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Title: Acoustic Imaging of Delaminations and Cracks Using Time Reversal and Nonlinear Spectroscopy Techniques

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Acoustic Imaging of Delaminations and Cracks Using Time Reversal and Nonlinear Spectroscopy Techniques

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Motivation for Our Work

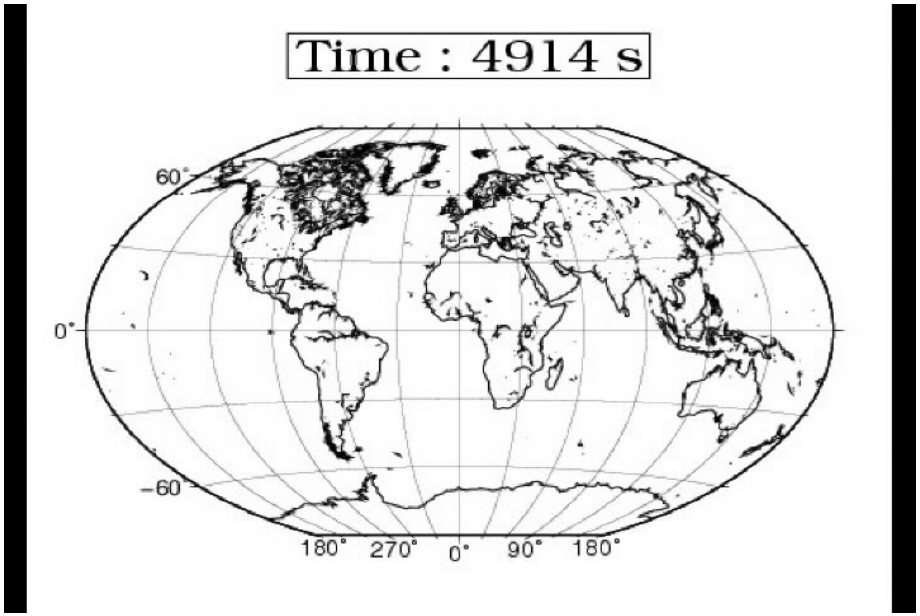
- China Lake rocket motors (solid fuel) - delaminations between fuel and outer casing.
- Mock propellant manufactured delamination sample.

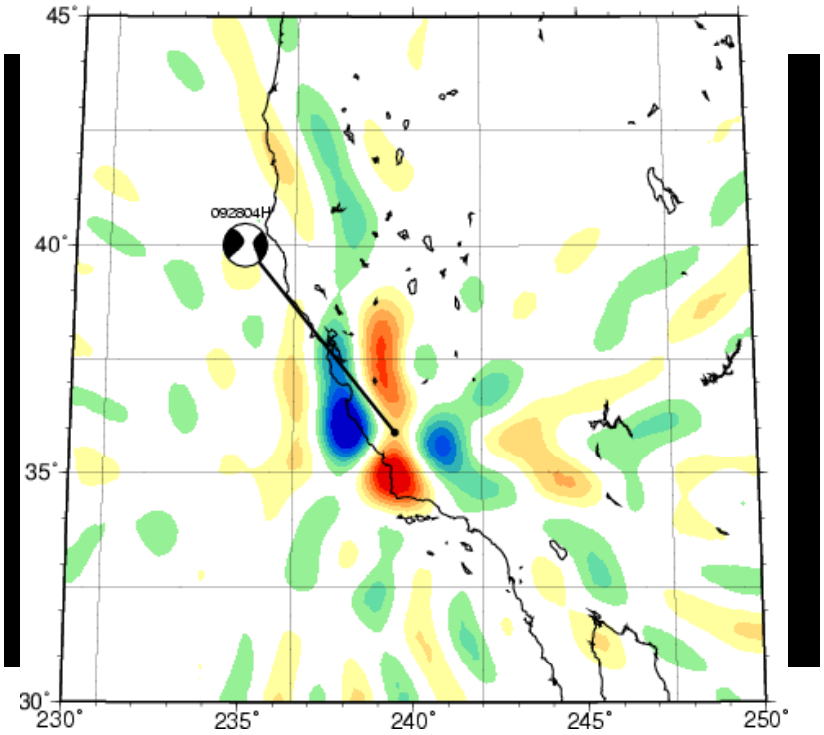
- We inspect samples at low vibration levels (doesn't further damage the samples).
- We look for delaminations and cracks.
- We're developing a noncontact source to use with our noncontact sensor for inspection of samples.

Imagine Reversing the Ripples in a Pond

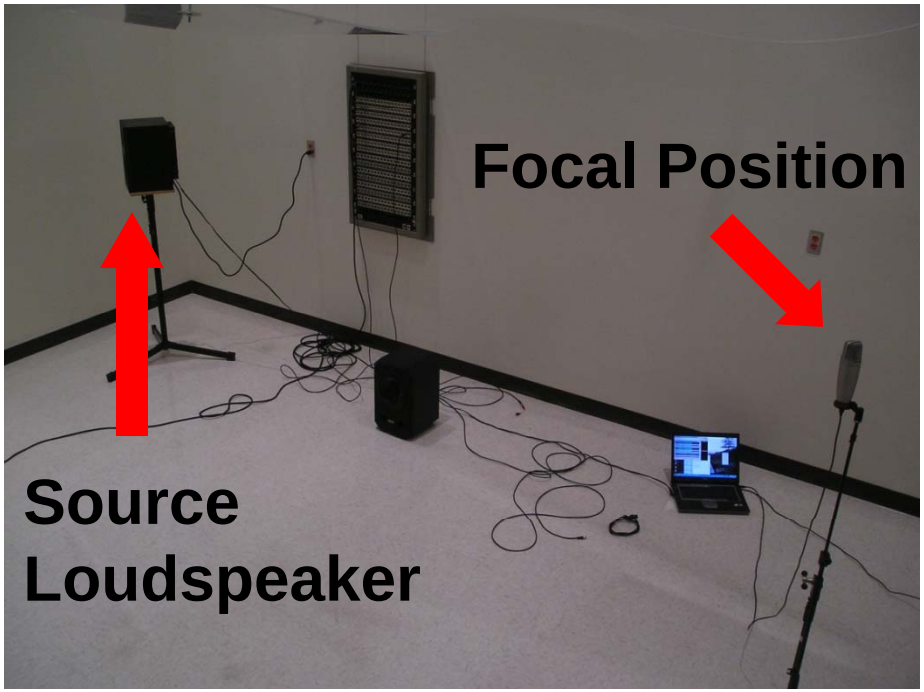
Larmat *et al*., Geophys. Res. Lett., (2009).
Anderson *et al*., Acoust. Today, (2008).

