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(Department of Mechanical Engineering)

Detecting defects (with ultrasound)?

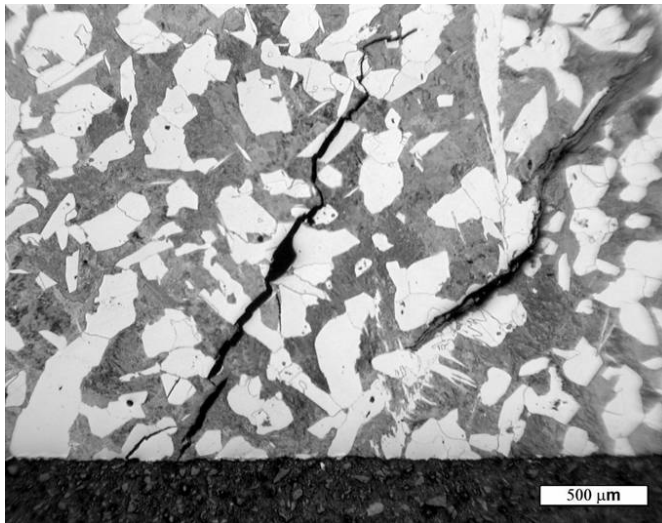
June 2008



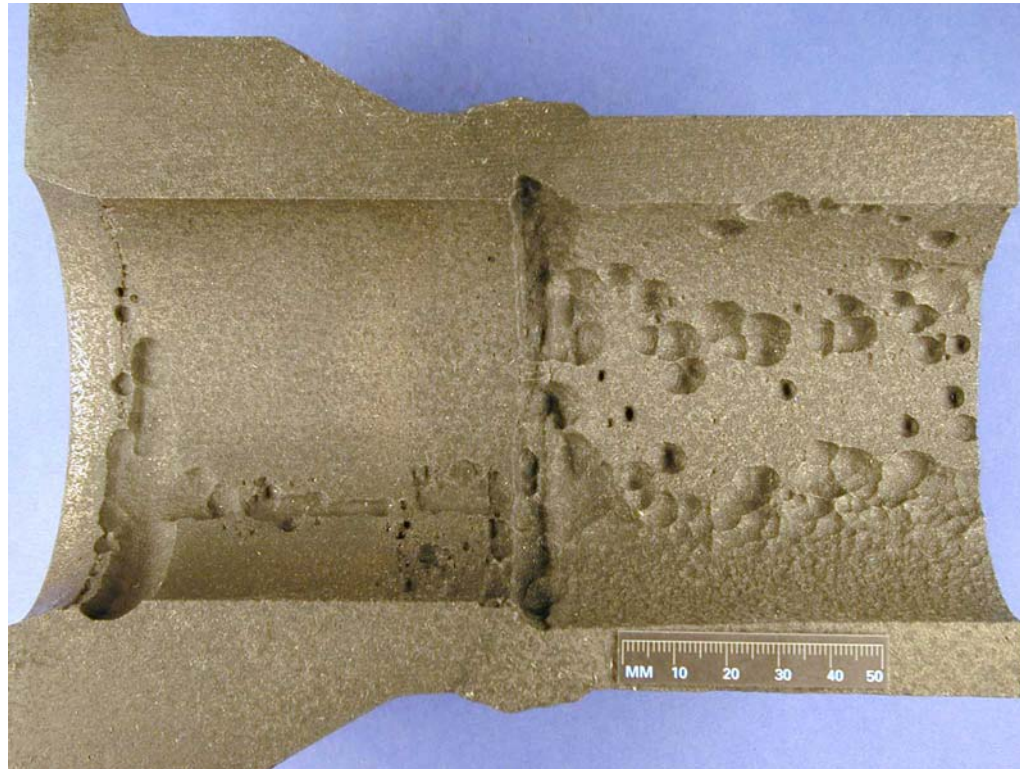
Outline

- The engineering non-destructive evaluation problem
- Extracting defect information
- Coping with uncertainty through autofocus
- Measuring displacement/strain
- Conclusions

Problem: Cracking



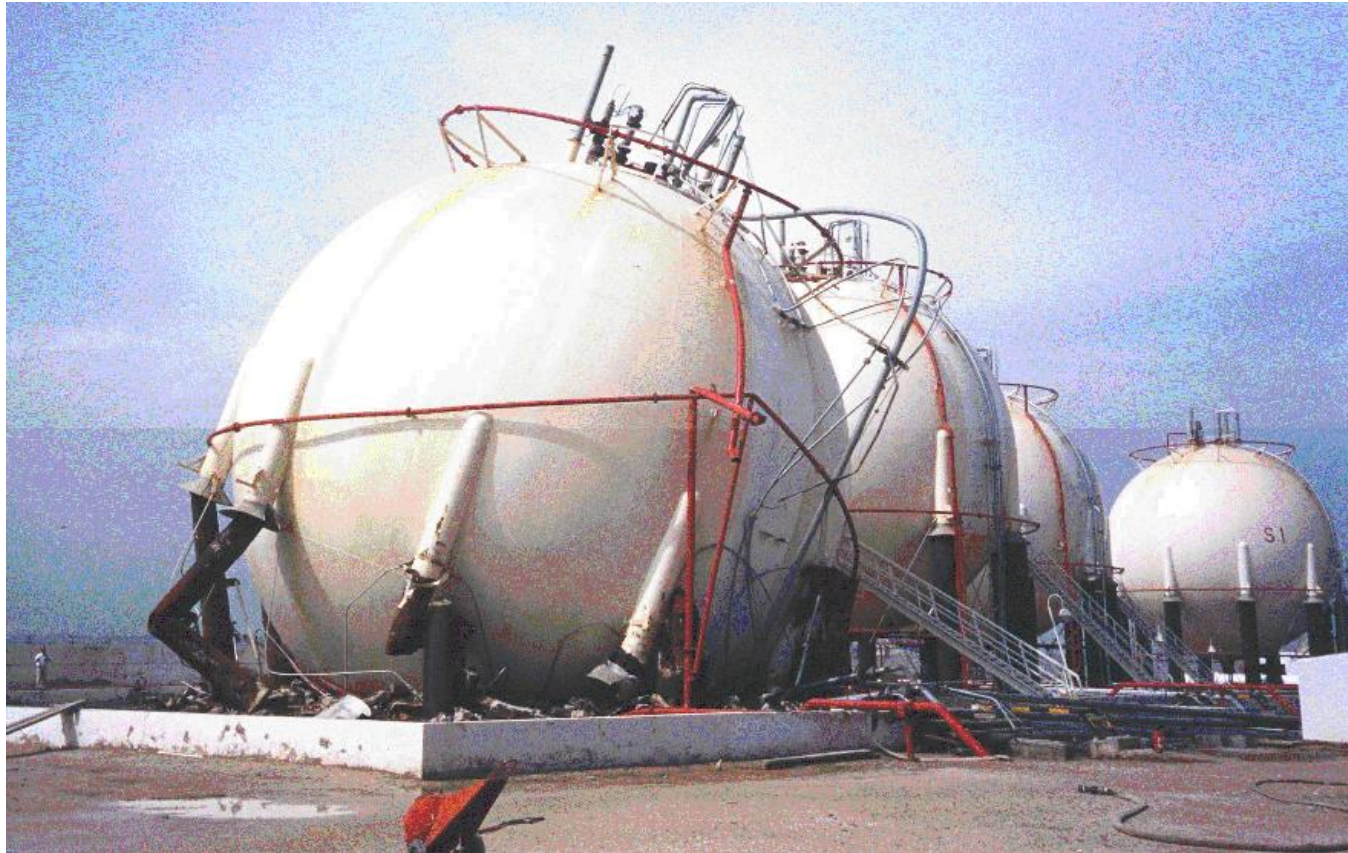
Problem: Corrosion



Problem: Long-term monitoring

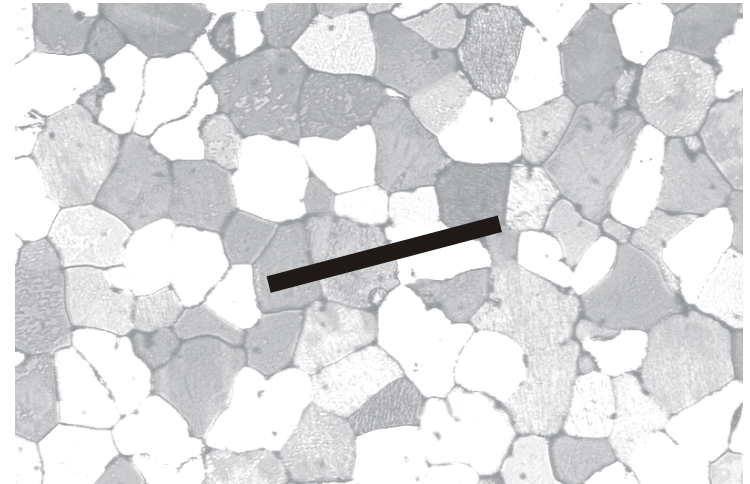


Consequence of failure



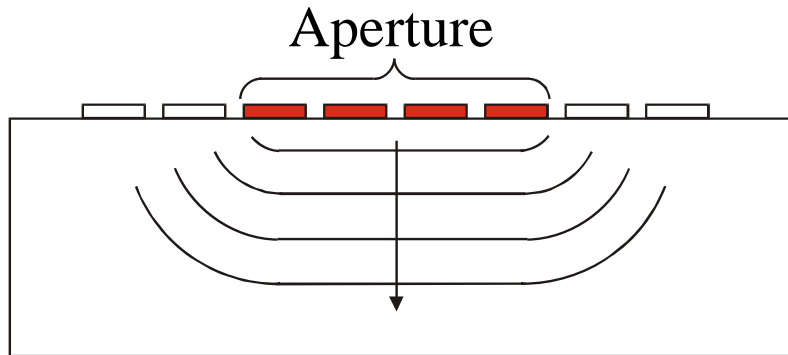
The nature of the 'test object'

- A small number of strong scatterers (defects)
- Potentially also a number of weak point scatterers and aberrating grain structure

