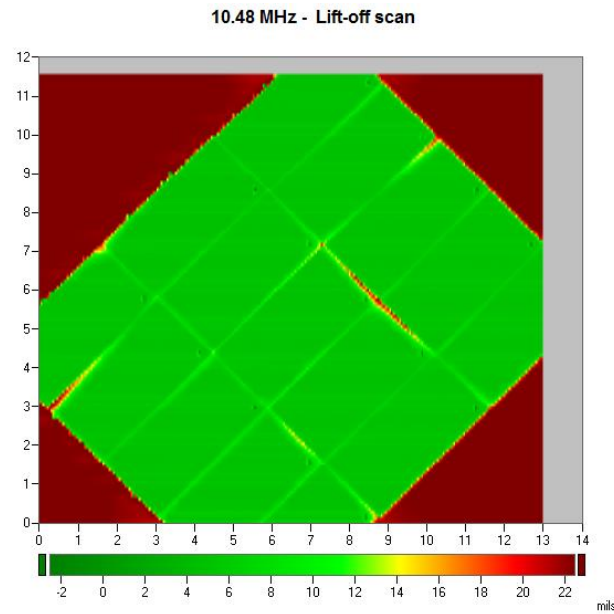


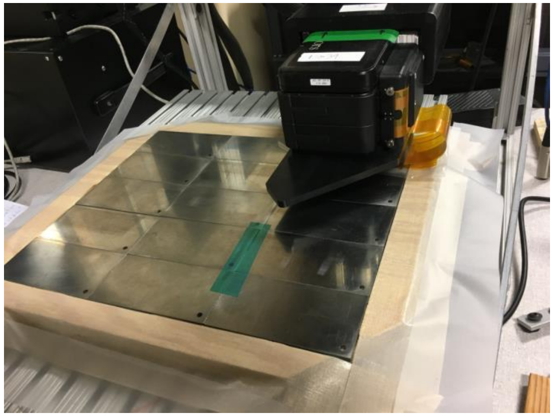


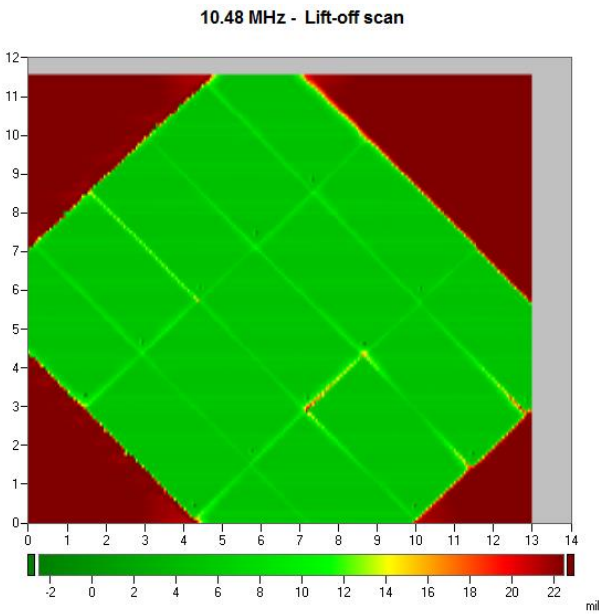


Continued HF Flat Plate Data (Lift-off)



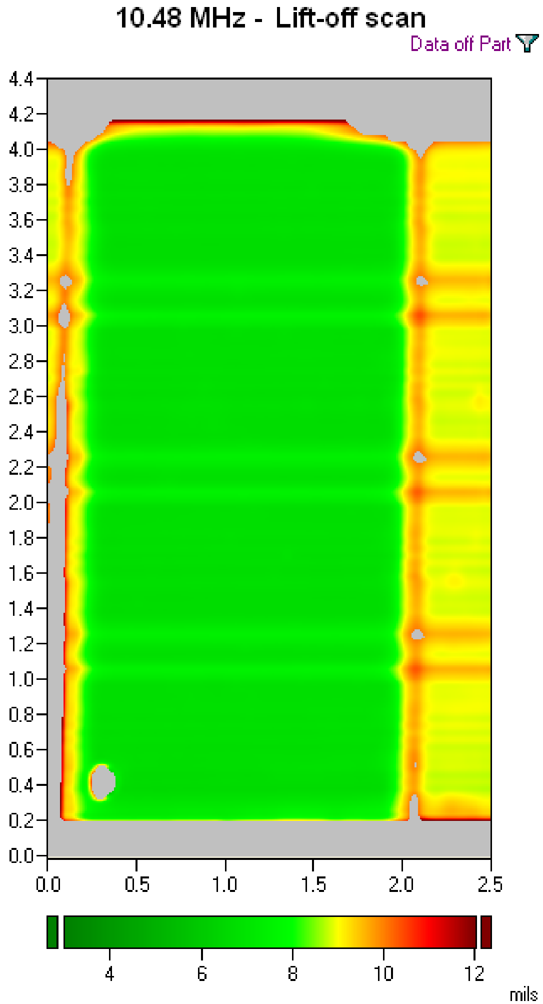


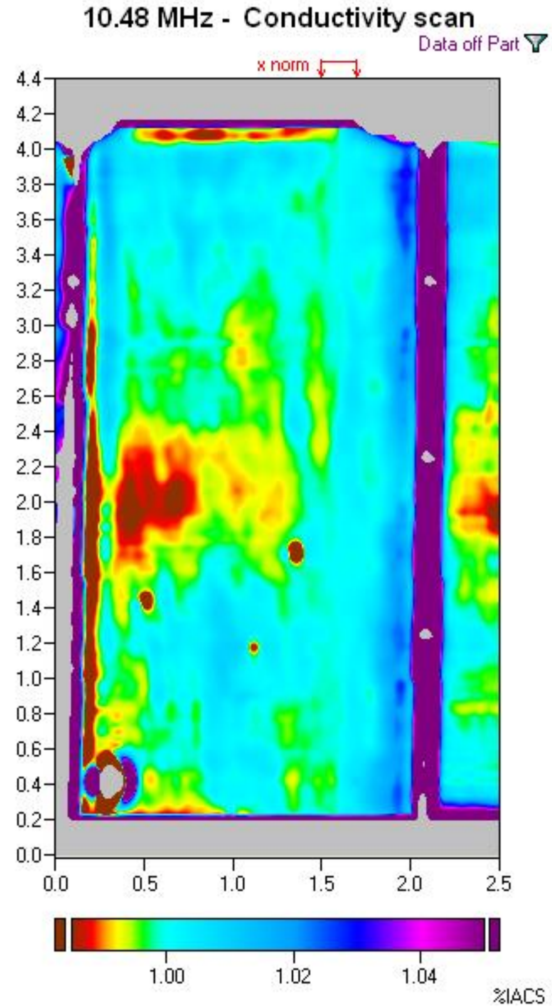


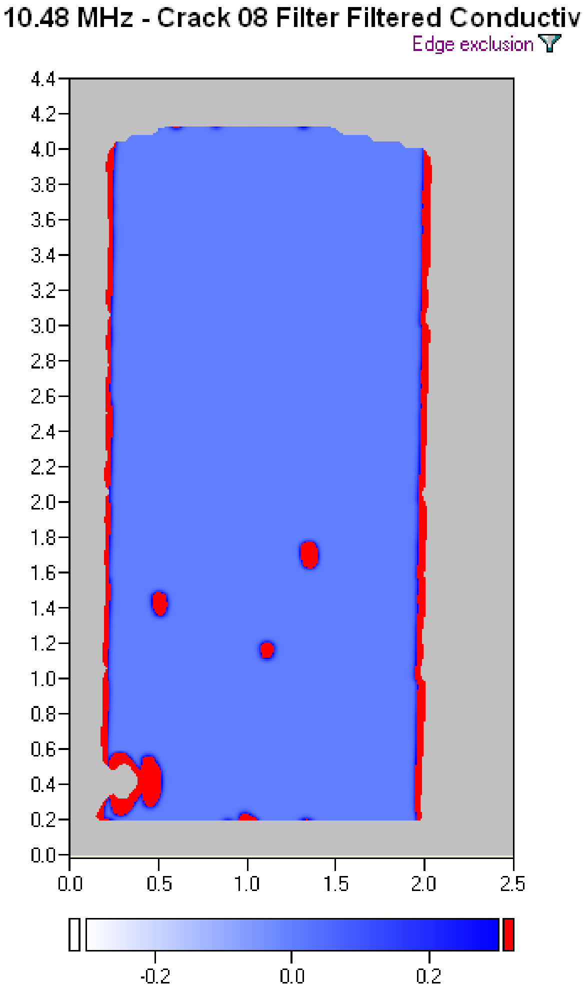


High Frequency ET Surface Crack Detection for Titanium Alloys

Plate WXXXA (Training Set)

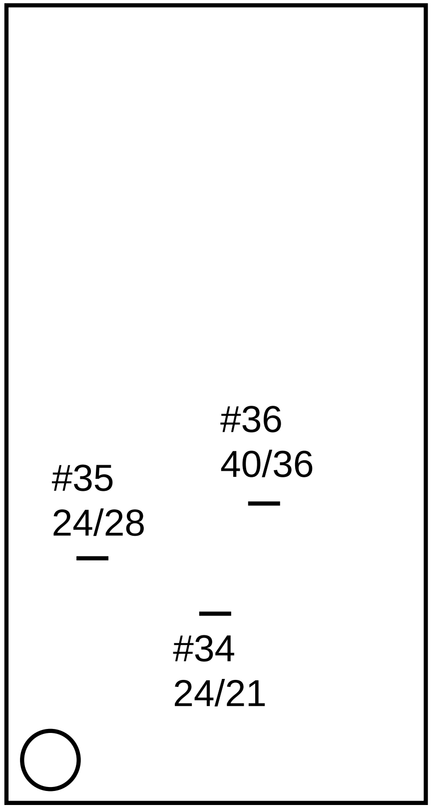




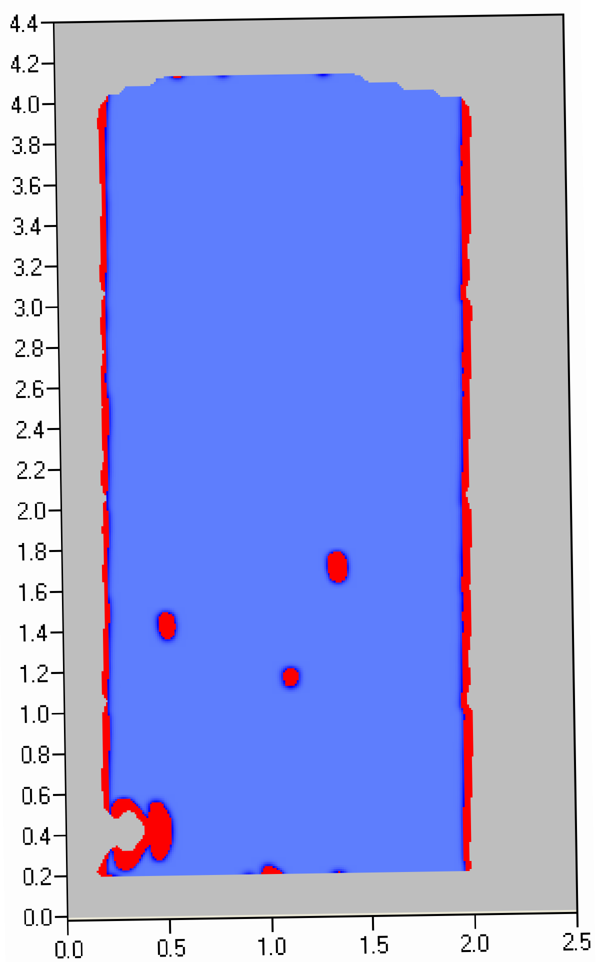


High Frequency ET Surface Crack Detection for Titanium Alloys

Plate WXXXA (Training Set)