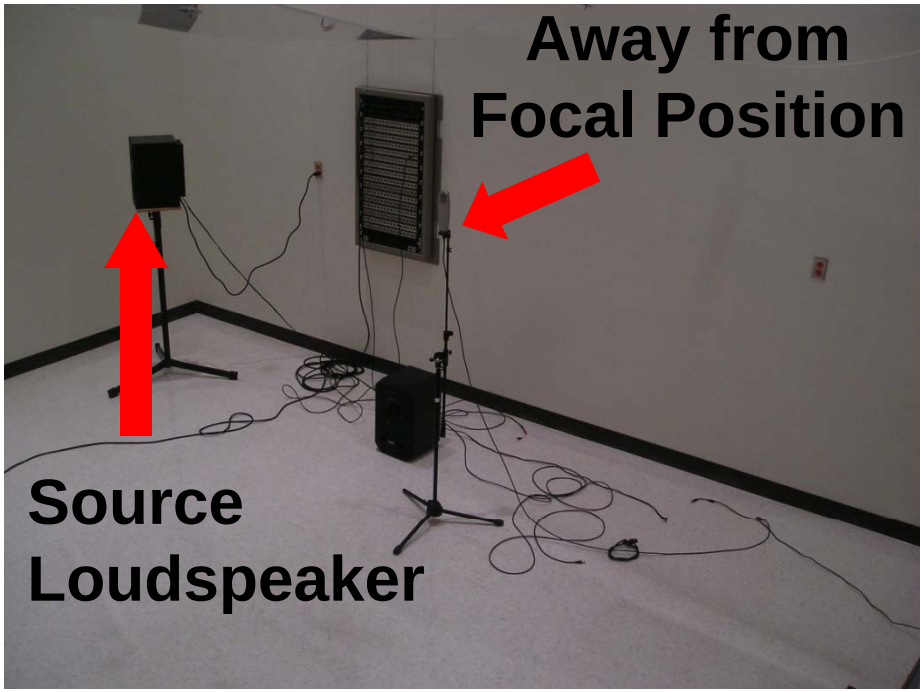
Time Reversal of Earthquakes





Audio Demonstration for Speech Privacy



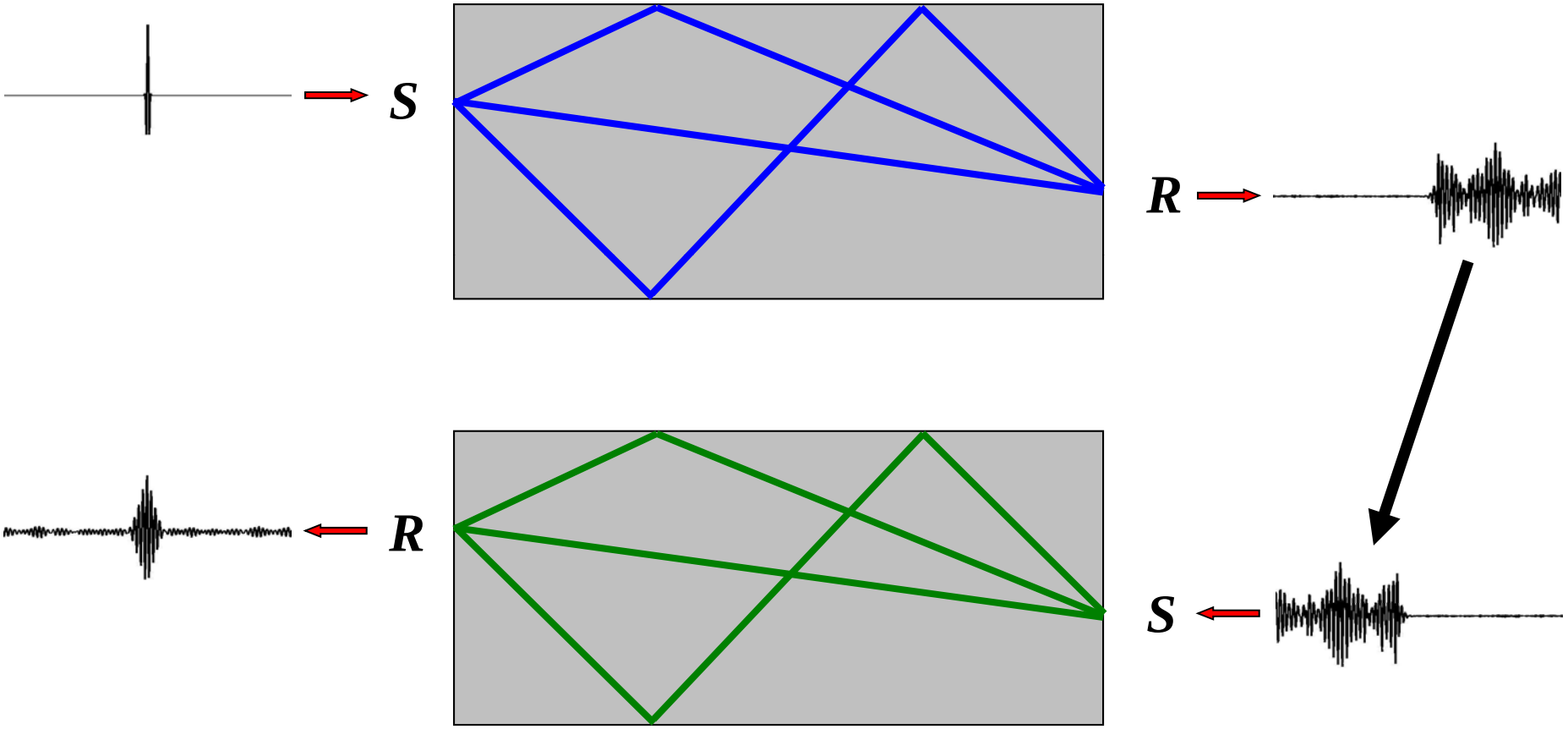


Clap

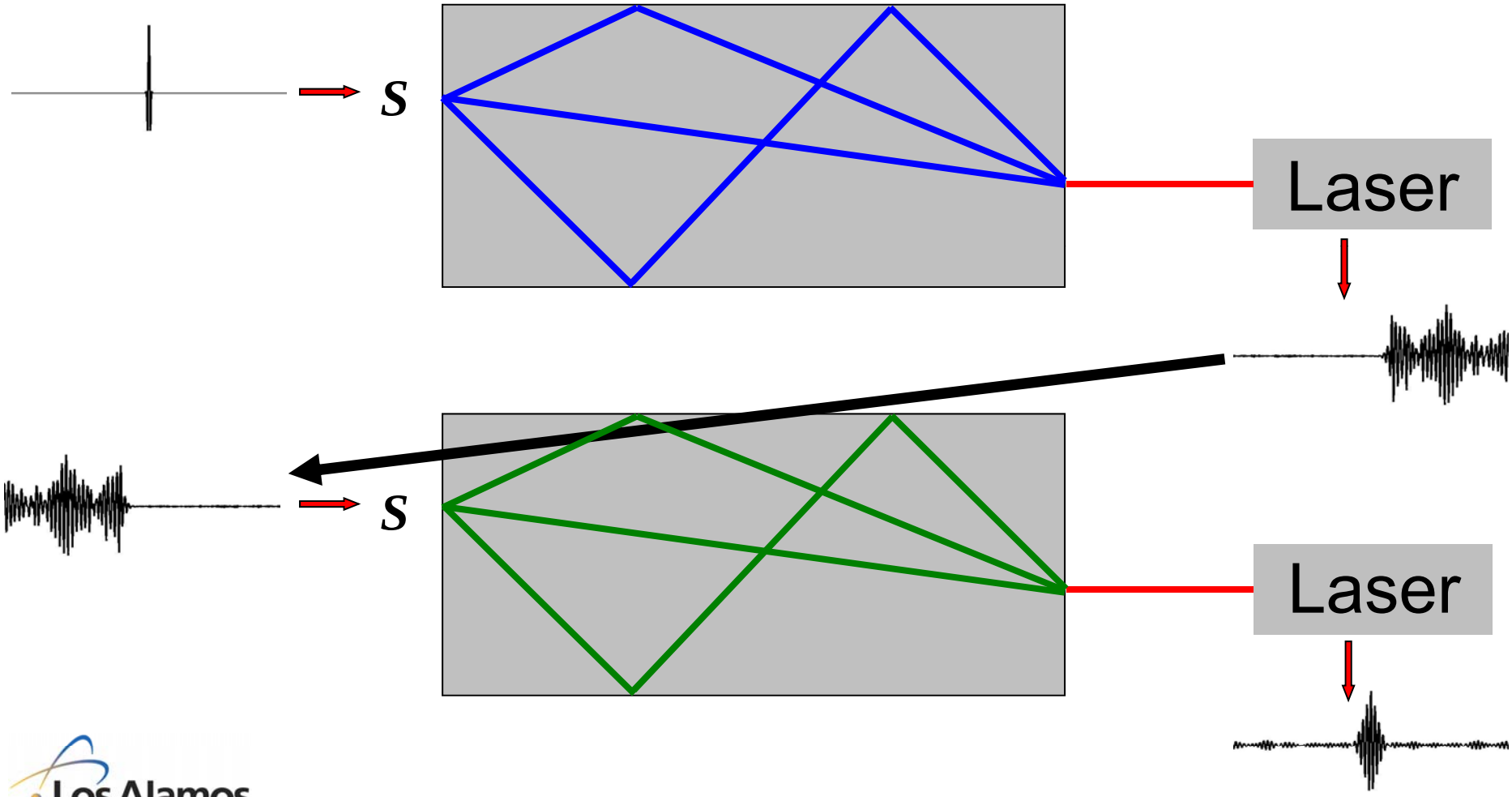
Away

Focus

Standard Time Reversal (Source Reconstruction)

