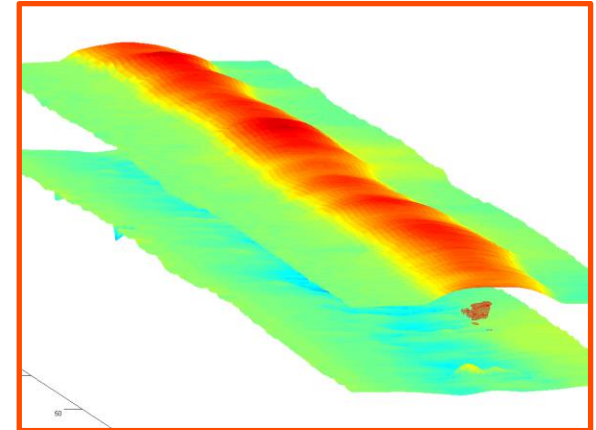
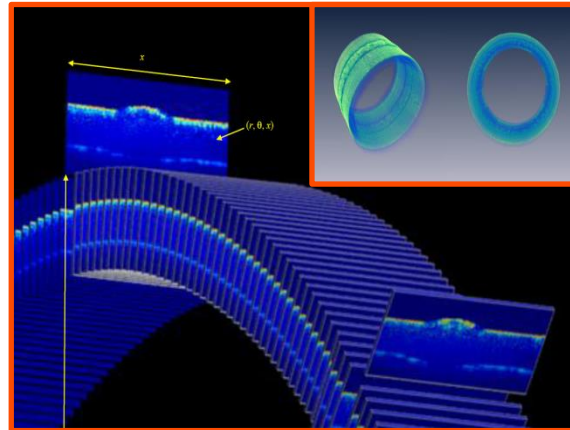
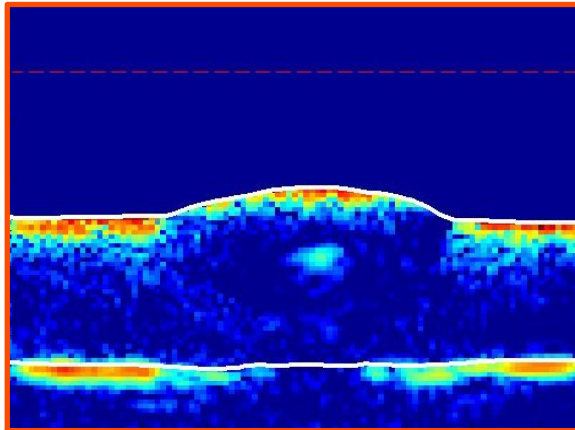


The Ultra-Sound Choice: Ultrasonic Imaging Using MATLAB AND BRAIN

Tom Barber

Anthony Croxford

BAE SYSTEMS



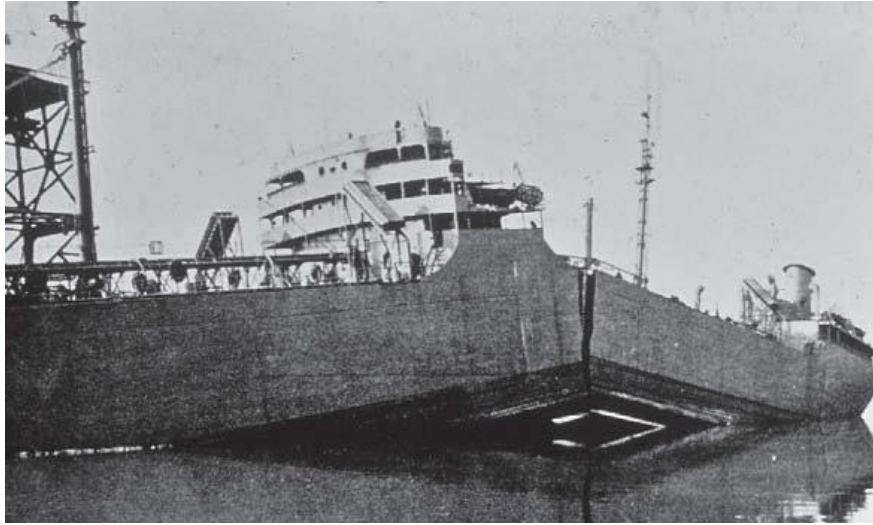
BAE SYSTEMS

Outline

- **The Engineering Need for Ultrasound**
- BRAIN: Development & Implementation
- Industrial Benefit & Outlook

Structural Engineering

When Things Go Wrong...



1940s: Liberty Cargo Vessels
Hull-cracking

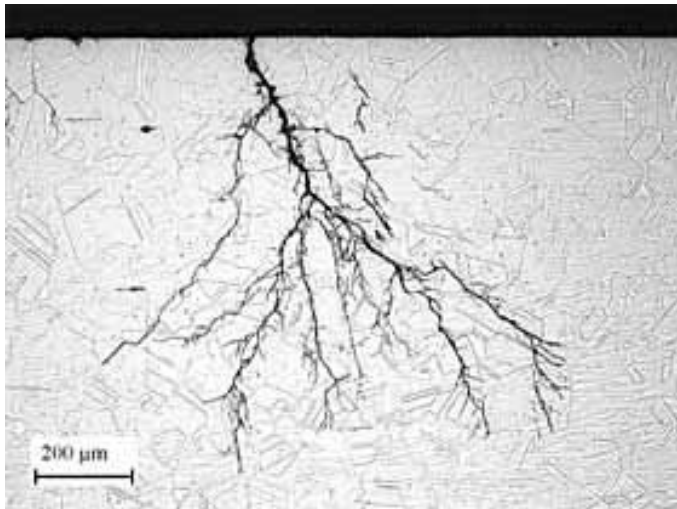


1988: Aloha Airlines Flight 243
Fatigue-cracking in lap-joint

Structural Engineering

Material Flaws: Causes of failure

Flaws in-service



twi-global.com

Stress-Corrosion Cracking

Flaws at manufacture



Crack in a butt-welded joint

- Cannot be detected reliably by the "Mk 1 Eyeball"
- Can occur sub-surface or in accessible areas
- How are flaws detected or monitored?

Non-Destructive Testing (NDT)

Use of sensor and imaging technology to assess the conditions of components, plant and engineering structures during manufacture and in-service

- 25,000 NDT inspections carried in the UK every day
- 120,000 NDT inspections world-wide

Cross-sector:

- Energy, nuclear, aerospace, renewables

Industry Trends:

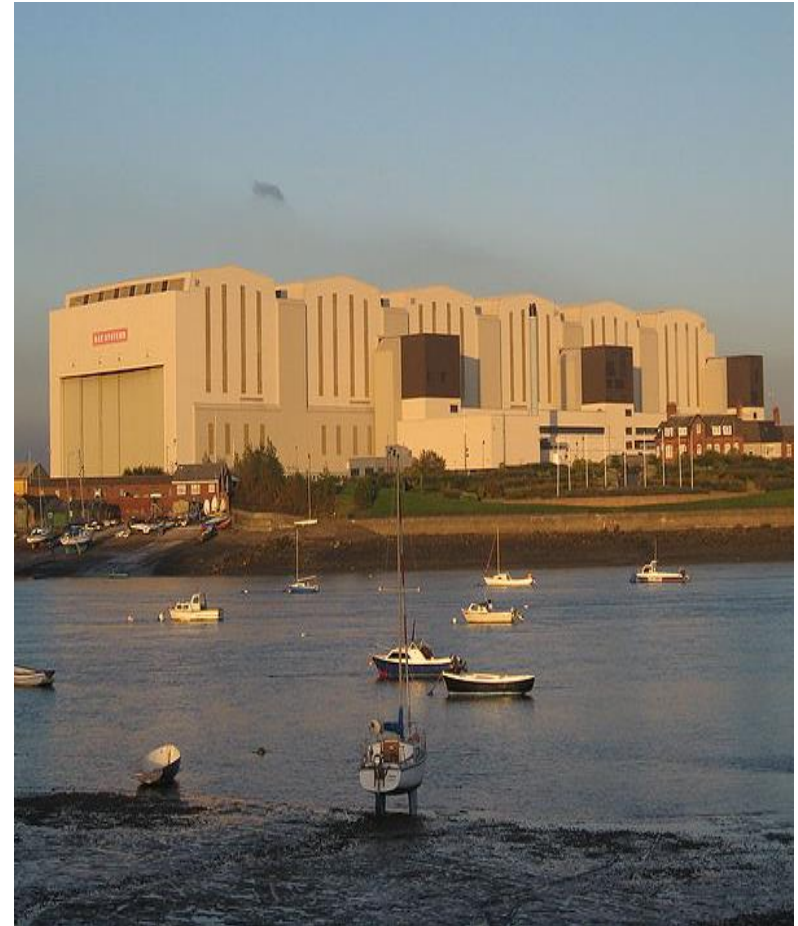
- Quantitative, data driven inspections
- Automation (robotics and data analysis)
- Probabilistic Risk-Based Inspection



stsgroupuk.co.uk

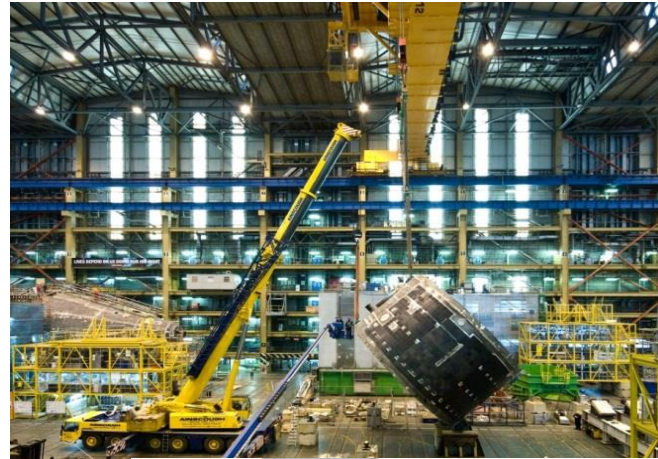
BAE Systems *Maritime*

- Naval Ships, Submarines, Maritime Services
- Design, fabrication and in-service support of surface vessels, submarines and combat systems
- ~15,000 employees



BAE Systems *Maritime*

- Shock-resistant structures and systems
- 100's of sailors on-board
- Welded together
- Submerged and PWR propulsion (submarines)



NDT at manufacture is a vital part of a vessels safety-case

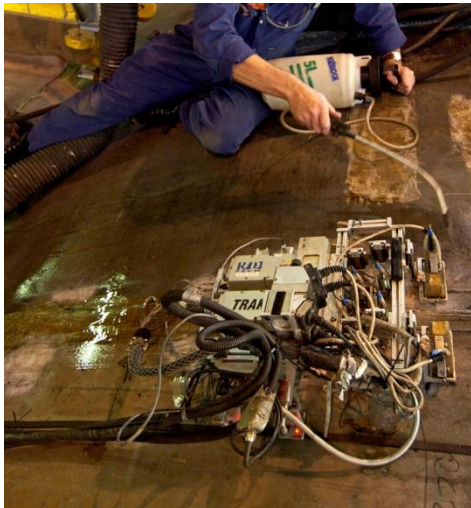
BAE Systems

The Benefit of Ultrasonic Imaging

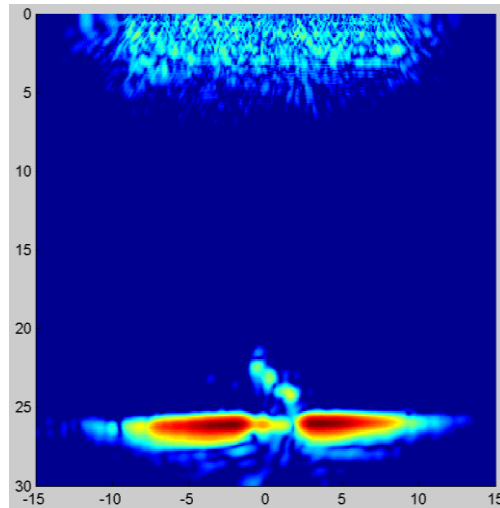
Ultrasonic and Radiographic Imaging are the main methods for sub-surface flaw detection in welded-joints

Ultrasonics is preferred:

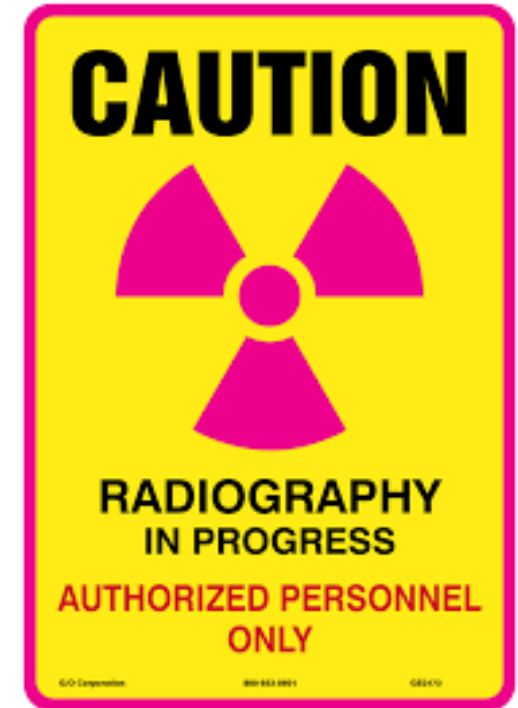
- Industrial radiography is heavily regulated
- Don't have to shut down production to perform



Ultrasonic scanner



Ultrasonic image of flaw



The Problem

Pipe-welds

On a typical vessel:

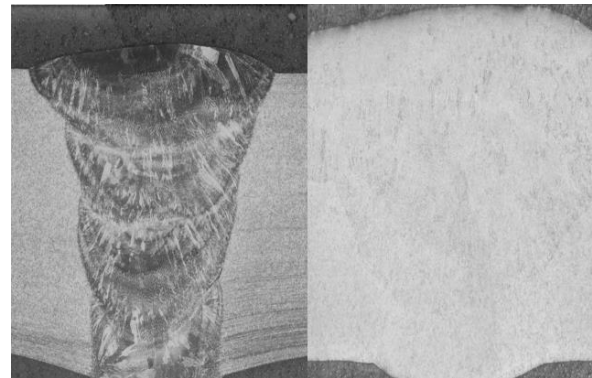
- ~100km of cabling and pipe-work
- ~10,000 welds that require NDT

Small-bore pipe-welds are difficult to inspect using ultrasound

- Geometry
- Material
- Spatial constraints – pipe spools, access to weld (bulk-heads, decks, fittings)



A pipe next to a pen



Micrographs of weld

MATLAB: Finding the Solution

Developing and Testing new Imaging Techniques

- End-users of NDT have a reliance on Commercial Off The Shelf equipment (COTS)
- No COTS equipment that meets requirements
- Innovations in ultrasonic imaging are slow to market in the NDT sector

