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Fusion of X-Ray and Ultrasound Images for As-Built Modeling

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Disclaimer and Auspices Statements

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Agenda

- Problem Definition
- Controlled Experiments with a “Phantom” Part
- Registration and Fusion Algorithms
- Experimental Results
- Conclusions

ME Techbase, "Process Development and Implementation of NDE-FEA Coupling for Numerical Analysis"

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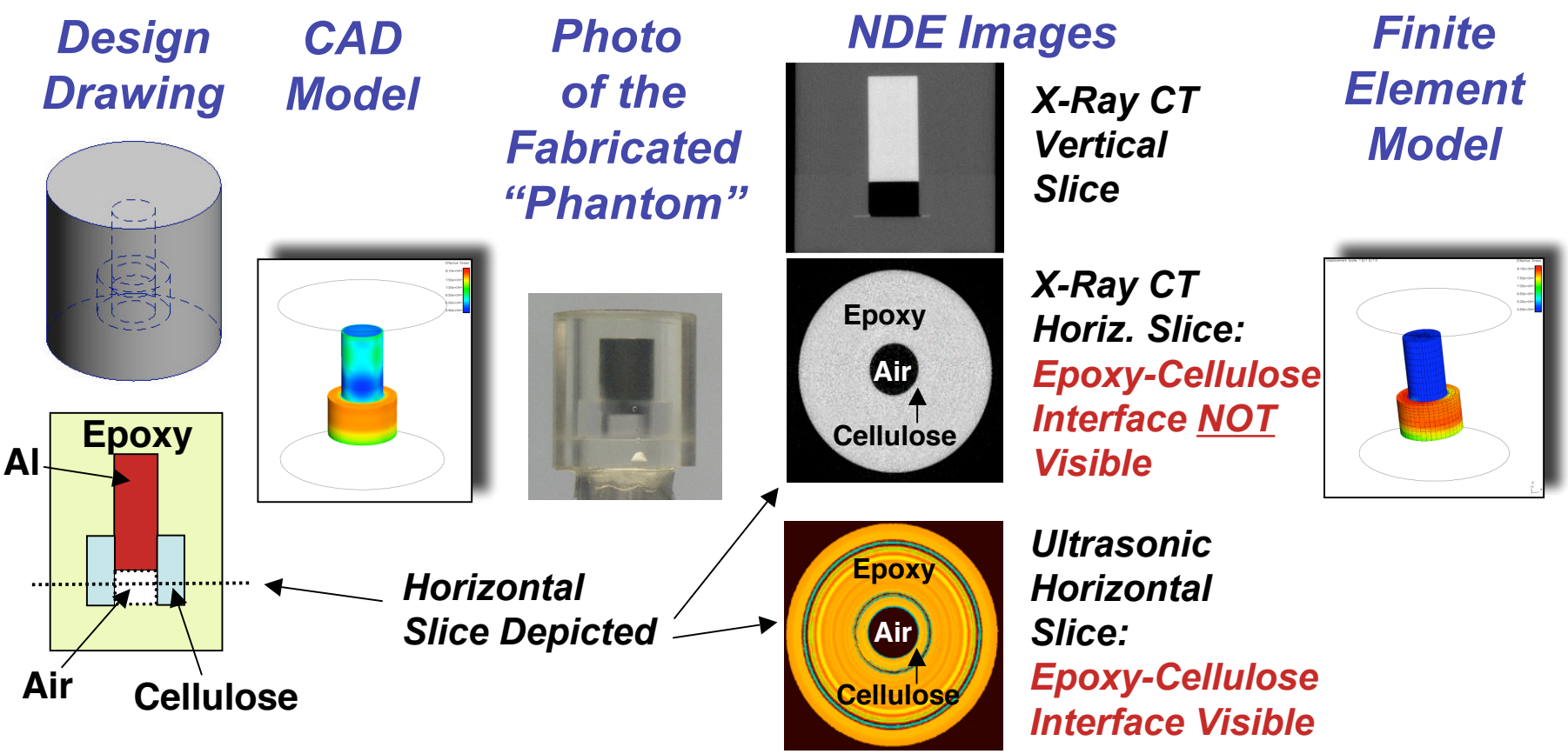
- *Created a RD&T Roadmap for Engineering Centers (CNDC and CCE)*
- *Multi-modal Sensor Fusion and Flaw Recognition for "As-Built Modeling"*
- *Processed X-Ray CT and Ultrasonic images from a known "phantom"*



As-Built Modeling:
Fabrication Errors Can Sometimes Be Significant

As-Designed

As-Built

The Literature Contains No Fusion of X-Ray and Ultrasound NDE Imagery

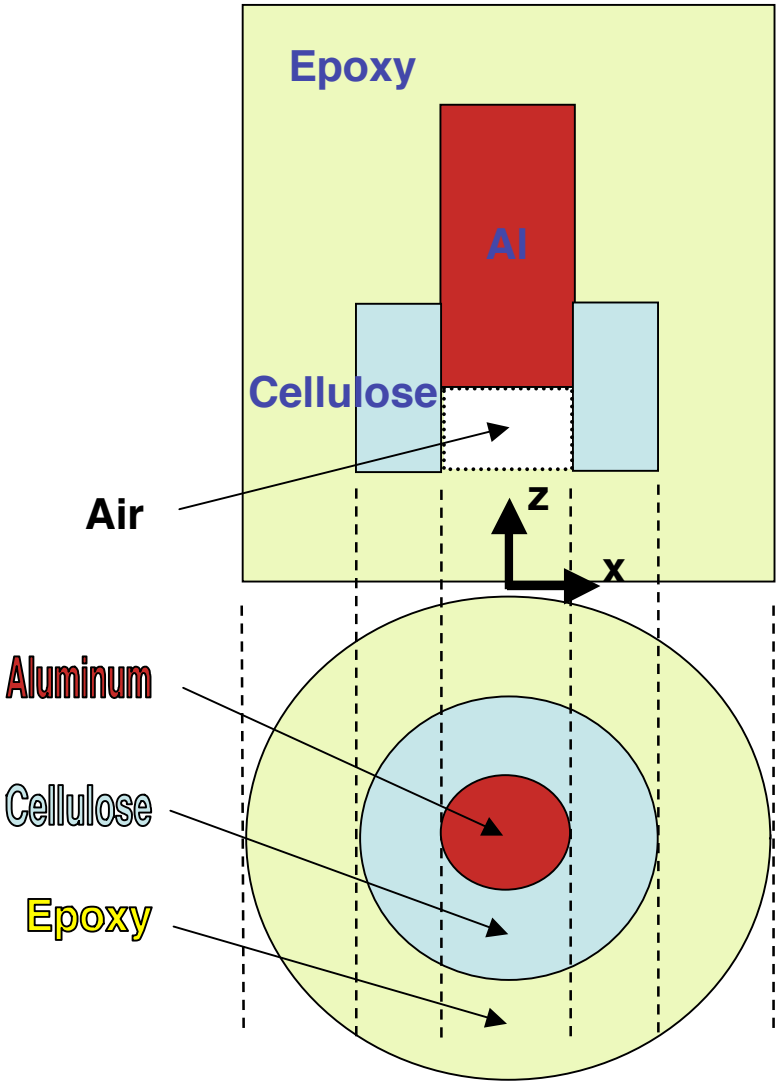
- The medical literature contains some fusion results, but they are not generally useful for NDE:

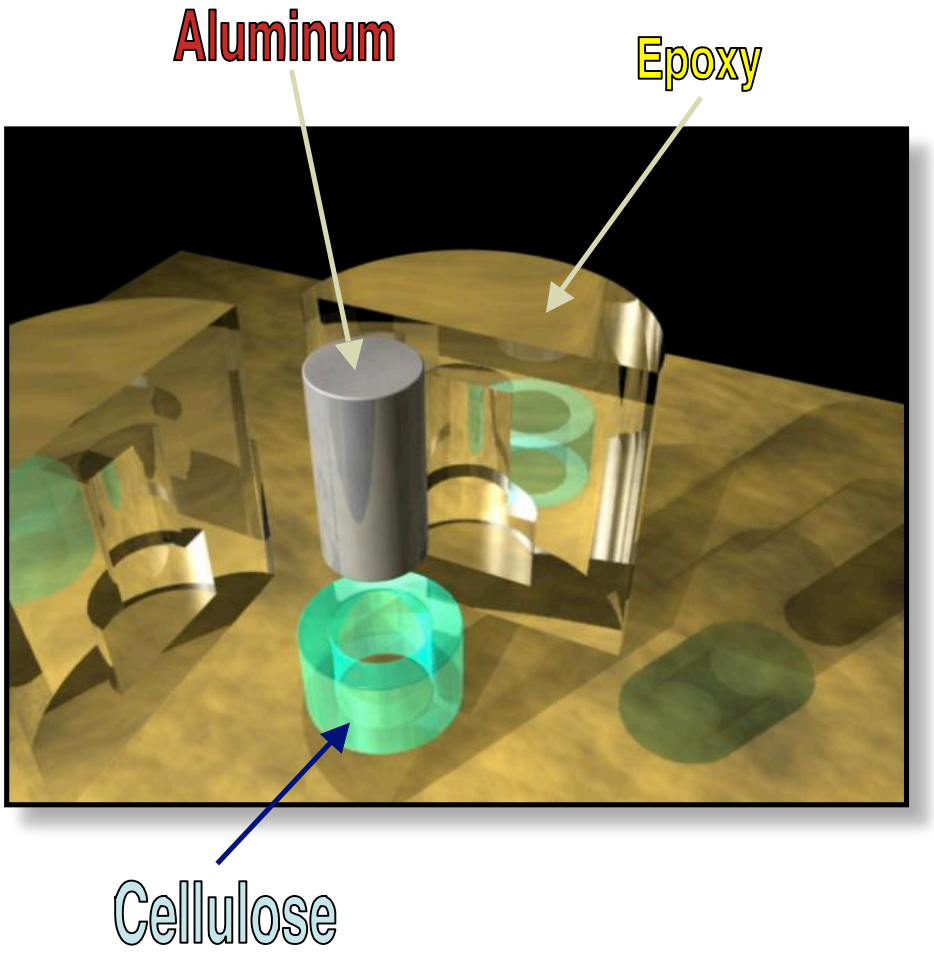
  - Allowable power levels are much lower for medicine
  - Attenuation effects are much different in medicine
  - Qualitative results (visual inspection) are usually sufficient
  - Fiducial marking is routine in medicine, but often not possible in NDE at LLNL

- Image registration is the "long pole in the tent" for fusing X-ray and Ultrasound NDE Images - Attempts have been unsuccessful

  - There are separate scanning systems for X-ray and Ultrasound, so mechanical registration is impossible
  - Image reconstruction and registration are coupled
  - Scaling the UT image requires ray tracing, event picking, and velocity estimation (as in seismic processing)
    - Difficult to automate

Our Test Part Consists of 3 Concentric Cylinders Made of Aluminum , Cellulose and Epoxy





CT and UT Measure Different Material Properties. Each Modality Has Strengths and Weaknesses.

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CT (X-Rays)

Measures X-Ray Attenuation

$$A = f\left[E_A, \rho, Z\right]$$

where :

E_A = Energy Applied

ρ = Density

Z = Atomic Number (# protons)

Strengths:

- **A strong function of Z (~ Z^r)**
- **High spatial resolution (good for observing part geometry)**
- **Spatial scaling is automatic**

Weaknesses:

- ***Not very sensitive to changes in density - Not good for detecting closed cracks***

UT (Ultrasonics)

Measures reflected acoustic energy

$$R = g\left[\rho, E\right]$$

where :

ρ = Density

E = Modulus of Elasticity

= Young's Modulus

Strengths:

- ***Good for detecting small changes in density and modulus***
- ***Good for detecting closed cracks***

Weaknesses:

- ***Low spatial resolution due to temporal "ringing" of band-limited ultrasonic transducers***
- ***Spatial scaling is complex, difficult***

Two Image "Slices" Demonstrate the Strengths and Weaknesses of CT and UT

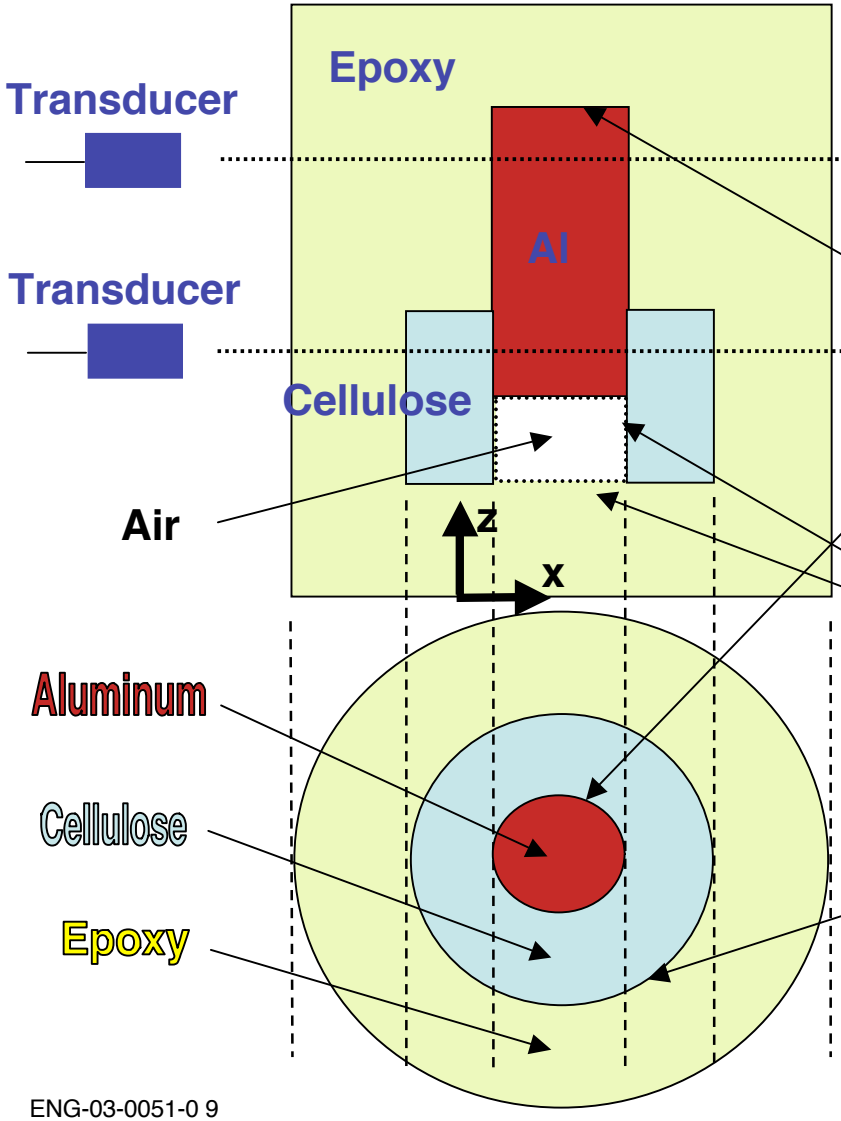


Image Slice 1:

- The aluminum-epoxy interface contrast is strong for both CT and UT

Image Slice 2:

- The *aluminum-cellulose* and *aluminum-epoxy* interface contrasts are strong for both CT and UT
- The air-cellulose and air-epoxy interface contrast is strong for both CT and UT
- The epoxy-cellulose interface contrast is: ***Strong for UT, Weak for CT***

The Epoxy-Cellulose Interface Has Low Contrast With CT, but Much Higher Contrast With UT

The Epoxy - Cellulose Interface:

- **Epoxy and Cellulose have approximately the same density and modulus:**

Composition

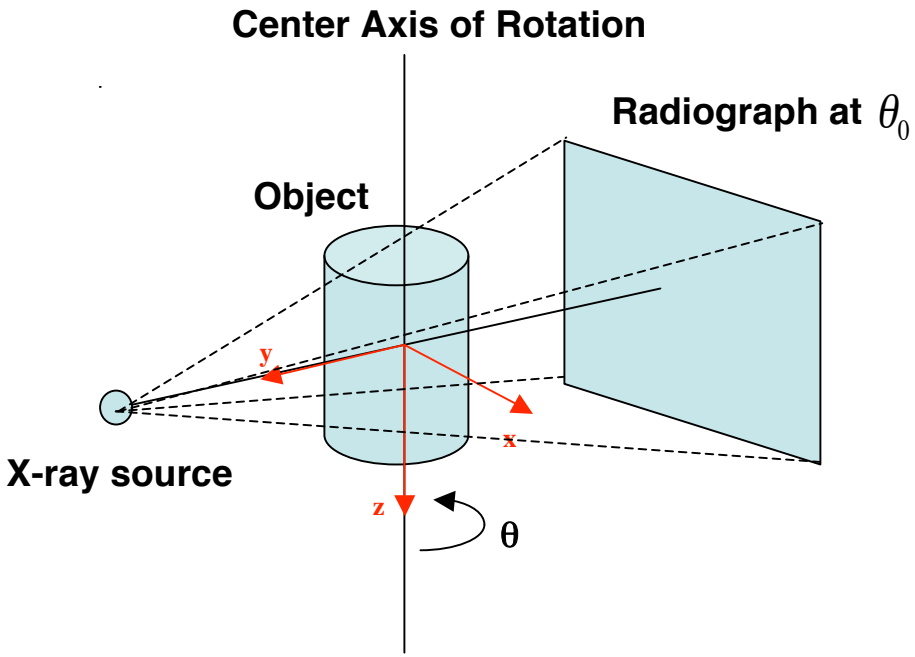
- **Density:** $\rho_{Epoxy} \approx \rho_{Cellulose}$
- **Coefficient of Elasticity: (Young's Modulus)** $E_{Epoxy} \approx E_{Cellulose}$
- **Atomic Number:** $Z^{eff}_{Epoxy} \approx Z^{eff}_{Cellulose}$

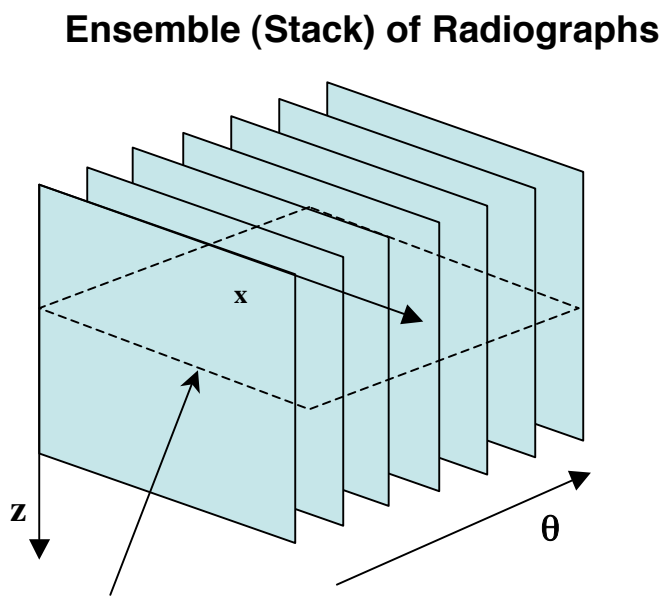
⇨

- **UT can detect interfaces well**
- **CT is minimally effective for interface detection, good for geometry characterization**

