2012 Aircraft Airworthiness & Sustainment (AA&S) Conference
Baltimore, MD, April 2-5, 2012

Composite NDT and SHM for Spacecraft and Aircraft, Using MWM-Arrays

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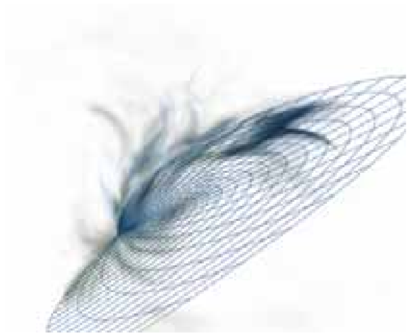
April 5, 2012



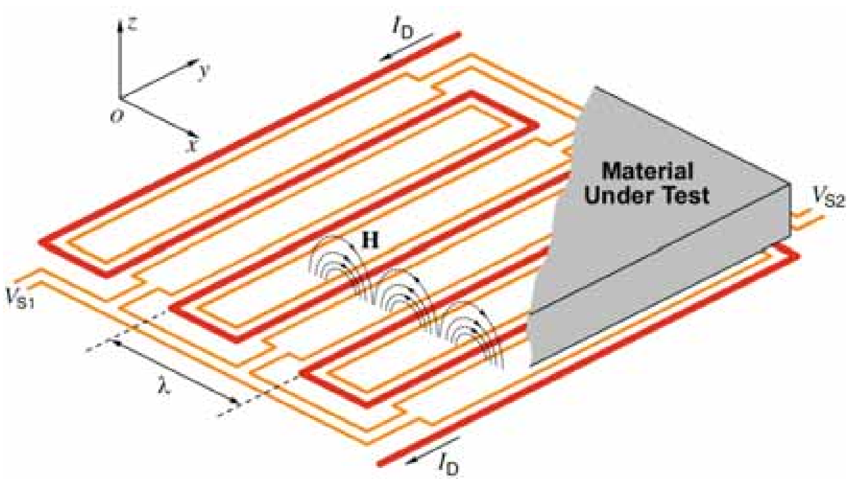
MWM sensors and MWM-Arrays covered by issued and pending patents, including, but not limited to:
8,050,883; 7,994,781; 7,876,094; 7,812,601; 7,188,532; 7,183,764; 7,161,351; 7,161,350; 7,106,055; 7,095,224; 7,049,811; 6,995,557; 6,992,482; 6,952,095; 6,798,198; 6,784,662; 6,781,387; 6,727,691; 6,657,429; 6,486,673; 6,420,876; 6,380,747; 6,377,039; 6,351,120; 6,198,279; 6,188,218; 6,144,206; 5,966,011; 5,793,206; RE39,206 E.

Goals, Technical Approach and Funding

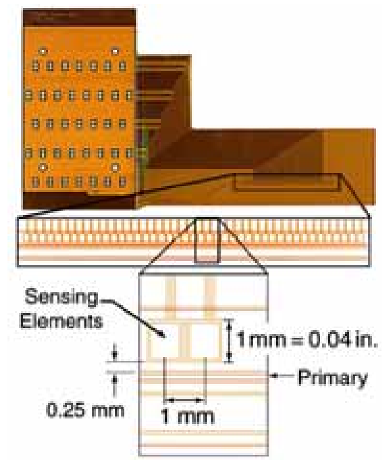
- **Goal** is to develop:
  - High resolution damage and condition imaging for carbon fiber composite NDT
  - Volumetric stress sensing magnetic stress gages for composites
- The **MWM-Array** is a linear drive eddy current sensor array construct
  - Can induce eddy currents in the linear fibers of carbon fiber composites
  - Use winding geometry changes to alter penetration depth and characterize damage
- **Detection/characterization** of impact and other damage and **monitoring of strain/stress** as a function of depth and fiber orientation is accomplished by modeling the fiber properties/orientation/density/contact. Simplified models are being used now with advanced models still under development.
- **Funding**
  - **NASA** for micromechanical model development and application to composite overwrapped pressure vessels (COPVs)
  - **Army** for rotorblade NDT
  - **Navy** for NDT of aircraft composites

Linear Drive Eddy Current Sensors

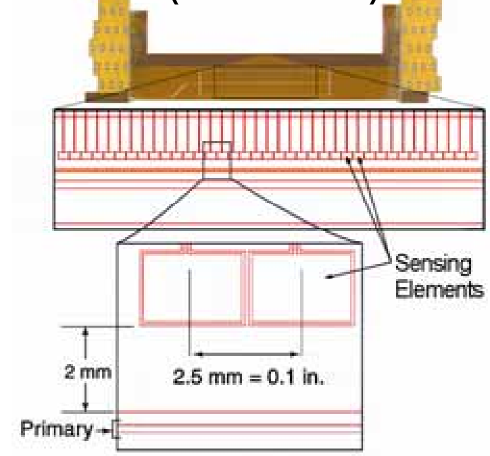
MWM® and MWM®-Arrays



FA28 MWM-Array



FA24 MWM-Array
(similar to FA26)

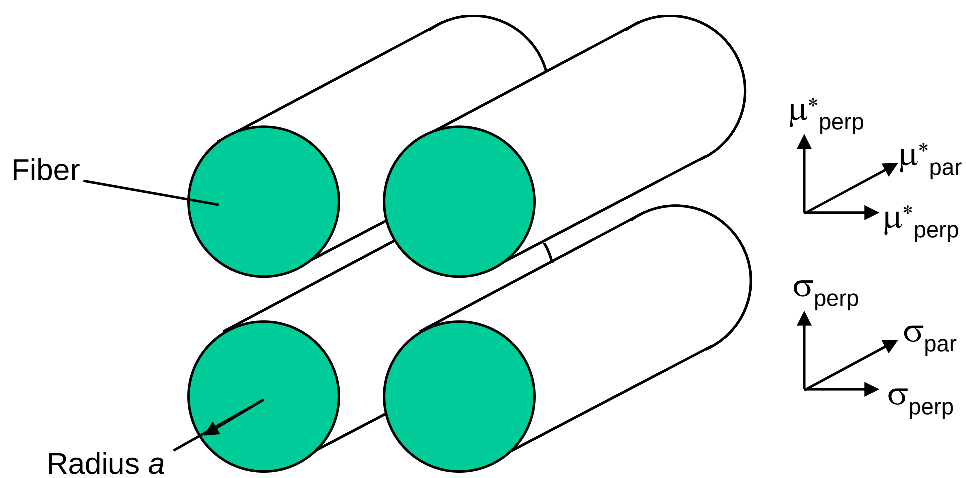


Parallel Architecture Instruments: GS-Durable and GS-HandHeld

Micromechanical Model: Eddy Current Extension
(Model under development in NASA Phase II SBIR)

- Linear drive MWM-Array sensing of composite with conducting fibers and insulating matrix
- Model uses a composite cylinder assemblage
  - Solve for field around a single fiber and extend to fiber bundle
  - Effective complex permeability and conductivity depend upon orientation with respect to fiber axis, fiber density and fiber contact
- Focus on Carbon Fiber/Epoxy composites

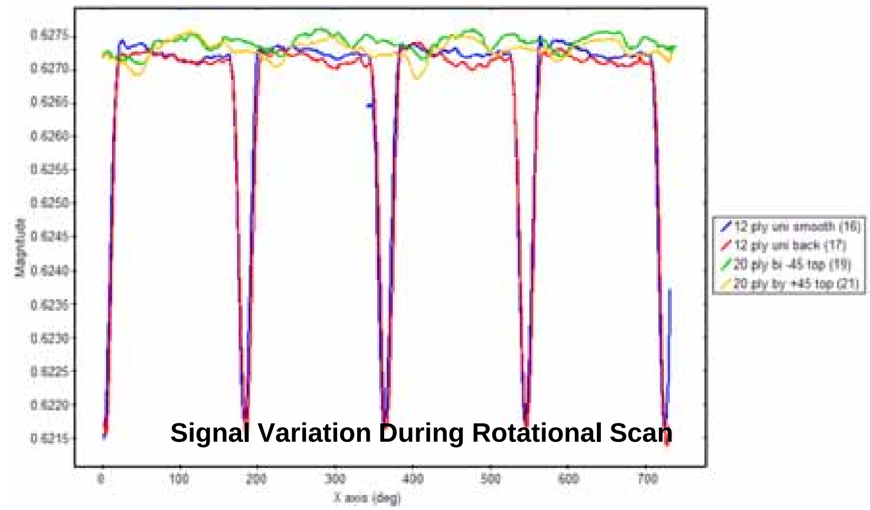
$\mu^*_{par} \approx \mu^*_{perp} \approx \mu_o$ $\sigma_{perp} \approx 0$ $\sigma_{par} \approx \sigma_f v_f$



Uniaxial/Biaxial Specimens: Orientation Varied

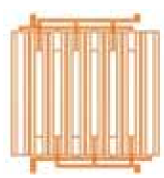
- Single element MWM sensor; 10 MHz
  - Air/shunt calibration
  - Sensor response highly directional
  - Highest response when fibers when sensor drive oriented parallel to fibers

For the uniaxial specimen, both the magnitude and phase of the sensor response are significant every 180º