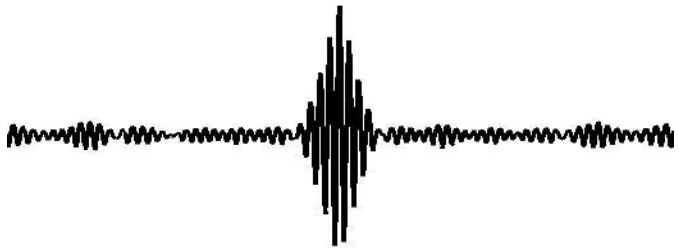


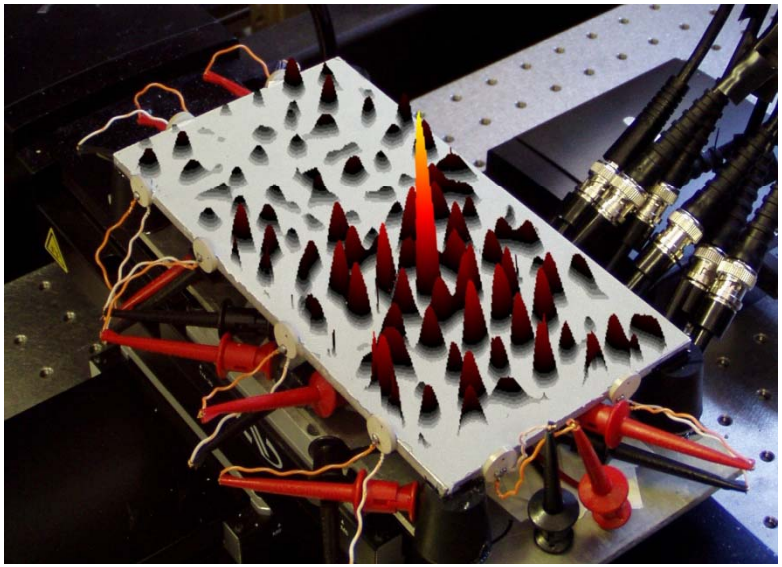
Reciprocal Time Reversal (High Amplitude Focusing)

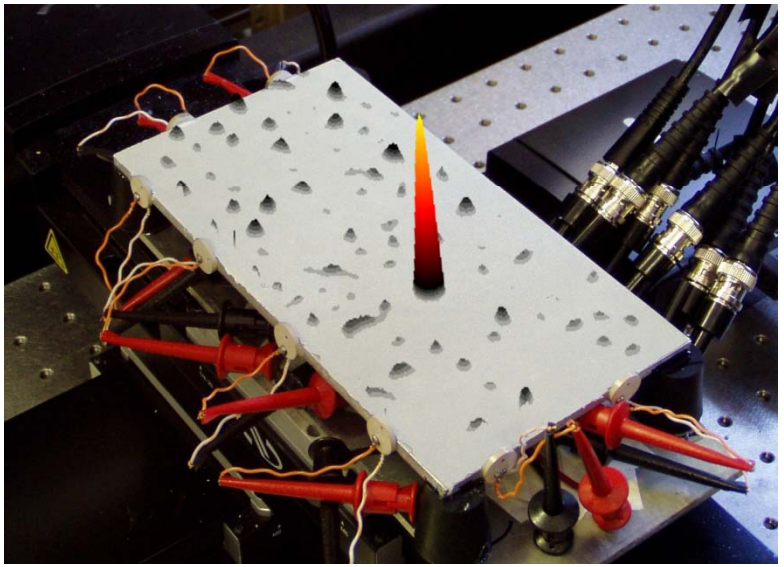


Anderson *et al*., Acoust. Today, (2008).
Ulrich *et al*., J. Acoust. Soc. Am., under review.