- **The other interface contrasts are strong for both CT and UT**

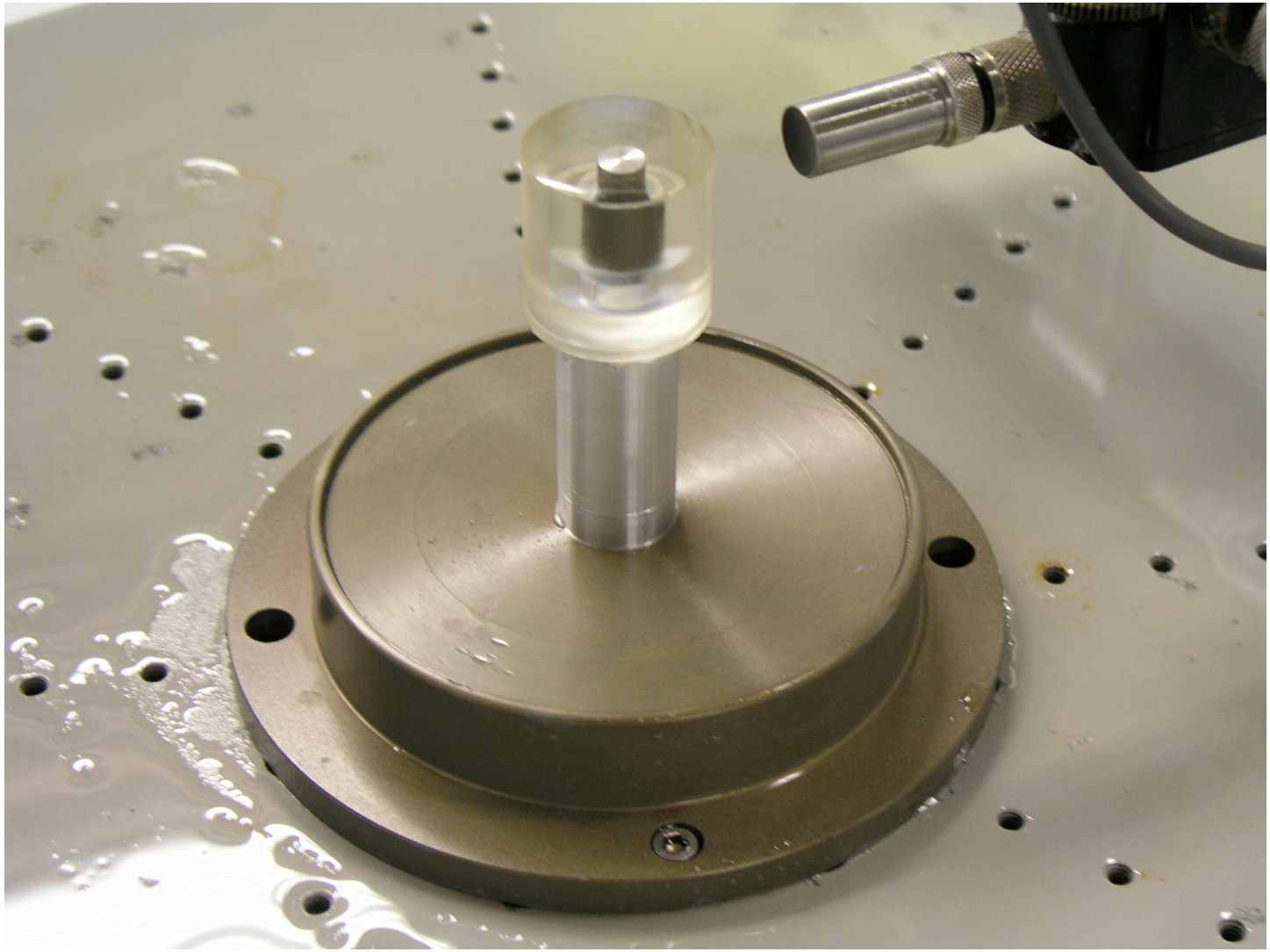
X-Ray Images (Radiographs) are Acquired by Fixing the X-Ray Source and Rotating the Object



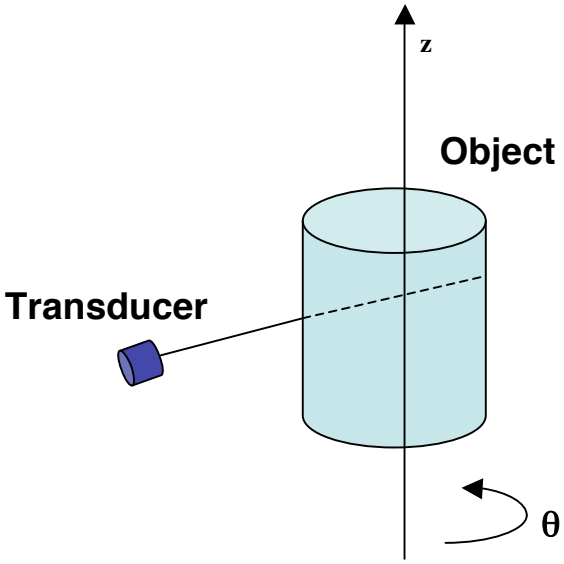


Polar Plot or "Sinogram"

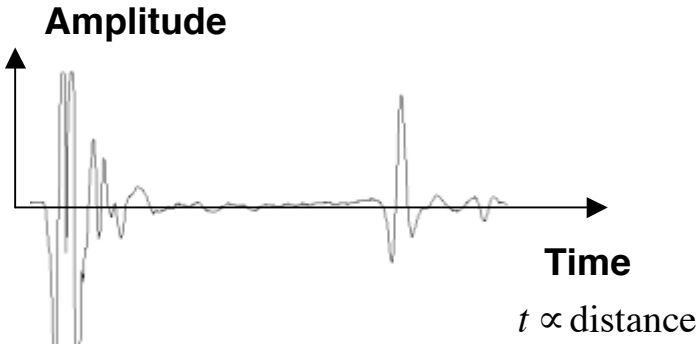
Ultrasound Images are Acquired Using a Separate Scanning System: *Source is Fixed, Object is Rotated*



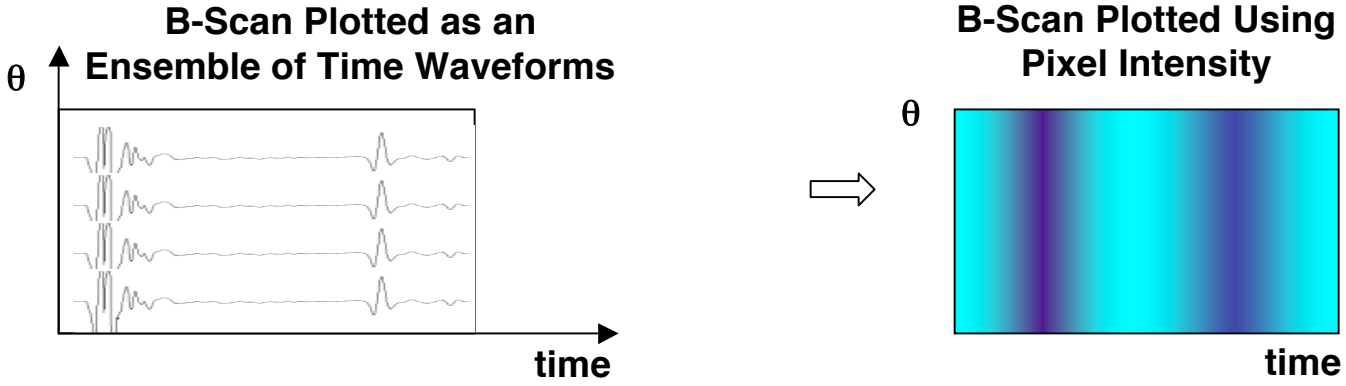
Ultrasound Images are Acquired in Pulse-Echo Mode, Scanning the Transducer Vertically as the Part is Rotated



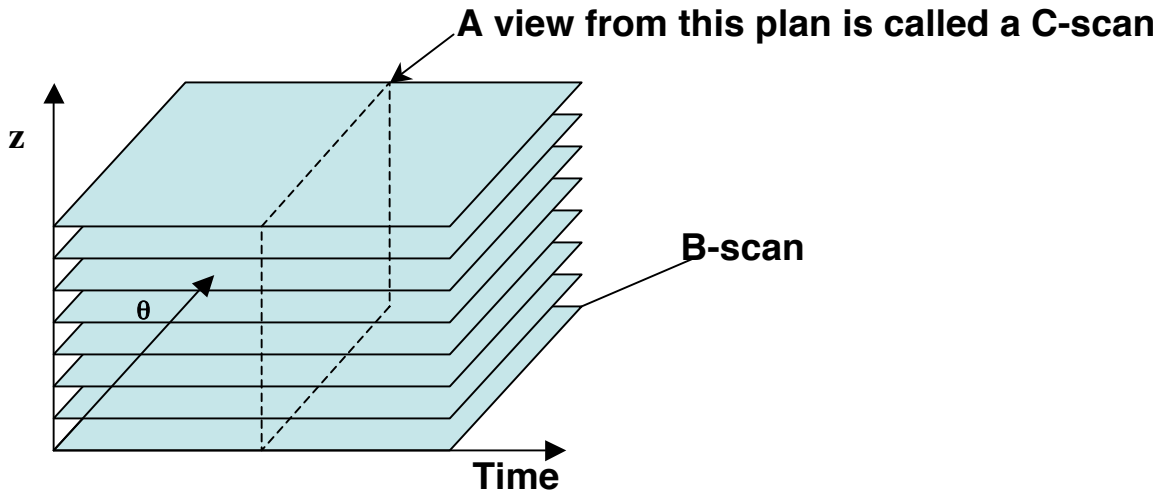
Raw A-scan (Time Waveform)