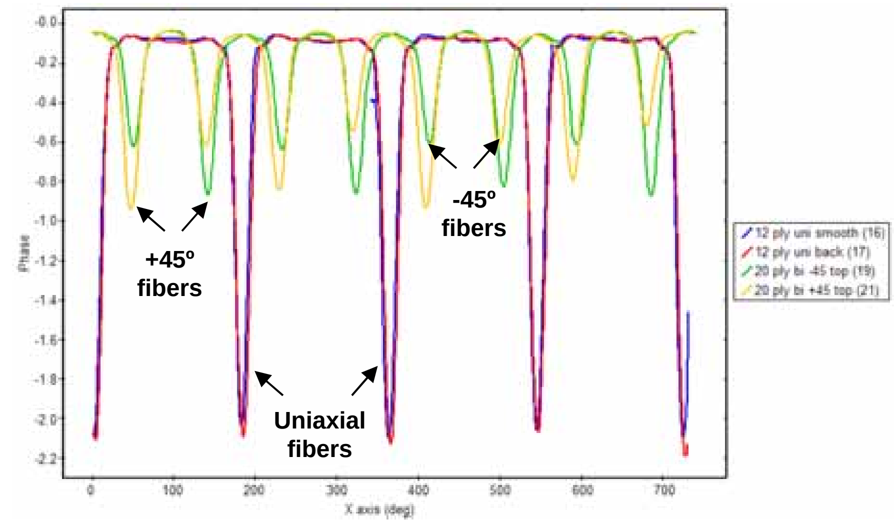
Uniaxial specimens

FS33 drive perpendicular to uniaxial fibers

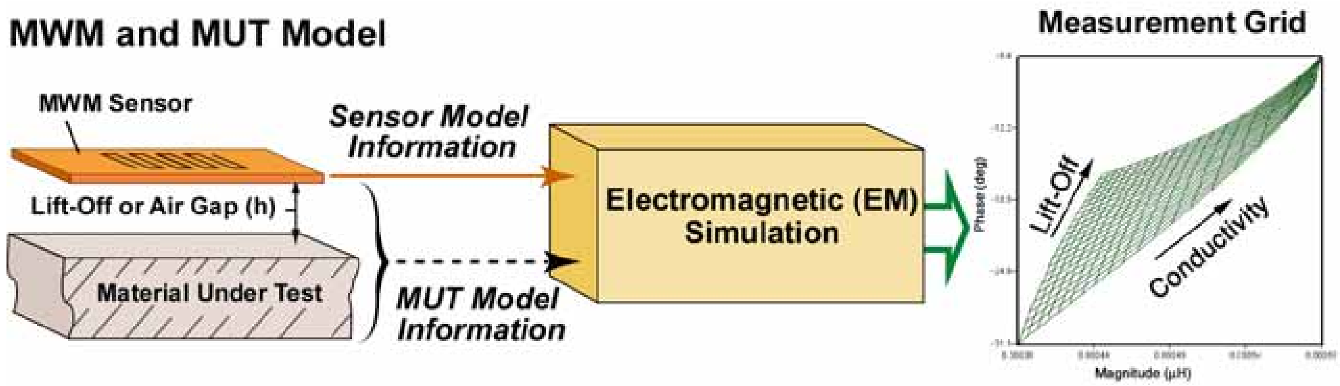


Biaxial (±45°) specimens

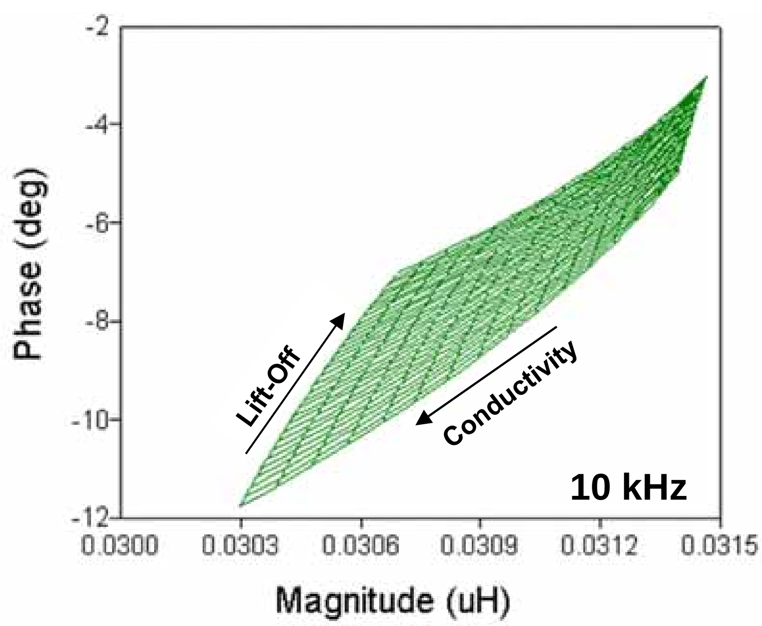
Graphite fiber epoxy composite samples provided by Boeing

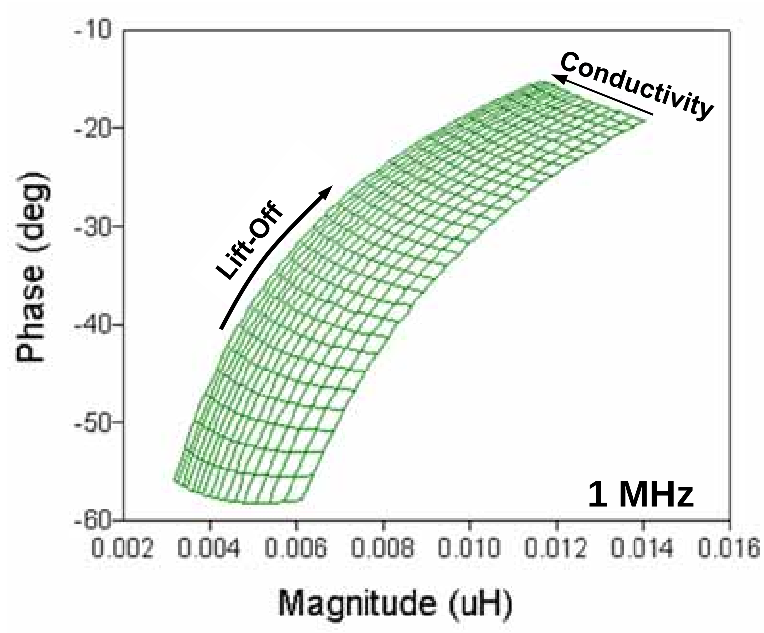


Measurement Grids for Simplified Model



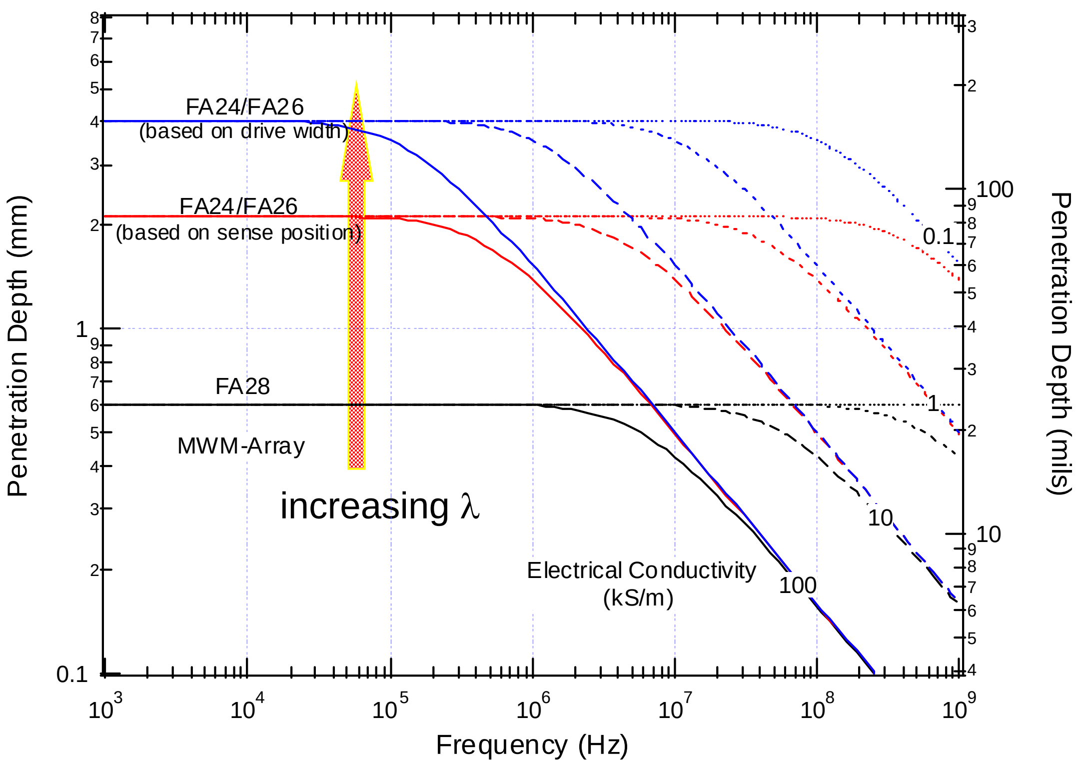
Example Grids for the MWM FS35 Sensor and Aluminum



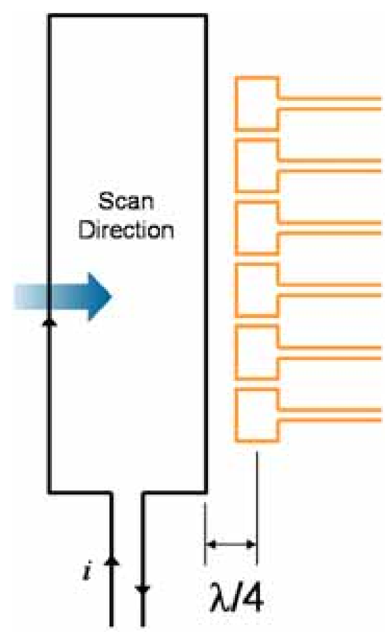


MWM Sensor Selection

- Magnetic field decays exponentially with distance away from sensor
  - Decay rate determined by skin depth at high freq. and sensor dimensions at low frequency
- High frequencies needed to induce significant eddy currents
- Large dimensions needed for thick composites

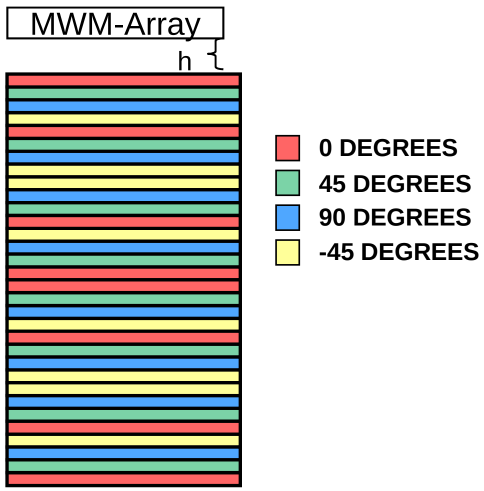


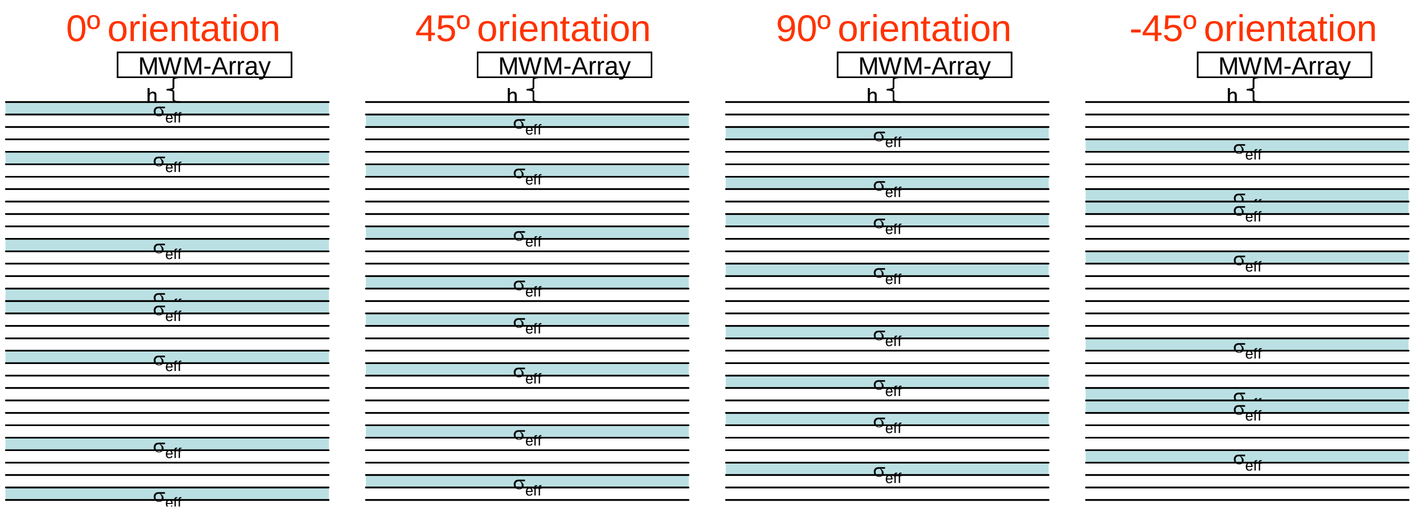
Skin depth: $\delta = \sqrt{\dfrac{1}{\pi f \mu \sigma}}$



