Materials / Damage State Characterization for the Digital Twin

Eric Lindgren

Materials State Awareness Branch

Materials and Manufacturing Directorate

October 10-12, 2023

Acknowledgments – Critical Contributors

Computational Tools: John Aldrin

KBR-Wyle: Eric Shell, Erin Oneida

Victor Technologies: Harold Sabbagh, Elias Sabbagh

Texas Research Institute – Austin: David Forsyth, Doyle Motes

University of Dayton Research Institute: Alisha Hutson

University of Utah: Tushar Gautam, Mike Kirby, Jacob Hochhalter, Shendian She

Air Force Research Laboratory: Michael Uchic

Outline

- Motivation / Impact
- History
- Challenge
- Technical Approach
- Case Studies
  - Examples
  - Considerations
- Way Forward
- Summary

Photograph by author

Definitions / Motivation

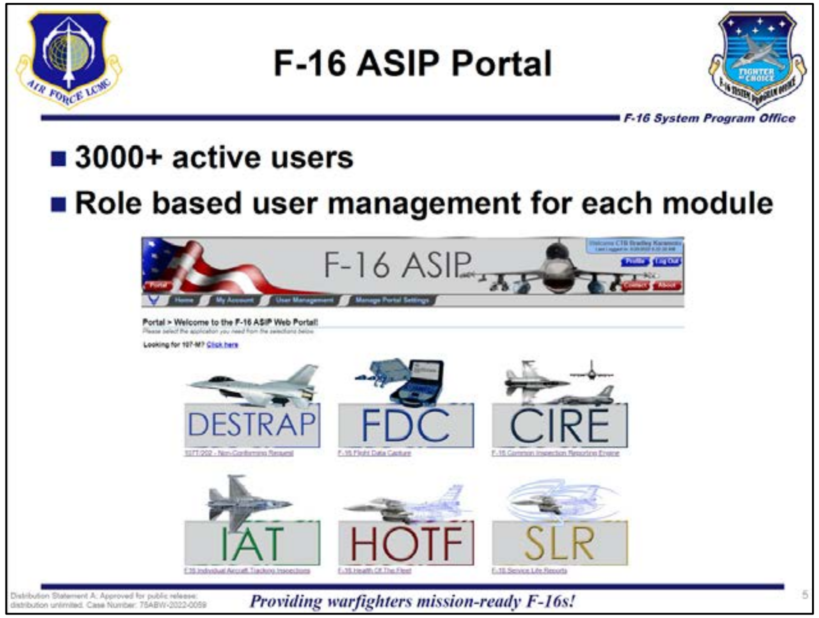
- **Digital Engineering**
  - **An integrated digital approach that uses authoritative sources of systems' data and models as a continuum across disciplines to support lifecycle activities <u>from concept through disposal</u>**
- **Digital Thread**
  - **An extensible, configurable and component enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative technical data, software, information, and knowledge in the enterprise data-information-knowledge systems, based on the Digital System Model template, to inform decision makers throughout a system's life cycle by providing the capability to access, integrate and transform disparate data into actionable information**
- **Digital Twin**
  - **A virtual replica of a physical entity that is synchronized across time. Digital twins exist to replicate configuration, performance, or history of a system. Two primary sub-categories of digital twin are *digital instance* and *digital prototype*.**
  - ***Digital Instance* is a virtual replica of the physical configuration of an existing entity. The digital instance typically exists to replicate each individual configuration of a product as-built or as-maintained**
  - ***Digital Prototype* is an integrated multi-physics, multiscale, probabilistic model of a system design. The digital prototype may use sensor information and input data to simulate the performance of its corresponding physical twin. The digital prototype may exist prior to realization of its physical counterpart**
- **Hypothesis: Enhance capability by characterization of flaws in systems**

DAU Definitions

Examples of Current USAF Force Management

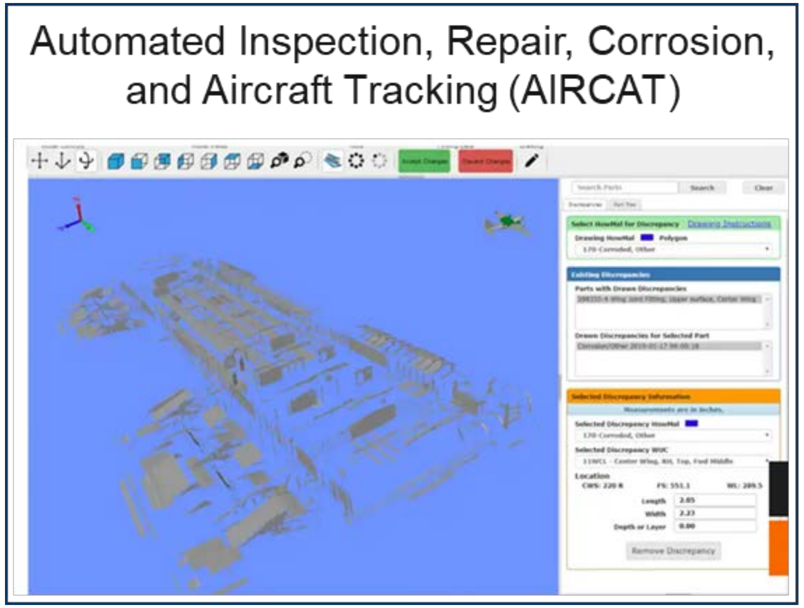
Options dependent of funding used for development:

- **Source code and data format owned by USAF**
- **Data rights, source code, and data format owned by contractor**
- **Lots of success – migrate to hi-fidelity twin to improve life management**



http://www.arctosmeetings.com/agenda/asip/2022/proceedings/presentations/P23268.pdf

