Hybrid Coherent/Incoherent Beam Forming

Diagnostic Approach to Naval Assets

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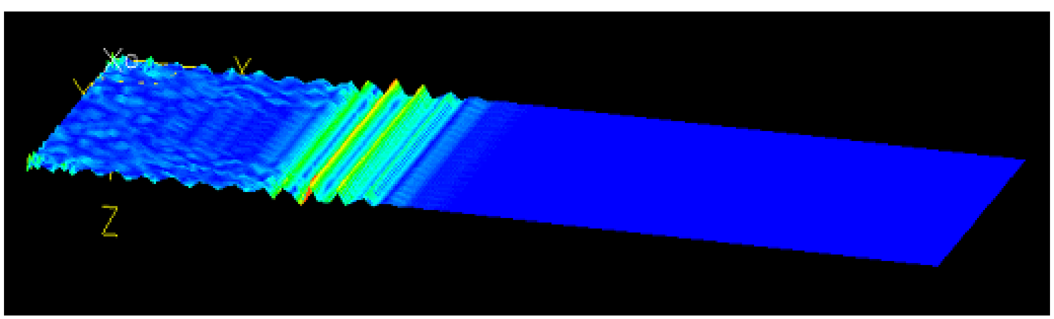
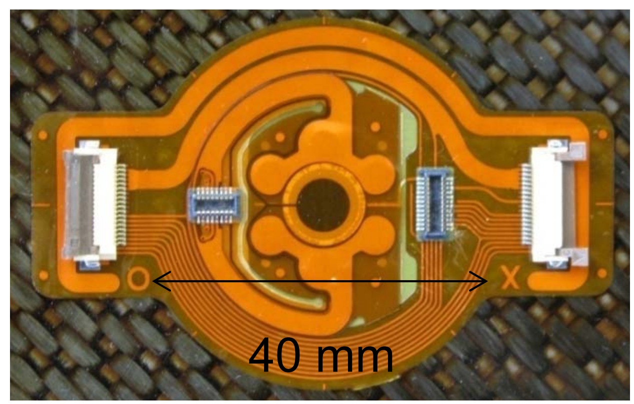
Guided Wave-Based SHM Methods

- Form of elastic perturbation that propagates in a solid medium
  - ➢ best damage size & detection range to sensor area ratio
  - ➢ sensitivity and range scales with input power level (with limitations)
  - ➢ advantages for detecting/characterizing local damage over large areas

- Research utilizes concentric piezoelectric transducers
  - ➢ central actuator emits omnidirectional narrowband excitation
  - ➢ surrounding 6 sensors record resulting echo response
  - ➢ precise position enables the collection of relative phase information

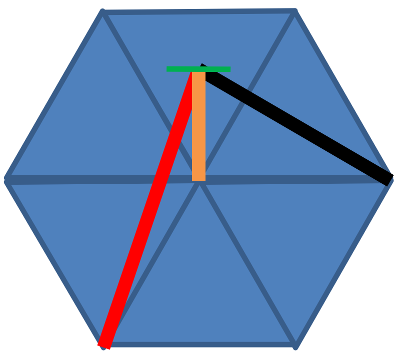


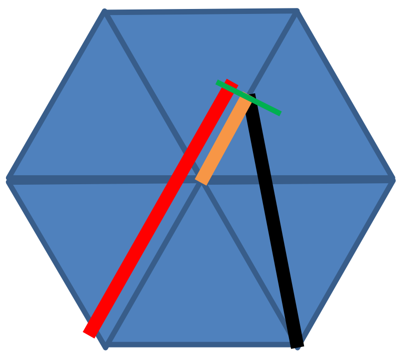


Motivations: Sensor Density

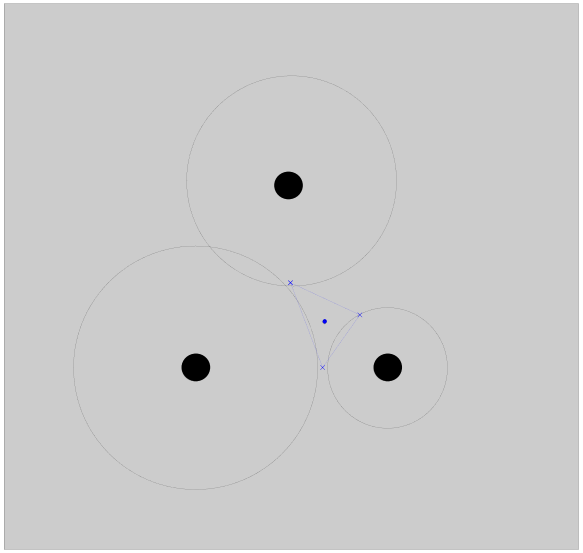
- Traditional methods need high sensor density for good location
  - pitch-catch measures delays and/or scatter along direct sensor line paths
  - pulse-echo determines reflected radius of damage from TOF
  - both cases require at least 3 nodes in close proximity to triangulate
- Prediction resolution scales w/sensor array proximity (density)

