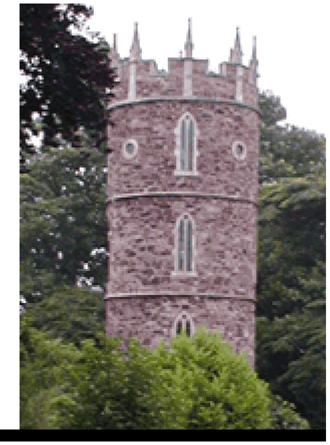
Imaging Algorithms for Locating Damage via in situ Ultrasonic Sensors



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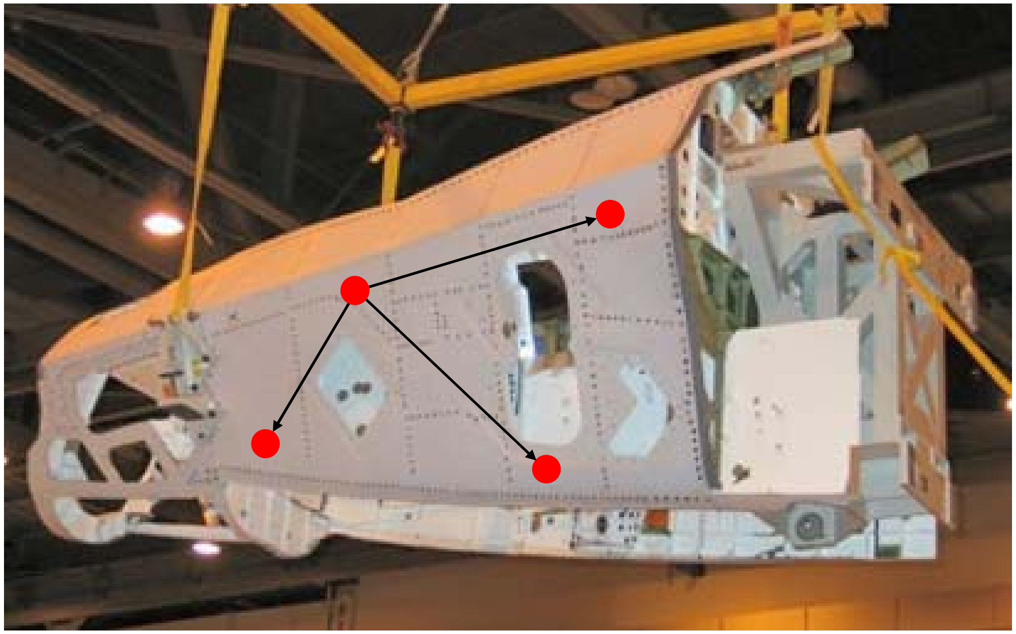
Damage Localization With Guided Ultrasonic Waves (Lamb Waves)

- Motivation: Detect and localize damage in plate-like structures with a spatially distributed array of attached piezoelectric transducers.



Flat Plate Experiments

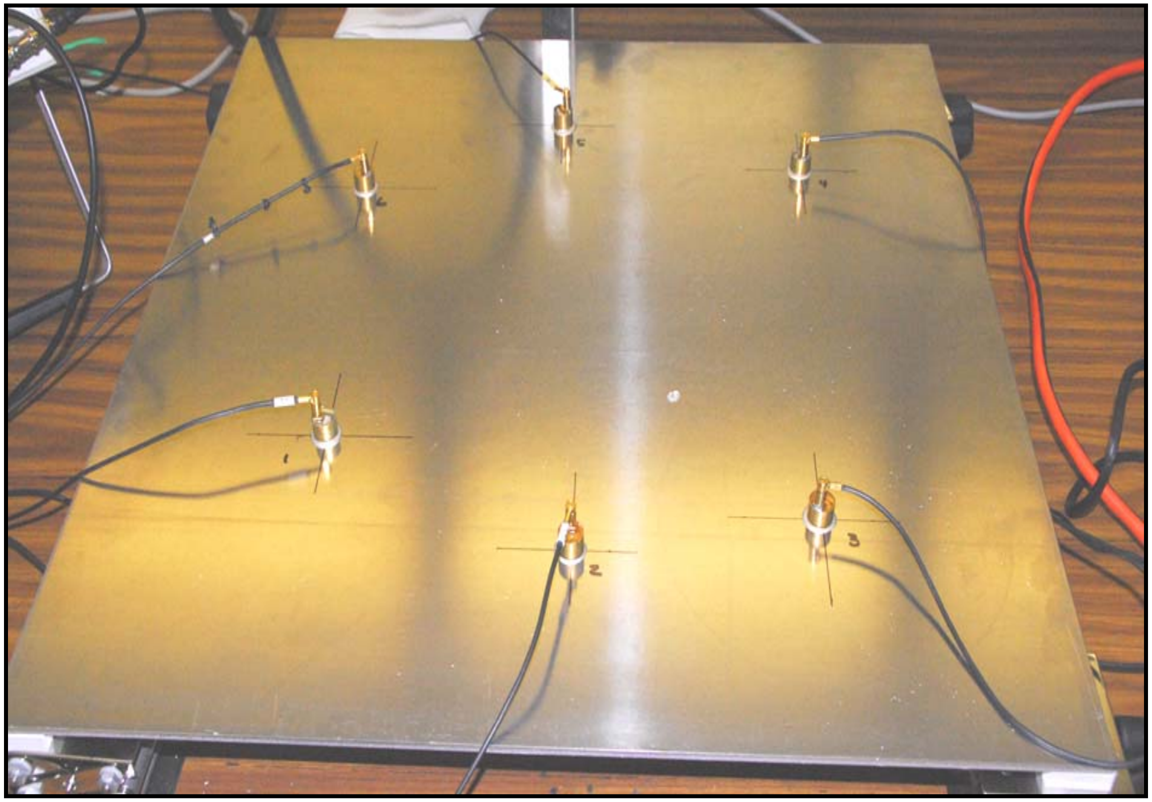


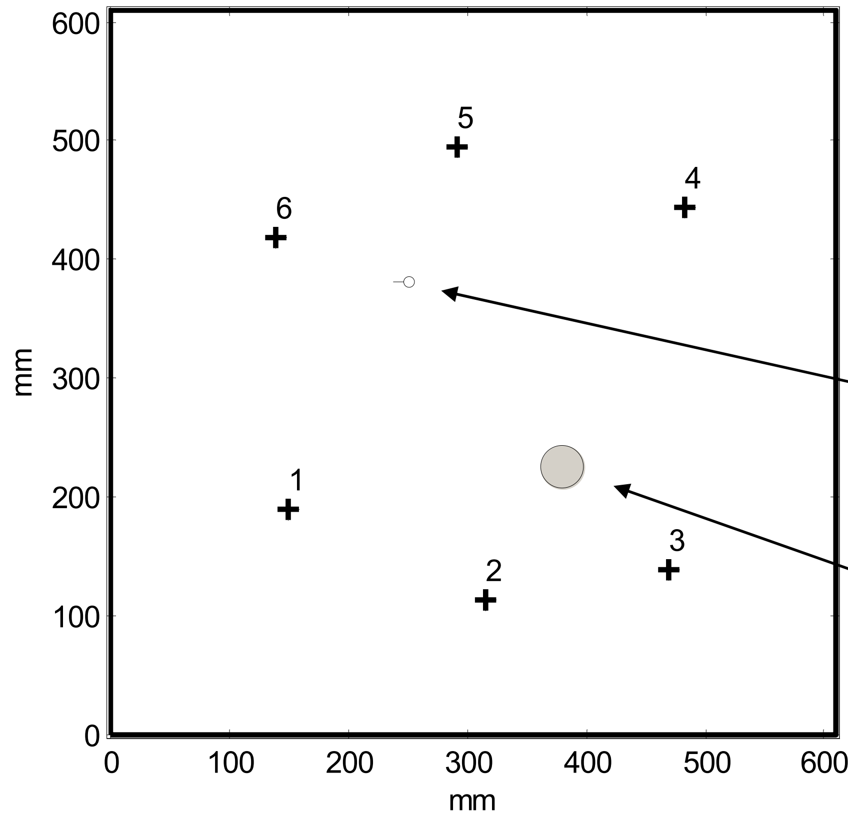
Plate instrumented with six active ultrasonic sensors

