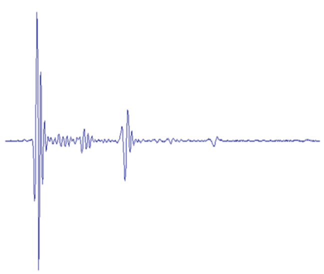
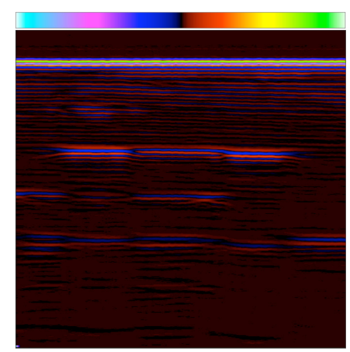
UCRL-CONF-226095
Signal and Imaging Sciences Workshop, Center for Advanced Signal and Imaging Sciences, Lawrence Livermore National Laboratory, November 16-17, 2006

Super-Resolution Algorithms for Ultrasonic Nondestructive Evaluation Imaging



Grace A. Clark (EE/EETD)
Jessie A. Jackson (EE/DSED)
Steven E. Benson (ME/MMED)



November 16-17, 2006

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Disclaimer and Auspices Statements

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Go Boilers!!!

Purdue's "All-American" Marching Band

Agenda

- **Problem Definition:**
  - **- Ultrasonic NDE measurements**
  - **- The spatial resolution problem**

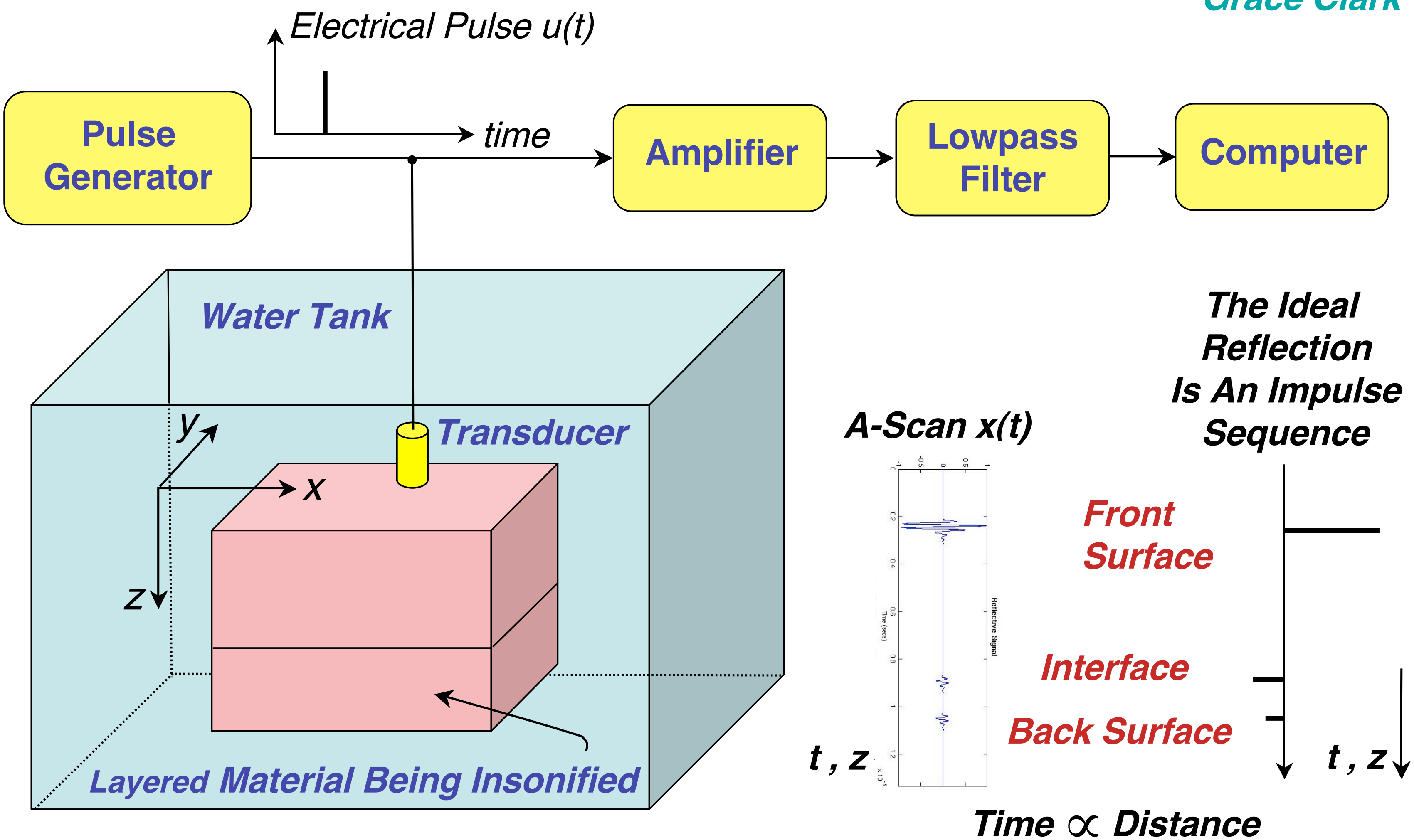
- ***Impulse Response Estimation*** **for Enhancing Spatial Resolution**
  - **- Mitigate "ringing" due to the transducer and propagation paths**

- ***Bandlimited Spectrum Extrapolation*** **for Super-Resolution**

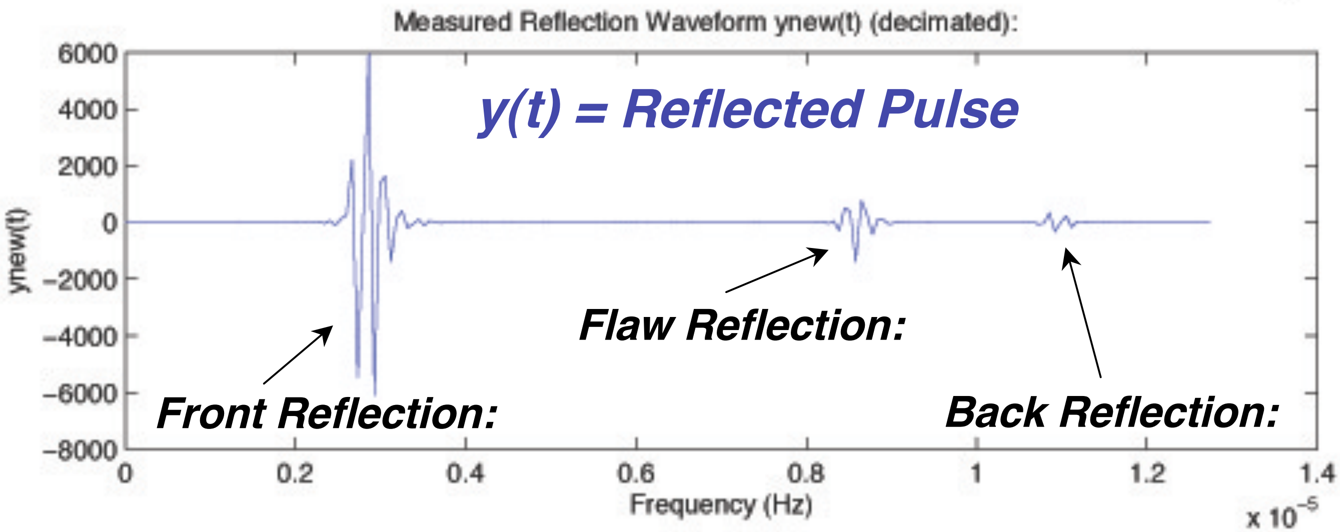
- **Examples of Processing Results**

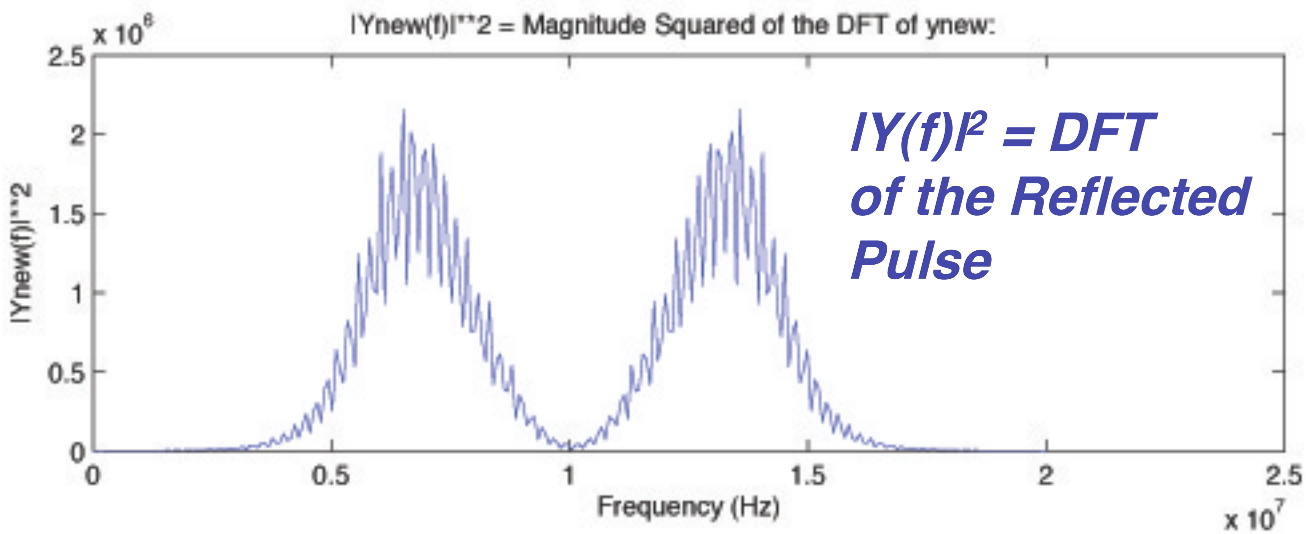
Ultrasonic Pulse-Echo Signals *(A-Scans)* Are *Distorted* By the *Transducer* and the *Propagation Paths ("Ringing")*

Grace Clark



Ultrasonic Pulses Are *Bandlimited* by the Transducer ==> The Pulses *"Ring"*, *Reducing Spatial Resolution*



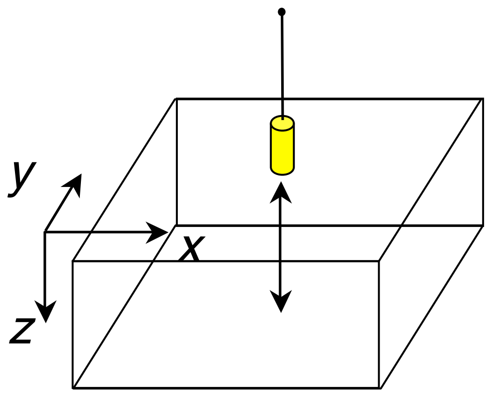


Grace A. Clark, Ph.D.

