Activity 2: Direct Condition Assessment Methods

Activity Co-leaders: A/Prof. Jaime Valls Miro, Prof. Gamini Dissanayake
UTS

Scope: Innovative Methods for Automatic Interpretation of Data Gathered from Existing Sensors

Key Expected Outcomes:

1. Algorithms for improved interpretation of data gathered from 4 direct condition assessment techniques:
    - (external) MFL
    - (external) BEM
    - (in-line) RFT
    - (in-line) Acoustics

2. Guidelines of relative merits of the technologies evaluated for inspection under common application scenarios

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Activity 2 – UTS Team

Academics (x5):

- Prof Gamini Dissanayake (Co-activity leader)
- A/Prof Jaime Valls Miro (Co-activity leader)
- A/Prof Sarath Kodagoda (Sensor modelling, MFL)
- Dr Alen Alempijevic (Sensor modelling, BEM)
- Dr Teresa Vidal Calleja (Data interpretation, machine learning, estimation theory)

Fully dedicated (funded from project) personnel (x6):

- Buddhi Wijerathna (PhD candidate)
  - Magnetic Flux Leakage modelling (AIA)
- Nalika Ulapane (PhD candidate)
  - Broadband Electromagnetics modelling (RSG)
- Daoblige Su (PhD candidate)
  - Acoustics modelling and localization (Pure/Aqua Environmental)
- Raphael Guenot (PhD candidate)
  - Remote Field Technology modelling and localization (Russell NDE/PICA)

Note:

Buddhi Wijerathna and Nalika Ulapane have been appointed Research Associates for ~1 day/week from March 2015 to stand in for the two people leaving UTS team, at least temporarily.

Engagement with Technology Providers

- Rock Solid Group* (BEM)
- Asset Integrity Australia* (Advanced Engineering Solutions Ltd) (MFL)
- Russell NDT Technologies/PICA (RFT SeeSnake)
- Pure Technologies Ltd* (Acoustic Sahara@PWA)

* Australian partners

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Presentation Outline

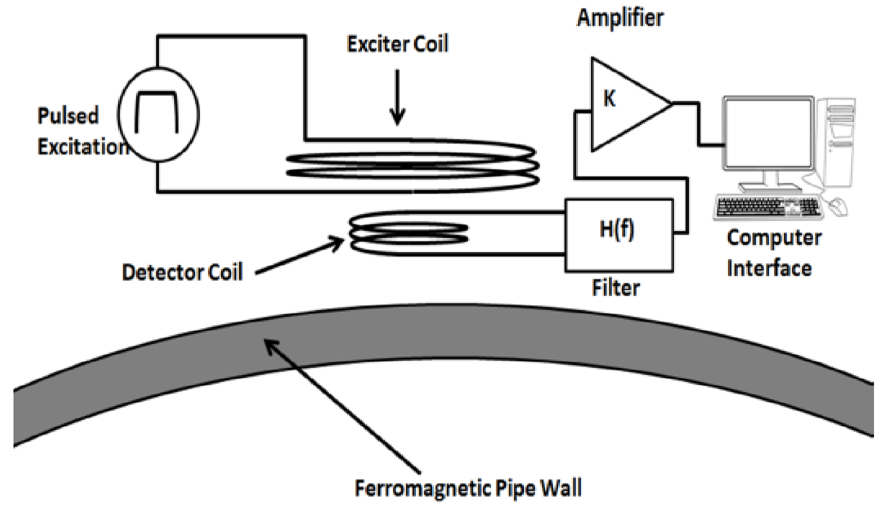
1. Latest research **progress** since last TAC
   - Rock Solid Group (BEM)
   - Asset Integrity Australia (Advanced Engineering Solutions Ltd) (MFL)
   - Russell NDT Technologies/PICA (RFT SeeSnake)