Pitch-Catch GW Methods





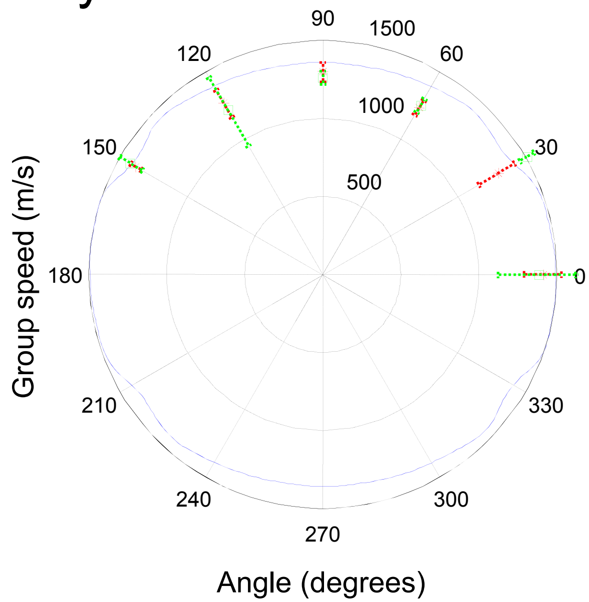
Pulse-Echo GW Methods



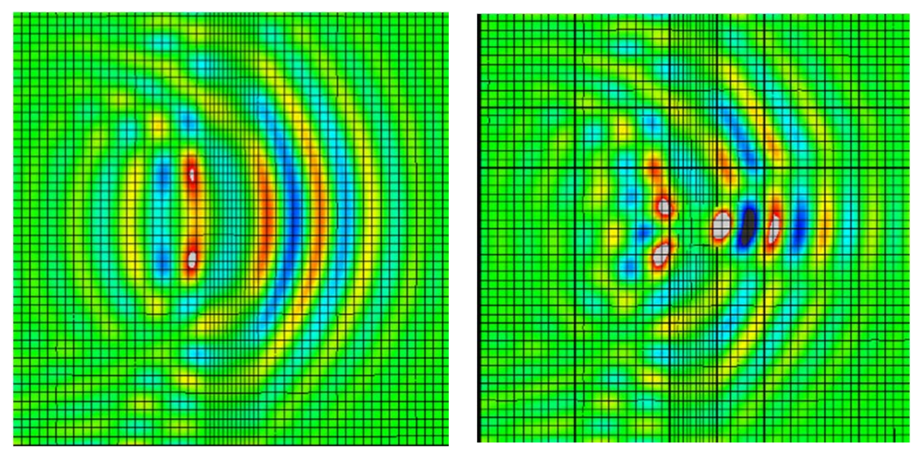
Motivations: Wave Velocity

- Complications arise in non-isotropic/homogeneous applications
  - composite & anisotropic materials present velocity ellipses & stars
  - stiffened regions with ribs or doublers exhibit local acceleration of wave
  - tapered or ply-drop-off regions yield continuously changing velocity
- Prediction resolution scales w/accuracy of wave velocity as f(θ)

Velocity as a function of composite θ



Wave acceleration through ribs



Ultrasonic Beam Forming

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- Present system is analogous to active sonar
  - each node actuates a narrowband "ping" using central actuator
  - pulses propagate, reflect and scatter at geometric features & damage
  - response sensed by 6 local sensing elements
- In traditional active sonar, bearing is determined by:
  - physically arranging array to maximize its sensitivity in one direction, then mechanically orientate array to scan multiple directions
  - artificially introduce delays in acquired, digitized responses to electronically steer array through a processes known as beam forming
- For SHM latter approach has two distinct advantages
  - position of the array elements can be fixed so there are no moving parts
  - single node can simultaneously scan for damage in every direction

Incoherent Beam Forming

- Where relative phase velocity is different & unknown between transducer pairs incoherent beam forming must be used

- *Envelopes* of waveforms must be summed together to eliminate the dependence on phase, otherwise risk:
  - destructively interfering at the true location of damage
  - constructively interfering away from damage due to phase mismatches

- If baseline-subtracted waveform from each transducer pair *m* according to its complex analytic signal is $w_{nm}(t)$, then statistic for incoherent detector for damage at *x* reduces to:

$$T_{\mathrm{I}}(\boldsymbol{x}) = \sum_{m=1}^{M} \left| w_m \left(t - \tau(m, \boldsymbol{x}) \right) \right|$$

where $\tau(m, \boldsymbol{x})$ is the time of flight from transducer *m* pair to *x*

Coherent Beam Forming

- If relative phase velocity between transducer pairs is the same, delayed waveforms can be combined without enveloping
  - summation tends to destructively combine at all locations except damage
  - for narrowband signals, time delays are substituted by faster phase shifts
- For average phase velocities along paths to each region of the structure to be same, transducers must be very closely spaced
  - less than a characteristic interrogation wavelength apart
  - limits coverage of the structure for a single transducer pair
- Statistic for coherent detector can be expressed as

$$T_C(\boldsymbol{x}) = \left| \sum_{m=1}^{M} w_m\left(t - \tau(m, \boldsymbol{x})\right) \right|$$

where magnitude is taken after summation rather than before

Hybrid Beam Forming

- Hybrid approach enables both effective imaging & effective coverage of large areas
  - across transducers in each node, average phase velocity is roughly equal, allowing for coherent beam forming
  - node to node, average phase velocity is generally not equal, scattered signals must be combined incoherently

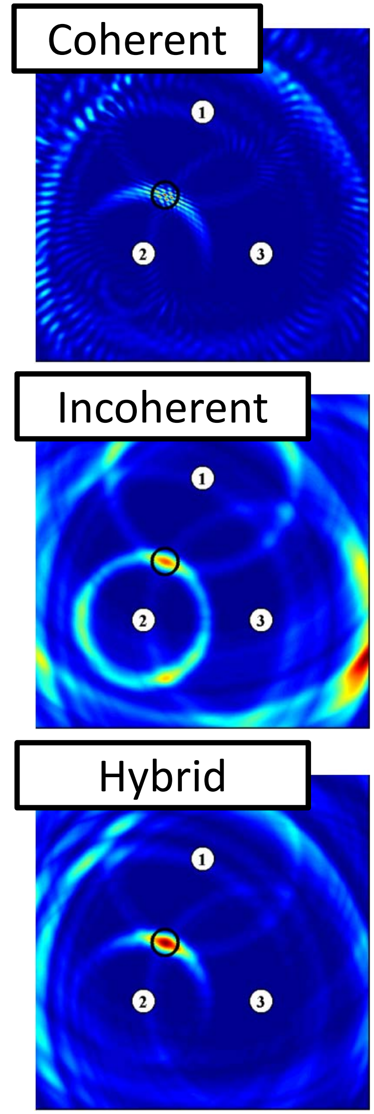
<u>Coherently</u> combine waveforms from sensors in nodes