ENGINEERING

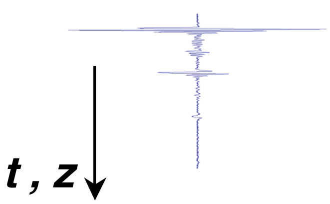
We Define Ultrasonic *A-, B-, and C-Scans* Used in Nondestructive Evaluation (NDE) Studies:

Grace Clark

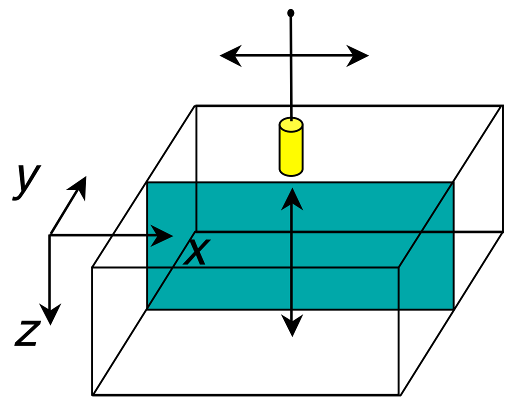


A-Scan x(t)

(A Single Waveform)

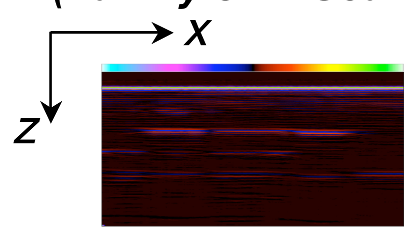


Time ∝ Distance



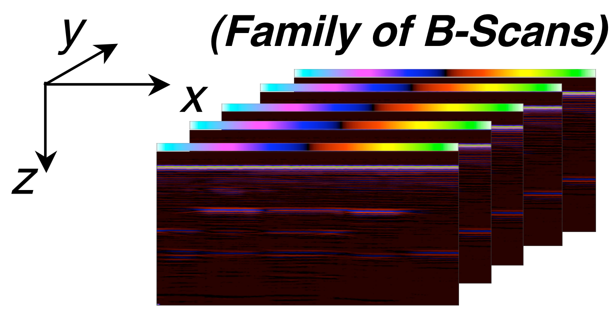
B-Scan

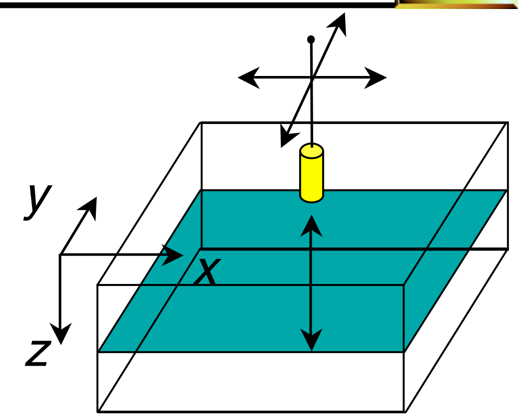
(Family of A-Scans)



3D Volume

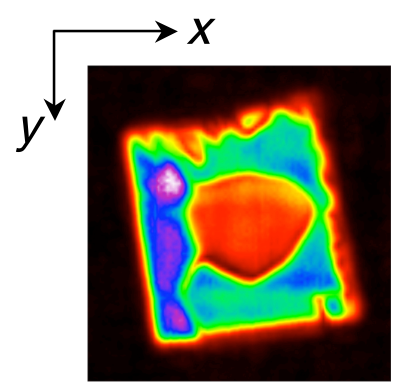
(Family of B-Scans)





C-Scan

(Horizontal Slice At Depth z: Use A Time Gate)

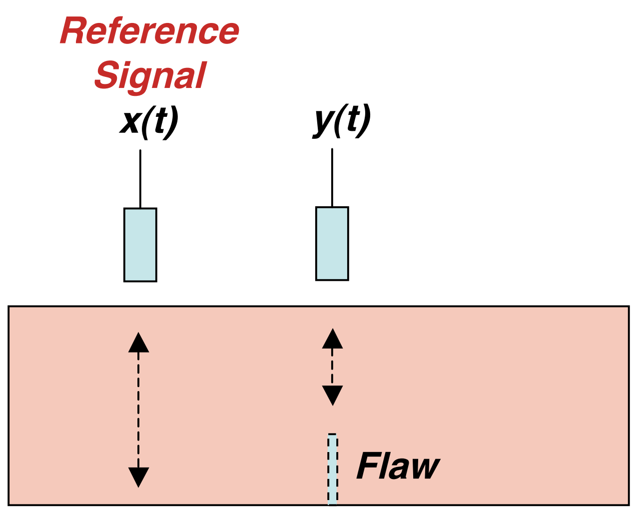


Grace A. Clark, Ph.D.

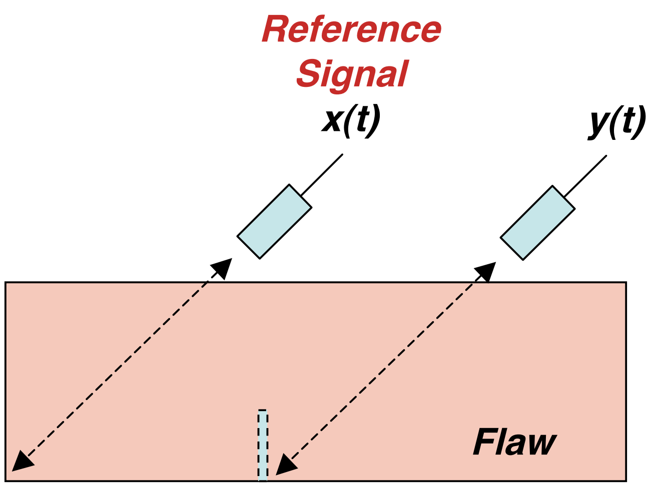
The Reference Scatterer is Chosen to Provide the Transducer / Path Response in the Absence of a Flaw

Desired properties of the reference scatterer:

- ***Reflects back most of the energy***
- ***Resembles some feature associated with the flaw environment***



