Design of an SHM Life-Cycle Management Software Tool

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Structural Health Monitoring (SHM)

Intelligent architecture can be designed to optimize SHM system for one or more mission roles

On-Demand NDE: In-situ inspection at fixed time or flight intervals replacing typical NDE, can enable condition-based maintenance

Real-Time Assessment: In-situ detection of impact events (bird strike, battle damage, etc.) & assessment of ability to fulfill mission

Hot-Spot Monitoring: Persistent & aggressive evaluation of failure critical or known problem areas to track present state with high precision

Motivation

- SHM hardware alone not sufficient to achieve desired benefits
  - improved asset availability
  - reduced sustainment costs

- Current SHM systems provide diagnostic information (at best)
  - typically in proprietary and/or stand-alone format
  - require subject-matter experts for placement, calibration & interpretation

- For practical deployed as part of ISHM, tools must be created for SHM life-cycle management (SHM-LCM)
  - sensor placement optimization to meet architecture & POD requirements
  - algorithms calibration for specific materials & structures
  - diagnostic visualization
  - hooks to enable prognosis & action

SHM Life-Cycle Management

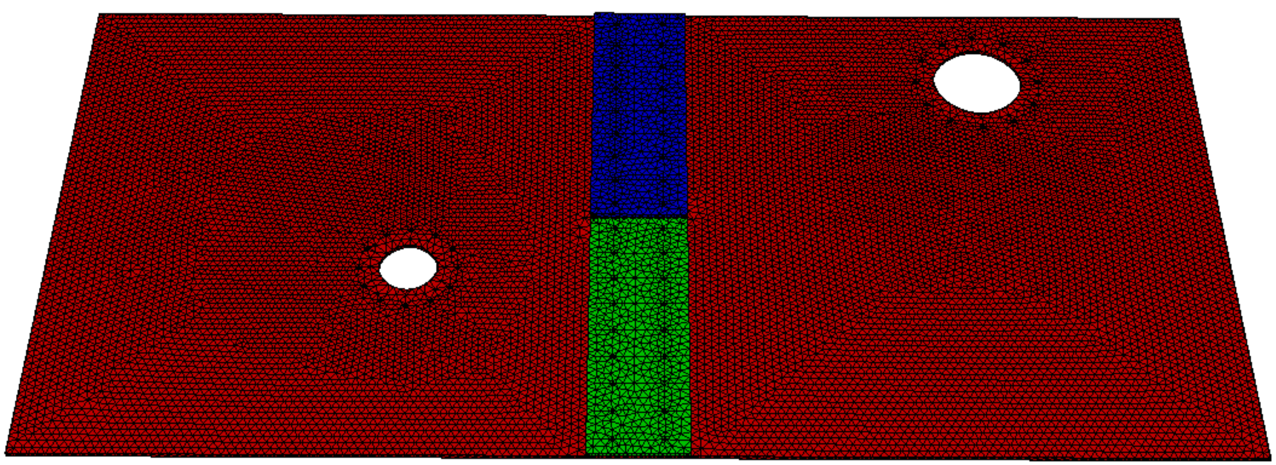
- SHM-LCM software being developed under ONR STTR funding
  - flexible application intended to manage the cradle-to-grave life-cycle
  - created to be generic & easily customized

- There are 4 core modules to facilitate critical roles:
  - Optimization – application-specific sensor placement
  - Calibration – application-specific algorithm tuning
  - Visualization – application-specific diagnostic data dissemination
  - Action – customizable tools to informed maintenance decisions

- Initial version focuses on contractor core-competencies
  - active pulse-echo style guided-wave beamforming with digital sensors
  - intent is to develop a framework that could be sensor agnostic

Optimization Module

- Optimization
  - seeks to devise optimal sensor placement & excitation parameters
  - achieve probability of detection (POD) coverage requirements
- Fueled by 3D mesh of structure to be monitored
  - user imposes POD distribution through graphical user interface (GUI)
  - resulting list of grid point to locate SHM sensors to meet requirements



Minimizing Bayes Risk

Three Basic Types of SHM Error & Their Associated Costs

Missed Detection
$$$ Structural failure during operation
$$ Structure repair/replacement

False Alarm
$$ Remove system from operation
$ Unnecessary manual inspection

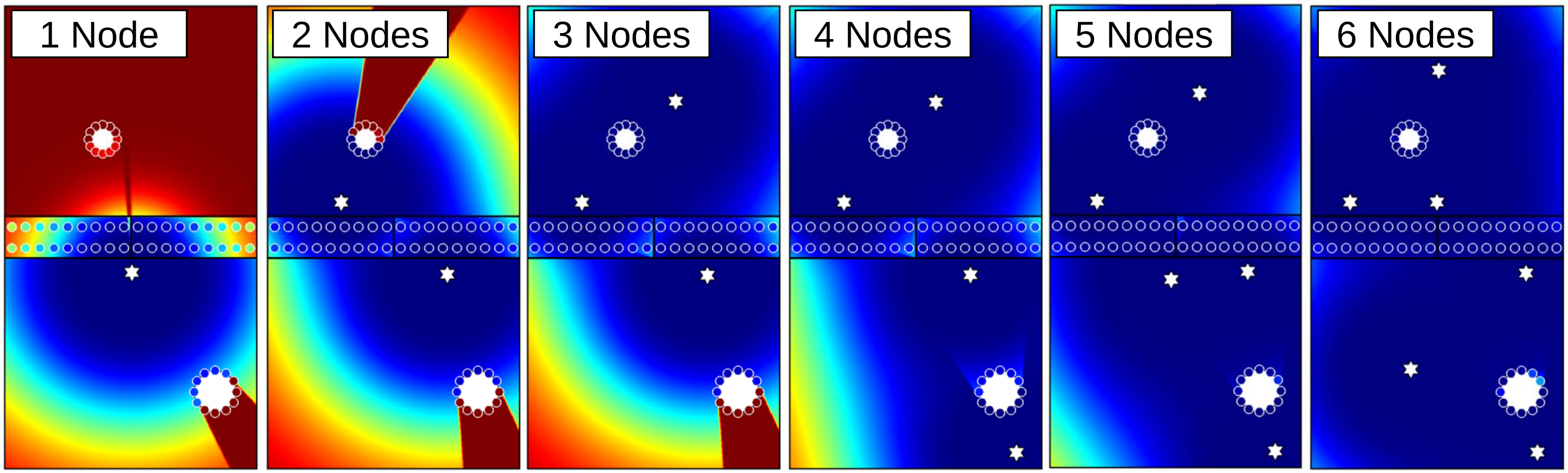
Localization Error
$ Longer inspection/structure down time
$$$ Not finding damage through manual inspection

$$\text{Expected Cost (i.e. Bayes Risk)} = \sum_{\substack{\text{Types of Error,}\\ \text{Potential Damage Locations,}\\ \text{Potential Types of Damage}}} \text{Error Cost} \times \text{Error Probability} \times \text{Damage Probability} + \text{Hardware Cost}$$

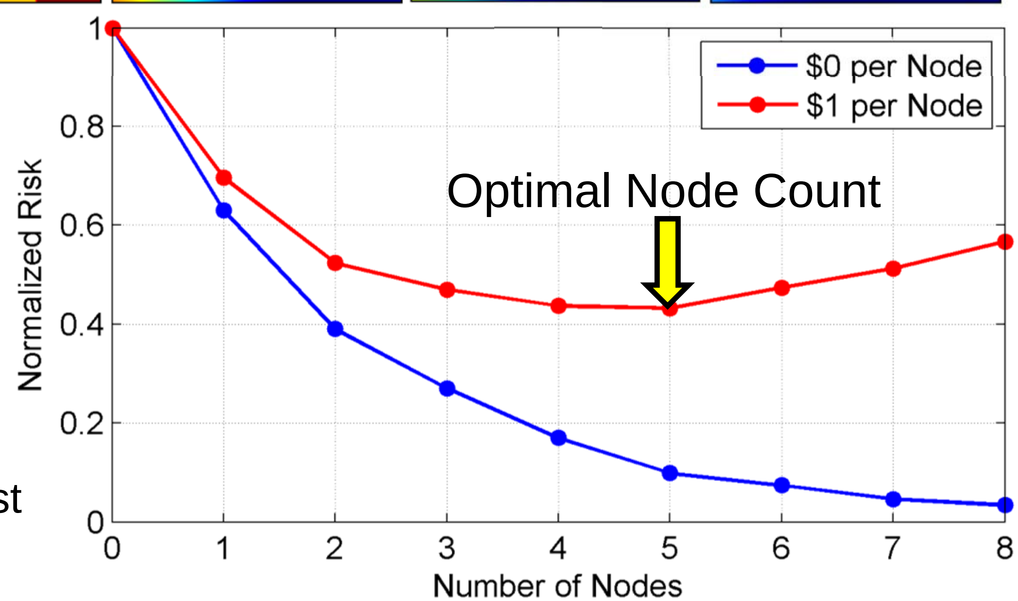
F (Hardware Design, Algorithm Design)