Comparison of Time Reversal w/ and w/o Deconvolution







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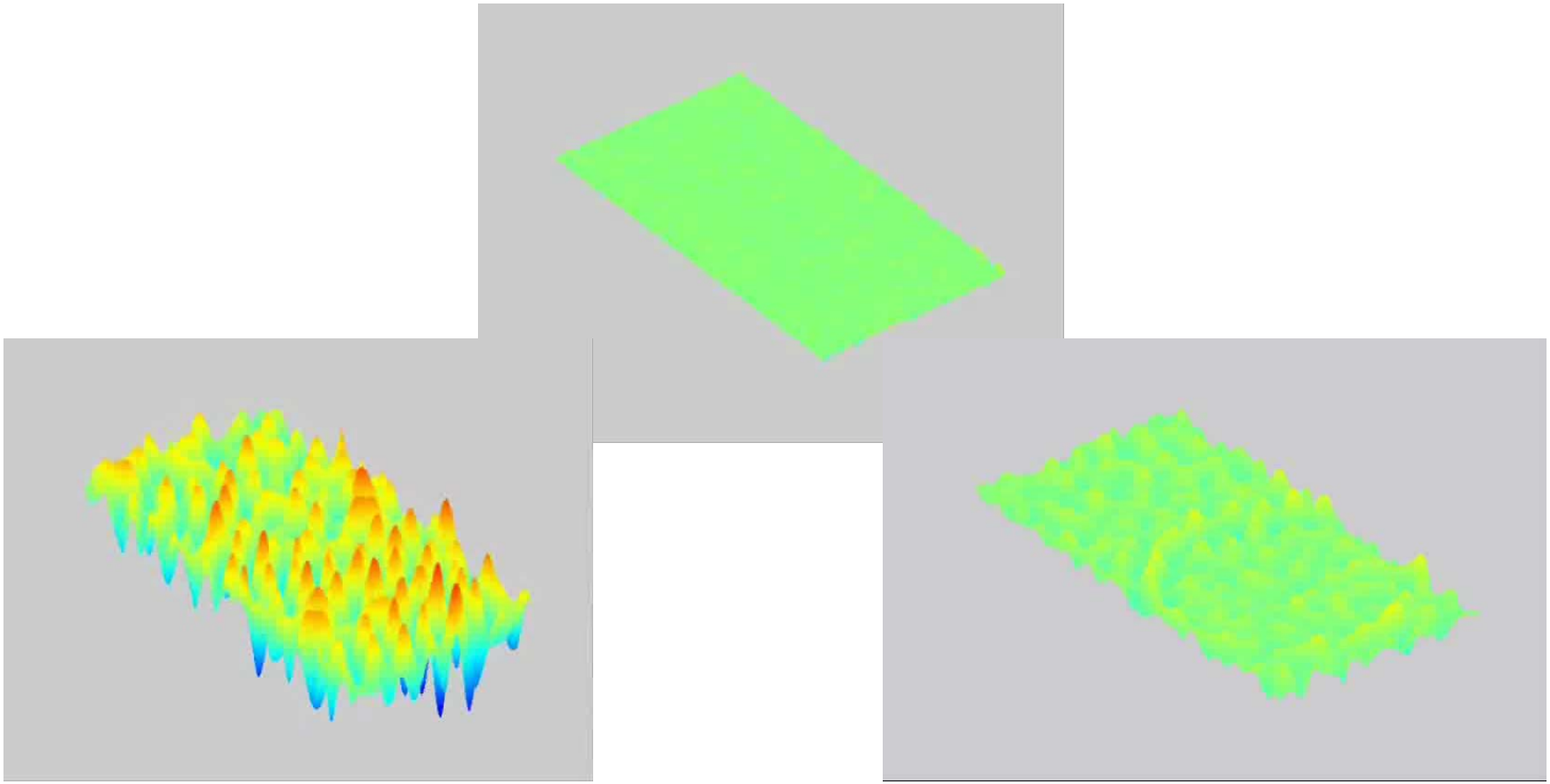
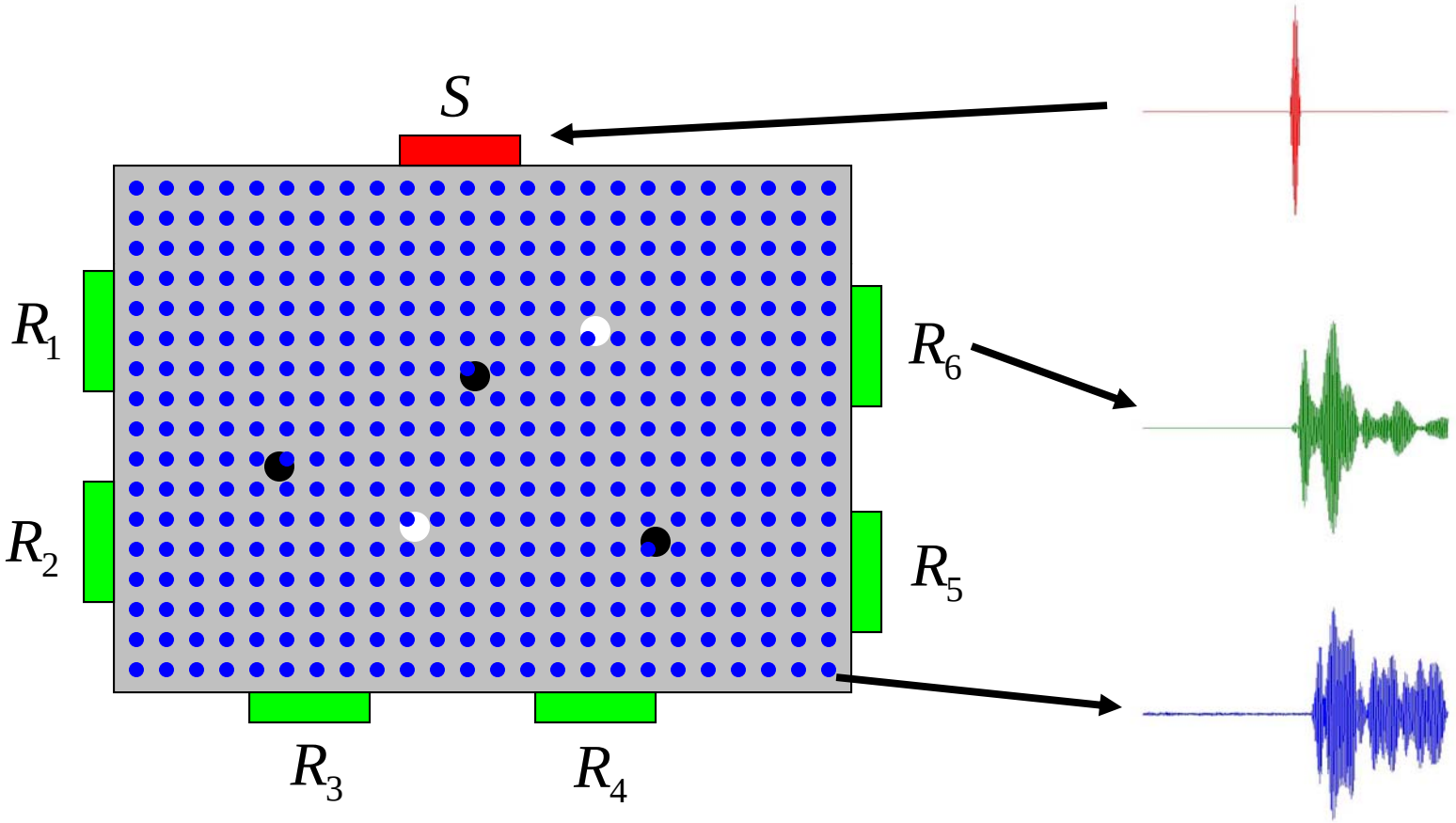
Time Reversal – Wave Propagation Movies



Anderson *et al*., J. Acoust. Soc. Am., (2011).

Reverse Time Migration to Image Delaminations



Anderson *et al*., J. Acoust. Soc. Am., (2011).