Analytic signal

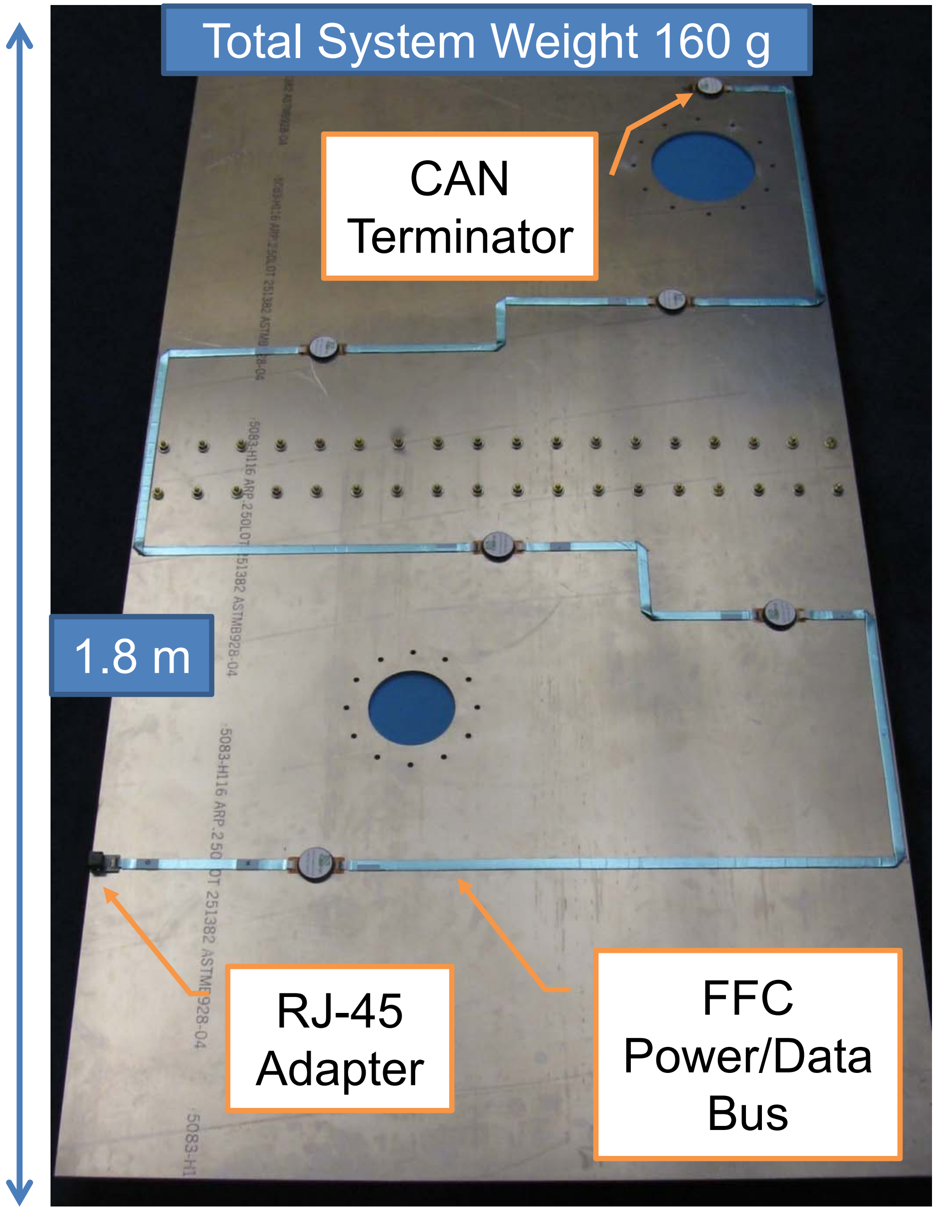
Time of flight to imaging point

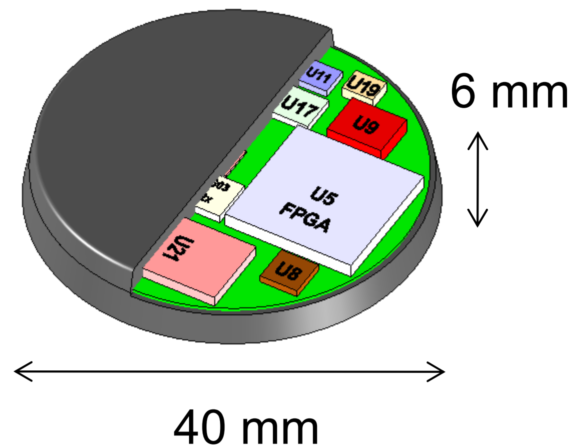
$$T_{\mathrm{H}}\left(\boldsymbol{x}\right)=\left|\sum_{n-1}^{N}\left|\sum_{m=1}^{6}w_{nm}\left(t-\tau\left(n,m,\boldsymbol{x}\right)\right)\right|\right|$$

<u>Incoherently</u> combine summed waveforms from nodes



SHM System Installation





Data Analysis & Reconstruction

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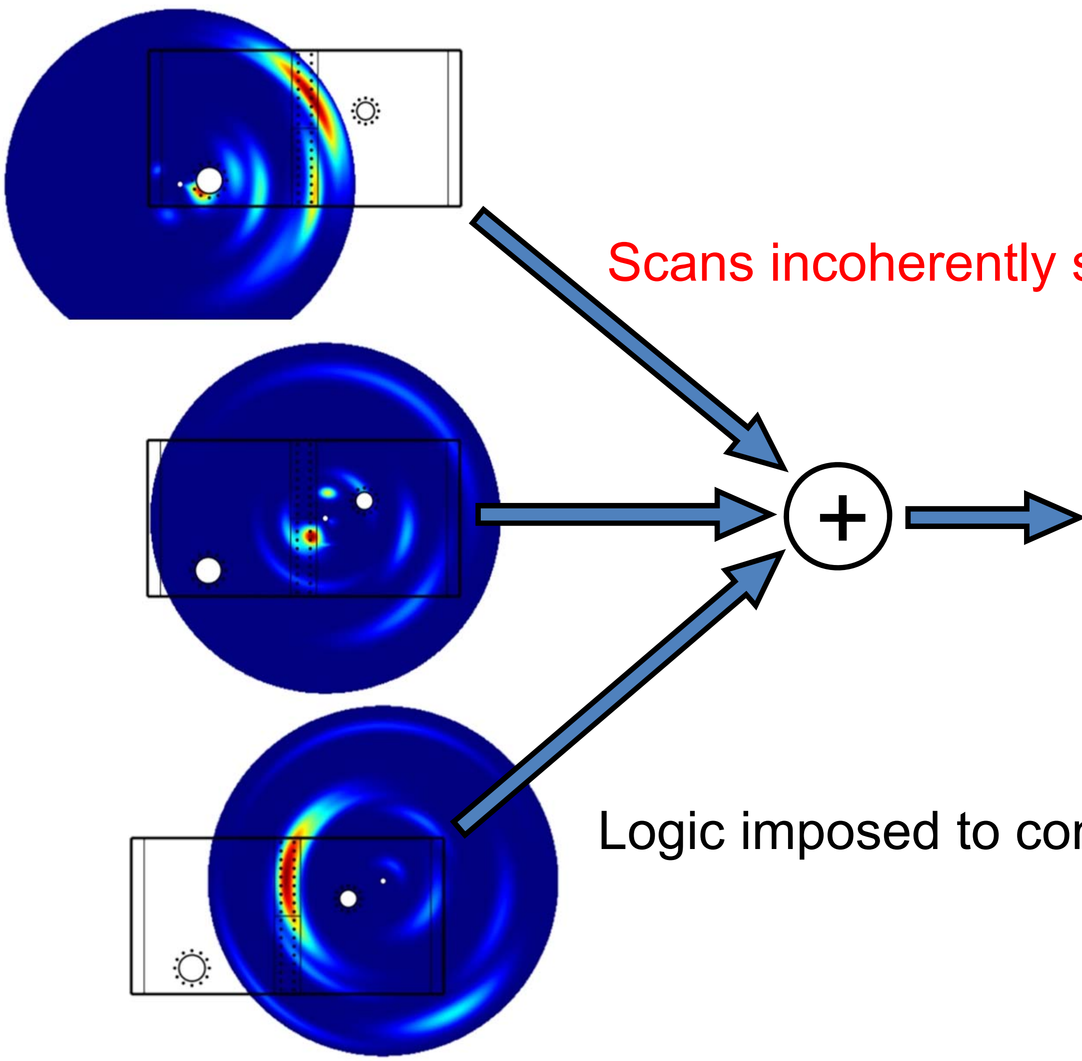
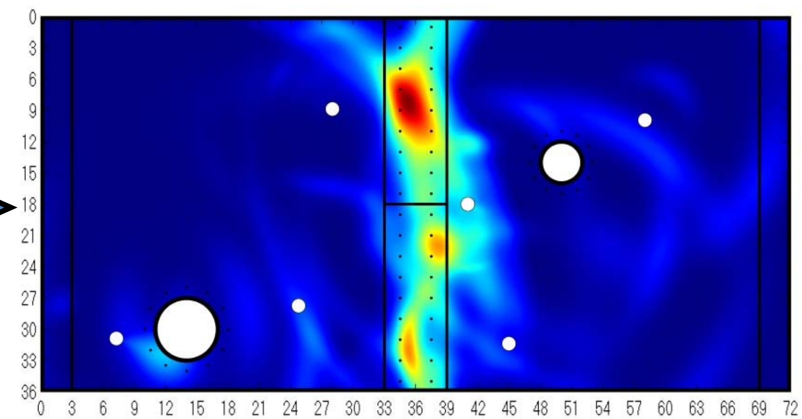
Each node processes phase-coherent, location independent “sonar-scan”