Optimal SHM Design:
Choose hardware & algorithm design to <u>minimize Expected Cost</u> (Bayes Risk)

Sensor Placement



- Probability of Damage: 50%
  - 37.5% @ Bolts or Holes
  - 12.5% @ Everywhere else
- Cost of Missed Detection: $30
- Cost of False Alarm: $30
- Localization Error: $15 /meter
- SHM Burden: $1 /sensor/test

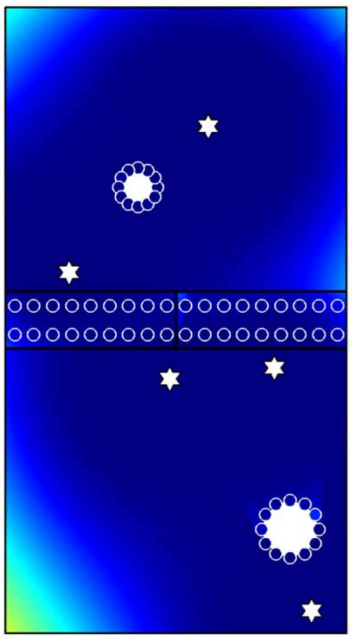


Why Defining the Problem Matters

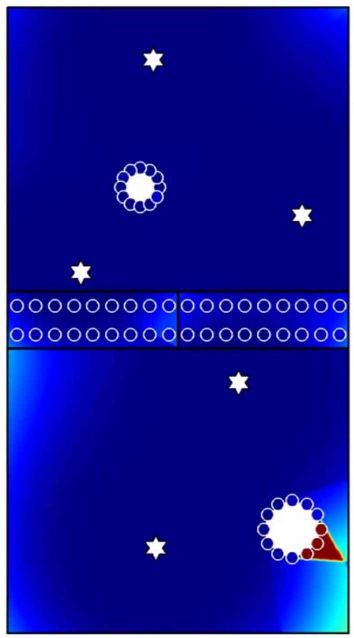
The error costs & damage probabilities ***drive*** SHM design

Design Optimized for 75% Probability of Damage @ Bolts or Holes

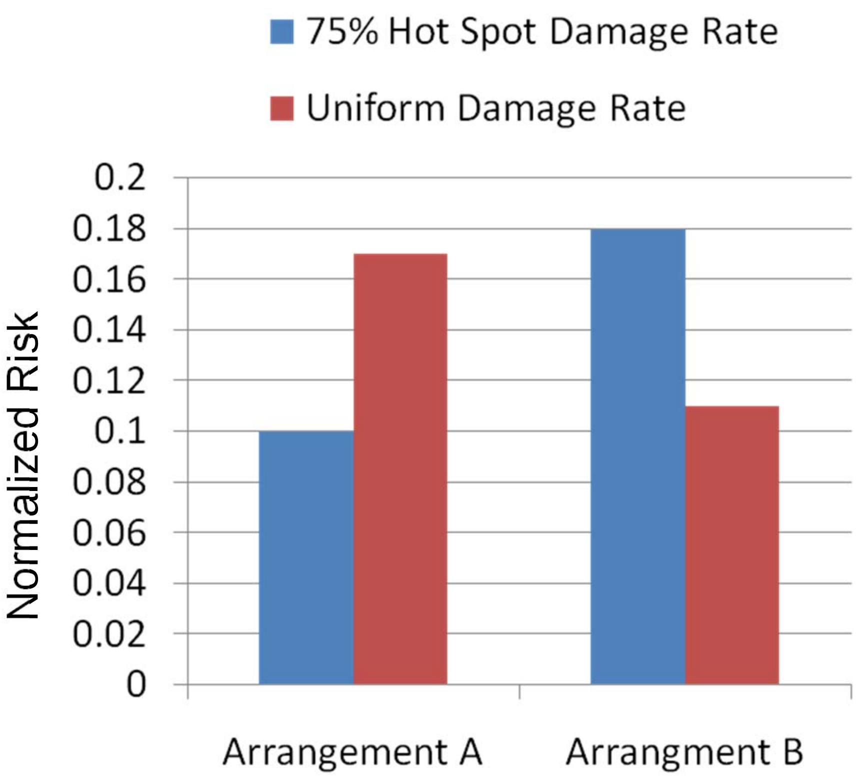
Design Optimized for Uniform Probability of Damage



Arrangement A



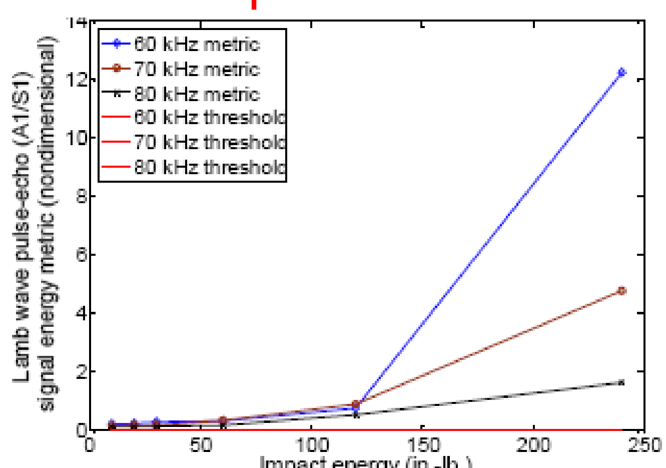
Arrangement B



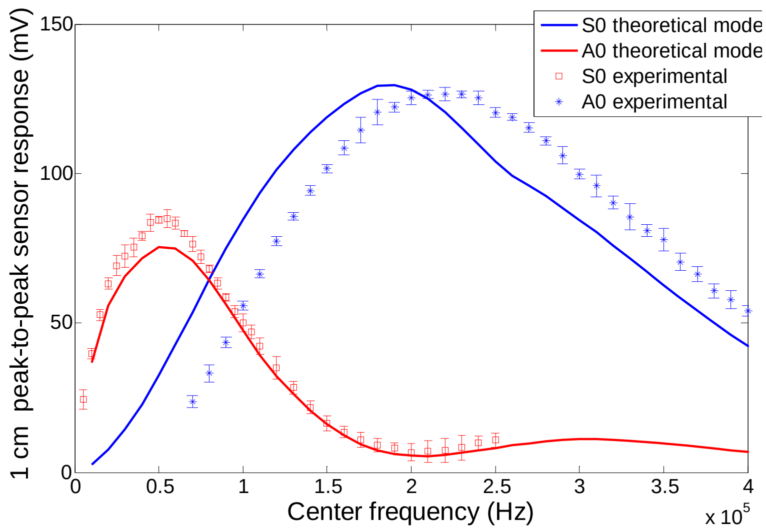
Optimizing for the wrong specs:
70% increase in expected cost!