BAE Systems partnered with University of Bristol and the RCNDE to develop and test new imaging techniques and algorithms for pipe welds

Requirements: Pipe Weld Ultrasonic Imaging

- Control, generation and acquisition of ultrasonic data
- Handle large sets of data (10-40GB)
- Real-time signal and image processing
- Rapid testing of new techniques
- Tools to support shop-floor deployment

MATLAB: Finding the Solution

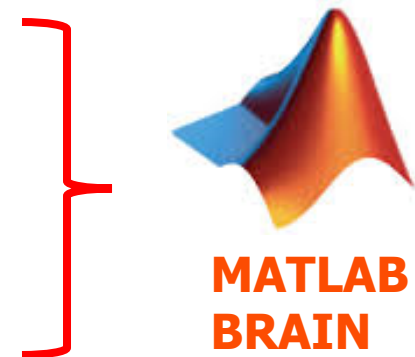
Developing and Testing new Imaging Techniques

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Outline

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- Industrial Benefit & Outlook

Ultrasonic Phased Arrays

Historical Background

- Sokolov (late 1920s) first use of ultrasound in NDE
- Dussik (late 1930s) first use of ultrasound in medicine
- Wild and Reid¹ (1952) first mechanical imaging in medicine
- Buschmann (1964) first array imaging in medicine
- Lemon and Posakony² (1980) first array imaging in NDE



Various contemporary NDE array systems

Ultrasonic Phased Arrays

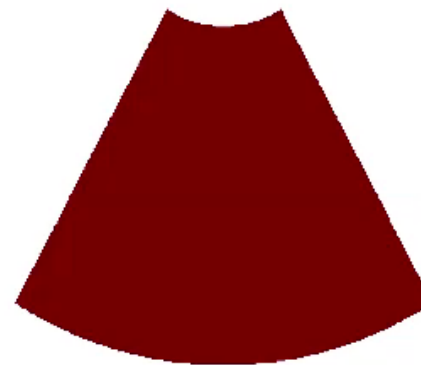
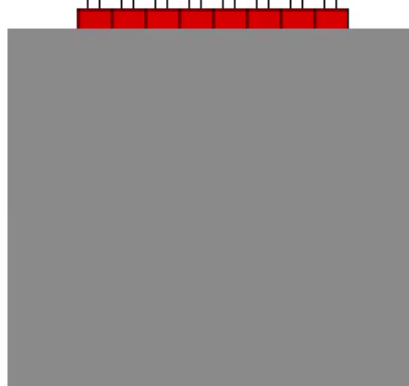
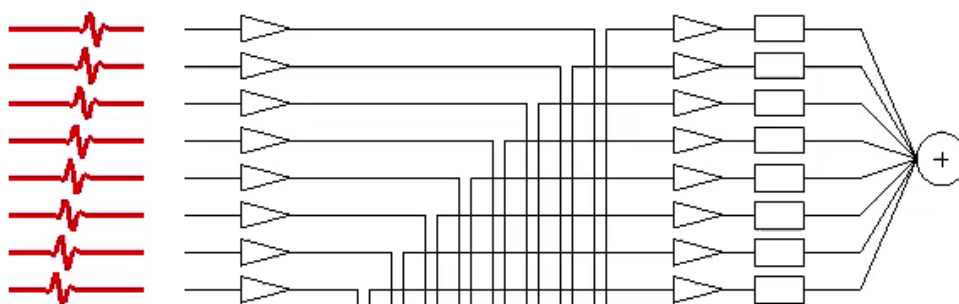
Classical B-scan

- Use like a radar or lens – Apply delays to focus at a point

Transmission

Delays

Reception



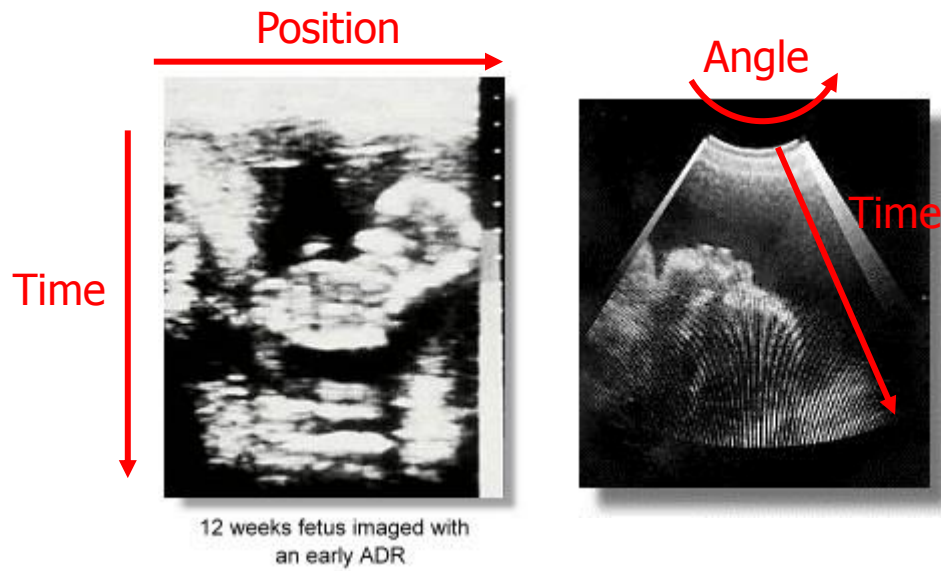
Output image

Ultrasonic Phased Arrays

Classical B-scan

- NDT simply applies these medical ideas
- Works well, very useful
- Not flexible
- Not playing to unique features of NDT – Stationary, few scatterers

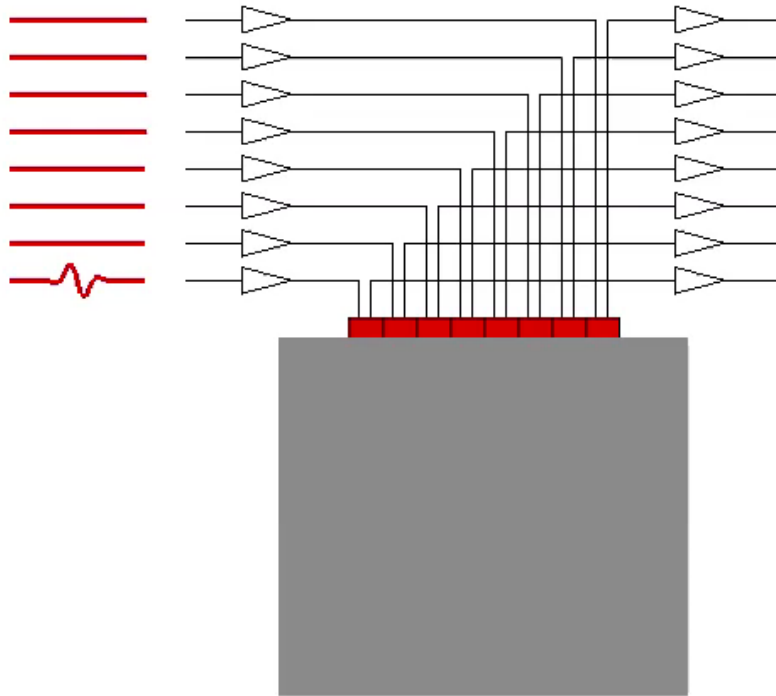
1975



How should we make measurements?