Quasi-isotropic Composite Panel Stackup

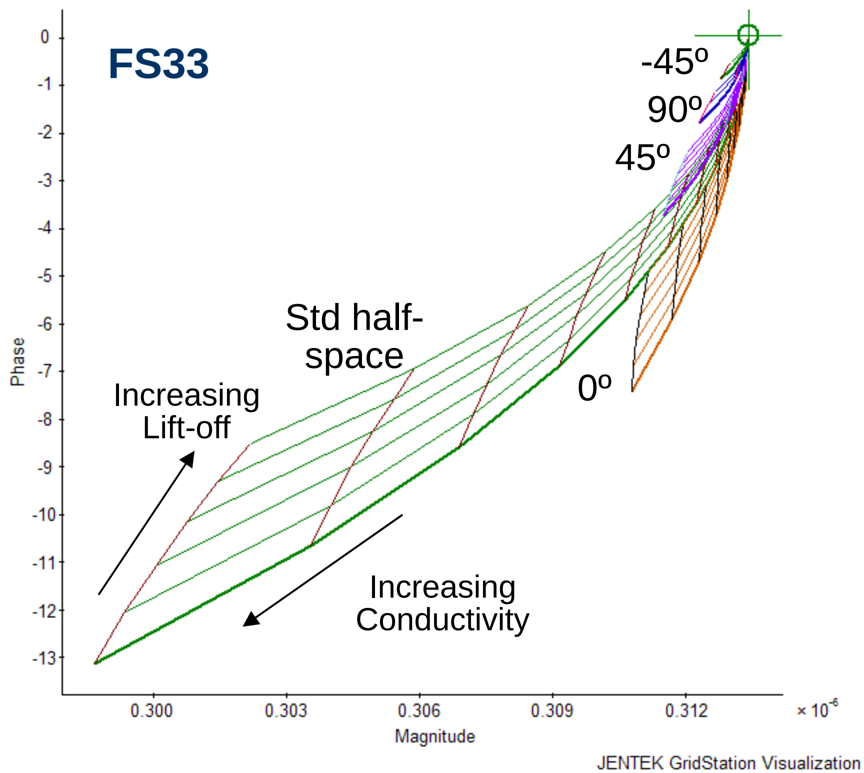
- **Stackup for bending test panel**
  - Uniaxial properties for each layer
- **MWM-Array sensitive to composite layers with fibers oriented parallel to drive windings**
- Composite layer considered insulating if fibers NOT within 5º of sensor orientation
- This visualization indicates that each sensor orientation is only sensitive to a subset of plies at varying depths within the composite.

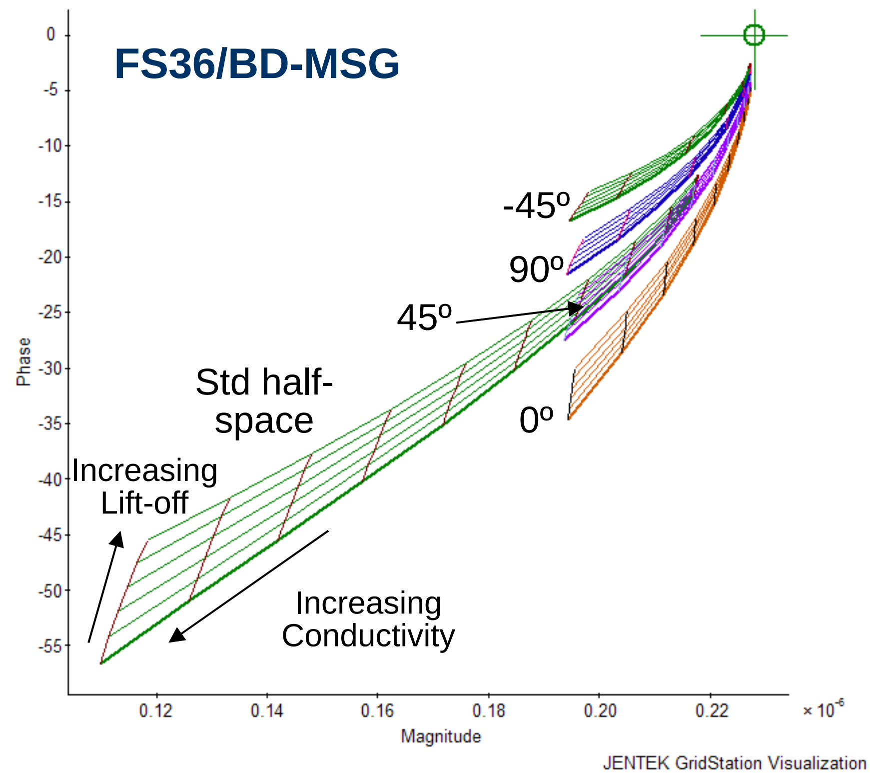




Simplified Grids for Quasi-isotropic Stackup

Grid size illustrates the effect of
fiber orientation and distance from the sensor

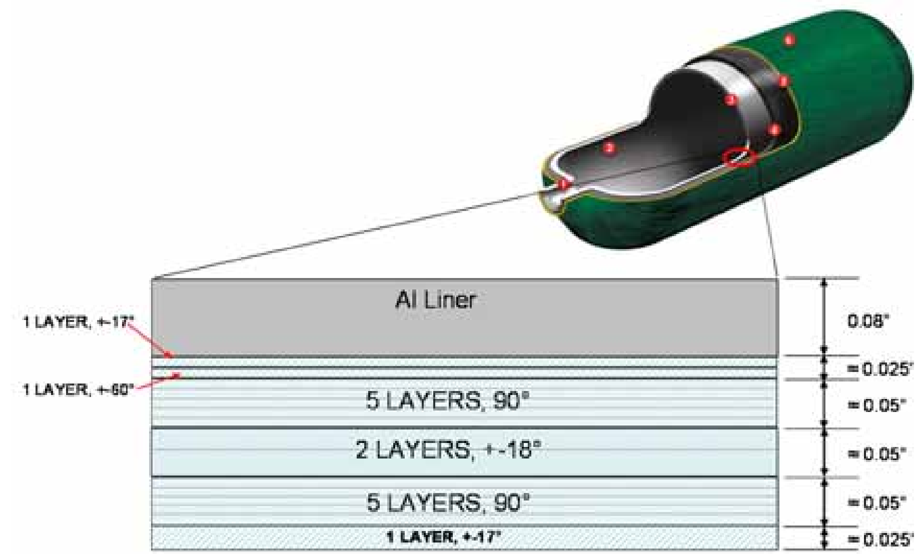


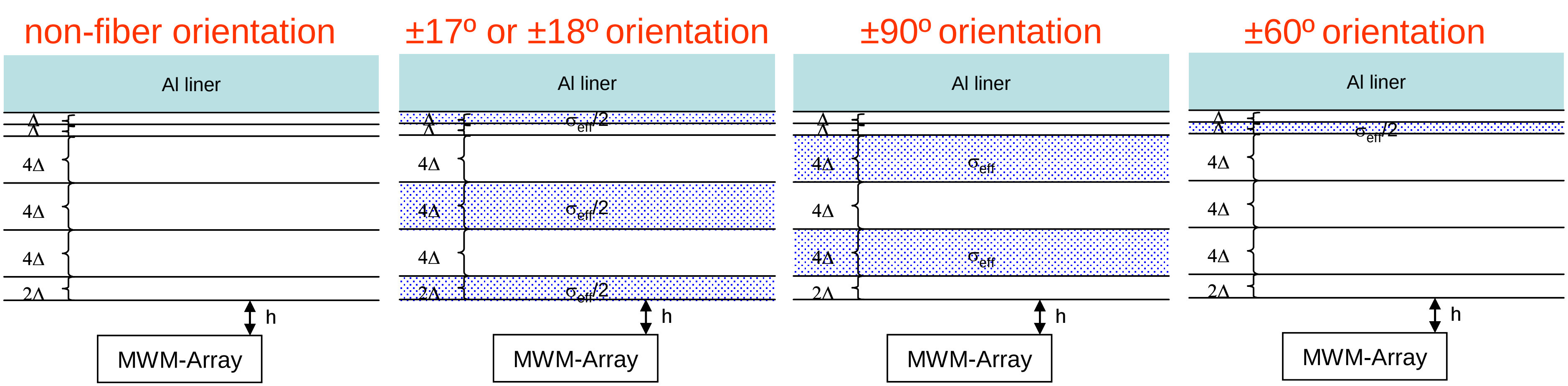


- The plots compare standard infinite half space grid to parameterized grids for each sensor orientation
- Sensitivity to a subset of plies causes a shift in effective property estimates compared to standard grids
- Smaller effective conductivities; effective lift-off can be high, lower, even negative, depending upon orientation

Example COPV Stackup

- Stackup for COPV and COPV ring specimen
- MWM-Array sensitive to composite layers with fibers oriented parallel to drive windings
- This indicates that the sensor orientation is important for assessing the fiber properties.

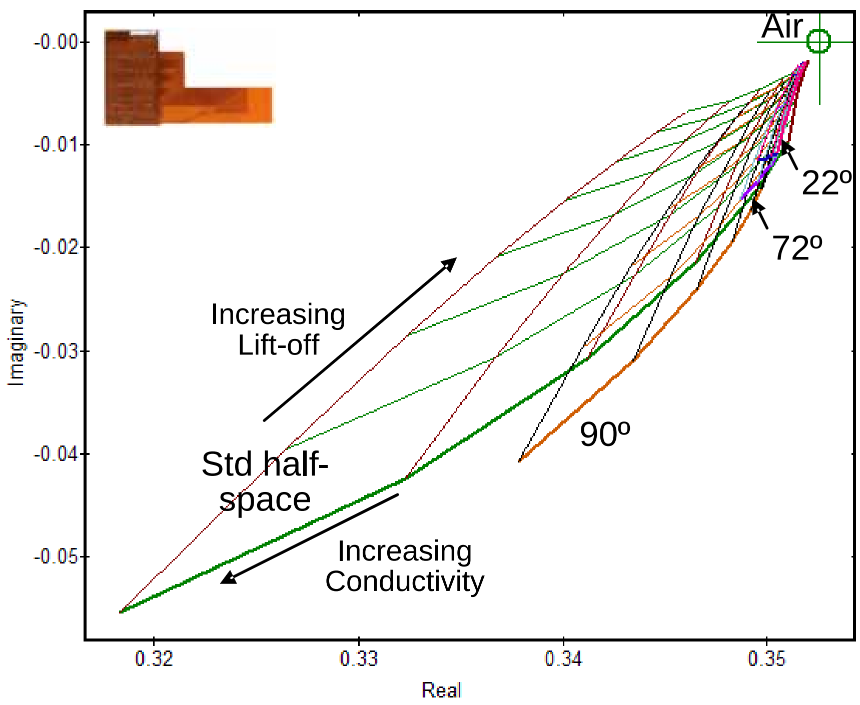




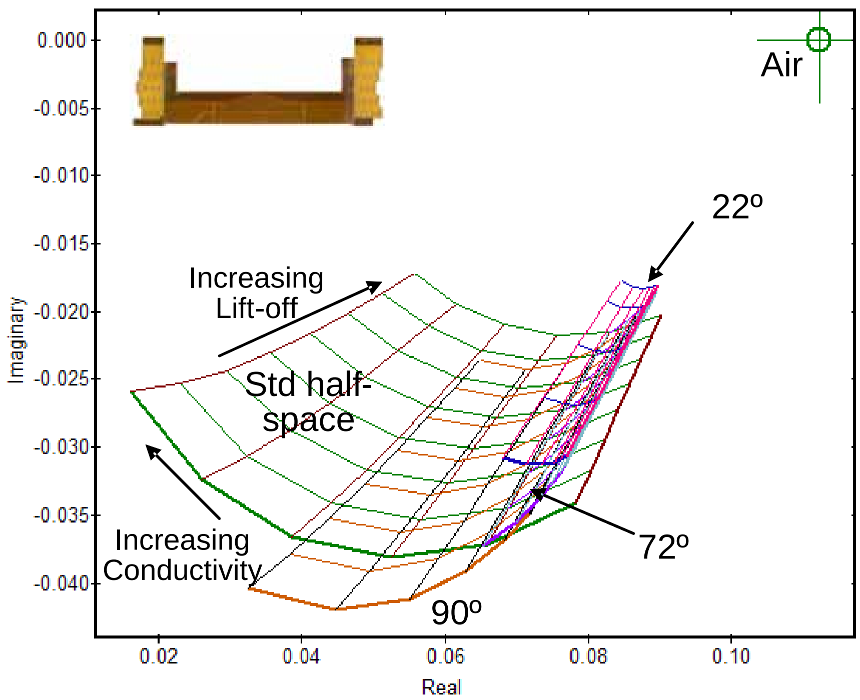
JENTEK Grids for MWM-Array on COPV Samples