An Ensemble of Ultrasonic A-Scans Forms a B-Scan

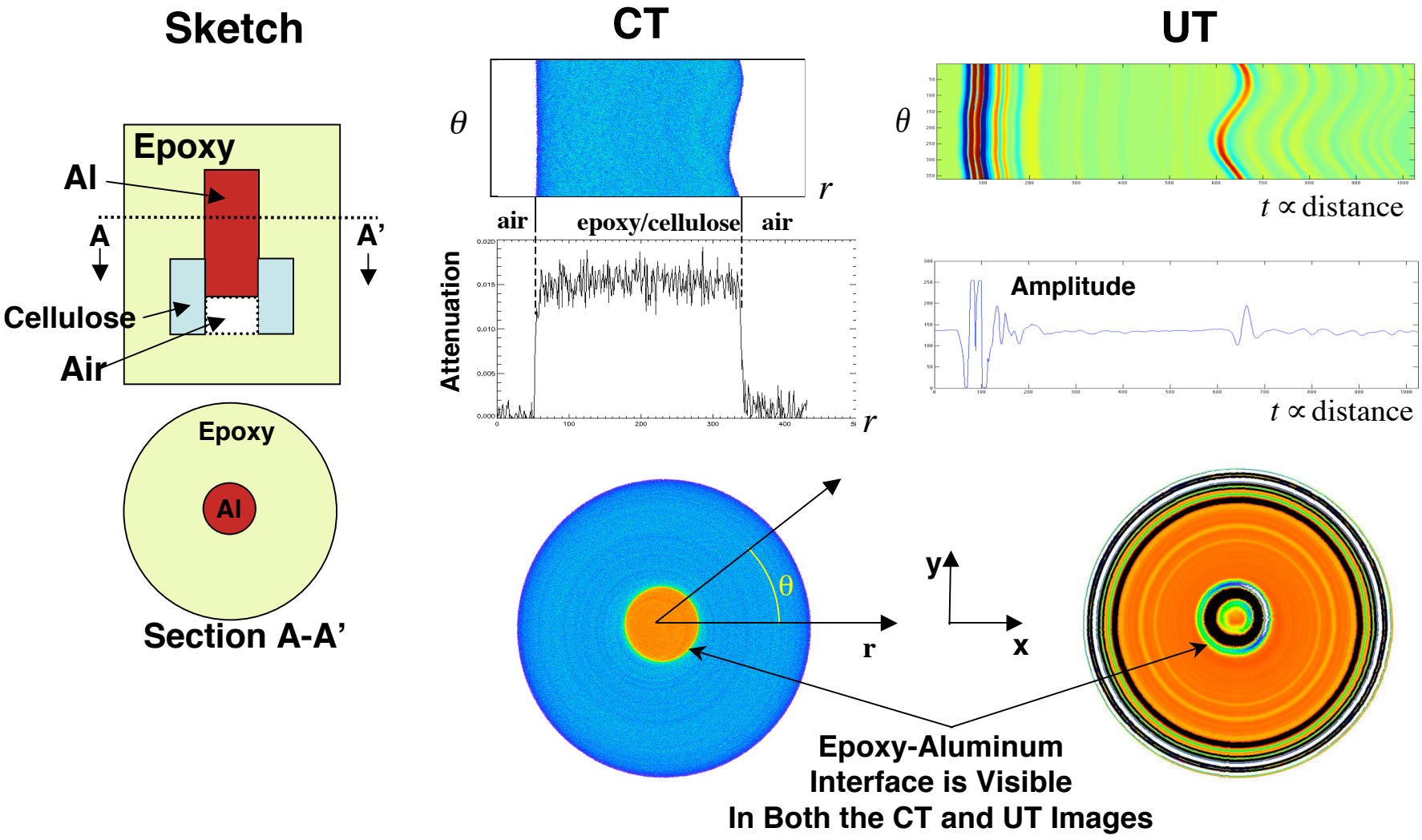


An Ensemble of B-Scans forms a 3D Volume



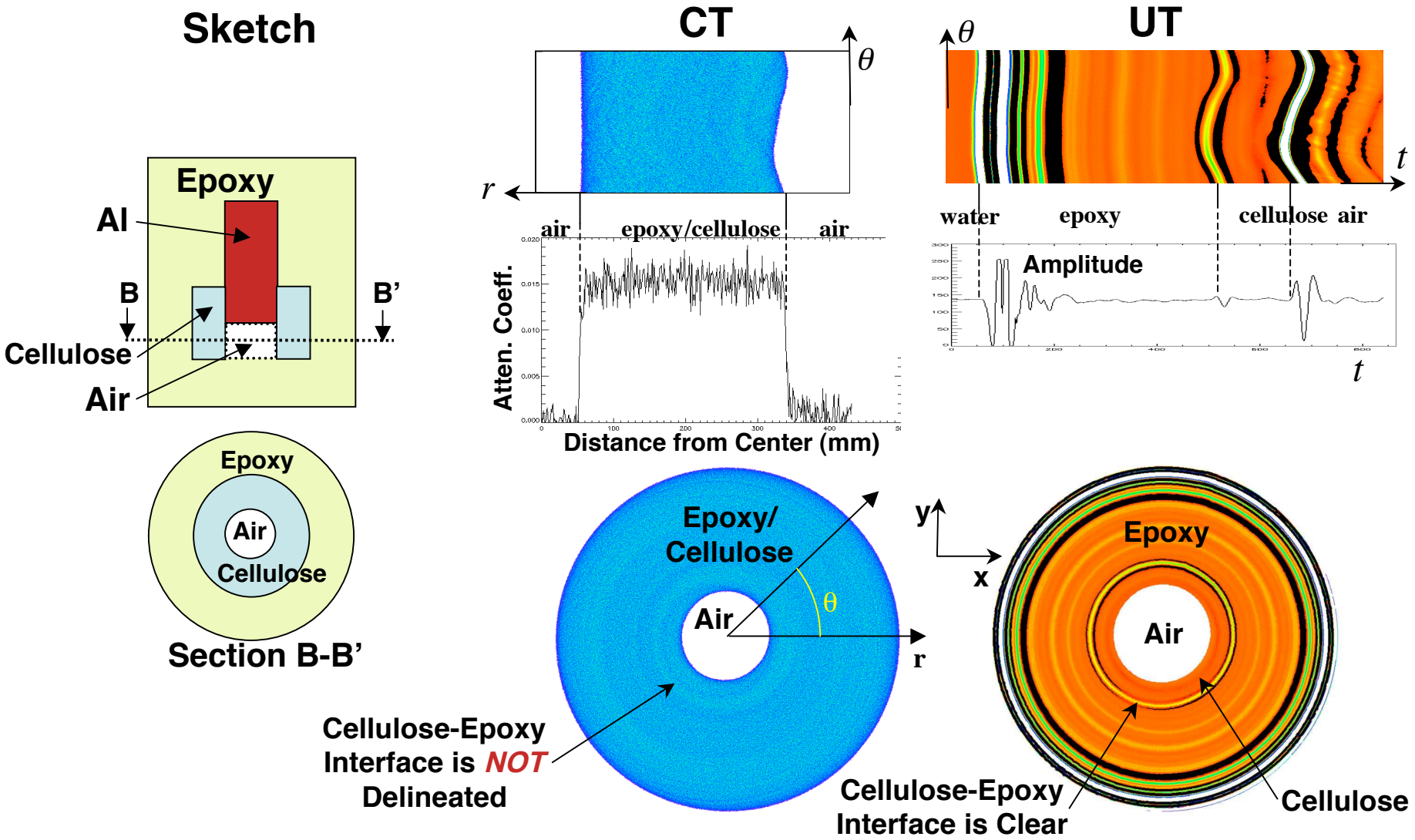
Summary of Horizontal Slice 40: Epoxy and Aluminum

