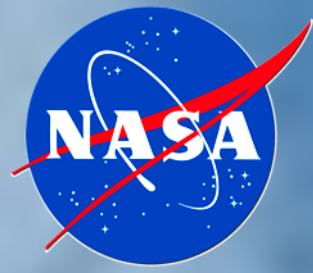


Composite Characterization using Ultrasonic Wavefield Techniques

Dr. Cara A.C. Leckey[1], Peter D. Juarez[1],

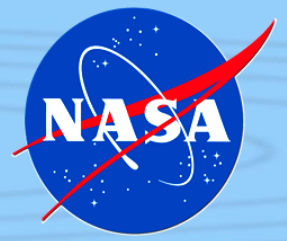
Jeffrey P. Seebo[2]

[1]Nondestructive Evaluation Sciences Branch, NASA Langley Research Center

[2]Analytical Mechanics Associates, NASA LaRC

Aircraft, Airworthiness, & Sustainment Conference
Grapevine TX, March 2016

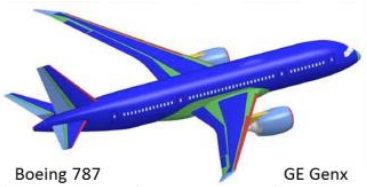
Overview



- Focus on NDE for Composites
- Noncontact Wavefield Methods
- NDE Simulation Tools
- Examples:
  - Delamination characterization
  - Waviness characterization
- Conclusion

Composites for Aeronautics

- **Advanced Composite Project** (5 Year Project):
  - Reduce timeline for certification of composite structures
  - Partnership: NASA, FAA, DoD, Industry, University
- Rapid Inspection Technical Challenge:
  - Focus areas:
    - Inspection of complex geometry components
    - Rapid large area inspection
    - Damage/defect characterization
    - Validation of detectability
  - Damage types:
    - Microcracking, fiber waviness, delamination, porosity



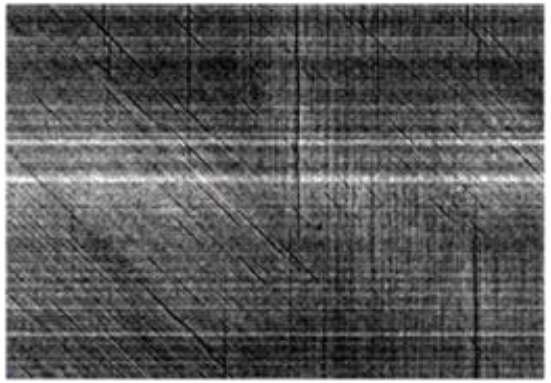

Lockheed Martin F-35


Northrop Grumman Fire Scout

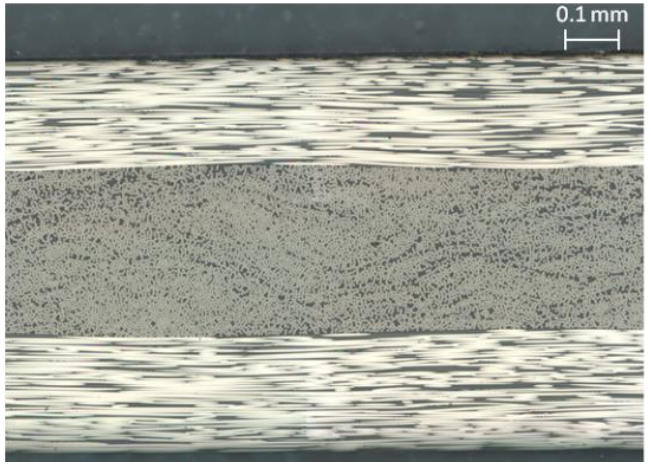
Composite Damage/Defect Types

Nondestructive Evaluation Sciences Branch

X-ray CT data of microcrack damage



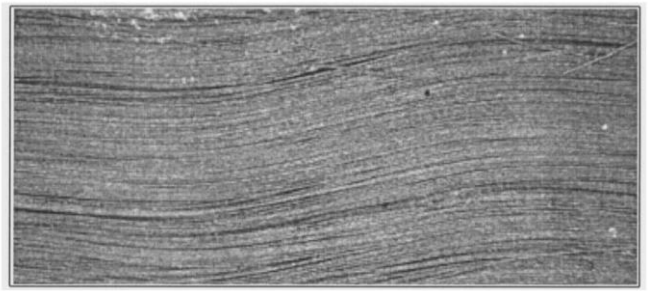
Micrograph showing resin rich regions and fiber misalignment



Fiber waviness (in-plane), i.e. marcelling

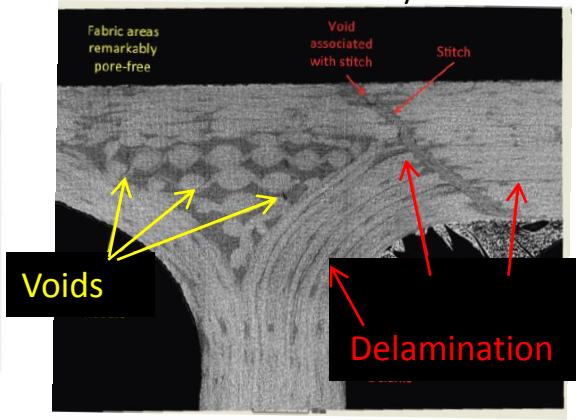
From Kugler and Moon 2002

doi: 10.1177/0021998302036012575



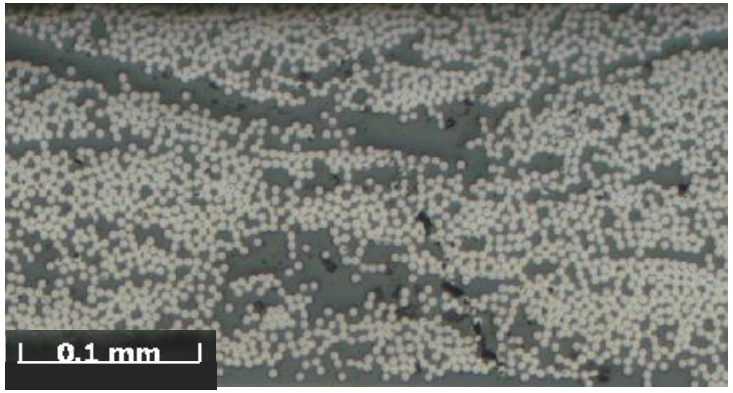
X-ray CT of PRSEUS Joint

From NASA TM-2013-217799 by Patrick Johnston

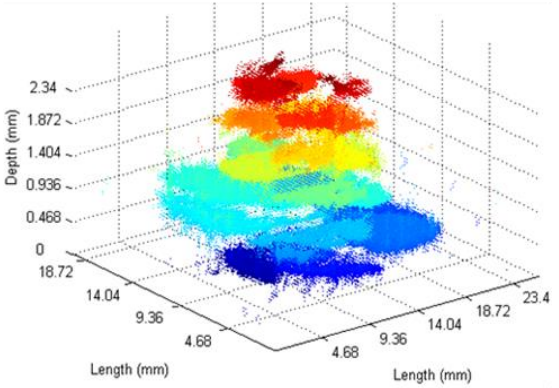


X-ray CT data of microcrack damage

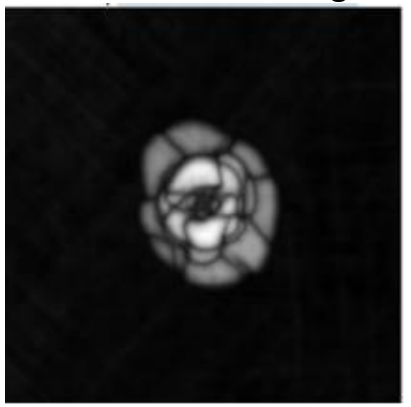
Micrograph showing porosity



X-ray CT data of delamination damage

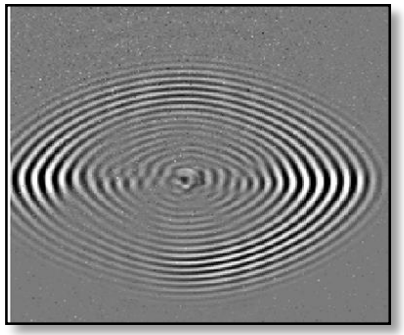


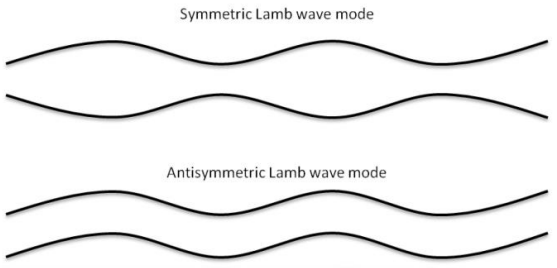
UT data of delamination damage

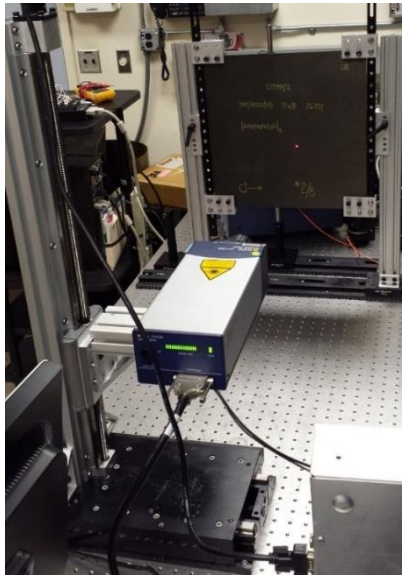


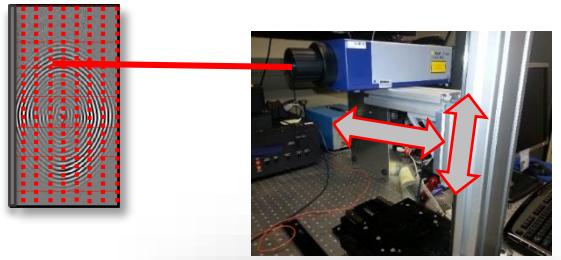
Wavefield Methods

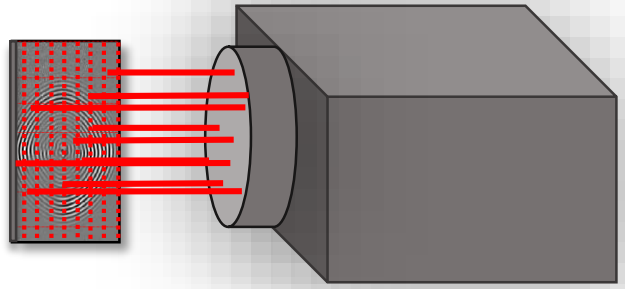
- GW's easily generated in plate-like specimens due to boundaries
- Promise for covering large areas via long distance travel
- *Noncontact measurement* with Laser Doppler Vibrometry (LDV)
- Multi-beam LDV's under development by commercial companies
- Simulation can aid in method development
  - Challenging to get representative experimental samples
  - Relying only on experiment is costly
  - Investigate larger number of scenarios