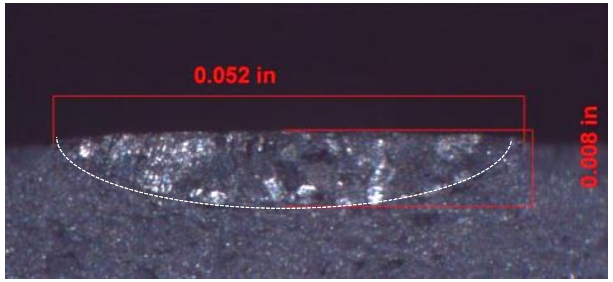
http://www.arctosmeetings.com/agenda/asip/2022/proceedings/presentations/P23269.pdf



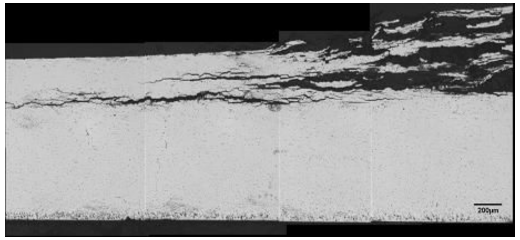
https://www.merc-mercer.org/project/aircat/

History

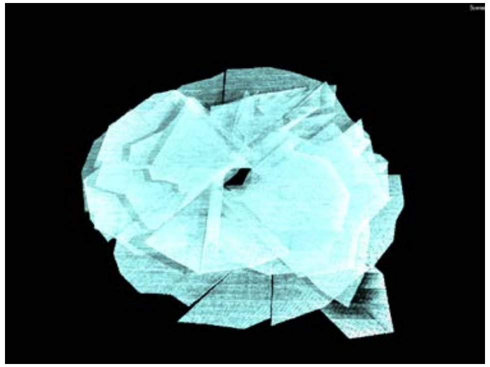
Multiple programs have pursued objective:



Representative fatigue crack*



Representative corrosion (intergranular)**



Representative composite impact damage

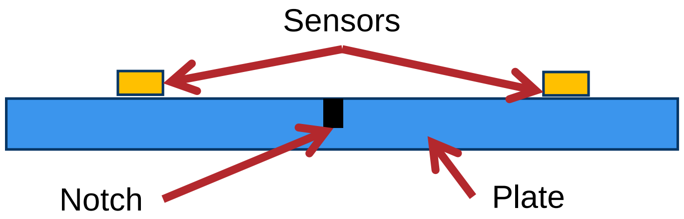
- **Example: DARPA Structural Integrity and Prognosis System (SIPS)**

Common incorrect assumption: current NDE methods can size flaws

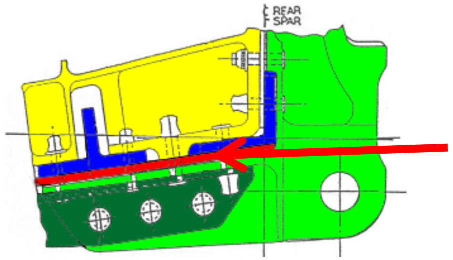
- **Can determine length as a function of method and spatial resolution of sensors**
- **Cannot determine depth with statistical metrics of accuracy (yet)**
- **Latter parameter required to manage risk, accelerate disposition, and realize a true digital twin**

*K. Jones, et.al., "Probing the Future: Better F-16 Inspections Using Conformal Eddy Current Inspection Tools," 2015 Intl Conference on Aerospace Fatigue Symposium, Helsinki, Finland
**Lepine, et. al., "Correlating Corrosion Characterization Metrics to Nondestructive Inspections of a 2024-T3 Fuselage Lap Splice," Proceedings of the 2002 ASIP Conference

Challenges: Flaw Detection / Characterization



≠



- **Equipment Variability**
- **Structural Complexity / Variability**
  - From design, manufacturing, repair, modification, maintenance, and usage
- **Flaw Complexity / Variability**
  - Stochastic variability (e.g. cracks)
  - Microstructural variability
  - Scale of flaw to detect
  - Boundary Conditions

- **Validation of Capability**
  - Required for ASIP / PSIP driven applications
  - POD or equivalent
- **Qualification**
- **Time variance in performance**
  - Includes durability
- **Environment**
  - Temperature, loads, etc.

Data variability affects reproducible detection/characterization of flaws

Complexity Example: Real Component*

- **Complexity: multiple materials in structure, critical flaws in remote locations, minimal access to area of interest**
- **Variability: geometry/material/condition, boundary conditions, characteristics of the feature(s) of interest**

*Pictures from: J. Hoffmann, J. Ullet, B. Drennen, "Development of a Nondestructive Inspection (NDI) Approach based on Bolt Hole Ultrasonic Testing (BHUT) for complex, multi-layered Aircraft Structures" ASIP 2007, http://www.asipcon.com/proceedings/Weds_1130_Drennen.pdf

Addressing Challenges: Intelligence Augmentation

Also known as Collaborative Intelligence

Integrates three general classes of algorithms:

- **Expert / heuristic-based algorithms**
  - **“Rules of the road” to help make decisions**
- **Model-based algorithms**
  - **Mental “what-if” scenarios**
- **Enhanced Data Analytics**
  - **Data-driven experience, aka “lessons learned”**
  - **Data quality is quantified**

All three in use today as part of daily life:

- **Optimal decision making can include two or more**
  - **Depends on circumstances**