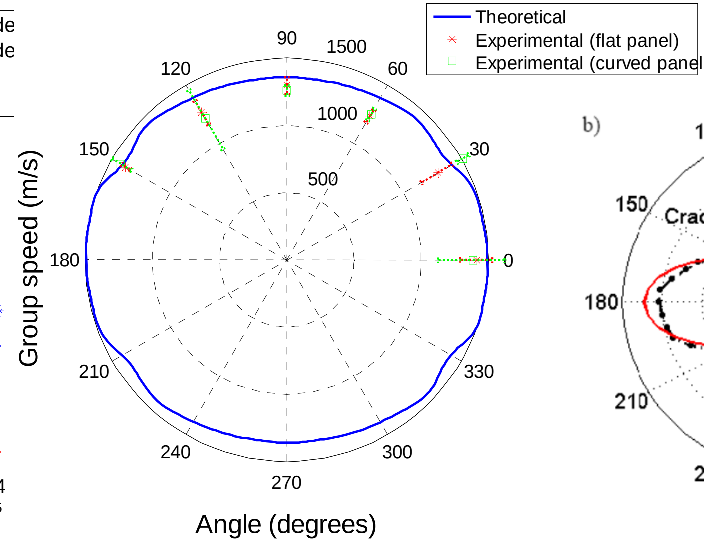
Calibration Module

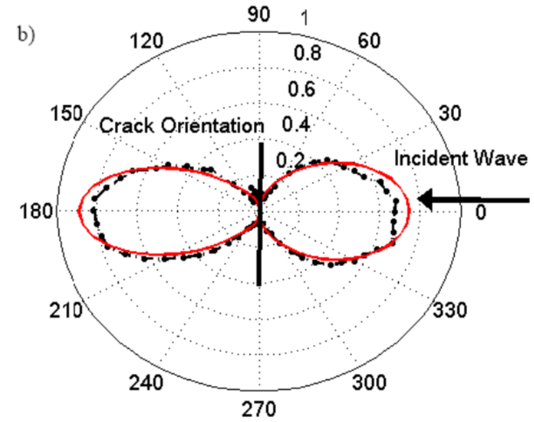
- Calibration
  - ➢ customize algorithm variables to the system being designed
  - ➢ used to translate individual sensor raw data into diagnostic results
- Fueled through a series of user-guided material-level tests
  - ➢ fuse data from both active & passive sensor sources
  - ➢ diagnostic structural/sensor health, including quantified uncertainty
  - ➢ bootloader used to disseminate constants through sensor network
  - ➢ output would be a file to be uploaded onto SHM system diagnostic server



Empirical Calibration





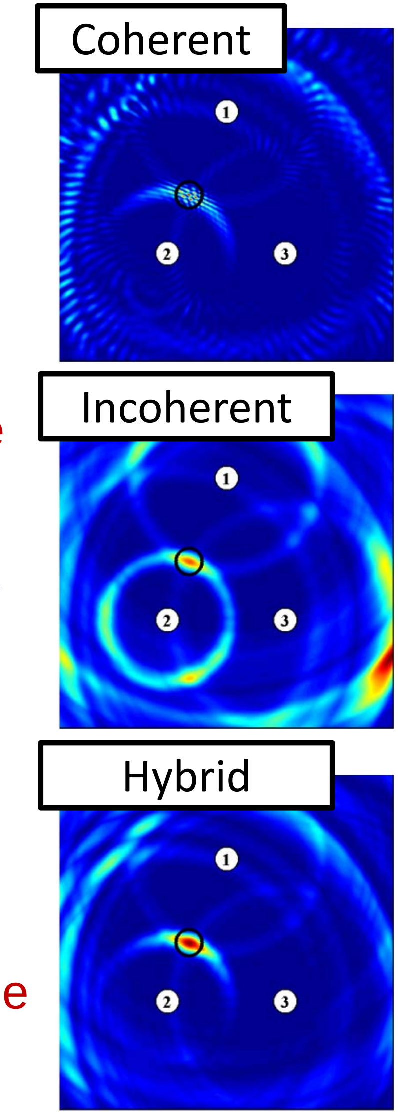


- Experiments designed to extract relevant parameters
  - wavespeed as a function of frequency and angle
  - dissipation/attenuation as a function of frequency
  - scatter response to various damage modes

- Data used to populate algorithm constants
  - can use pure theory, but empirical data improves uncertainty
  - parameters can be stored in database and reused for similar applications

Localization Algorithms

Hybrid Coherent-Incoherent Processing:
- Phase-coherent among transducers in each node
- Phase-incoherent from node to node
- Both a function of false-positive minimizing threshold value



<u>Coherently</u> combine waveforms from transducers in each node

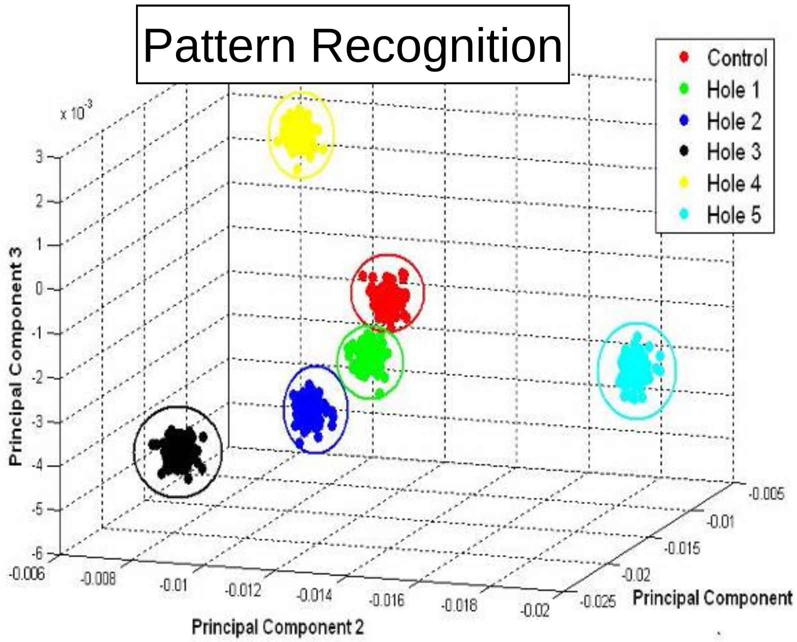
Analytic signal

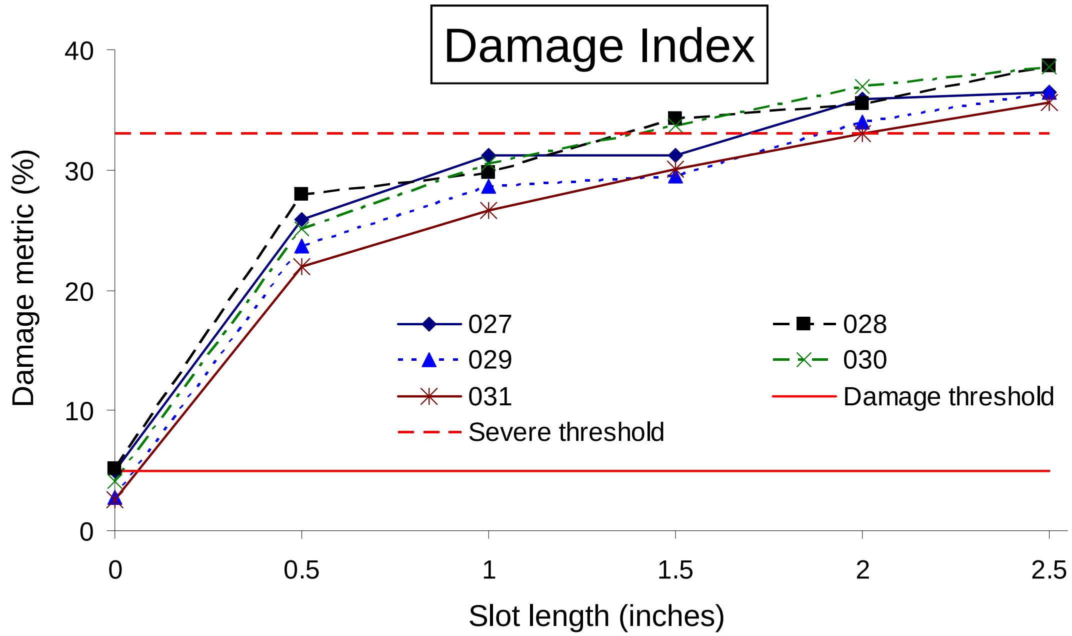
Time of flight to imaging point

$$T_{\mathrm{H}}(\boldsymbol{x}) = \left| \sum_{n-1}^{N} \left| \sum_{p=1}^{6} w_{np}\left(t - \tau\left(n, p, \boldsymbol{x}\right)\right) \right| \right|$$