- Representative grids for a composite overwrapped pressure vessel (COPV)
- Models account for layered geometry and orientation effects on properties within each layer

FA28

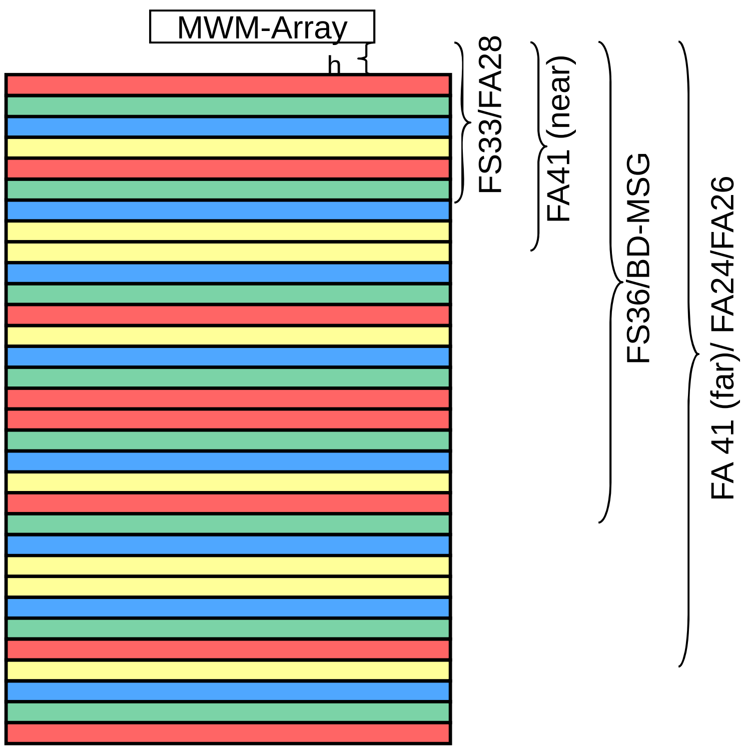


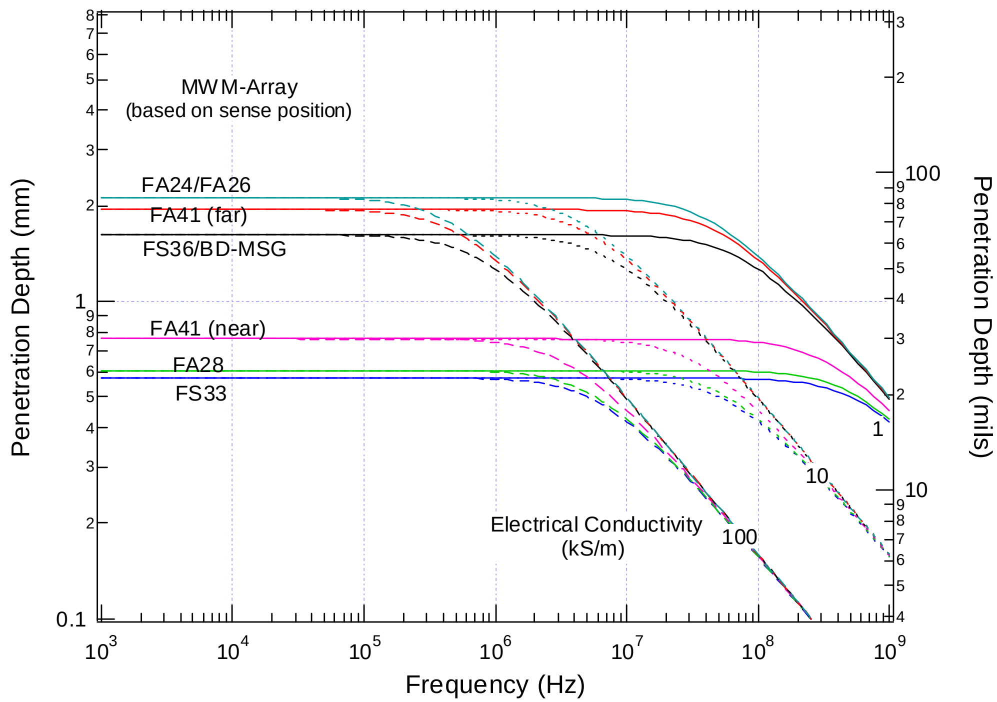
FA24



Segmented Field Magnetometry

- Different sensor geometries provide different penetration depths
- **Segmented field sensors** such as FA41 can provide two depths in a single scan
- Depth of sensitivity variation needed to characterize damage variation with depth
- ***Frequency variation alone is not sufficient***

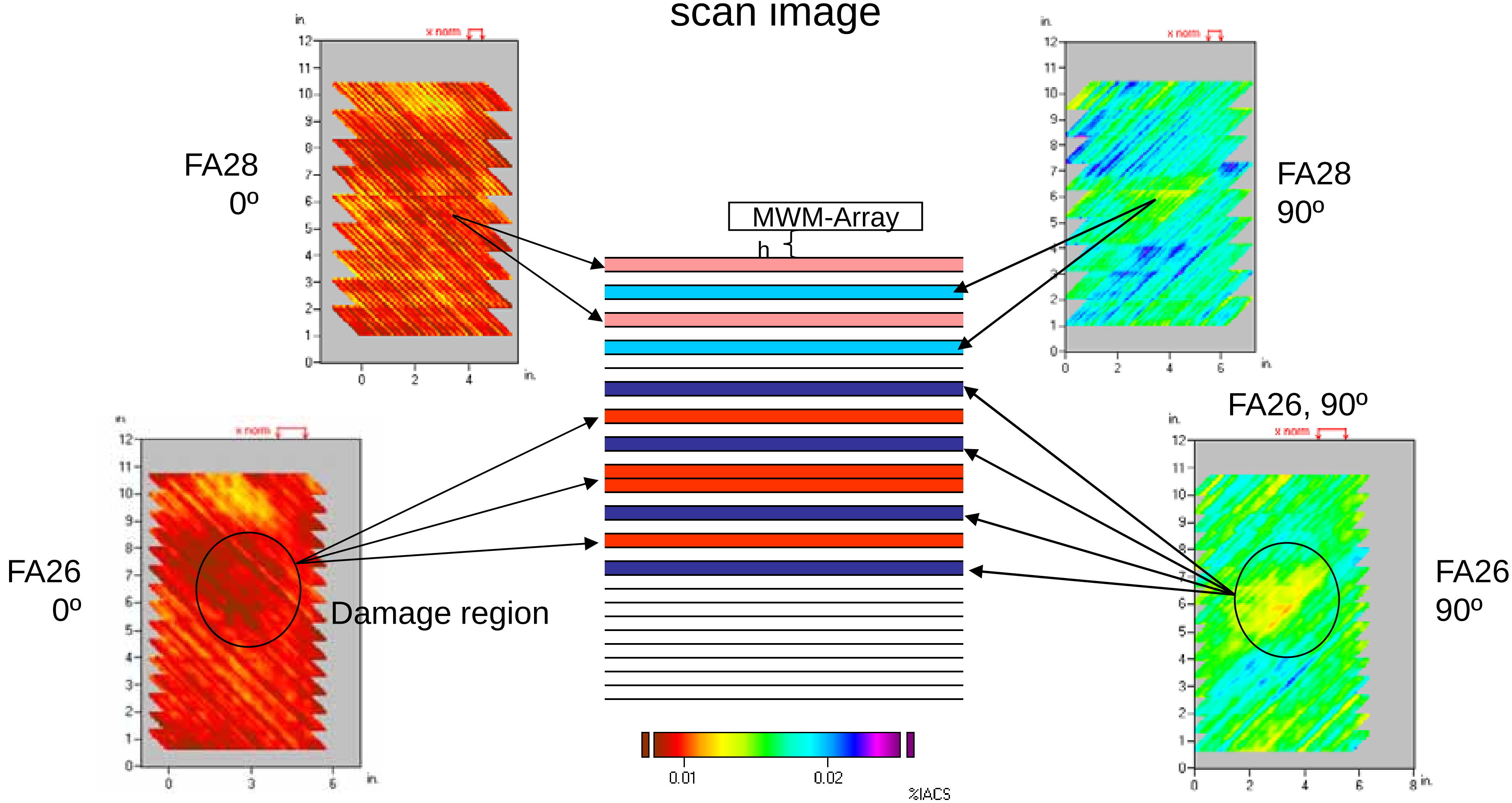




Skin depth: $\delta = \sqrt{\dfrac{1}{\pi f \mu \sigma}}$

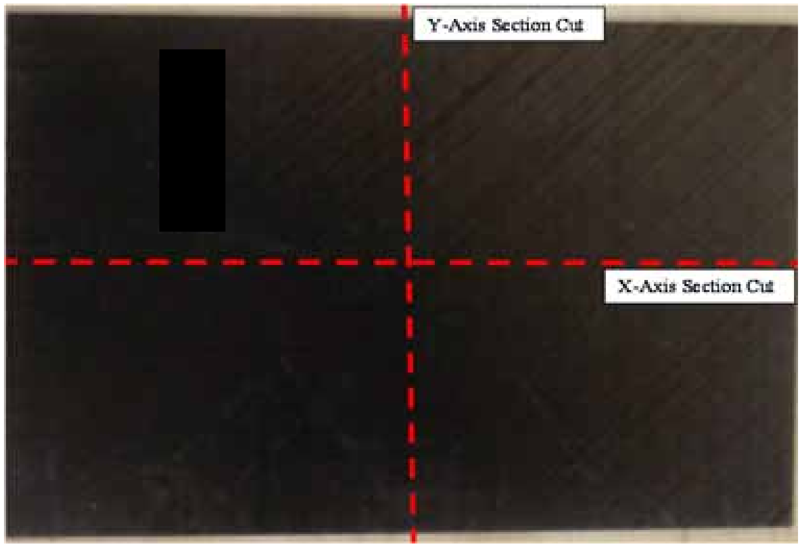
Approach to Volumetric Imaging

Combination of sensor orientation and geometry can help isolate depth and region of damage: (i) sensor orientation determines plies, (ii) sensor geometry determines depth of sensitivity, (iii) spatial extent of damage determined from scan image