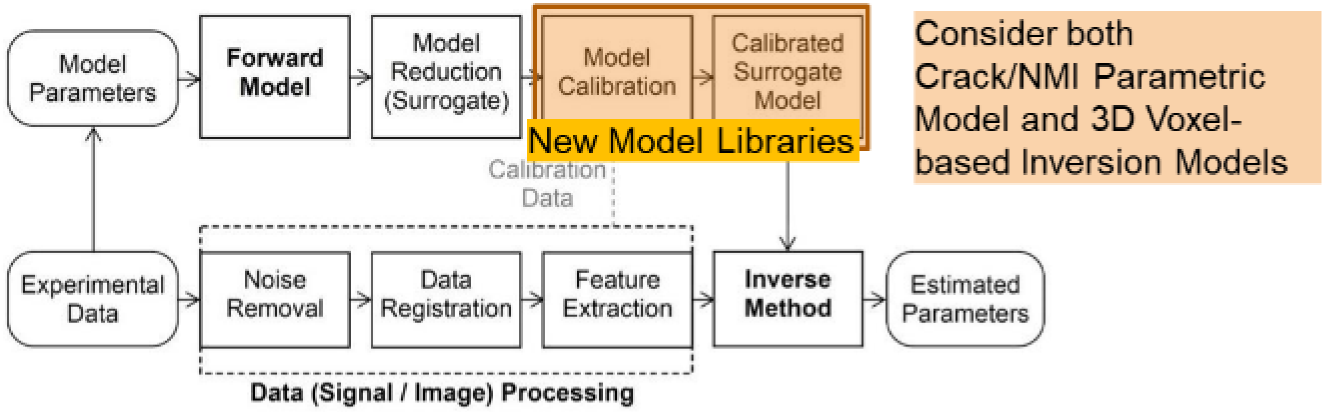
Retaining human-in-the-loop

Case Study: Fatigue Crack Sizing

Objective: length and depth of cracks, plus discriminate non-metallic inclusions

- **Propulsion components eliminate most structural variability**
- **Eddy current inspection stations provides highly registered data**
  - **Up to 8 fully automated inspection axes**

Approach: Model-based Inversion + Heuristics

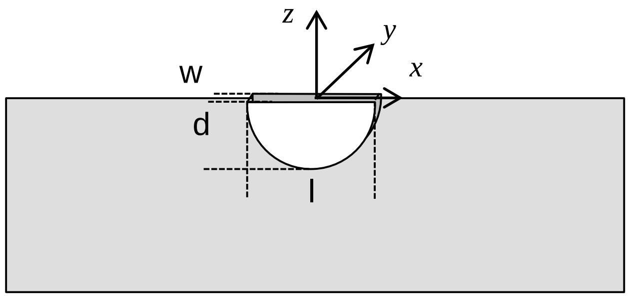


Detecting and sizing shallow fatigue crack in propulsion components

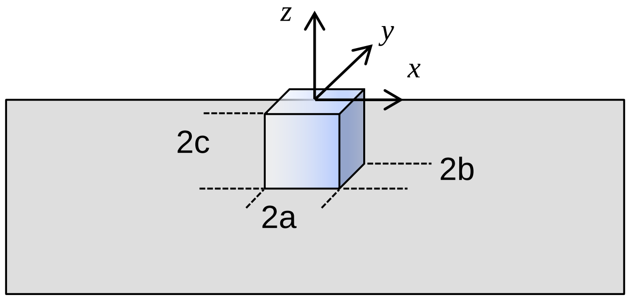
- **Assessing very shallow cracks**
- **Requires use of reactance and resistance**
- **Quantifiable correlation between crack depth determination and measured crack depth**
- **Validation studies required for implementation**
- **Expanding capability to non-flat surfaces**

Multiple Forward Models

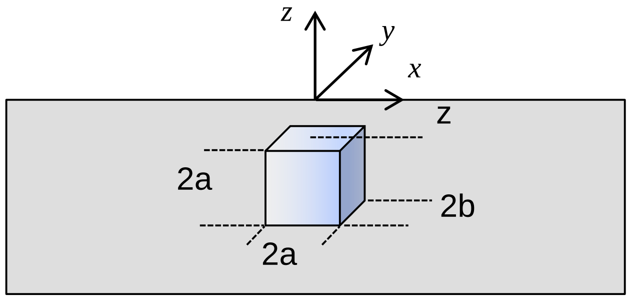
Forward Model Libraries (FMLs) for Cracks/Notches and NMIs