<u>Incoherently</u> combine summed waveforms from each node

Type & Severity Algorithms

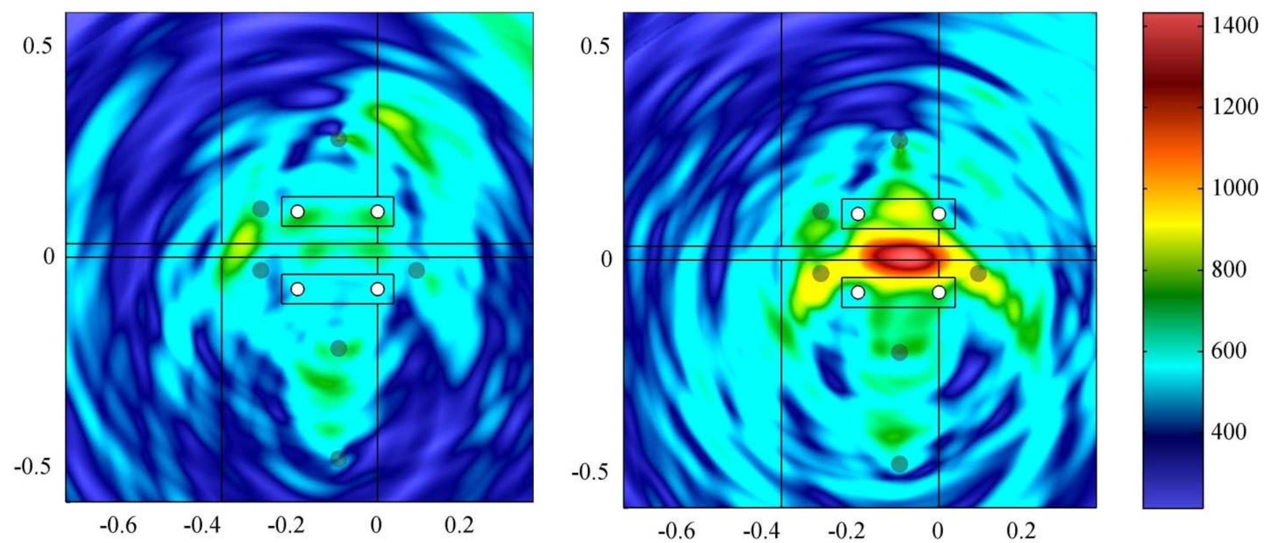




- Pattern recognition techniques used for type discrimination
  - ➢ have achieve repeatable results for both metal & composites
  - ➢ models have been demonstrated for reduced training set
- Damage index used for severity classification
  - ➢ have shown success in composite, metals and hybrid materials (GLARE)
  - ➢ demonstrated blind fatigue crack resolution as small as 0.1 mm in Ti

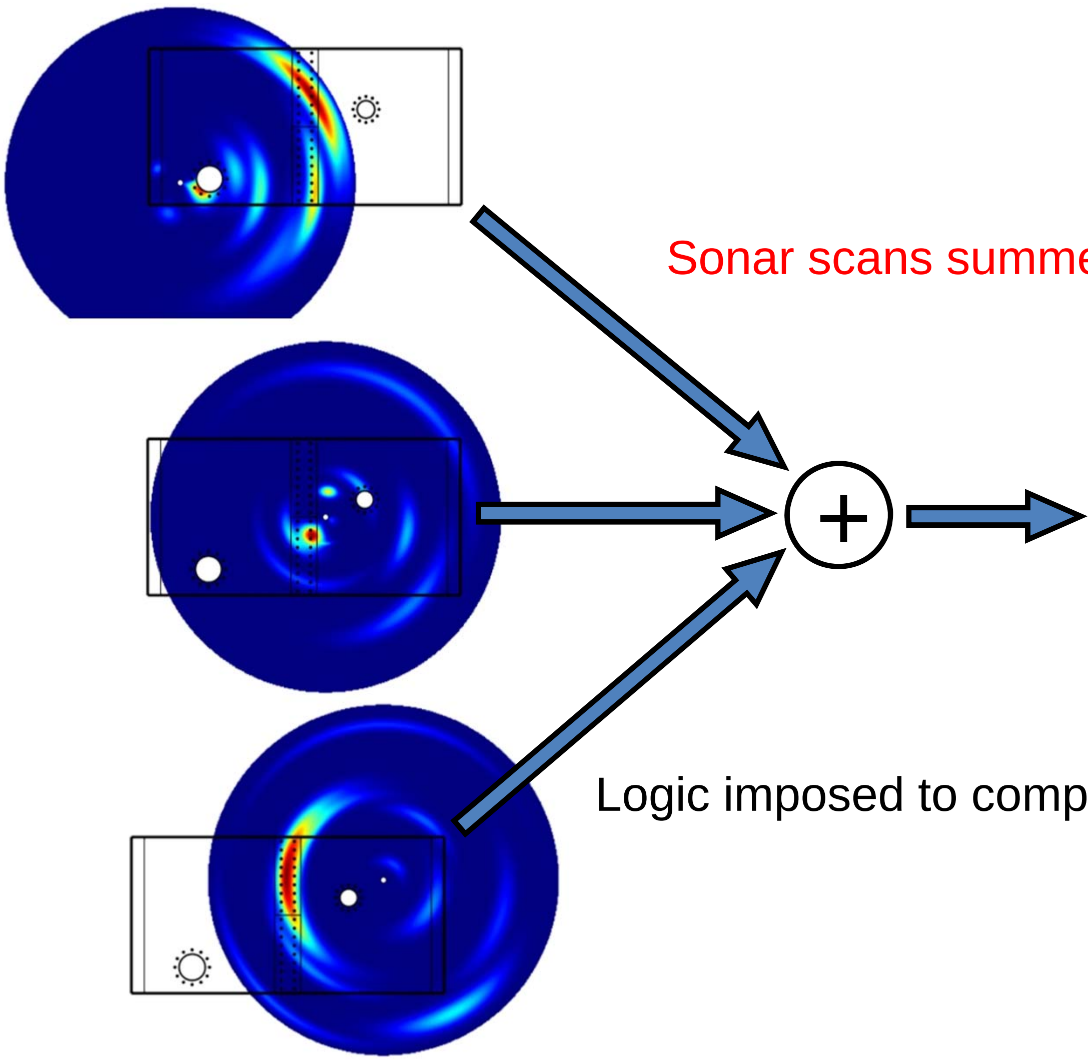
Visualization Module

- Visualization
  - generates a diagnostic composite picture for the application
  - stitched to original 3D mesh
- Fueled by data downloaded from diagnostic server
  - output provides users with manipulatable GUI (zoom, rotate, x-section)
  - toggle between probability of damage for various calibrated modes
  - can update mesh for residual prognostic analysis (untied nodes, etc)