Specimen and Transducers

6 Transducers, 15 Pairs

Baseline: Plate with simulated corrosion but no hole or notch

Transducers: 12.5 mm in diameter, primarily generate the S_0 mode



Data were recorded between all sensor pairs before and after introduction of damage (hole drilled / notch added)

Drilled Hole with Notch

Simulated Corrosion (added as part of an earlier experiment)

Plate Thickness of 4.8 mm

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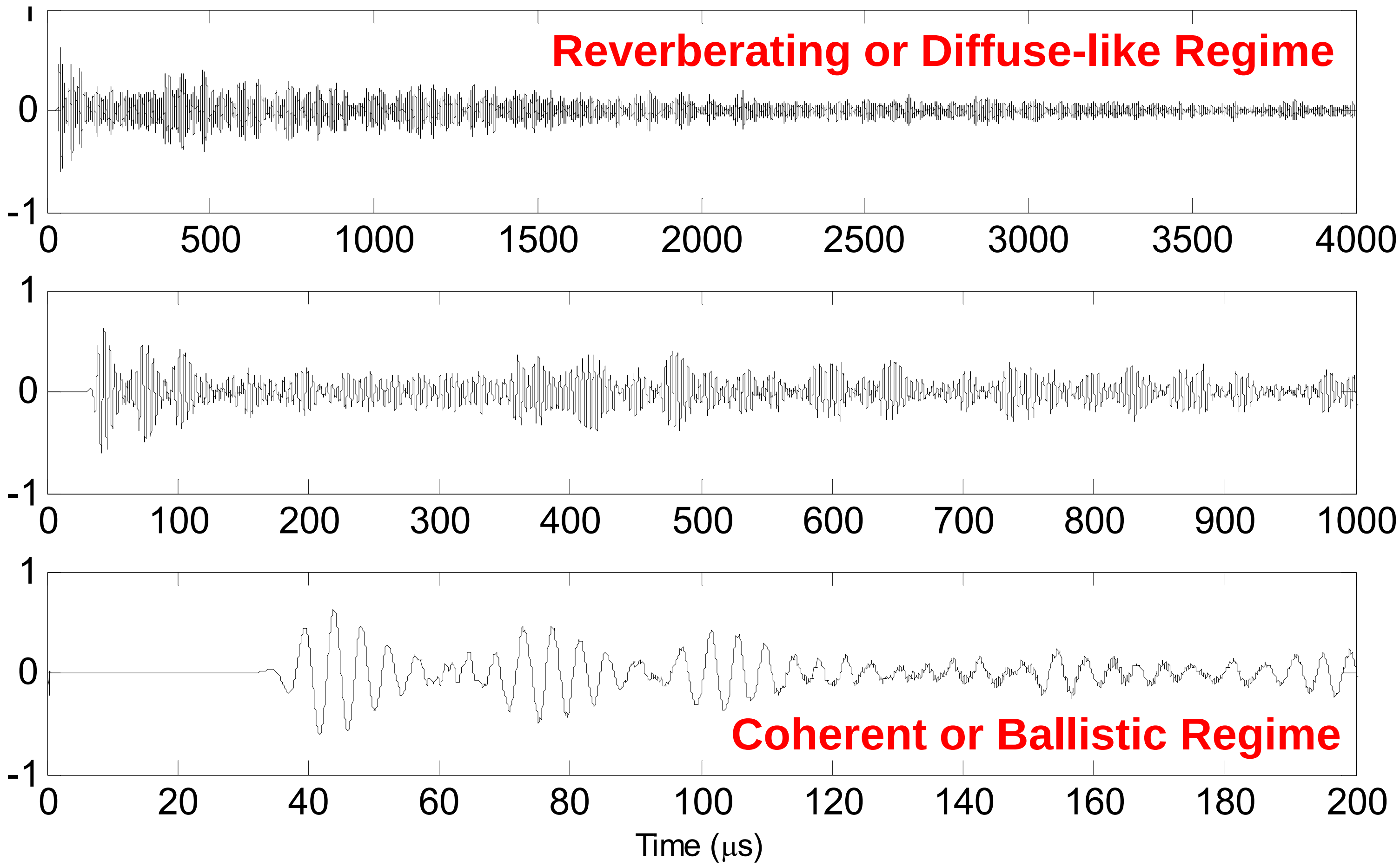
Signal Examples

Long-time and Short-time Behavior



Time for an S_0 wave to traverse the plate: ~110 μs

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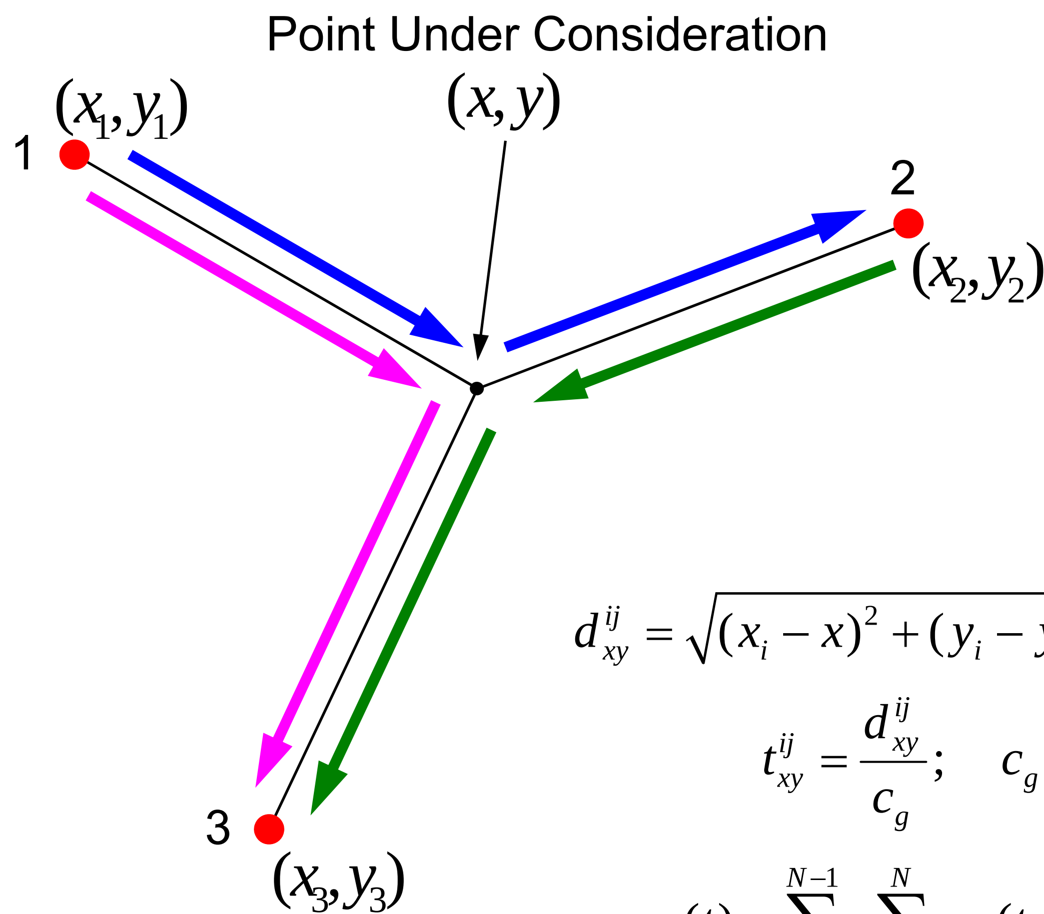
Imaging Strategy

- Images are typically generated to localize damage after it has been detected
- Imaging can also help reduce false alarms if detected damage is not confirmed by good localization
- Signals are first band-pass filtered to restrict the frequency content since the Lamb wave modes are very dispersive
- The imaging methods considered here are based upon the differenced signals (signal – baseline)

Time-of-Arrival (Ellipse) Imaging
(Delay-and-Sum Beamforming)