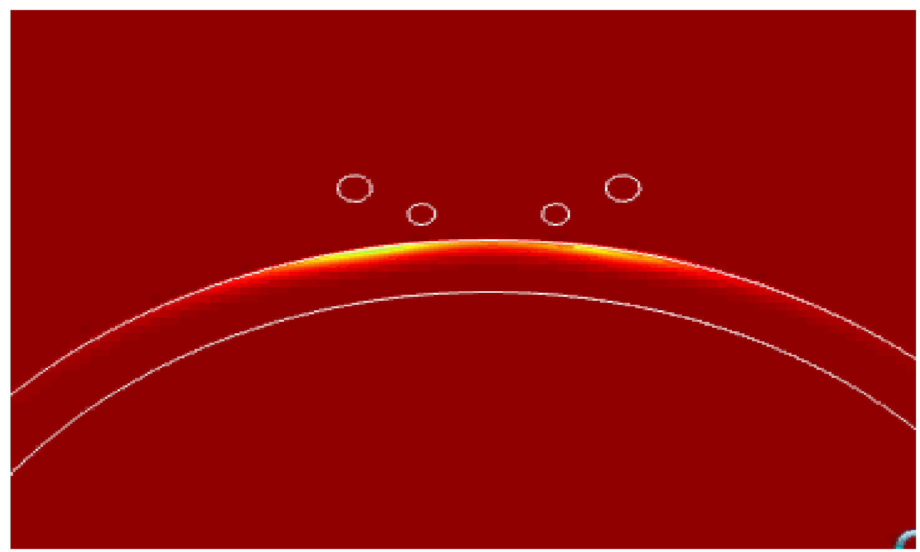
2. What have we learned **so far** about capabilities and limitations of MFL, BEM, RFT and Acoustic PWA

RSG (BEM): State of Affairs and Current Progress

Broadband Electro-Magnetics (BEM): Brief Technical Description

- A BEM probe consists of two electromagnetically coupled coils (exciter and detector)
- The exciter coil is excited by a voltage pulse; Eddy currents are induced in the pipe
- The detector coil captures the resulting magnetic field
- This field contains information about the geometry and electromagnetic properties of the pipe





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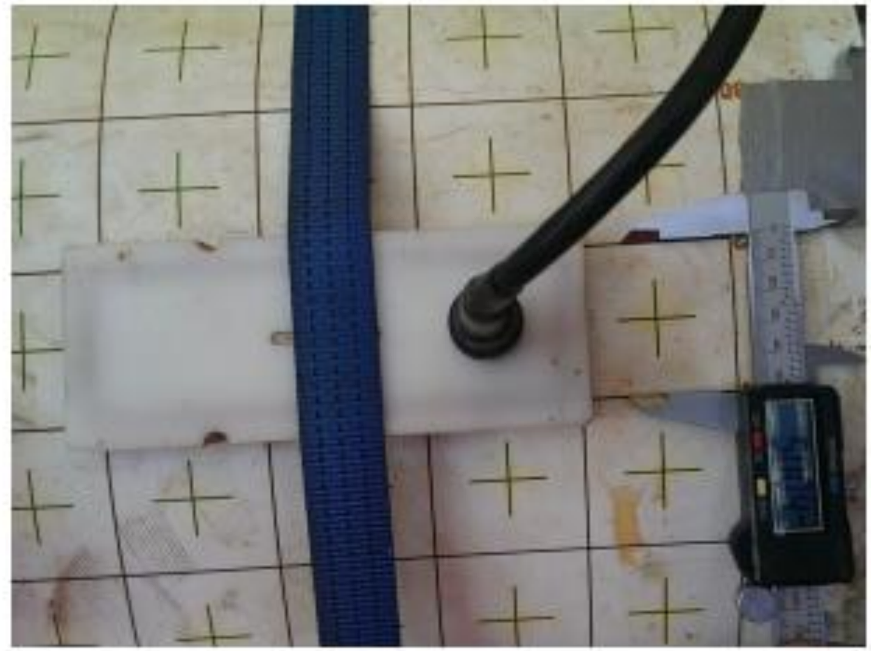
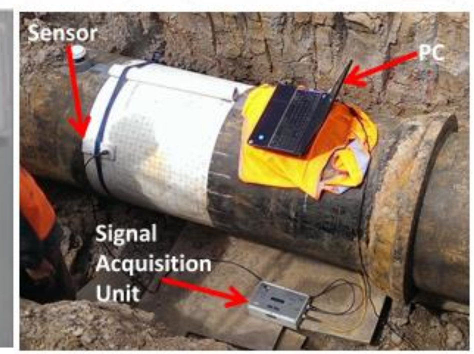
Broadband Electro-Magnetics (BEM): Brief Technical Description (cont.)