Full Matrix Capture (FMC)

Transmission



Reception

Output

- Fire elements individually
- Focus everywhere in post processing

Full Matrix Capture (FMC)

Why do it?

- Captures all possible data from array
- Allows operations not otherwise feasible (or even possible)
- Moves emphasis from hardware to software
- Improvements in technique can be applied retrospectively

Challenges

- Does not work on classical hardware
- Needs a new way of thinking

Our History

- Doing this since 2003 - Initially took hours to capture and process
- High impact papers
- Slow industrial uptake
- Led to desire to develop tools to take academic research into industry

What BRAIN is

BRAIN

- Software platform for array processing based on FMC
 - Demonstrations
 - Initial industrial trials
 - Development of new algorithms
 - Let end users try and develop approaches in a Graphical Environment
- Generic user interface; modular architecture
- Compiled and scripted versions

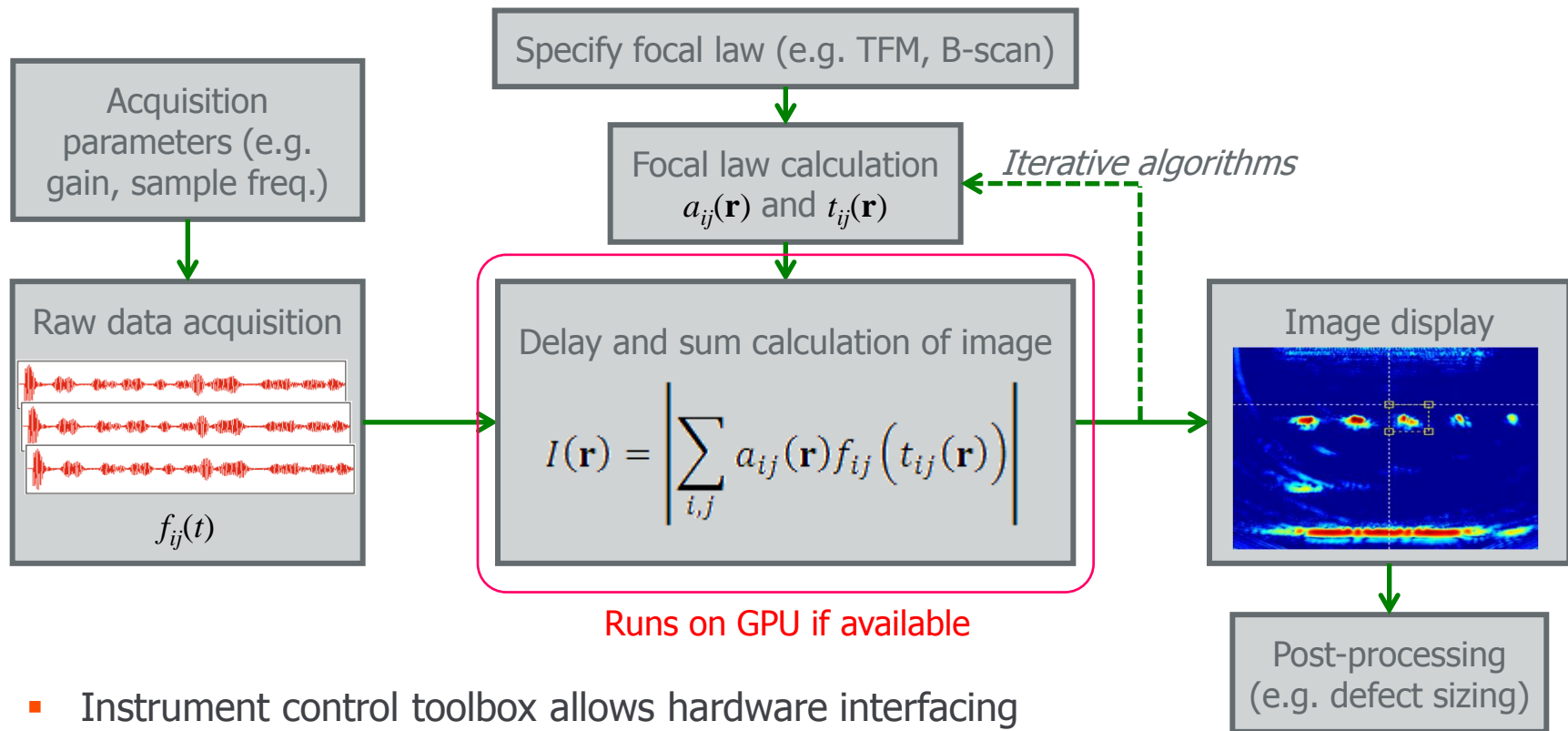
FREE!

Ideally suited to Matlab

- Extensive experience in group – Build on existing code base
- Allows testing of algorithms as scripts first
- Using the Matlab Runtime for compiled use
- Distributing files for scripted version

BRAIN

Structural Overview



- Instrument control toolbox allows hardware interfacing
- Good and useful
- However imaging is slow - GPU support is the final step

How we image

- Focus whole array at every image point in transmission and reception
- Close to theoretical image resolution (diffraction limit)

$$I(\mathbf{r}) = \sum_{i=1}^n \sum_{j=1}^n a_{ij}(\mathbf{r}) f_{ij}(\tau_{ij}(\mathbf{r}))$$

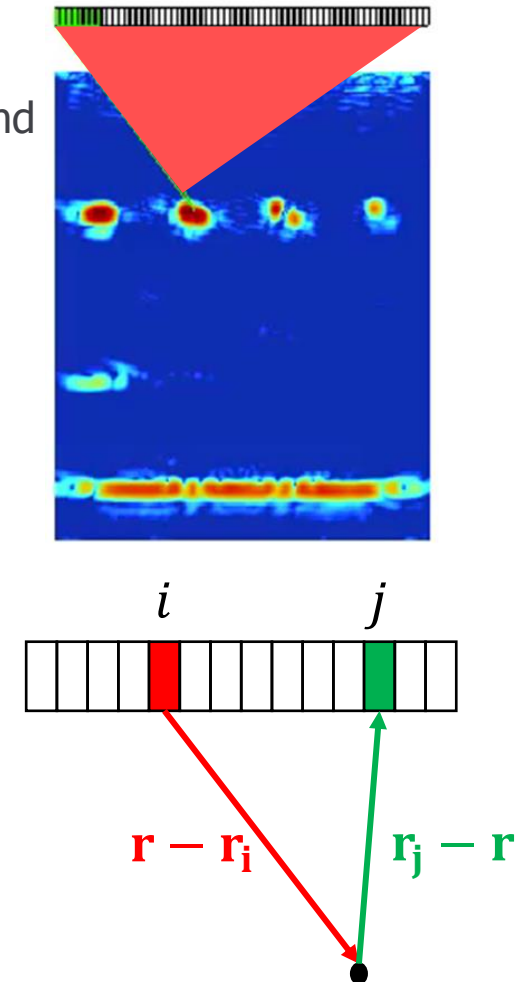
Parameters are:

$$a_{ij}(\mathbf{r}) = 1$$

$$\tau_{ij}(\mathbf{r}) = \frac{|\mathbf{r} - \mathbf{r}_i|}{c} + \frac{|\mathbf{r}_j - \mathbf{r}|}{c}$$