Both CT and UT Show the Epoxy-Al Interface



Summary of Horizontal Slice 20: Epoxy, Cellulose, Air

Cellulose-Epoxy Interface is Visible Only in the UT Image



Optimal (Desired) Approach to Fusion:
Fully Automatic Processing at All Steps

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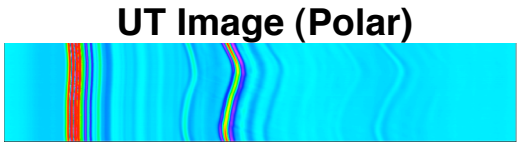


Off-Line Velocity, Density, and Geometry Measurements

UT Image *(Polar Coord's)*

Velocity Model

Ray Trace *(Automatically)*

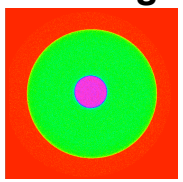
Form UT Image: *Polar to Rectangular Coordinate Conversion*

Co-Register CT and UT Images *(Automatically)*

Update Velocity Model *(Automatically)*

Pick Events *(Automatically)*

CT Image



Registered Images

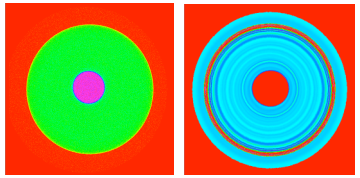
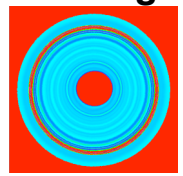


Image Sharpening

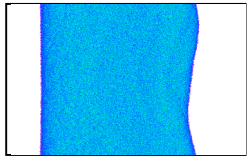
- **Impulse Response Est.**
- **Super-Resolution Algs.**

UT Image

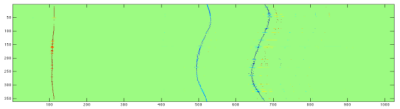


Suboptimal Semi-Manual Fusion: Build a *"UT Edge Map"* and Superimpose it on the CT Image

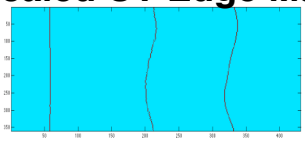
CT Polar Image



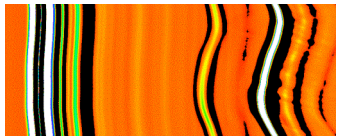
Unscaled UT Edge Map



Scaled UT Edge Map



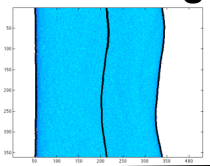
UT Polar Image



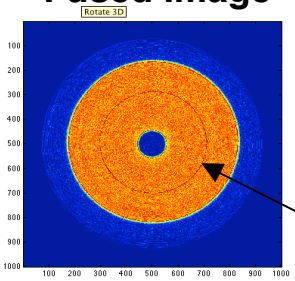
Super-Resolution To Create an Ultrasound "Edge Map"