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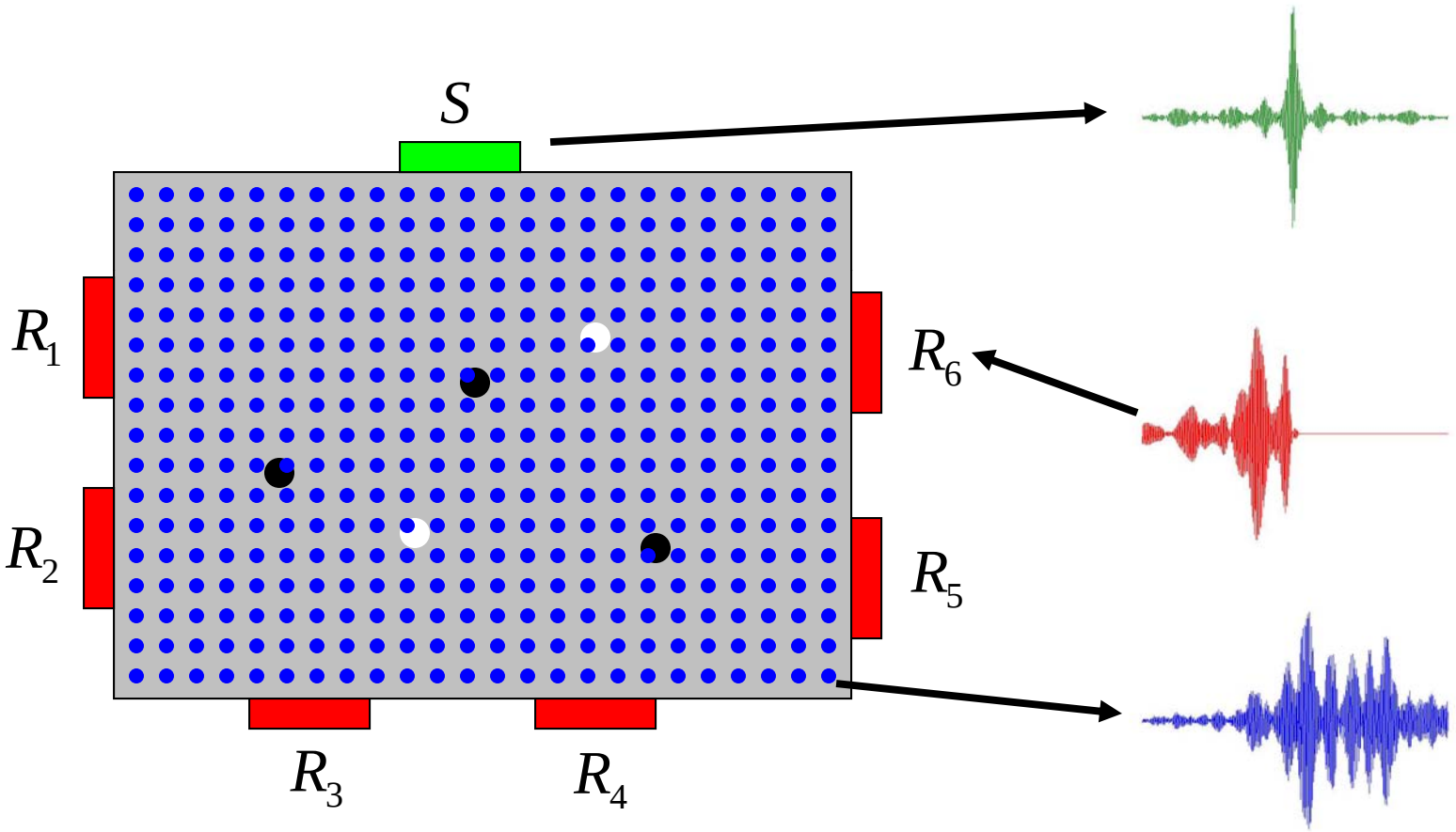
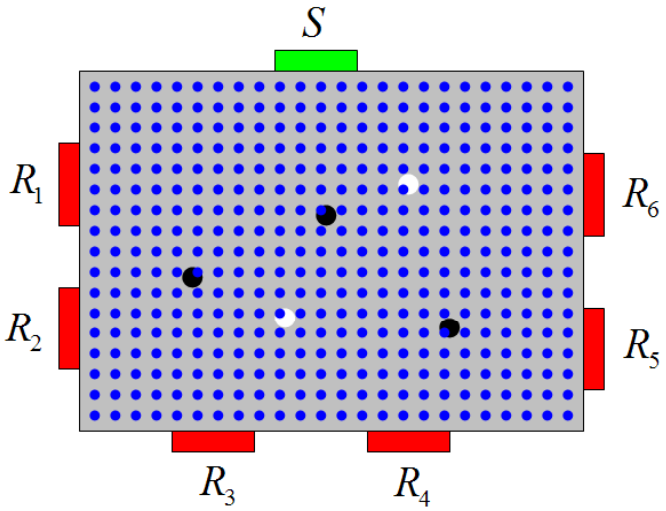
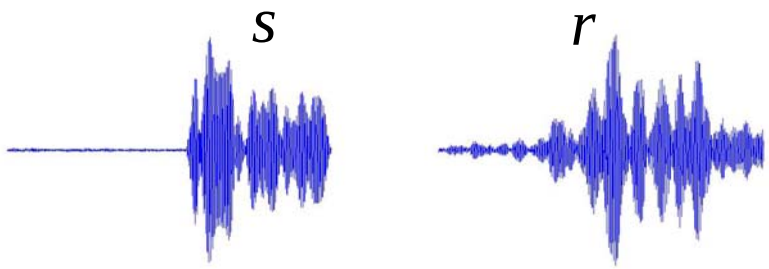


Anderson *et al*., J. Acoust. Soc. Am., (2011).

Reverse Time Migration to Image Delaminations





$$IC = \left\{ s\left(x_s, y_s, t\right) \otimes r\left(x_s, y_s, t\right) \right\}_{t=0}$$

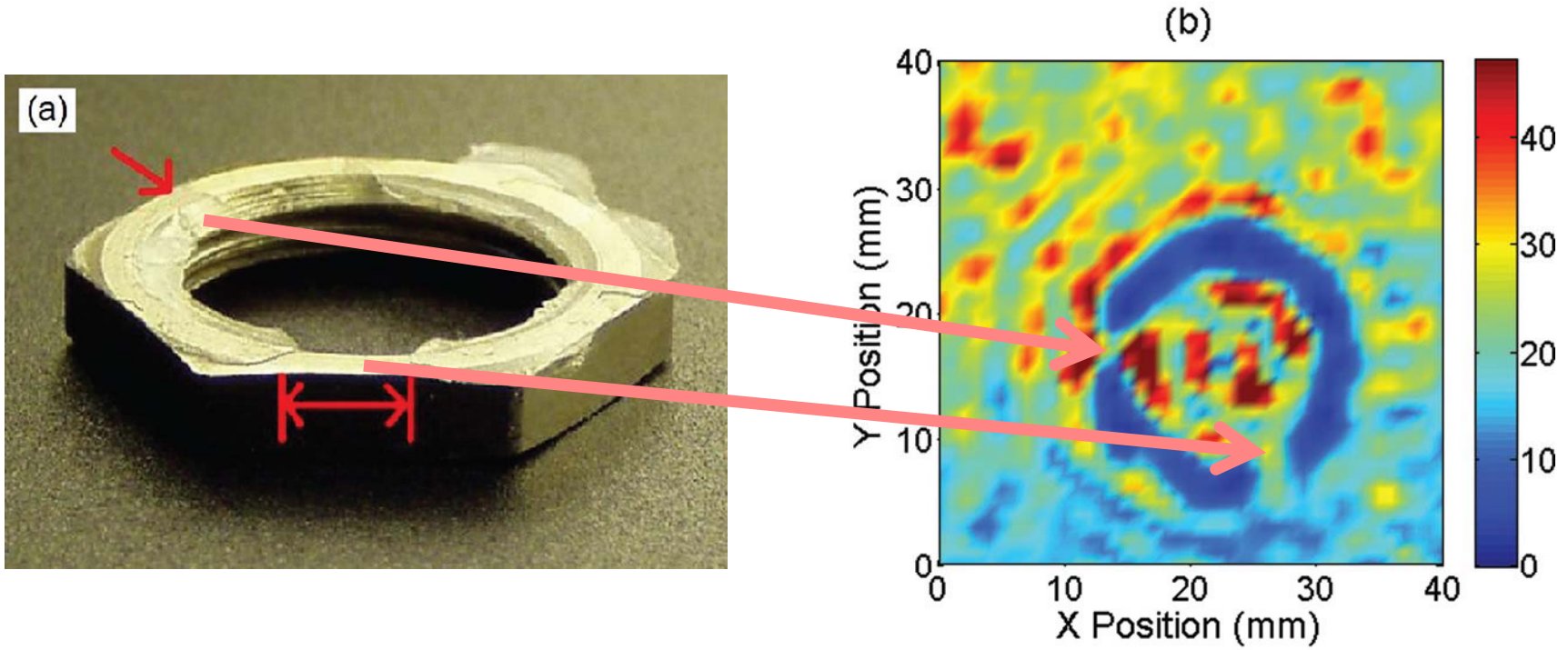
$$IC = \sum_{i=f_L}^{f_H} \left| S\left(x, y, \omega_i\right) \cdot R\left(x, y, \omega_i\right) \right|$$