- The BEM coils need to be sufficiently large to energise the material in order to detect thickness of Critical Mains
- This is not a point measurement, rather a domain measurement
- Eddy currents detected belong to the energised **volume** of material beneath the sensor, it is a measure of **averages**
- Regular grid used to place sensor





Summary Current State of Affairs

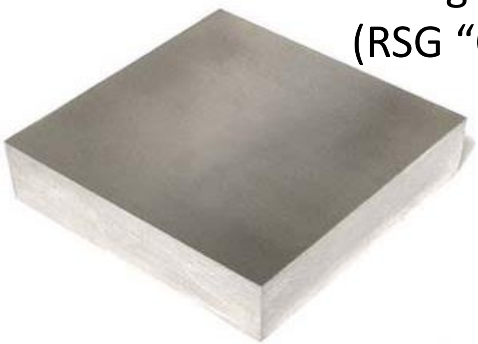
1. UTS has delivered preliminary software for enhanced estimation of thickness from BEM data from their Single Sensor Antenna design
   - Readily available for use by Technology Provider
   - Added estimate of uncertainty
   - In accordance with desired project outcomes

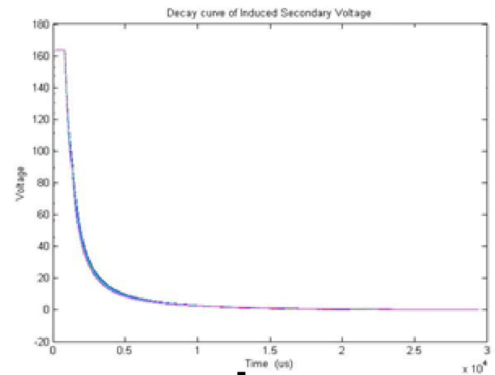
2. Software performs estimation of thickness on-the-spot
   - 16ms per measurement, including obtaining measurements from HSK Kit (~14.4s)

3. A further revision to this approach using more discriminative features from the BEM raw data provides more accurate estimates

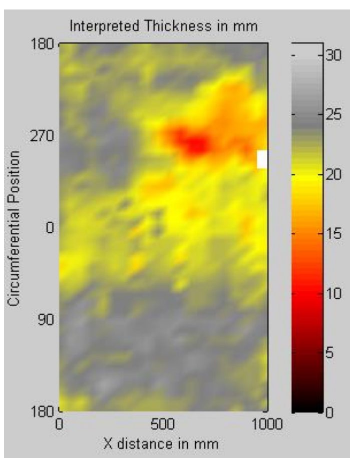
UTS Development: BEM Data Interpretation Model based on Calibration Blocks

Obtain generic calibration data (RSG "Calibration Blocks")





Pipe profile



Data Interpretation Mode (Analytical or Probabilistic)

Testing data from pipe

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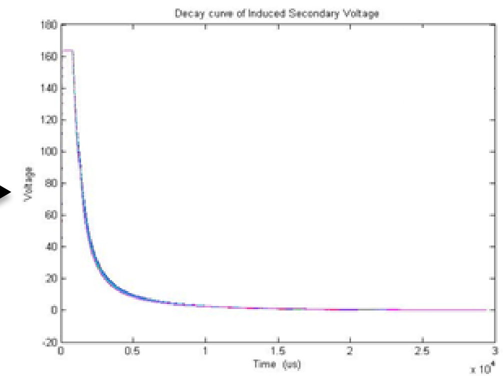
UTS Development: BEM Data Interpretation Model based on Numerical Simulations