Manual Scaling
-Ray Tracing
- Event Picking
- Velocity Estimation

Fused Polar Edge Map



Fused Image



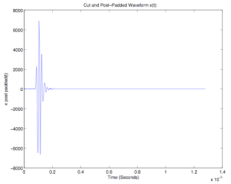
Polar-to-Rectangular Conversion

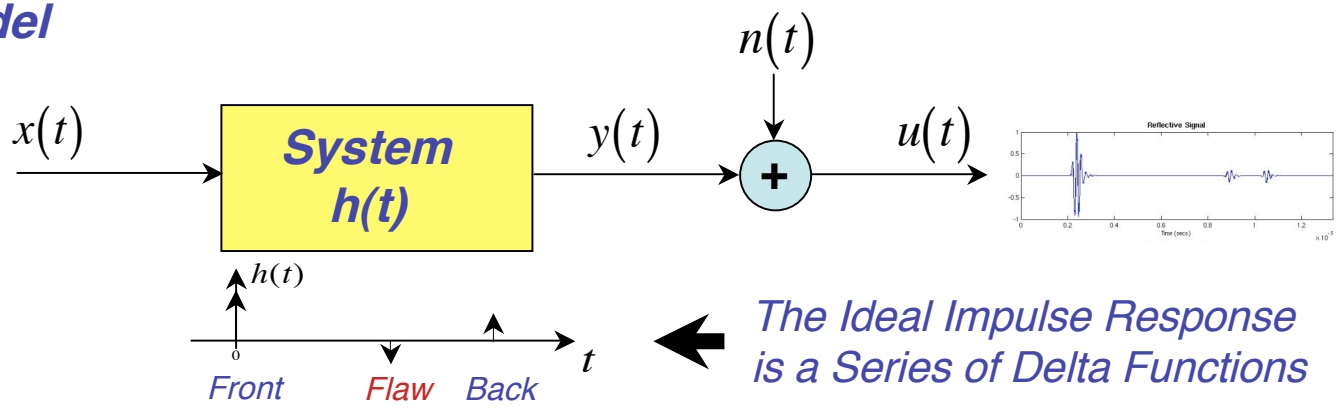
Superimpose

The Epoxy-Cellulose Interface is Now Clearly Delineated

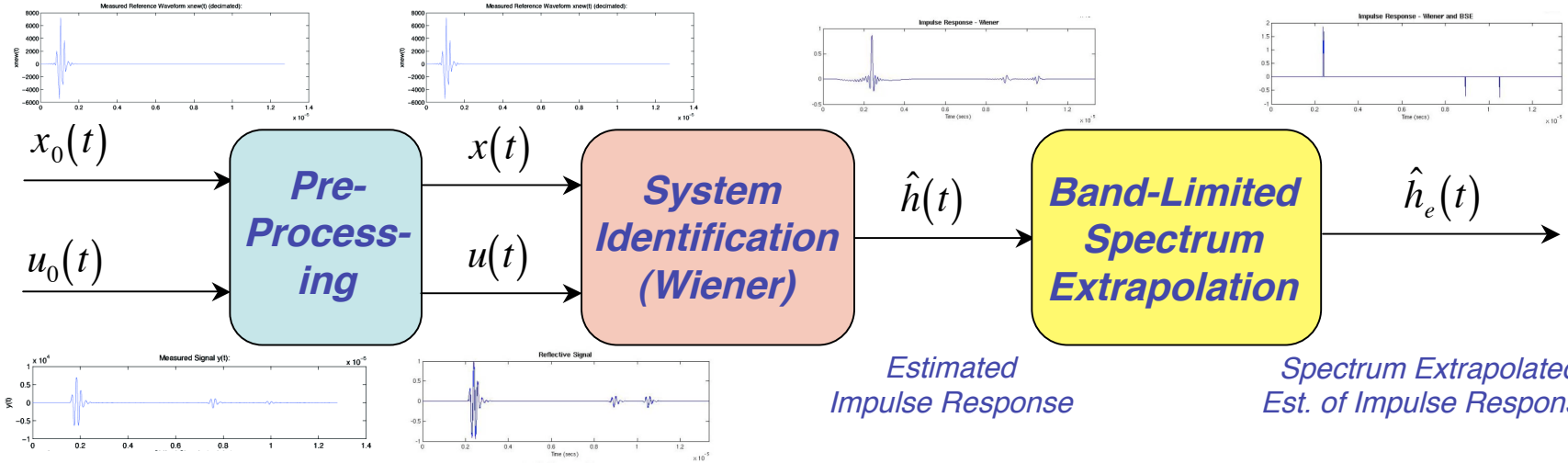
The *System Model* and *Super-Resolution Algorithms* Are Summarized in Block Diagrams