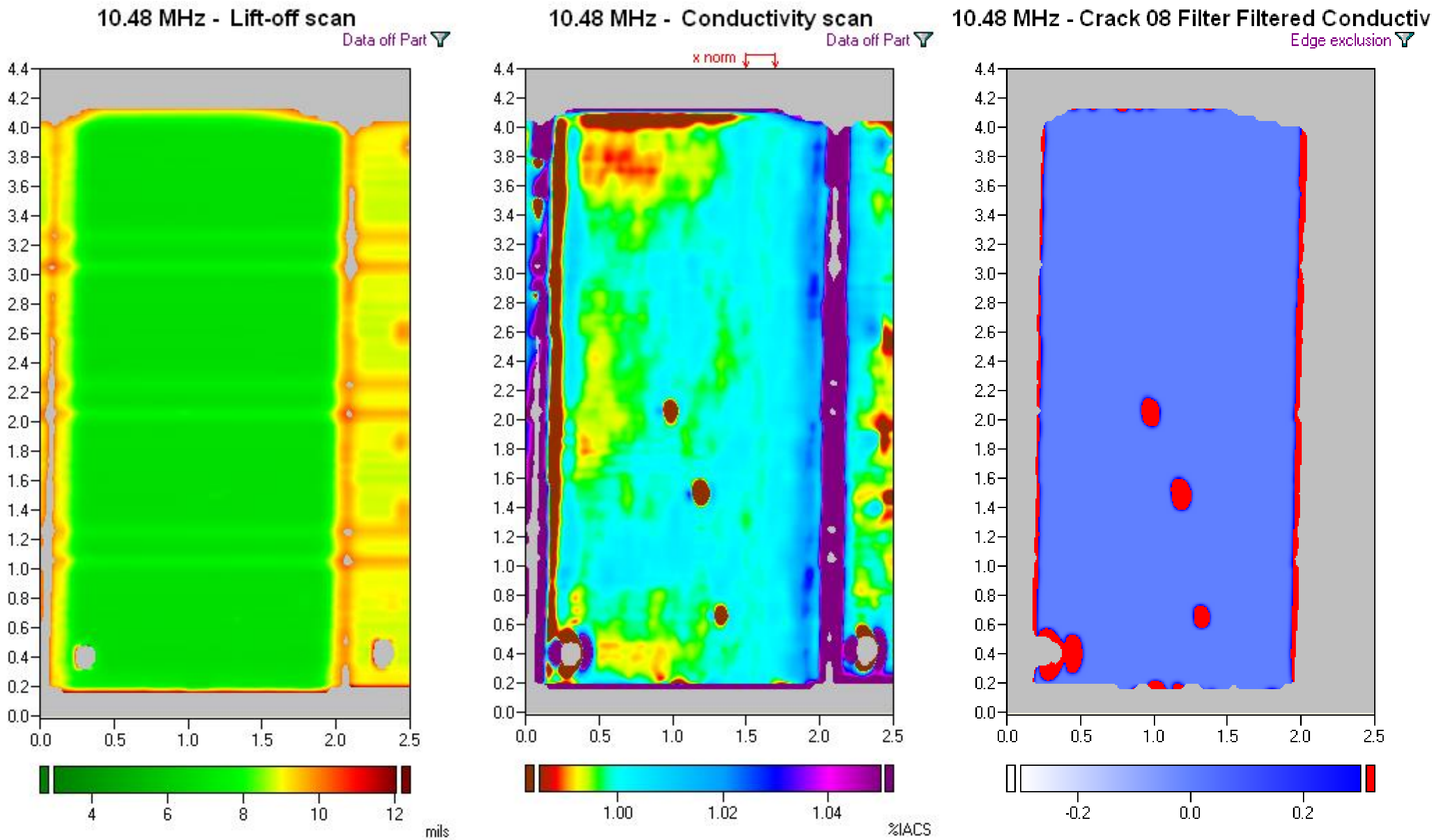


Trueflaw/Keyence lengths in mils

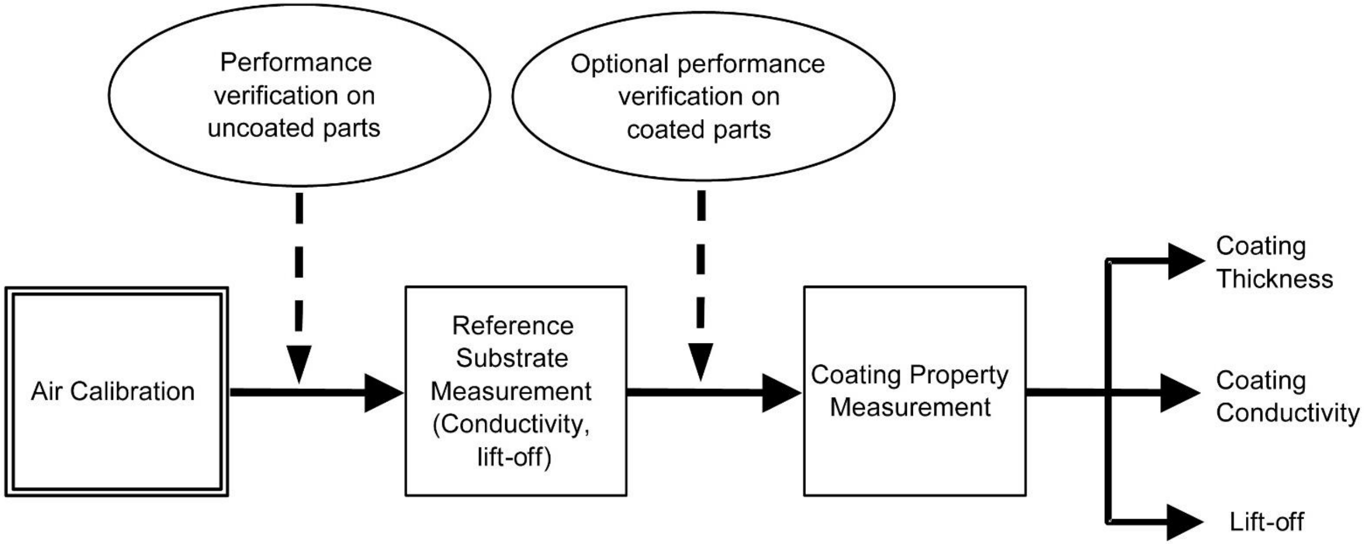


High Frequency ET Surface Crack Detection for Titanium Alloys

Plate WXXXB (Test Set)



ASTM Standard E2338-11



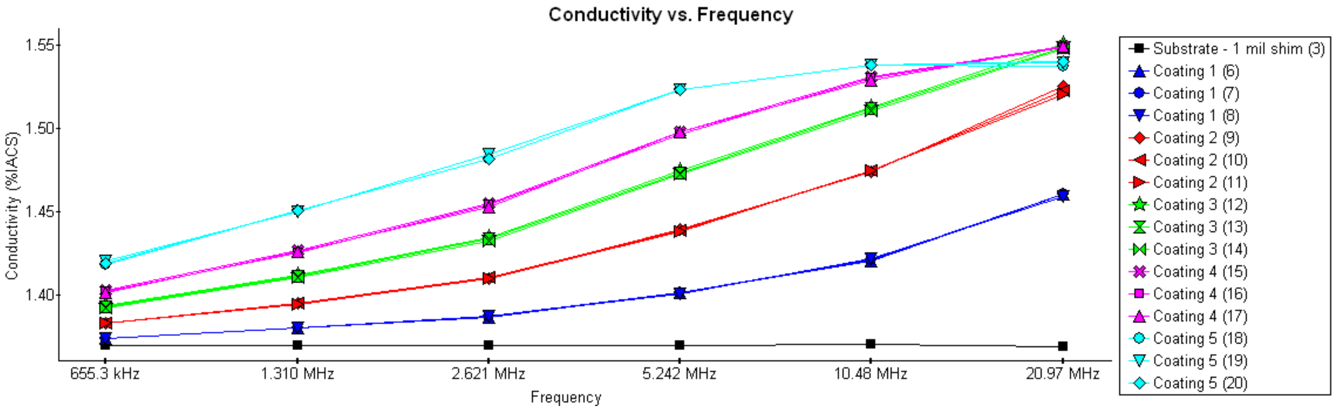
INTERNATIONAL

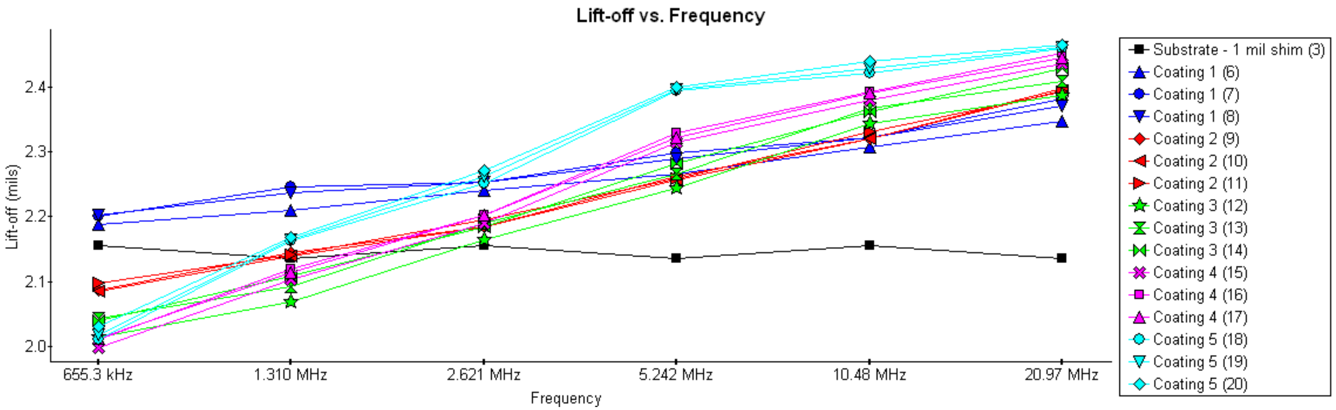
Designation: E 2338 – 06

Standard Practice for
Characterization of Coatings Using Conformable Eddy-Current Sensors without Coating Reference Standards[1]