High Impedance Scatterers → Minima

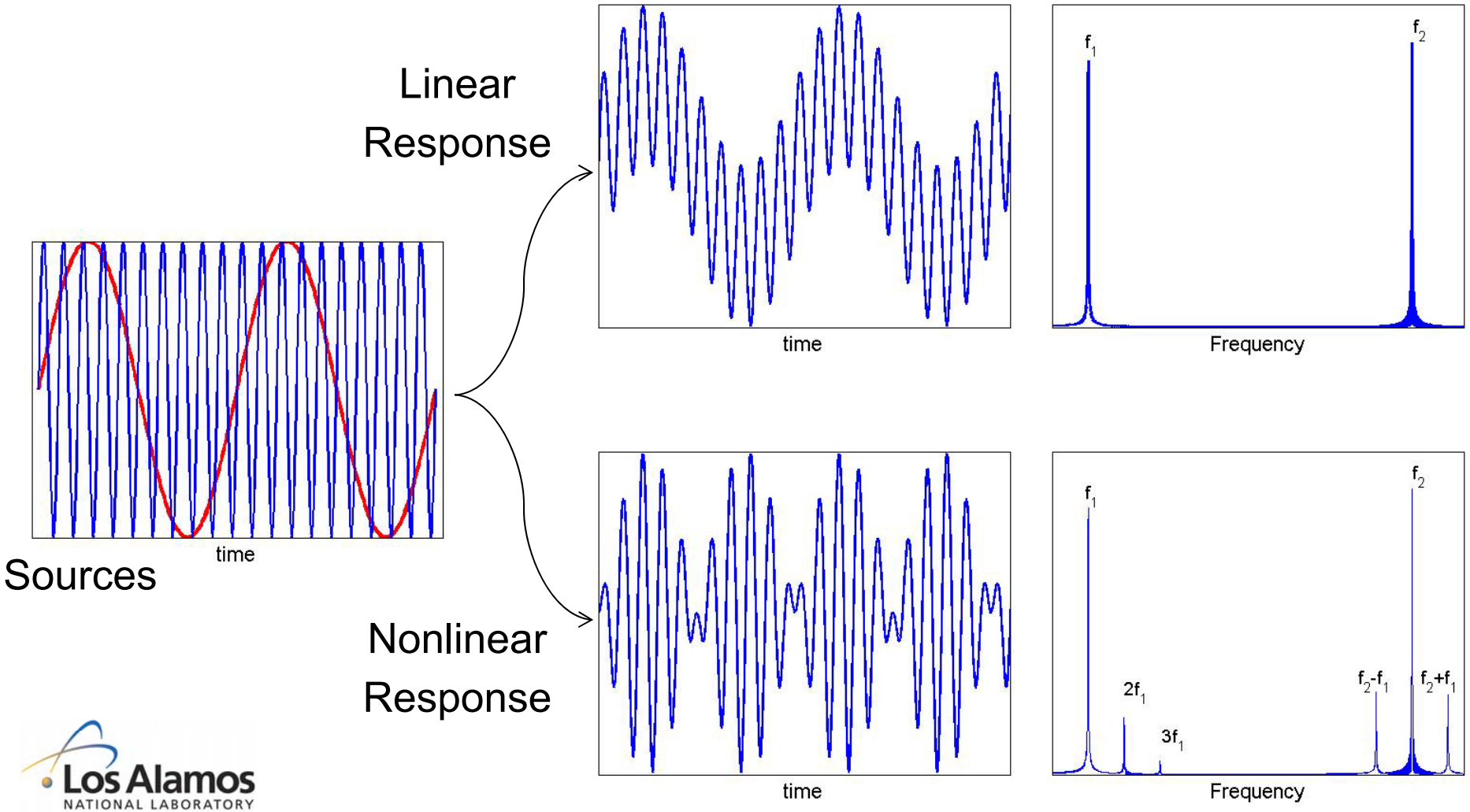
Low Impedance Scatterers → Maxima

Anderson *et al*., J. Acoust. Soc. Am., (2011).

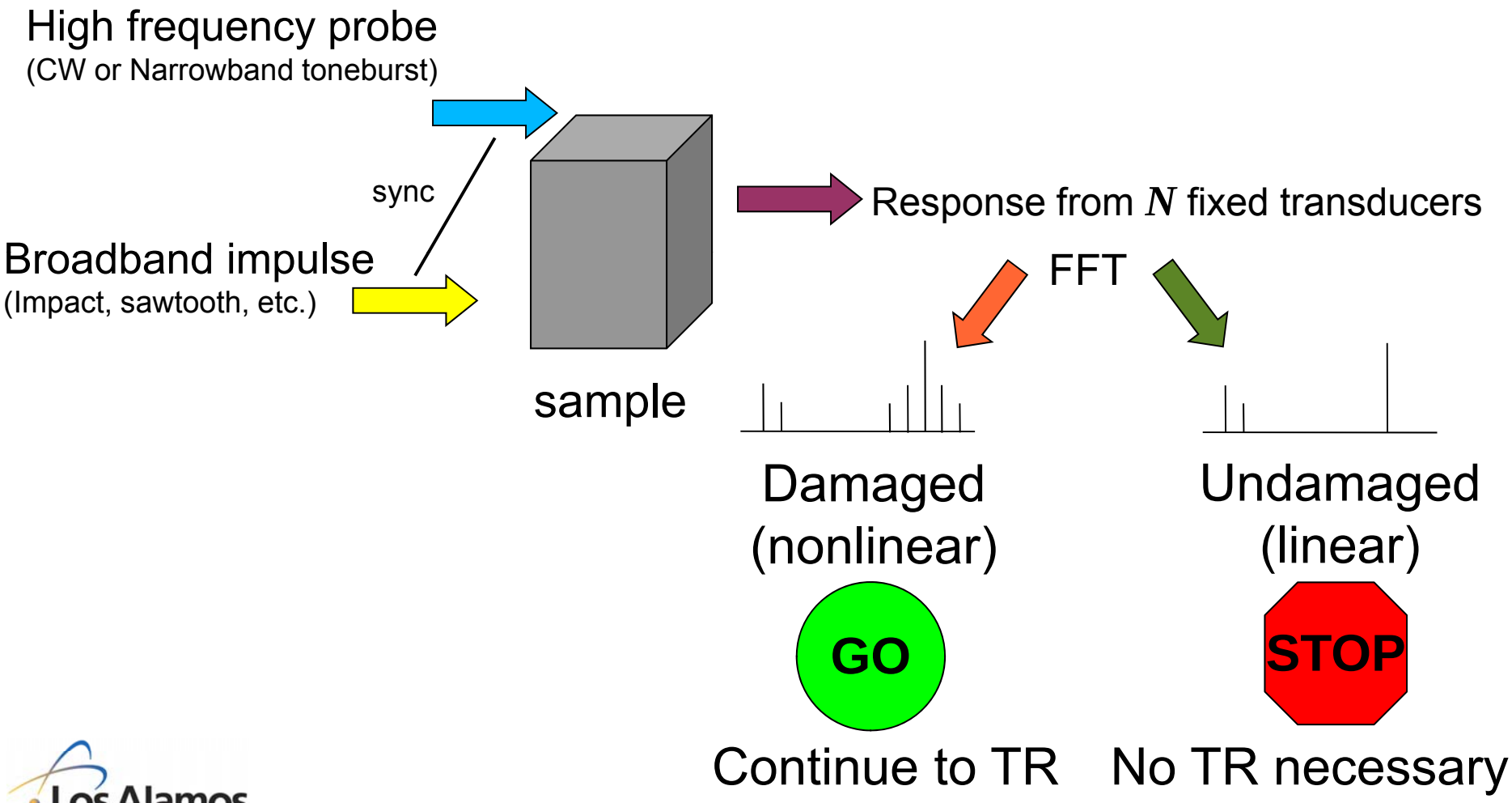
Reverse Time Migration to Image Delaminations