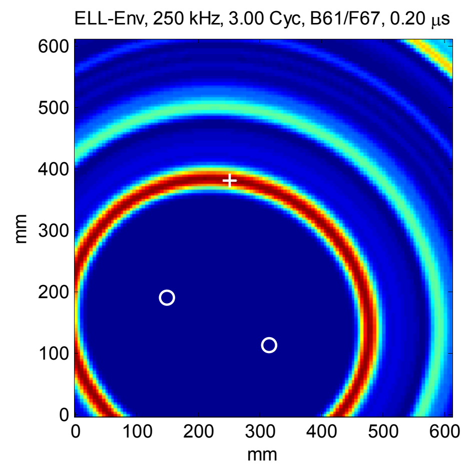
- All transducer pairs contribute to the image at each point
- Window scattered signal as per calculated arrival time
- Sum windowed signals to form image at the point
- Scattered energy from flaws will be reinforced
- Use either raw (RF) or envelope detected signals

$$d_{xy}^{ij} = \sqrt{(x_i - x)^2 + (y_i - y)^2} + \sqrt{(x_j - x)^2 + (y_j - y)^2}$$

$$t_{xy}^{ij} = \frac{d_{xy}^{ij}}{c_g}; \quad c_g = \text{ group velocity}$$

$$w_{xy}(t) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} w_{ij}(t - t_{xy}^{ij}) \text{ and } E_{xy} = \int_{t_1}^{t_2} w_{xy}^2(t)dt$$

TOA Imaging Process



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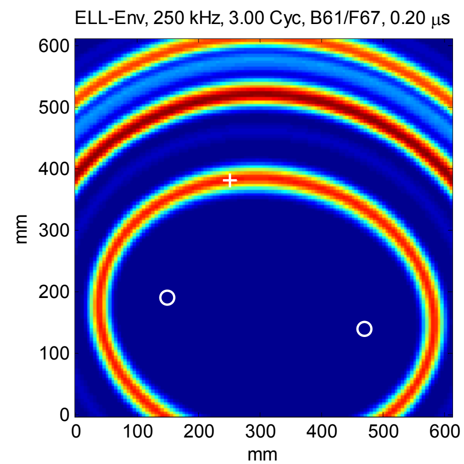

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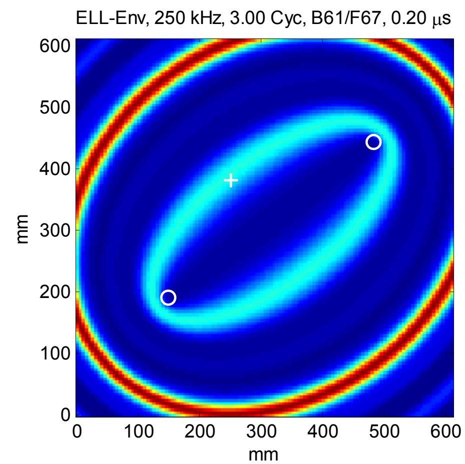

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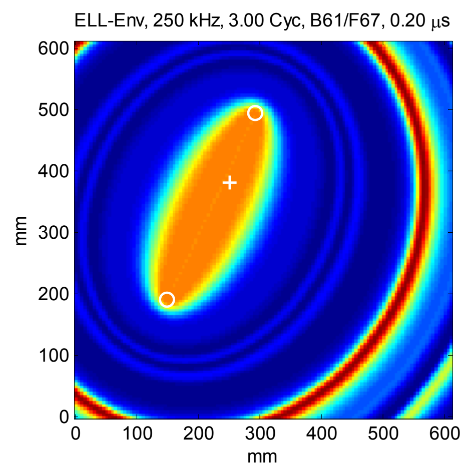

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TOA Images From Remaining 11 Transducer Pairs

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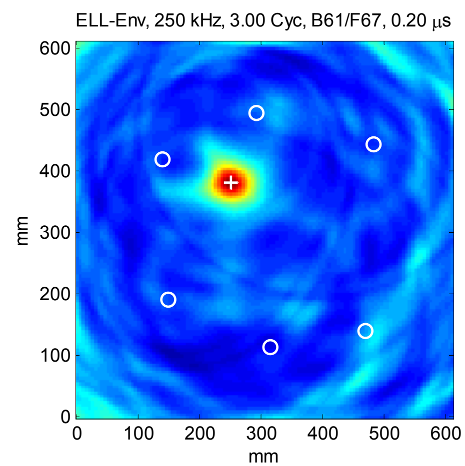


$$N_{pairs} = N(N-1)/2$$

Windowing to Reduce Artifacts

- Artifacts near the boundaries are primarily due to multiple scattering from damage and geometrical reflectors (e.g., waves scattered from damage and subsequently reflected from boundaries)
- Baseline subtraction cannot eliminate these artifacts
- One approach is to exponentially window received signals referenced from the arrival time

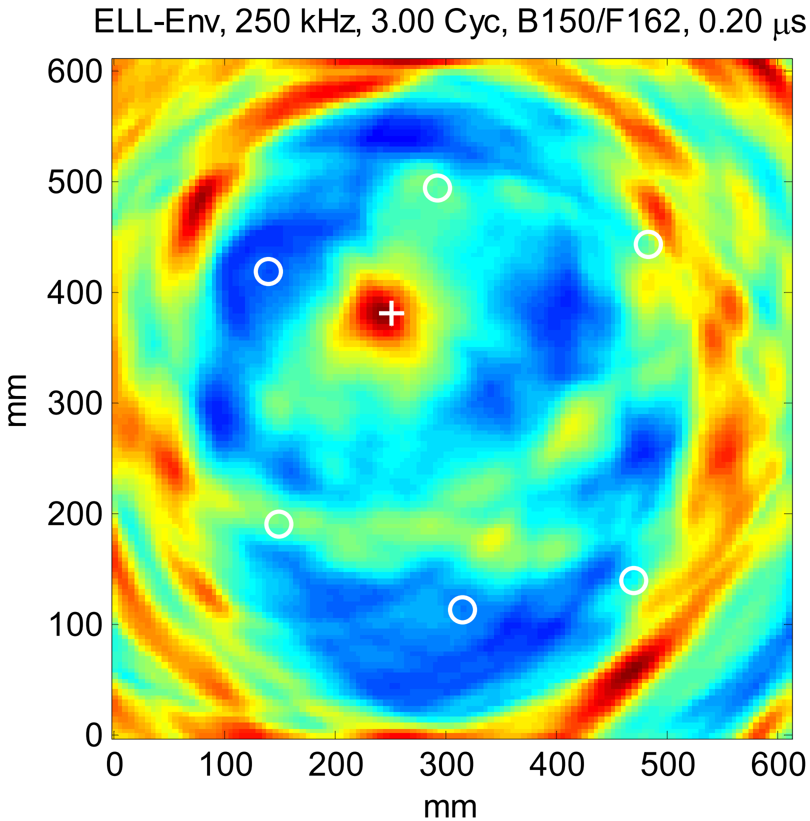
$$\widehat{w}_{ij}(t) = w_{ij}(t)e^{-(t-t_{ij})/t_d}u(t-t_{ij})$$