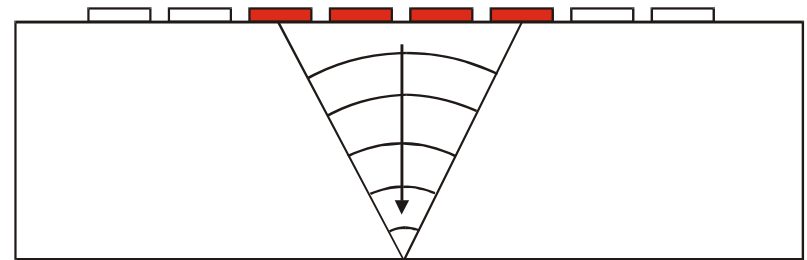


Array inspection modalities

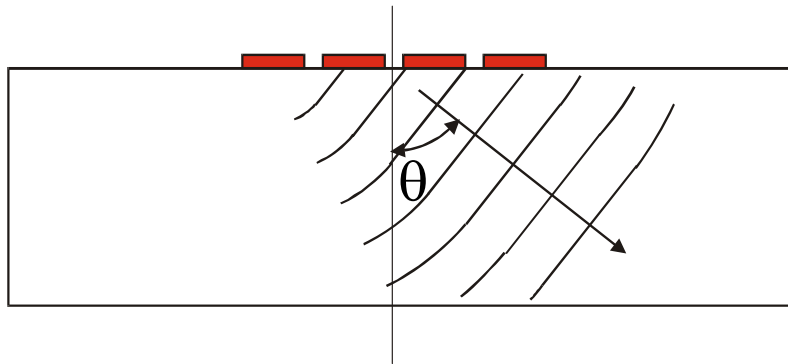
Plane B-scan



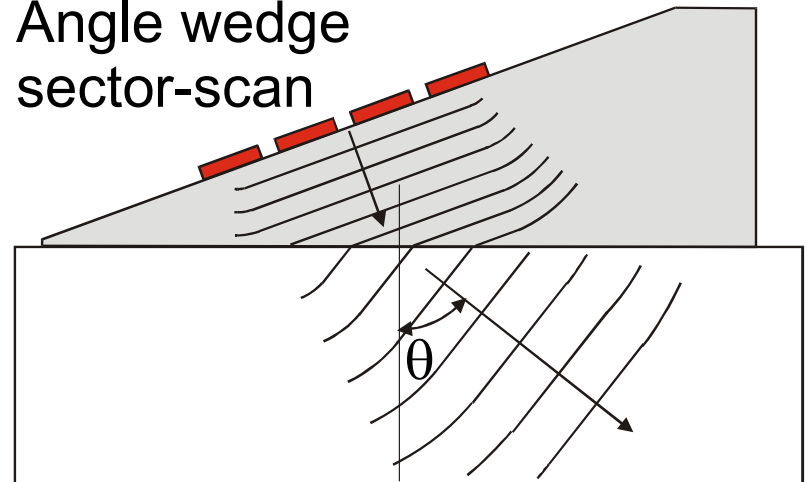
Focused B-scan



Sector-scan

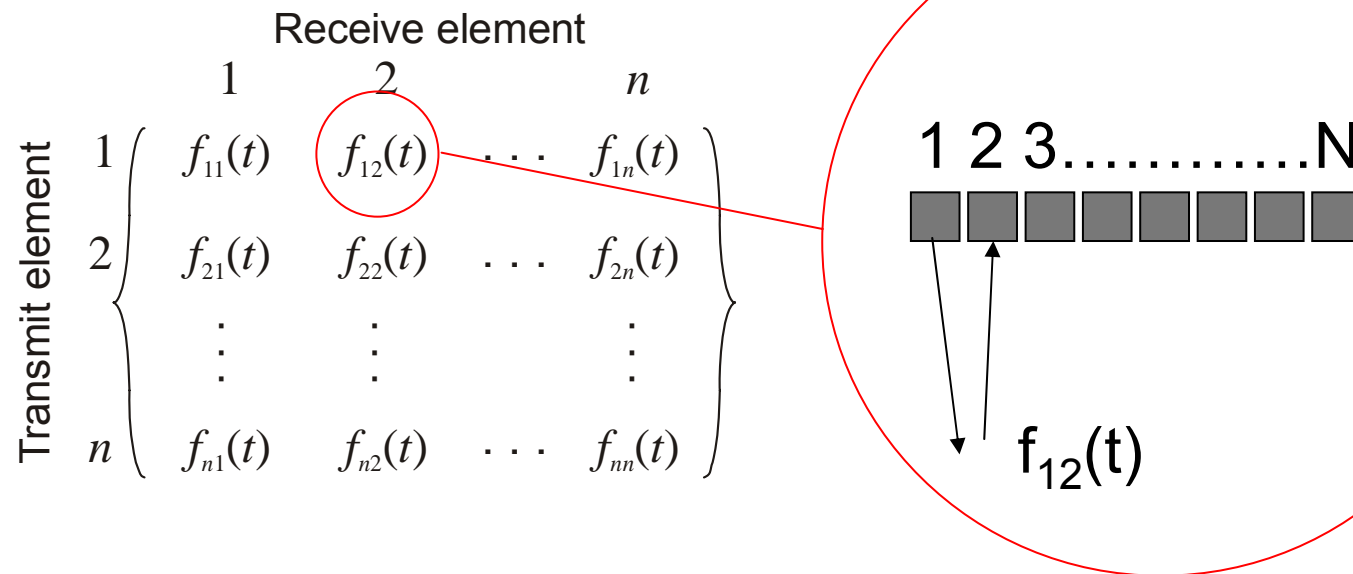


Angle wedge sector-scan



Post-processing – the data

- Use array controller to capture every independent time domain signal

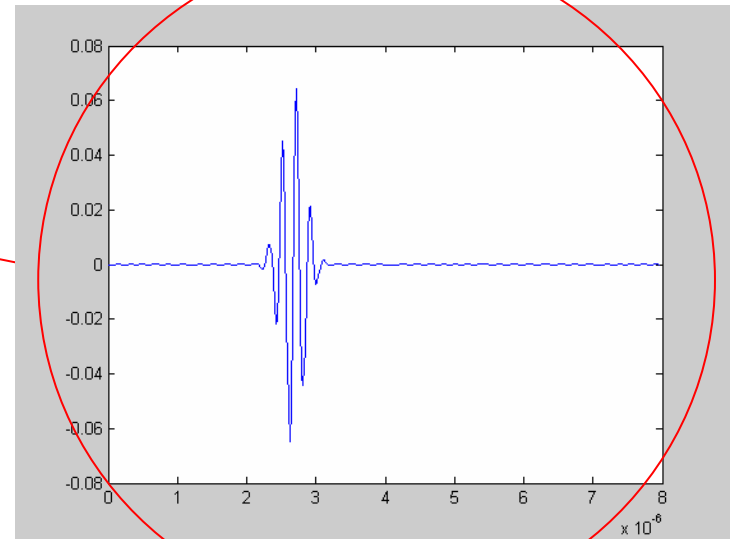


- Perform all imaging in post-processing

Post-processing – the data

- Use array controller to capture every independent time domain signal

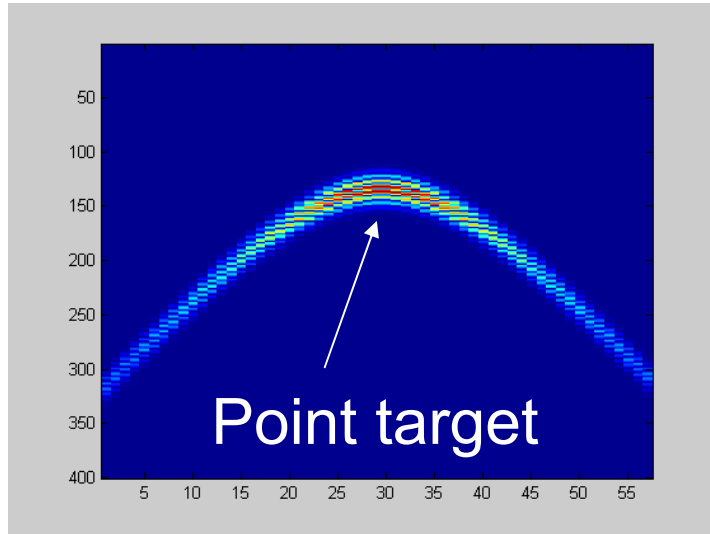
$$\begin{array}{c}
 \text{Transmit element} \\
 \left. \begin{array}{c} 1 \\ 2 \\ \vdots \\ n \end{array} \right\}
 \end{array}
 \begin{array}{c}
 \text{Receive element} \\
 \begin{array}{cccc}
 1 & 2 & \dots & n \\
 \left(\begin{array}{cccc}
 f_{11}(t) & f_{12}(t) & \dots & f_{1n}(t) \\
 f_{21}(t) & f_{22}(t) & \dots & f_{2n}(t) \\
 \vdots & \vdots & \dots & \vdots \\
 f_{n1}(t) & f_{n2}(t) & \dots & f_{nn}(t)
 \end{array} \right)
 \end{array}
 \end{array}$$



- Perform all imaging in post-processing

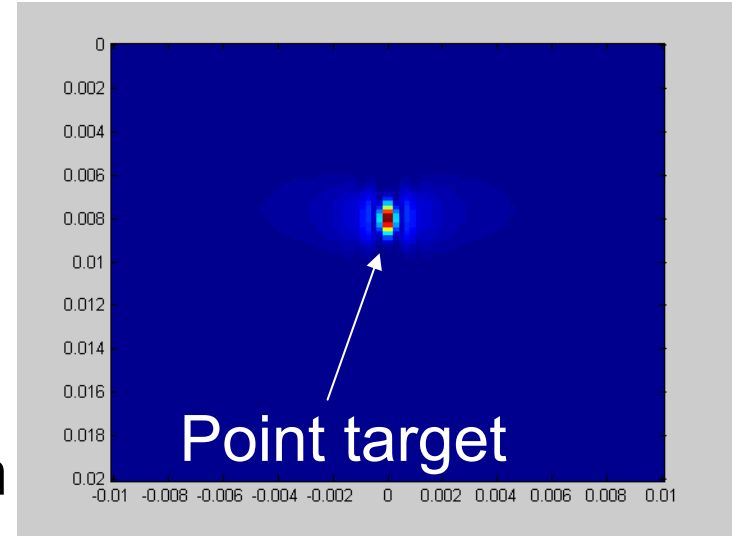
Imaging - from time domain data to image