Parametric Crack/Notch Model



Parametric Surface Inclusion Model



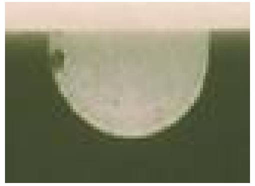
Parametric Sub-surface Inclusion Model

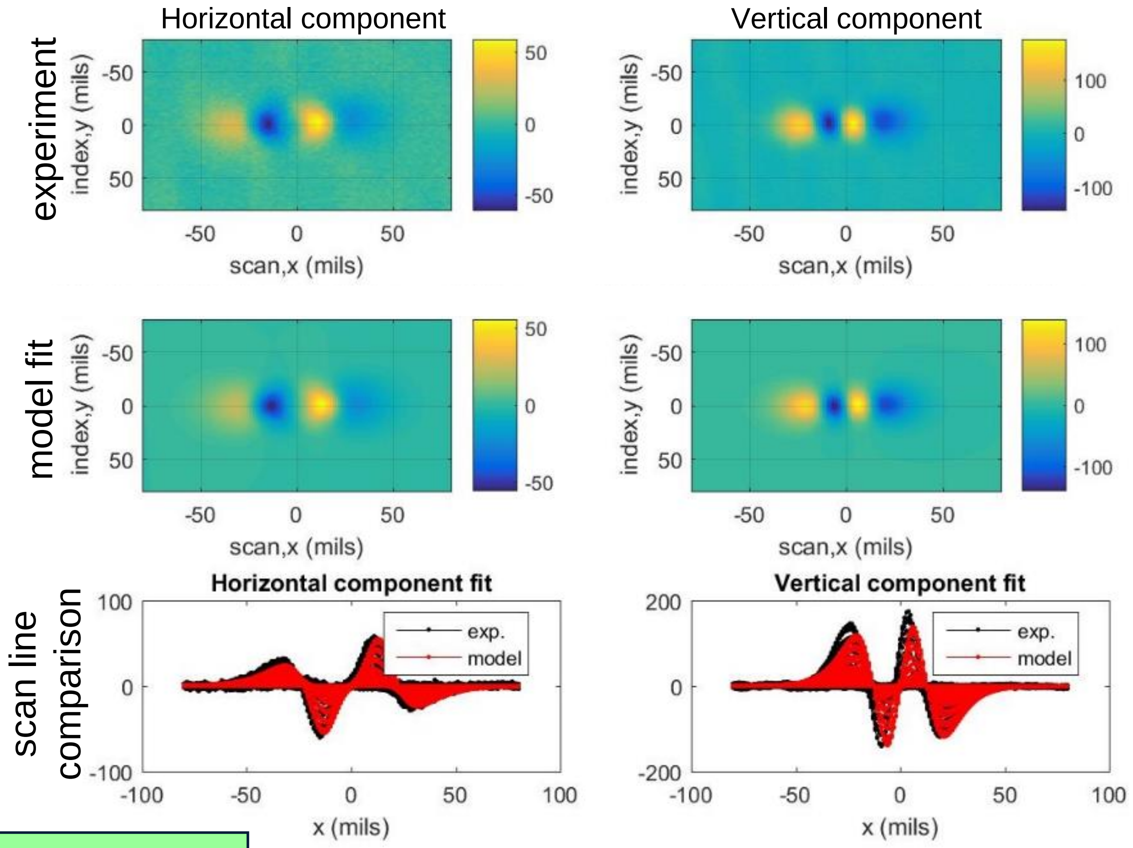
Parametric studies, value ranges (in mm unless otherwise specified):

- **Crack/notch depth, length, width, and angle: 0.0625 – 0.5; 0.125 – 2.0; 25nm – 0.125; 0° - 90°**
- **Surface inclusion width, depth, aspect ratio, angle: 0.625 – 0.25; 0.325 – 0.25; 1:1&1:2&2:1; 0° - 90°**
- **Sub-surface inclusion size, depth, aspect ratio, angle: 0.625 – 0.25; 0.3125 – 0.25 1:1&1:2&2:1; 0° - 90°**
- **6 MHz and 2 MHz eddy current probes, 0.05 x 0.0625 mm spatially registered scans**

Model-Based Inversion Approach – Results

- **EDM Notch: 0.245 x 0.2375 mm**





Crack/notch model produces best fit based on mean square error (MSE)

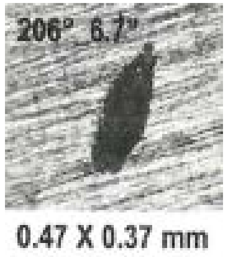
All values in mm

Depth: 0.2375 actual, 0.24 estimated // Length: 0.245 actual, 0.26 estimated

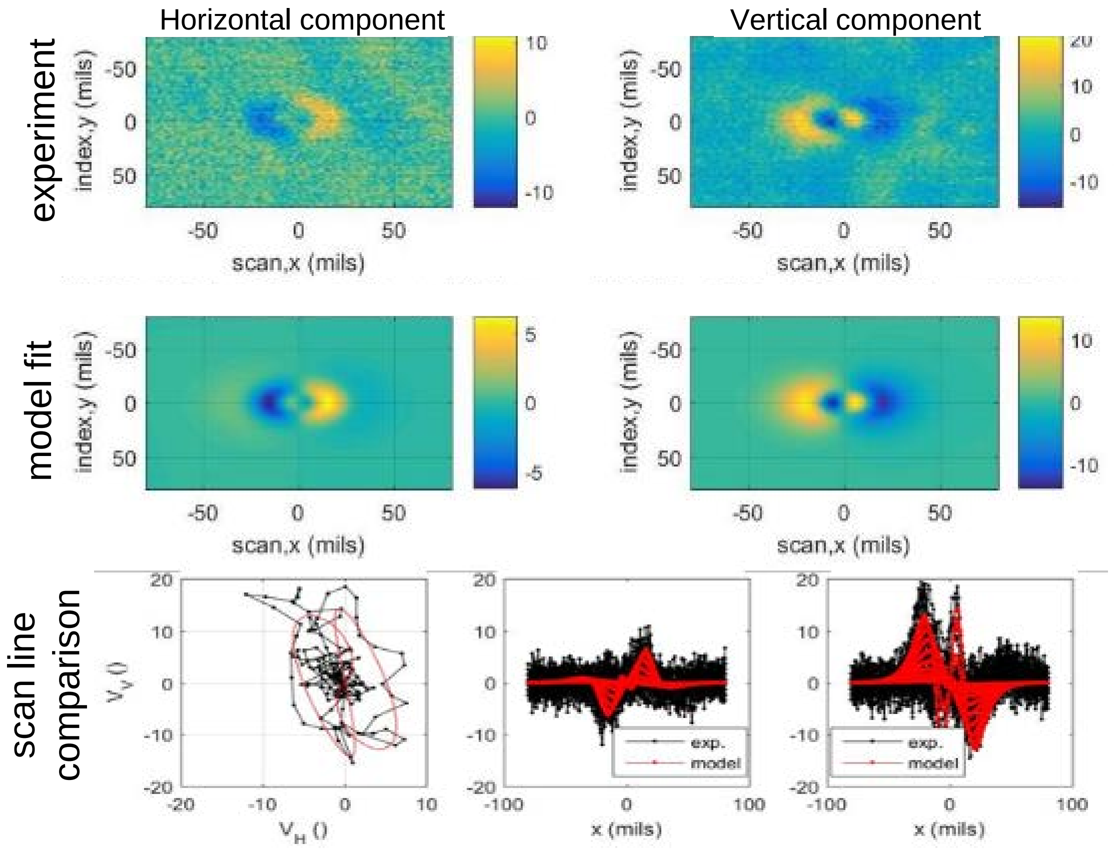
Width: 0.03 actual, .035 estimated // Aspect ratio: 8.2 actual, 7.6 estimated