$$t_{ij} = \text{arrival time for transmitter } i \text{ and receiver } j$$

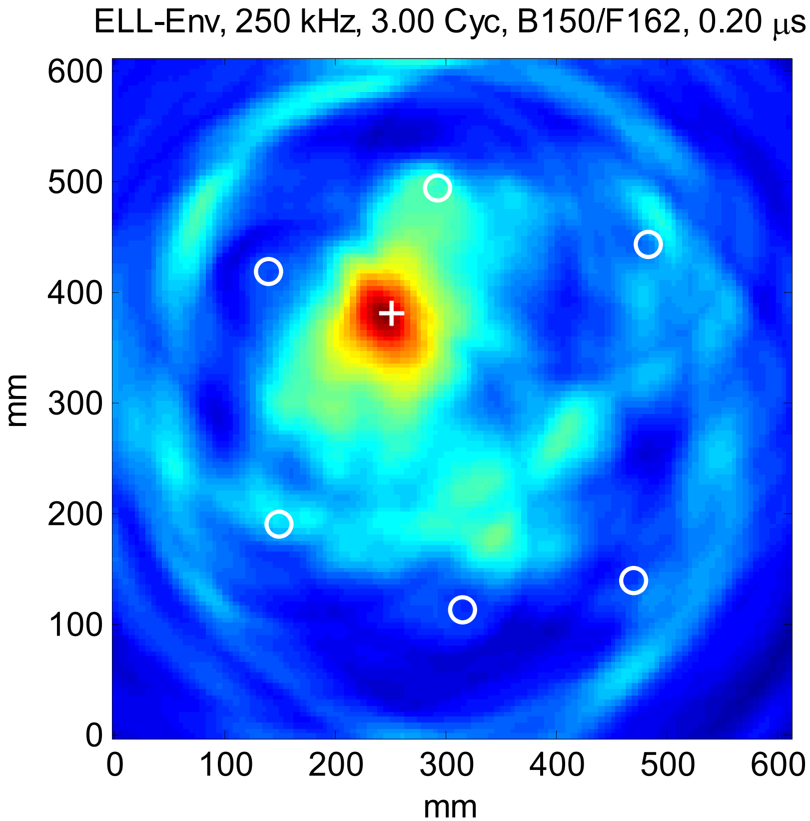
$$t_d = \text{decay constant (2x to 4x minimum arrival time)}$$

$$u(t) = \text{step function}$$

TOA Imaging – Effect of Exponential Windowing



No Windowing



Windowing, T_d = 100 μs

Damage: 9 mm Notch

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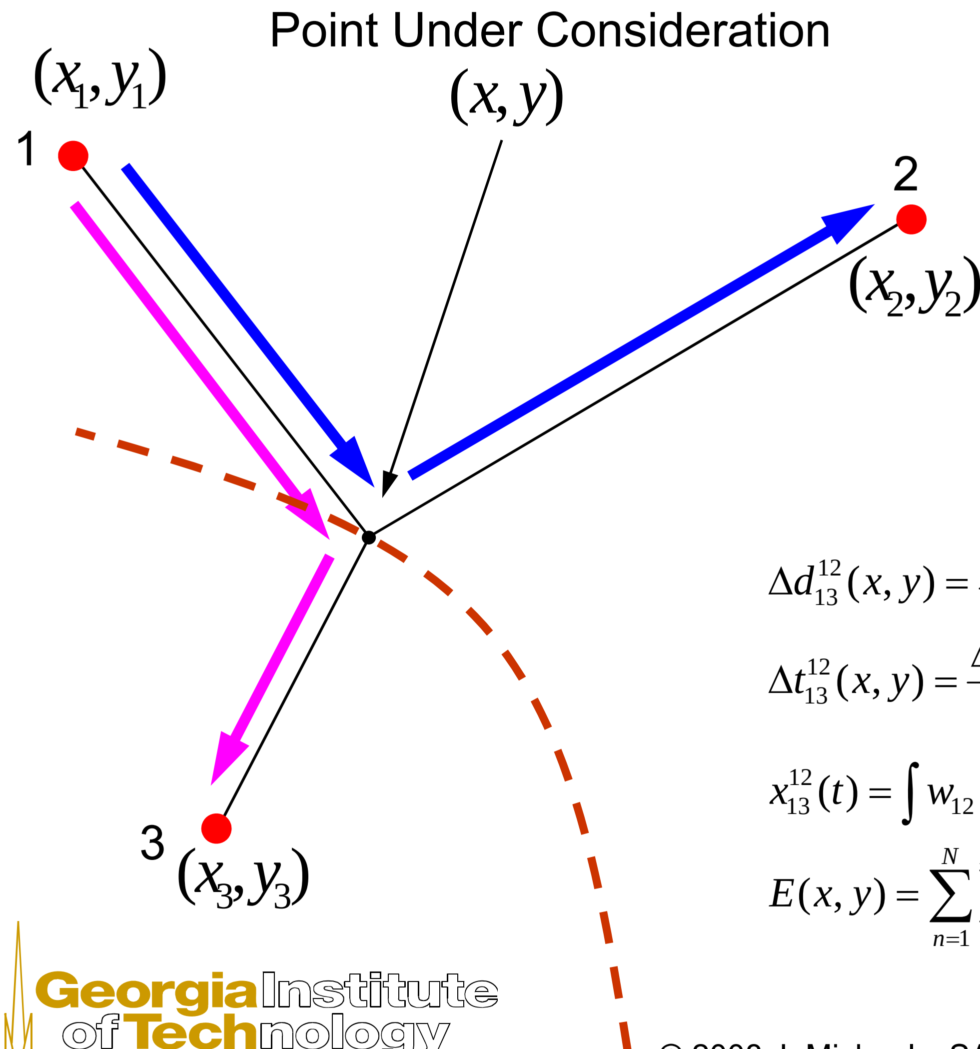
Time-Difference-of-Arrival (Hyperbola) Imaging
(Delay-and-Sum Signal Cross-Correlations)



- Form cross correlations between differenced (scattered) signals from same-transmitter signal pairs
- Sum time delayed cross correlations to form image at the point
- Use either raw (RF) or envelope detected cross correlations

$$\Delta d_{13}^{12}(x, y) = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} - \sqrt{(x_3 - x)^2 + (y_3 - y)^2}$$

$$\Delta t_{13}^{12}(x, y) = \frac{\Delta d_{13}^{12}(x, y)}{c_g}$$

$$x_{13}^{12}(t) = \int w_{12}(\tau) e^{-(\tau - t_{12})/t_d} w_{13}(\tau + t) e^{-(t + \tau - t_{ij})/t_d} d\tau$$

$$E(x, y) = \sum_{n=1}^{N} \sum_{\substack{i=1 \\ i \neq n}}^{N-1} \sum_{\substack{j=i+1 \\ j \neq n}}^{N} x_{nj}^{ni}(\Delta t_{nj}^{ni}(x, y))$$

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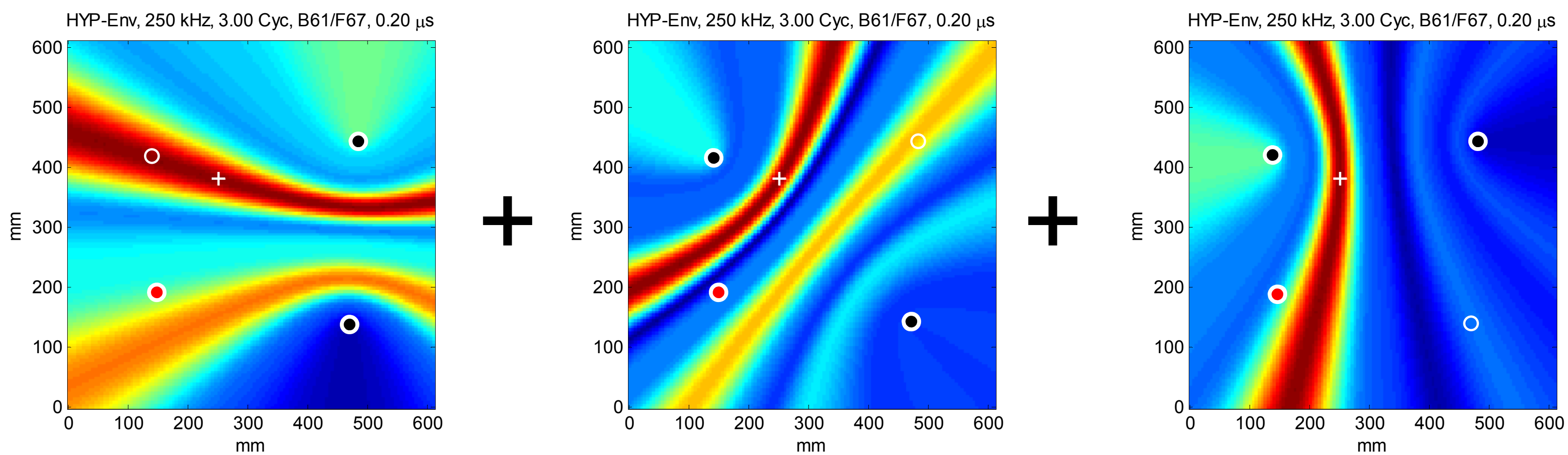
TDOA Imaging Example