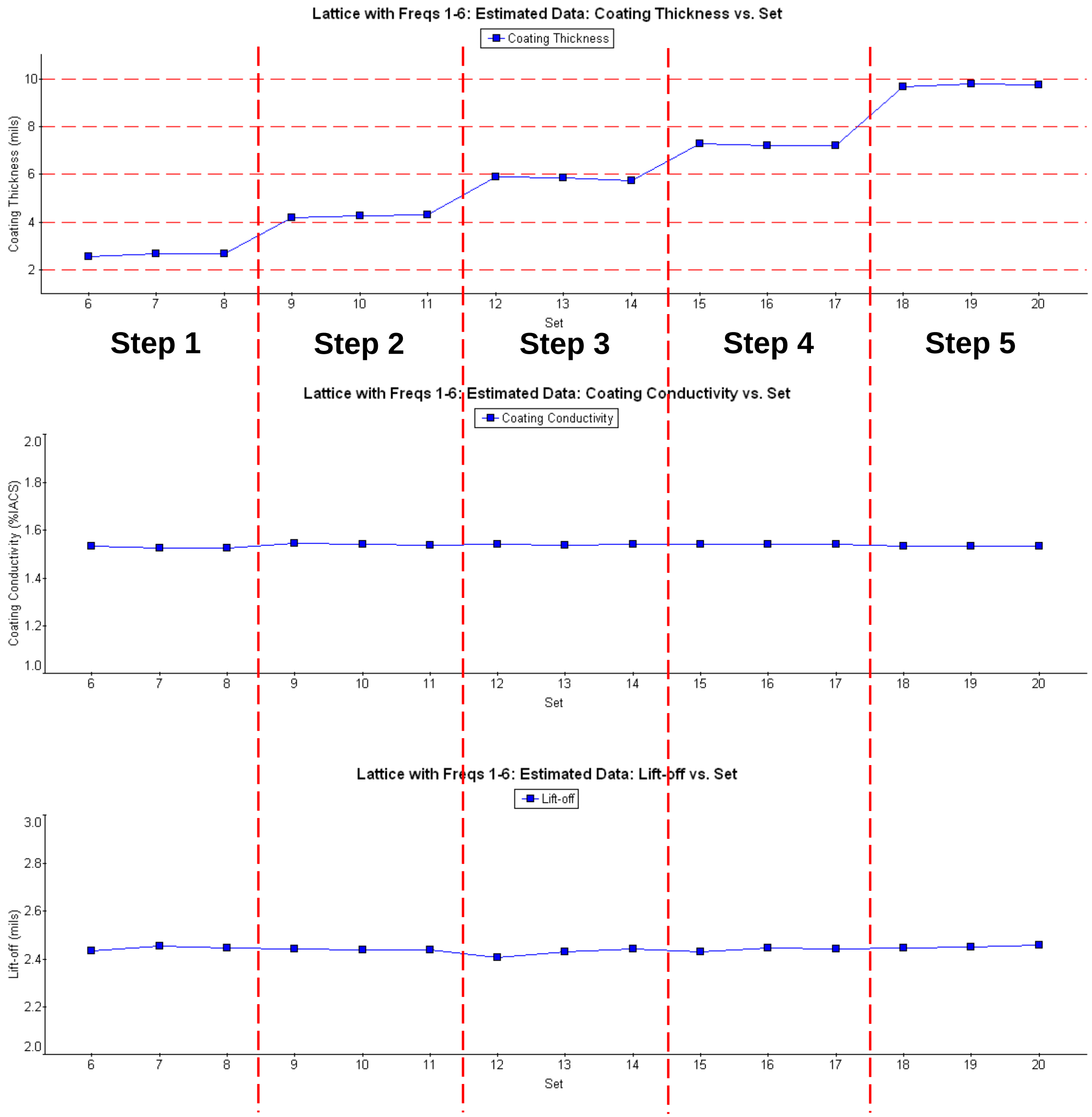
This standard is issued under the fixed designation E 2338; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

7-2 Specimen


Conductivity vs. Frequency
Conductivity (%IACS)
1.55
1.50
1.45
1.40
655.3 kHz
1.310 MHz
2.621 MHz
5.242 MHz
10.48 MHz
20.97 MHz
Frequency
Substrate - 1 mil shim (3)
Coating 1 (6)
Coating 1 (7)
Coating 1 (8)
Coating 2 (9)
Coating 2 (10)
Coating 2 (11)
Coating 3 (12)
Coating 3 (13)
Coating 3 (14)
Coating 4 (15)
Coating 4 (16)
Coating 4 (17)
Coating 5 (18)
Coating 5 (19)
Coating 5 (20)

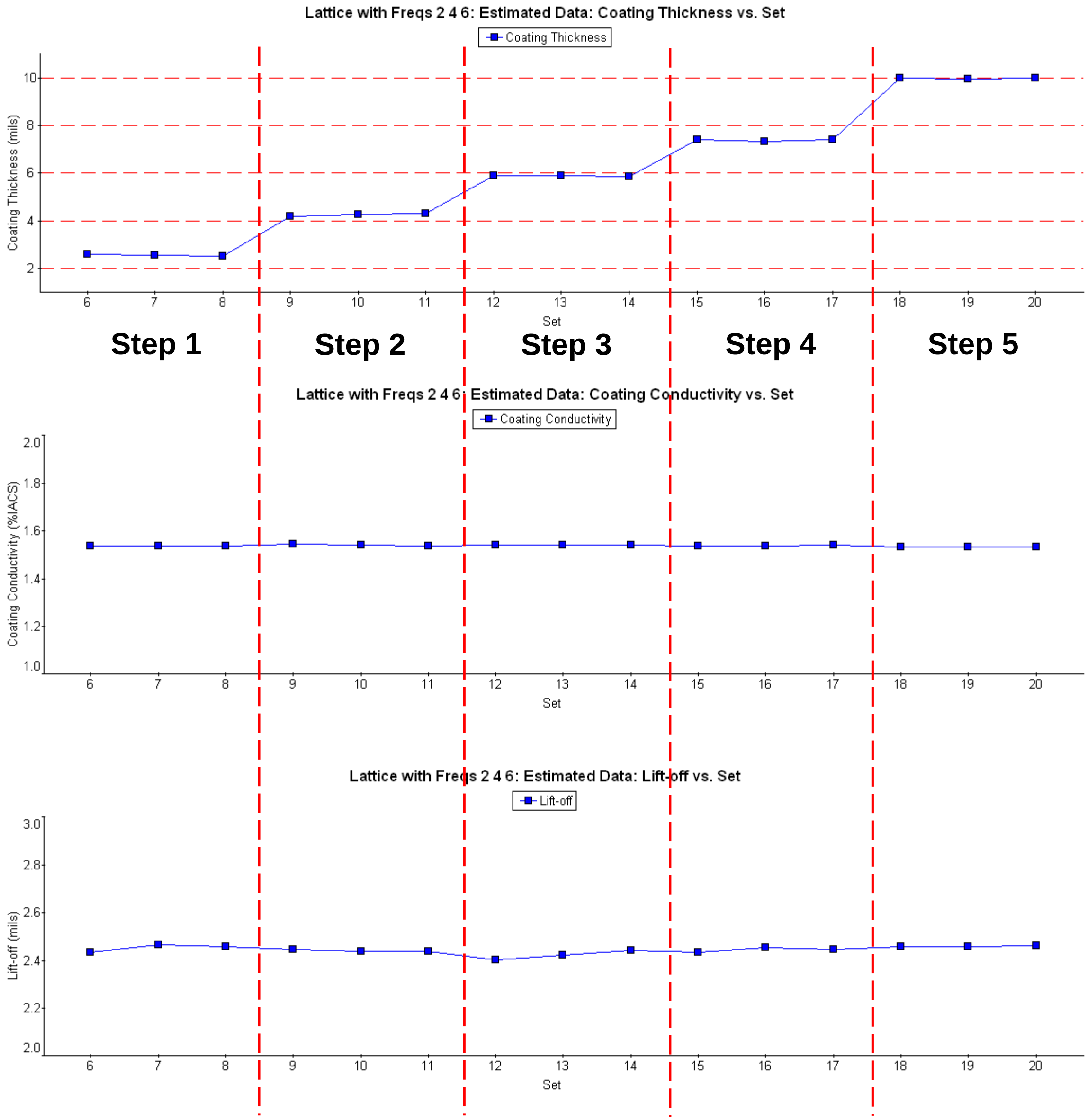

Lift-off vs. Frequency
Lift-off (mils)
2.4
2.3
2.2
2.1
2.0
655.3 kHz
1.310 MHz
2.621 MHz
5.242 MHz
10.48 MHz
20.97 MHz
Frequency
Substrate - 1 mil shim (3)
Coating 1 (6)
Coating 1 (7)
Coating 1 (8)
Coating 2 (9)
Coating 2 (10)
Coating 2 (11)
Coating 3 (12)
Coating 3 (13)
Coating 3 (14)
Coating 4 (15)
Coating 4 (16)
Coating 4 (17)
Coating 5 (18)
Coating 5 (19)
Coating 5 (20)

7-2 Specimen: 6-Frequency Method (No interdiffusion layer)



6 frequencies used:
655 kHz, 1.31 MHz, 2.62 MHz,
5.242 MHz, 10.48 MHz, 20.97 MHz

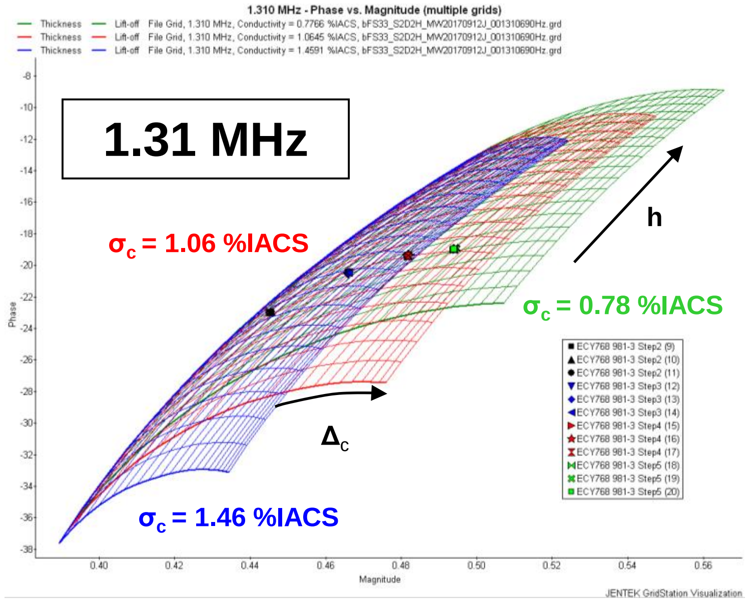
7-2 Specimen: 3-Frequency Method (No interdiffusion layer)