Nonlinear Wave Modulation & Harmonic Generation

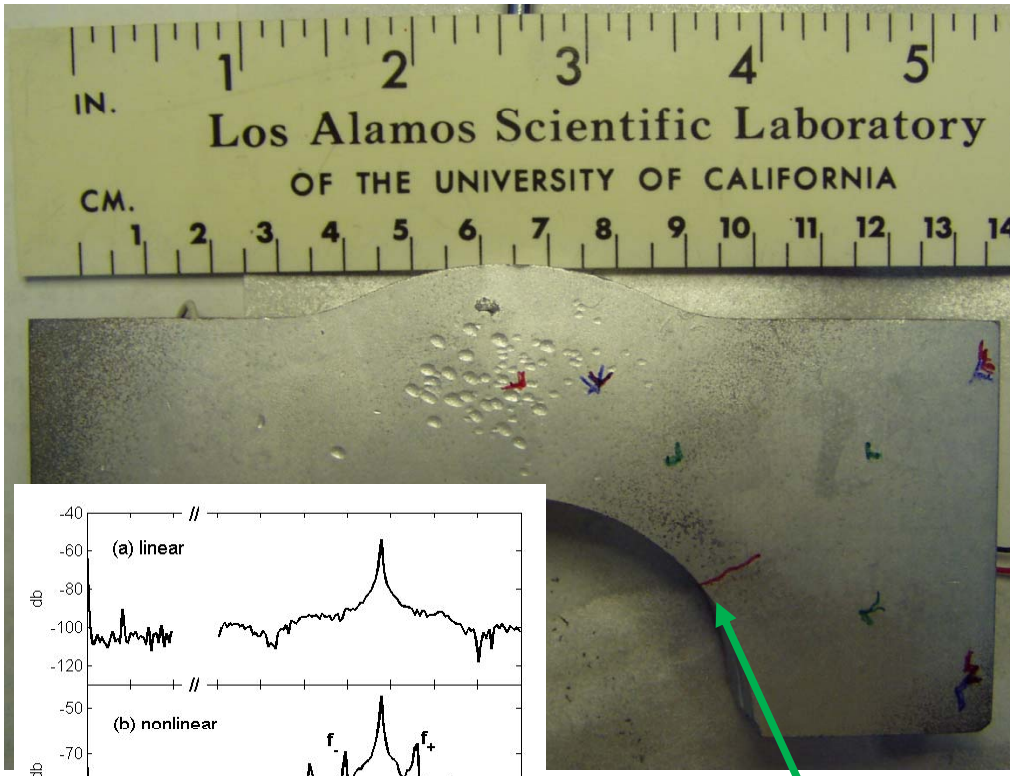


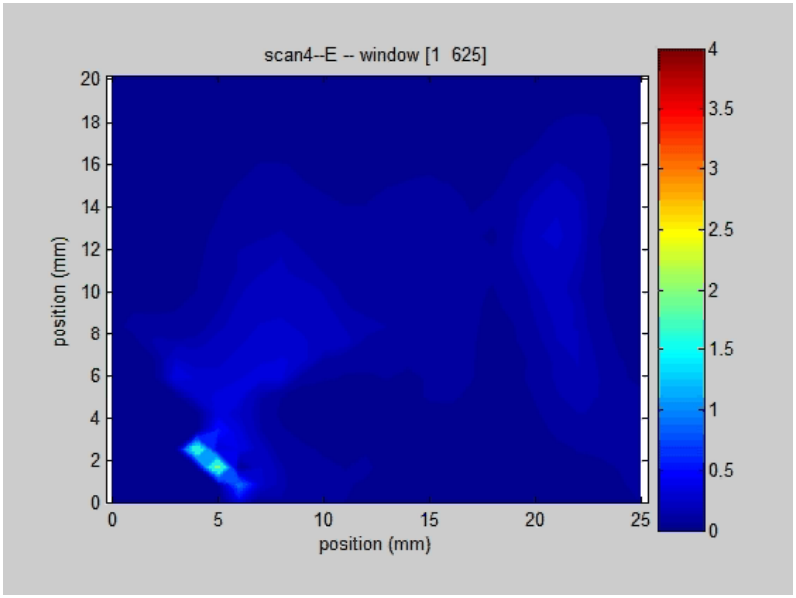
Damage Diagnosis through Nondestructive Evaluation (Nonlinear Techniques)



Ulrich *et al*., Phys. Rev. Lett., (2007).

Imaging of a Crack Using Time Reversal



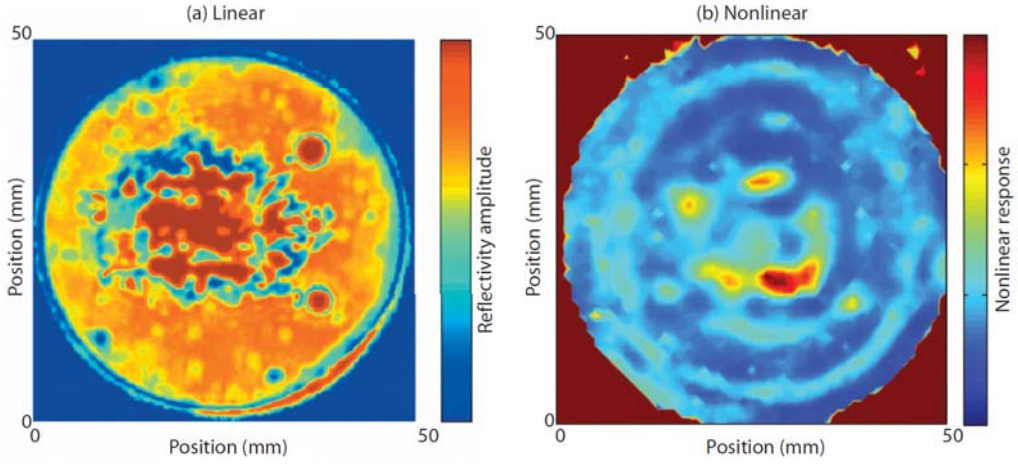


crack

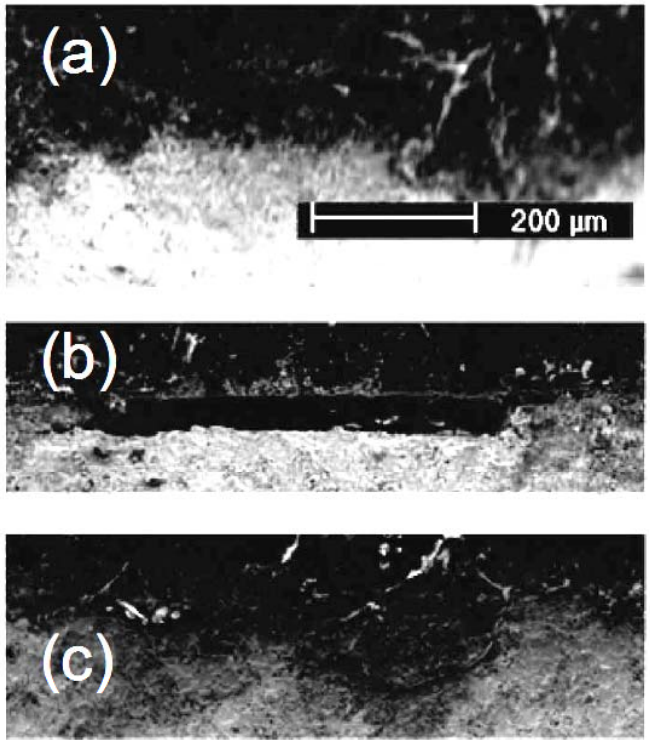
Ulrich *et al*., Appl. Phys. Lett., (2008).