Front or Back Surface Reference

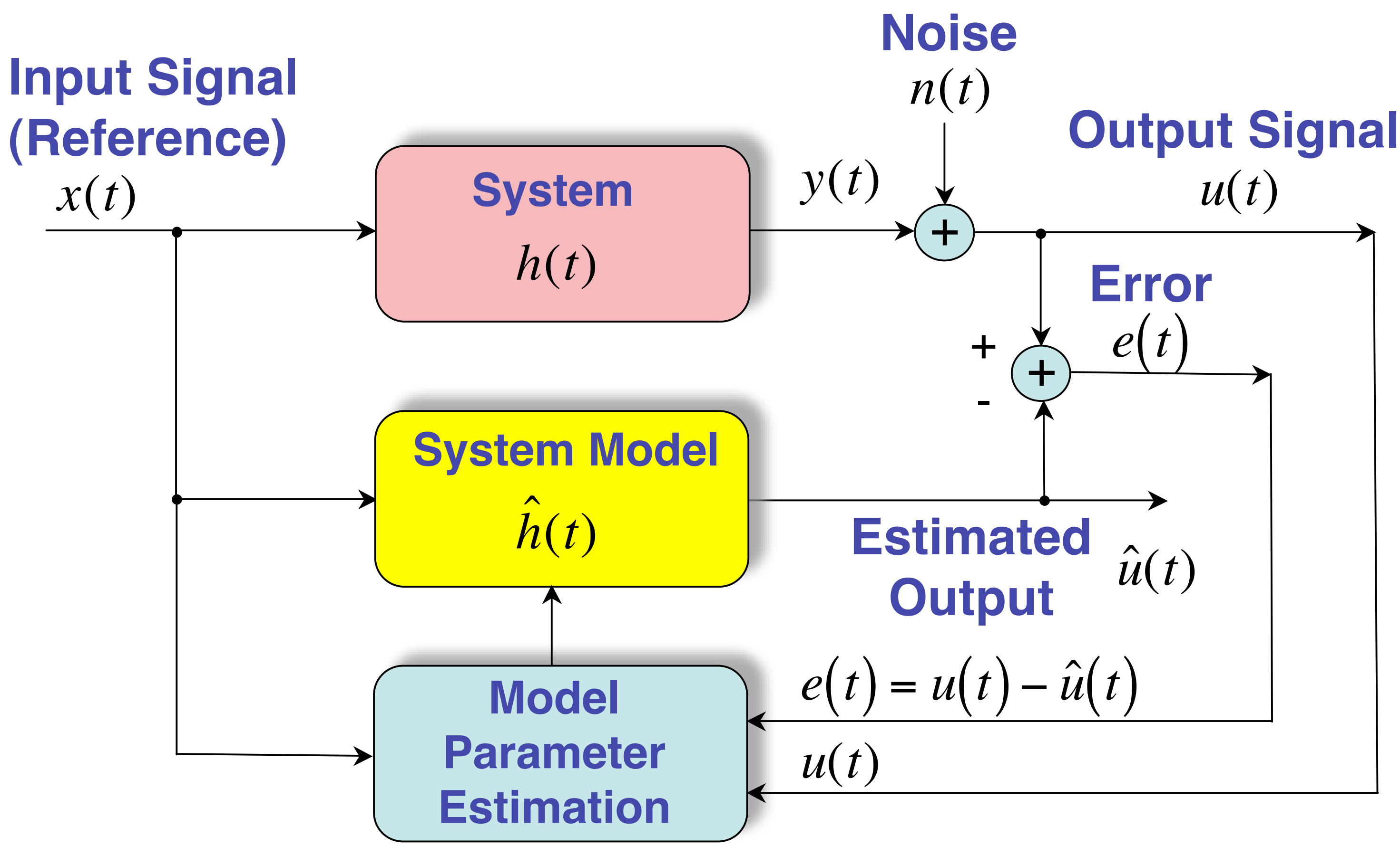


Corner Reflector Reference

Grace A. Clark, Ph.D.

System Identification: Estimate the Impulse Response $\hat{h}(t)$

Given: $x(t)$ **and** $u(t)$ **Estimate:** $\hat{h}(t)$



Grace A. Clark, Ph.D.

The Inverse Problem Is Very Difficult
➡ *We Must Regularize the Problem*

- Ill-Posed
  (Infinite Number
  of possible
  solutions)

- Bandlimited
  Transducer
  Spectral
  Response

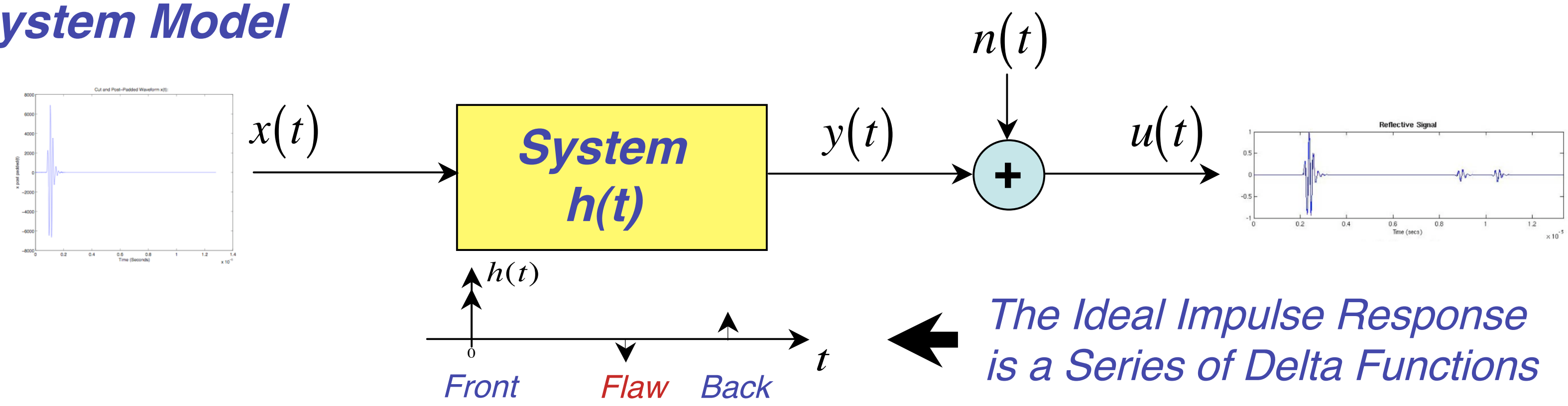
- Ill-Conditioned -
  Numerical Errors
  Due to Spectral
  Zeros

Grace A. Clark, Ph.D.

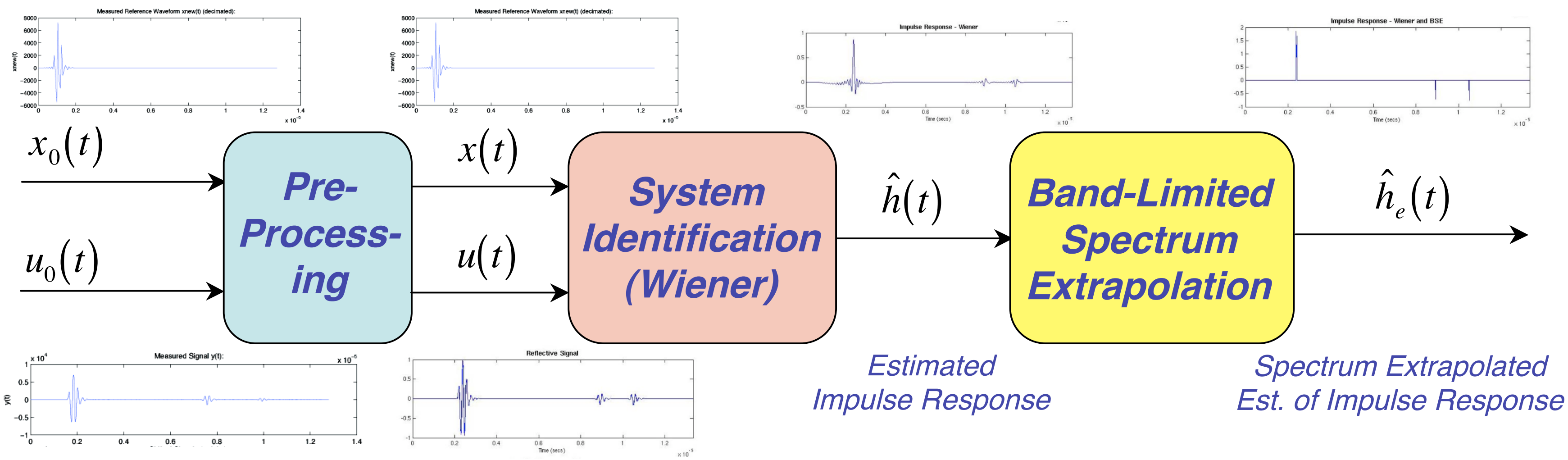
The *System Model* and *Processing Algorithms* Are Summarized in Block Diagrams

Grace Clark

System Model

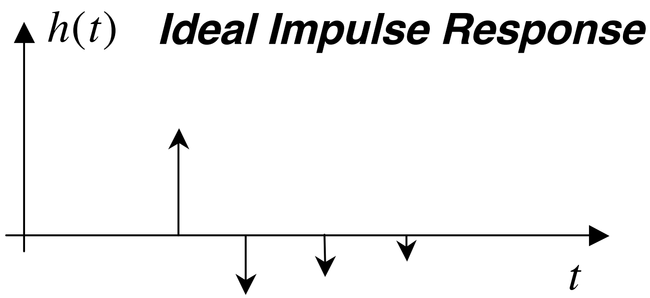


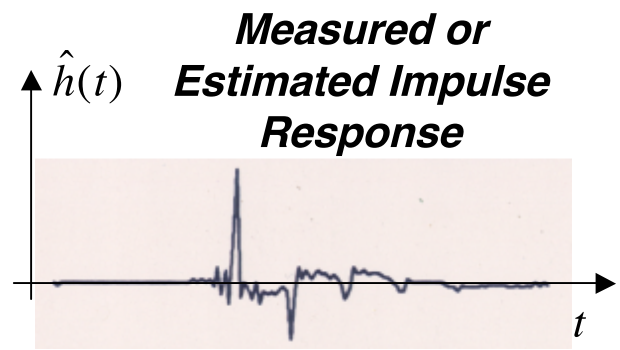
Processing Algorithms

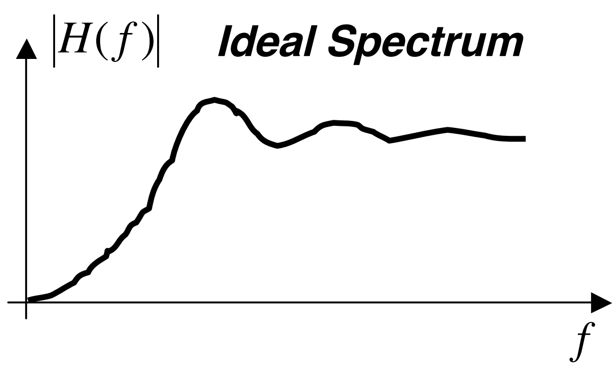


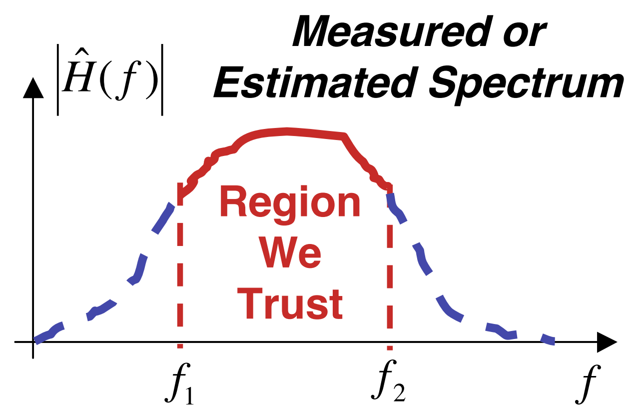
We Use *Bandlimited Spectrum Extrapolation* To Improve *Spatial Resolution*

Ideal	Measured or Estimated









$h(t)$

Grace A. Clark, Ph.D.