Scans incoherently summed to form composite image

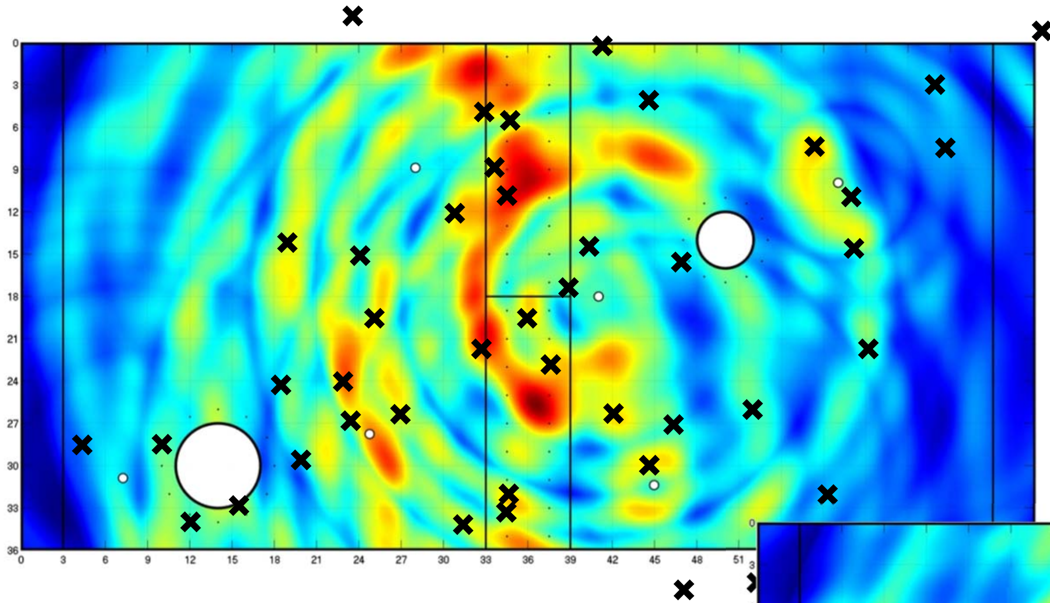


Logic imposed to compensate for view area obstacles

color represents # of standard deviations above mean of damage-free data

Image Processing I

Raw Image → Identify Scatter Sources using Matching Pursuit



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Reconstruct Image Using Identified Scatter Sources