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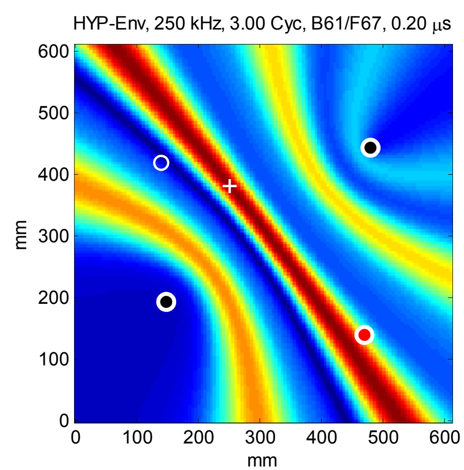

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TDOA Images From Remaining 8 Transducer Triplets

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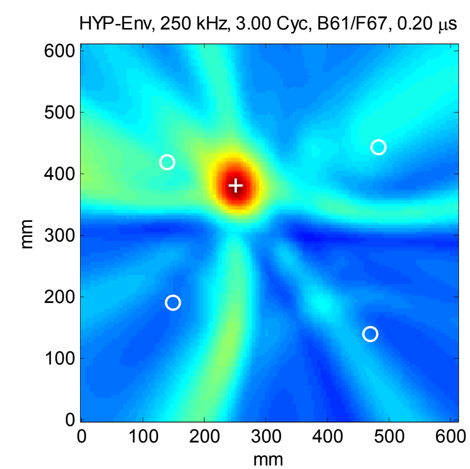

$$N_{triplets} = N(N-1)(N-2)/2$$

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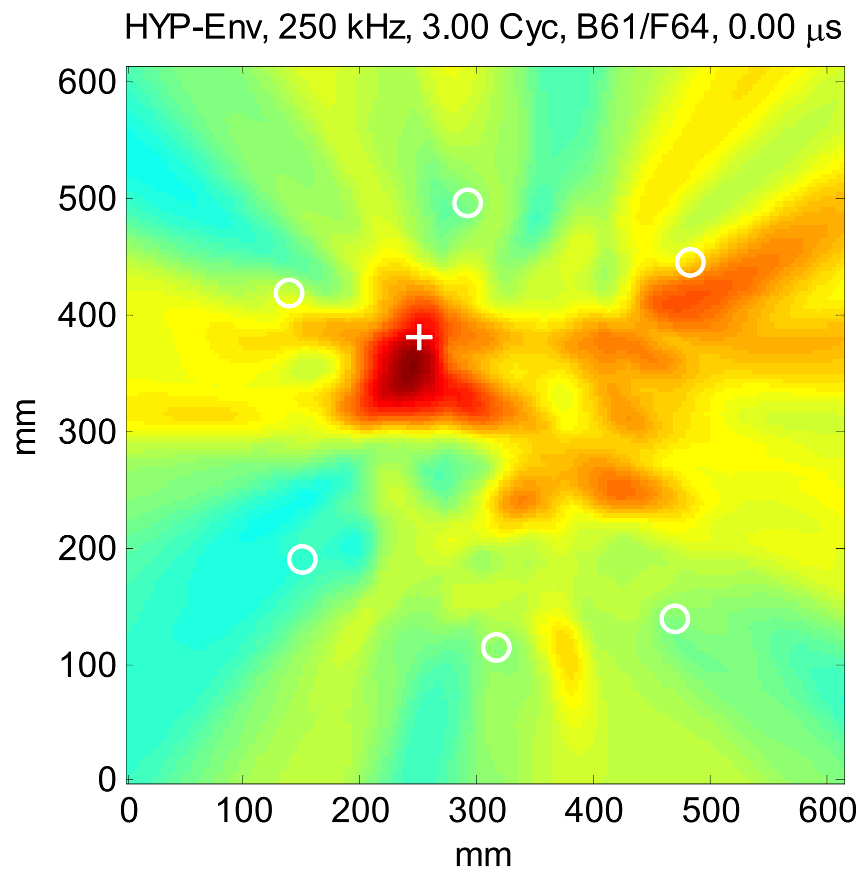
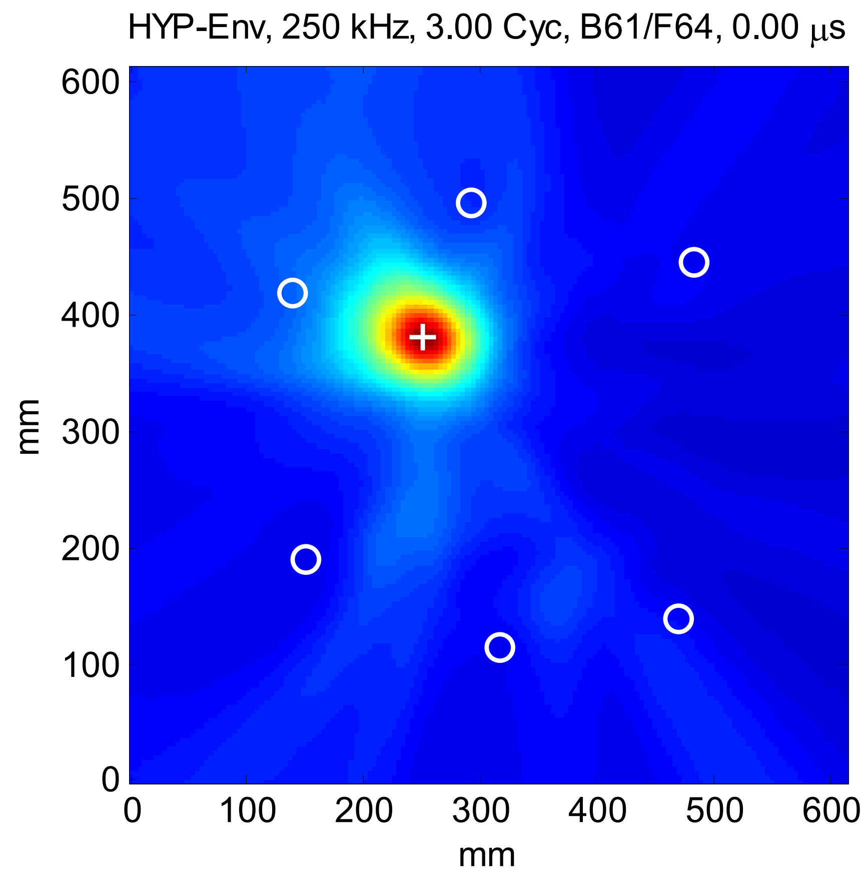
Comparison of Sensor Combinations

Number of Sensors	TOA Method (# of Pairs)	TDOA Method (# of Triplets)
3	3	3
4	6	12
5	10	30
6	**15**	**60**
7	21	105
8	28	168