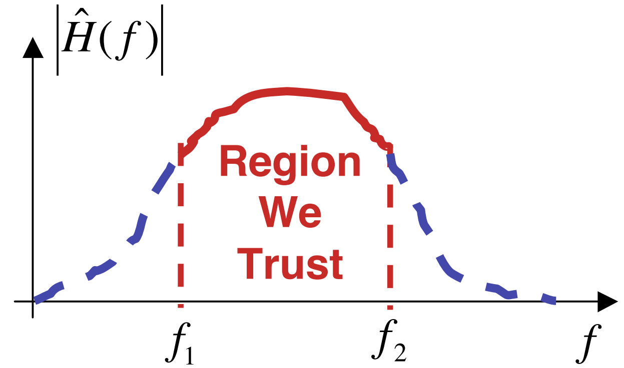
ENGINEERING

Complex Variable Theory Gives Us a Solid Theoretical Basis for Spectrum Extrapolation

- Our temporal signals have ***bounded support***:
  - They are transient (finite length) signals in the time domain

- **The Fourier Transform of a signal with bounded support is *ANALYTIC* (continuous, all derivatives exist).**

- **If any analytic function in the complex plane is known exactly in an arbitrarily small (but finite) region of that plane, then the *entire function* can be found *(uniquely)* by *ANALYTIC CONTINUATION*.**



Analytic Continuation Algorithms are Hypersensitive to Noise - *Must Regularize*

- Prior knowledge can be used as constraints to regularize the problem

- Iterative algorithms *(method of successive approximations)* are *slow*, not *unique*, but *can incorporate constraints*.

- Non-iterative algorithms are faster, but can't usually incorporate constraints.

- Often, it is not necessary to determine the inverse of the distortion operator
  - Good for nonlinear or time-varying operators

Grace A. Clark, Ph.D.

We Use an Iterative Algorithm for *Regularized* Analytic Continuation

- Estimate the impulse response at the next iteration as a function F of the impulse response at the last iteration:

$$h_{k+1}(t) = Fh_k(\mathrm{t}), \qquad \text{for } k = 0, 1, 2, \cdots$$

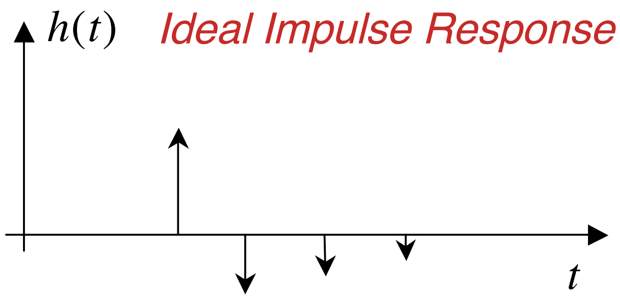
- Iterate between the time and frequency domains *(Method of Alternating Orthogonal Projections)*

- Convergence is proved using contraction mapping theorems from functional analysis

- Use an *"adaptive algorithm"* that assumes the impulse response to be a sequence of impulses - *constrain the time domain signal to be an impulse train:*

$$h(t) = \sum_i c_i \delta(t - t_i)$$

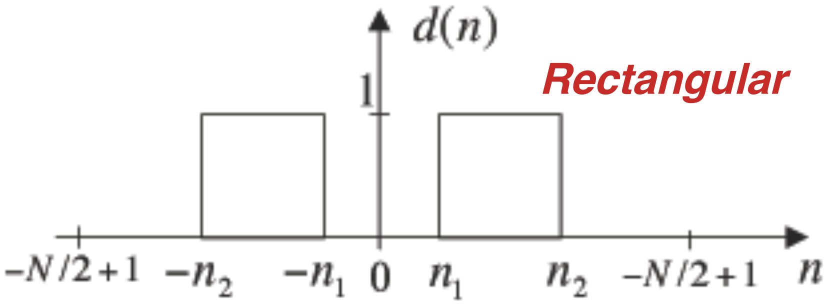
$$u(t) = \sum_i c_i x(t - t_i) + n(t)$$

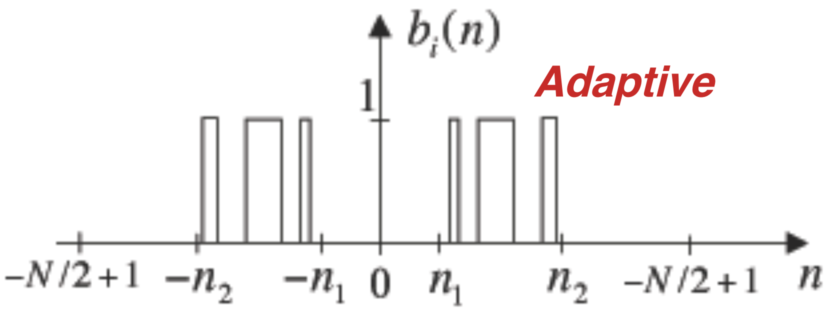


Grace A. Clark, Ph.D.