System Model

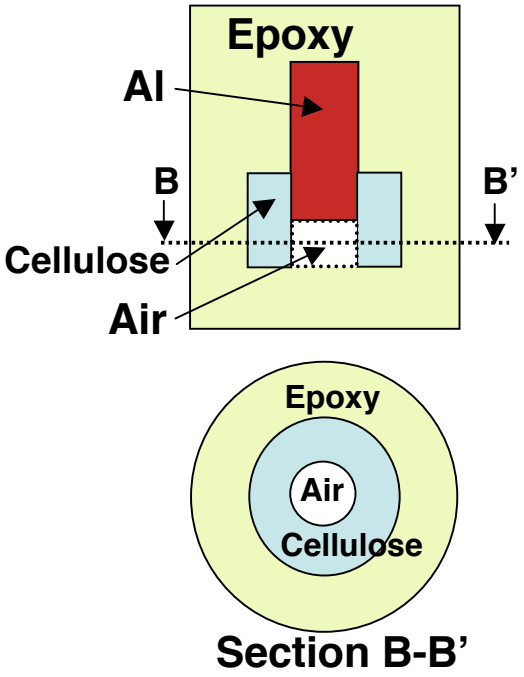


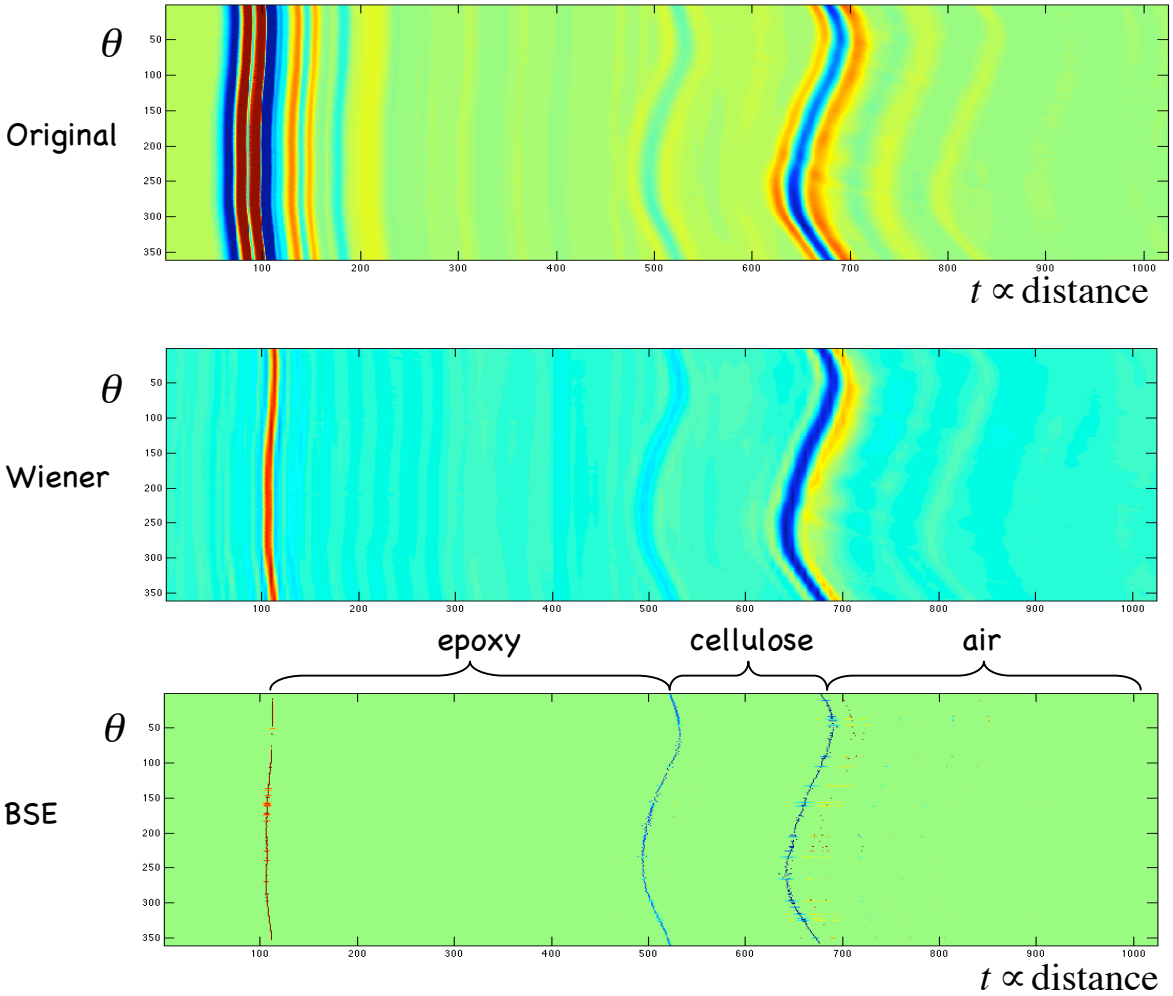


Super-Resolution Algorithms



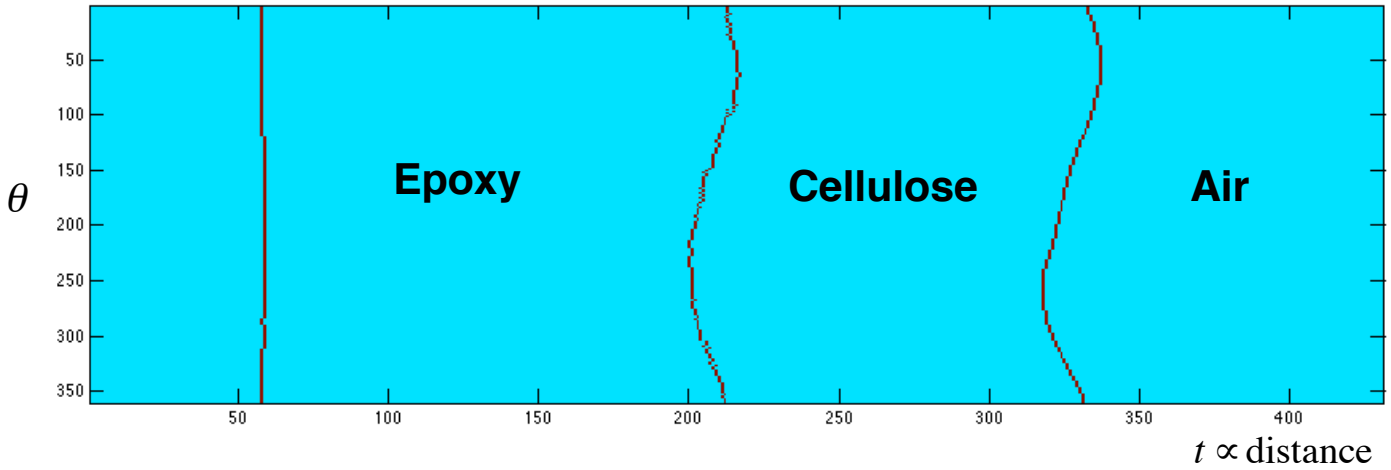
Super-Resolution Result: Resolution is Enhanced in the Ultrasound Polar Plots of *Slice 20*





An *"Ultrasound Edge Map"* Polar Plot is Created from *Slice 20* Using the Super-Resolution Results

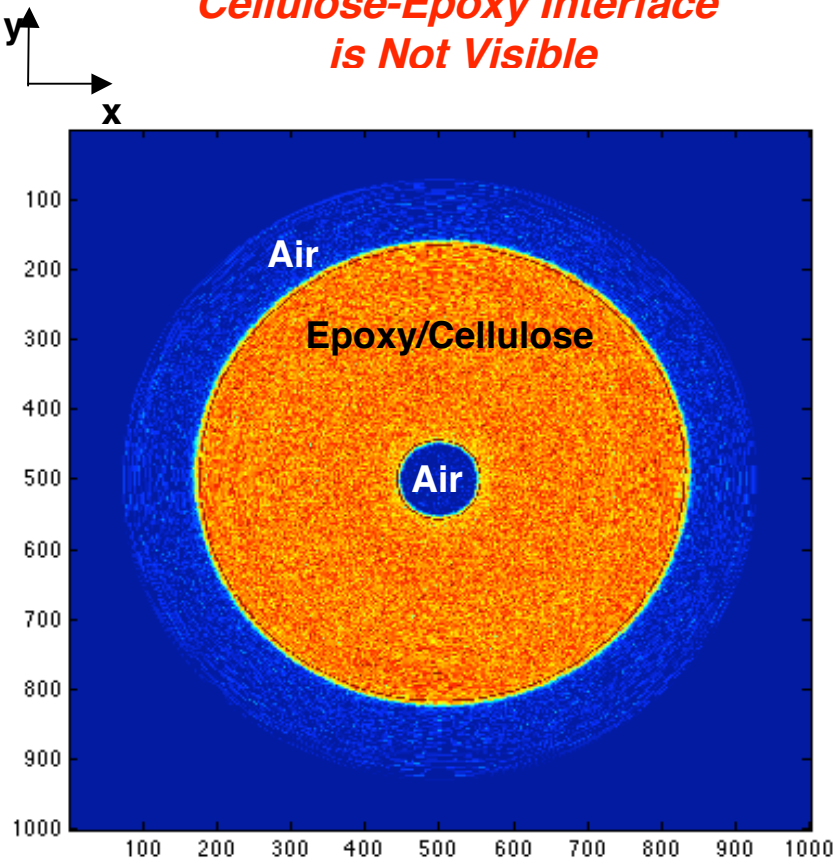
By Manually Comparing the CT Image and the UT Edge Map,
A Spatially Scaled UT Edge Map can be Determined:
(Ray Tracing, Event Picking and Velocity Estimation are Done Manually)



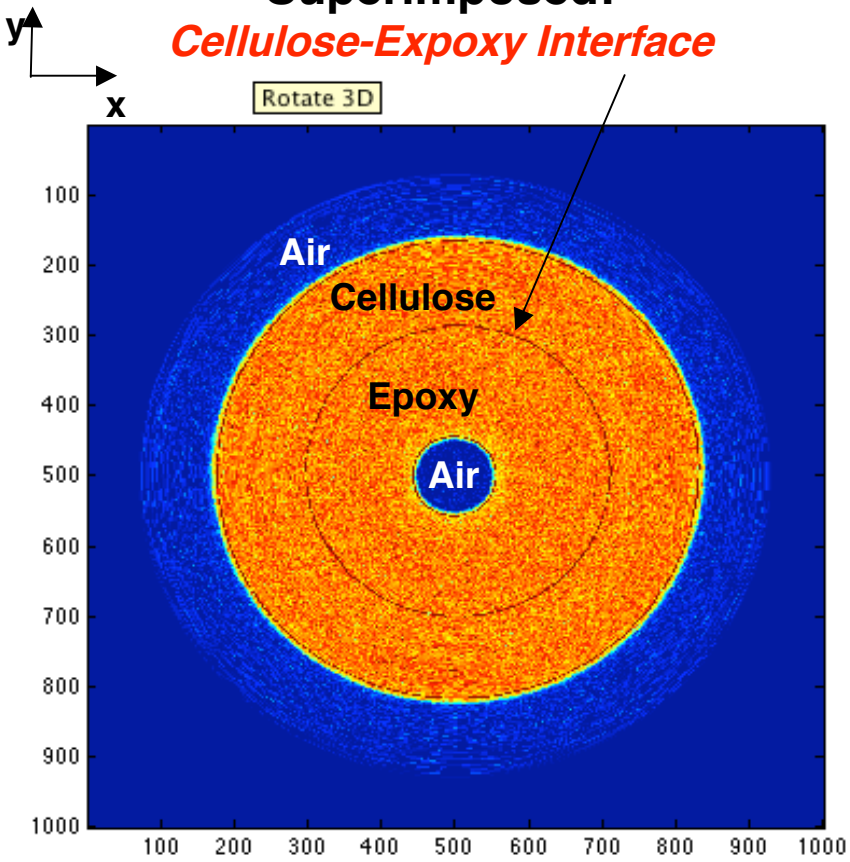
Fusion: The *"UT Edge Map"* is Superimposed on the CT Image of *Slice 20* to Show the Cellulose-Epoxy Interface

Slice 20

X-Ray CT Image:
Cellulose-Epoxy Interface is Not Visible



X-Ray CT Image with the *"UT Edge Map"* Superimposed:
Cellulose-Expoxy Interface



Conclusions

- We demonstrated a semi-manual method for fusing X-ray and Ultrasound images

  - Using super-resolution algorithms to build an "edge map"

  - Manually performing ray tracing, even picking, and velocity estimation

- Future work:
  - Automating the registration and fusion processes