Model-Based Inversion Approach – Results

- **Non-metallic Inclusion (NMI)**



Surface pit model produces best fit based on mean square error (MSE)



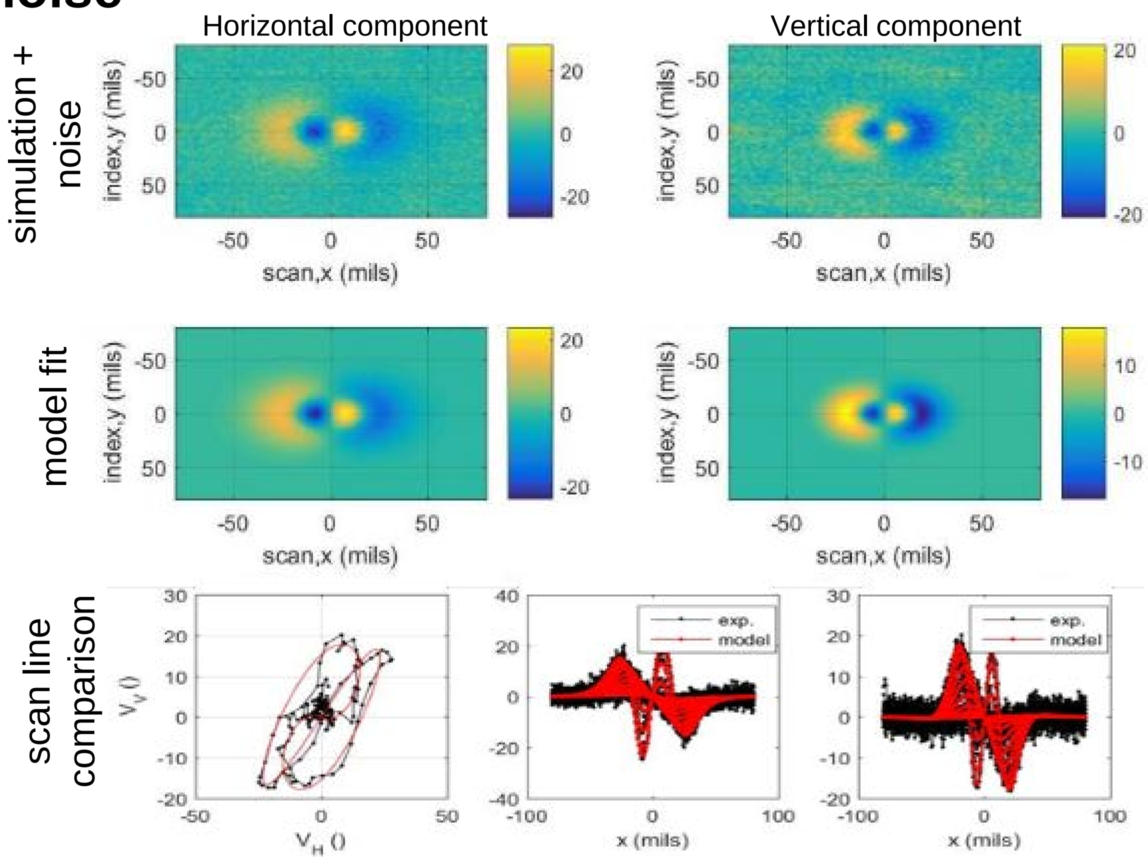
All values in mm

Depth: 0.015 estimated // Length: 0.1775 estimated // Width: 0.1475 estimated //

Aspect ratio: 0.8 estimated // actuals not measured

Model-Based Inversion Approach – Results

- **Simulated sub-surface NMI plus noise**



Sub-surface pit model has best fit based on MSE

All values in mm

Depth: 0.145 simulated, 0.1425 estimated // Length: 0.145 simulated, 0.1425 estimated

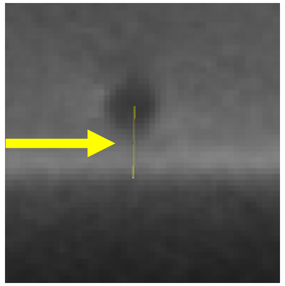
Width: 0.145 simulated, 0.1425 estimated // Aspect ratio: 1.0 simulated, 1.0 estimated