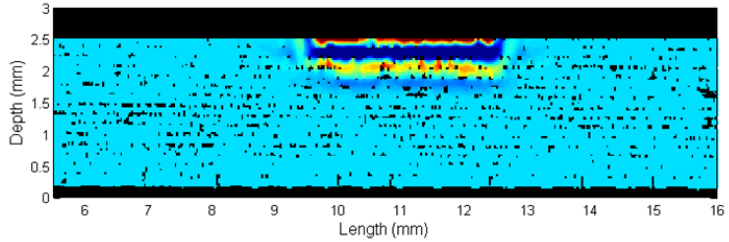


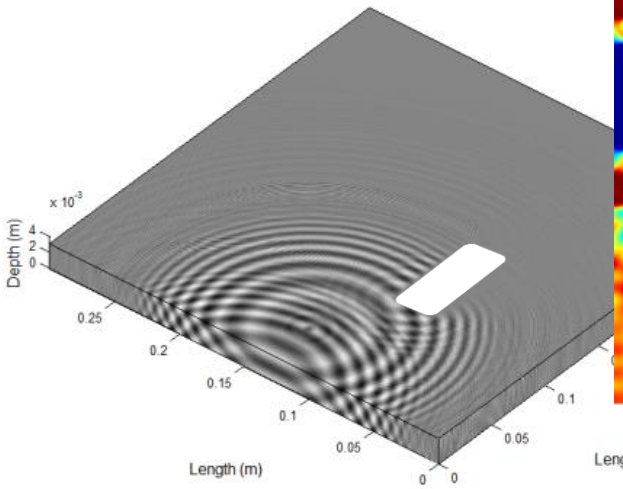


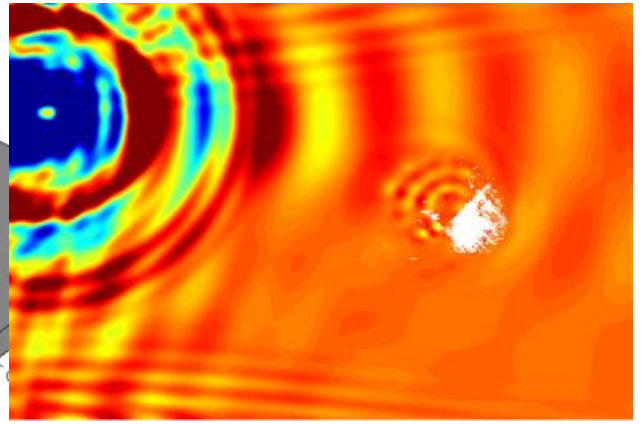
Ultrasound Simulation

Nondestructive Evaluation Sciences Branch

- Elastodynamic finite integration technique ultrasonic simulation code
  - Custom C++ and MPI
  - Similar to finite difference
  - Adaptable, equations directly under our control
  - Output analogous to LDV wavefield data

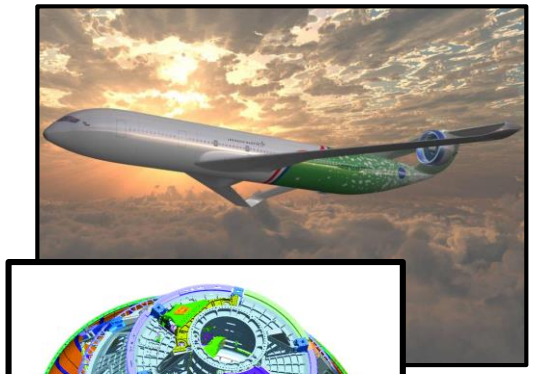


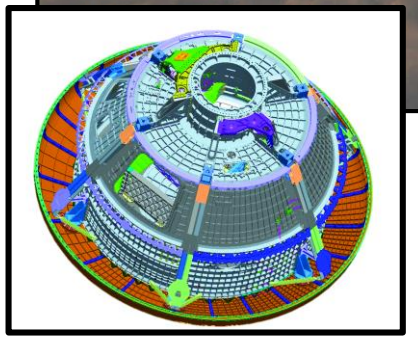




Broader Need for NDE Simulation

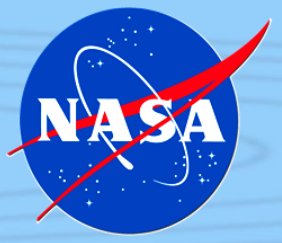
- Simulation tools to model the physics of the NDE inspection are needed to enable:
  - Consideration of NDE during design stage, leading to less conservative designs
  - Feasibility to study a large number of damage scenarios to establish confidence in inspectability
  - Cost-effective development of optimal methodologies for advanced materials and structures
  - Computational NDE is likely the only cost-effective approach for structural health monitoring system validation





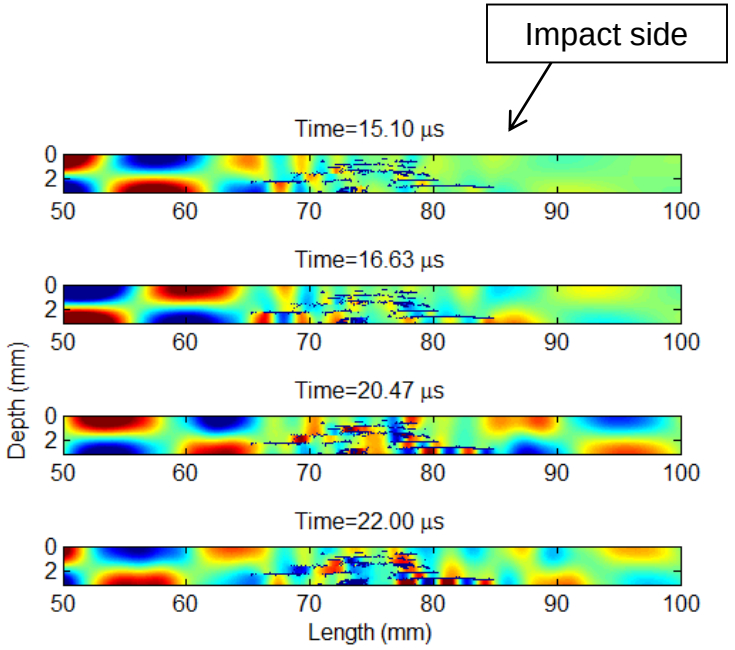
Wavefield Method Examples

Delamination Characterization

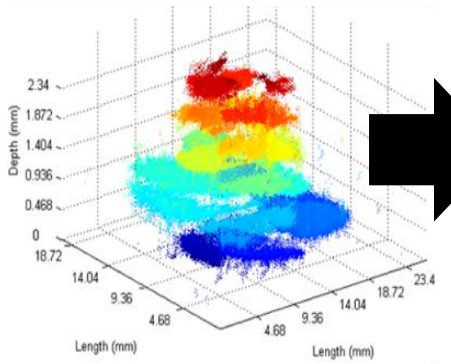


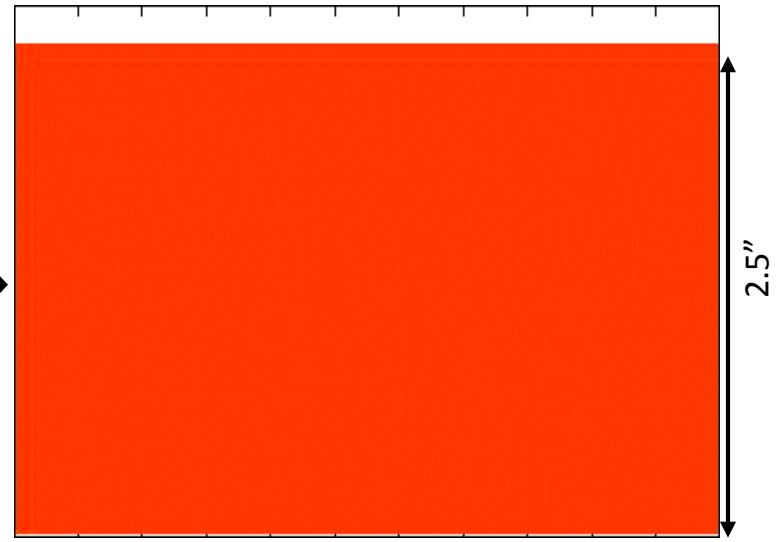
Nondestructive Evaluation Sciences Branch

- 3D EFIT: 1.8 billion grid cells
  - 110 mm x 65 mm x 3.2 mm
- Run on 80 core 1TB shared memory machine
- Step size=23.4µm, $\lambda_{min}/64$

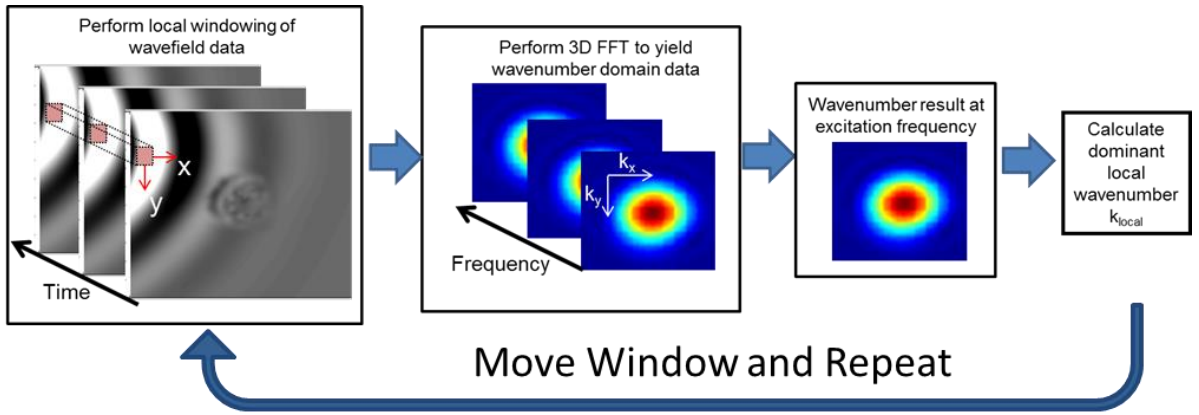


NASA X-ray CT data of delamination damage





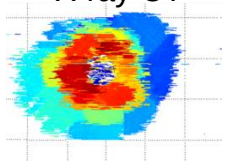
Data Processing: Wavenumber Analysis

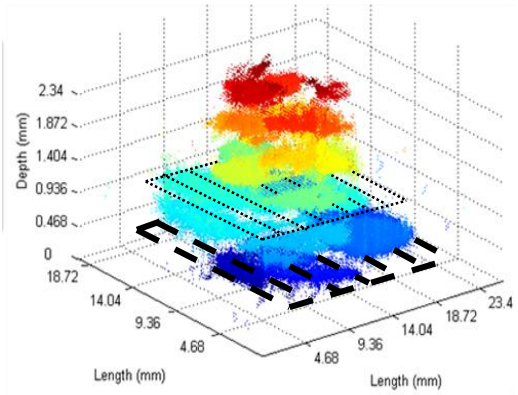


Local Wavenumber Analysis Technique:

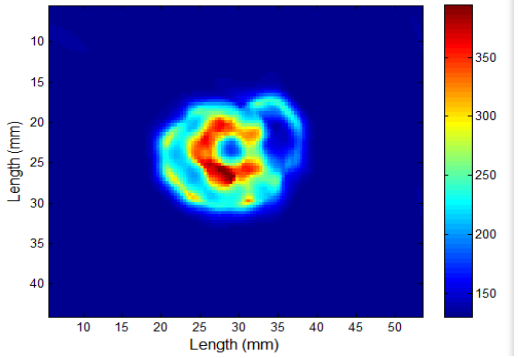
1) 3D FT of Hann windowed wavefield, local window
2) Select 3D FT slice at excitation center frequency
3) Calculate dominant wavenumber of local window