Echo data



Imaging
algorithm

Image



$$I(x, y) = \int \sum_j A_j(x, y, \omega) F_j(\omega) d\omega$$

A_j = coefficient

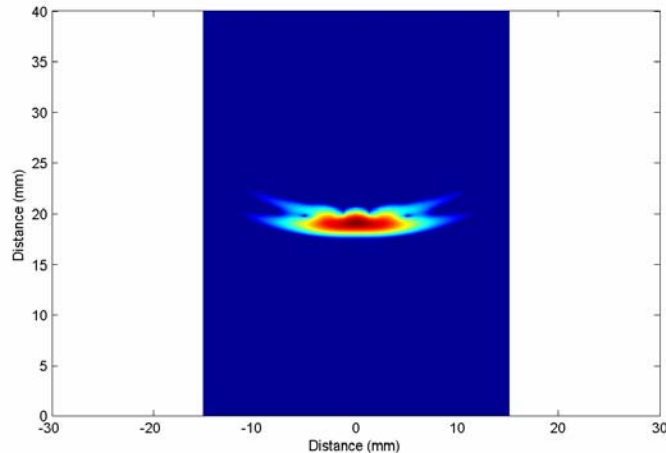
F_j = spectrum of $f_j(t)$

- Based on inverse model
- or pragmatism
- or iteration

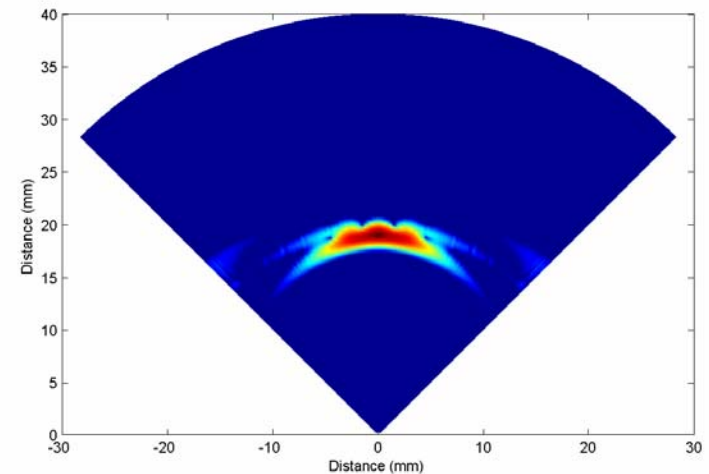
Imaging - background

- Numerous linear imaging algorithms (B-scan, sector-scan etc.) to choose from ...

Plane B-scan



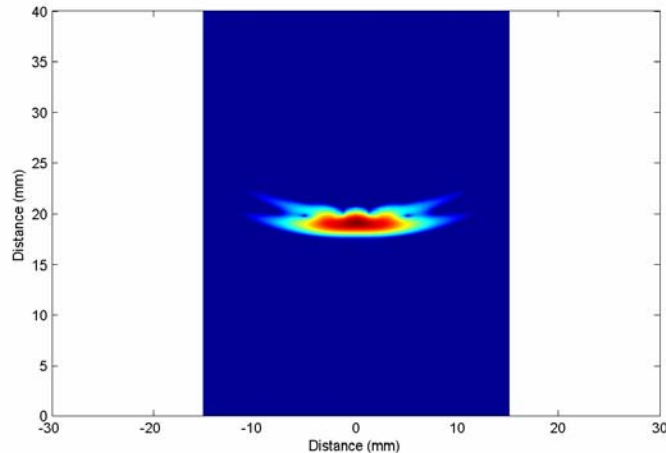
Sector-scan



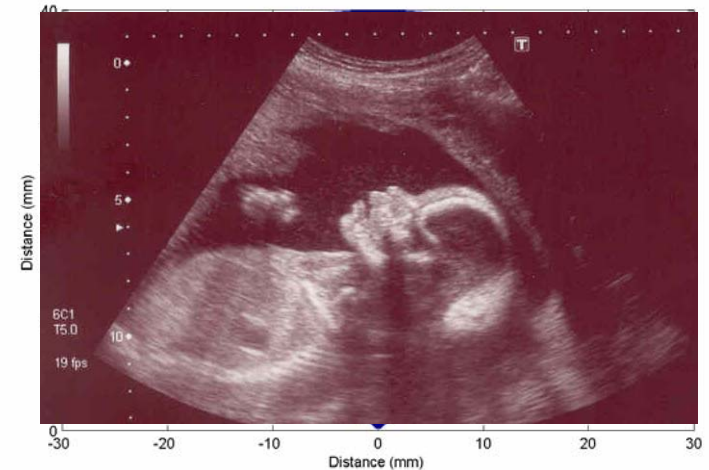
Imaging - background

- Numerous linear imaging algorithms (B-scan, sector-scan etc.) to choose from ...

Plane B-scan



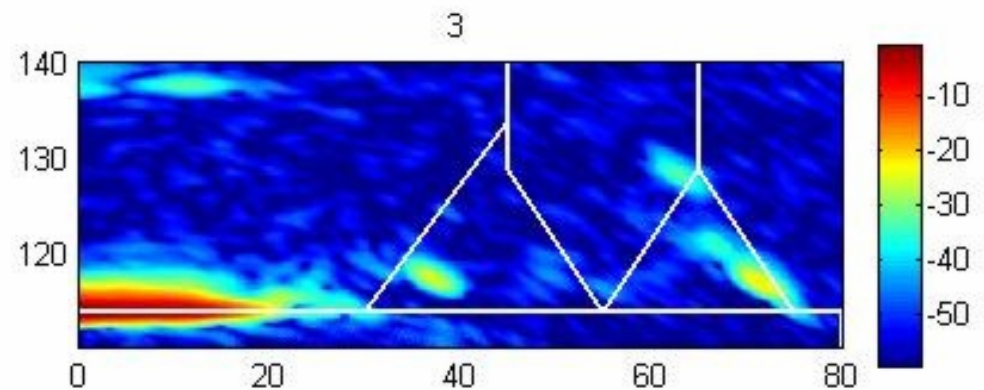
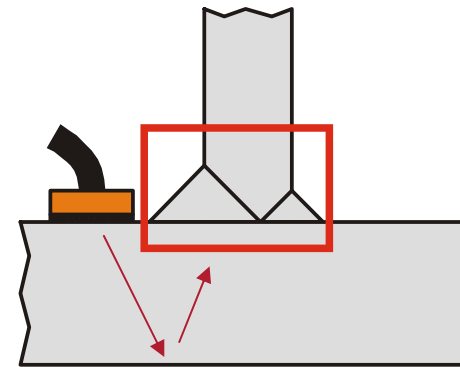
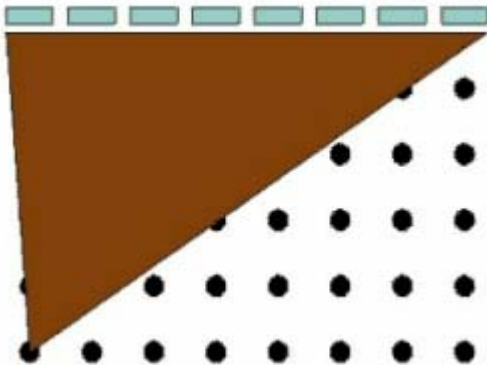
Sector-scan