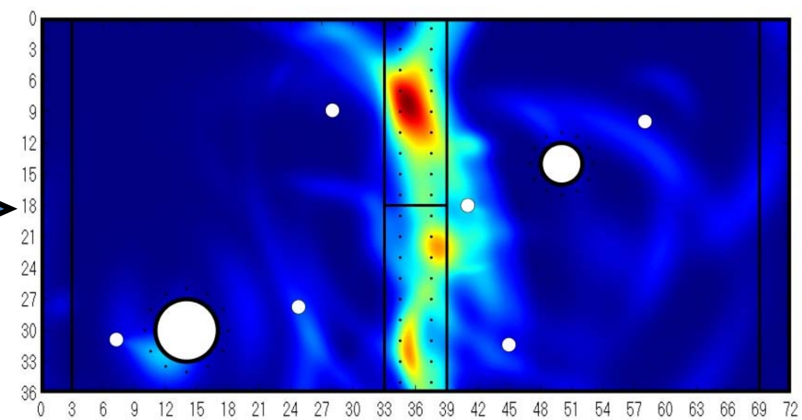


Data Analysis & Reconstruction

Each node processed individually to provide location-independent sonar-scan

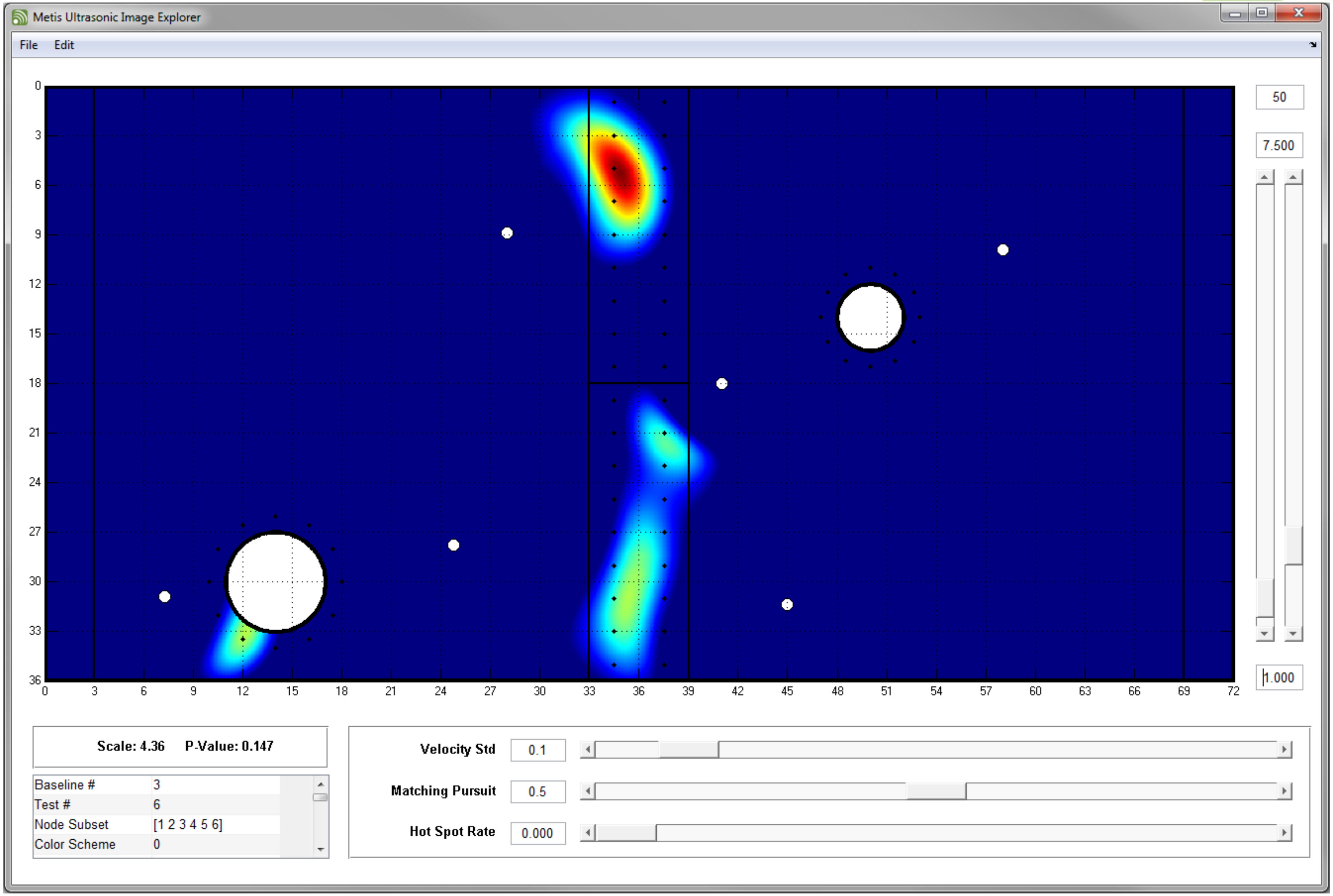


Sonar scans summed to form weighted composite image



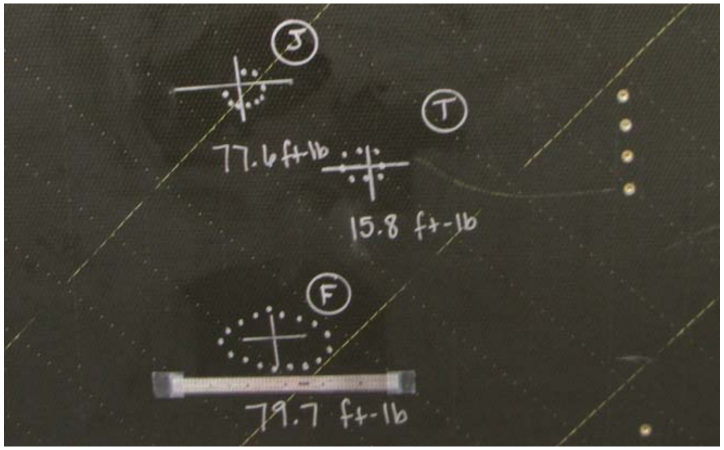
Logic imposed to compensate for boundaries, features, FOV