We Constrain the Temporal and Spectral *Support* Using *Projection Operators*

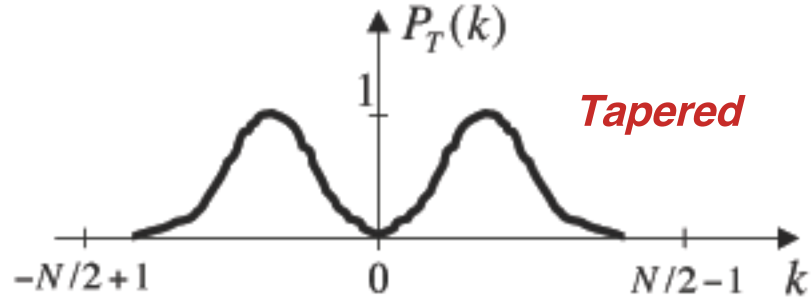
Temporal Projection Operators

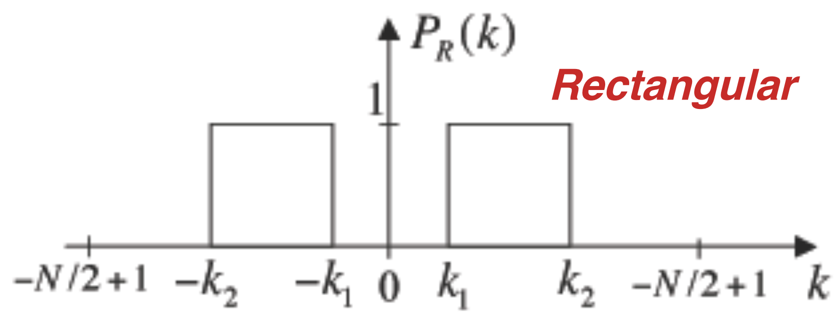




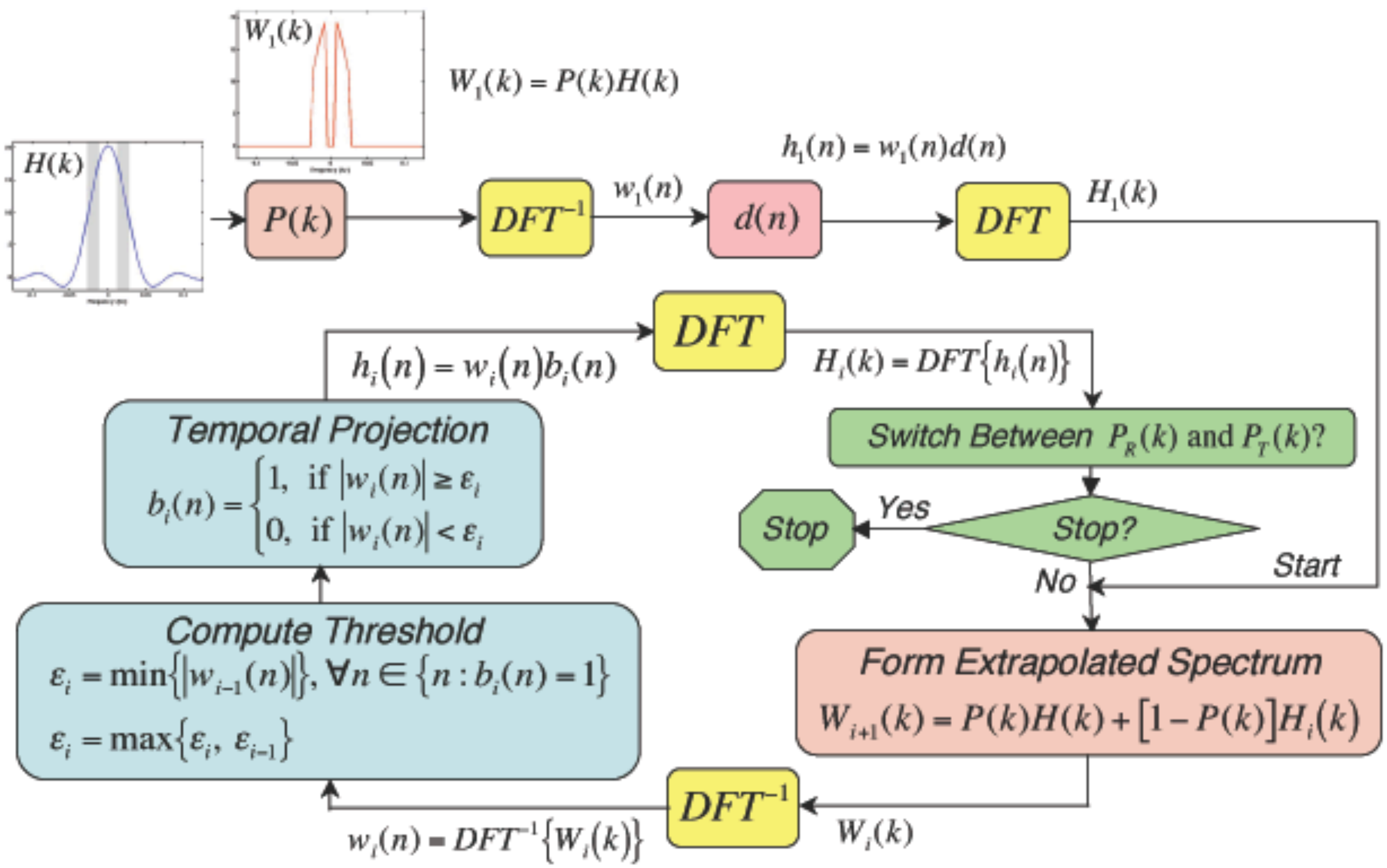
Spectral Projection Operators

$$P_T(k) = \text{Envelope}\left\{ \frac{|X(k)|}{\max|X(k)|} \right\}$$

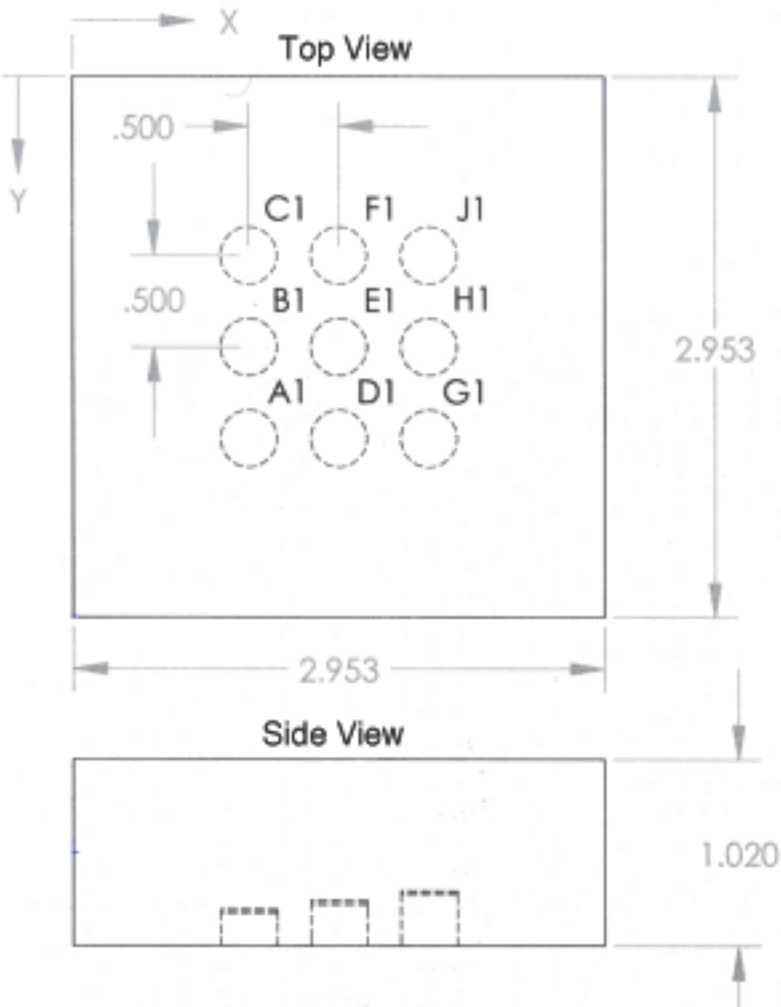


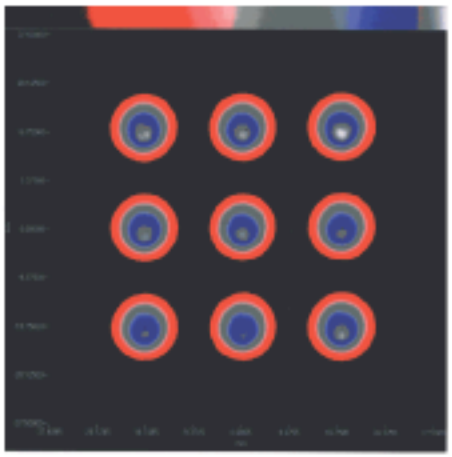


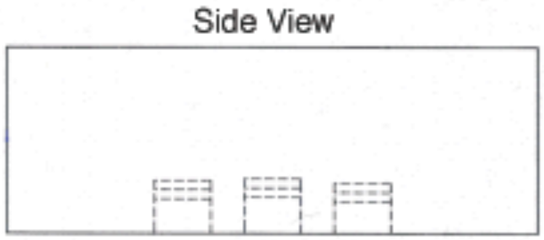
ith Iteration of the Spectrum Extrapolation Algorithm: *Alternating Orthogonal Projections, w/Adaptive Algorithm*



We Constructed a "Phantom" Part - *Aluminum Block* Containing *Flat-Bottom Holes*