Defect detection and characterisation

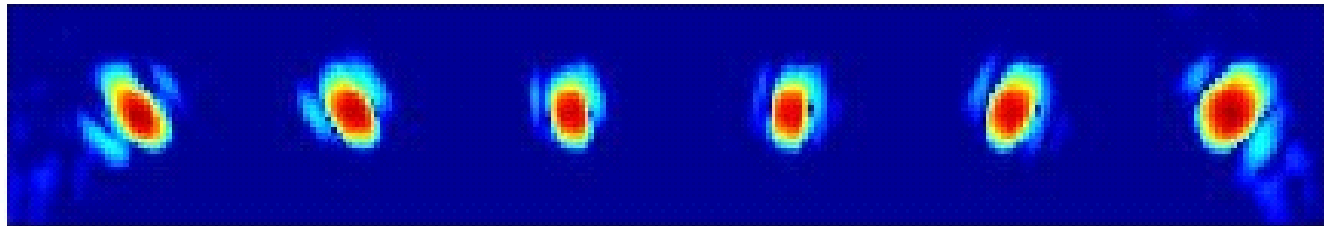
Total focusing method

- Array focuses in transmission and reception on every point



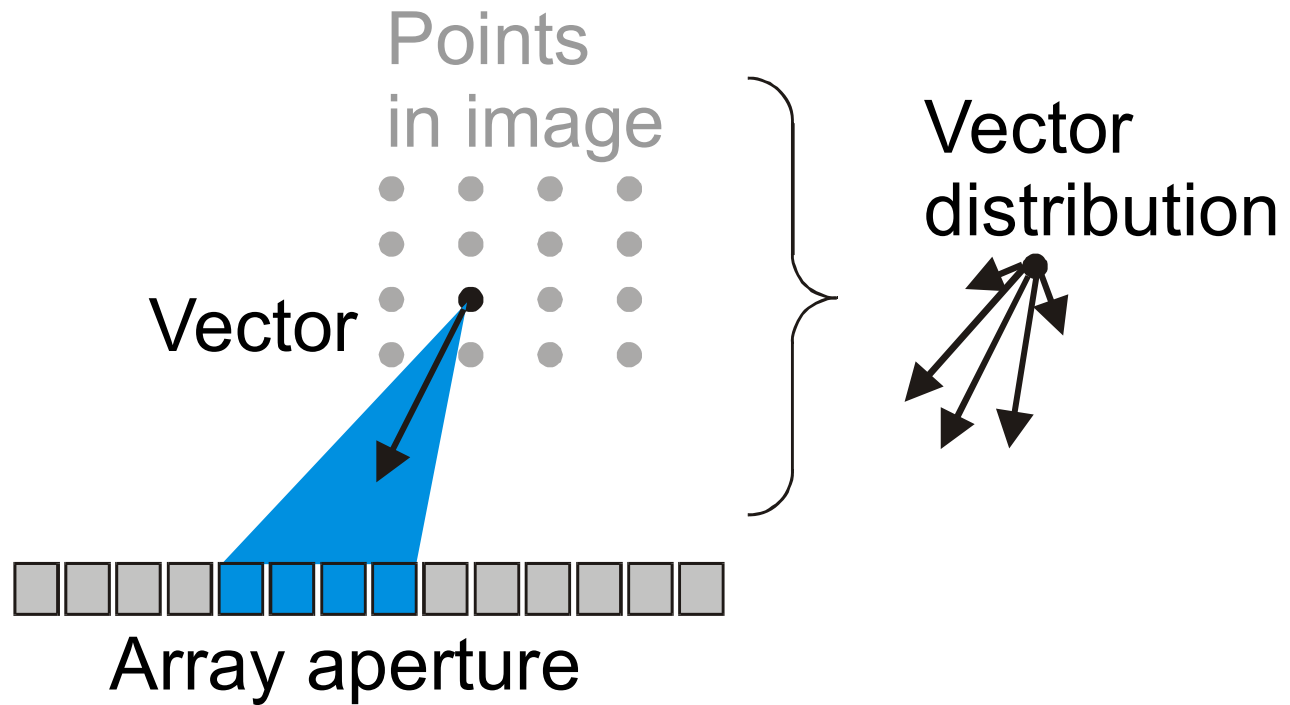
Extracting information from a defect

- Linear imaging cannot provide detail beyond diffraction limit
 - Example 1 mm SDH and 5 x 1 mm long cracks, $\lambda = 1.2$ mm (64 elements across a 32λ aperture)



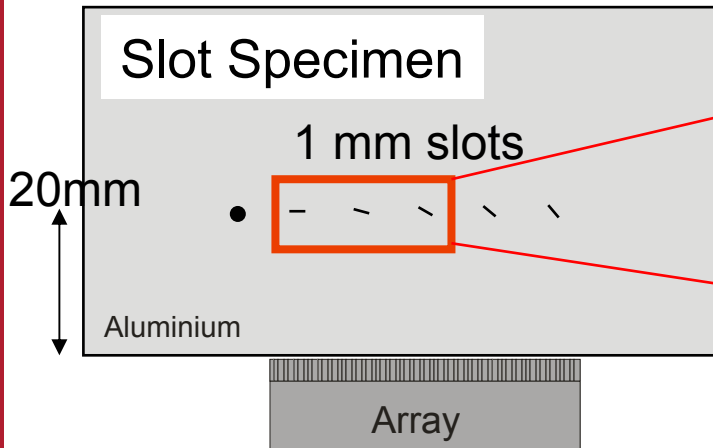
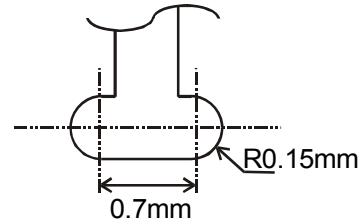
- Can more information be extracted from full matrix of data?

Vector Total Focusing Method



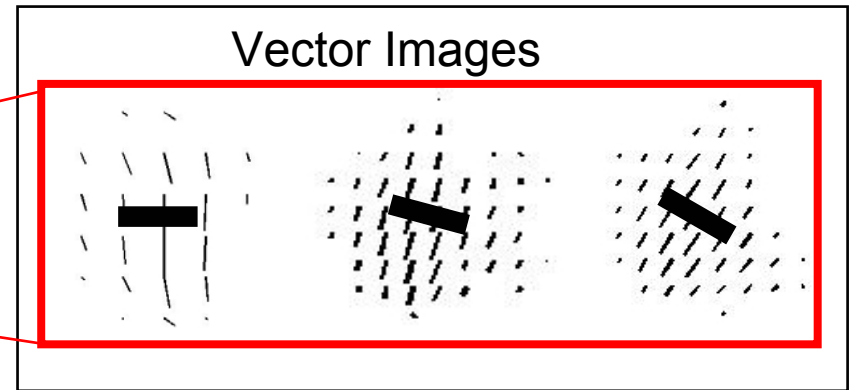
Orientation of small cracks (slots)