TDOA Imaging Examples



No Exponential Windowing



With Exponential Windowing

Damage: 3 mm Hole

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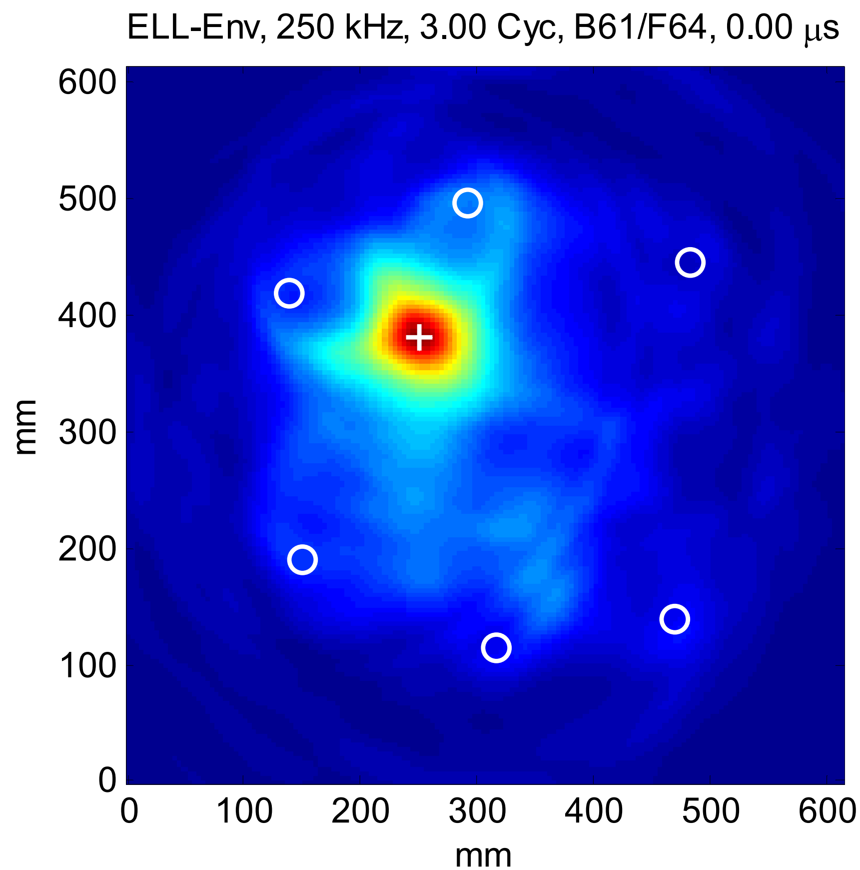
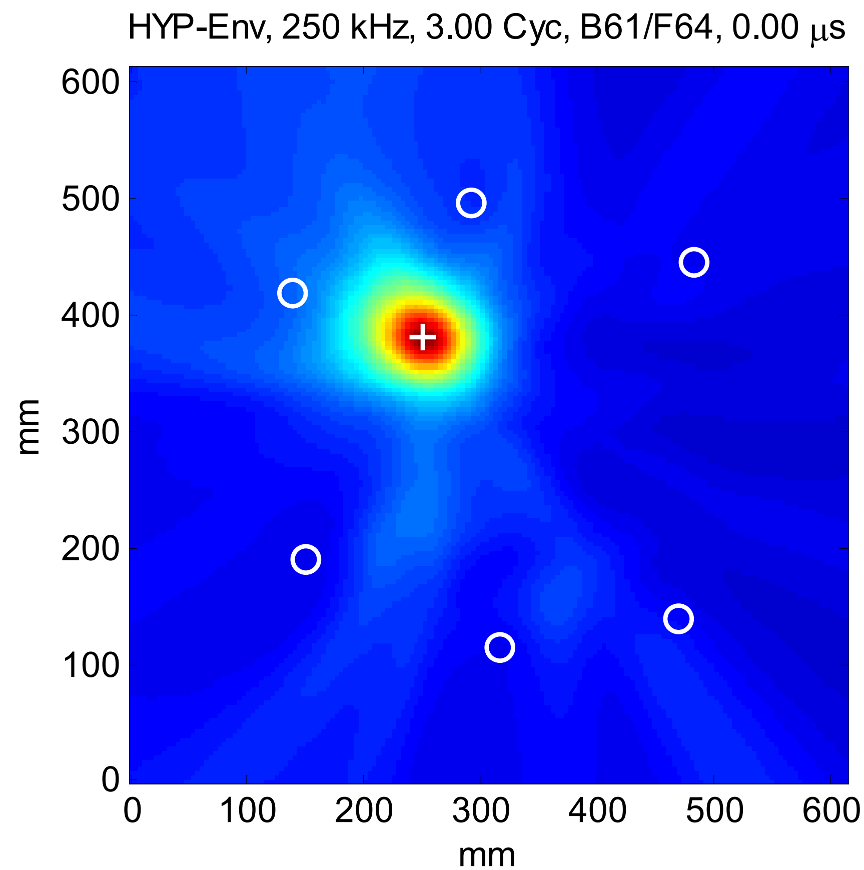
Comparison of TOA and TDOA Images

3 mm Hole



TOA Method



TDOA Method

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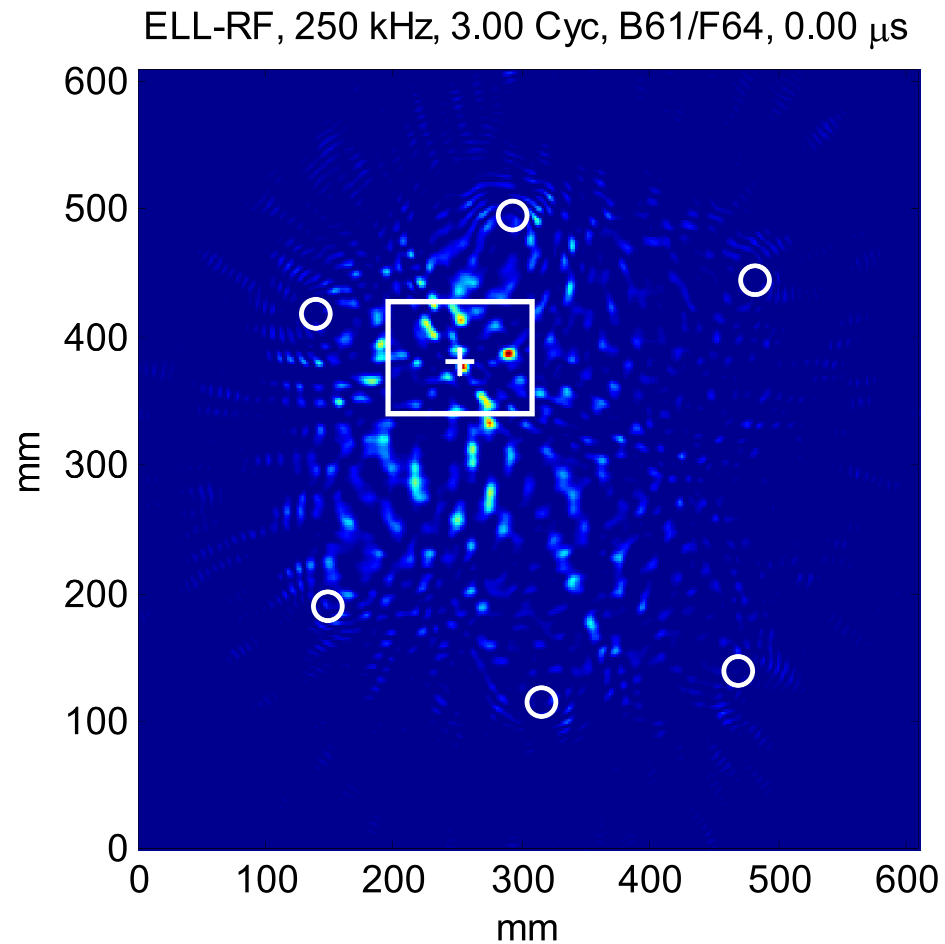
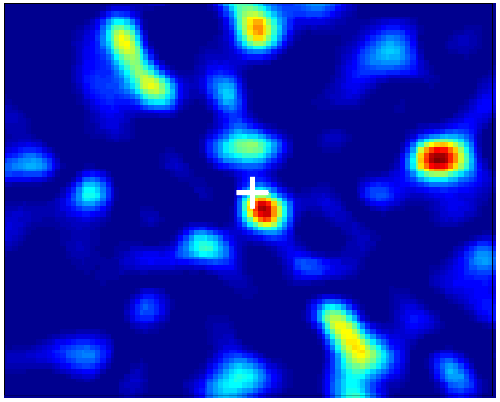
TOA Imaging with RF (raw) Waveforms