What this means

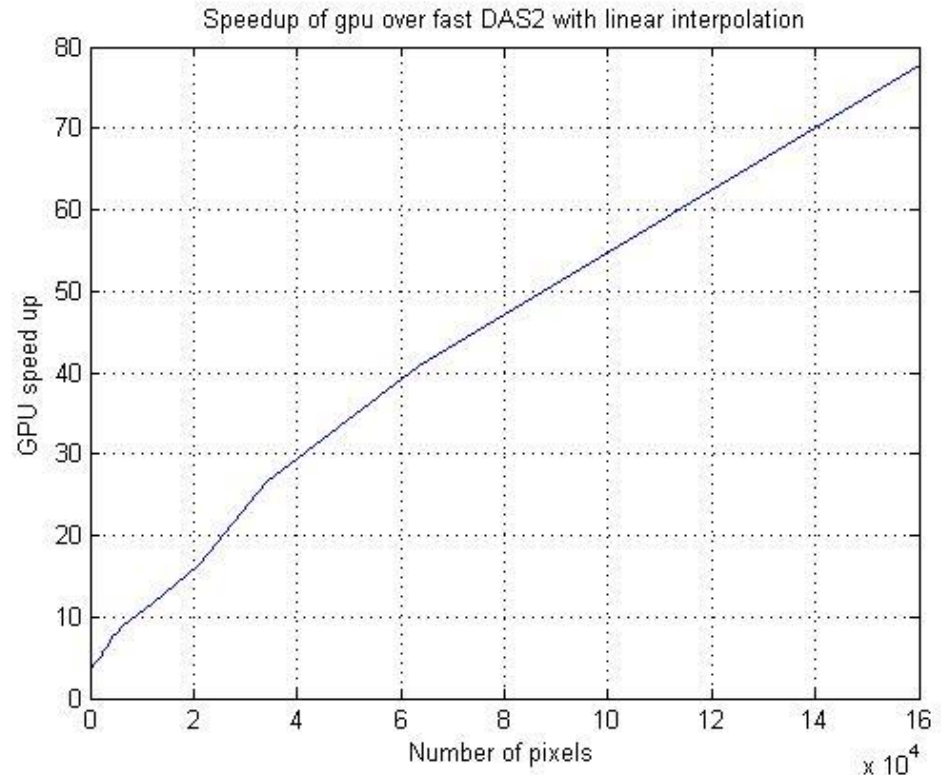
- Same operation carried out at each pixel - suited to parallelisation
- Many options in Matlab
- Written basic imaging CUDA kernel, good mix of low level code and direct access in Matlab



Imaging speedup

Comparison of GPU and CPU in Matlab

- Order of 100x speedup
- Easy and fast to implement in Matlab
- Lower overhead allows better imaging
 - High resolution
 - Interpolated images
- Makes industrial trials feasible
- Opens up new computationally complex imaging options



BRAIN approach

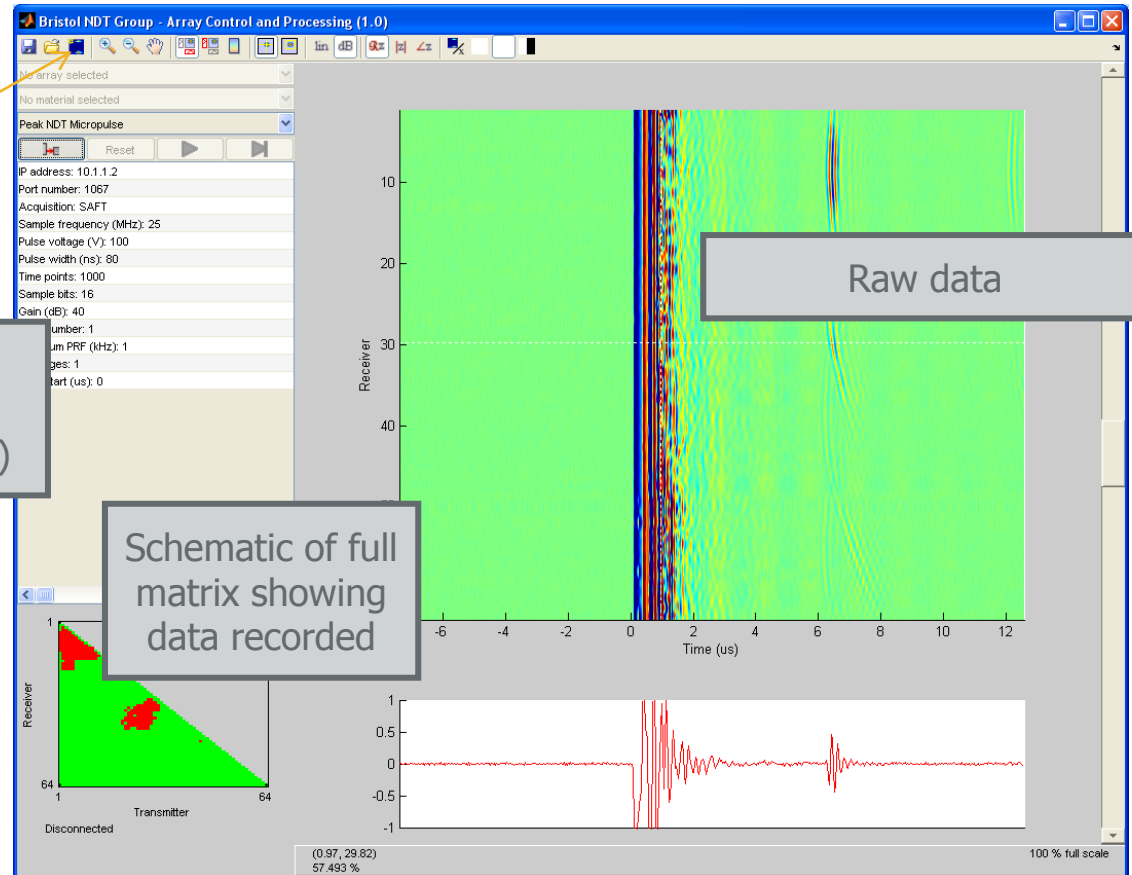
Data capture

Click here

Acquisition parameters (e.g. gain, sample freq.)

Schematic of full matrix showing data recorded

Raw data



Instrument control

- Allows many different acquisition approaches – FMC, HMC, SAFT, Hadamard
- Acquisition can be tested as scripts, dropped into BRAIN
- Single-shot or continuous operation
- Spawn Imaging windows