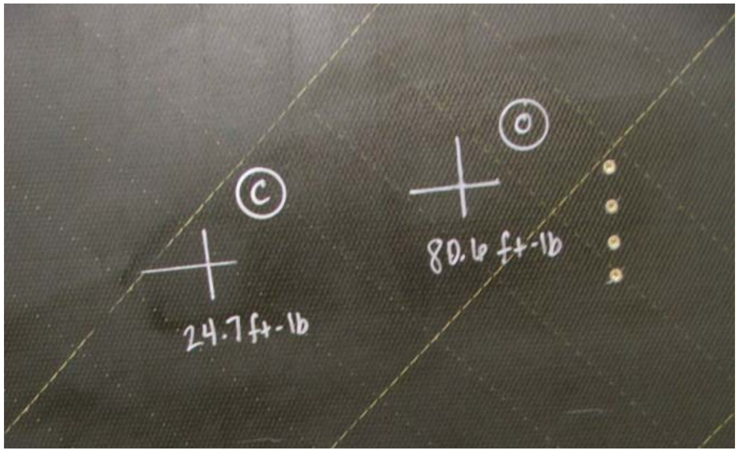
Diagnostic Visualization



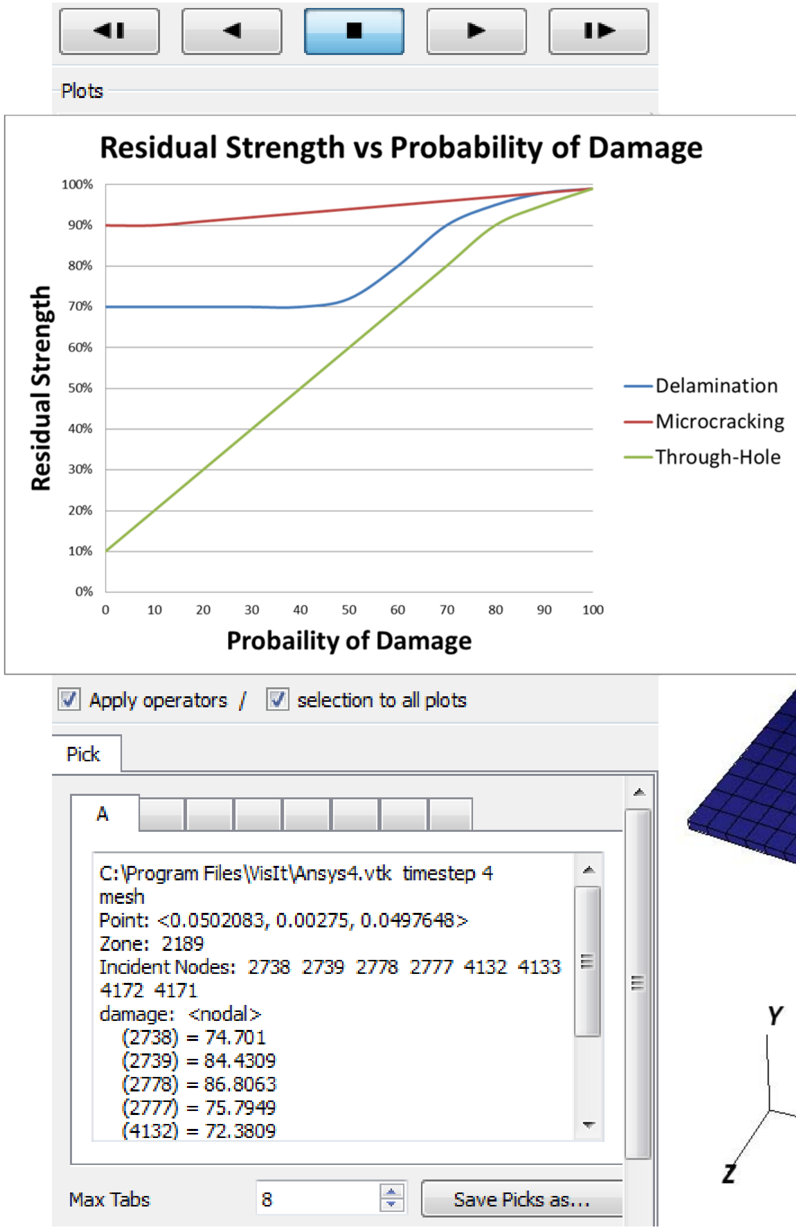
Action Module

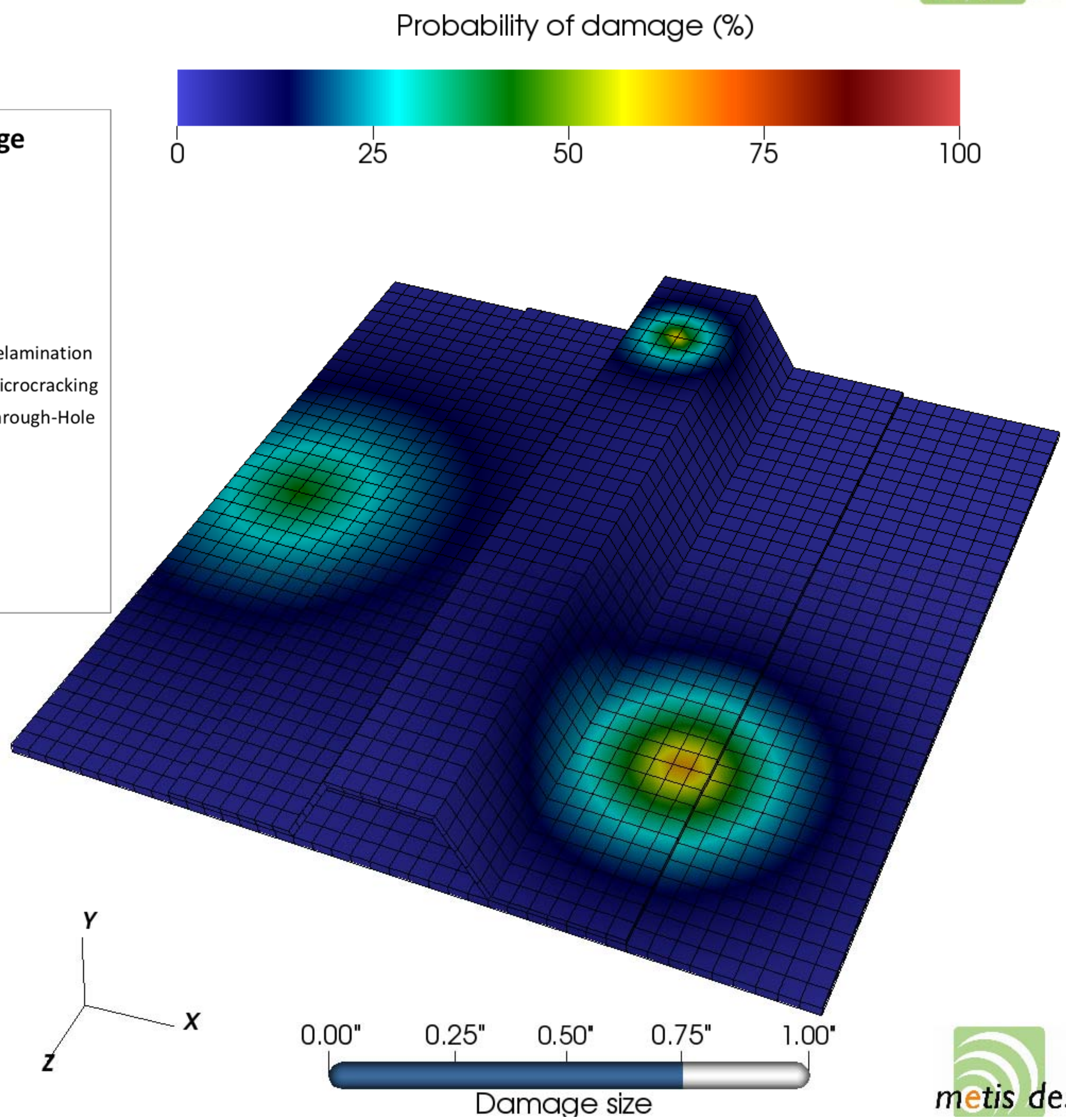
- Action
  - provides users with guides for responses to the diagnostic results
  - allows users to weigh detection confidence against impact to capabilities
- Fueled by analytical comparison of baseline/diagnosis
  - residual performance plots as a function of probability of damage
  - could enable fly-by-feel methodologies for adaptive control
  - repair optimization plug-in for restoring original performance level
  - could be local data accumulator or card in a HUMS or AHM system box