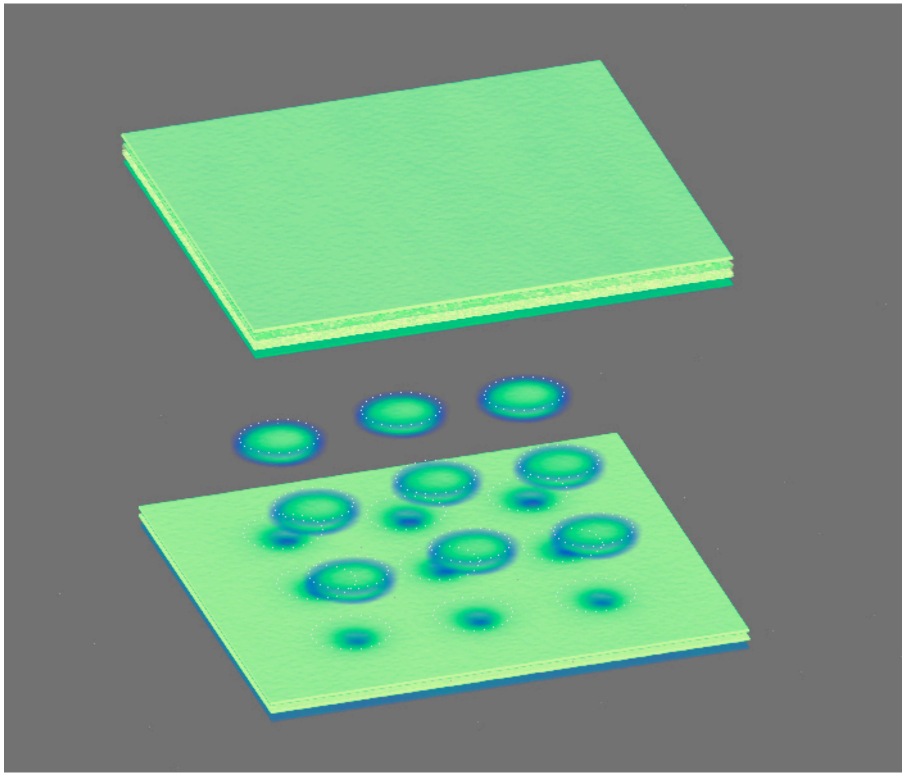




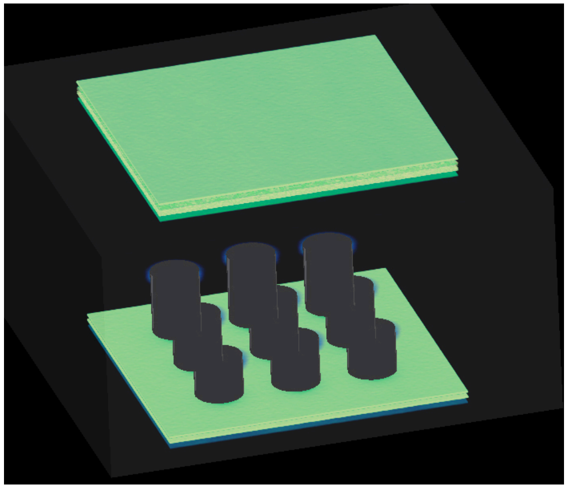


We Can Combine CAD Models With 3-D Data To Clarify Ultrasonic Evaluation Results

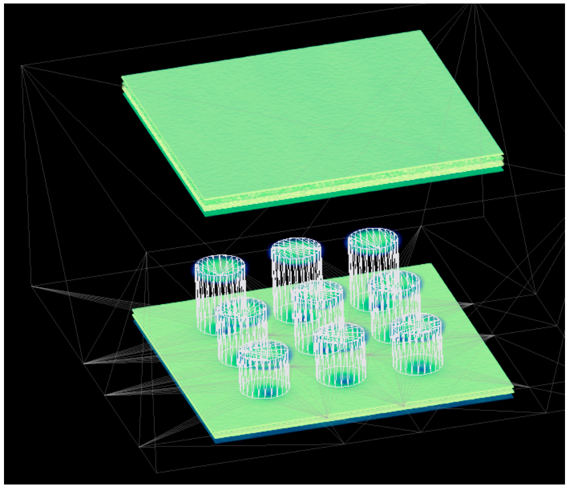
3-D Ultrasonic Data Set



3-D data and CAD Model-*Solid*

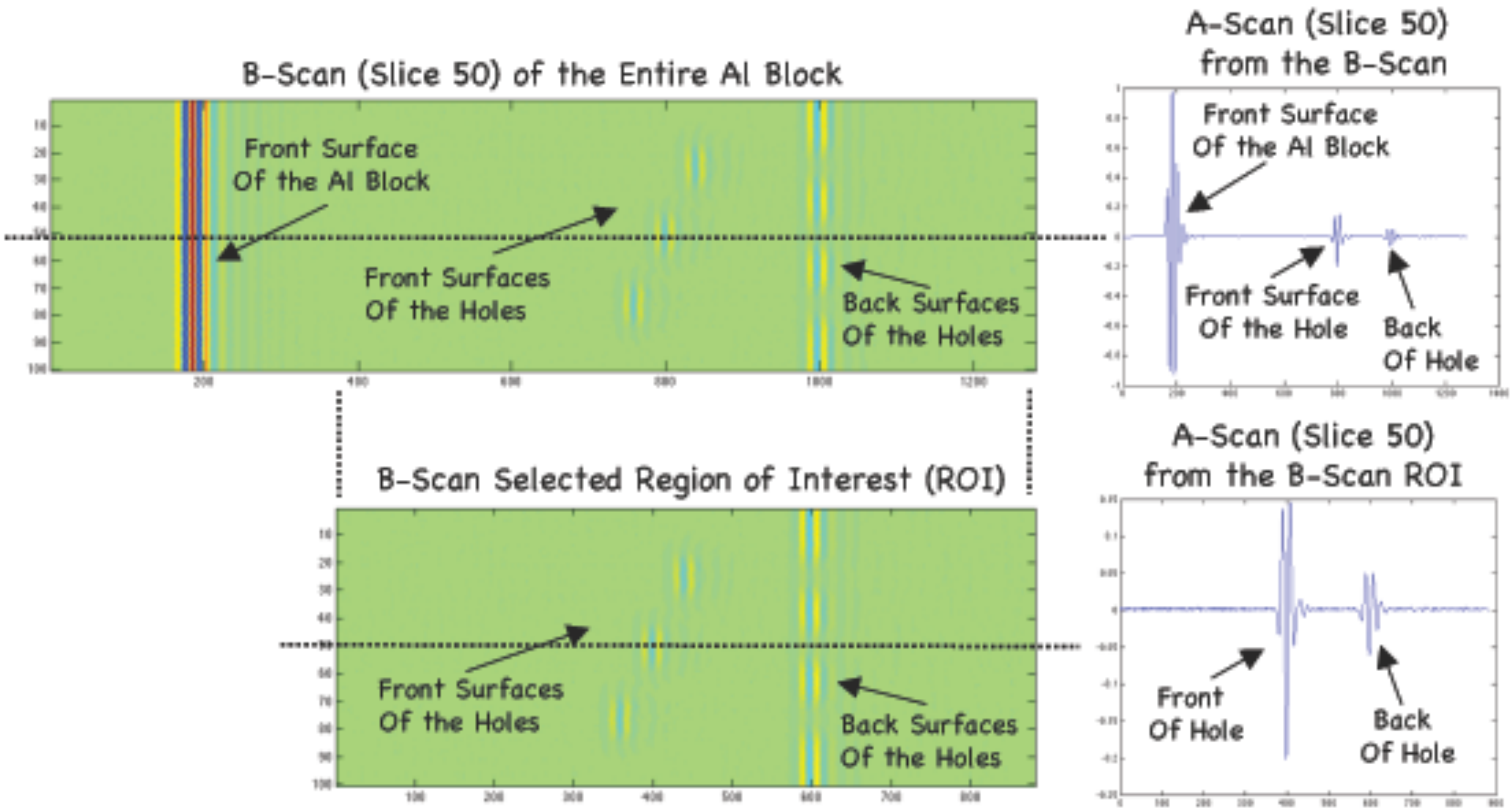


3-D data and CAD Model-*Lines*

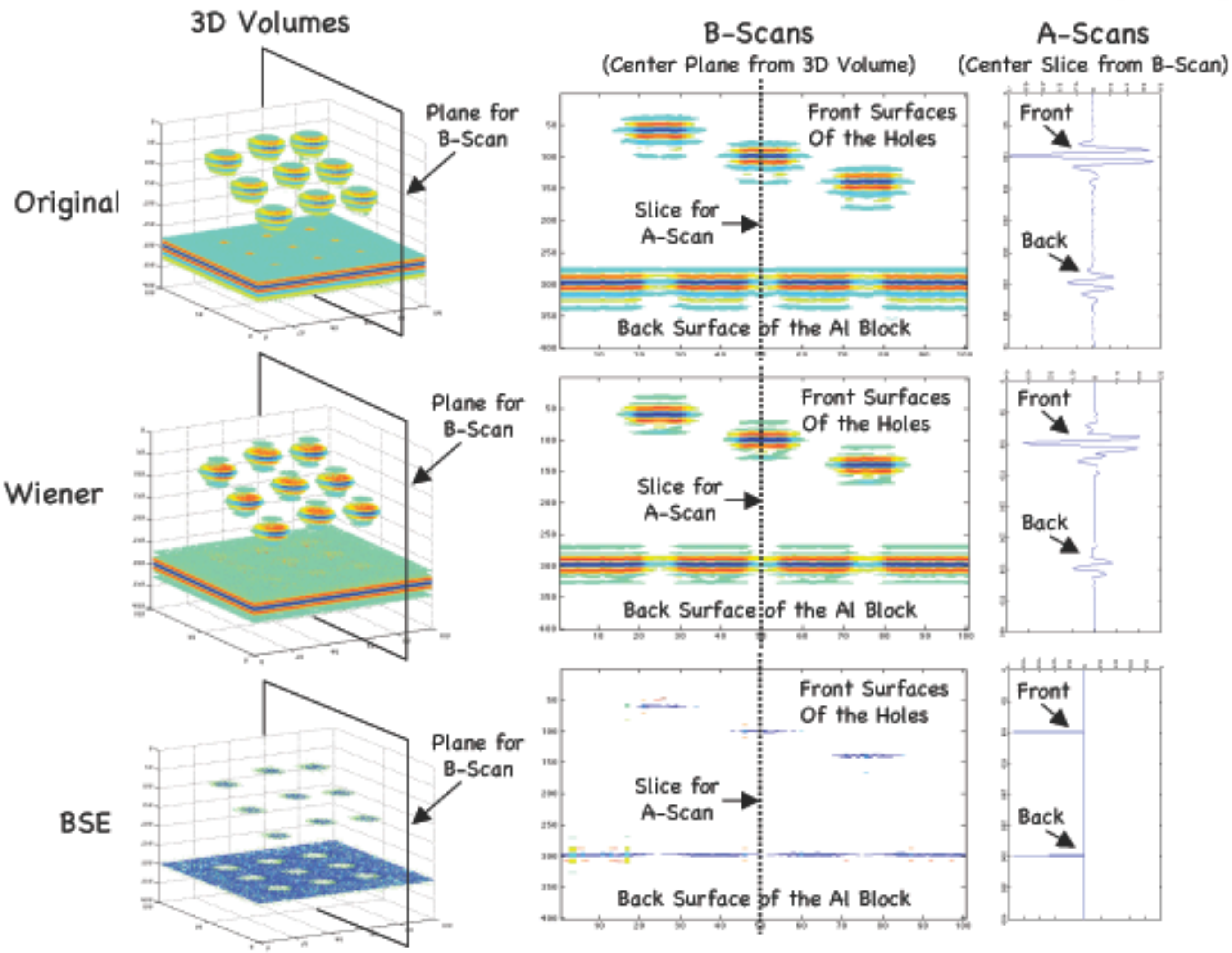


Grace A. Clark, Ph.D.

A-scan and B-scan Data Show that Material Interface Reflections Are Blurred Because of Transducer Ringing



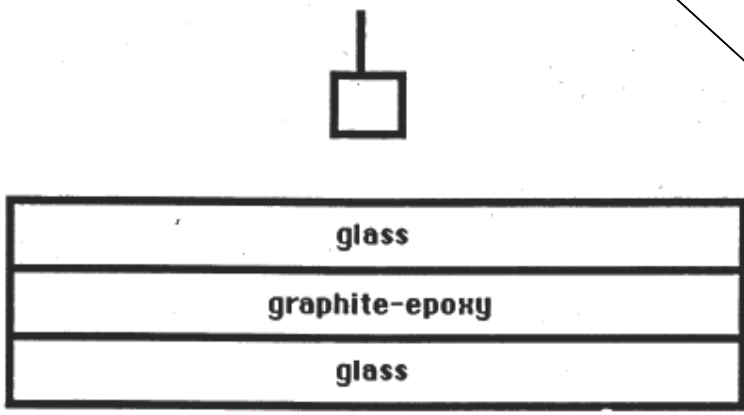
System Identification and Spectrum Extrapolation Results Are *Summarized* for the *Flat-Bottom Hole Phantom* Signals



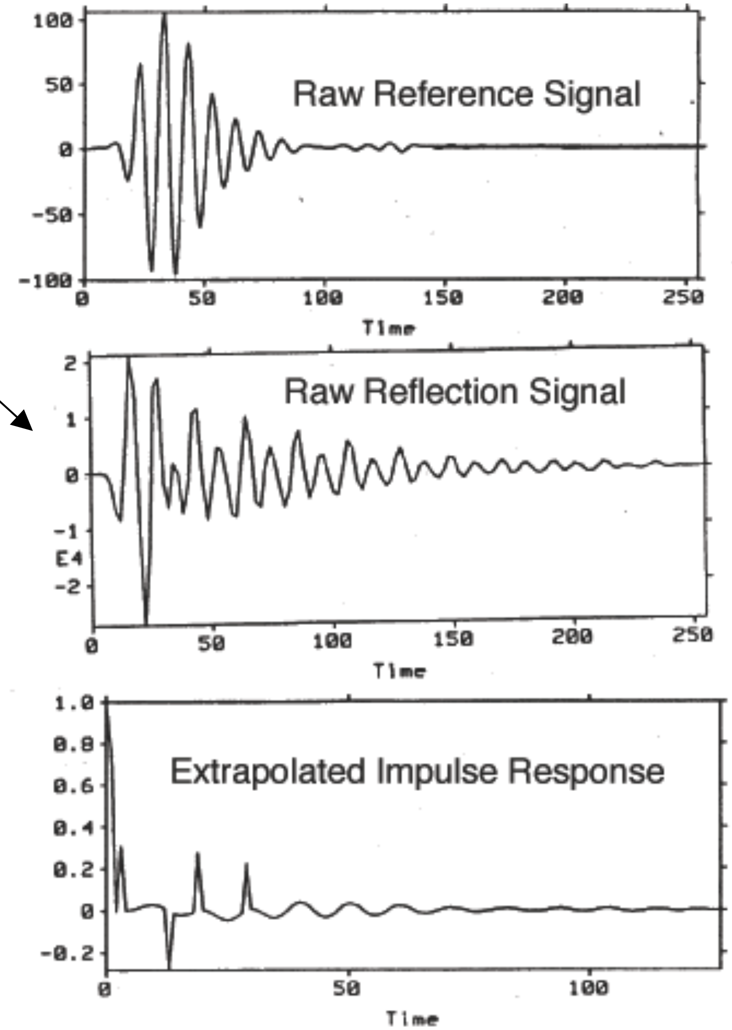
Grace A. Clark, Ph.D.