Slot detail



5MHz, $\lambda=1.2\text{mm}$

Vector Images

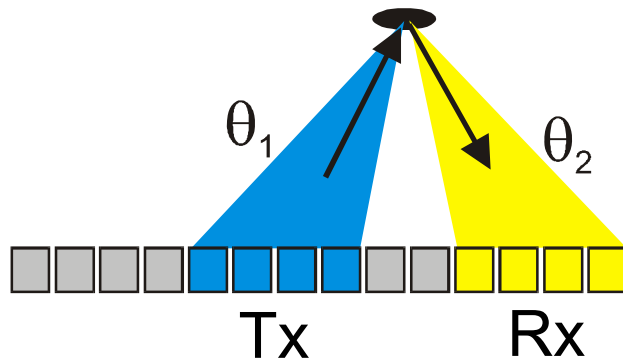


Actual angle	0°	15°	30°
Measured angle	-5.4°	15.7°	31.0°

Defect Characterisation – Scattering Matrix

The concept

Scatterer of interest



Scattering matrix

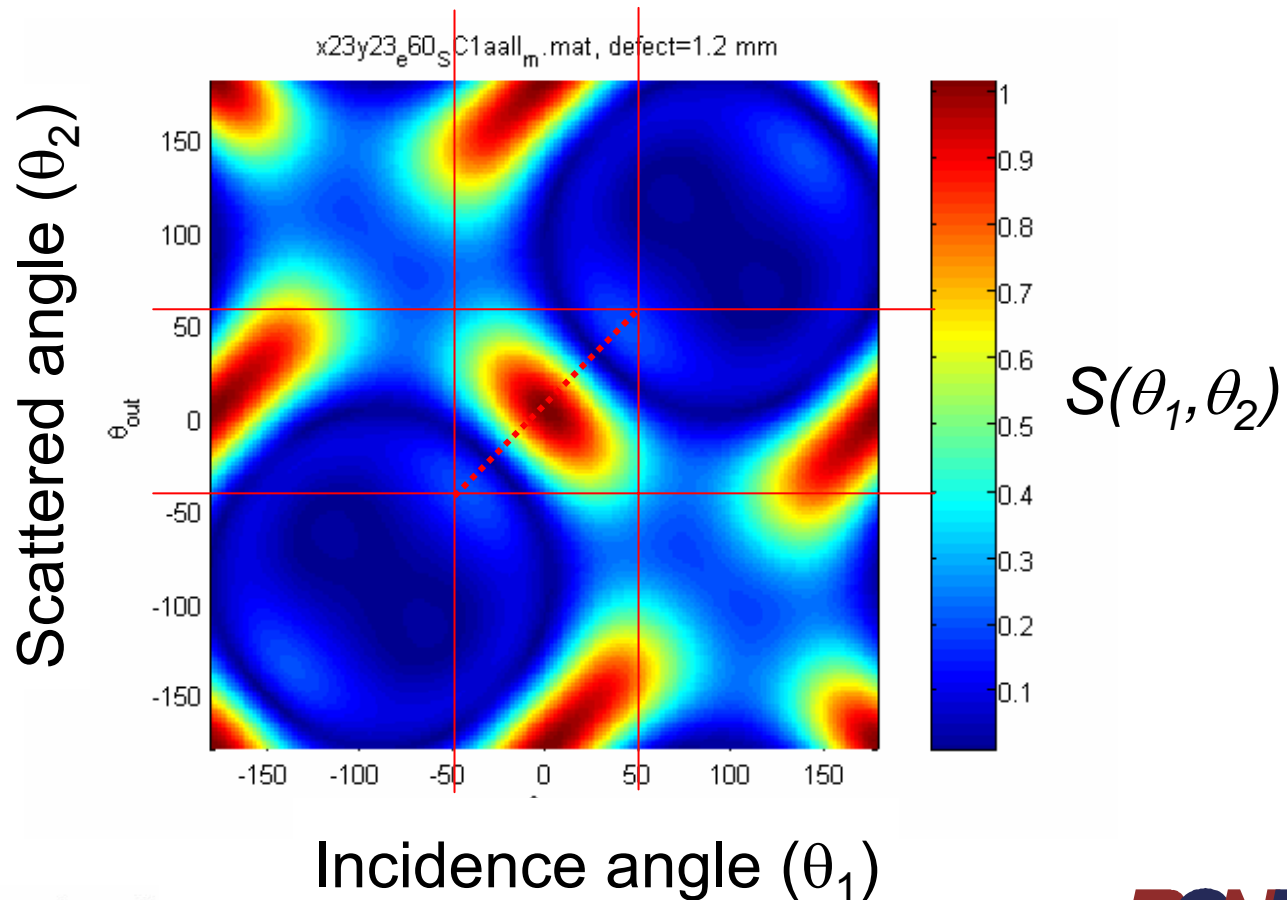
Rx angle, θ_2

Tx angle, θ_1

Region
of S
probed
by array

Defect Characterisation – Scattering Matrix

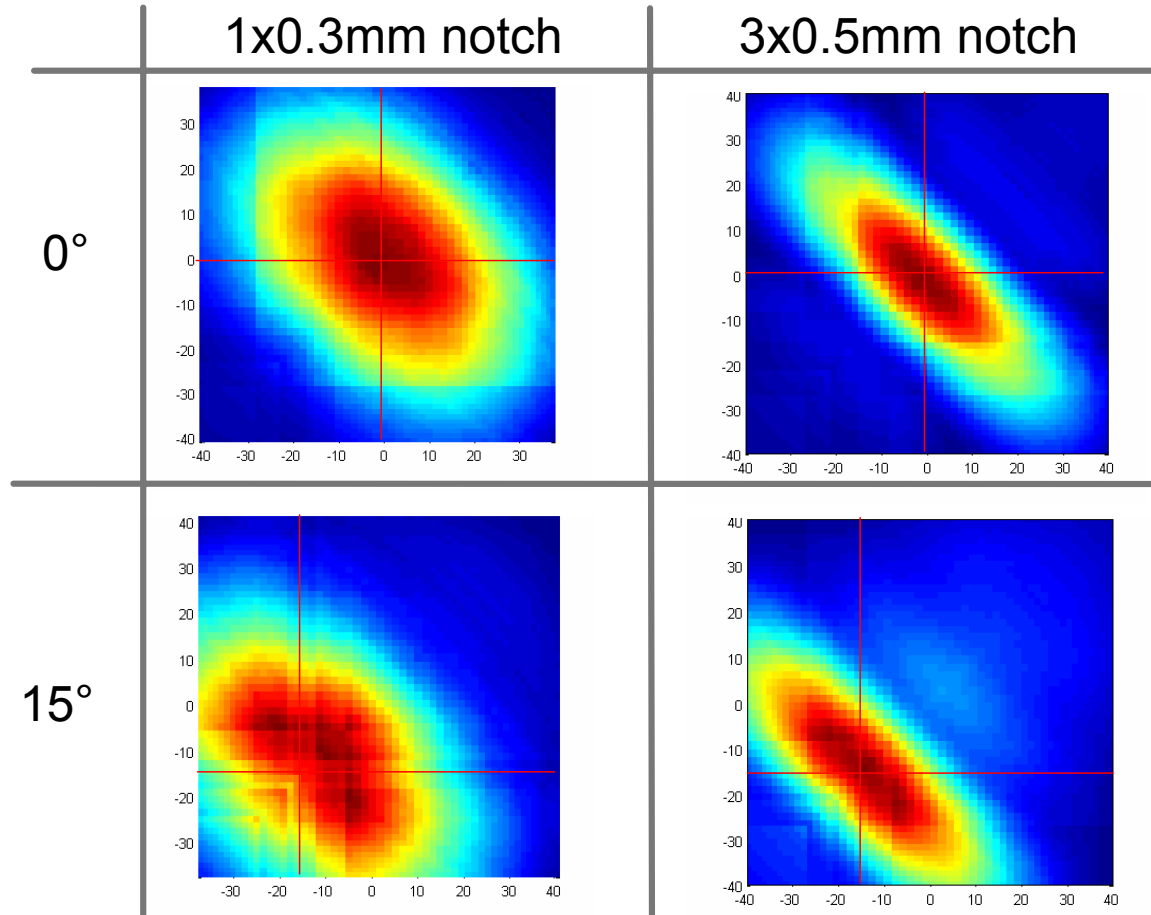
- Scattering matrix ($a=\lambda$ crack) using Finite Elements



Experimental example

**Bulk wave
example**

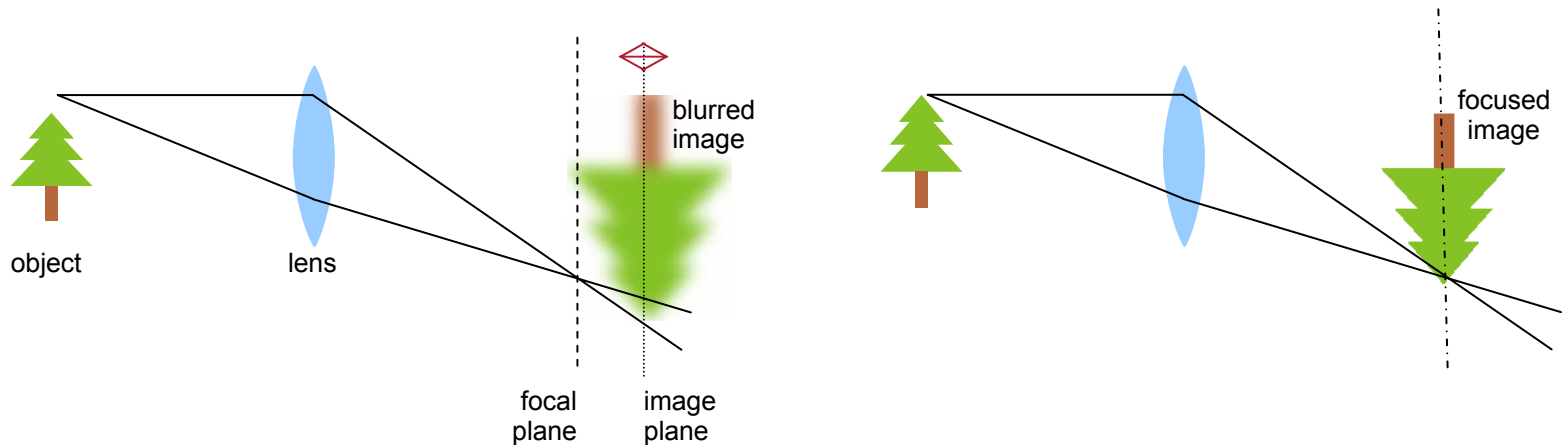
$a \approx \lambda, 3\lambda$



Autofocus

Using autofocus to cope with uncertainty

- Automated estimation of unknown parameters
 - e.g., focal length for a camera
 - Modern cameras often implement autofocus, i.e., by holding the shutter button part-way down before shooting



Using autofocus to cope with uncertainty

- Problem: how to produce a focus if array profile, material properties etc. are uncertain?
- Solution: iteratively adjusts element firing delays until optimal image achieved

Adjustment of assumed element location

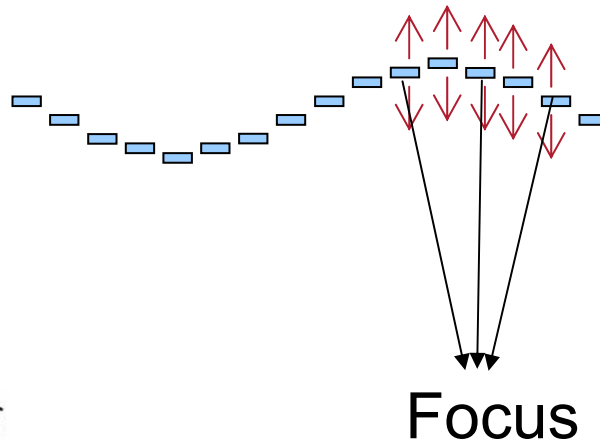
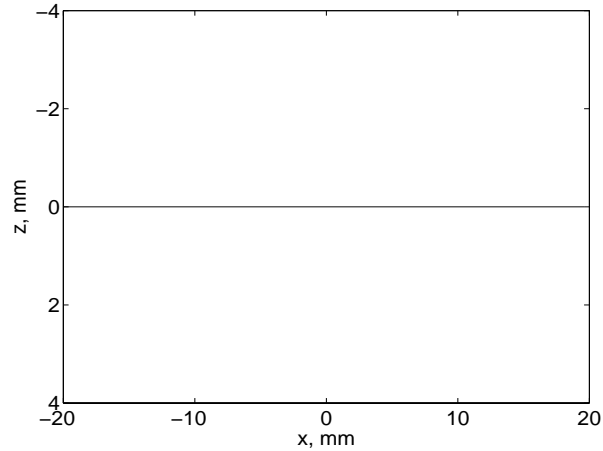
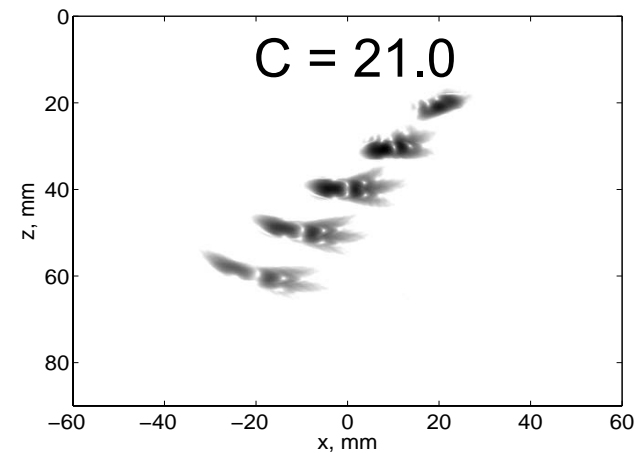
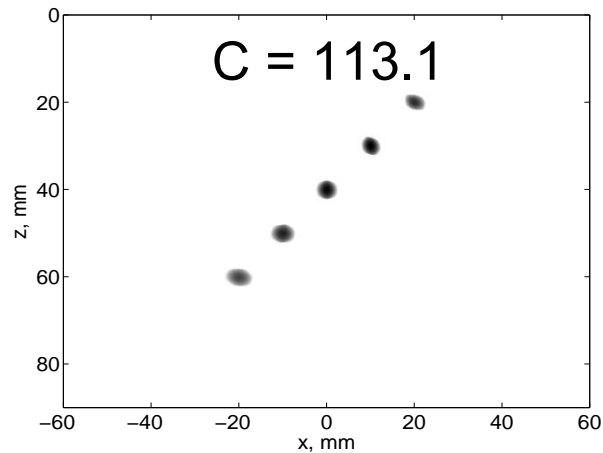
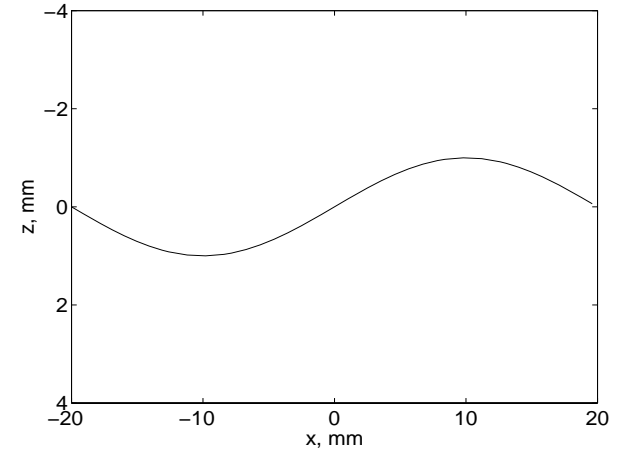