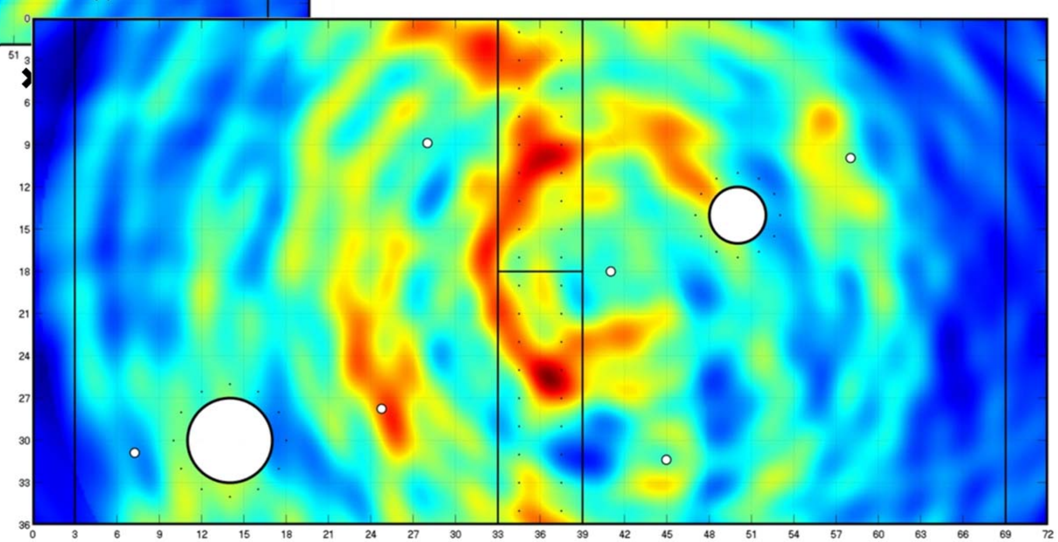
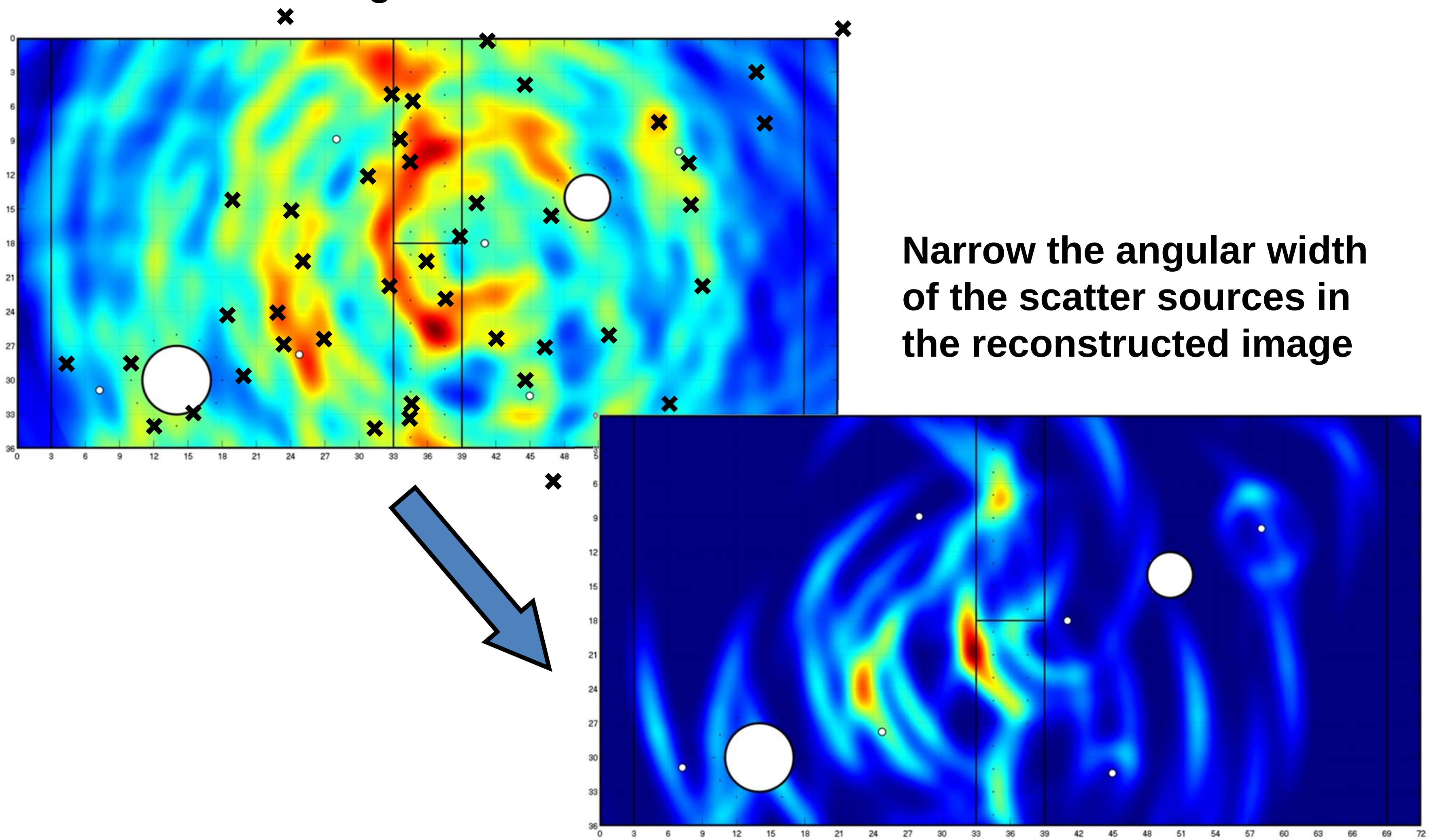