X-ray CT

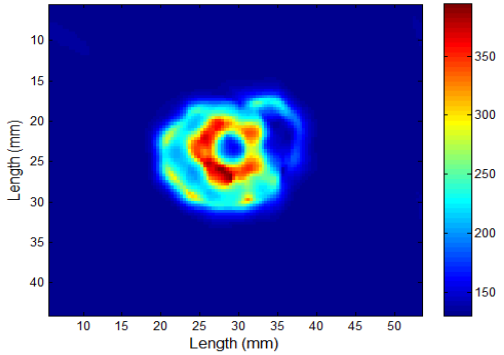




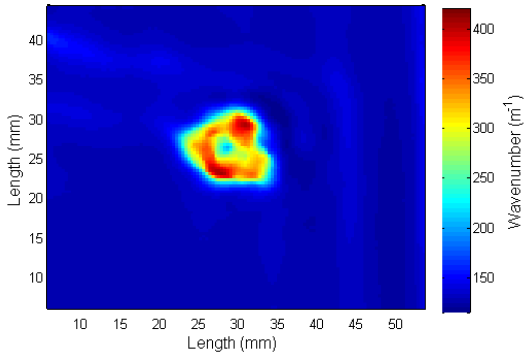
Case 1
Full delam



Case 2,
Hidden delam removed



Case 3,



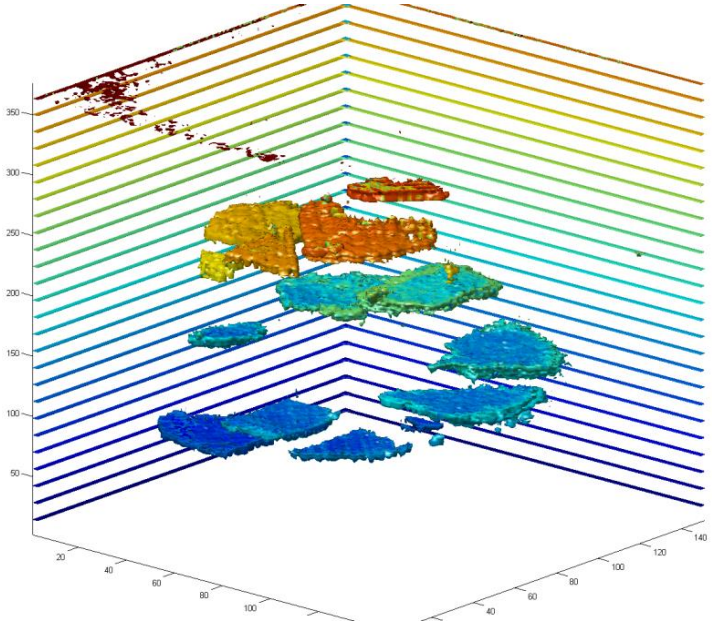
Rogge, M. and Leckey, C.; "Characterization of impact damage in composite laminates using guided wavefield imaging and local wavenumber domain analysis"; *Ultrasonics,* Vol 53, pp 1217-1226 (2013)

Experimental Results

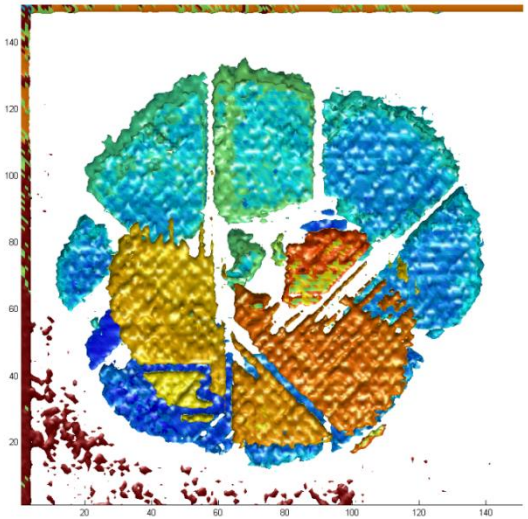
Nondestructive Evaluation Sciences Branch

- Multi-frequency wavenumber analysis

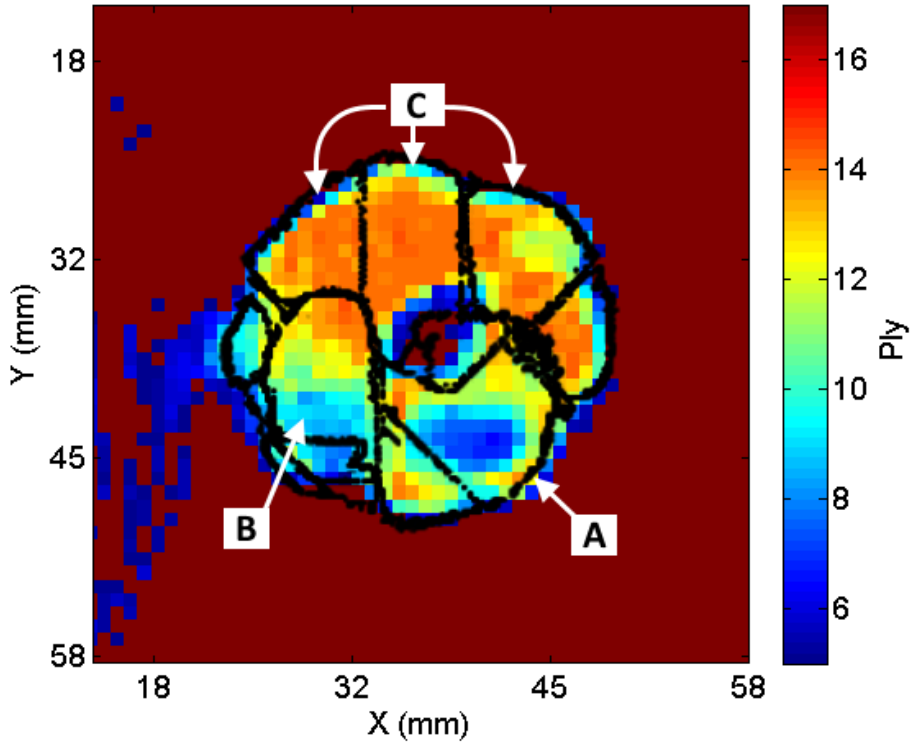
Immersion Ultrasound



Immersion Ultrasound



Noncontact LDV Wavenumber Analysis



[1] Juarez, P. and Leckey, C. "Multi-frequency Local Wavenumber Analysis and Ply Correlation of Delamination Damage". *Submitted to Ultrasonics*

Can this be applied to other defects?

Cases where traditional C-scan may not work well?

Wrinkling and Waviness

- Wrinkling (OOP) and waviness/marcelling (IP) can be created during fabrication - layup and cure (e.g. uneven curing and resin shrinkage)
- Strength affected by both
  - Wrinkling more readily visible to the eye, can readily occur in complex joints and be converted to in-plane waviness during fabrication

Images From: Cinar and Ersoy, "Effect of fibre wrinkling to the spring-in behavior of L-shaped composite materials", *Composites Part A* (2015)

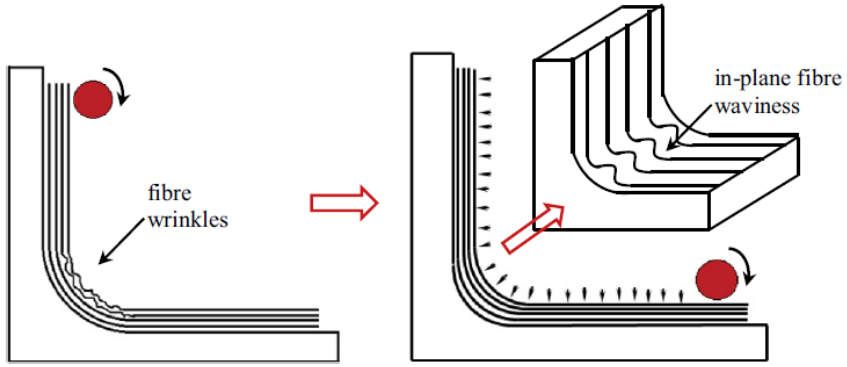


Fig. 6. Initial fibre wrinkles convert to in-plane fibre waviness after curing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

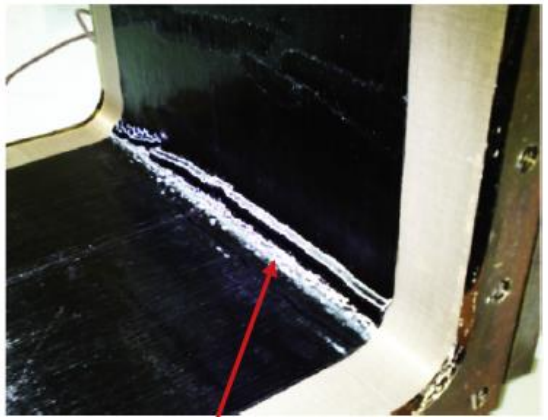
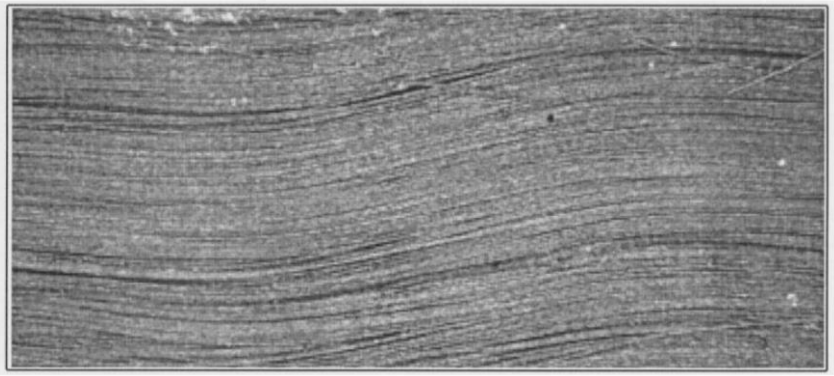


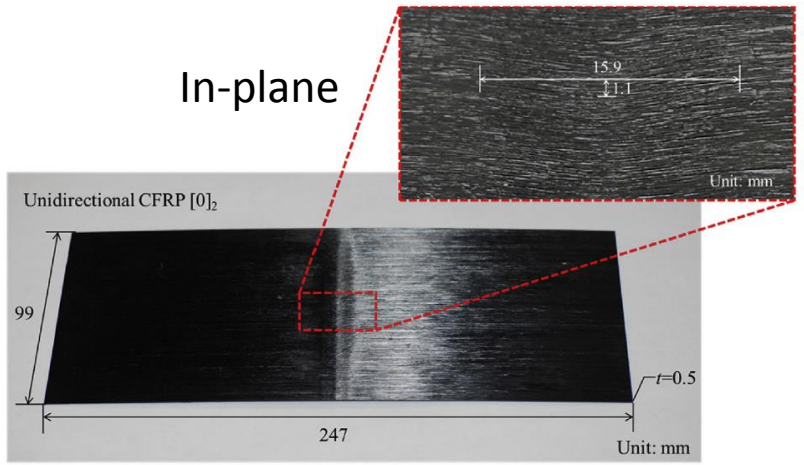
Image From: Kugler and Moon, "Identification of the most significant processing parameters on the development of fiber waviness in thin laminates" *J Composite Materials* (2001)



Waviness

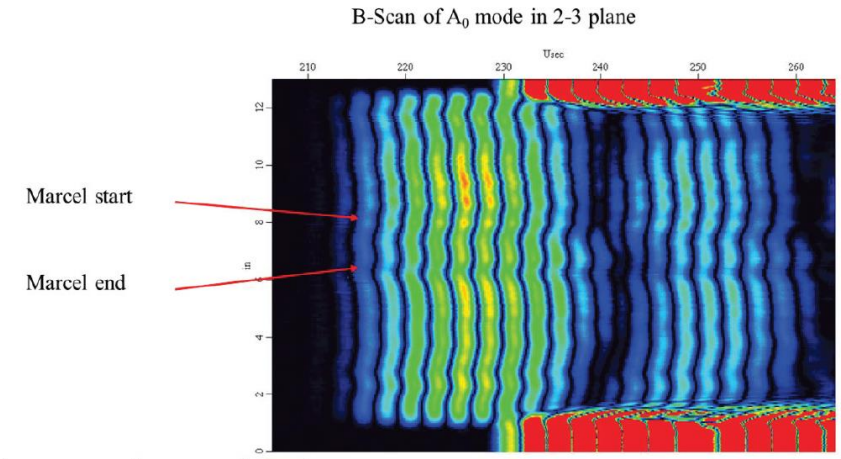
- IP more likely to occur in thin laminates and OOP more likely in thick laminates
- In-plane waviness can lead to microbuckling, kinking, and matrix cracking (Berbinau 1999, Jumahat 2010)
- More difficult to create representative samples with this defect
- Simulation studies enable analysis of ultrasound effects from in-plane waviness

Image From: Mizukami, et al; "Detection of in-plane and out-of-plane waviness in unidirectional carbon fiber reinforced composites using eddy current testing", *Composites*



Noncontact Methods: Waviness?