Image contrast examples

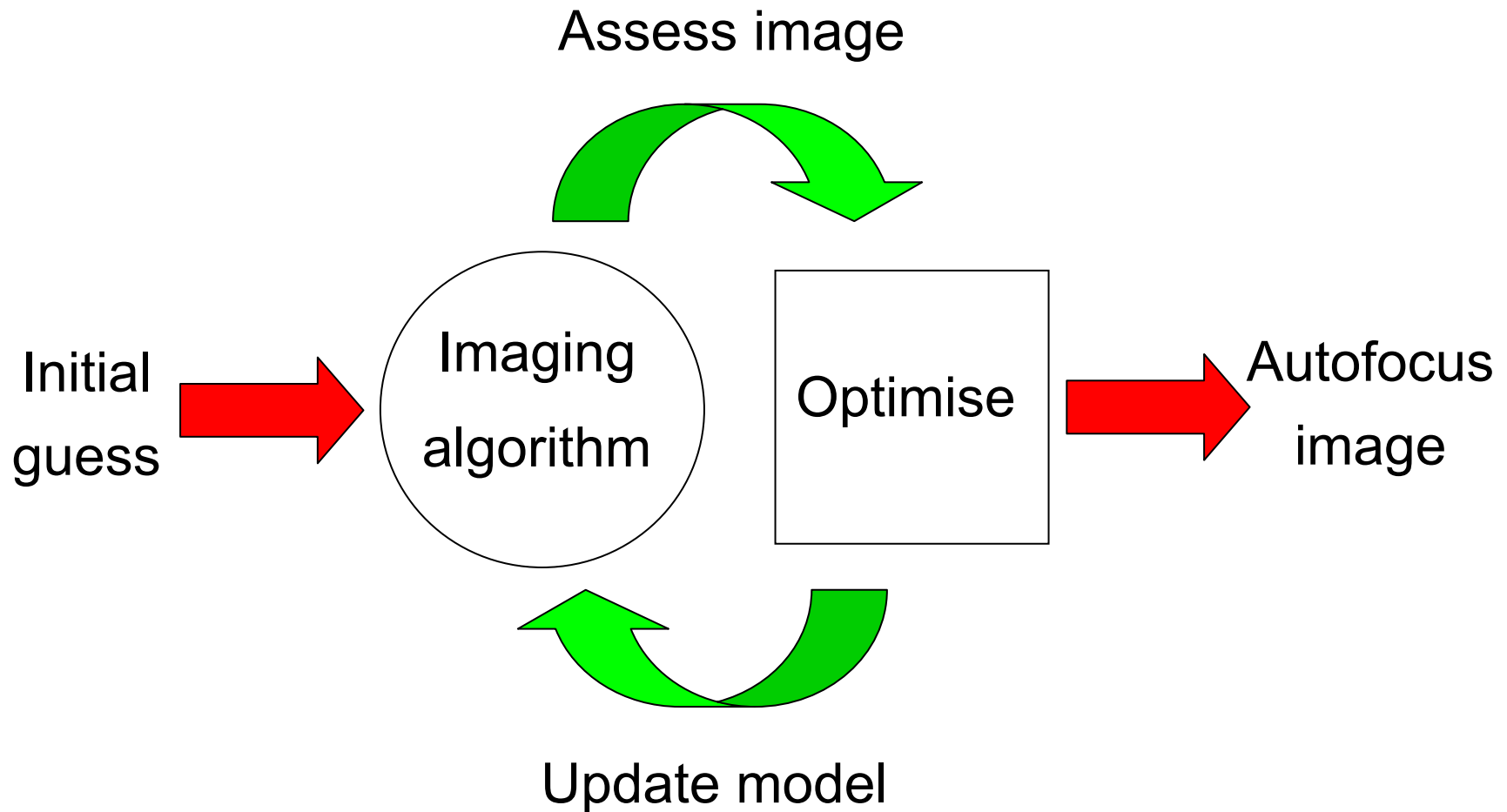
flat



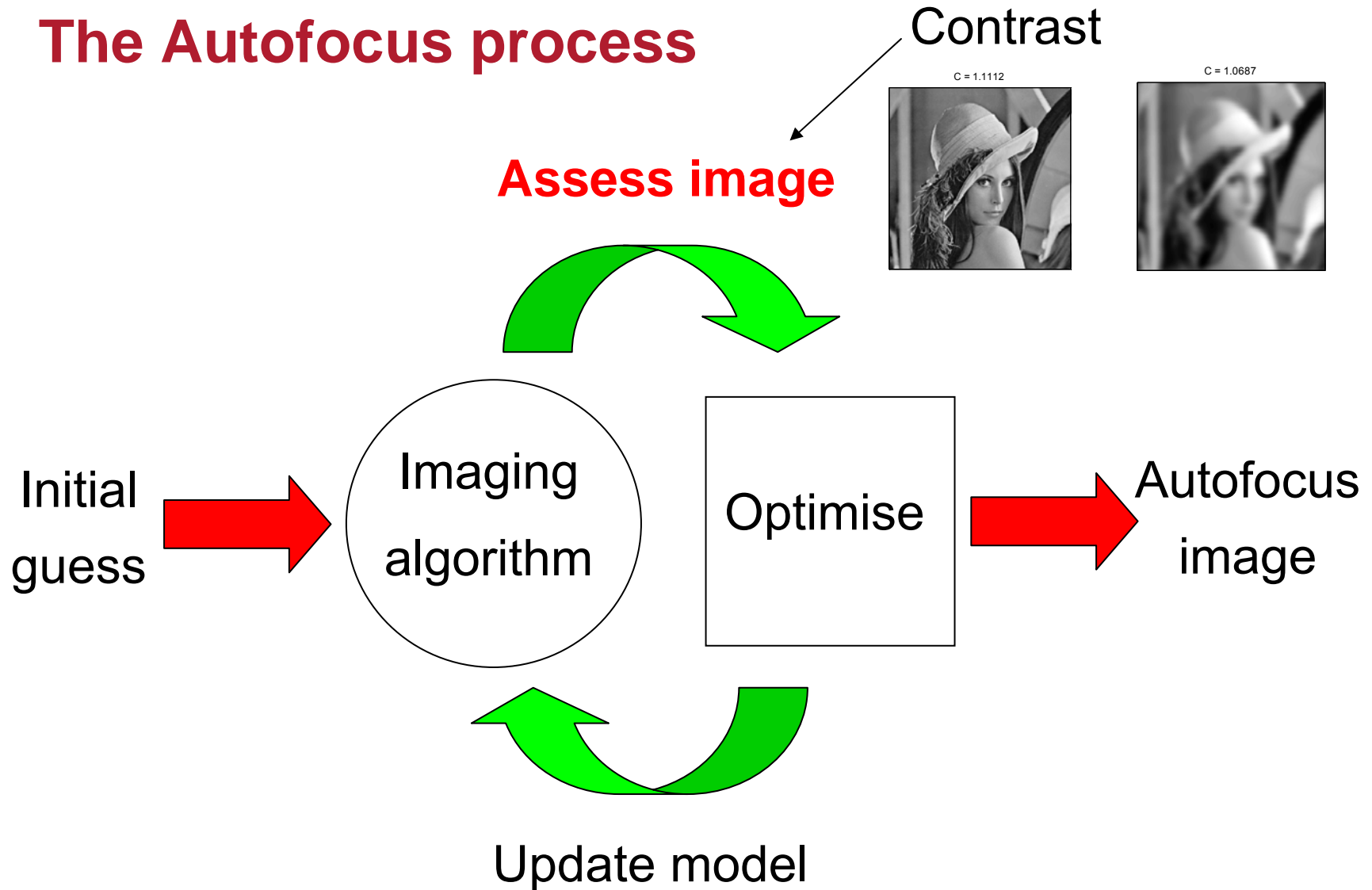
1mm sin



The Autofocus process



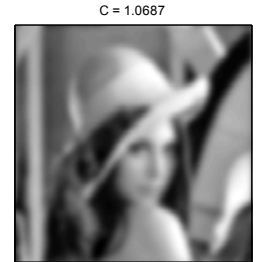
The Autofocus process



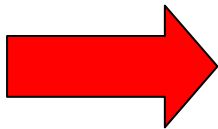
The Autofocus process

Contrast

Assess image



Initial
guess



Imaging
algorithm

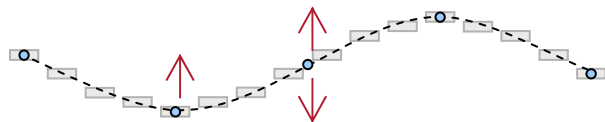
Optimise



Autofocus
image

Spline

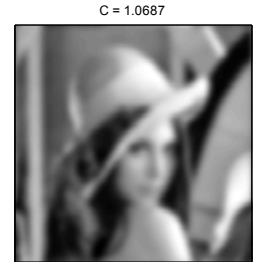
Update model



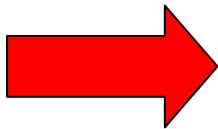
The Autofocus process

Contrast

Assess image



Initial guess



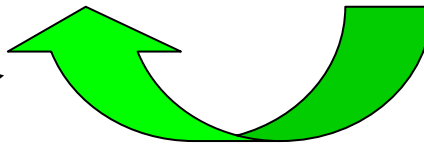
Imaging algorithm

Optimise



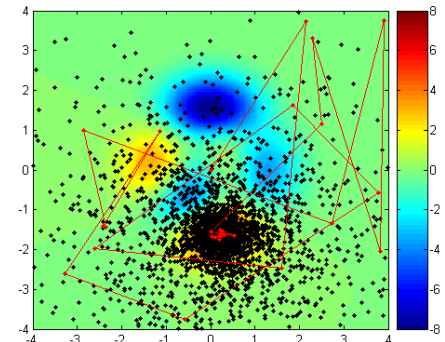
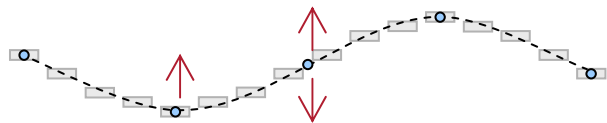
Autofocus image