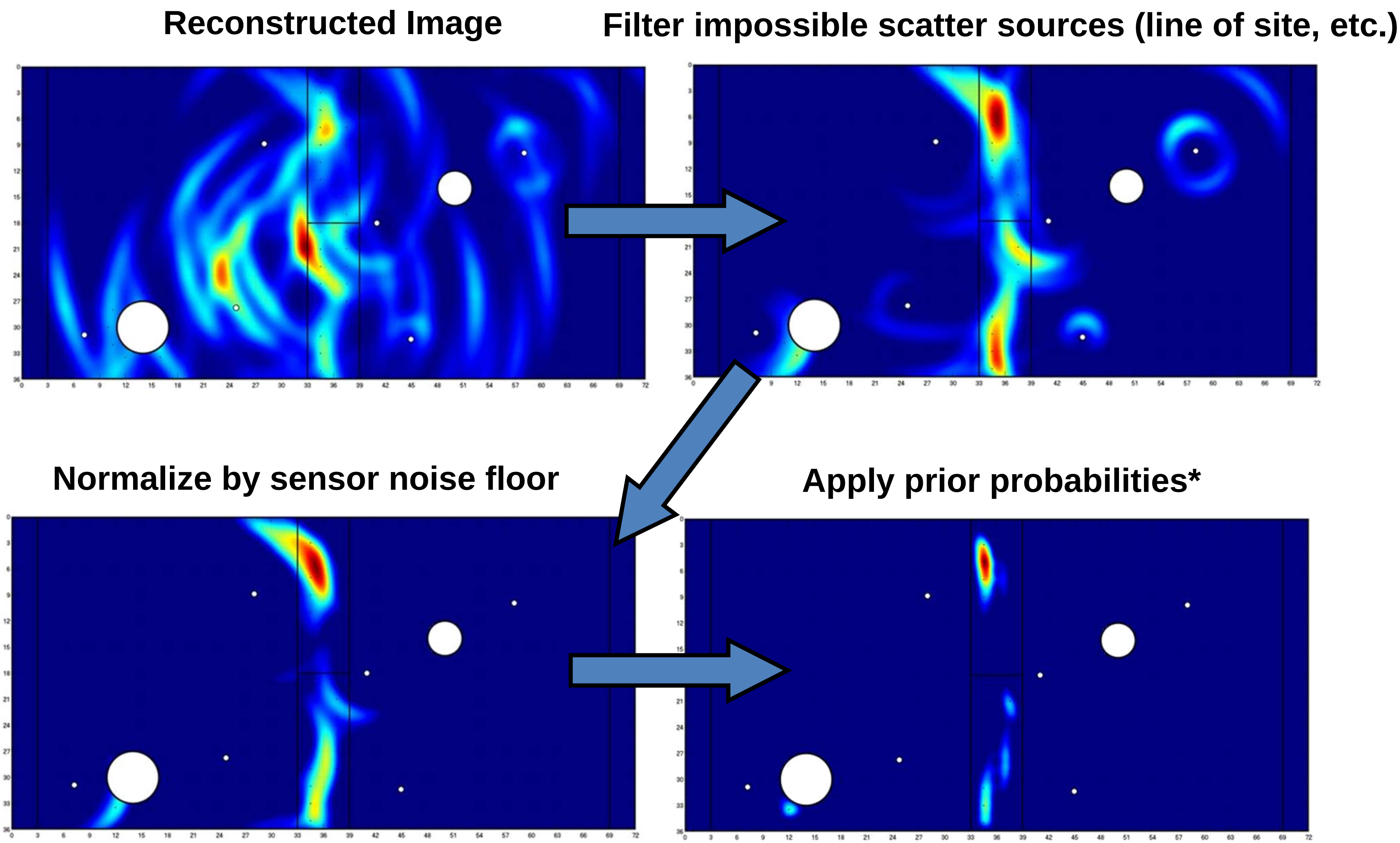
Image Processing II

Reconstructed image



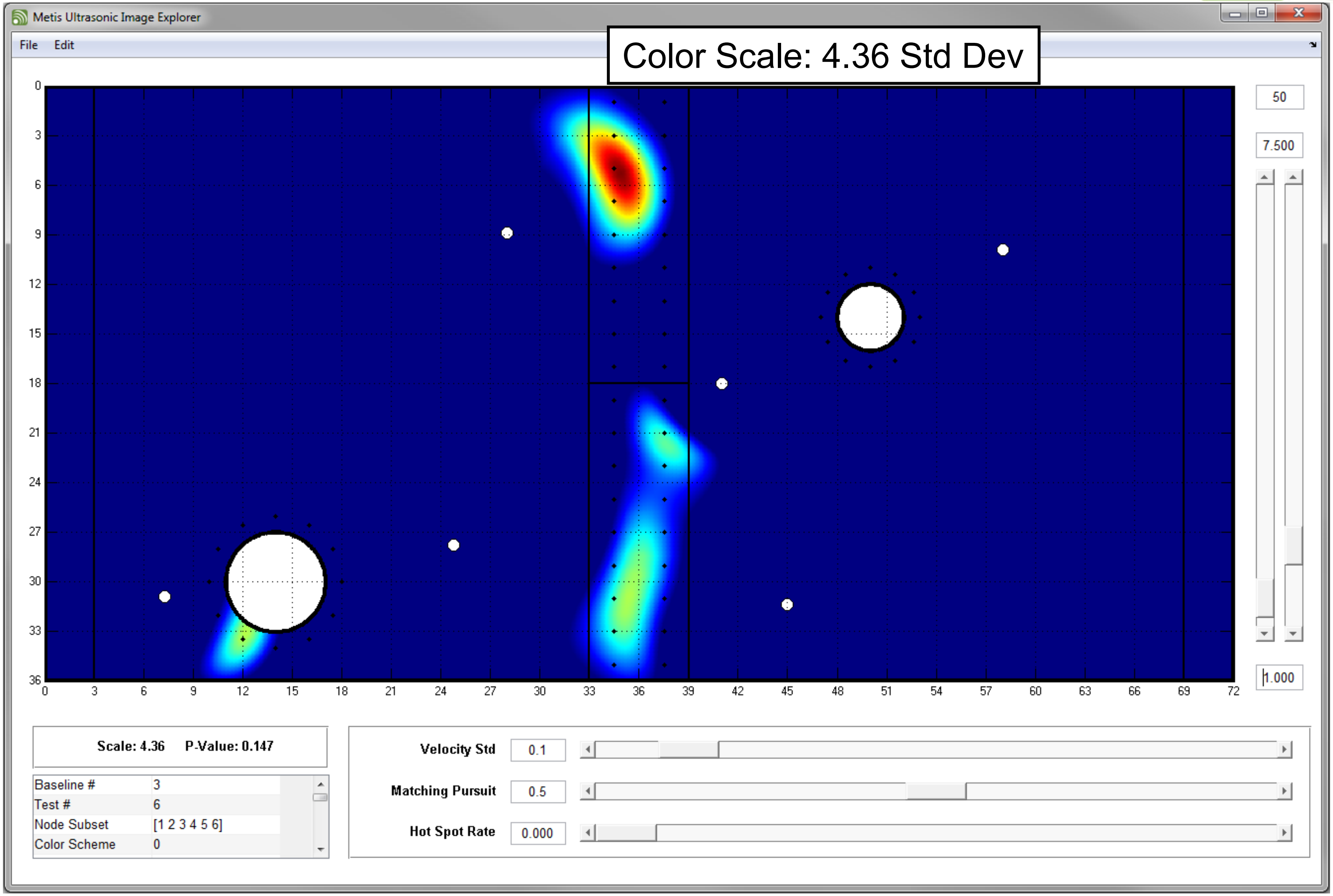
Narrow the angular width of the scatter sources in the reconstructed image