- Literature reports changes in group velocity[1] of guided waves
  - 15˚ fiber wave → 4% change velocity (fairly small change)
- Other wave changes might be detected with advanced processing methods



From: [1]Chakrapani, et al. "Detection of in-plane fiber waviness in composite laminates using guided Lamb modes." *Rev Prog QNDE* Vol. 1581. No. 1. AIP Publishing, 2014.

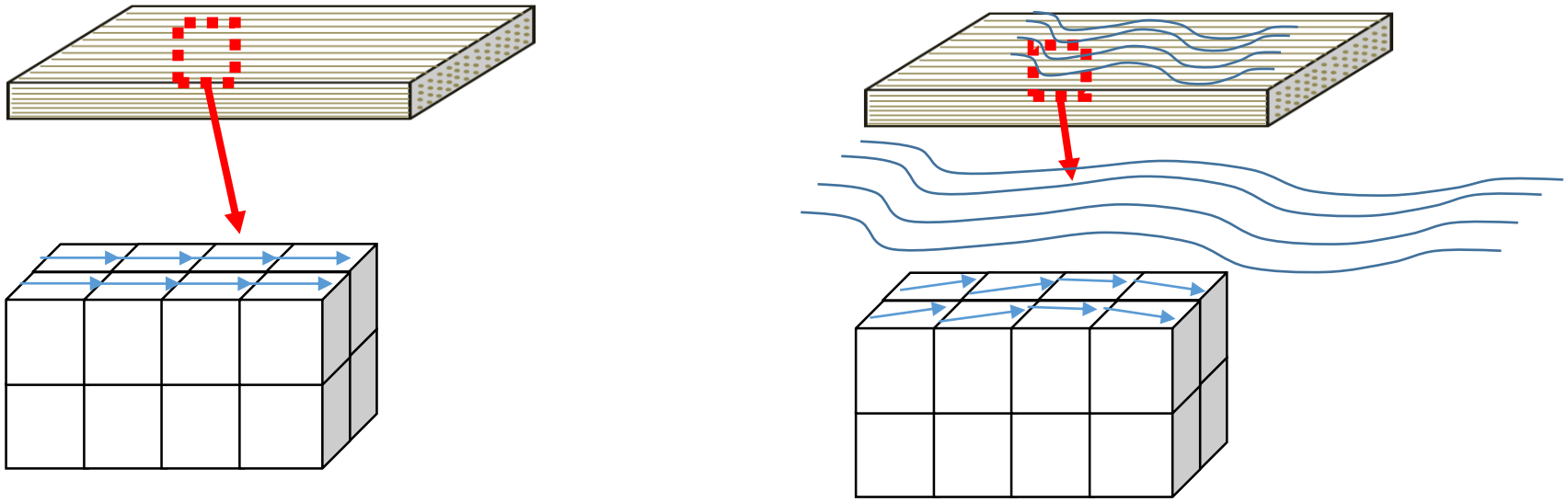
Modeling of Waviness

- Individual fibers are not modeled, but C_{ij} matrix defined at each grid position

$$\begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}$$

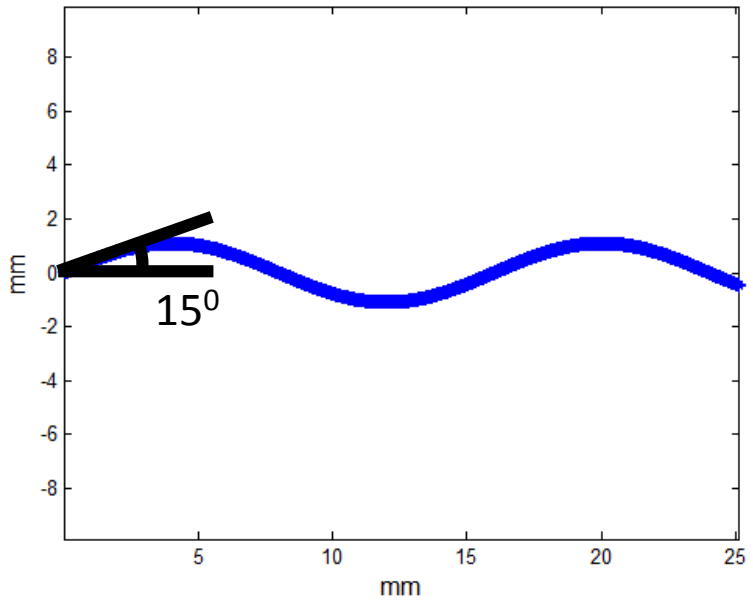
Rotation matrix

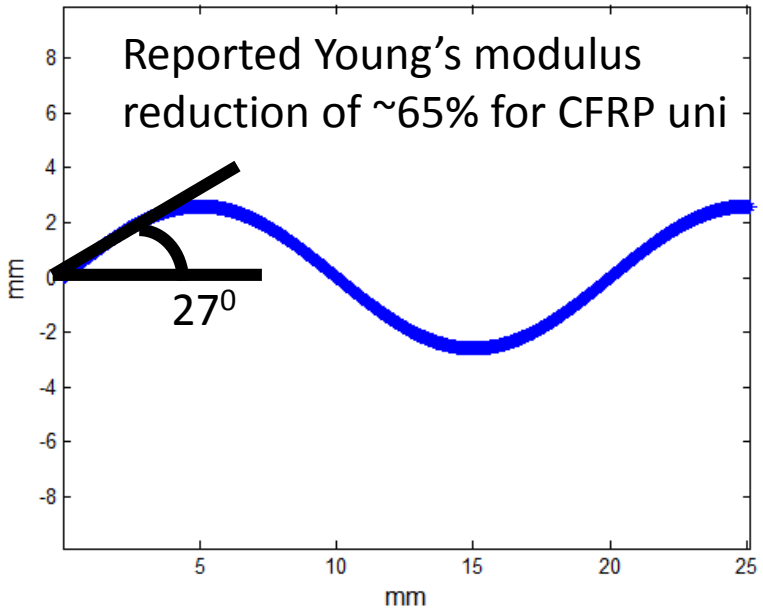
$$\begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\ C_{21} & C_{22} & C_{23} & 0 & 0 & C_{26} \\ C_{31} & C_{32} & C_{33} & 0 & 0 & C_{36} \\ 0 & 0 & 0 & C_{44} & C_{45} & 0 \\ 0 & 0 & 0 & C_{54} & C_{55} & 0 \\ C_{61} & C_{62} & C_{63} & 0 & 0 & C_{66} \end{pmatrix}$$

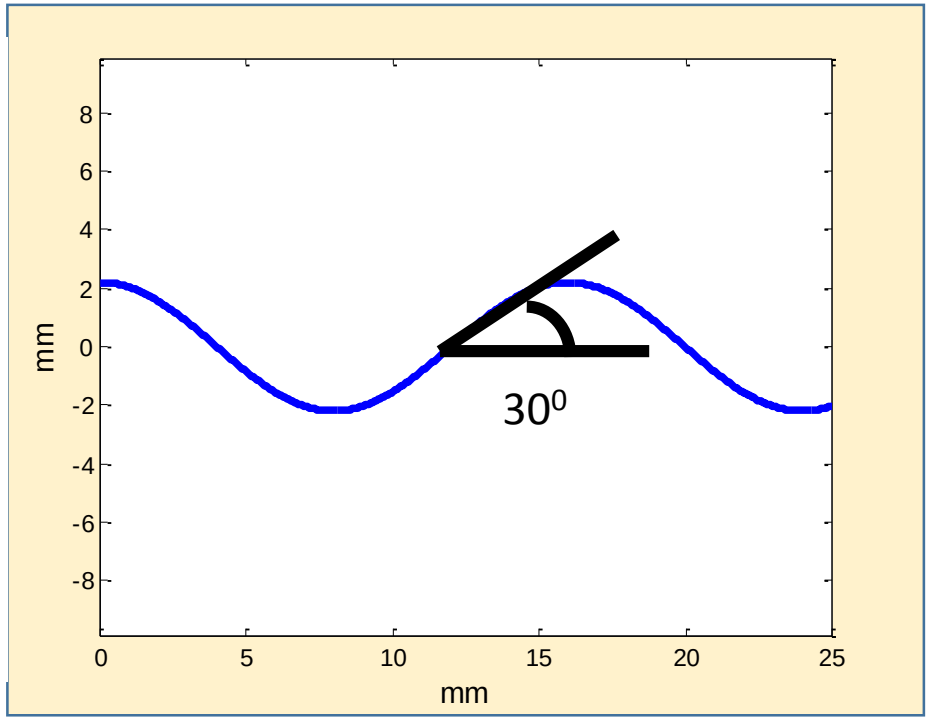


In-plane waviness

- Representative waviness amplitudes in CFRP, wavelength determined from literature (Mizukami 2016, Fuhr 2013)