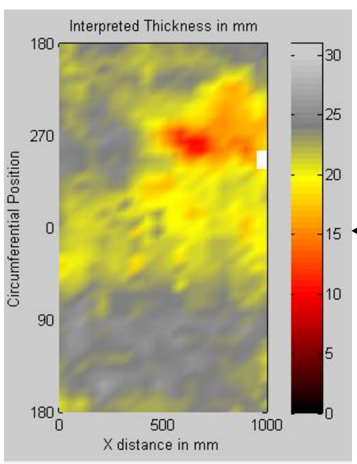
To account for possible effects from variations in material properties

Obtain electromagnetic properties of pipe material

Numerical simulation of BEM tool = generate curves specific to pipe of interest



Pipe profile



Data Interpretation Mode (Analytical or Probabilistic)

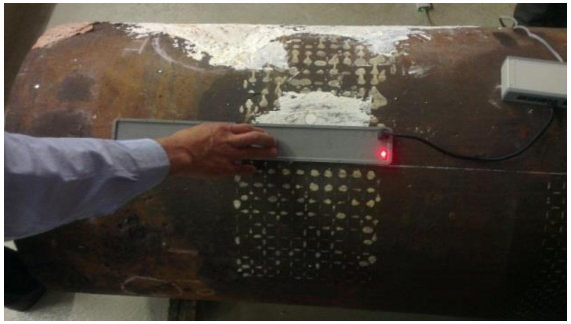
Testing data from pipe

Latest Progress

1. Further validation of data interpretation models developed by UTS with data from Trial 5 and Perth trial (350 mm CI Pipes)

2. Driving towards extracting electrical and magnetic properties of pipe materials to enable more accurate numerical simulations and data interpretation
   - Coupons extracted from test bed and pipes from Perth trial and sent to University of Wollongong for laboratory testing
   - XRF training done (XRF is a nondestructive testing device used to identify composition of materials, i.e. pipe materials)

3. RSG visited UTS on 12/06/2015 and experimented their newly developed multi-sensor array partly on the basis of outcomes from this research collaboration. Development in early stages. RSG are keen on obtaining support from UTS to model the new sensor architecture



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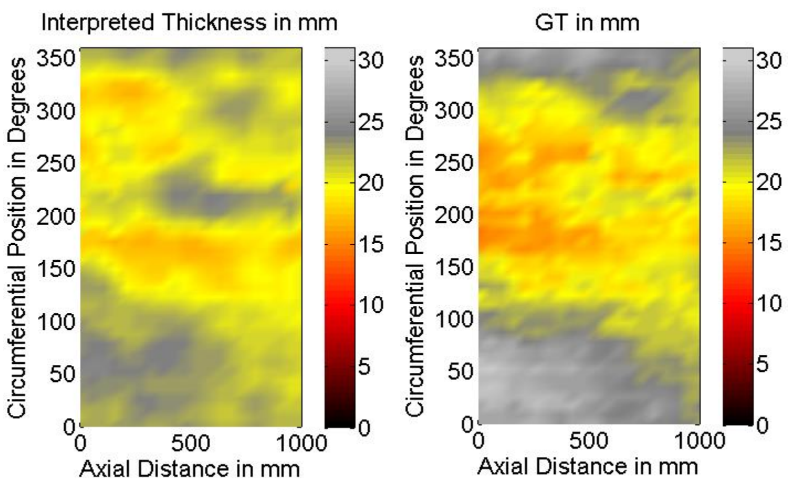
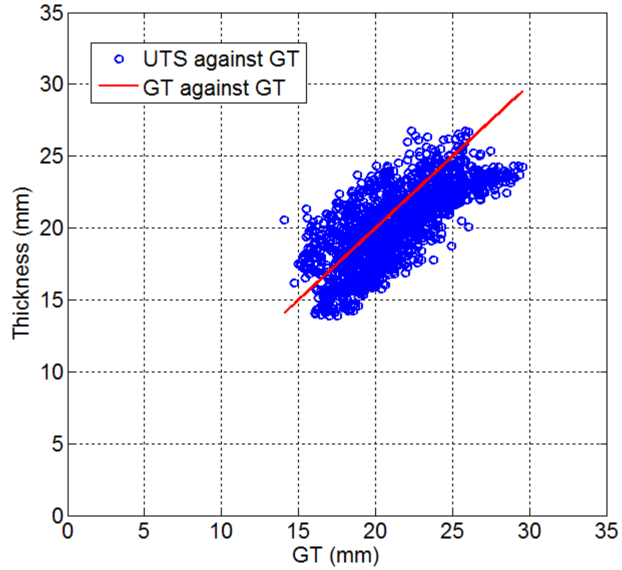
Analysis from Trial 5 (Anomaly 1)