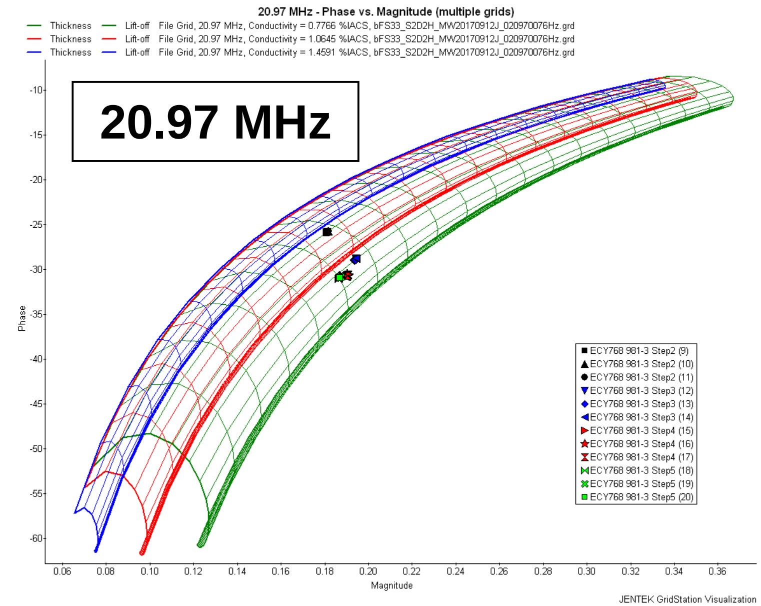


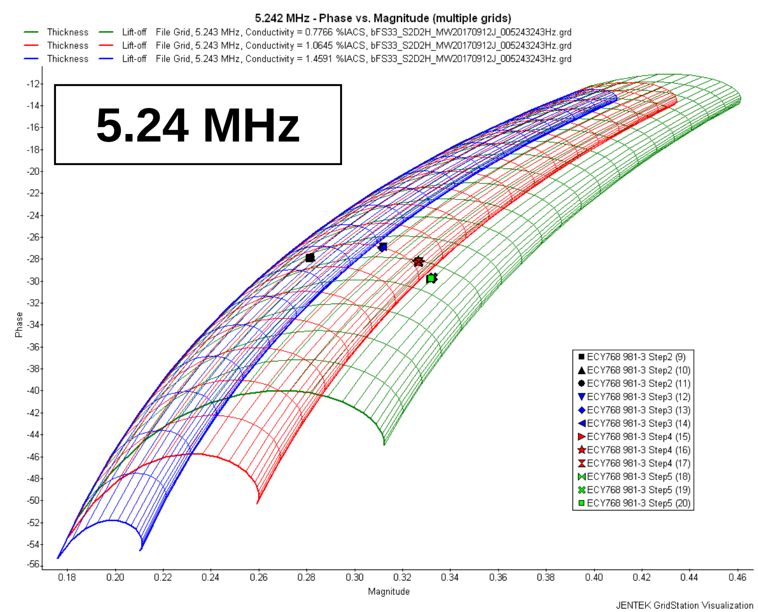
3 frequencies used:
1.31 MHz, 5.242 MHz, 20.97 MHz