Spline



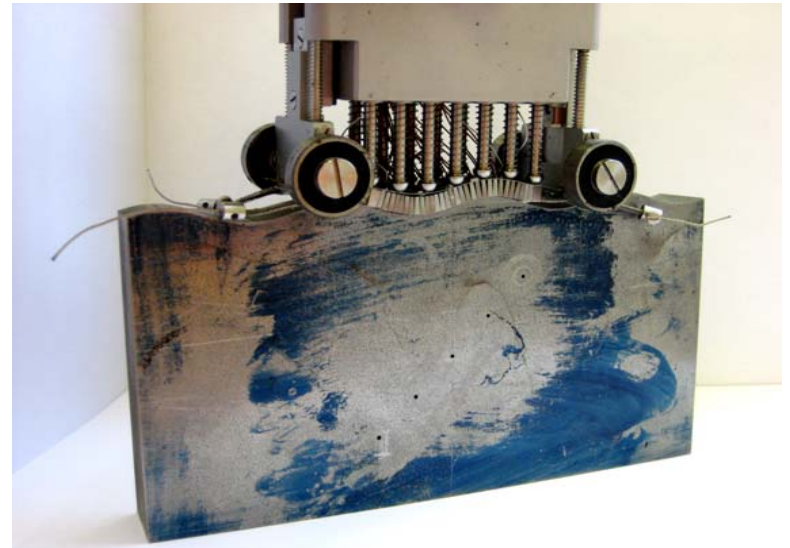
Update model

Simulated annealing



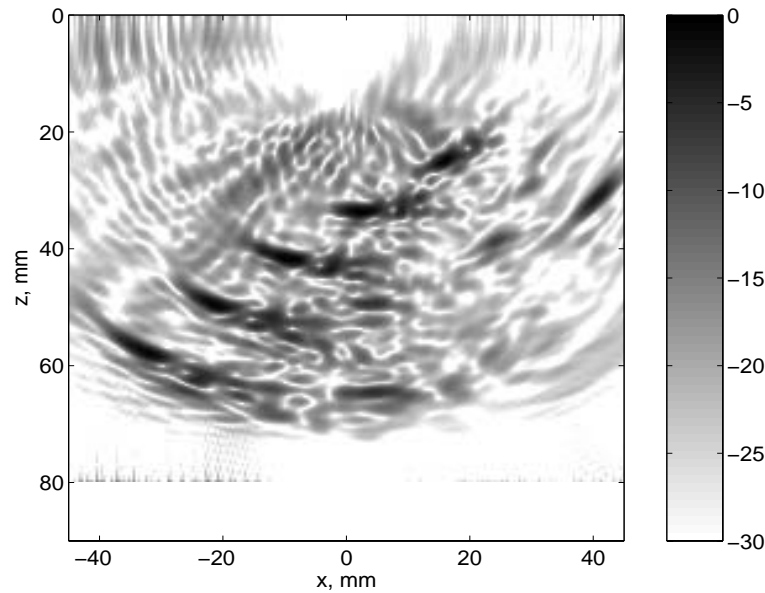
Autofocus experiment

- Flexible array
 - Prototype manufactured by CEA/Immasonic
 - 2 MHz, 30 elements, 40 mm length
- Sinusoidal surface profile
 - ± 2 mm amplitude, 40 mm period
 - Curvature typical of weld
- “Defects”
 - 5 side-drilled holes, 1 mm diameter

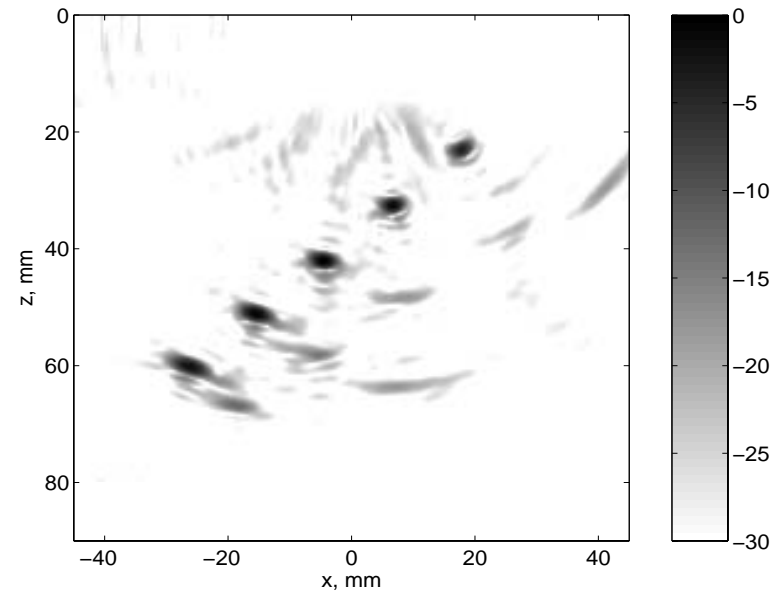


Results before & after autofocus

Uncorrected image



Autofocused image



Measuring displacement/strain

Ultrasonic speckle image correlation

- Extends existing work in medicine (elastography) and optical digital image correlation to volumetric strain measurement in solids.
- Potential uses;
 - FE model validation
 - Mechanical property mapping
 - Fracture Mechanics
 - Defect detection

Ultrasonic speckle image correlation

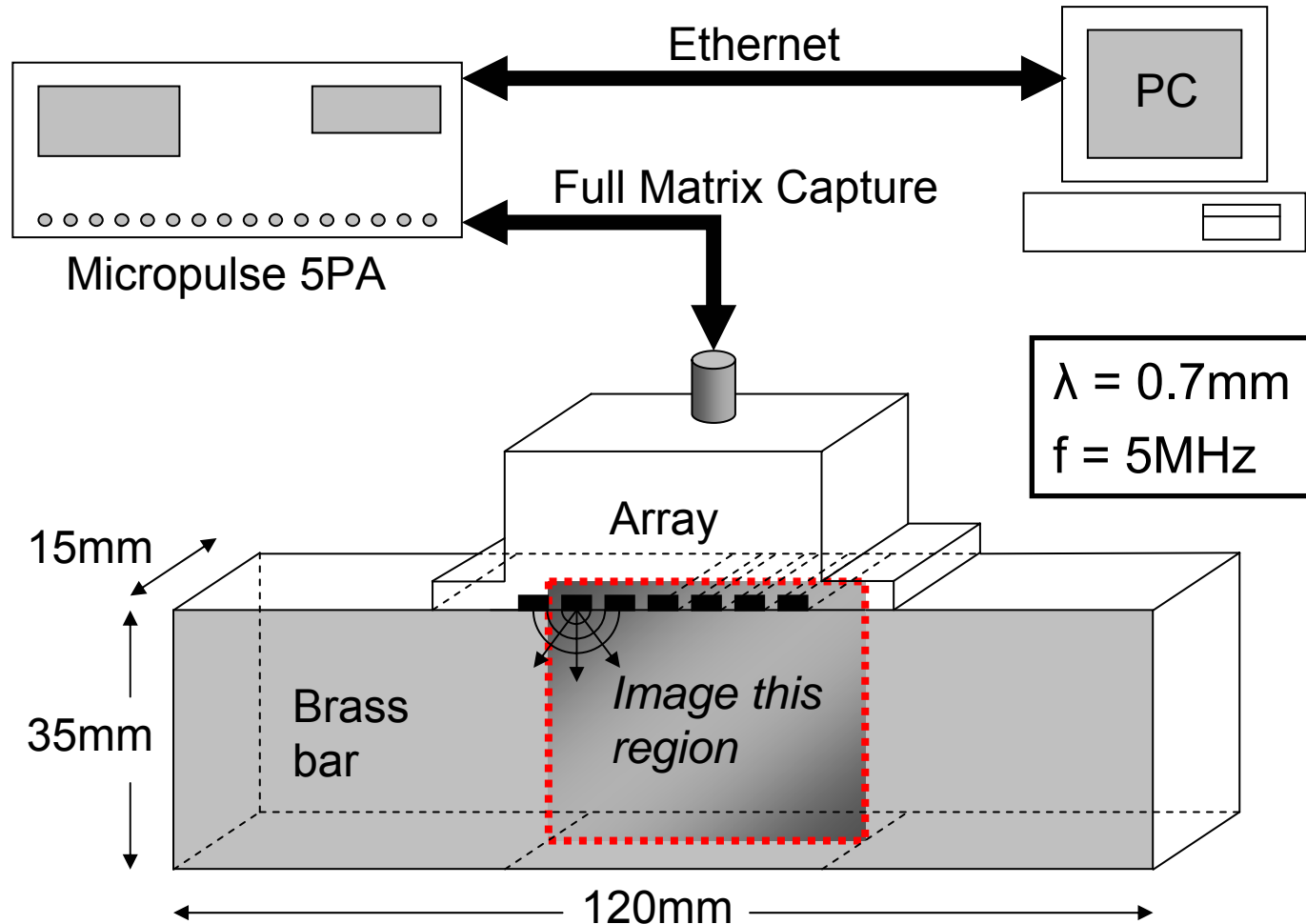
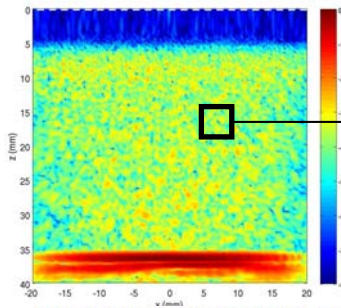


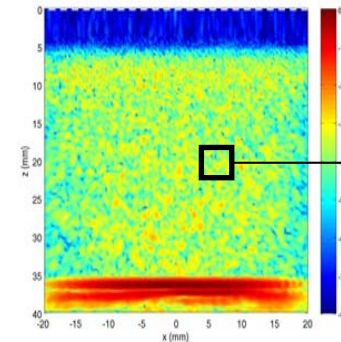
Image correlation – basic principle

- Aim: evaluate 2-D displacements between reference and deformed images

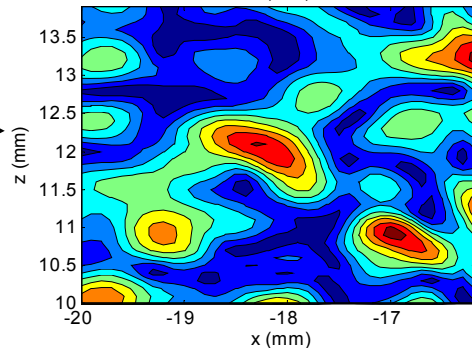
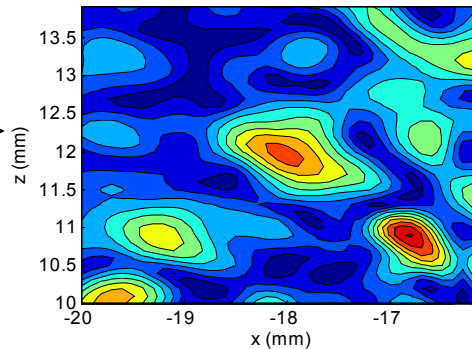
Deformed Image