Graphite Fiber Composite Material: *Thickness Measurements from Superimposed Layer Reflections*

The layer thicknesses are much smaller than the transducer ring-down time



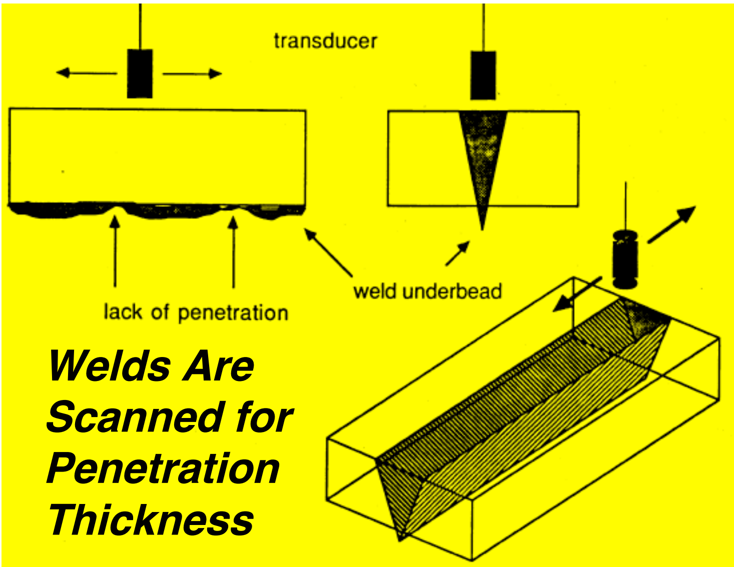
graphite weave
in expoxy

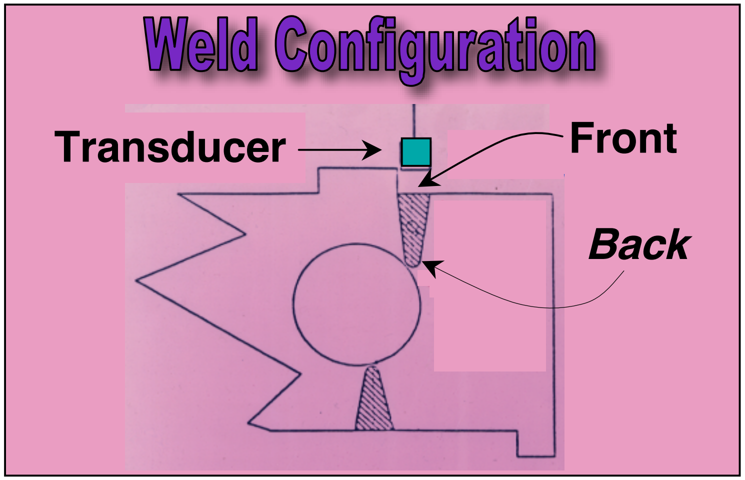


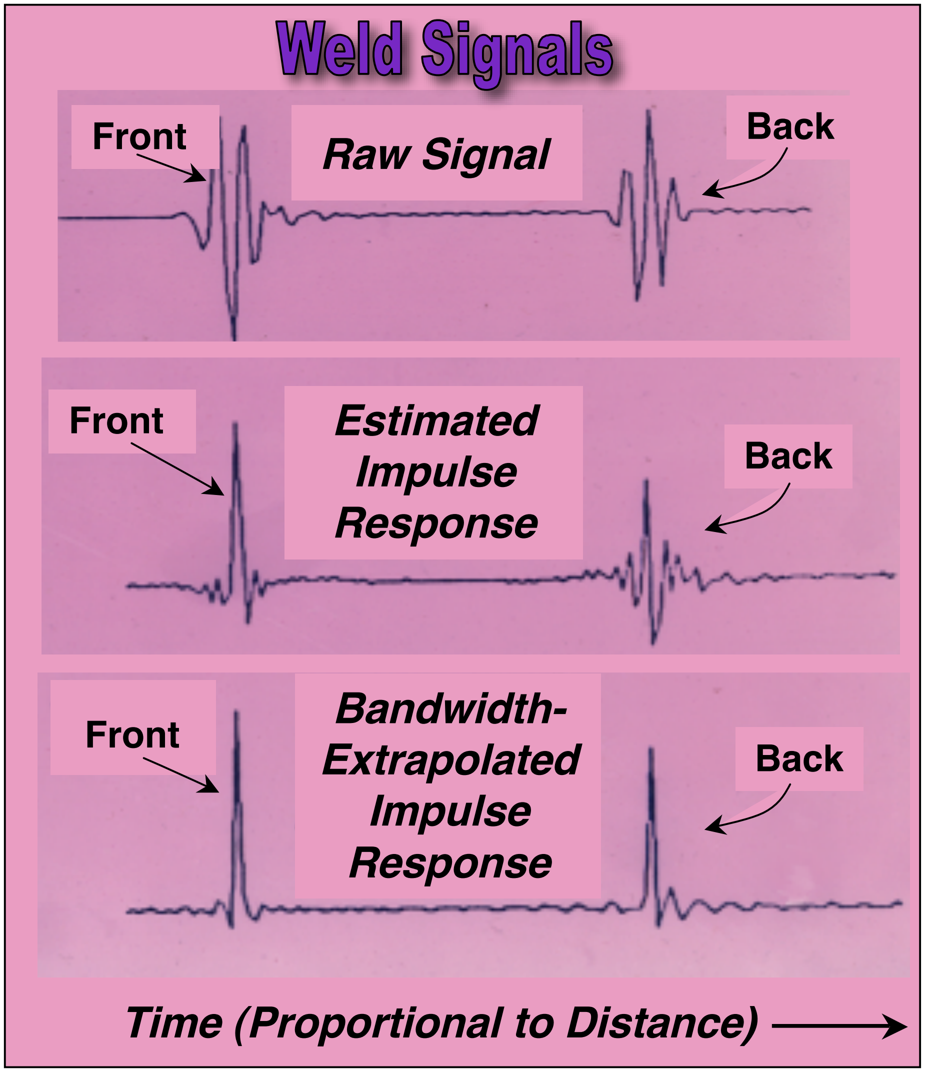
Grace A. Clark, Ph.D.

Ultrasonic Pulse-Echo Signals Are Distorted by the Transducer and the Propagation Paths