Statistical Parameter	Value
Root Mean Square	2.4369 mm
Mean Absolute Error	2.0256 mm
Standard Deviation	1.3553 mm
Maximum Error	7.2712 mm
Percentage Accuracy	90.0705%

A Sample Pipe Section



Comparison for whole of Anomaly 1



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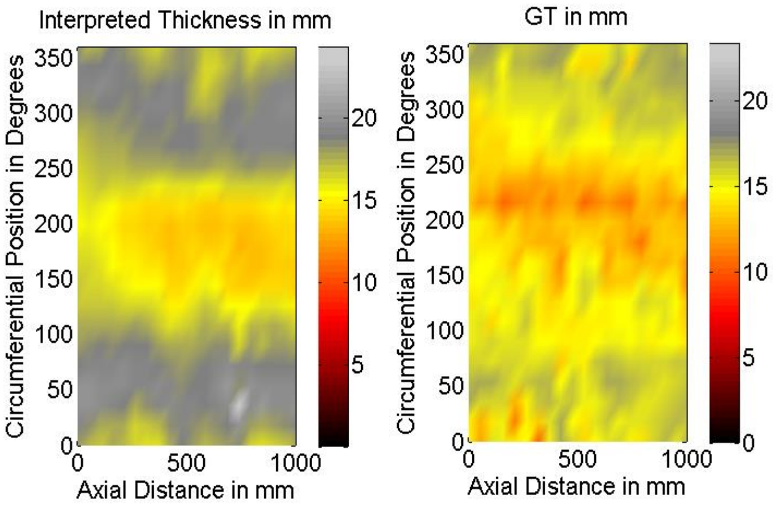
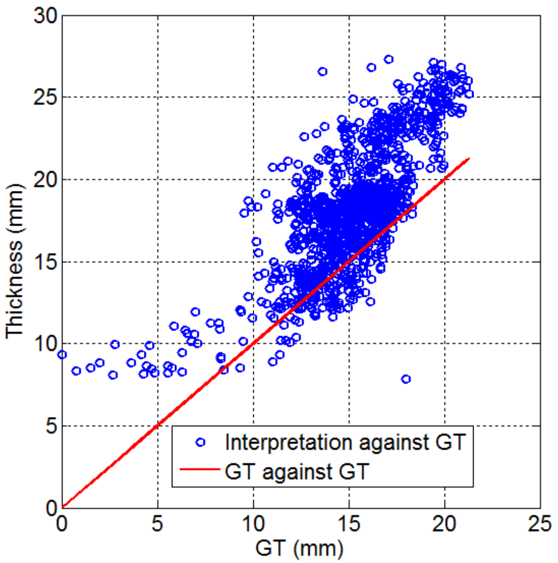
Analysis from Perth Trial

Statistical Parameter	Value
Root Mean Square	3.8905 mm
Mean Absolute Error	3.2041 mm
Standard Deviation	2.2078 mm
Maximum Error	9.7405 mm
Percentage Accuracy	78.0463 %

A Sample Pipe Section



Comparison of all the 350 mm CI Pipes



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On-going Work

- Coupons have been extracted from different locations of the test bed segments and from pipes from Perth

- Coupons have been sent to UoW for measuring electrical and magnetic properties using a Quantum Design Physical Property Measurement System (PPMS-9T)