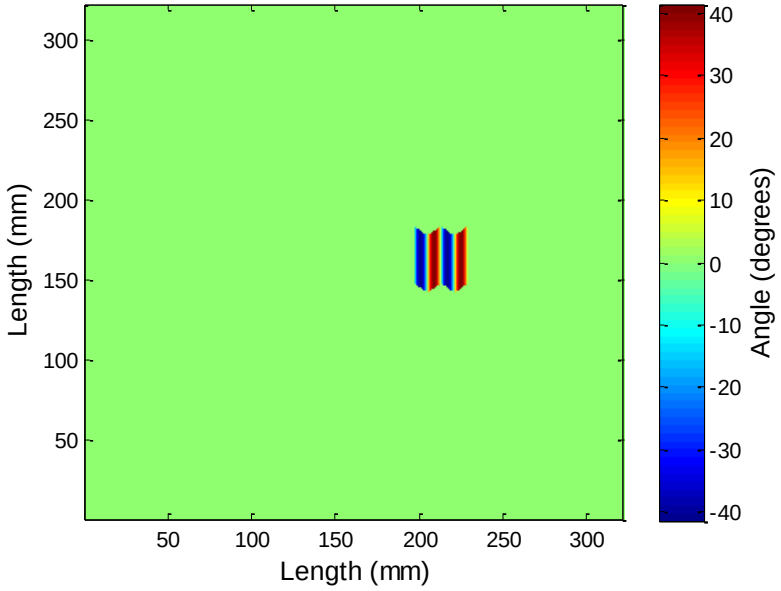




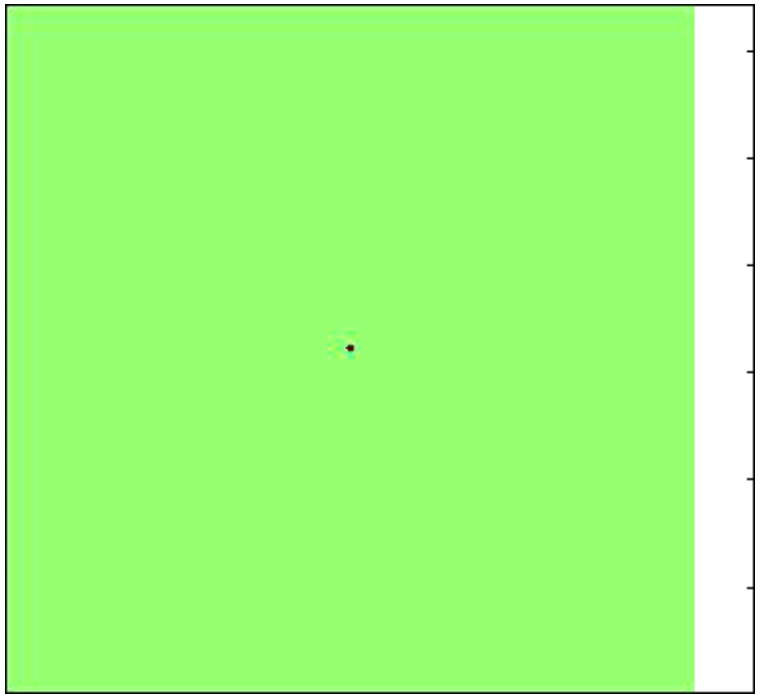
Unidirectional, Top ply wavy

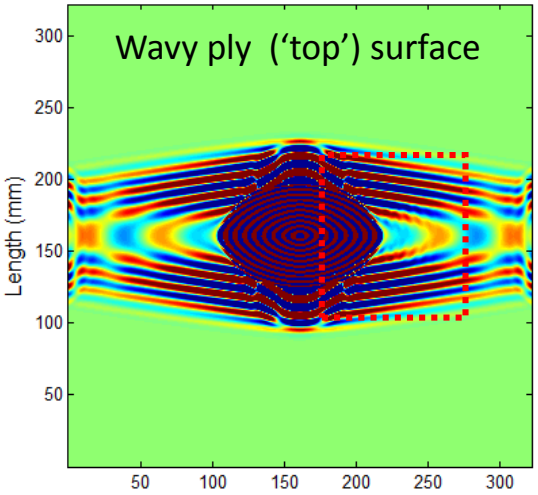
Nondestructive Evaluation Sciences Branch

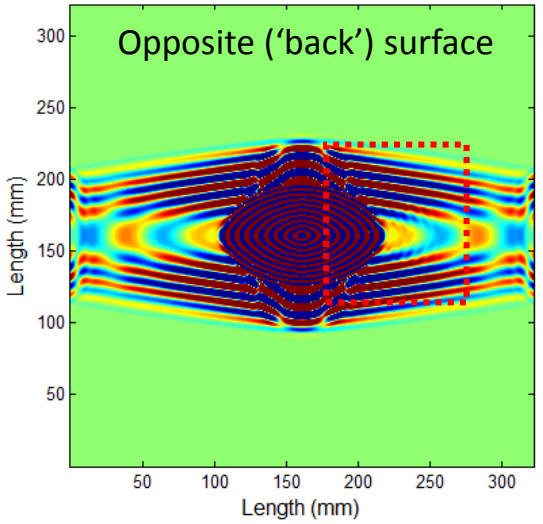
- 8-plies, top ply contains waviness
- Observe change in wave directionality (human eye good at picking it out)
- Observable at both surfaces
- Try methods for automated data processing