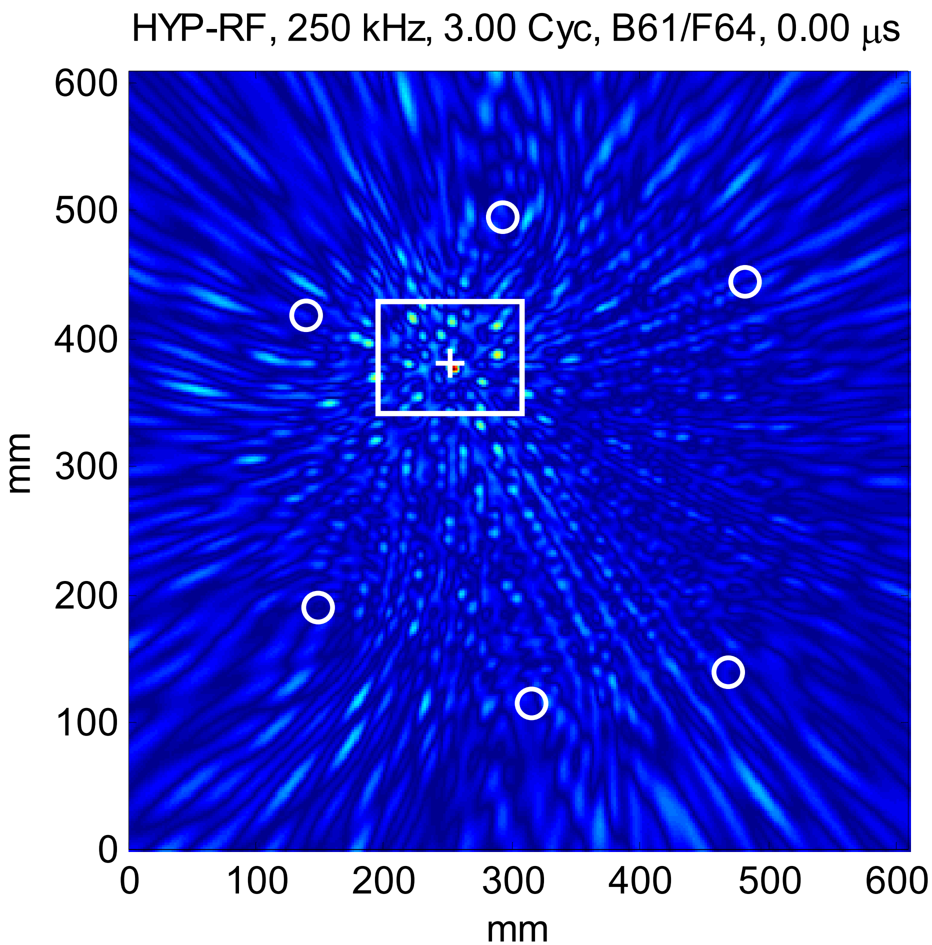


Excellent Localization

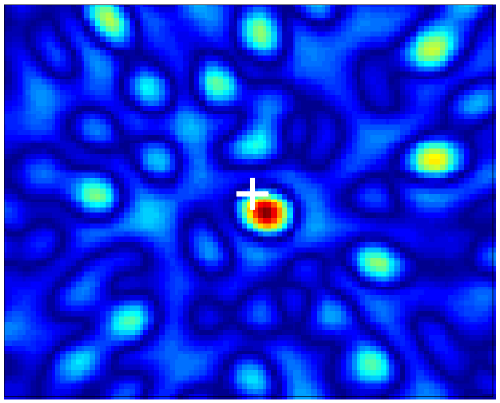


Very Large Side Lobes

TDOA Imaging with RF (raw) Waveforms



Excellent Localization



Significant Side Lobes

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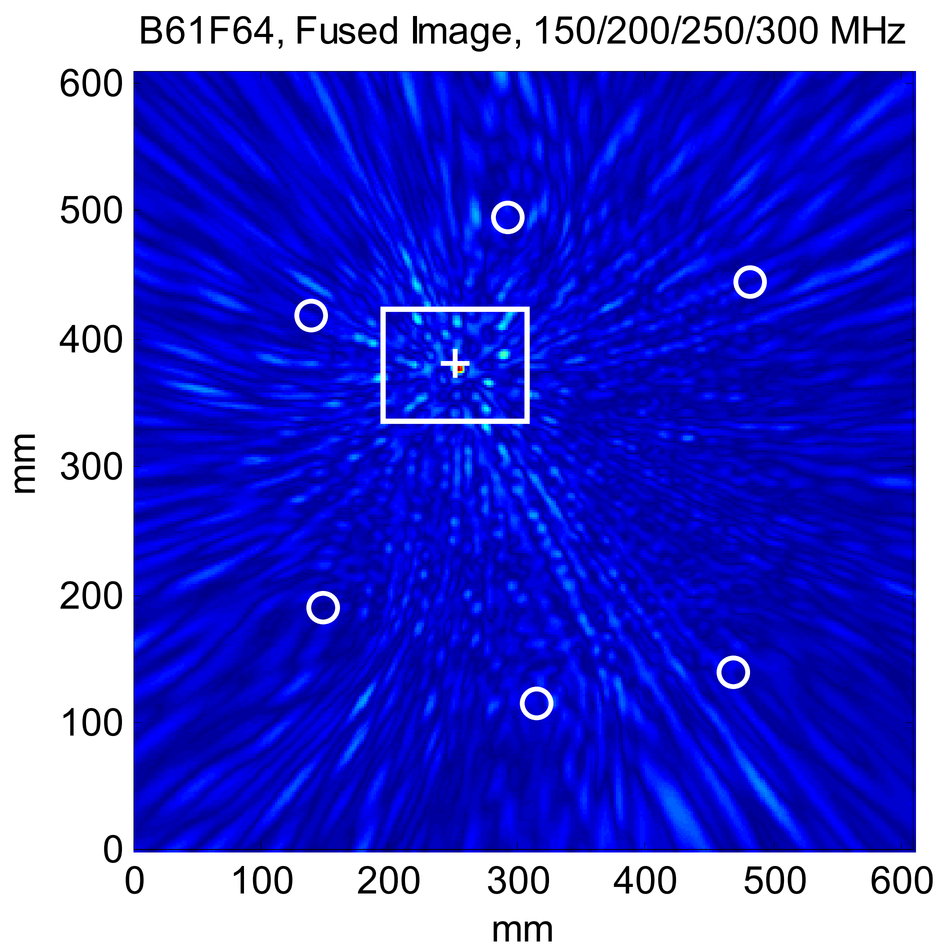
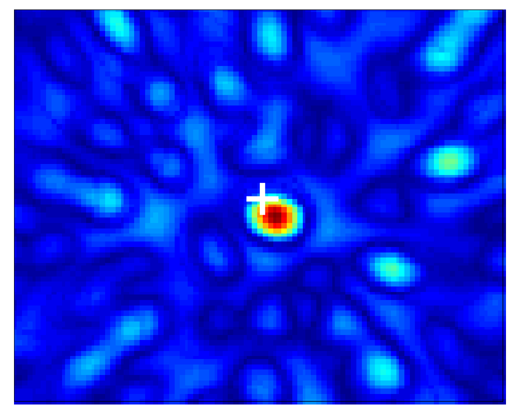
Fused TDOA Image