Imaging of Delamination Edges Using Time Reversal and Nonlinear Spectroscopy

- **Two metal disks were diffusion bonded together.**
- **A linear C-scan imaged voids.**
- **A nonlinear TR scan imaged edges.**
- **Small cores were taken to verify findings.**

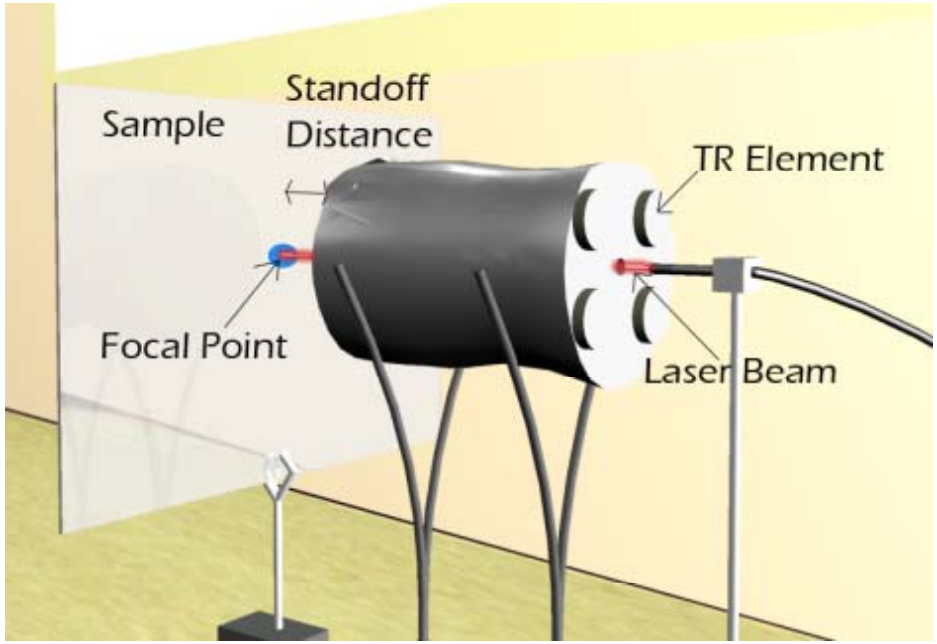


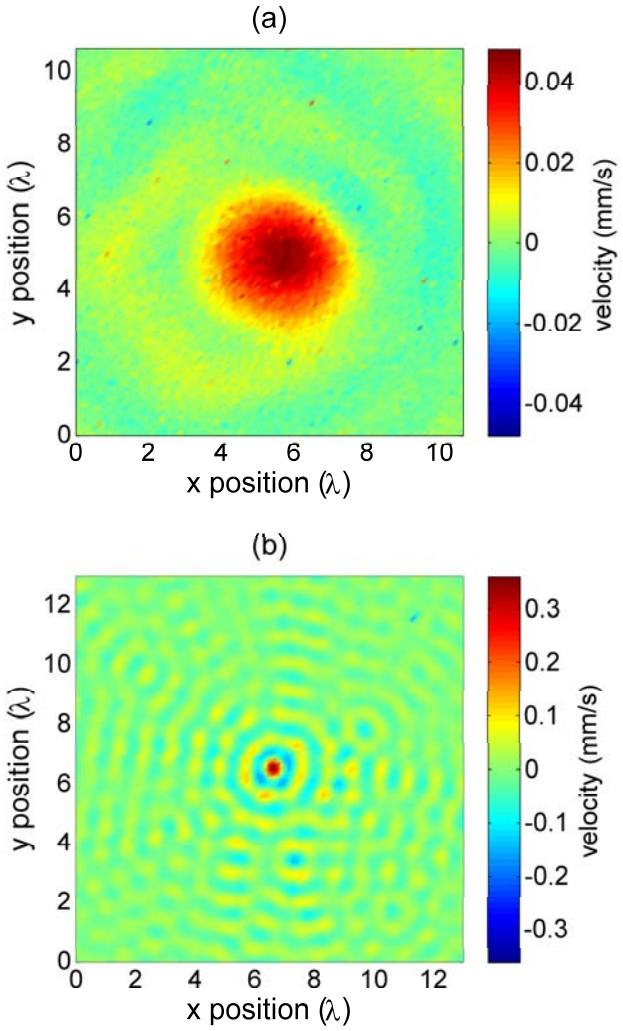
SEM Photos



Ulrich *et al*., Patent Application, (2011).
Le Bas *et al*., LDRD-ER, (FY12-FY14).

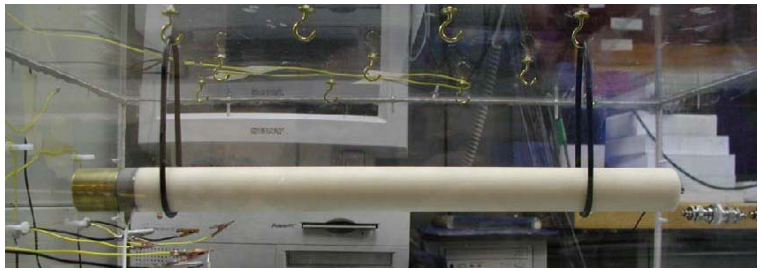
Time Reversal Acoustic Noncontact Source

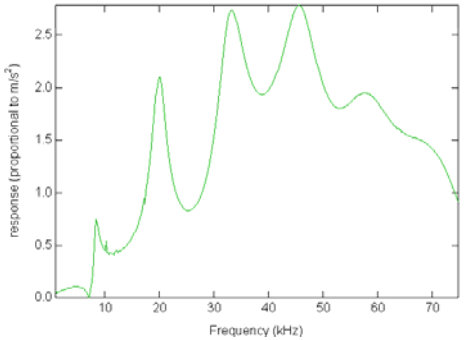




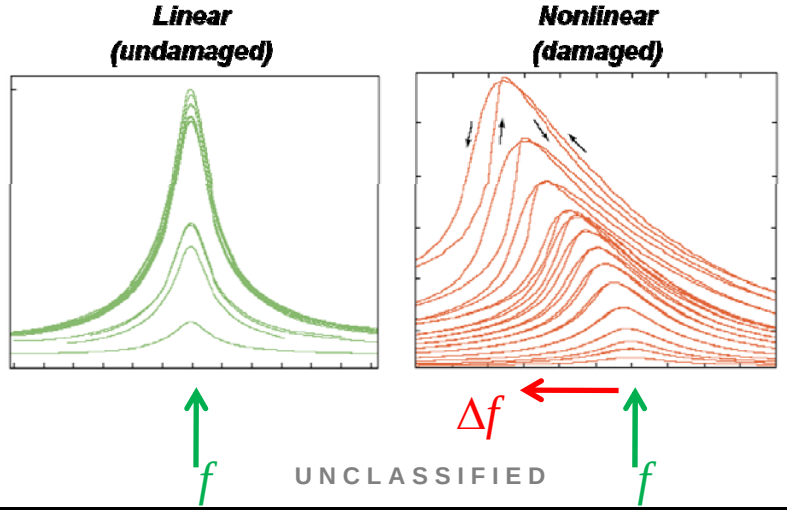
Material Property Determination: RUS & NRUS

- **We measure elastic properties of samples using Resonant Ultrasound Spectroscopy (RUS).**





- **We also measure the nonlinearities in a sample (crack density, damage indicator, etc.) using Nonlinear Resonant Ultrasound Spectroscopy (NRUS).**



Conclusions

- **Time reversal yields source localization and source characterization, or it may be used to focus high amplitude sound for damage interrogation.**
- **We use linear and nonlinear acoustic techniques to locate delaminations and cracks.**
- **Our nonlinear techniques are very sensitive to damage detection.**
- **Noncontact acoustic source allows sample inspection without contact.**
- **The goal is to be able to inspect samples for delaminations and cracks without touching them.**