Non-metallic Inclusions

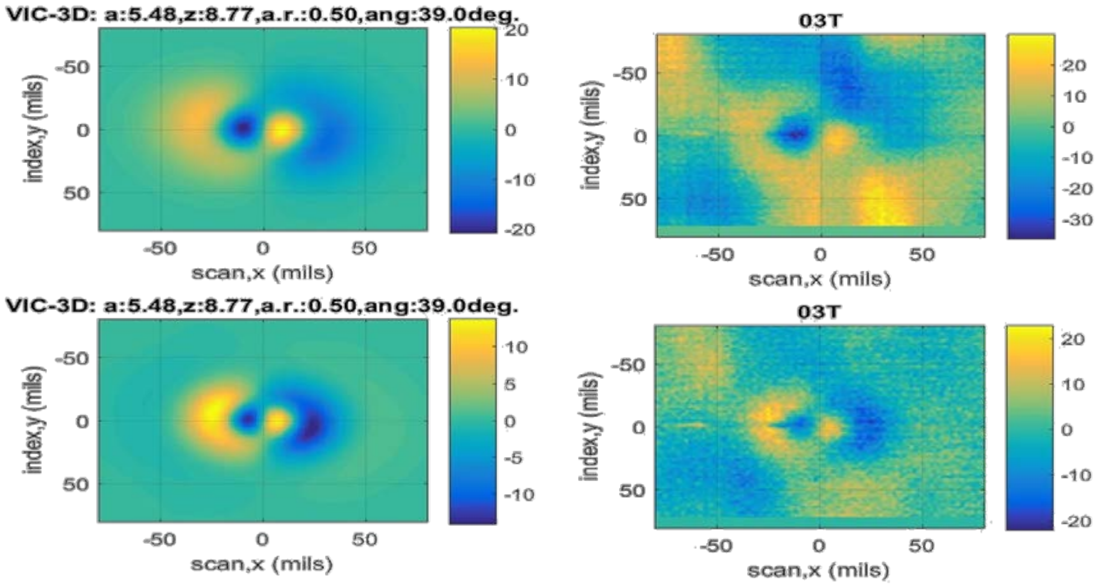
SPS Sample

X-ray CT Image

0.22 - 0.305 mm

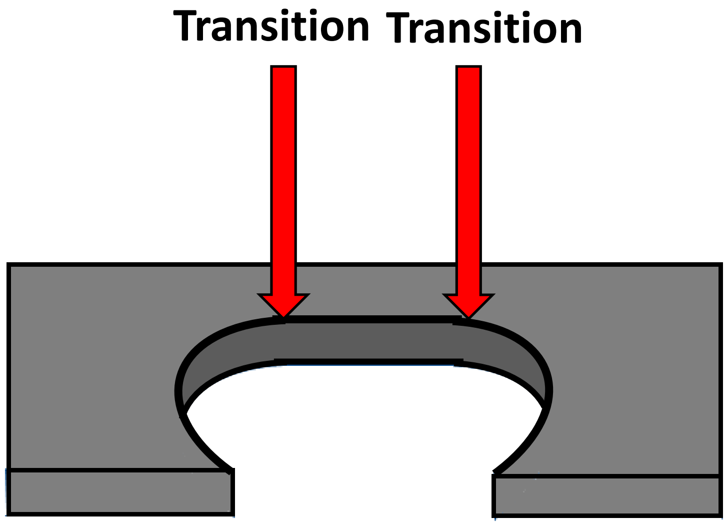


Models ***Experiments***

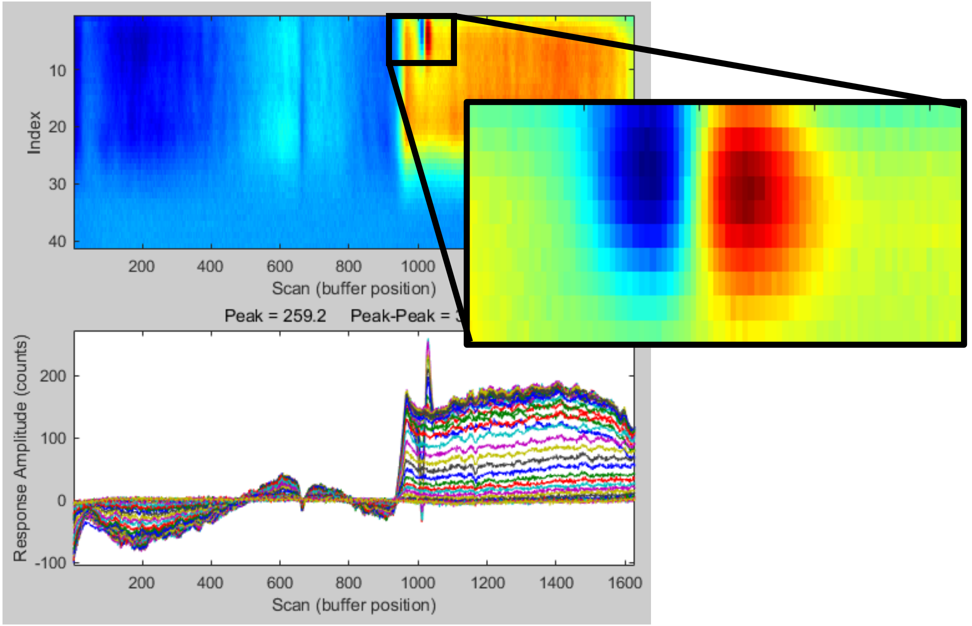


- **Model-based characterization can provide information on depth of indications**
  - **Experiments compared with models to determine size and location of NMI**
- **Sample spark-plasma sintered with embedded NMIs under 0.5 mm layer**
  - **Eddy current characterization predicted 0.22 mm depth and 0.1375x0.1375x0.275 mm dimensions**
- **X-ray CT depth of NMI: 0.22 – 0.305 mm**
  - **Model-based characterization: size and location of voids within first 0.25 – 0.5 mm of surface**