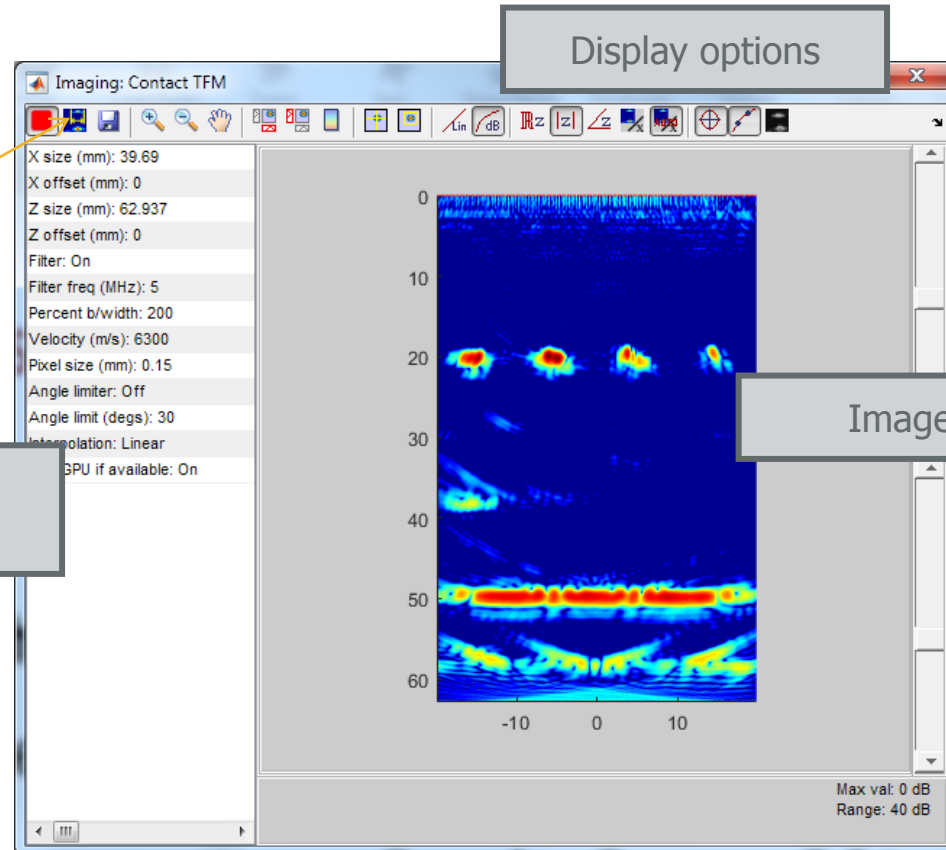
BRAIN approach *Imaging*

Click here

Imaging
parameters

Display options

Image output



Visualisation

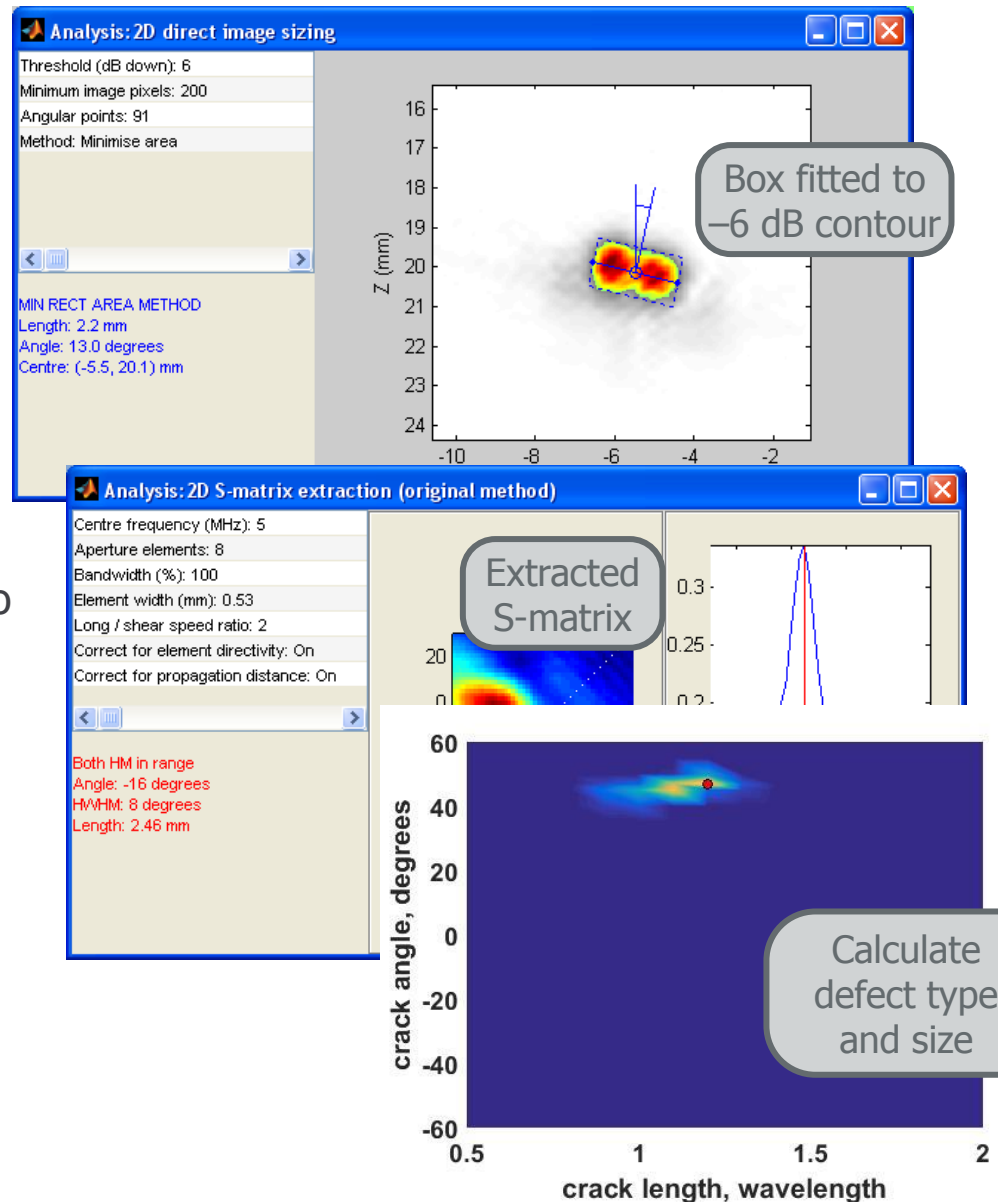
- Completely flexible, built from a standard Matlab script definition
- Many imaging approaches
 - Contact TFM, Contact B-scan, Contact Sector scan, Oblique incidence TFM, Immersion TFM through irregular interface, Contact TFM for composites
 - High computational load, runs fast
- Rapidly produce industrially testable solutions

BRAIN approach

Data processing

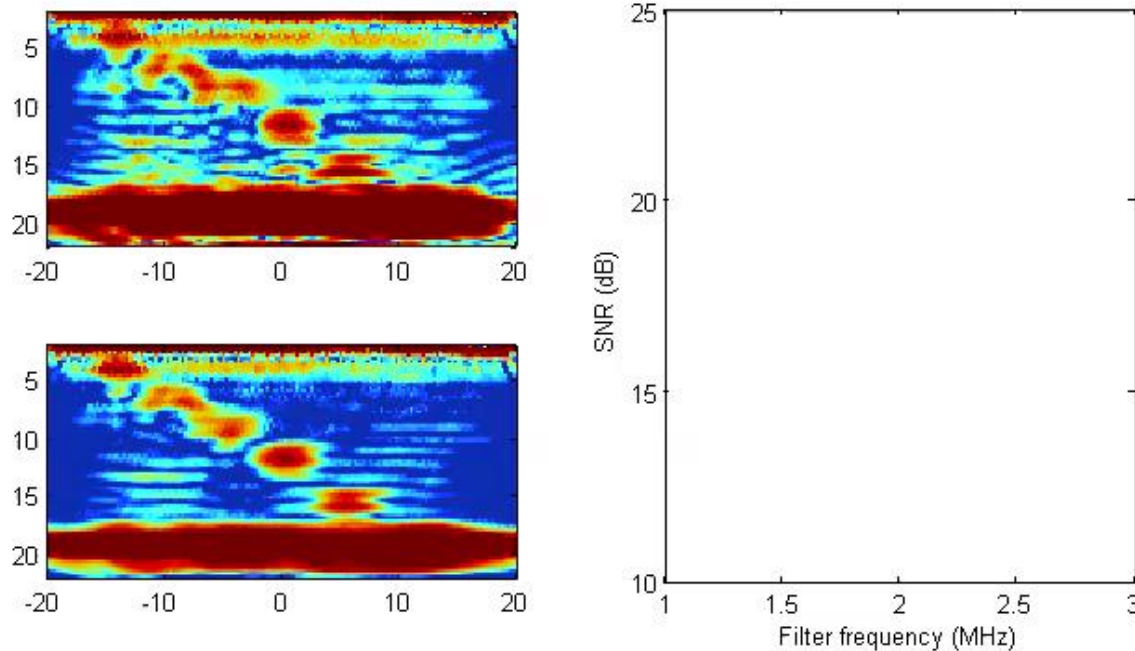
Characterise material and defects

- For industrial relevance this is the next step
- Not widely used
- Papers are good but OEMs want to try techniques
- Characterise defects
- Characterise material
- Low overhead to demonstrate and try these
- Used at multiple tech transfer events
- Carried out several site trials