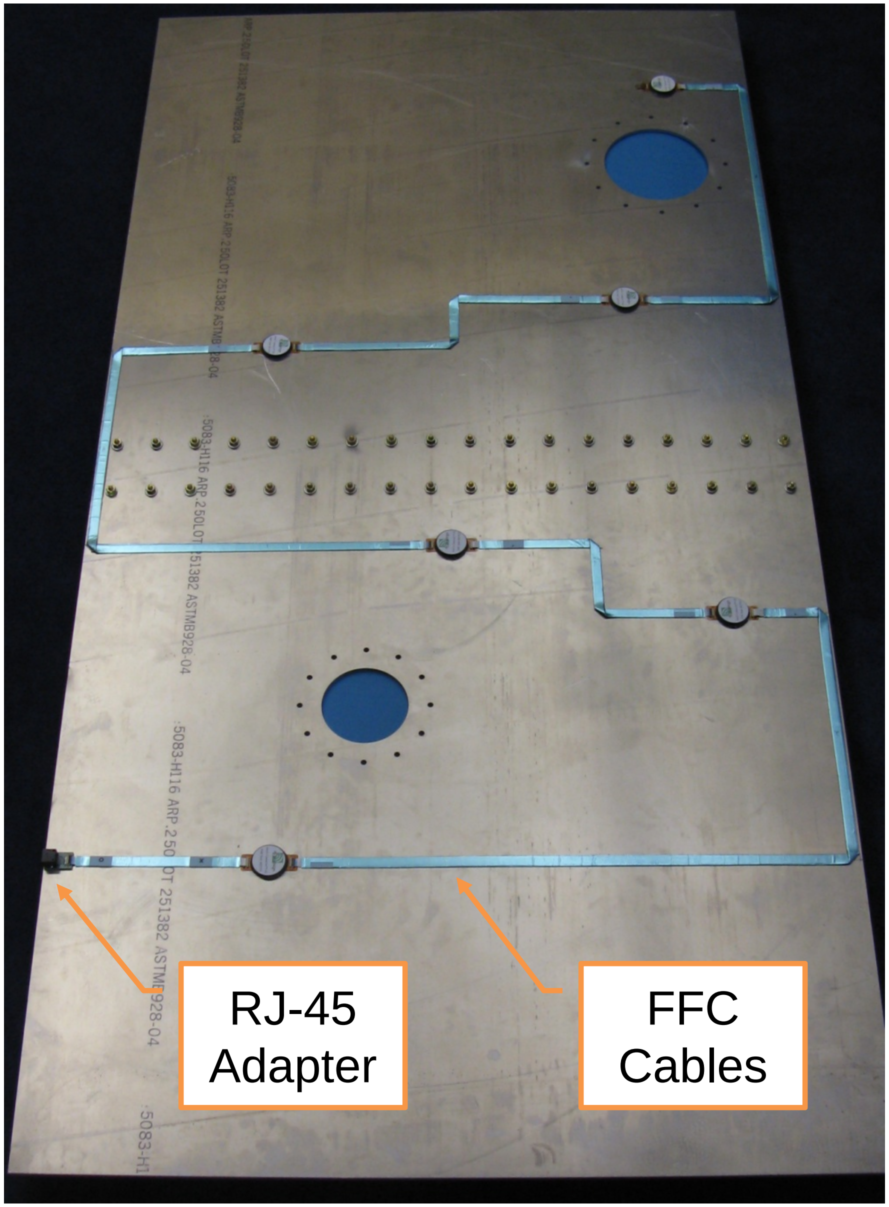


Diagnostics to Prognostics





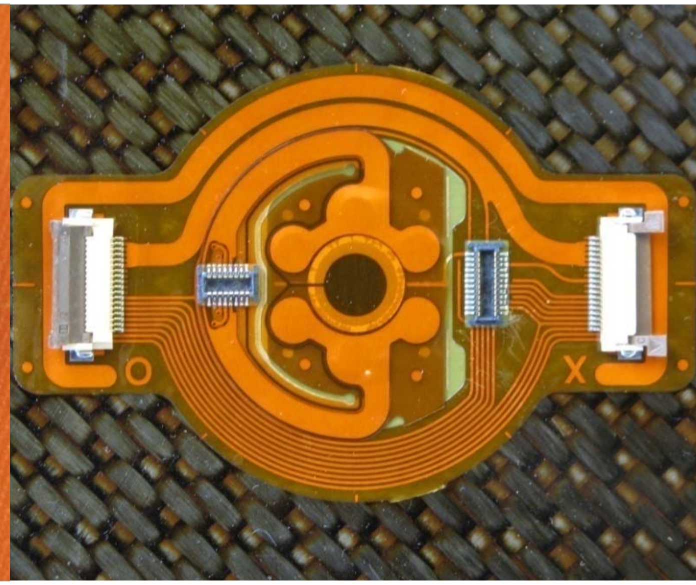
Prototype Example Problem



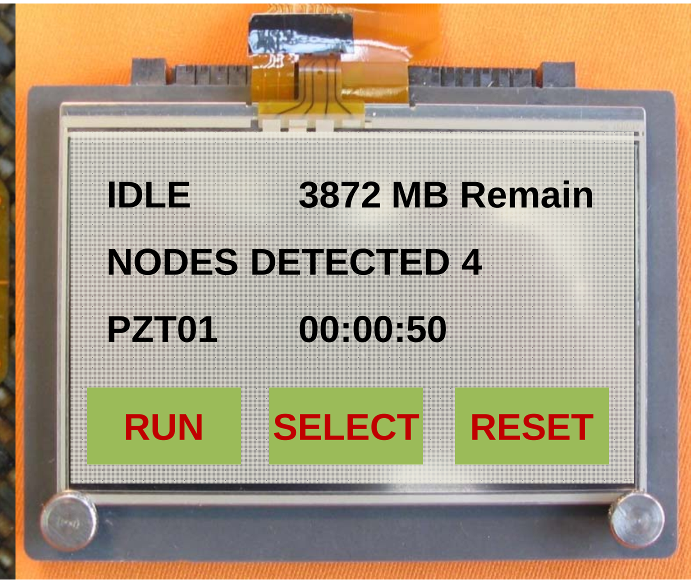
MD7 Digital SHM System

MD7 IntelliConnector™

MD7 VectorLocator™



MD7 HubTouch™



- IntelliConnector™ (digital element)
  - provides excitation, data acquisition, some signal processing
- VectorLocator™ (analog element)
  - contains 6 PZT sensor elements & 1 PZT actuator to form 1 SHM node
- HubTouch™ (network element)
  - drives data bus, commands testing, synchronizes nodes, stores data

Placement Optimization

- 6 SHM nodes in optimized locations
  - ➢ minimized Bayesian risk used
  - ➢ assumed more damage at holes/bolts
  - ➢ “greedy” approach to analyze 4-6 nodes

- System installation before shipping
  1. FFC mounted w/semi-permanent tape
  2. VectorLocator flex bond w/AE-10
  3. IntelliConnectors bond w/5-min epoxy

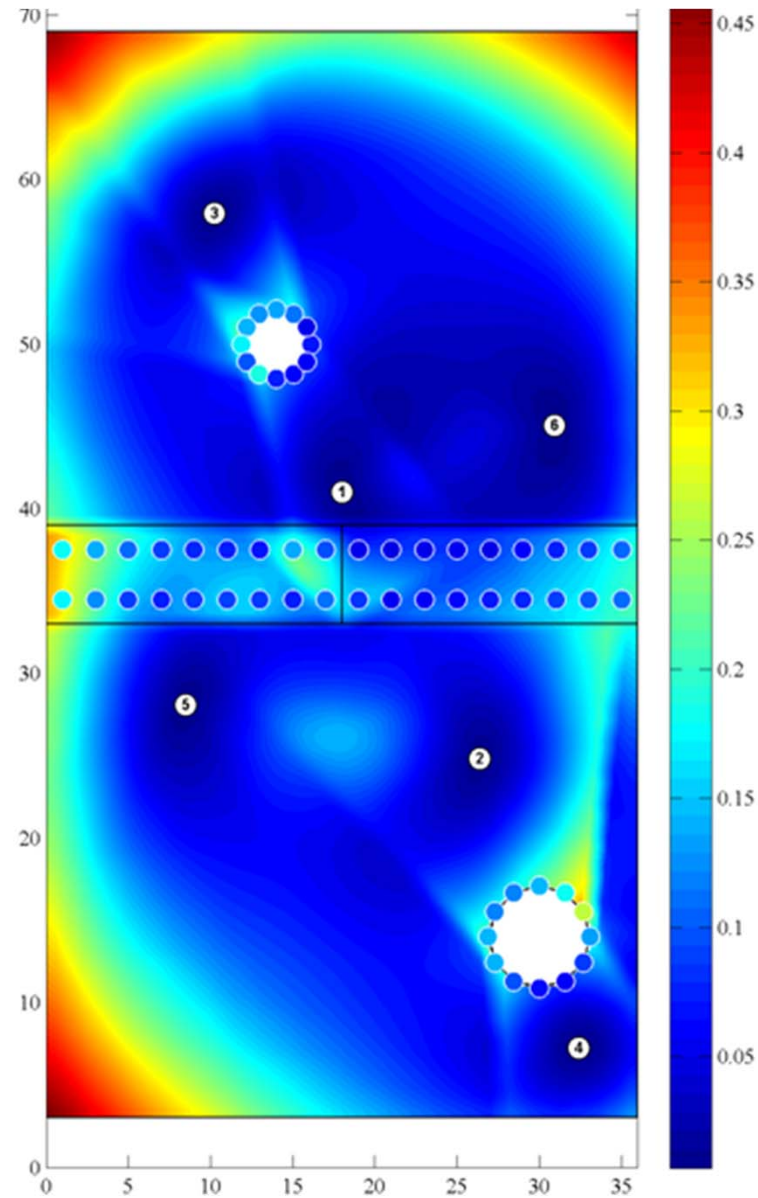
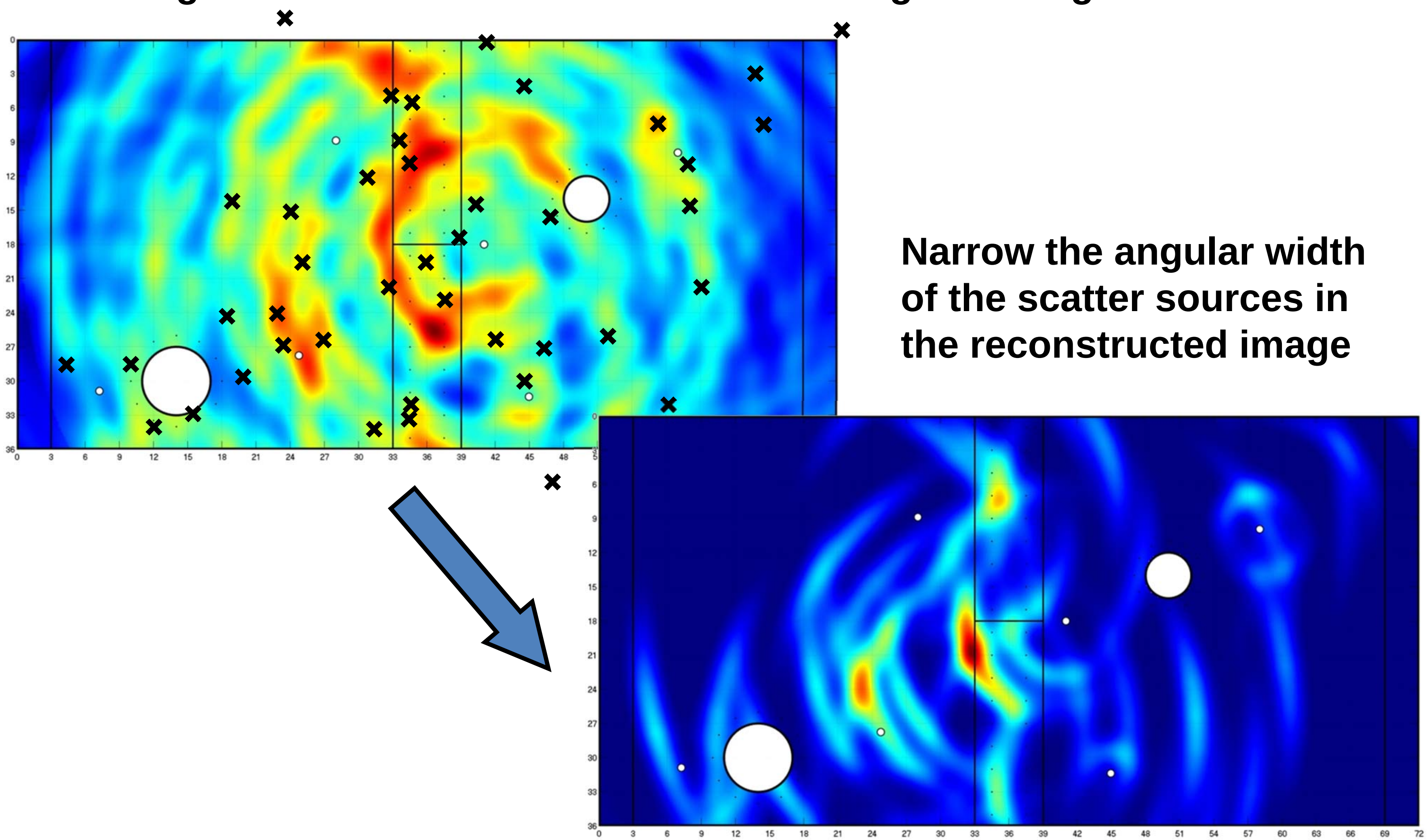