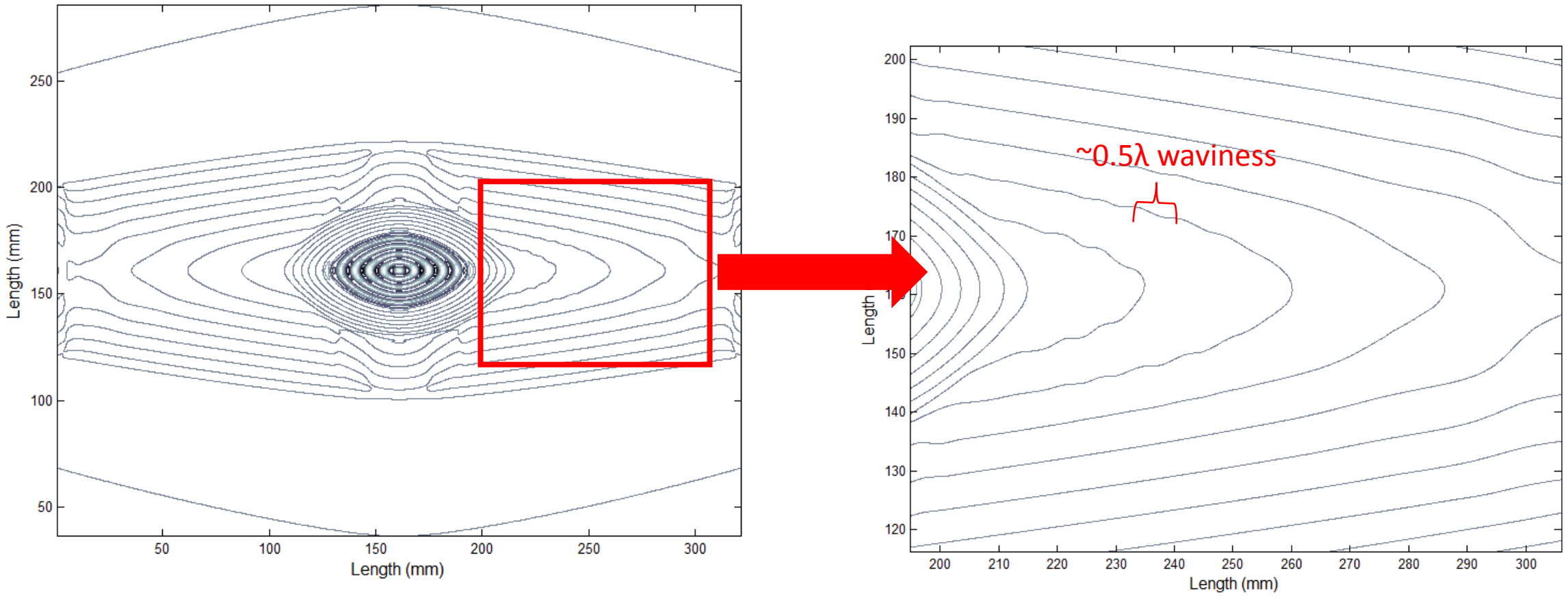
OOP



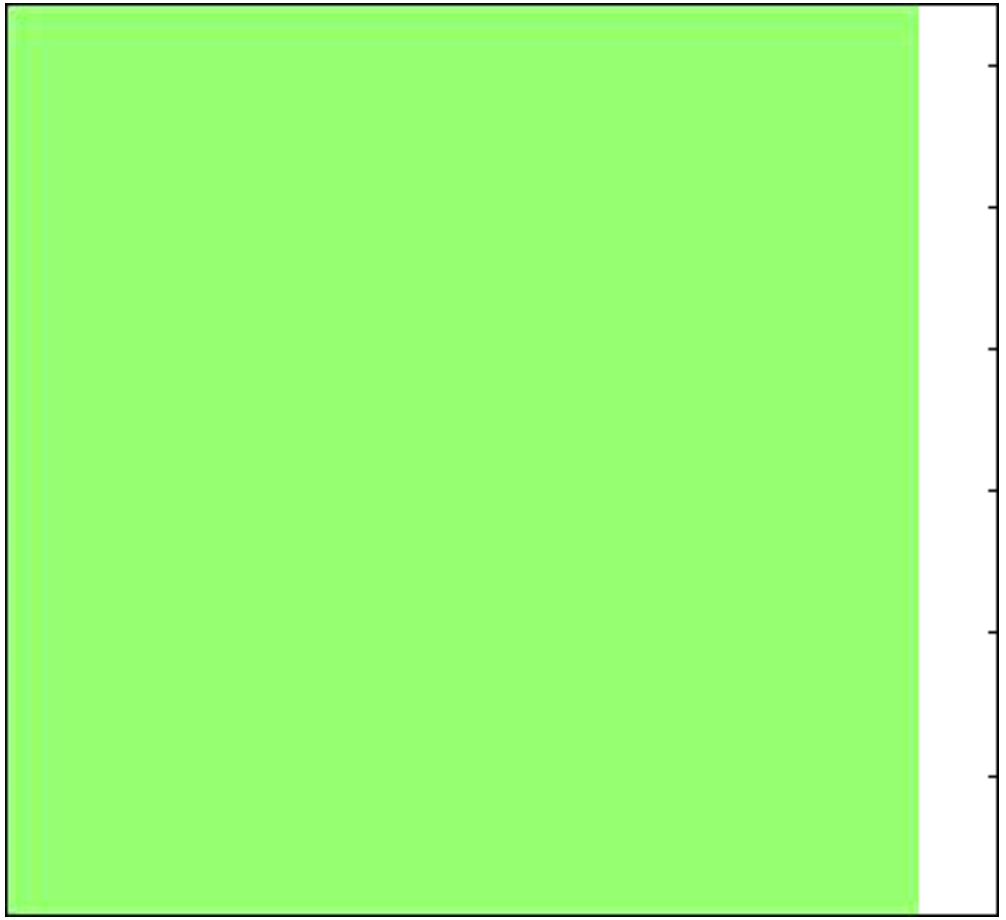




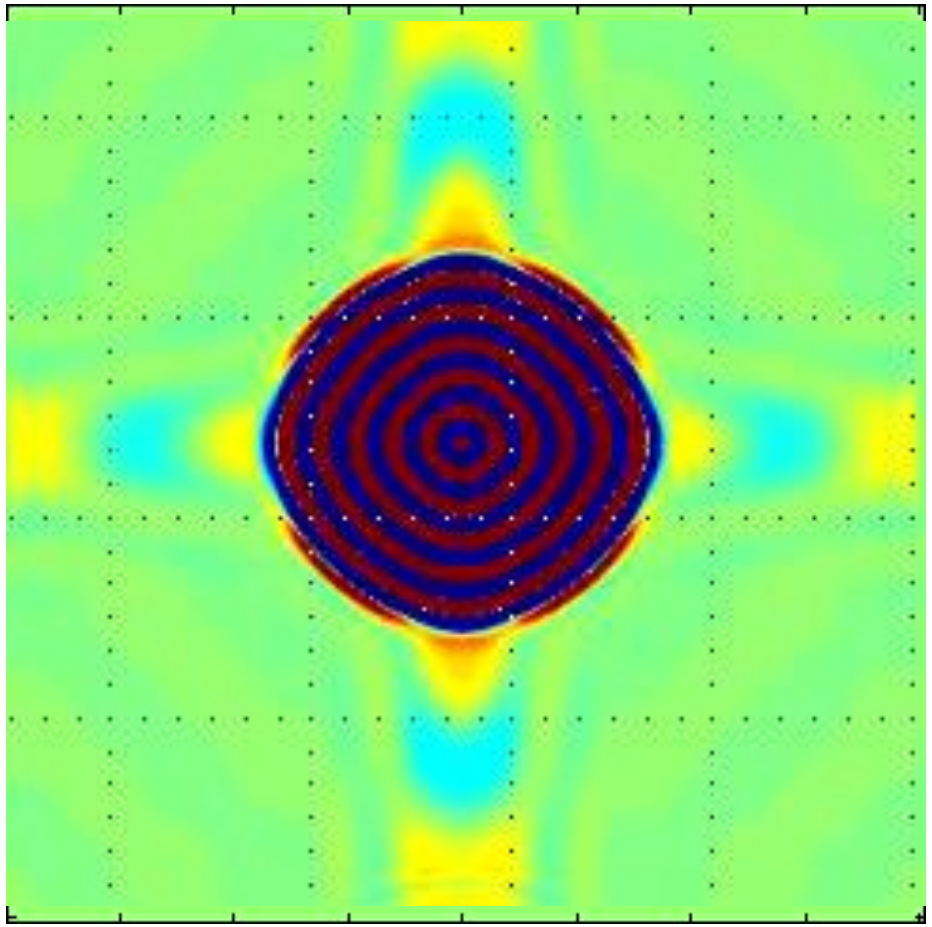
Unidirectional, Top ply wavy

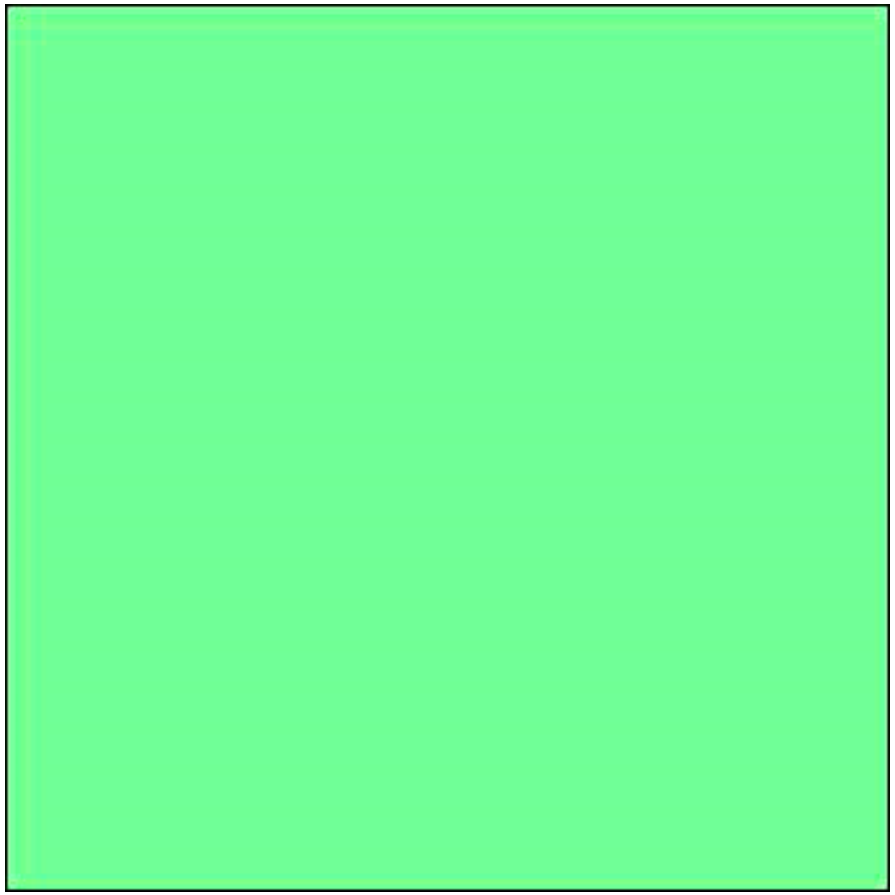


Unidirectional, Top ply wavy



Crossply, Top ply wavy

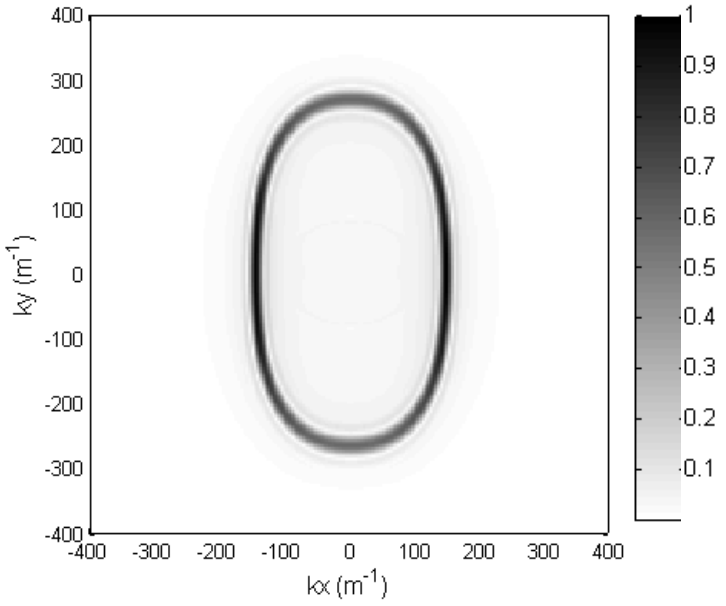




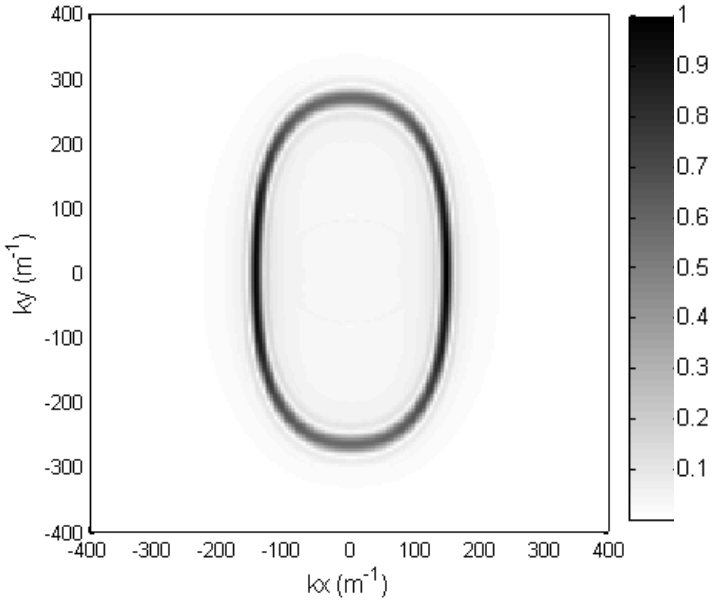
Unidirectional: Wavenumer Analysis

- 3DFFT performed to study modes, directional wavenumbers, and associated amplitudes
- Shows presence of waviness and quadrants, but requires background subtraction and does now show specific spatial location or characterization information
- Would like automated processing to locate waviness, and ideally characterize it