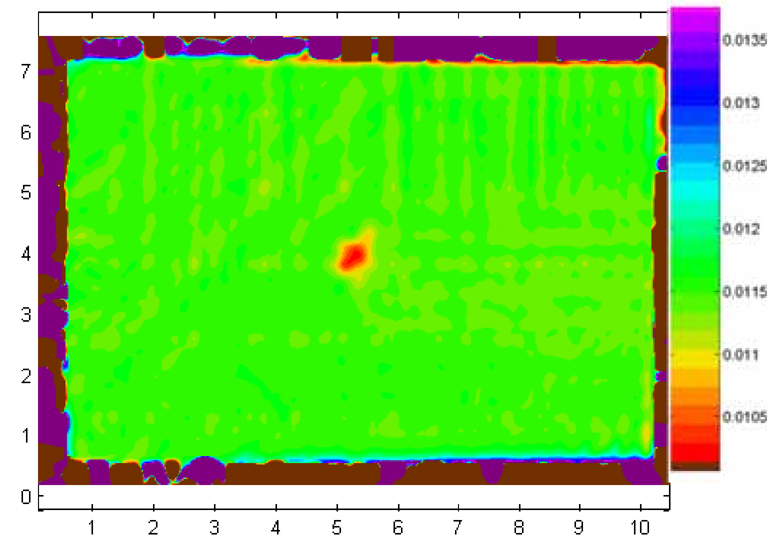


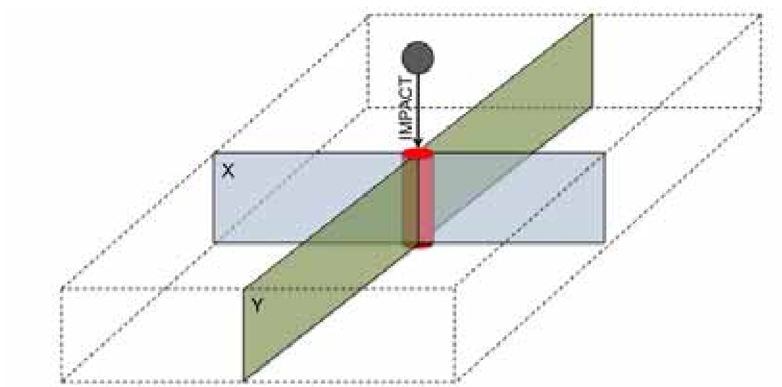
Volumetric Imaging of Composite Impact Damage

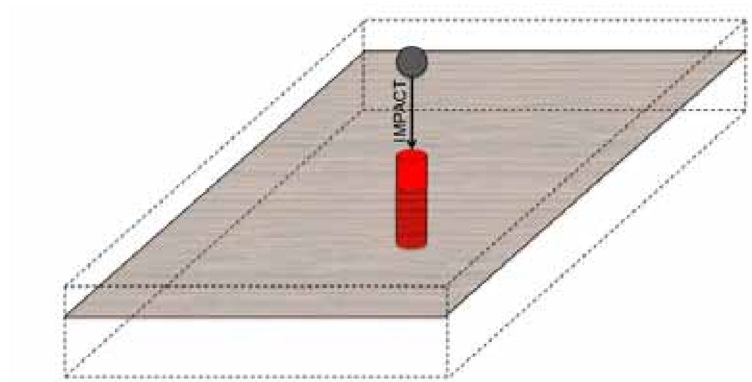
Sample provided courtesy of Lockheed Martin



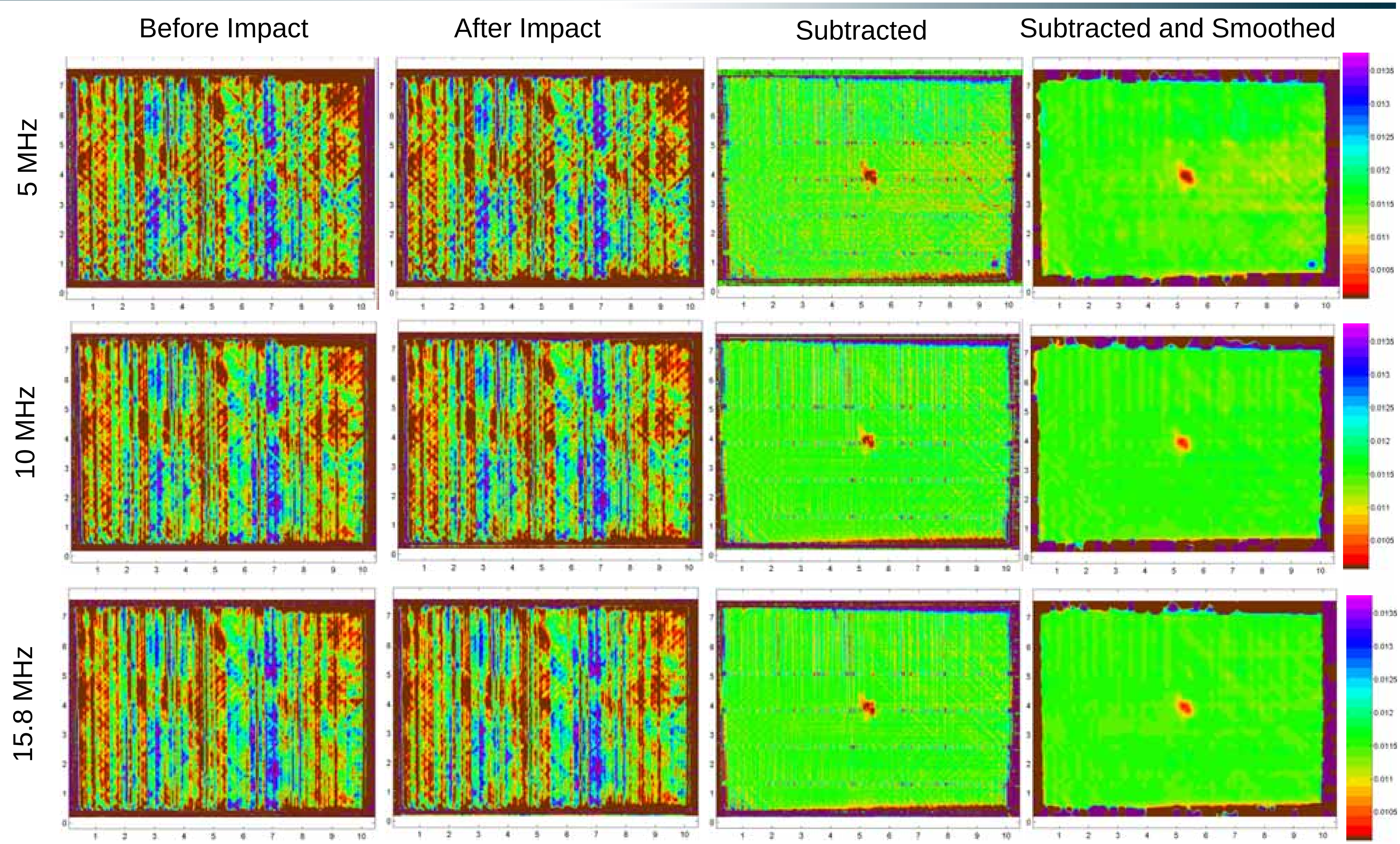
Representative MWM-Array Scan Image





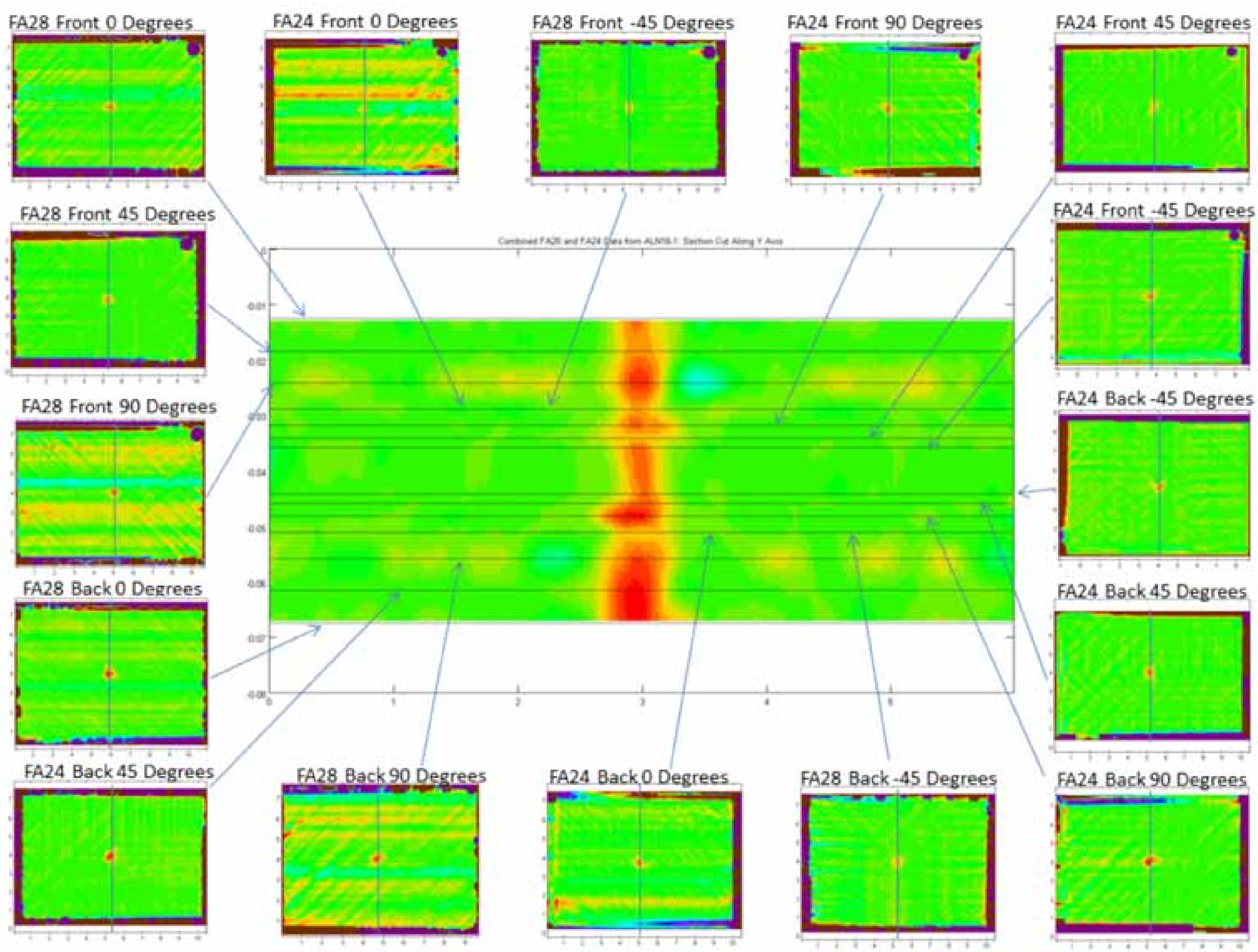


Representative Quasi-isotropic Panel Scan Images



Summary Image

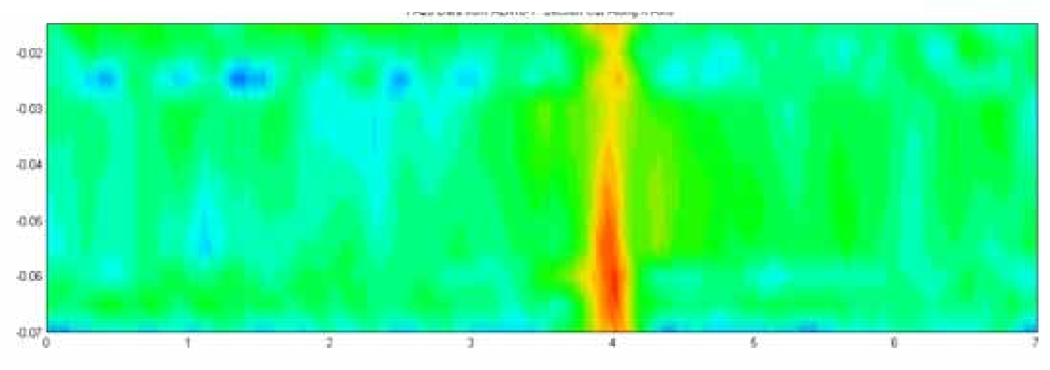
Individual scans combined together to create composite cross-sectional view