- Currently awaiting specimen preparation and laboratory testing to be performed to carry on further analysis

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Latest Findings

- UTS interpretations for both (Trial 5 and Perth trial) were done using simulations based on material properties extracted from the Sydney Water test bed (660 mm CI pipe)
- The overall percentage accuracy for the Perth trial (350 mm CI Pipes) was observed to drop to 78% in contrast to 90% for Trial 5 (from test bed)
- We hypothesize this to be attributed to variation of material properties of the 350mm Cast Iron pipes from Perth from those of the test bed. Steps have been undertaken to confirm this, we are currently awaiting analysis of coupons from UoW
- Parallel XRF analysis as a more straightforward, proxy field test for material property analysis, will be done on all Trial pipes after completion of scheduled (final) Trial 6

BEM: Current Progress and Future Goals

Goal	Status
Developing a preliminary BEM data interpretation software package usable to RSG	Completed Beta version delivered to RSG
Developing more advance GP models using more discriminative features	Completed
Developing analytical model to infer pipe wall thickness (for Grey Cast Iron, Ductile Iron and Mild Steel), tested on calibration data from RSG	Completed
Numerically simulating the BEM Antenna interacting with pipe materials by using realistic material properties	Completed
RSG interpretation vs. Ground truth comparison (Trial 2,3,4,5)	Completed
UTS interpretations vs. Ground truth comparison (Trial 2,3,4,5 & Perth)	Completed
Capturing variations in material properties and developing an advanced “Simulation + GP” based model to infer pipe wall thickness	In progress
Studying the effect of lift-off on the BEM antenna to evaluate the capability of scanning through cement lining	In progress
Liaison with RSG to validate and advance the multi single antennae sensor for field deployment	In progress
Developing BEM laboratory setup	On-going, operational “as is” for lab analysis

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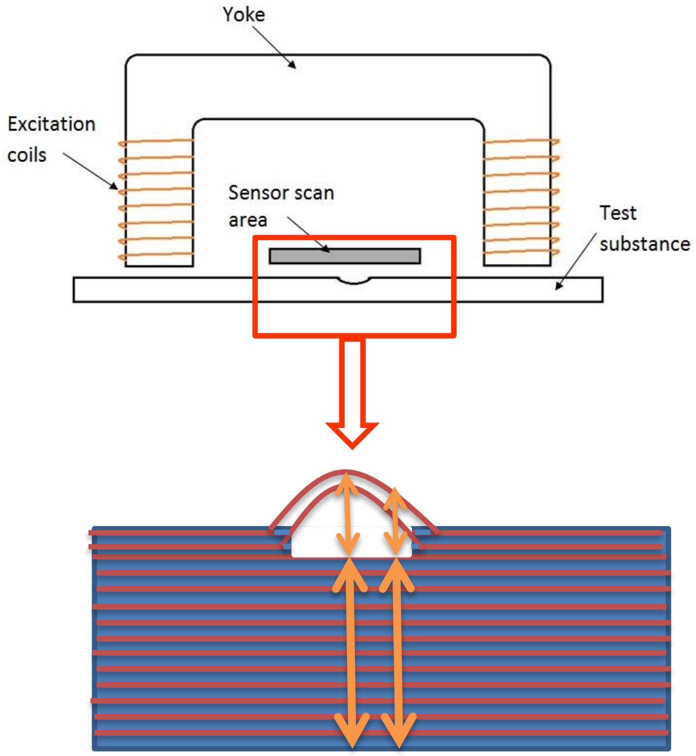
MFL (AIA): State of Affairs and Current Progress

Magnetic Flux Leakage (MFL): Brief Technical Description

- Saturate the pipe material with a strong magnetic field
- Flux tends to leak out with cracks/defects
- Magnitude of the leakage flux is used to estimate the remaining wall thickness at defects
- Therefore, the state of the art MFL technologies provide measles plots (not 3 dimensional reconstruction)