Image Processing III

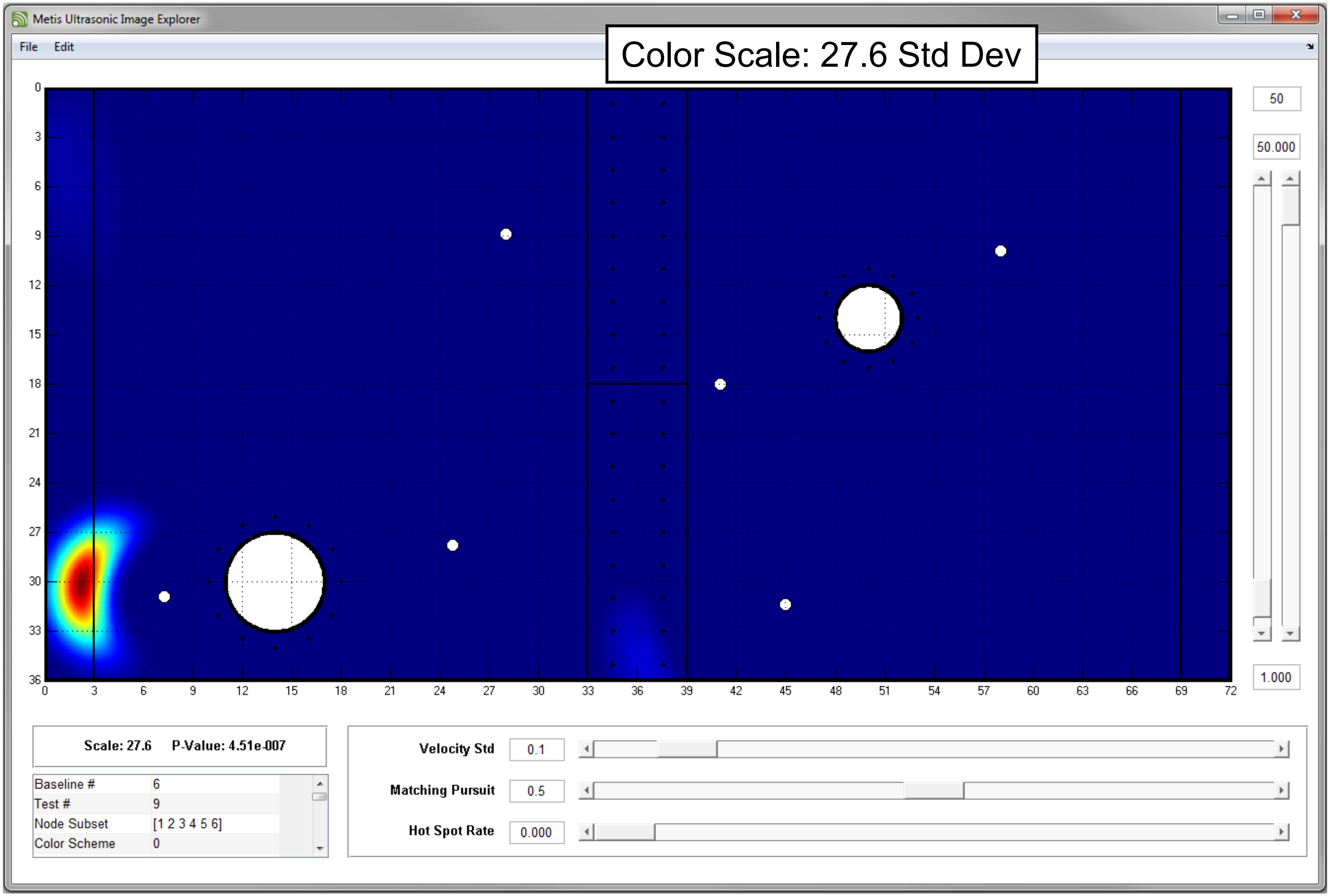


* Only if applicable

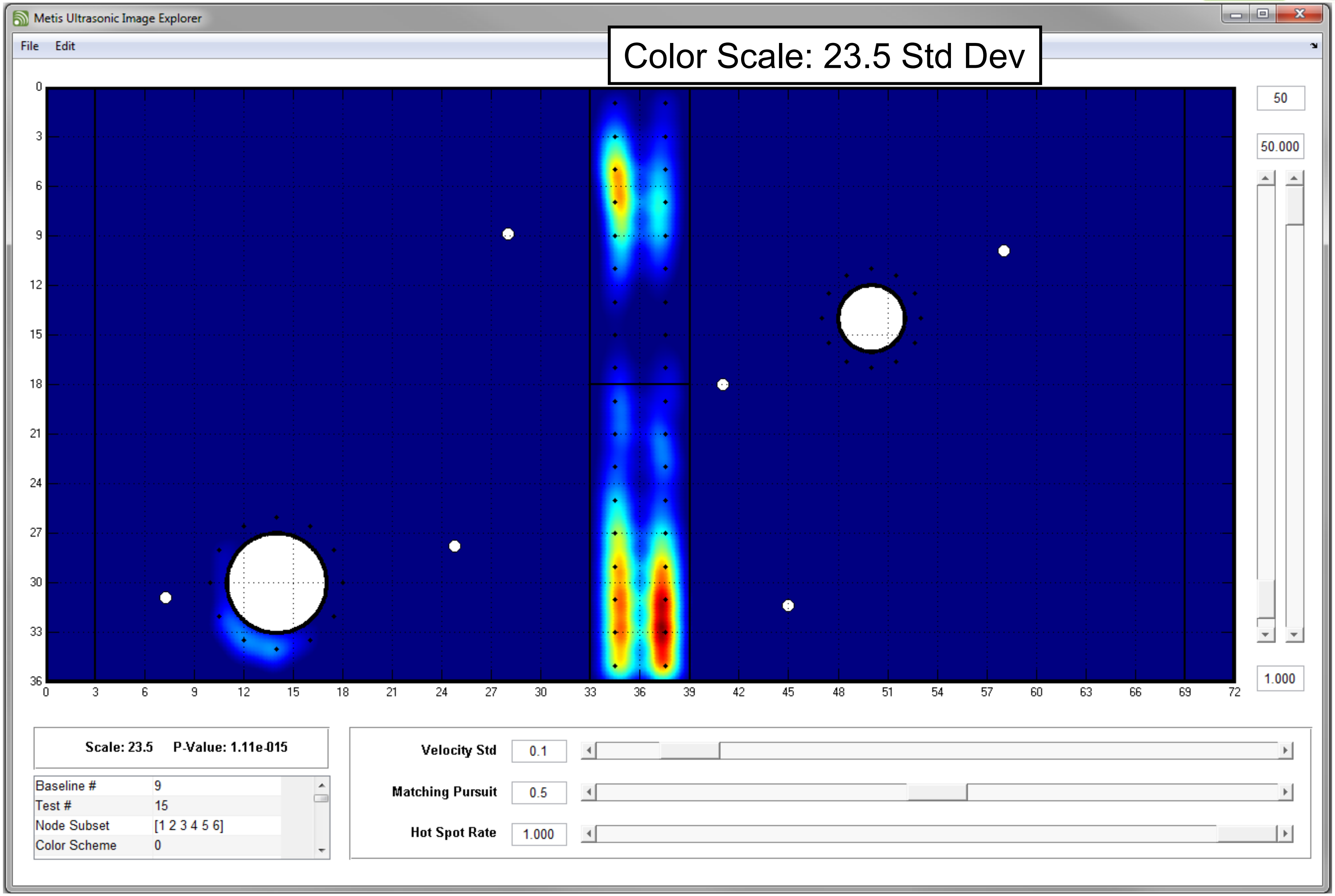
Results for Test Case 1



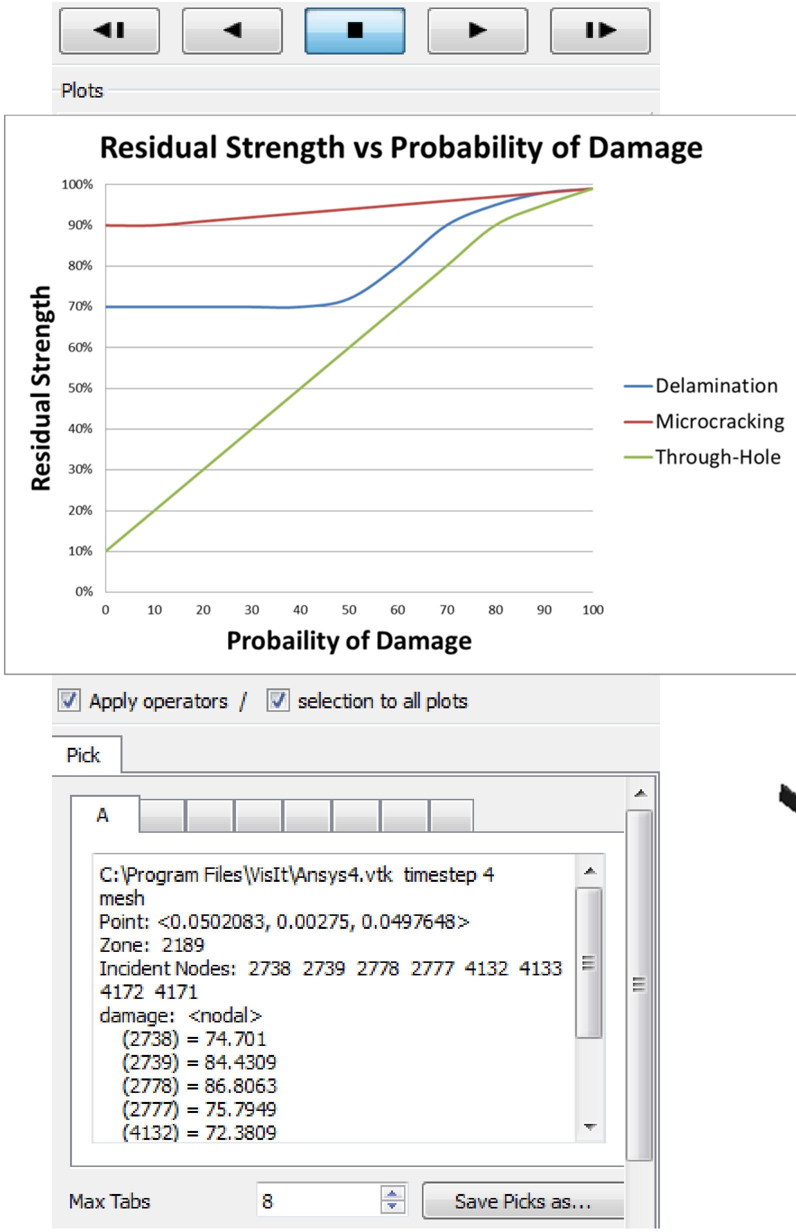
Results for Test Case 2

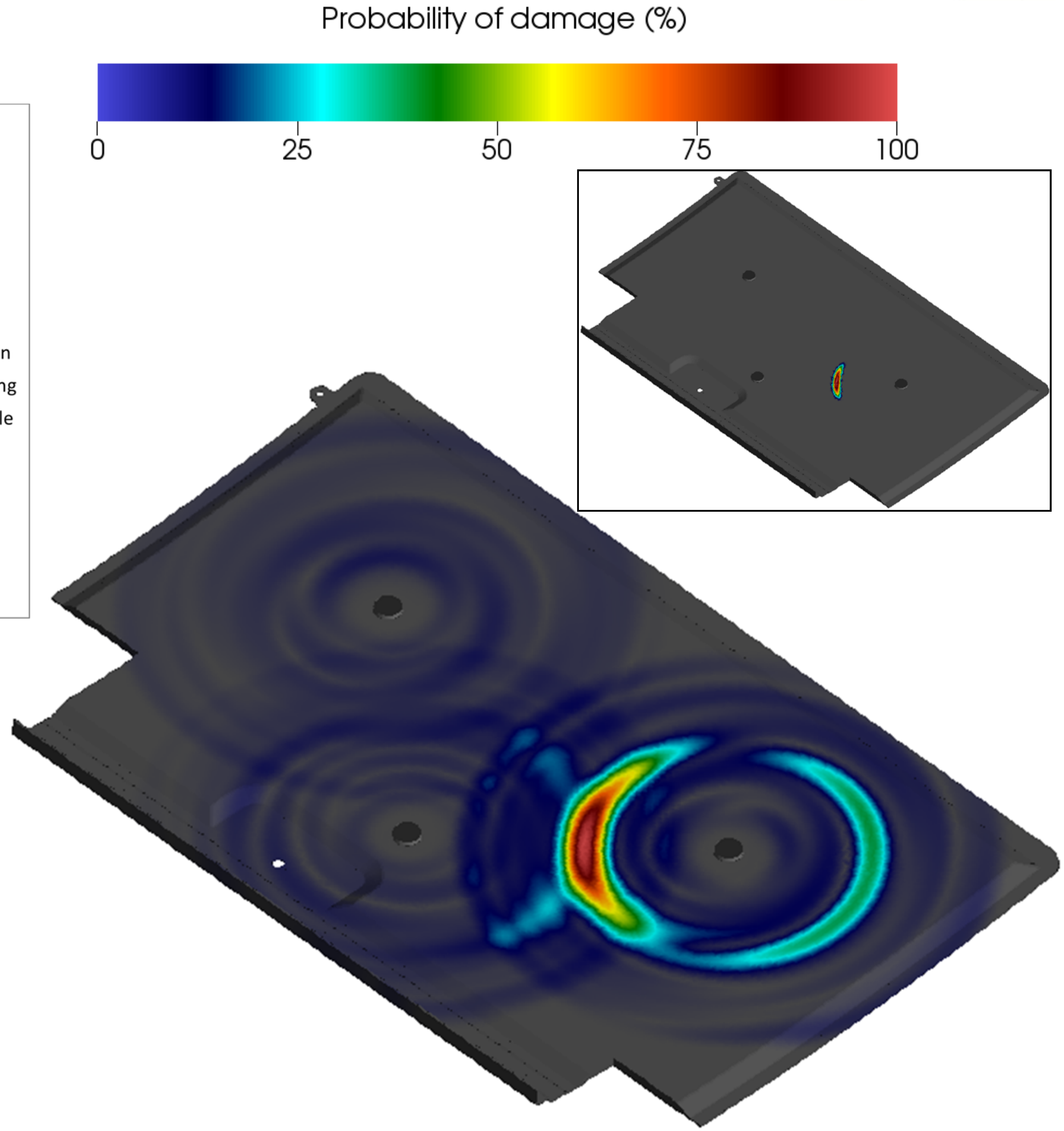


Results for Test Case 3 (Weighted)



Diagnostics to Prognostics





Summary

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- Hybrid coherent/incoherent beam forming approach enables both effective imaging & effective coverage of large areas
  - coherent across transducers in each node, average phase velocity $\cong$
  - incoherent node to node, average phase velocity $\neq$
- Method provides path to reliable & efficient damage location detection for large-scale complex composite structures
  - requires minimum sensor density
  - requires no material properties or structural configuration information
- Future work
  - embed algorithms within FPGA for digital sonar output
  - couple method with damage characterization algorithms (type)
  - explore diagnostic to prognostic link further

Acknowledgments

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