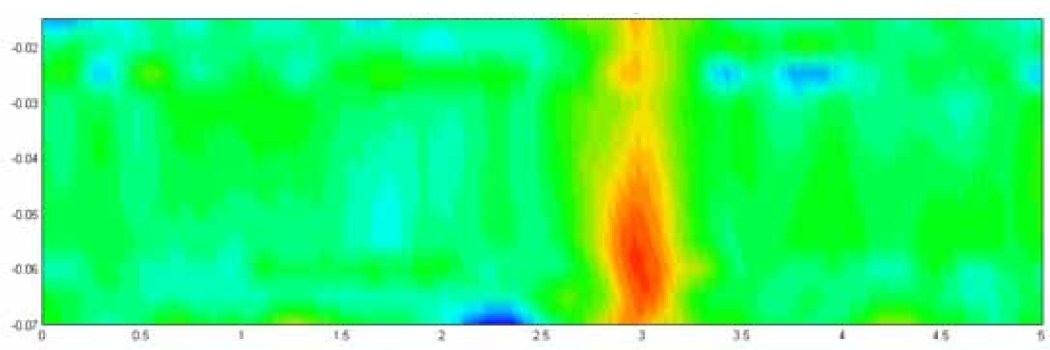
Cross Sectional Images: Panel 1, Low Impact Level

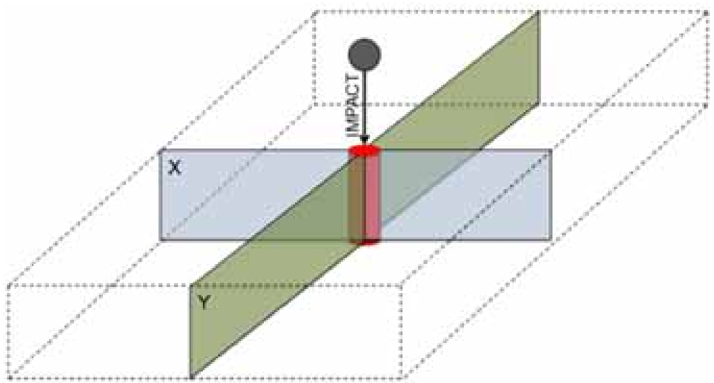
MWM-Array FA28 Data

Cross Sectional View along X-axis



Cross Sectional View along Y-axis

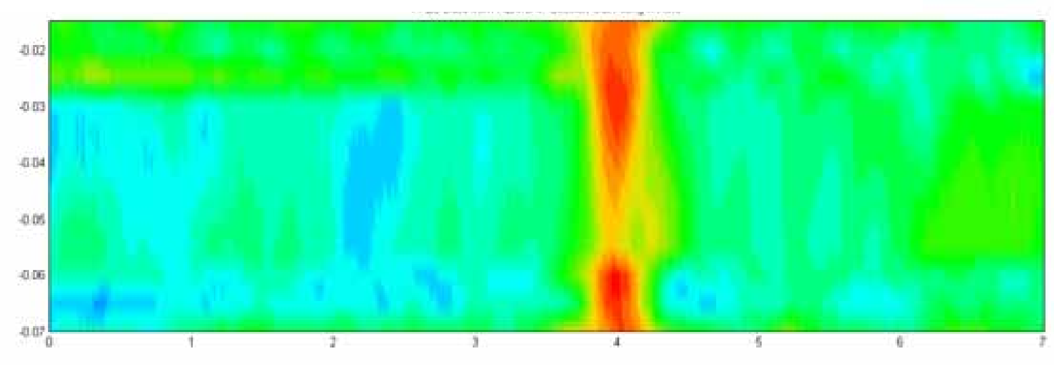




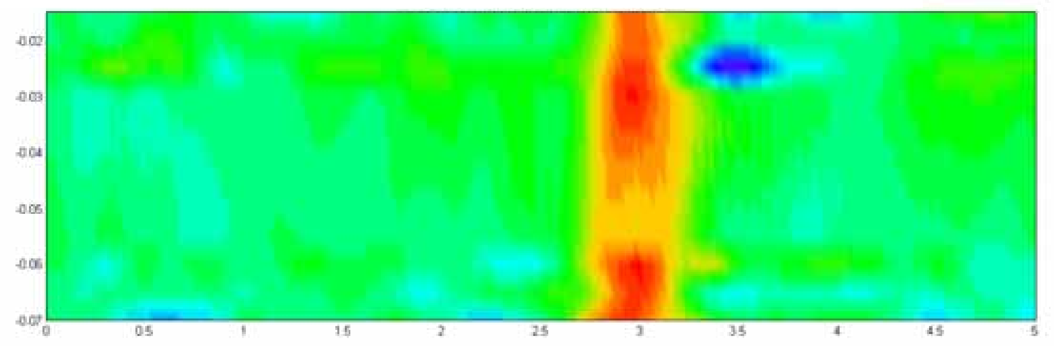
Cross Sectional Images: Panel 2, Medium Impact Level

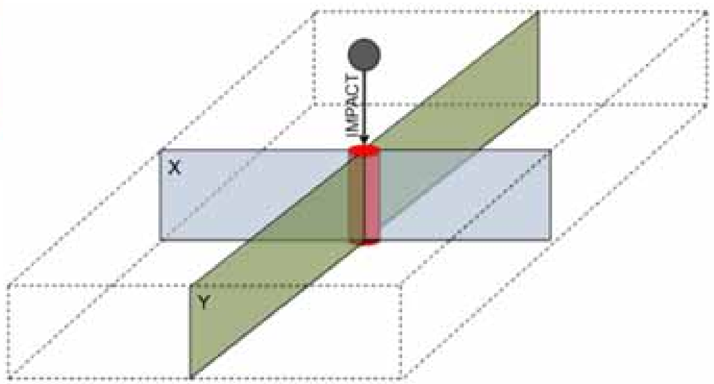
MWM-Array FA28 Data

Cross Sectional View along X-axis



Cross Sectional View along Y-axis

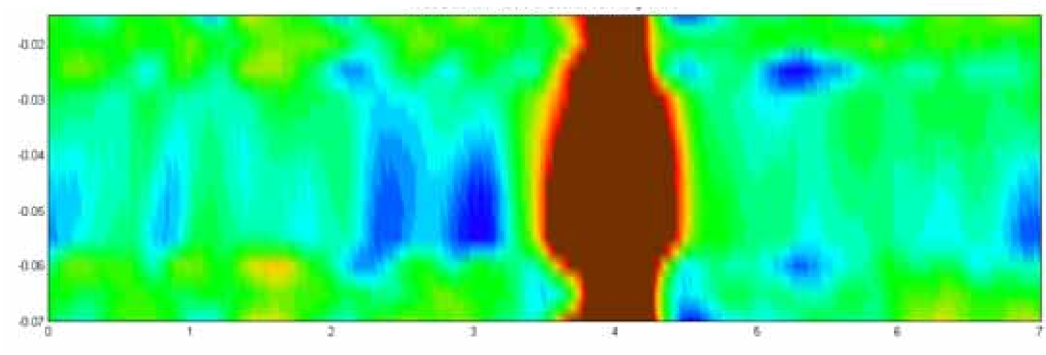




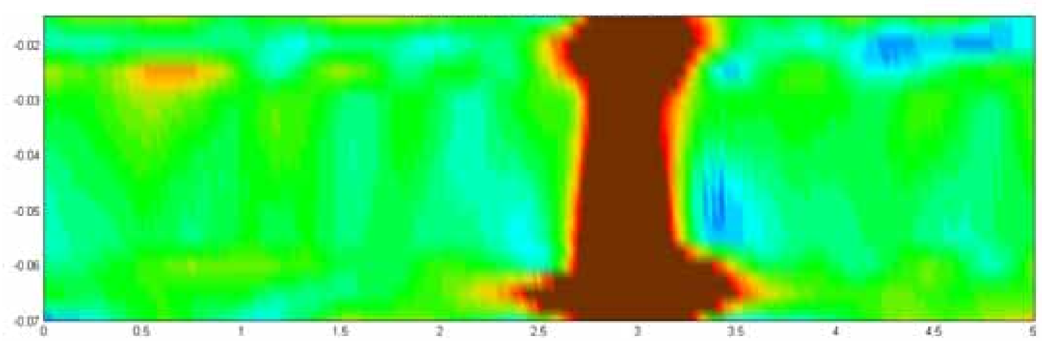
Cross Sectional Images: Panel 3, High Impact Level