Average of Four Images: 150, 200, 250 and 300 kHz



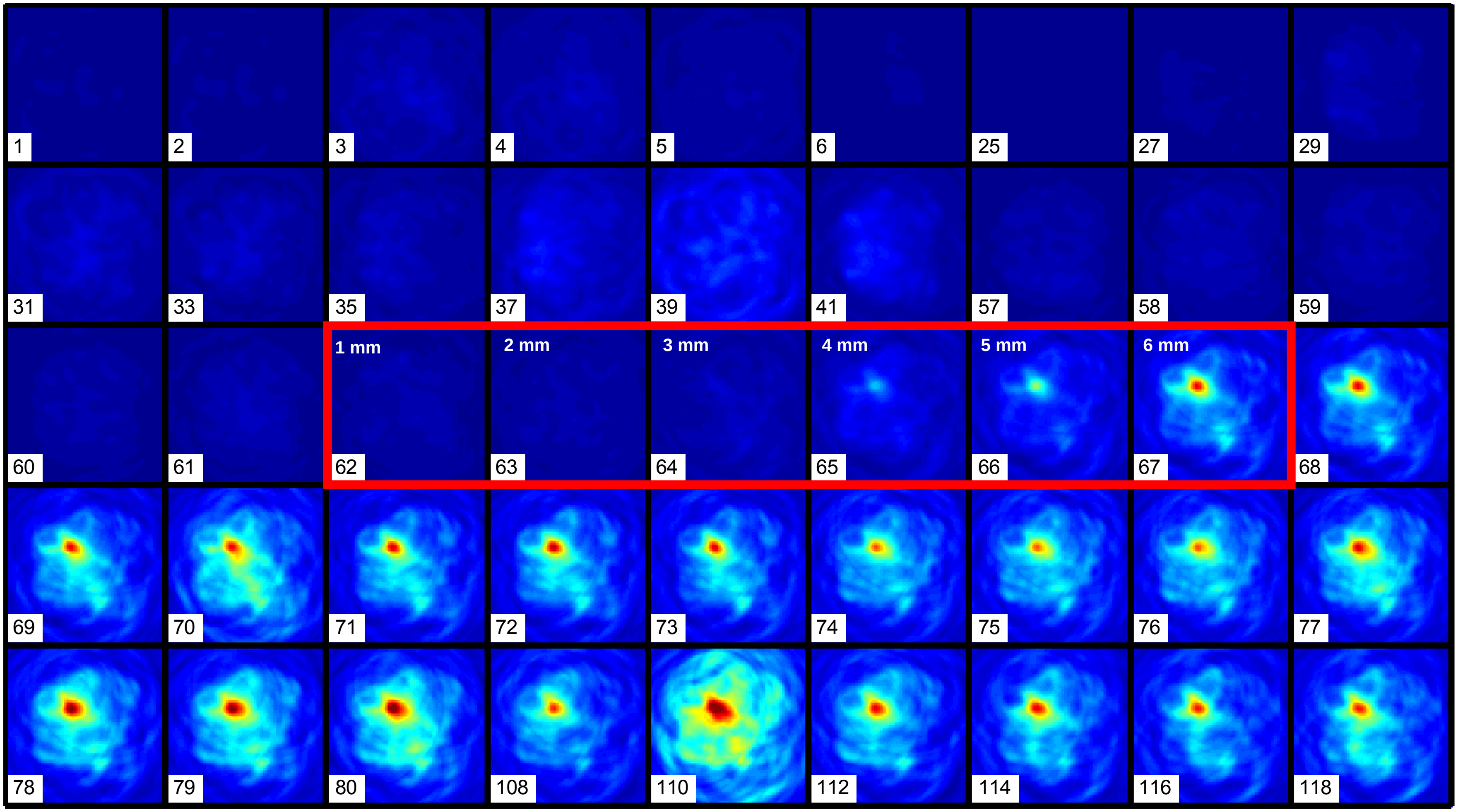
Excellent Localization



Reduced Side Lobes

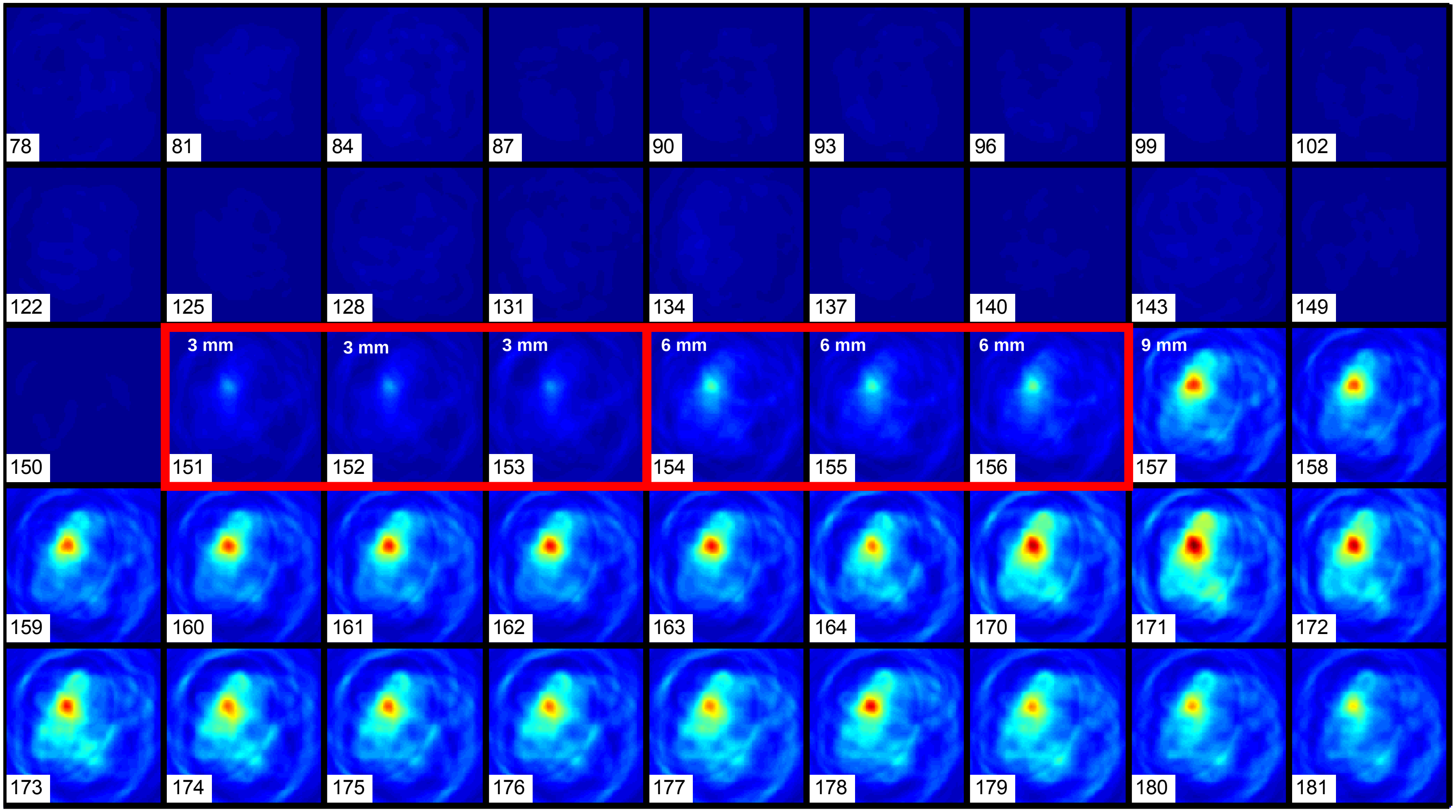
TOA Image History – Drilled Hole

Damage Initiation and Growth are Clearly Evident



TOA Image History – Notch

Damage Initiation and Growth are Clearly Evident



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Summary and Conclusions

- It is possible to localize damage by applying delay-and-sum algorithms to differenced guided wave signals generated with a spatially distributed array.
- Both Time-of-Arrival and Time-Difference-of-Arrival algorithms are effective, with the TDOA method having a more uniform but higher amplitude background noise level.
- Using the RF (raw) signals as opposed to envelope detected signals results in better localization at the expense of higher side lobes.
- Fusing images from difference frequencies can reduce the side lobes.
- Initiation and growth of artificial damage are clearly evident when viewing time histories of images.

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Ongoing and Future Work

- Detection algorithms
- Other imaging algorithms
- Consideration of environmental effects such as temperature and surface variations
- Real damage vs. artificial damage
- Aging effects (e.g., sensors, sealants, etc.)
- Quantifying damage estimates
- Characterizing uncertainty (POD, PFA)
- Wave propagation modeling

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QUEST Laboratory at Georgia Tech

www.quest.gatech.edu

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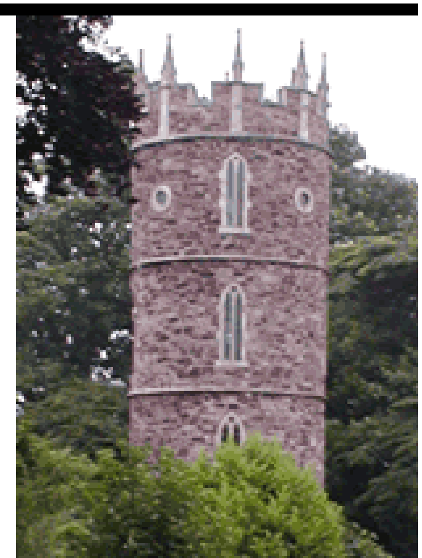

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QUESTIONS ?

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