σ_c-Δ_c-h Lattices for 1.31 MHz, 5.24 MHz, 20.97 MHz

JENTEK Sensors

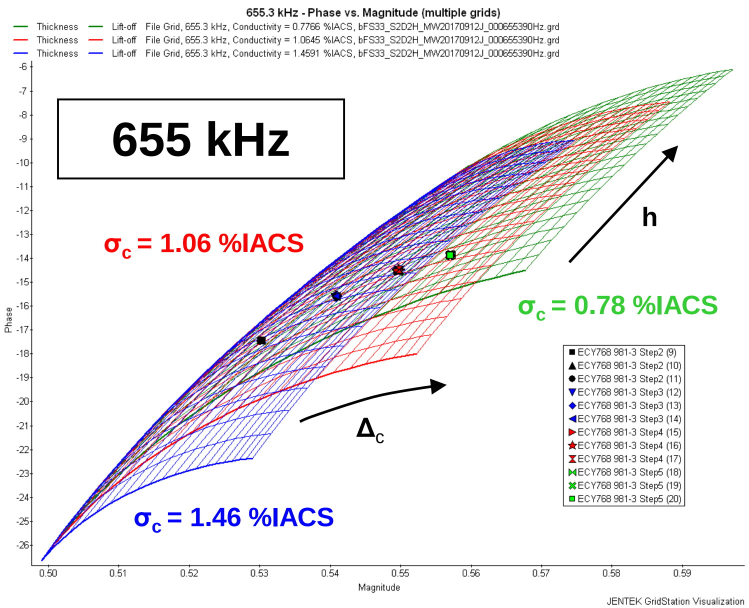


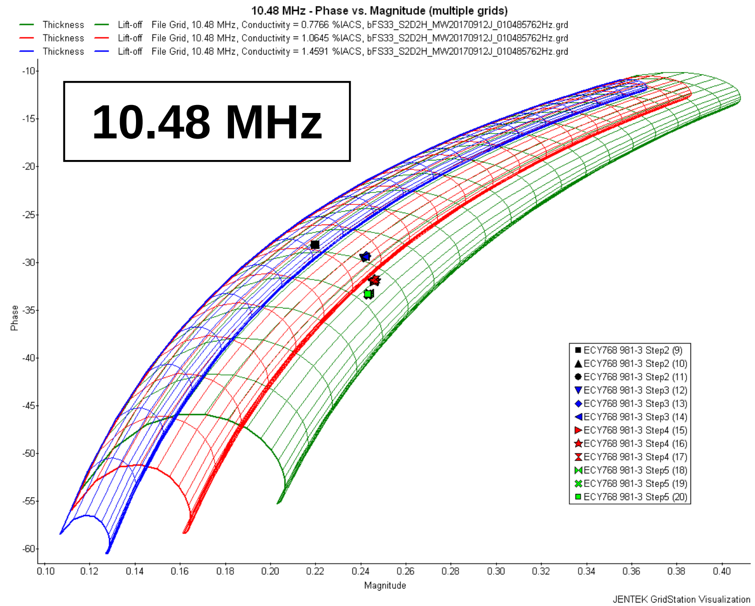


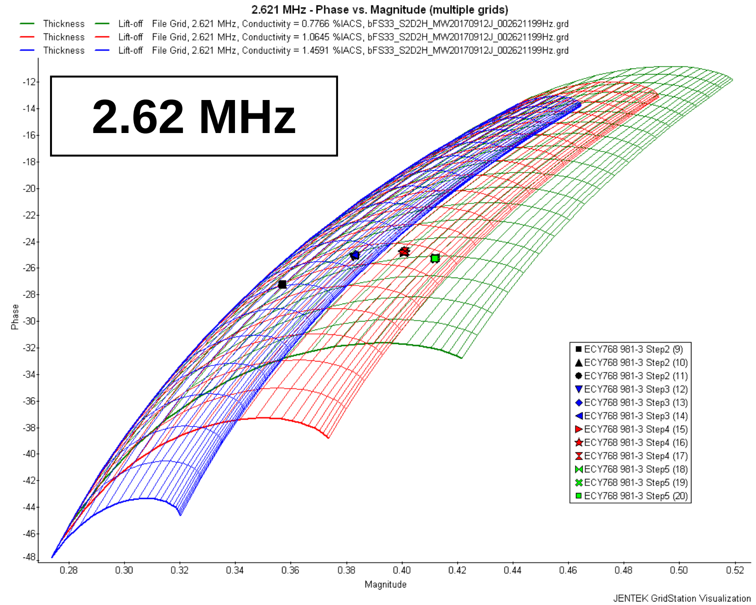


σ_s = 1.97 %IACS

σ_c-Δ_c-h Lattices for 655 kHz, 2.62 MHz, 10.48 MHz



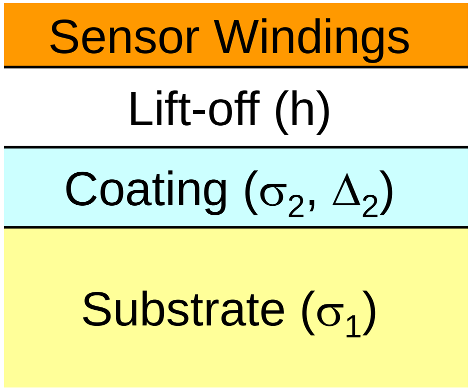


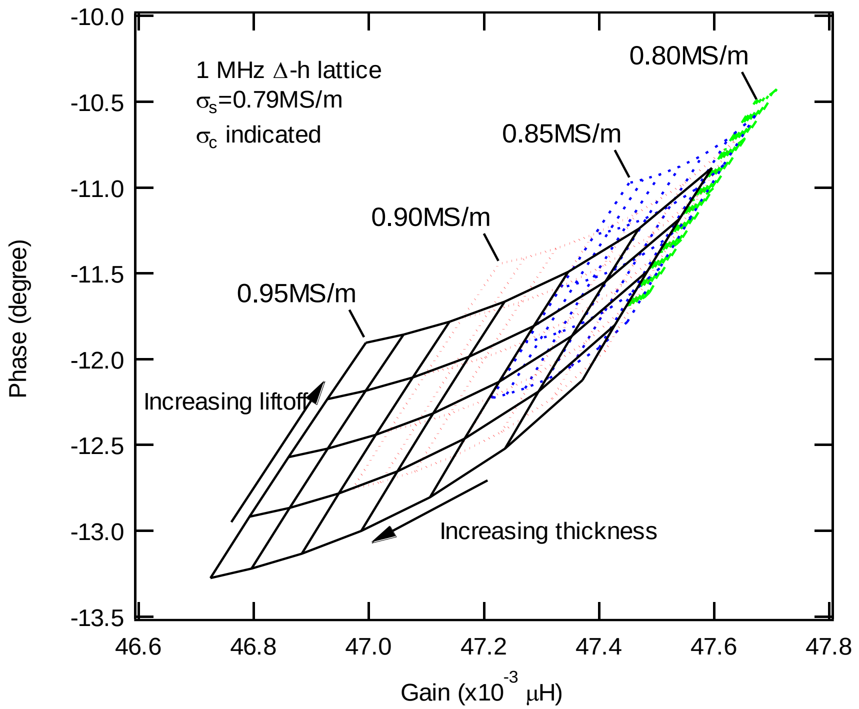


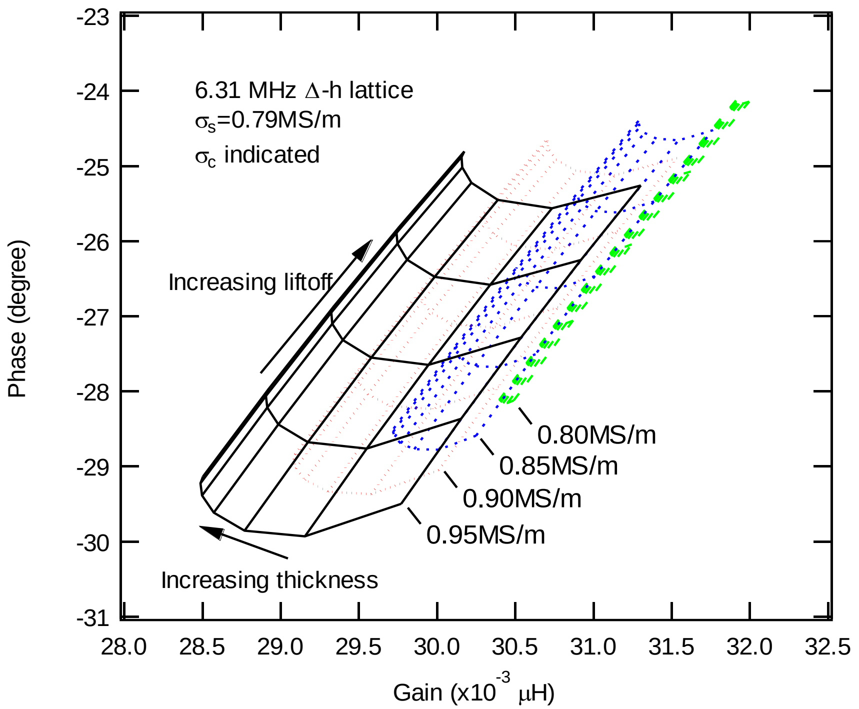
σ_s = 1.97 %IACS

Historical Success: Measurement Grid Lattice Algorithm

- Collections of 2-D grids
  - coating conductivity, coating thickness, lift-off
- Approach:
  - conductivity/lift-off to determine coating presence
  - use lattices to find properties that are independent of frequency



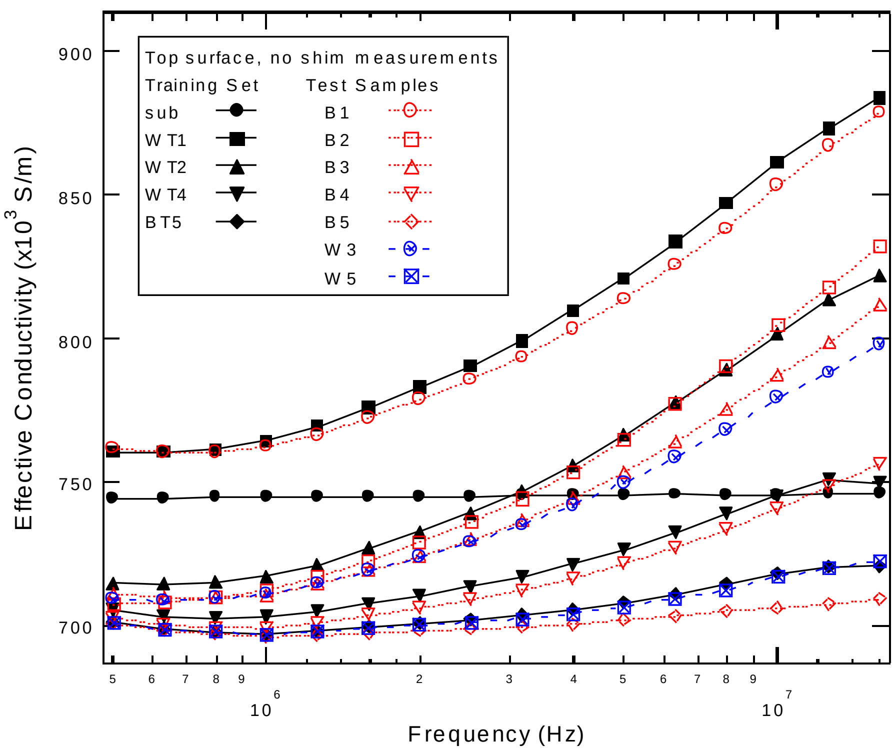


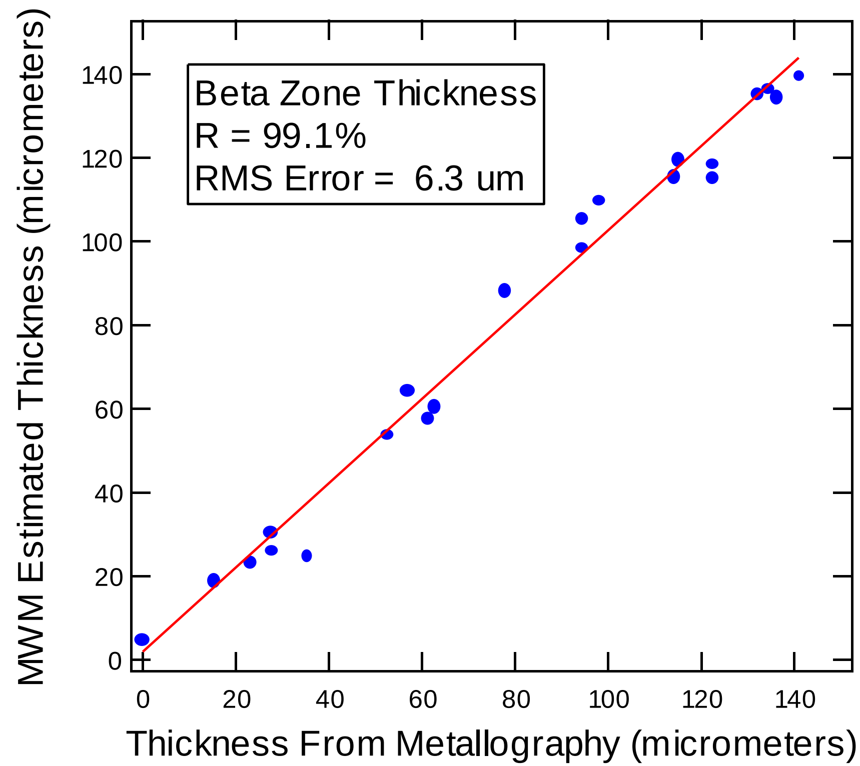


Historical Success: Thermal Spray Coating: Thermal Aging

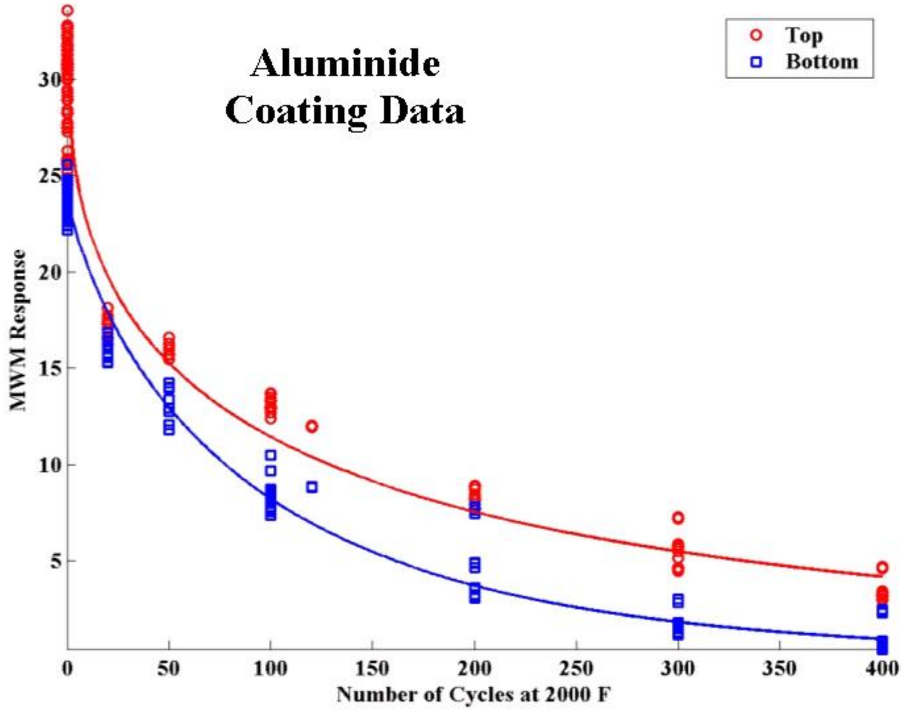
Left: **Comparison of the MWM multifrequency effective conductivity measurements for training set and blind test samples;**

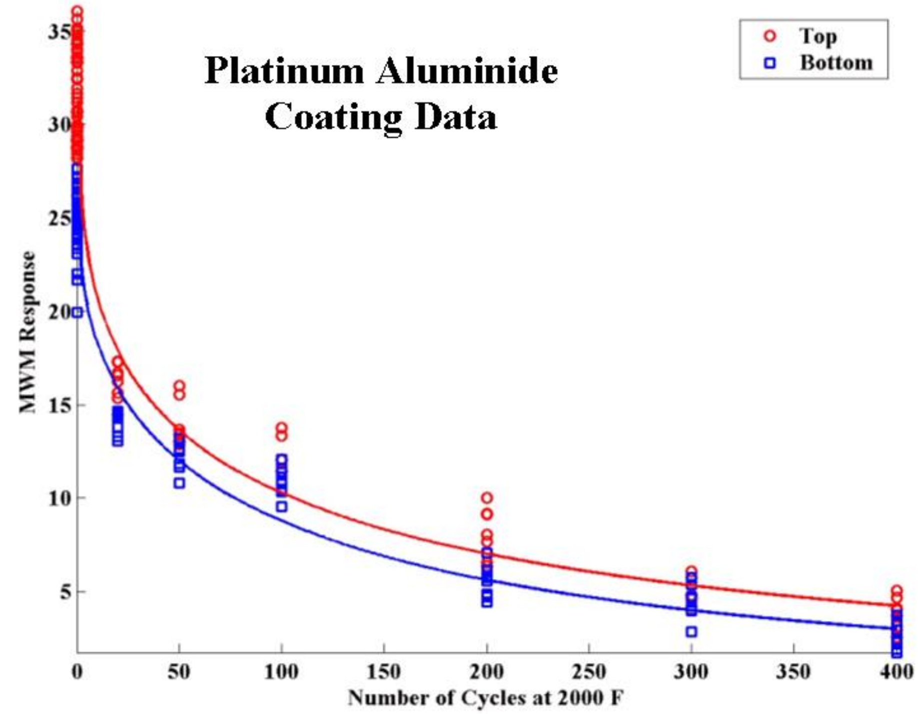
Right: **MWM measured beta-phase layer thickness versus reported beta-phase layer thickness for blind test set.**