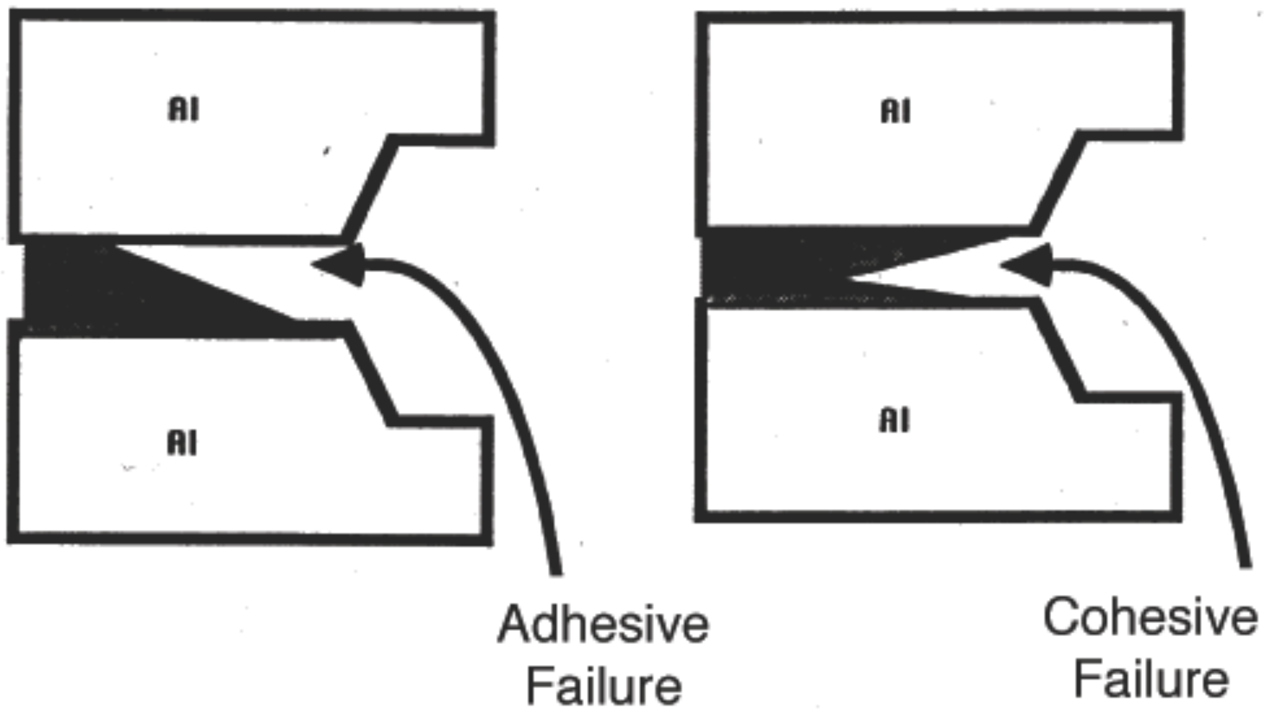
Grace Clark







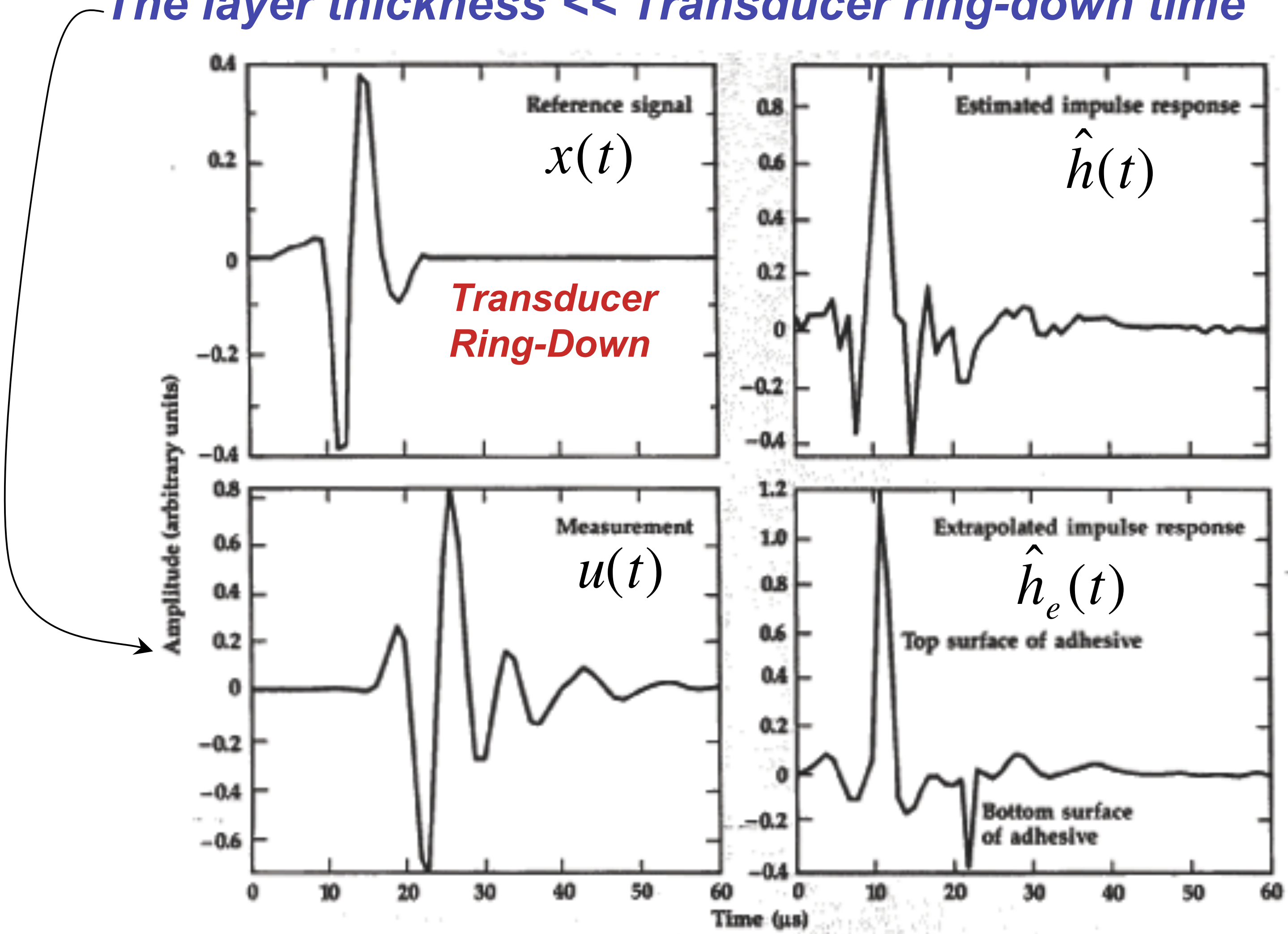
Adhesive Thickness Measurements Require Resolved Layer Reflections



Grace A. Clark, Ph.D.

Adhesive Thickness Measurements from *Superimposed Layer Reflections*

The layer thickness << Transducer ring-down time



Grace A. Clark, Ph.D.

Conclusions

- We have MATLAB software for these algorithms
  - From a recent Engineering Techbase project
- Future work: New programmatic applications
  - Contact the author

Grace A. Clark, Ph.D.

Contingency VG's

Grace A. Clark

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

ENGINEERING

Our Objective is to Improve Temporal Resolution by *Extrapolating Spectra*

- The transducer bandlimits our signals
  - System identification solutions are not unique
  - System identification solutions are valid only in a finite frequency interval *$[f_1, f_2]$.* They give us the optimal least squares solution, given the bandwidth of the transducer.
  - We can never obtain narrow impulses in the time domain

- We wish to extrapolate spectra beyond *$[f_1, f_2]$.*
  - This can allow us to obtain better approximations to impulses in the time domain.

- We propose to extrapolate the spectra of:

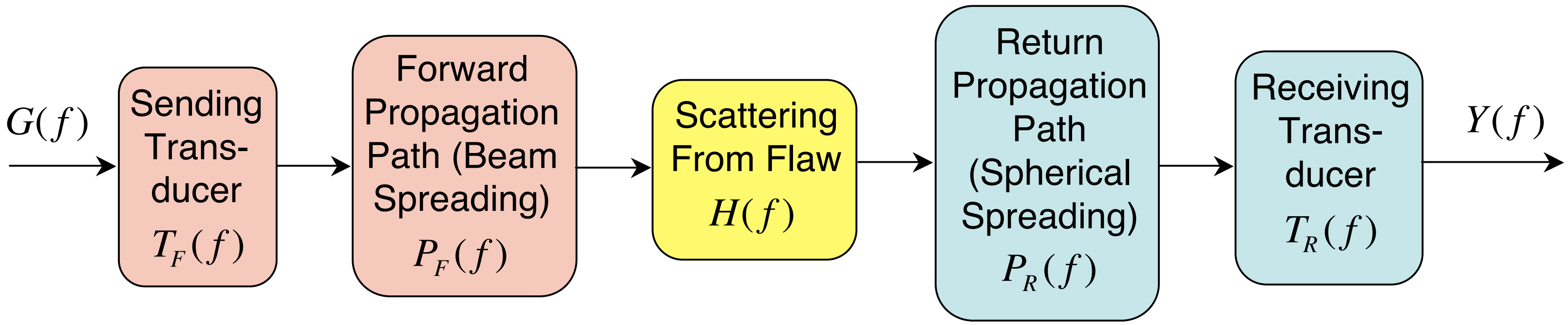
$u(t)$ *The measured pulse-echo signal*

$\hat{h}(t)$ *The estimated impulse response*

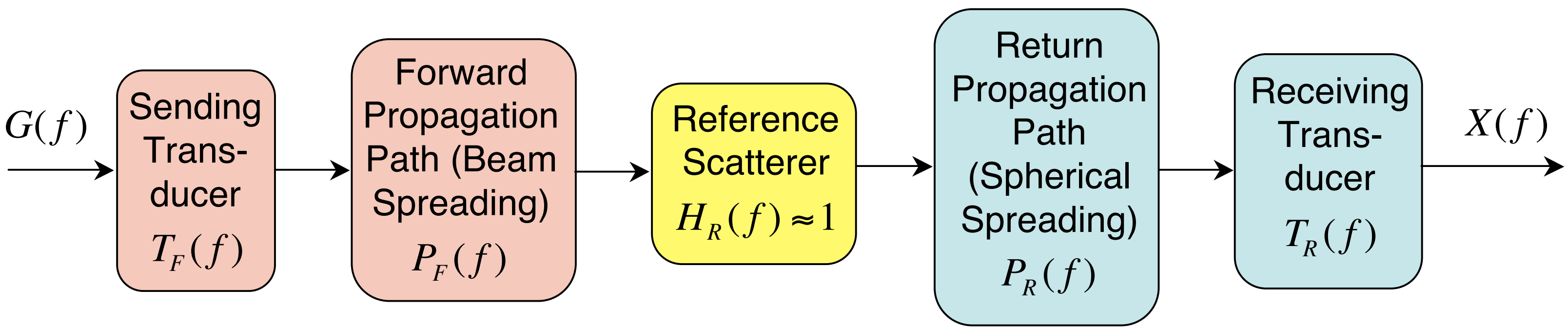
Grace A. Clark, Ph.D.

We Use a Reference Scatterer to Help Remove Distortion: Conceptually, This is a *"System Identification"* Problem

Experiment to Measure the Scattered Signal $Y(f)$



Experiment to Measure the Reference Signal $X(f)$



Conceptually:

$$\frac{Y(f)}{X(f)} = \frac{T_F(f)P_F(f)H(f)P_R(f)T_R(f)}{T_F(f)P_F(f)\;(1)\;P_R(f)T_R(f)} \approx H(f) \overset{F^{-1}}{\longleftrightarrow} h(t)$$