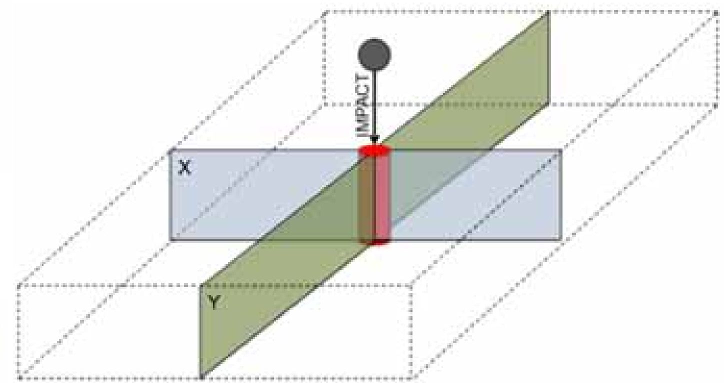
MWM-Array FA28 Data

Cross Sectional View along X-axis

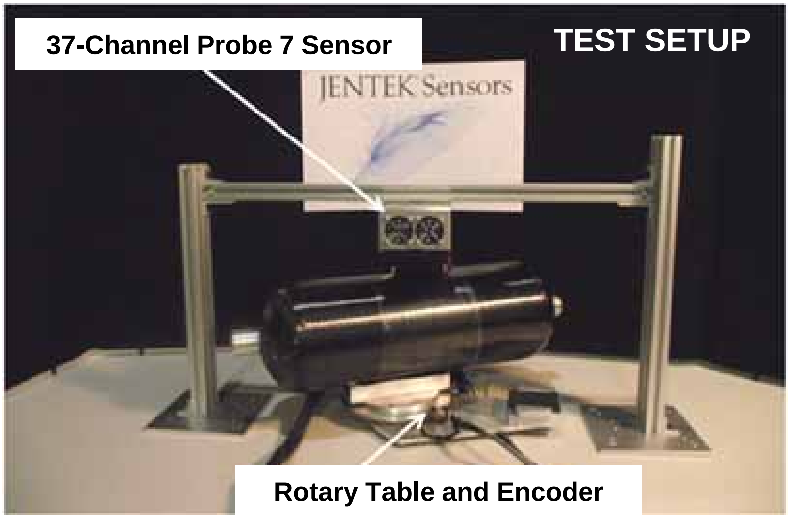


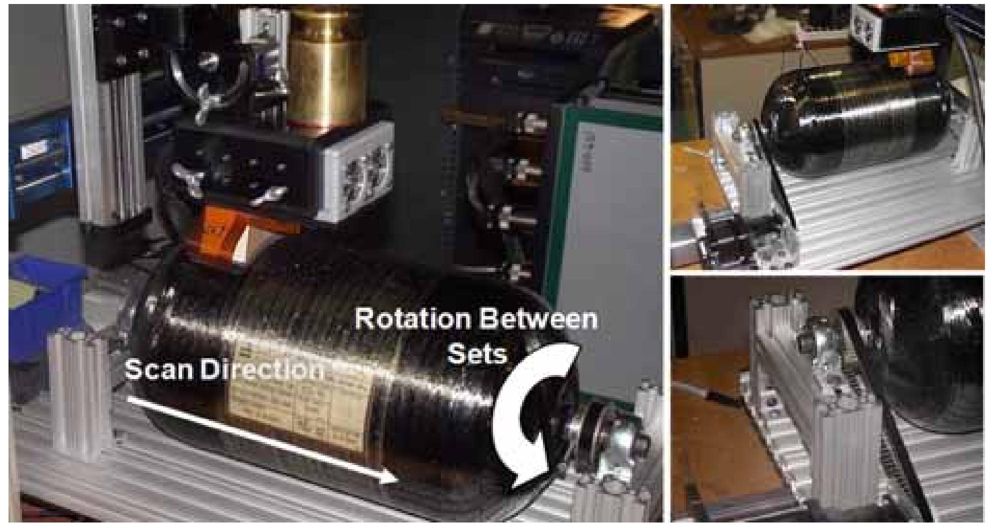
Cross Sectional View along Y-axis





COPV Testing





See complimentary presentation:

"Continued Development of Meandering Winding Magnetometer (MWM®) Eddy Current Sensors for the Health Monitoring, Modeling and Damage Detection of Composite Materials"

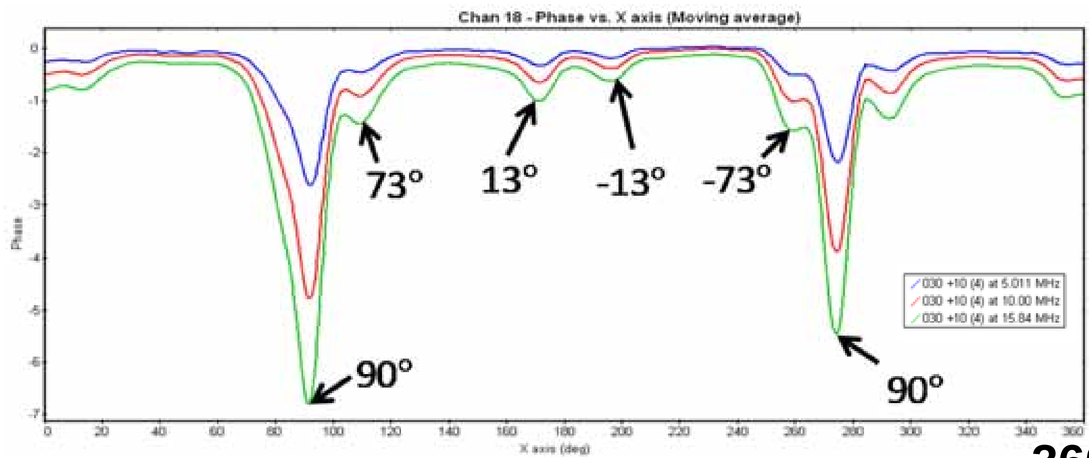
Session:
IVHM - Structural Health Monitoring for Damage Detection
Presentation time:
Thursday, April 05, 2012
2:30 PM

Rotation Scan of Vessels AC-5250 S/N:030

Shallow

λ/4 = 37 mils

FA28 MWM-Array Scan



0° **360°**

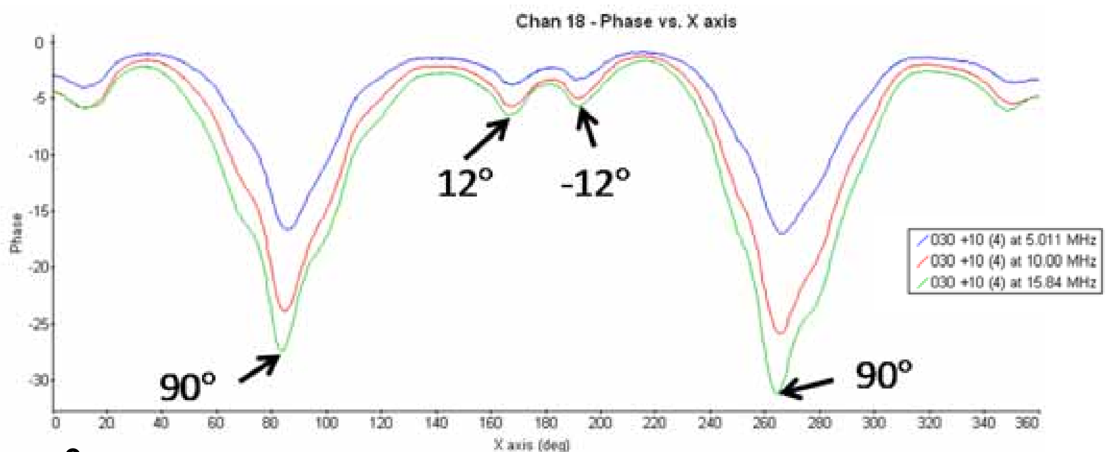
Manufacturer Fiber Layup

Fiber orientation	Material
±9.5°	Carbon fiber composite
±9.5°	Carbon fiber composite
±72°	Carbon fiber composite
90°	Carbon fiber composite
90°	Carbon fiber composite
90°	Glass fiber composite

FA24 MWM-Array Scan

Deeper

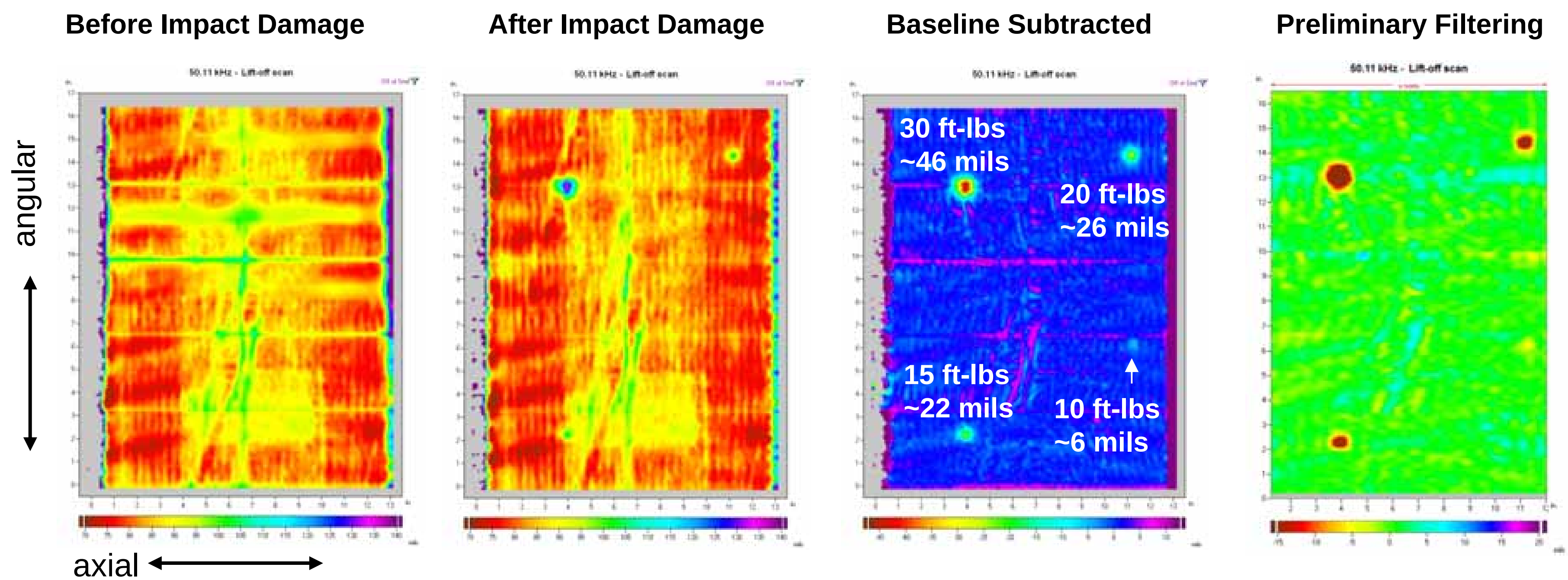
λ/4 = 130 mils



0° **360°**

MWM-Array Low Freq. Lift-Off Scans on COPV

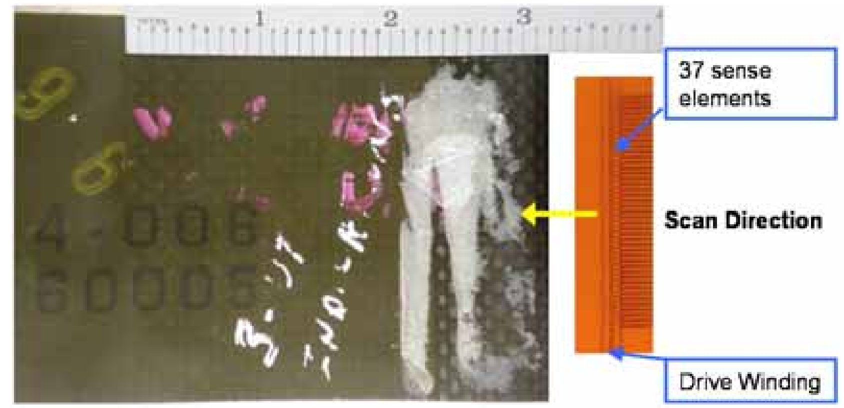
Lift-Off image shows liner damage; freq. 50.11 kHz