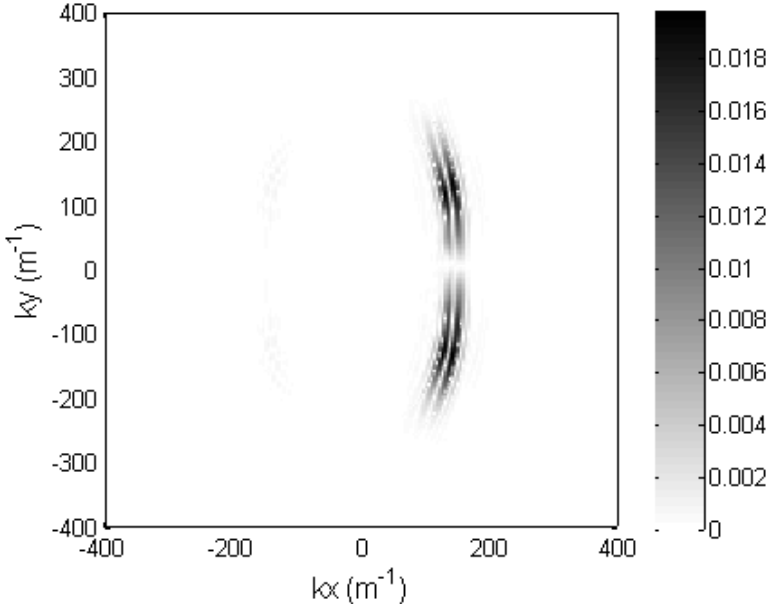
Pristine



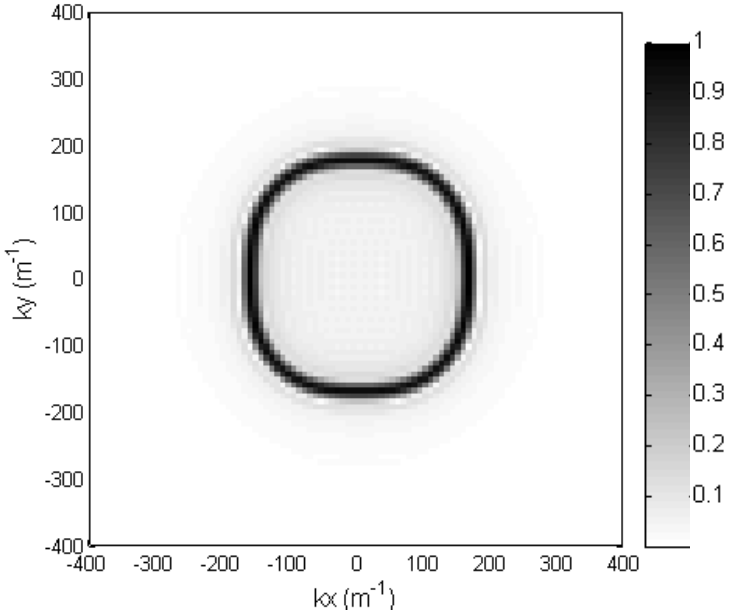
Wavy

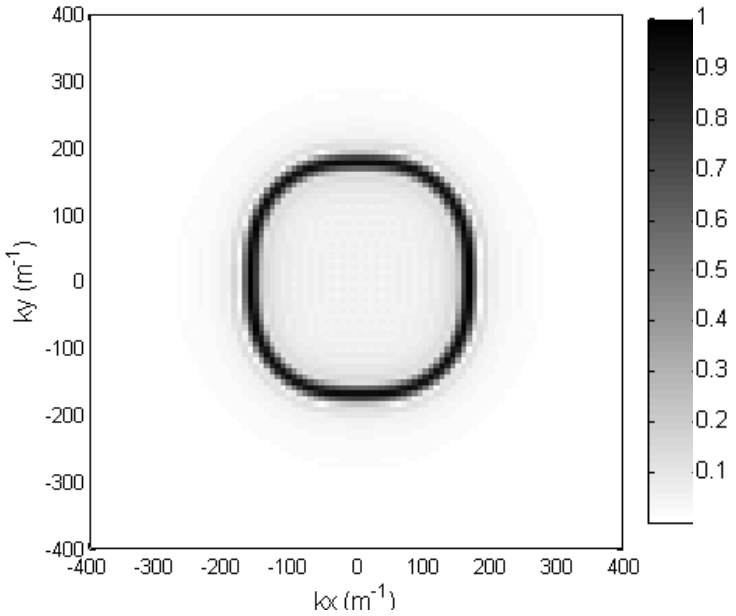


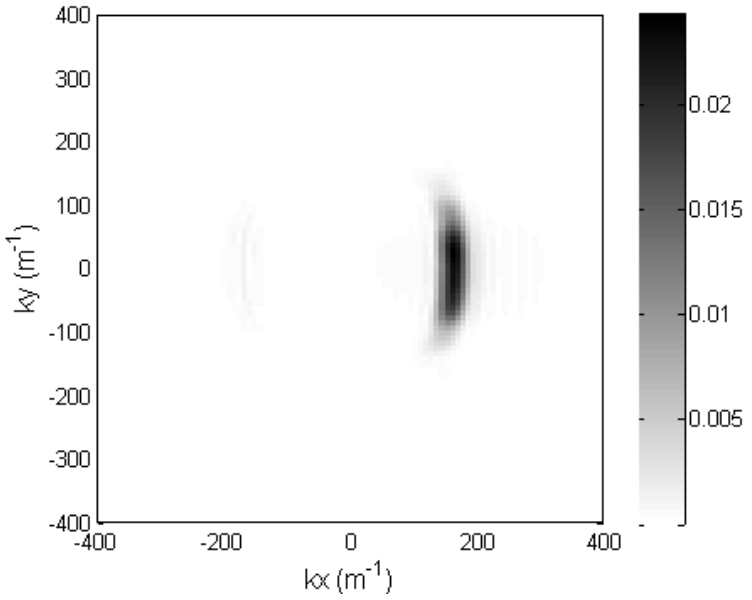
Difference



Crossply: Wavenumber Analysis

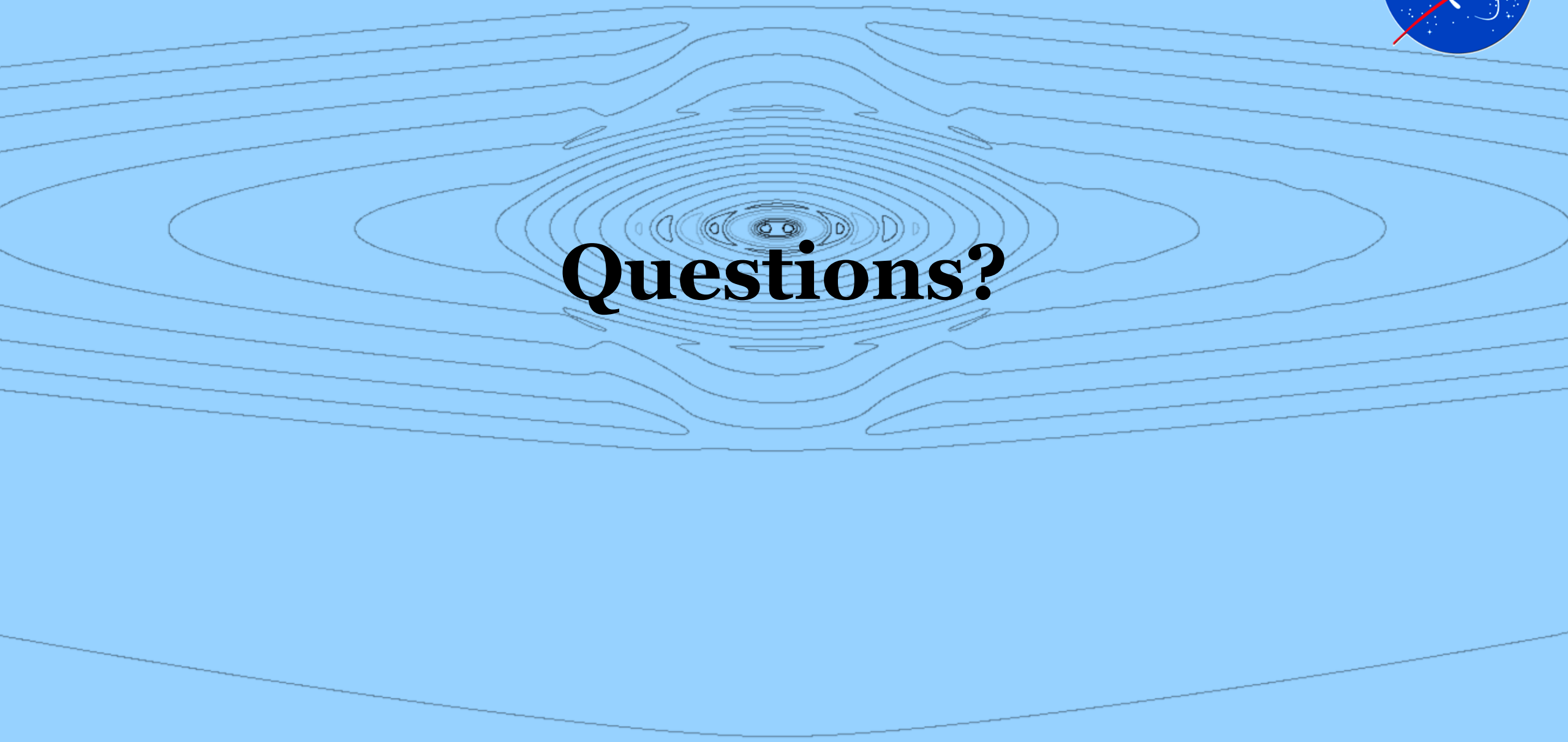






Conclusion

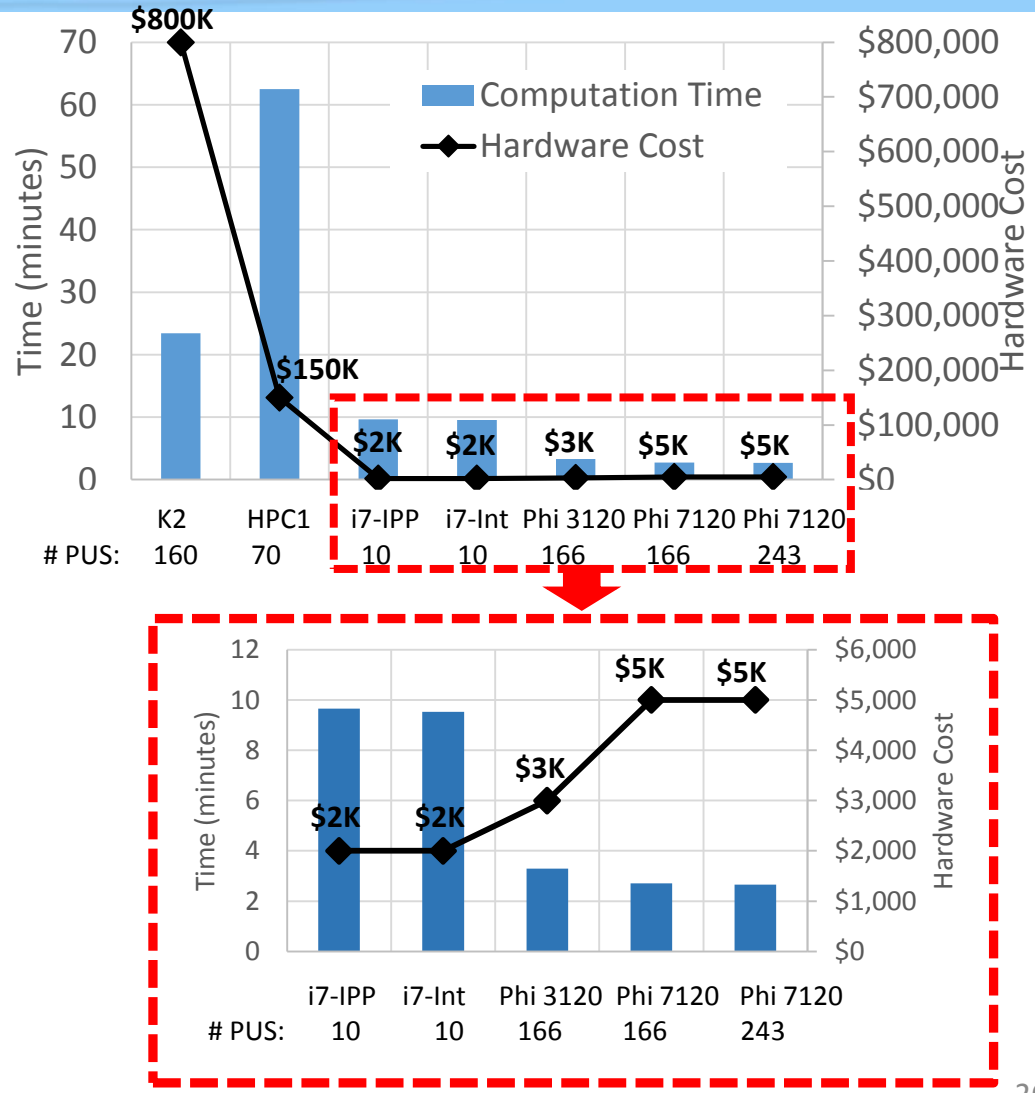
- Wavefield methods have potential for rapid inspection and large area coverage
- Limitations/capabilities of the method still being explored
- Simulation can aid development of methods for detecting and characterizing composite damage/defects



Questions?

Computational Benefit

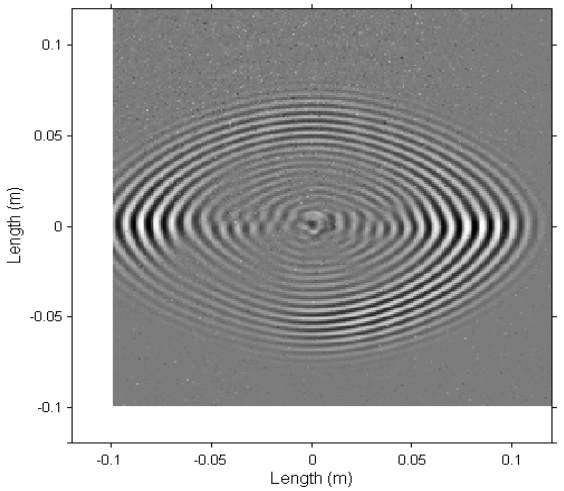
- Need rapid, realistic NDE simulation capabilities to have a practical tool
- Advanced computing architectures continue to emerge
- In-house code adaptable to various computer architectures
  - Computing clusters
  - GPU and Many integrated core (e.g., Intel Xeon Phi)
- Phi Example: ~10X faster, ~0.6% cost



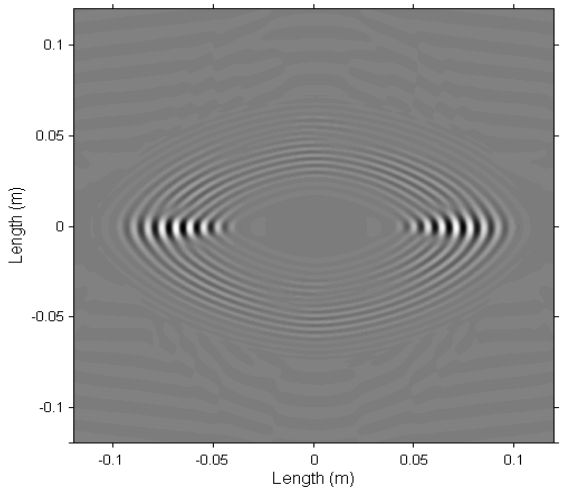
Validation

- Validation is a key step
- Use Laser Doppler Vibrometry for direct comparisons to experiment