Increased Complex Geometry

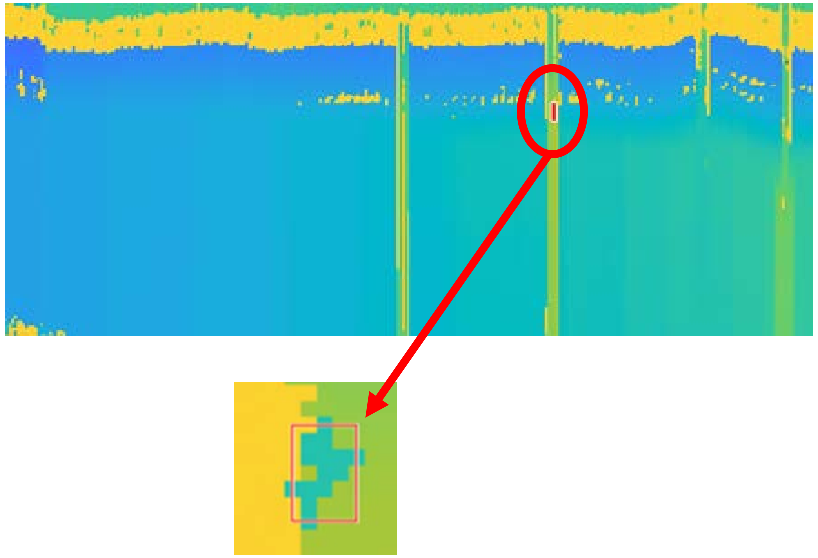


Top Corner Crack



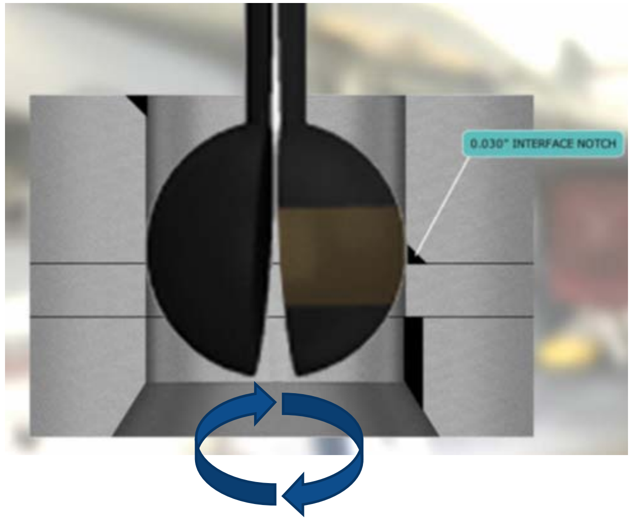
- Coil moves along the surface at a constant rate, ideally coil oriented normal to the surface
- In reality, probe, coil, part, and station alignment affect normality between coil and part surface
- Typical production coils can have small amount of acceptable tilt
- At transitions between arc and flat regions, coupling variations can cause signal spikes

Composites



- **Combination of heuristics and data to assist inspectors**
- **Can size area of flaw and track size changes as a function of use**
- **Data registered as a function of location on system**

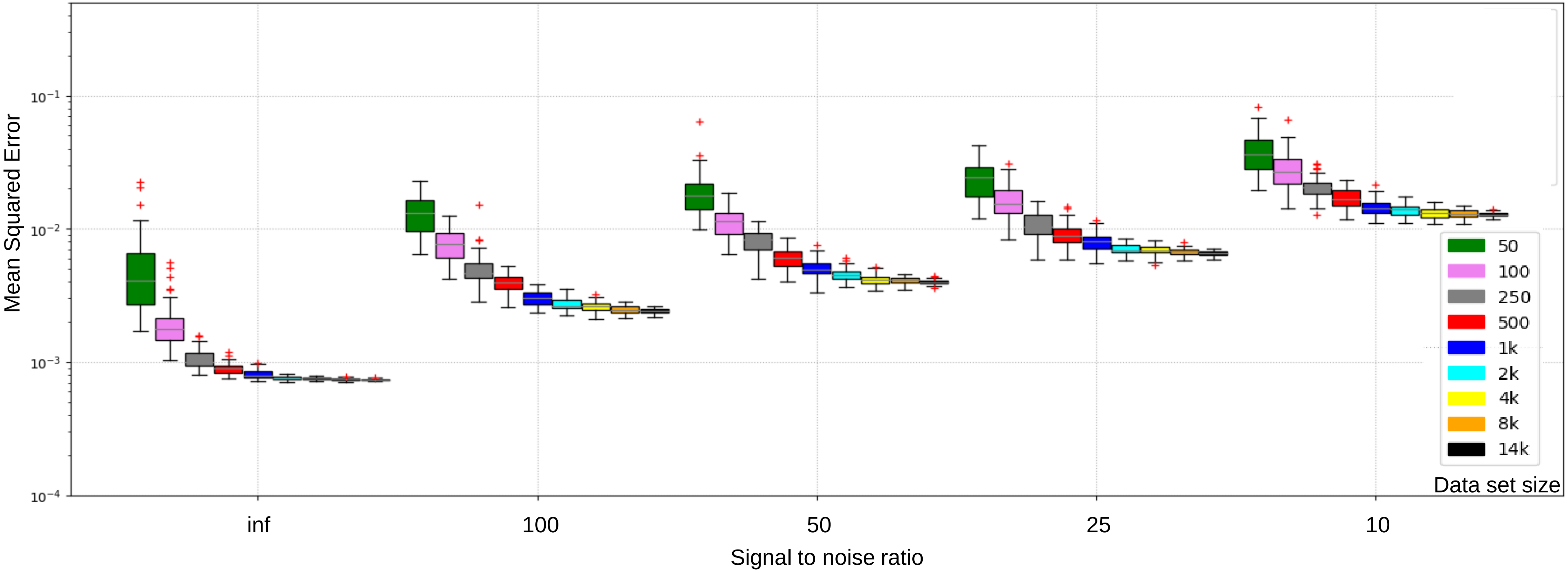
Bolt Hole Eddy Current – Combining All Three



Presented at 2021 ASIP Conference:

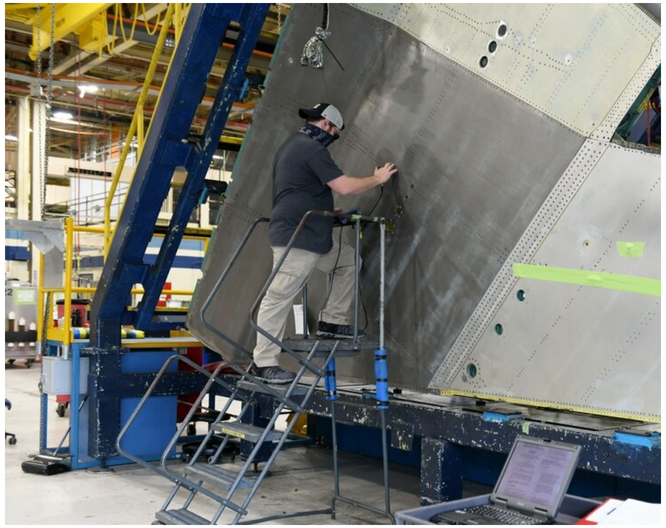
- **Bolt Hole Eddy Current Crack Sizing: Depth and length**
- **Accuracy: within 8.5% of actual depth**
  - **Mitigated all equipment / sensor variability**
  - **Within bounds of first oversize**
  - **Enables one-step disposition**
- **Work in progress, next step addresses structural variability**

Enhanced Data Analytics (aka Statistics)



- **Multi-layer perceptron results**
- **Not enough NDE data for this approach**

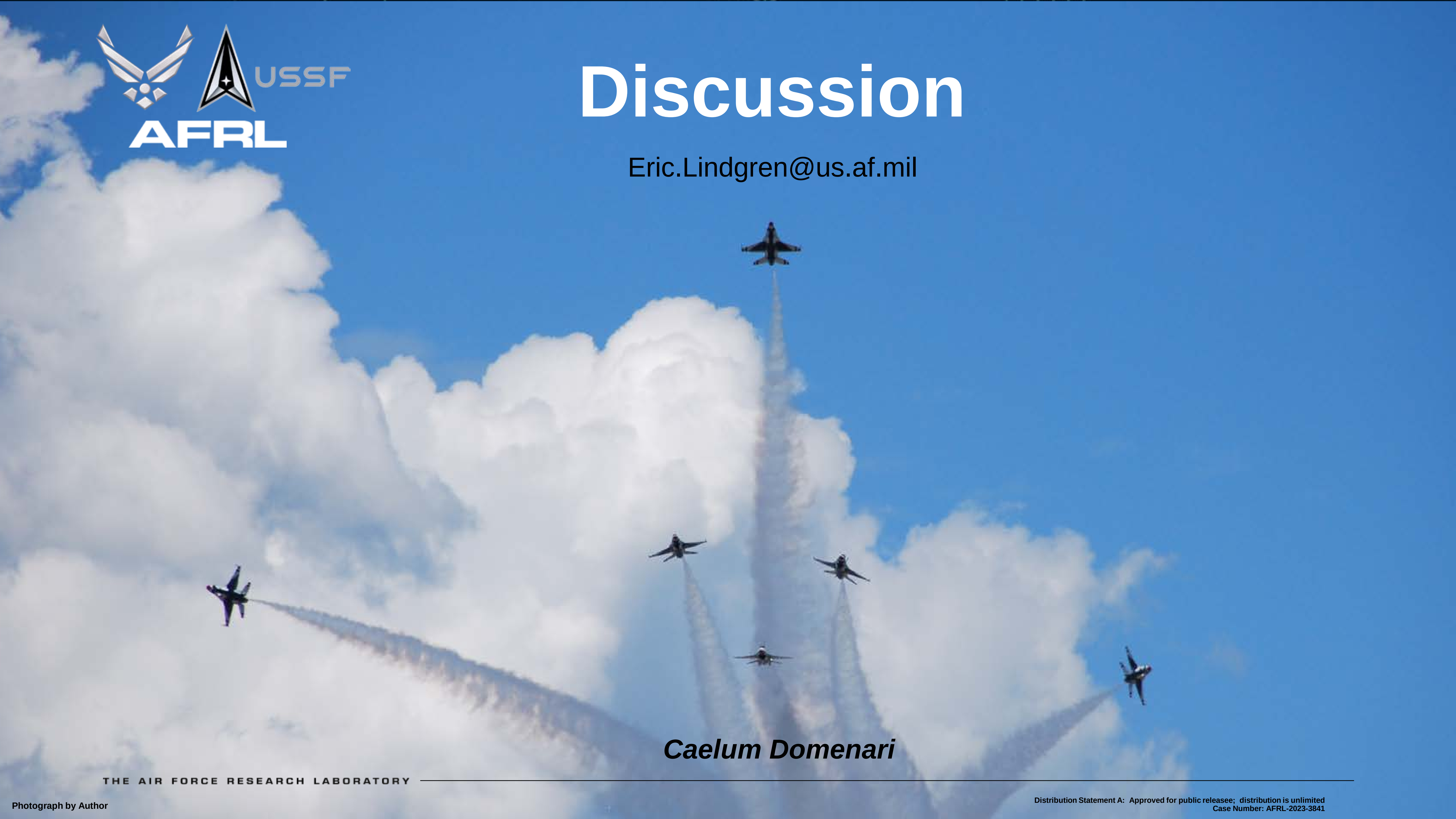
Way Forward – Flaw / Material Characterization



- Integrate all relevant data analytical methods for addressing ill-posed inversion
    - Heuristics, model-based, and data-driven
- Integrate variability into diagnostic algorithms
- Sensitivity analysis and statistical metrics of accuracy
- Validate on representative challenge problems
- Integrate into architecture of next gen NDE analytics

Summary

- **Flaw characterization completes the digital twin**
  - **Enhanced life management – cradle to grave**
- **Challenges with NDE-based data has prevented characterization with statistical metrics of accuracy**
  - **Variability and complexity: equipment, structures, flaws**
- **Assisted diagnostic algorithms for NDE include at least two: heuristics, model-based, and data-driven**
- **Feasibility of flaw characterization demonstrated**
- **Capabilities being enhanced to address increasing complexity**



AFRL USSF

Discussion

Eric.Lindgren@us.af.mil

Caelum Domenari

Photograph by Author