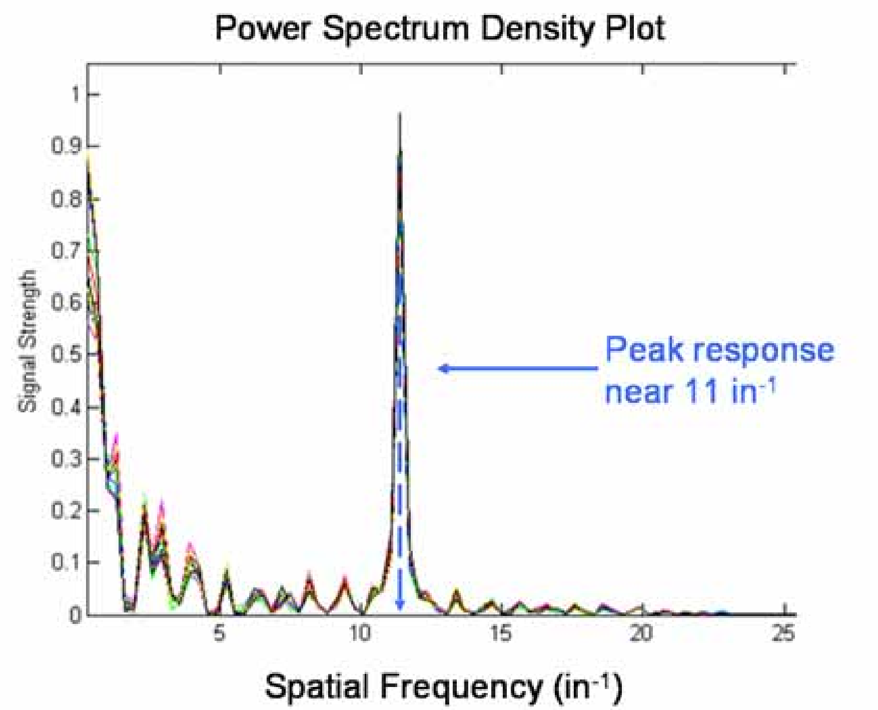


- Sample AC5250-030; 90° Sensor drive orientation
- Higher impact energy results in larger dents in the aluminum liner
- Sensor: MWM-Array FA24

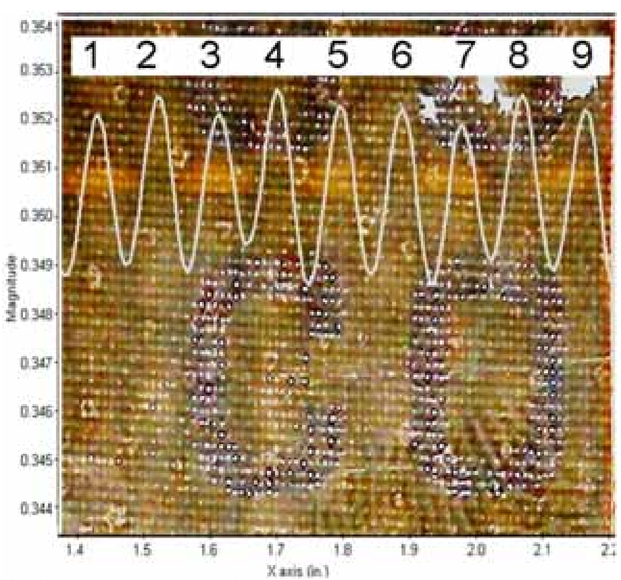
Periodic Response to Woven Plies

- FA28 scanned over a Gr/Ep composite with a coarse woven fabric ply near the surface
- The spatially periodic sensor response is consistent with the woven fabric tow width
  - Distance between peaks ~0.09-in.
  - This corresponds to 11 oscillations/in.
- Power spectrum density plot indicates strong spatial frequency near 11/in.





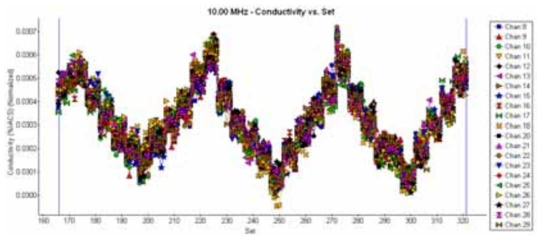
Magnitude of 1 channel with photograph of specimen

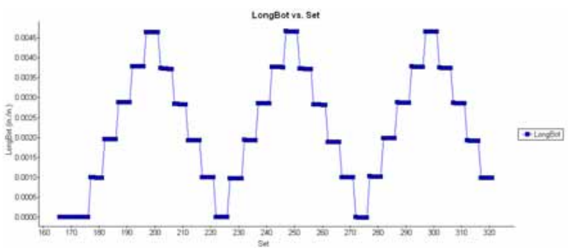


MWM Response to Stress in 4pt Bending

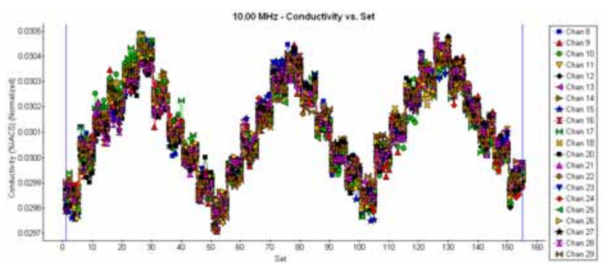
Unidirectional Carbon Fiber Composite

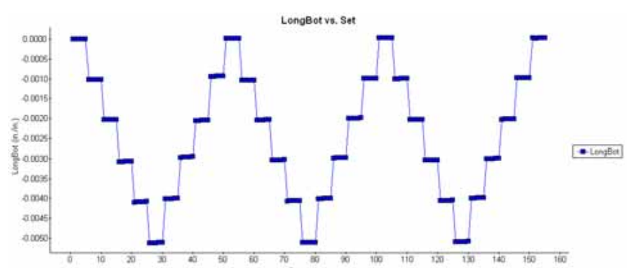
FA28 Tension

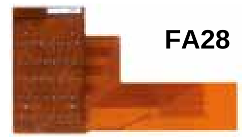




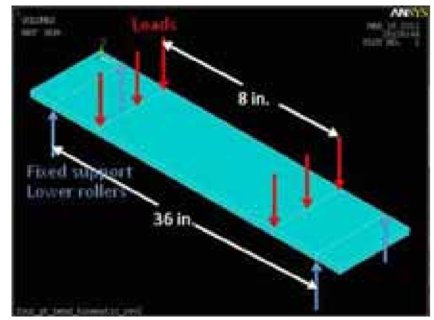
FA28 Compression

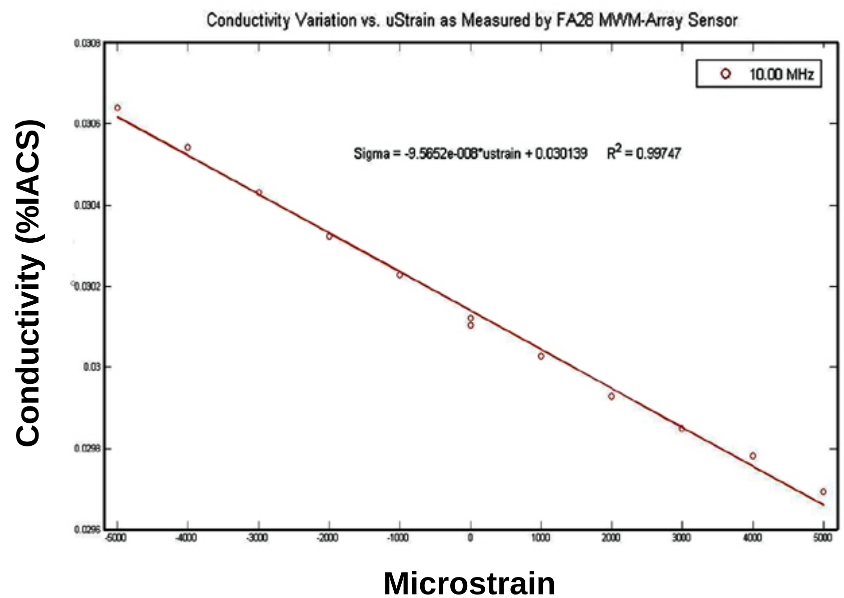






FA28

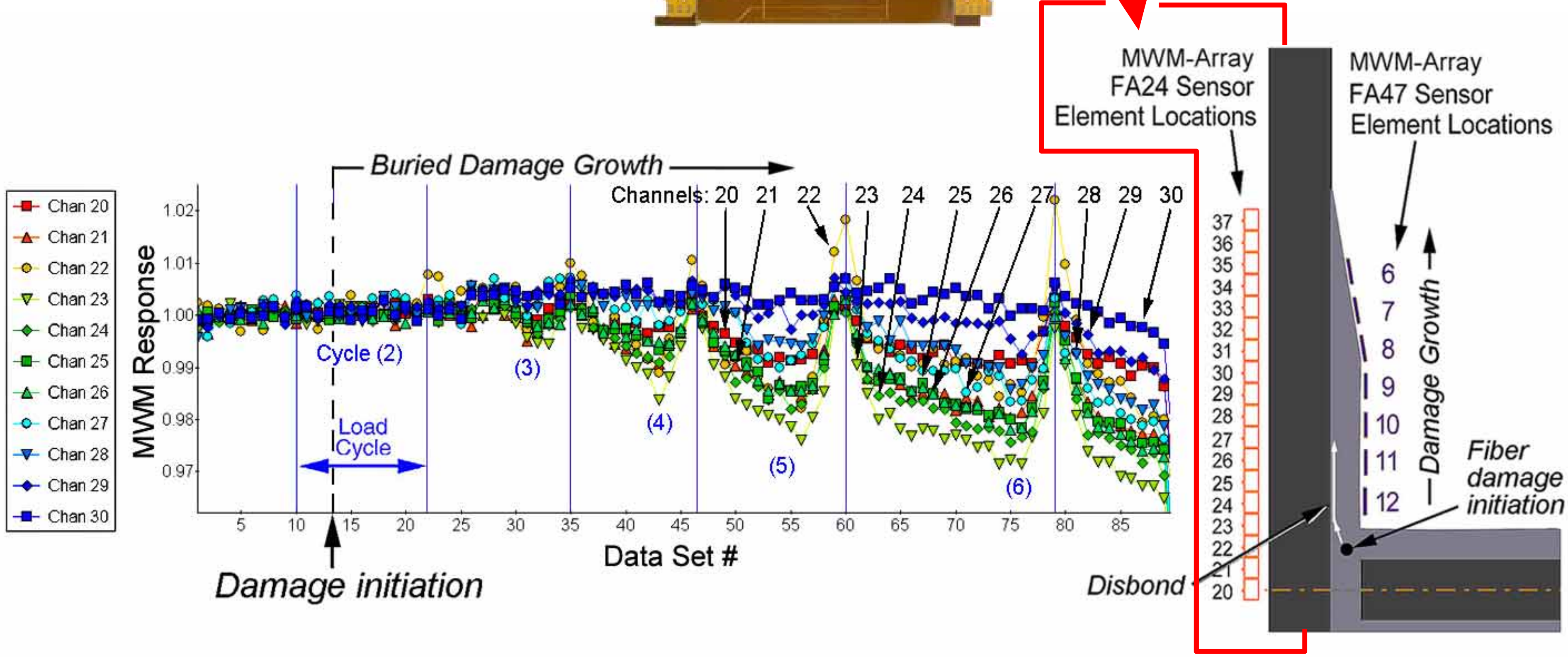




As presented at NASA Sensors Tech Forum Boston, MA; October 10-12, 2011

Surface-Mounted Sensor Damage Monitoring

MWM-Array FA24



Tests run under NAVAIR SBIR at
Lockheed Martin Aeronautics, Ft. Worth, TX

Review: Goals, Technical Approach and Funding

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  - **Army** for rotorblade NDT
  - **Navy** for NDT of aircraft composites

Questions?

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Website: www.jenteksensors.com