Historical Success: MWM Response vs. # Thermal Cycles

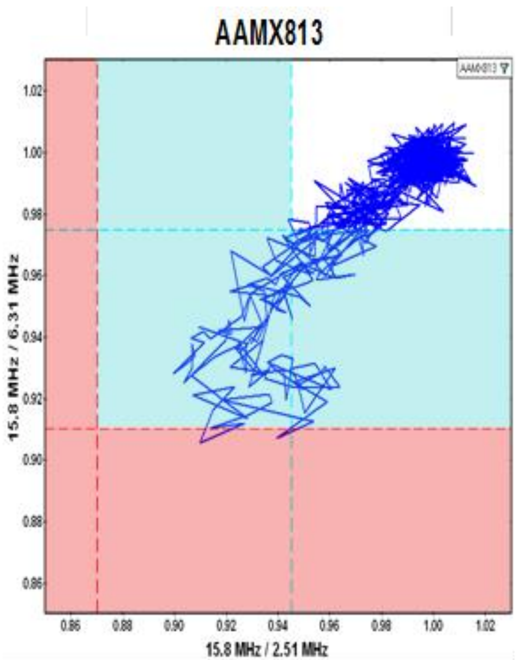


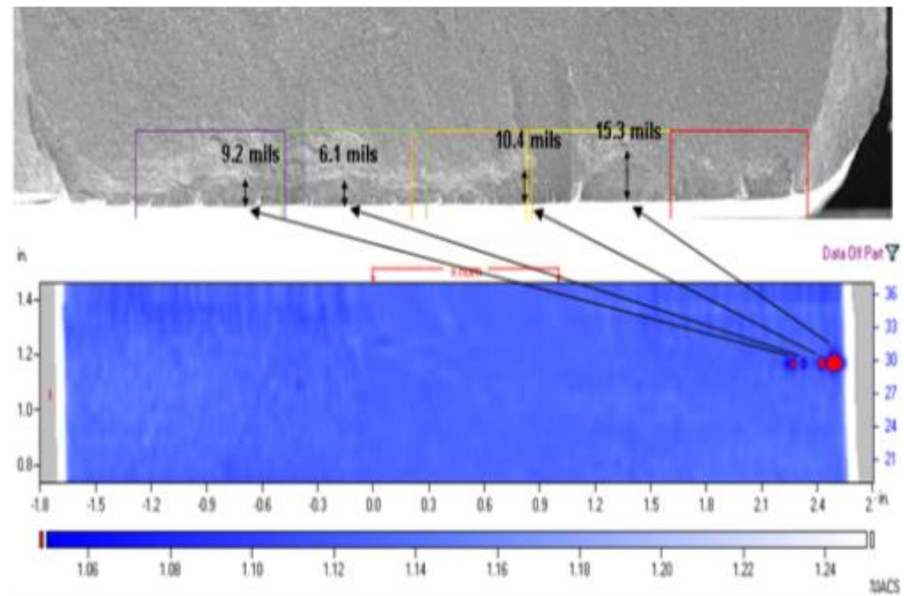


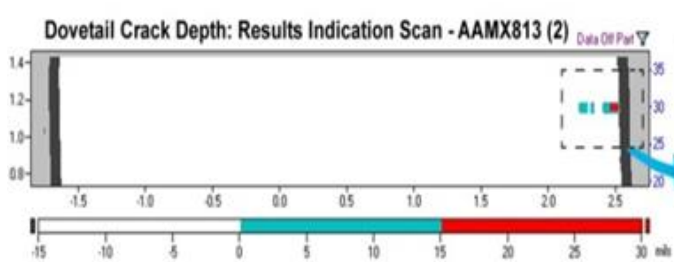
"Top" and "bottom" refer to the coating on opposite sides of each specimen

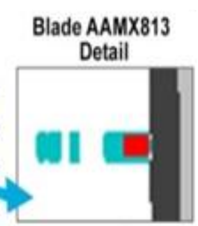
Historical Success: Crack Detection and Depth Estimation (Titanium Alloy Blade Dovetail)

Earlier results for crack detection and depth estimation for an engine blade dovetail on a military engine component





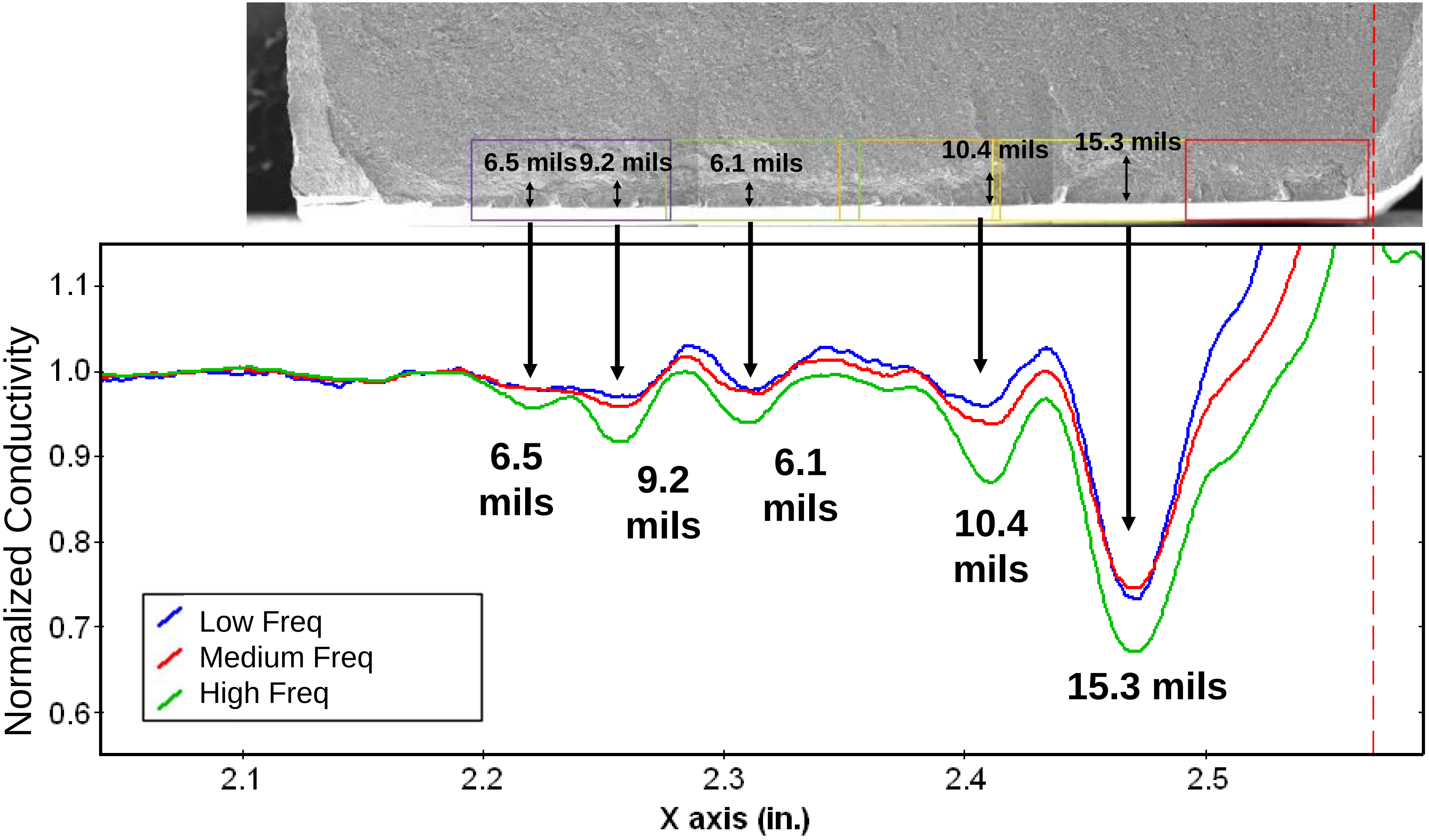




Crack Depth Image

Historical Success: Crack Detection and Depth Estimation (Titanium Alloy Blade Dovetail)

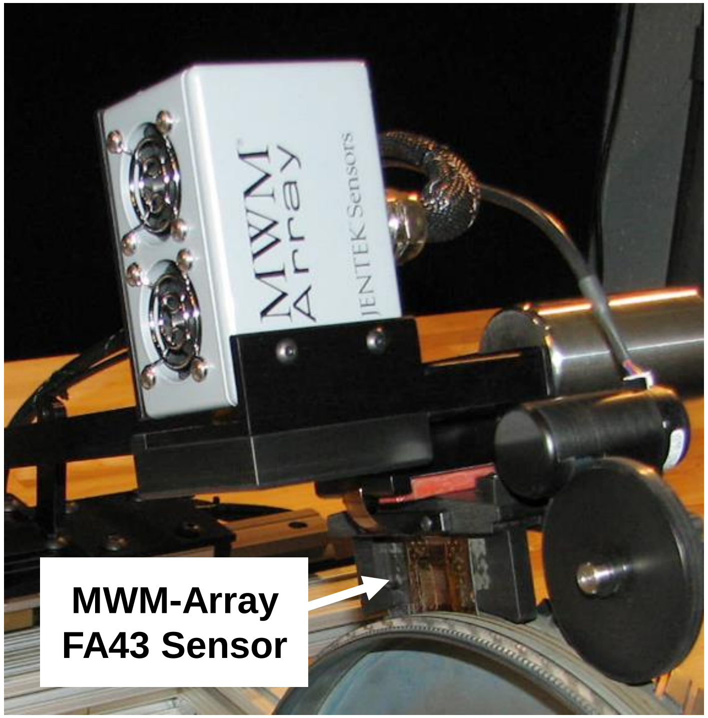
Blade #13



Distribution Statement A -- Approved for public release; distribution is unlimited, as submitted under NAVAIR Public Release Authorization Tracking number 2015-217.