BRAIN example

Anisotropic material – eg carbon fibre

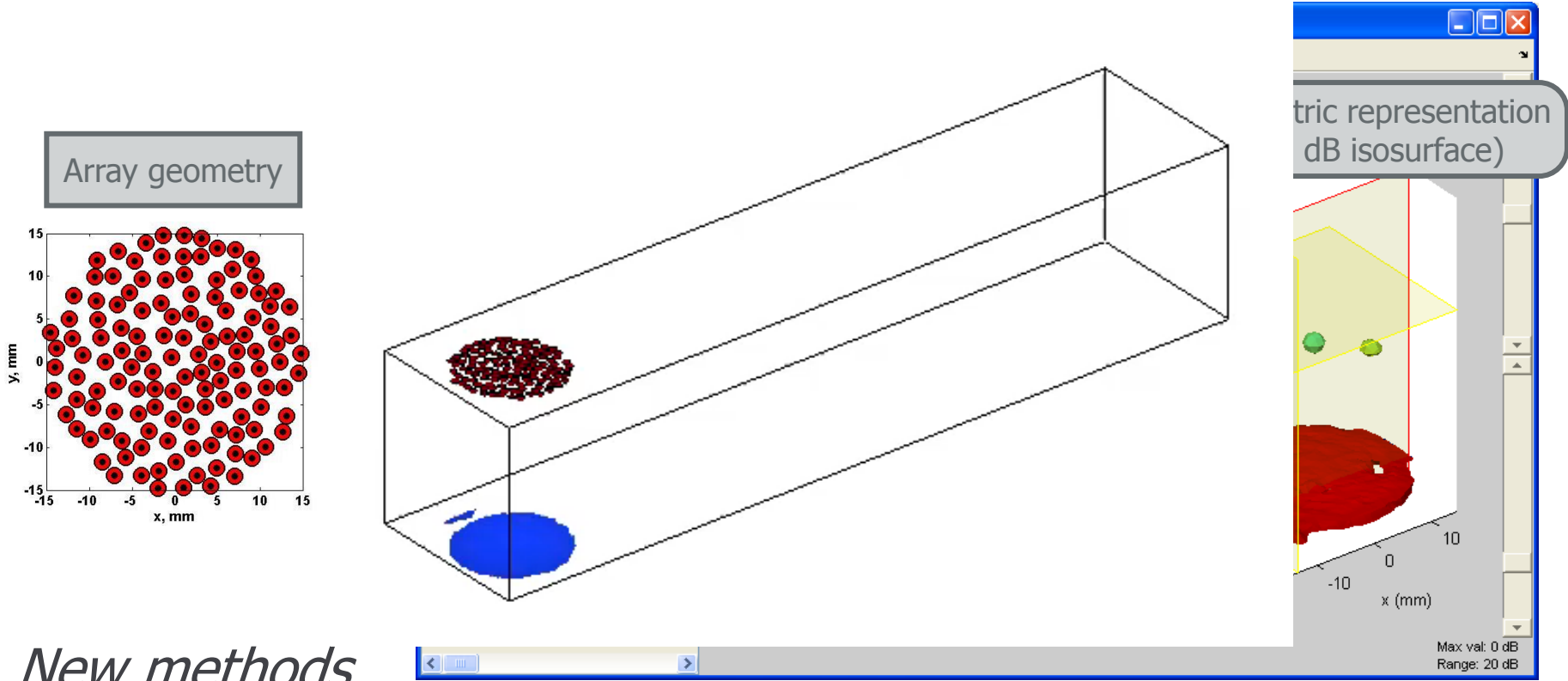


Difficulties

- High attenuation, Angular dependant velocity, Energy steering
- Partners want to try imaging in practise
- Scripts written then converted to BRAIN wrappers