Reference Image

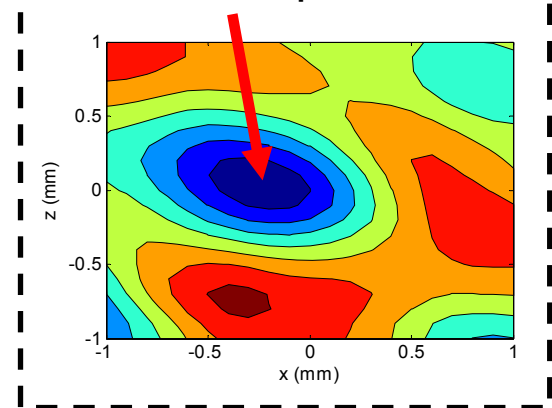


2mm² sub-images

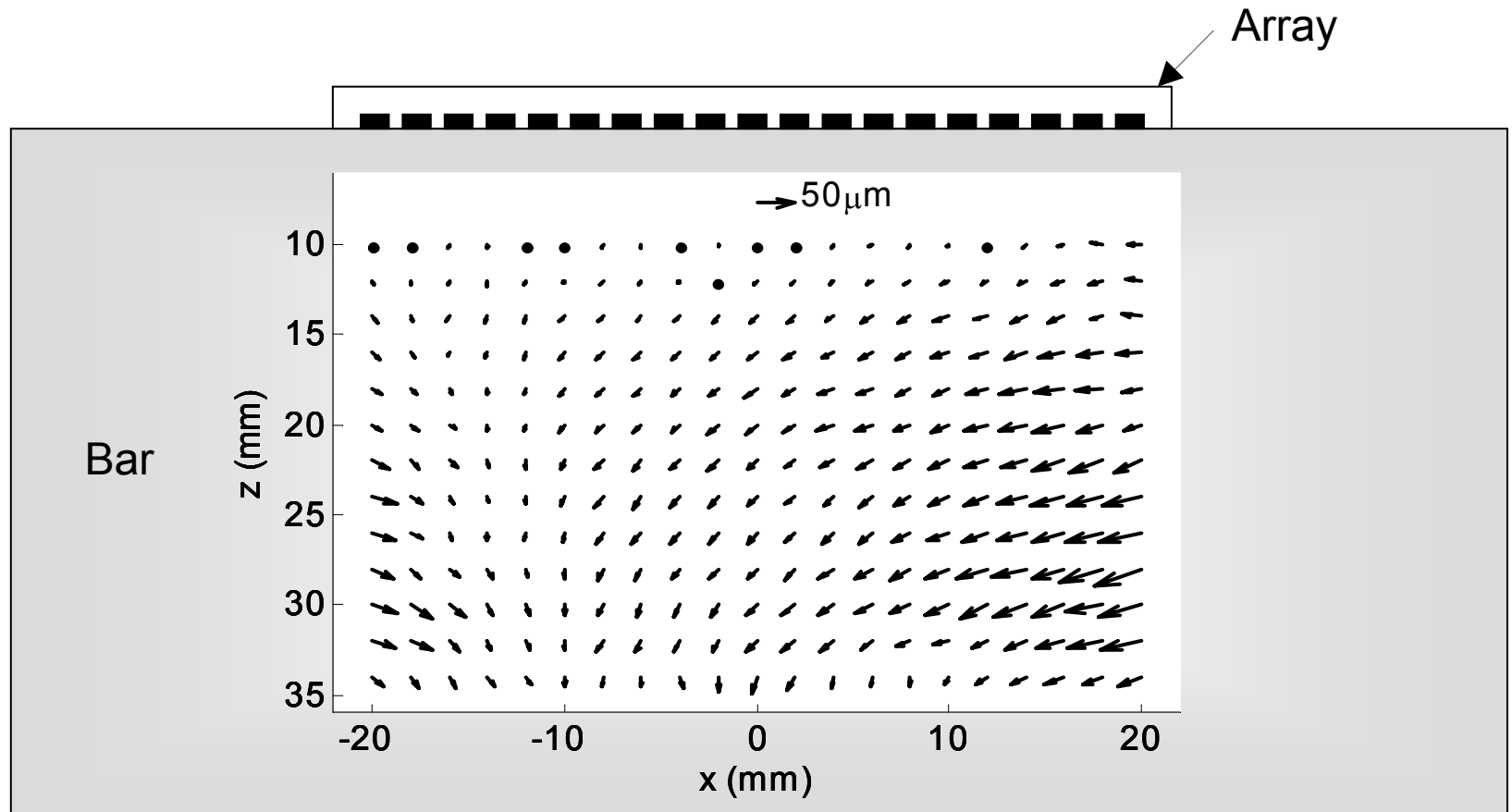


Least-Mean-Square-Error-Map

Position of minimum shows displacement



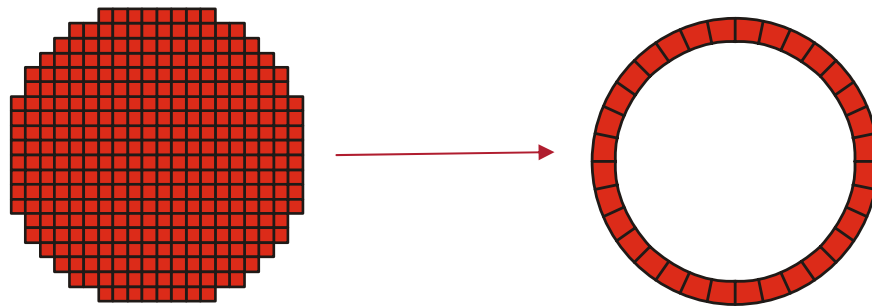
Compression experiment



Future directions

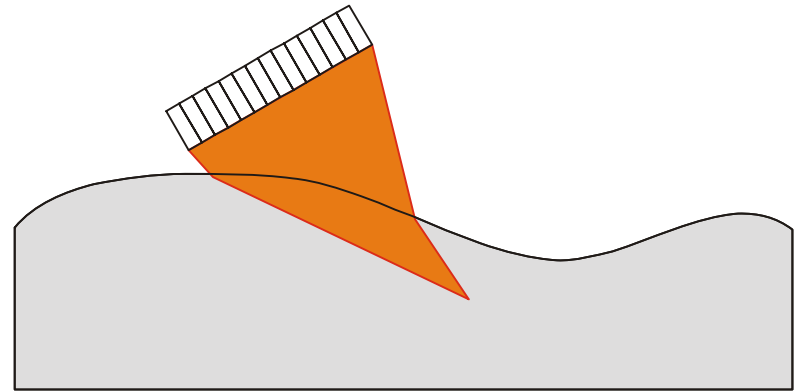
The future: array hardware

- Big challenge is 2D arrays for volumetric imaging
 - Connectivity within array and to controller
 - Incentive for sparse elements – optimisation of layout?



The future: processing and interpretation

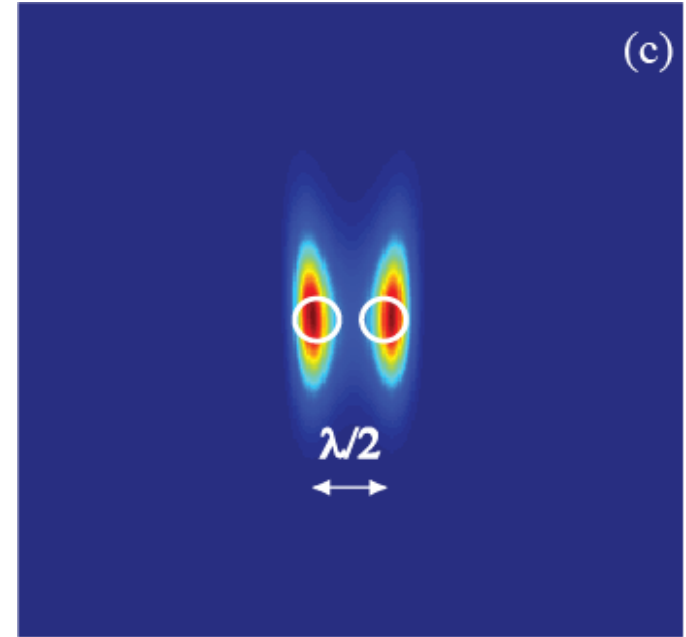
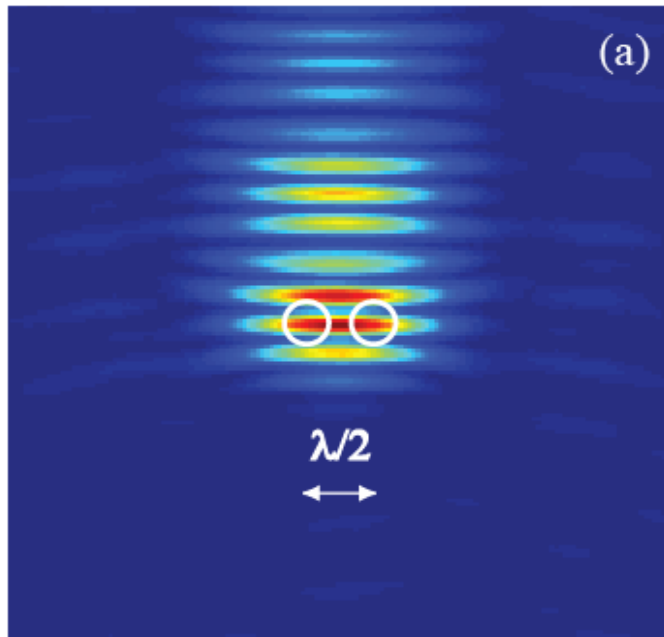
- Automated defect sizing and classification libraries
- Adaptive beamforming in post-processing for difficult inspections



- Display and interpretation of 3D data from 2D arrays

The future: beating the diffraction limit

- Example of separation of side-drilled hole targets using MUSIC algorithm
 - Experimental results from Francesco Simonetti (Imperial College NDT Group) *Phys Rev E*, **73**, 036619, 2006



Thank you for your attention