Historical Success: Commercial Engine Knife Seal Inspection

- "Technical aspects of the method are FAA approved" (See Service Bulletin)
- Engine OEM implemented this inspection
- Multiple systems in use world-wide since 2011
- AE family engine knife seal Inspection on several stages for cracks
- Thousands of engine stages inspected per year
- Inspection performed with blades in place (minimal disassembly saves substantial dollars)




MWM-Array FA43 Sensor adapted for knife seal inspection

AE SERIES PROPULSION SYSTEM
Service Bulletin Index

Rolls-Royce

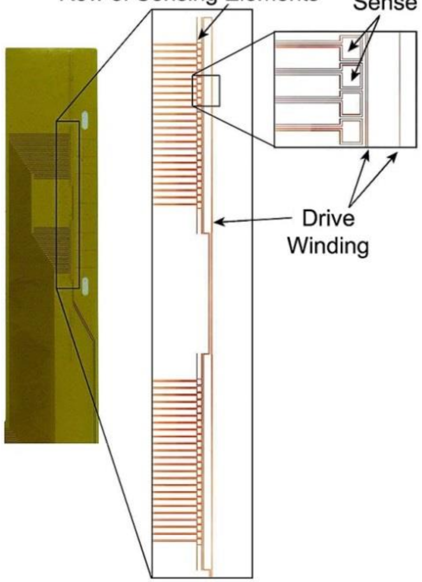
LIST OF AE 3007A SERIES SERVICE BULLETINS

SB No.	Rev No.	Title	Compliance Category	Date	Models Affected	Module or ATA Locator
AE 3007A-72-386		See AE 3007A-A-72-386				
AE 3007A-72-388	1	Engine - 6th- thru 13th-Stage Compressor Wheel Knife Edge Seals - Jentek Eddy Current Inspection	8	09-May-11	7A, 7A1/1, 7A1/3, 7A1, 7A1E, 7A1P, 7A2, 7A3	72-37-00

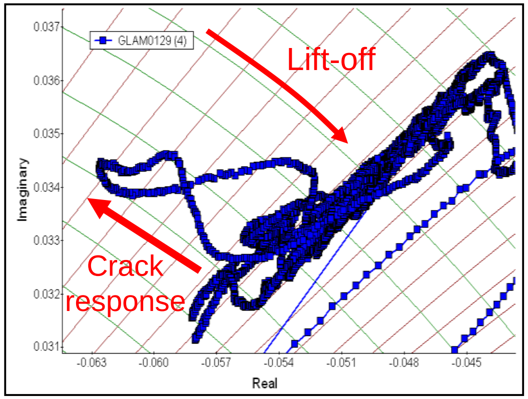
Reference: https://aeromanager.rolls-royce.com/control/publicsite/publicnoticeboard/categorylist?userAction=performDisplayDocument&selectedLevel=2&selectedLevelID=65

Historical Success: Military Blade Dovetail (Ti Alloy)

MMW-Array Sensors

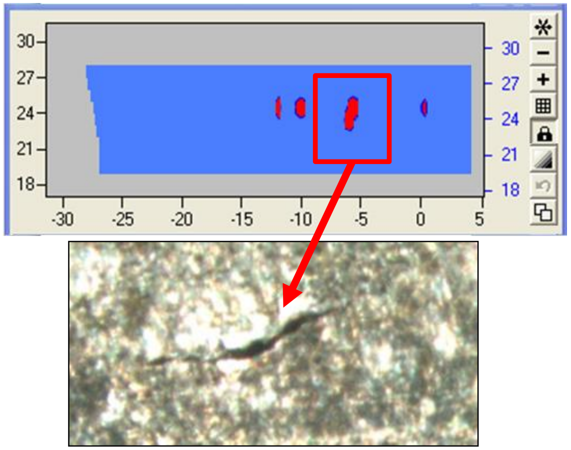


Precomputed Database (Grid)



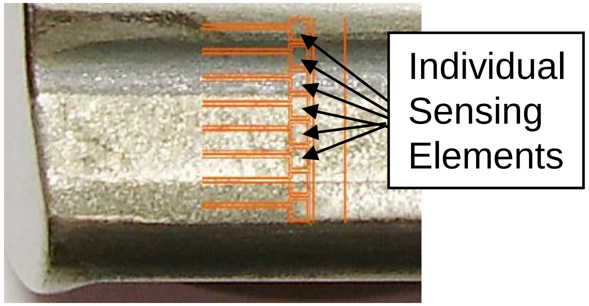
Crack response rescaled based on lift-off

C-Scan Image

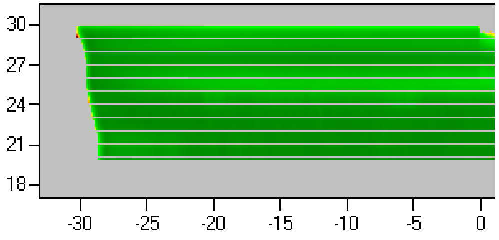


42-mil Crack

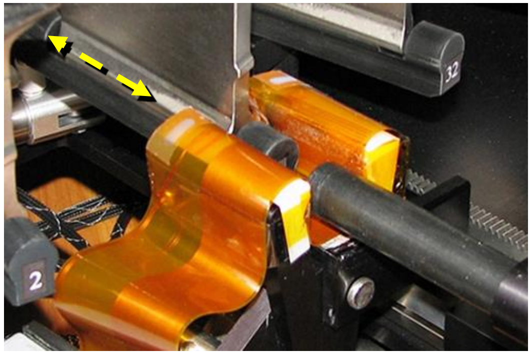
Sensor Coverage



Lift-Off Imaging



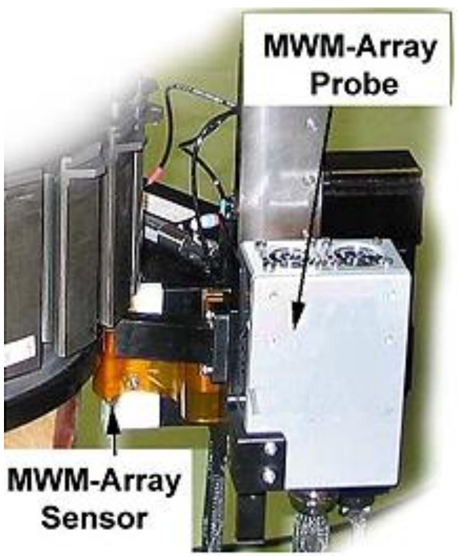
Sensor Position at Edge of Dovetail



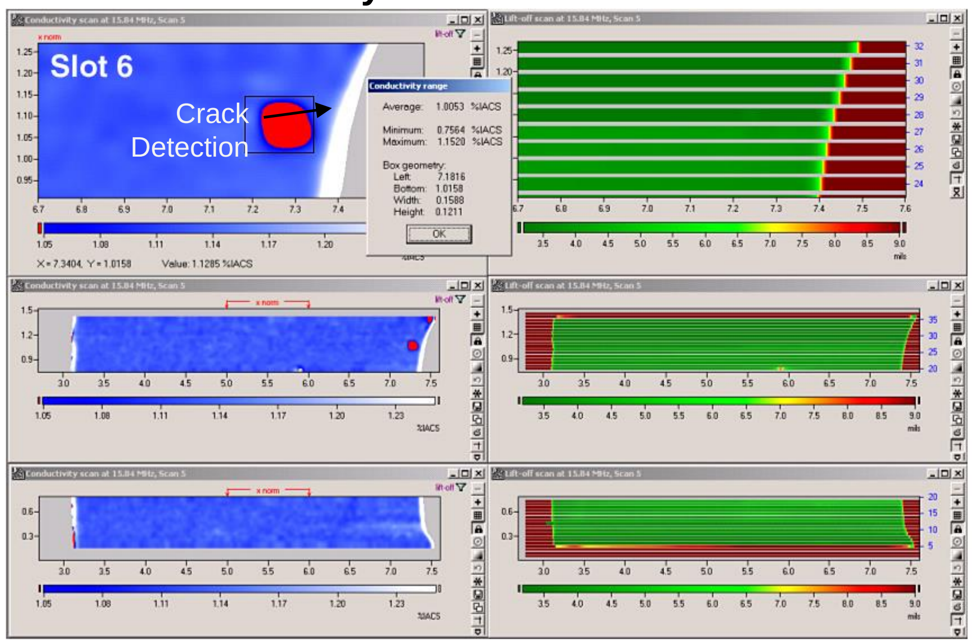
Distribution Statement A -- Approved for public release; distribution is unlimited,
as submitted under NAVAIR Public Release Authorization Tracking number 2015-217.

Historical Success: Automated Engine Disk Inspection

- In use at NAVAIR Depot since April 2005, **for a decade**
- Nine disks with **verified cracks detected**, several of these large and small cracks **not detected by conventional ET and LPI**
- No false indications (numerous slots inspected)

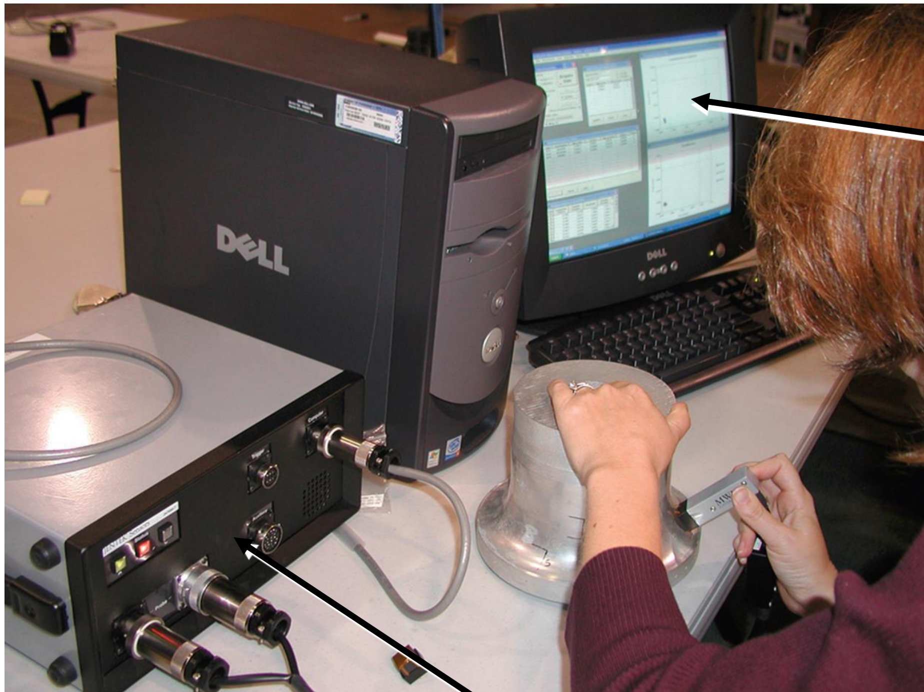


Conductivity **Lift-Off**



Winner, FAA-Air Transport Association 2007 "Better Way" Award for "MWM and MWM-Array Engine Component Inspection Technology"

Historical Success: Inspection of Cold Rolling Integrity on C-130 Propeller Blades



GridStation Display

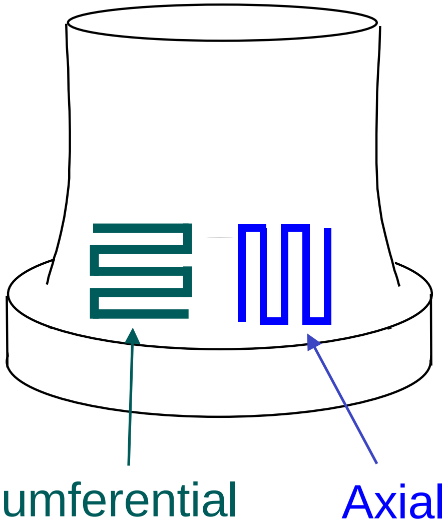
JENTEK GridStation System for C-130 Propeller Cold Rolling Inspection