BRAIN example

3D imaging with 2D array

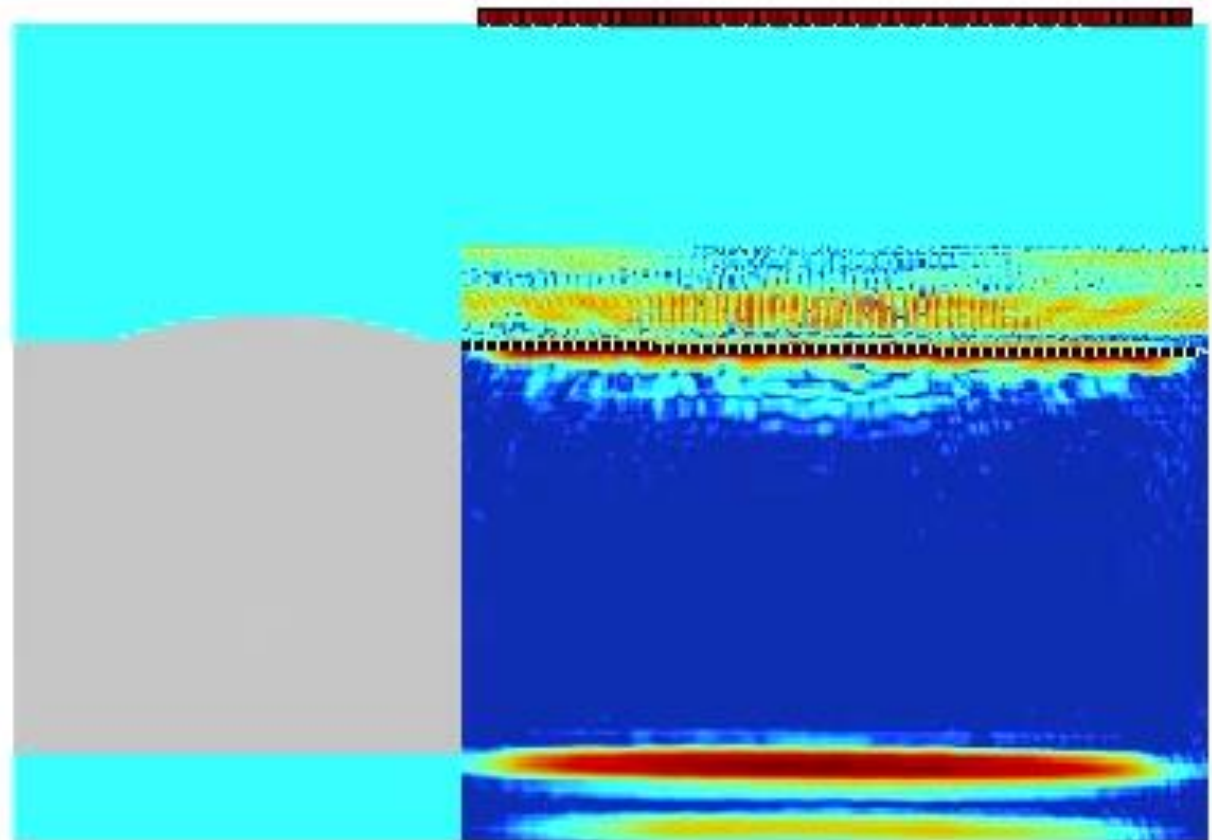


New methods

- Get shape information
- Lots of data and computationally heavy

BRAIN example

Immersion imaging



Difficulties

- Computationally heavy, not previously tractable

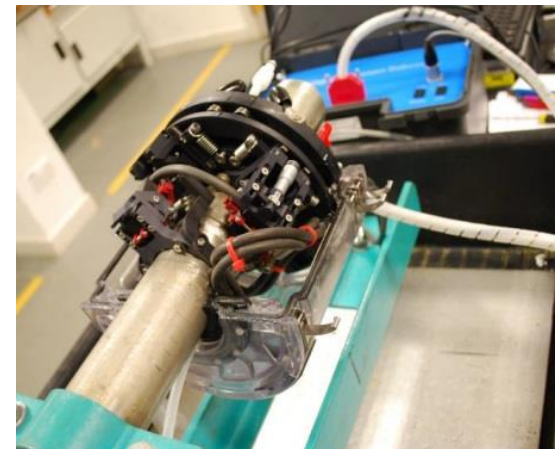
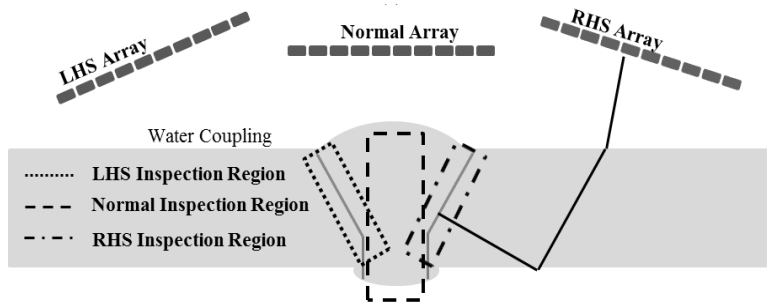
Outline

- The Engineering Need for Ultrasound
- BRAIN: Development & Implementation
- **Industrial Benefit & Outlook**

Benefits

Pipe Welds

- Immersion inspection, 3 arrays scan around weld

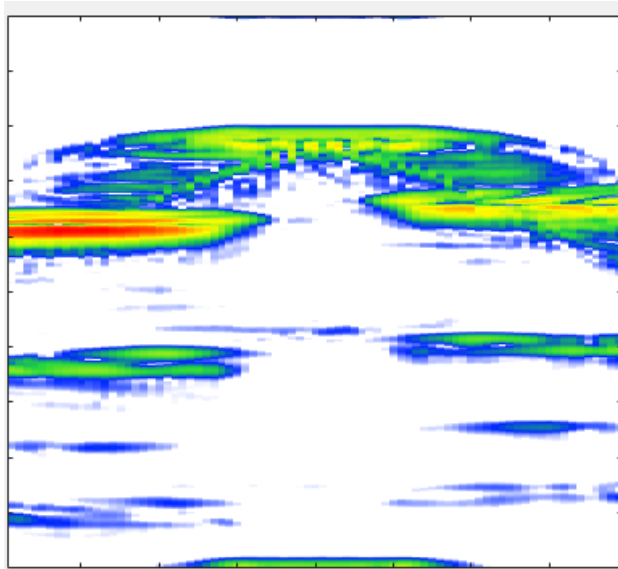
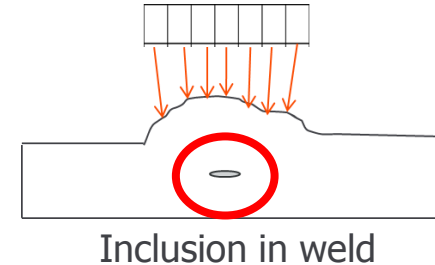


- MATLAB and BRAIN have enabled rapid development and testing of imaging techniques for new inspection methodologies
- High level language - effort is spent understanding the problem

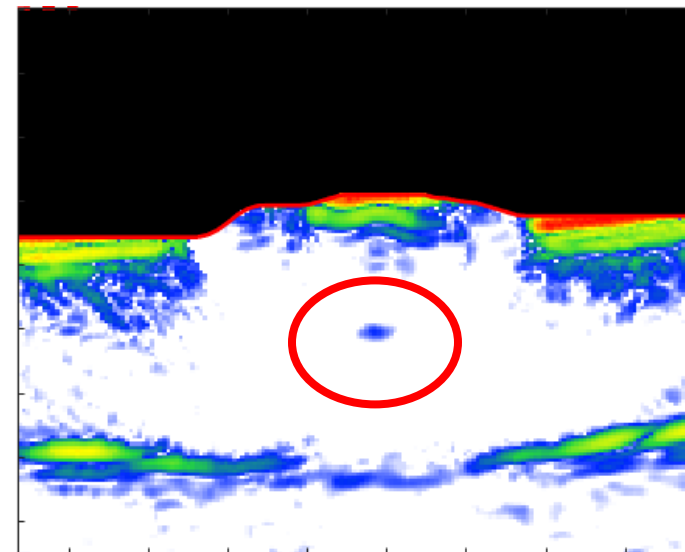
Benefits

Novel capability

- Through weld-cap adaptive imaging of thin-walled pipes
- Key enabler for ultrasound to replace radiography



"Conventional" imaging capability



Adaptive imaging with BRAIN and MATLAB

Benefits

Inspection Speed

- Ultrasonic imaging reduces time NDT inspectors are required on shop-floor – NDT is less disruptive to build activities
- MATLAB GPU support enables practical ultrasonic imaging of pipe-welds practical on a typical desktop workstation

Inspection time (hours)

Process	Radiography	Ultrasonic Imaging (No GPU)	Ultrasonic Imaging (GPU)
Set-up	3	0.5	0.5
Data Collection	1	0.5	0.5
Imaging and Analysis	1	12	1
Time on Shop-Floor	4	1	1
Time in office	1	12	1

Outlook

Future Plans

Capability has been developed and demonstrated in the lab

Goal is for the technology to be a day-to-day operational activity

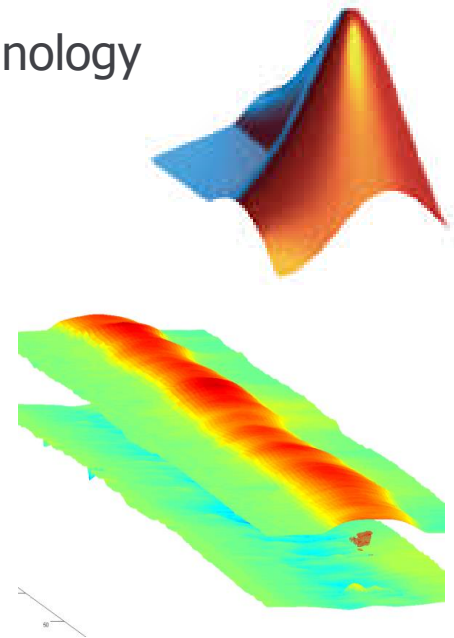
- Validation
- Qualification
 - Regulator and customer approval to use the technology
- “Productionisation” - shop-floor ready
 - Mechanical system development
 - Inspector training and in-house certification
 - Integration with other business processes

Developing Image Processing Techniques

Analysis of the ultrasonic images

Automatic sentencing of images (accept/reject weld)

Explore AI opportunities



Summary