Image Processing

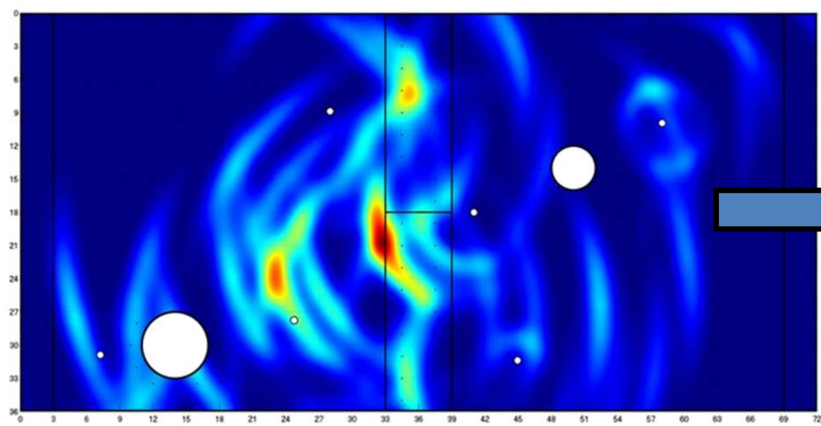
Raw Image with Identified Scatter Sources using Matching Pursuit



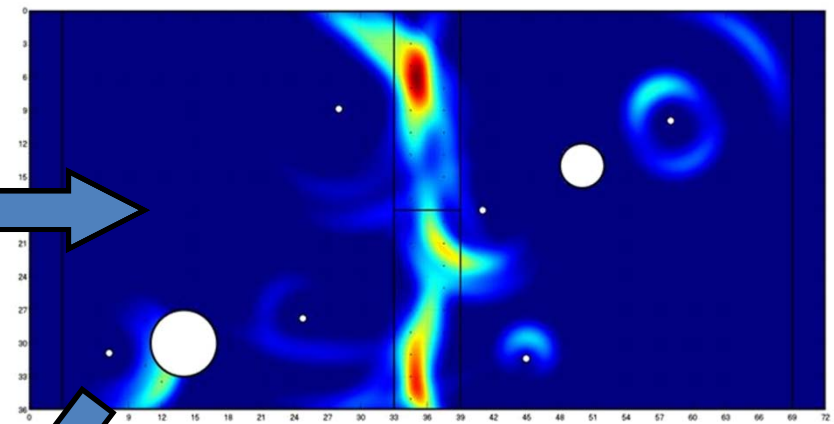
Narrow the angular width of the scatter sources in the reconstructed image

Visualization Options

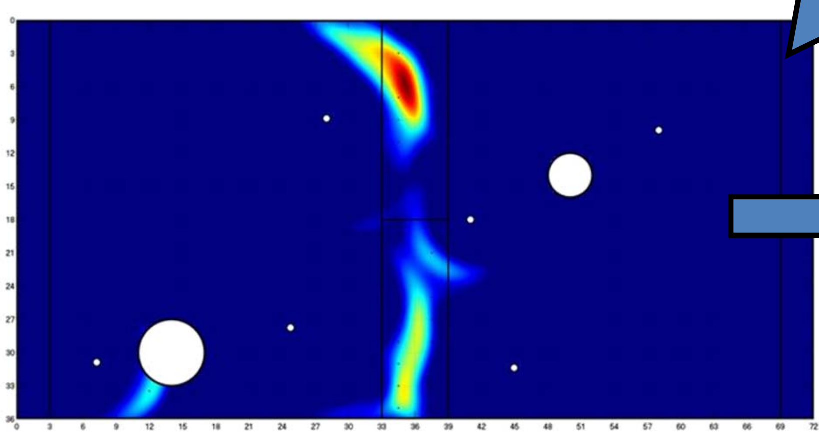
Reconstructed Image



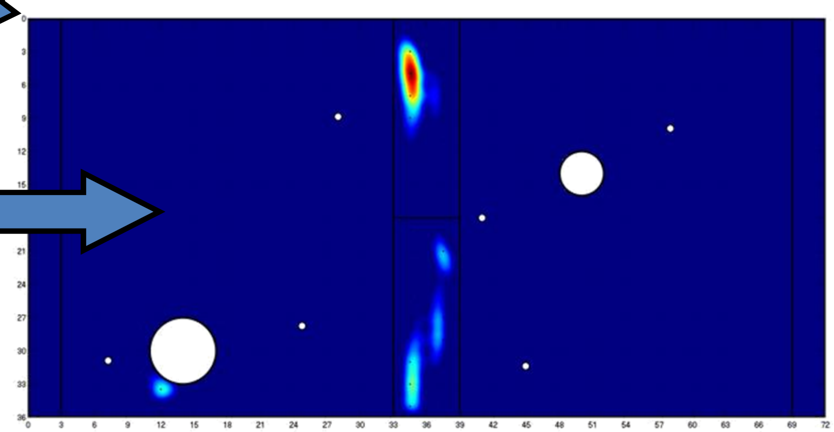
Filter impossible scatter sources (line of site, etc.)



Normalize by sensor noise floor



Apply prior probabilities*



* Only if applicable

Overall Vision

- SHM-LCM stool aims to make technology more accessible
  - enables non-expert engineers to design & use SHM systems
  - reduce cost/time of platform implantation, more commercially practical
  - envision tool used just like FEA is used today to certify structural designs
- Visualization tool aligns well with Navy strategies/initiatives
  - NDE-like interface eases transition, eliminate manual probes & teardown
  - toggle between damage modes to view diagnostic probabilistic results
  - integrate with FEA for residual performance vs damage probability plots
  - integrate with optimization tools for repair patch recommendation
- Sponsored by ONR, Littoral Combat Ship (LCS) program
  - presently participating in large scale testing of ship aluminum deck
  - intend to participate in sea-trials in late 2011 or early 2012

Acknowledgments

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