Historical Success: Bi-Directional Conductivity Measurements and Definition of Conductivity Ratios

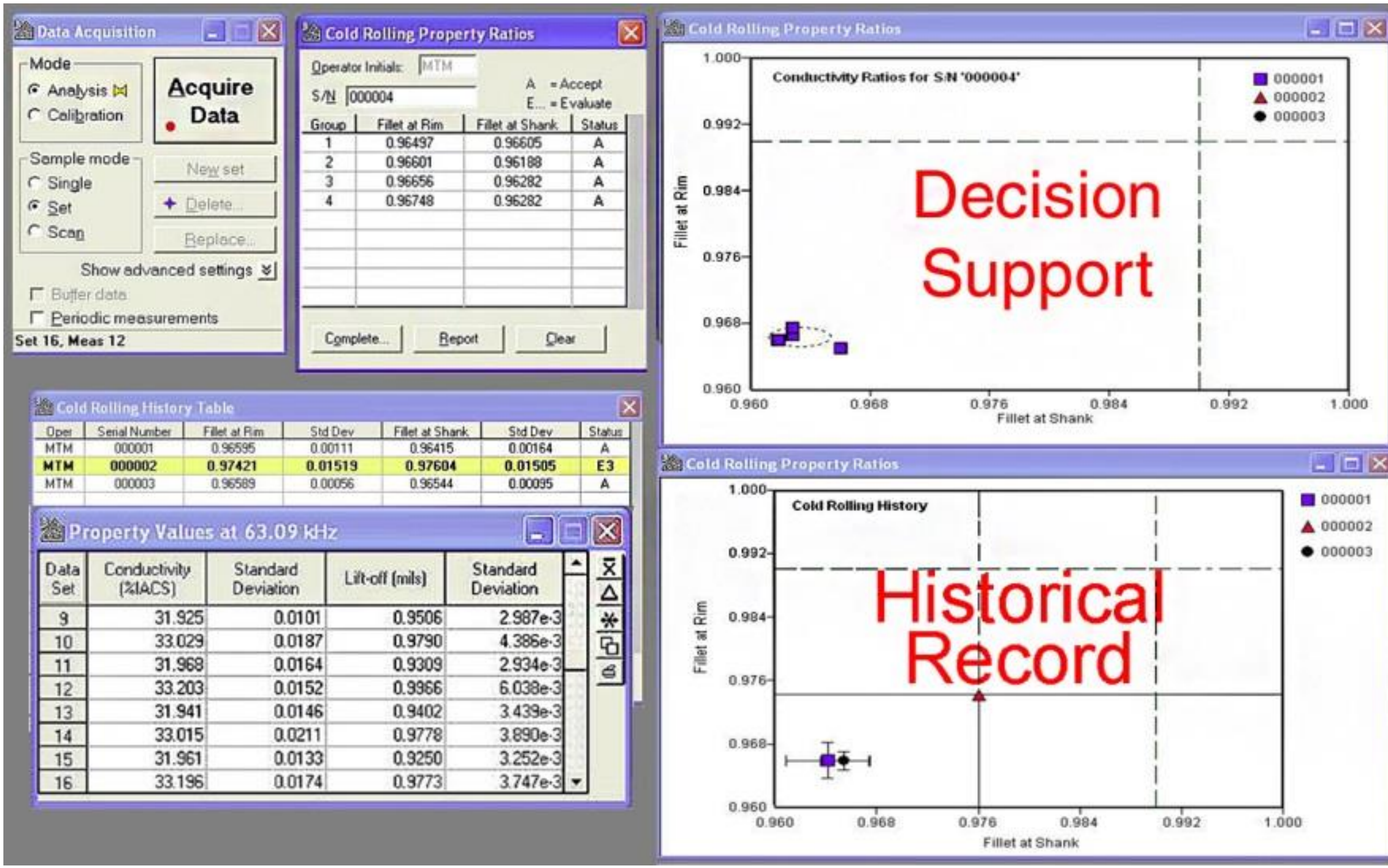
Ratio Analysis

$$\text{Fillet Ratio} = \frac{\text{Fillet Axial}}{\text{Fillet Cir.}}$$

$$\text{Shank Ratio} = \frac{\text{Shank Axial}}{\text{Shank Cir.}}$$

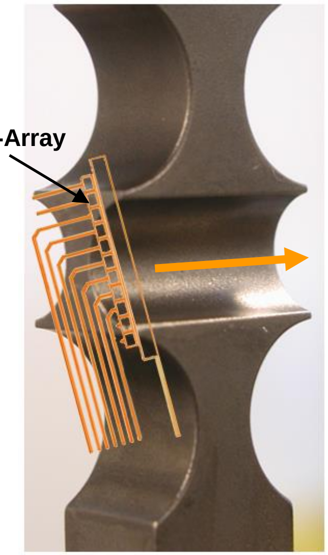


Historical Success: Typical Interface for Cold Work Quality Control

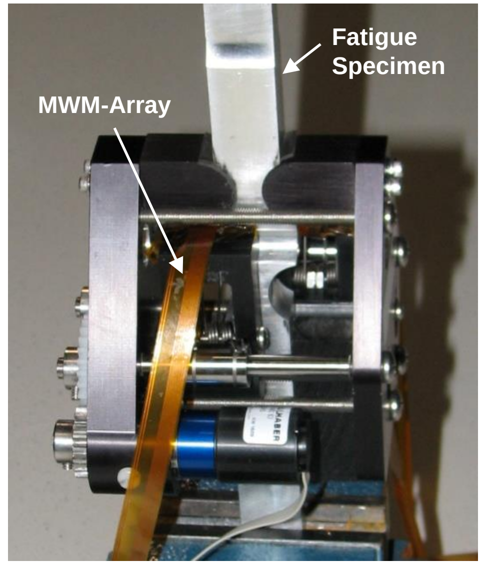


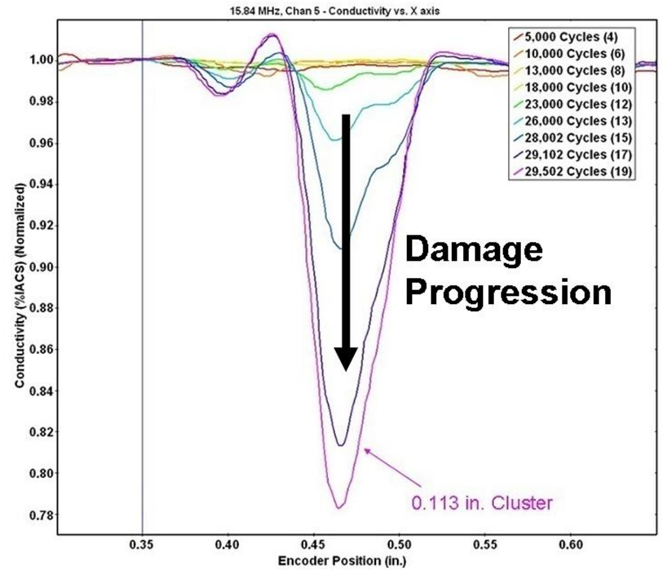
POD Real Crack Sample Fabrication using Fatigue Specimen with Continual MWM-Array Scanning

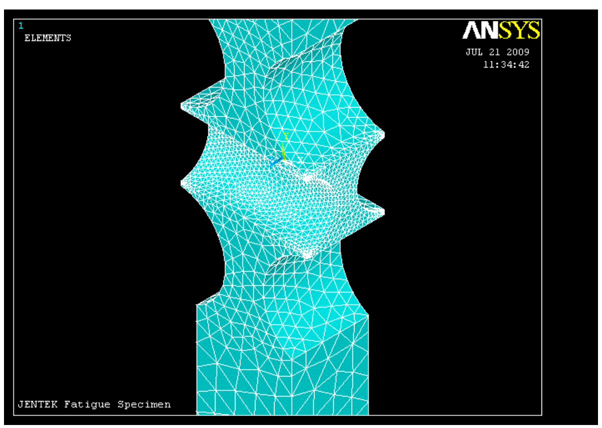
MWM-Array

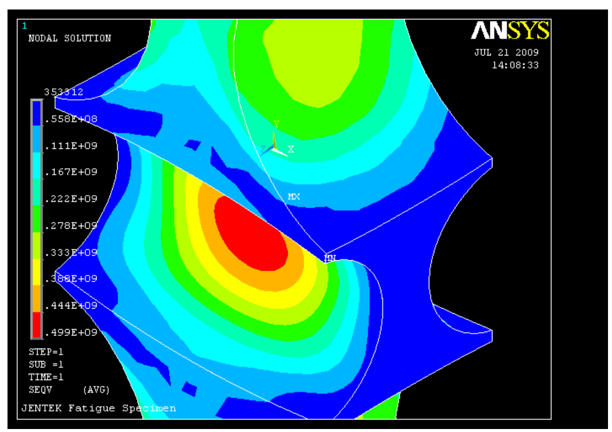


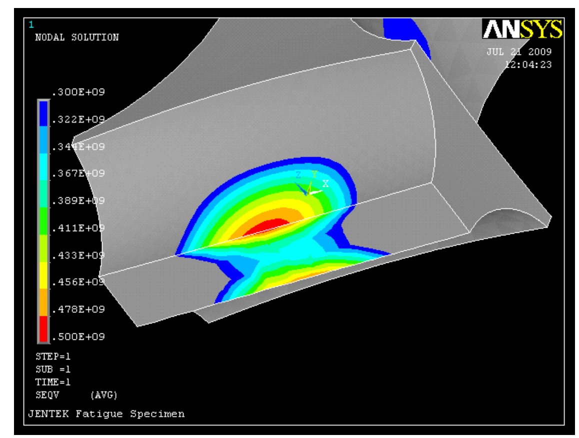
Scan Direction











What is next for Eddy Current Testing of Engines?

- More ***accessible*** ET array tech
- More ***portable*** handhelds for arrays
- More ***adaptable*** by operators
- More ***predictable*** performance
- Plus
  - Reduced false indication rates
  - Less training requirements
  - Less surface preparation
  - Reduced automation costs
  - On-aircraft inspection in difficult to access areas
  - Support for complementary installed sensors
  - Inspection through coatings
  - Reliable inspection of shot peened and otherwise cold worked surfaces
  - Improved quality assessment for coatings, cold working, additive manufactured parts for porosity, metallurgical condition. geometric feature dimensions, and cracks
  - Real crack specimens with as manufactured conditions and curvatures.

Challenges that must be met