Experiment



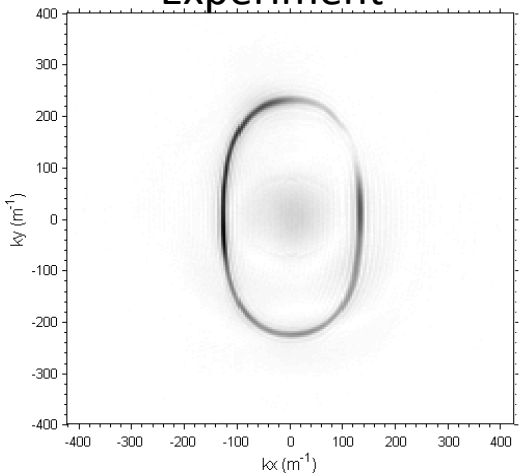
Simulation



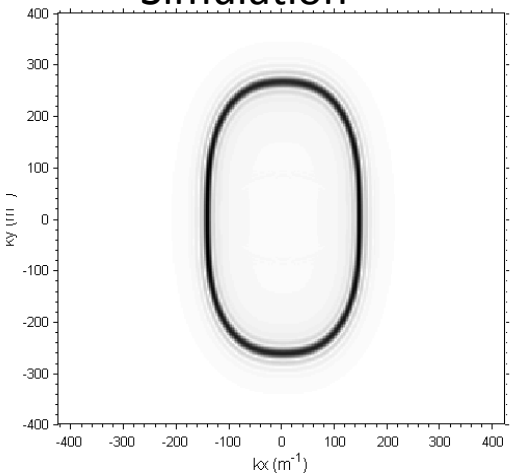
Approximate time=56 microseconds after initial excitation

Wavenumber plots

Experiment

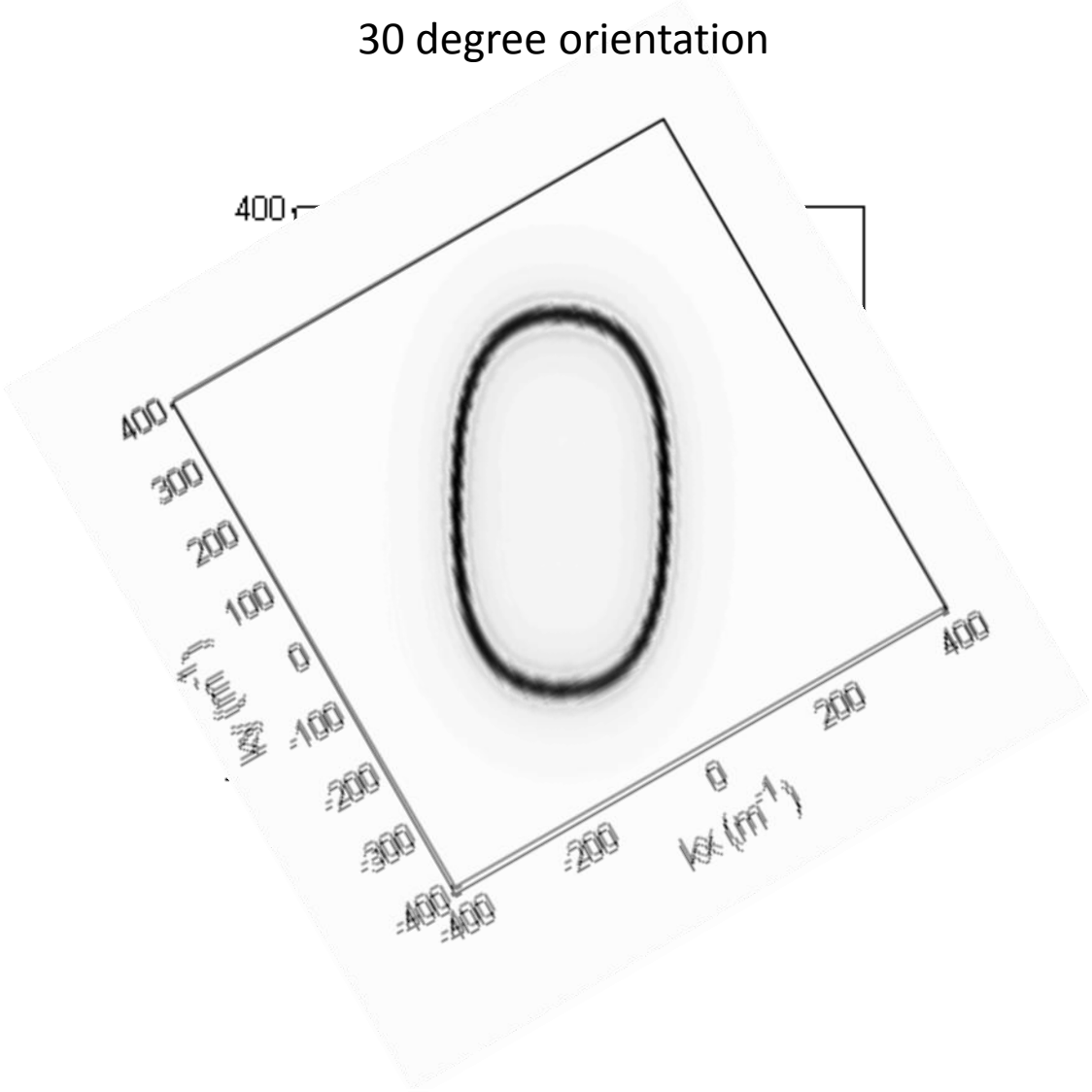


Simulation

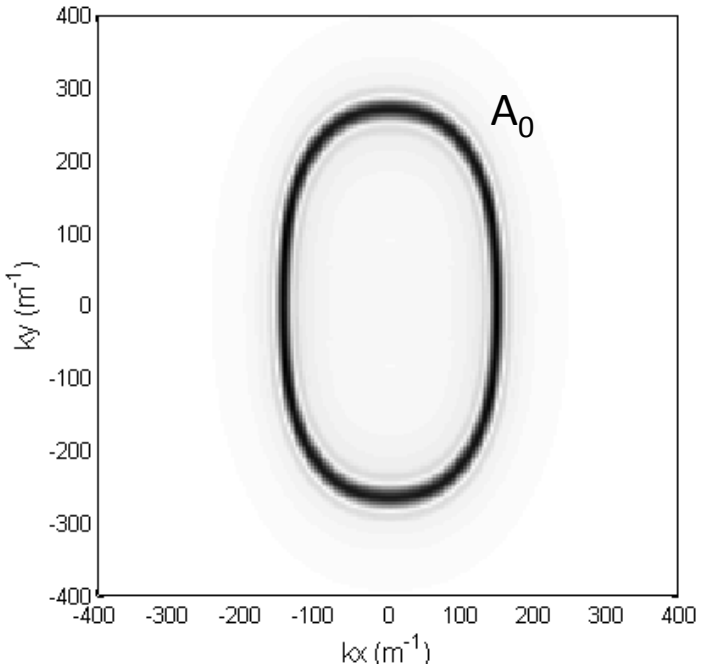


Off-angle example: Out-of-plane

30 degree orientation

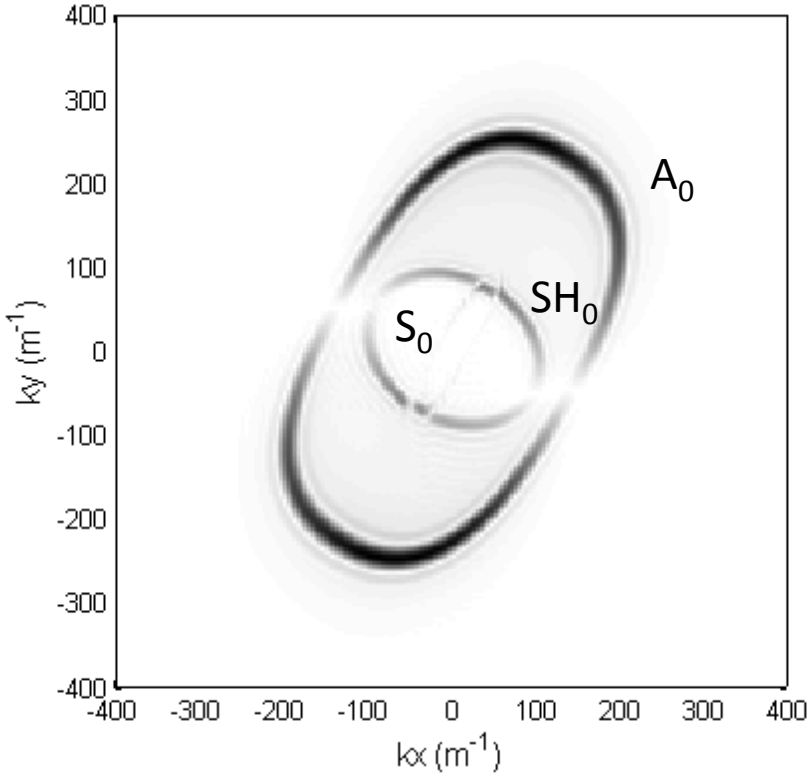


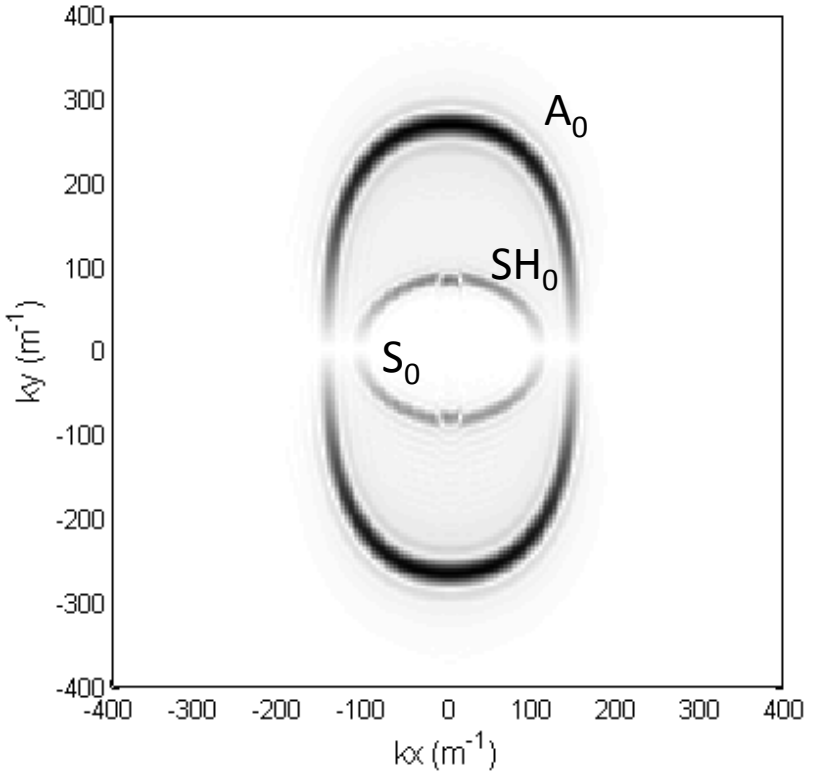
0 degree orientation



Off-angle example: In-plane

- For some cases, comparisons with theory (required due to 1-D LDV)





Composites for Space

Nondestructive Evaluation Sciences Branch