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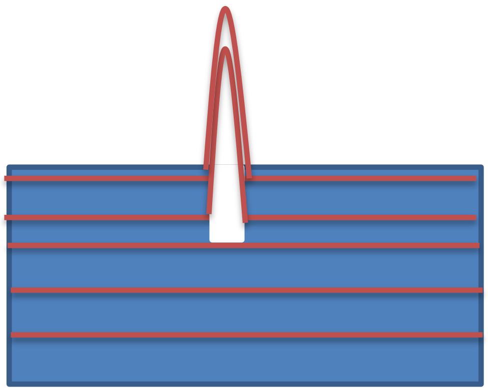
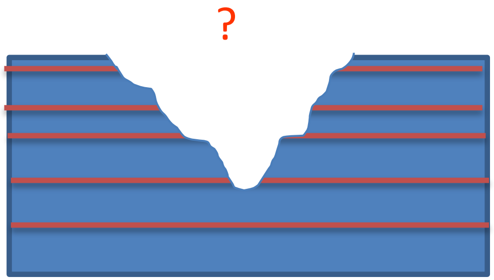
Magnetic Flux Leakage (MFL): Challenges

- MFL signal is affected by (not exhaustive)
  - Variations in the air gap - needs to be kept constant
  - Variations in the pipe materials (inhomogeneous)
  - Variations in pipe thickness - in manufacturing
  - Shape of the defects - cylindrical, conical etc.
  - Distribution of the defects



- Combination of above and possibly others can contribute to prediction errors



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Summary Current State of Affairs

1. UTS has delivered a preliminary software module for enhanced estimation of thickness profiles from AIA/AESL 'SmartCAT' data
   - Released to technology provider (AIA)
   - Added estimate of uncertainty
   - Proved increased accuracy

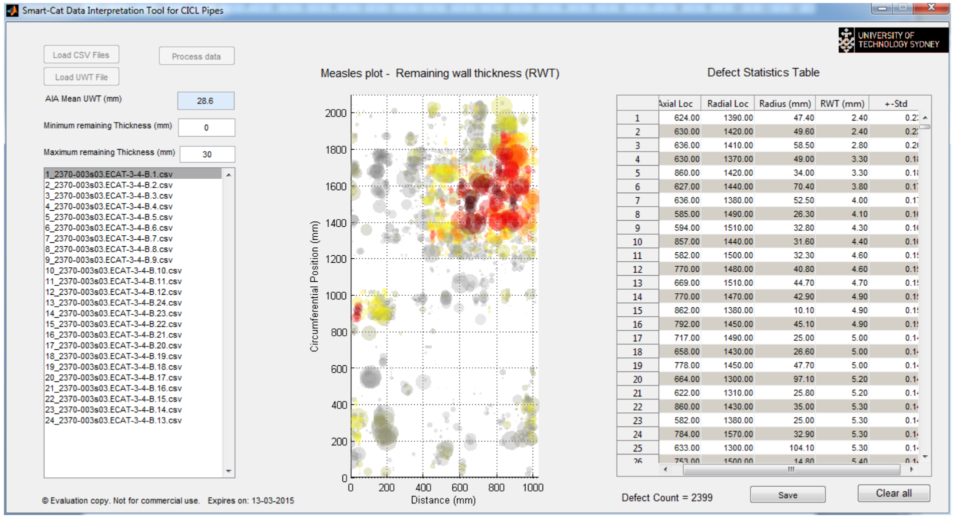
2. UTS has compiled a comprehensive document illustrating the accuracy of AIA/AESL predictions and UTS predictions on the test-bed trial inspections
   - Sent to AIA
   - Limited comments from AESL, vague

UTS Development: Deliverable of Software Package

- The first version of the UTS data interpreter ‘*MFL_Data_Interpreter_v1.exe*’ was delivered to AIA/AESL on 17/03/2014 and received feedback on 03/06/2014 It was only designed for CI, 30mm thickness pipes

- The software was generalized to interpret data from different pipe thicknesses

- A new version of the algorithm and software to incorporate AIA ultrasound measurements as a-priory knowledge of average wall thickness. Tests and analysis in progress



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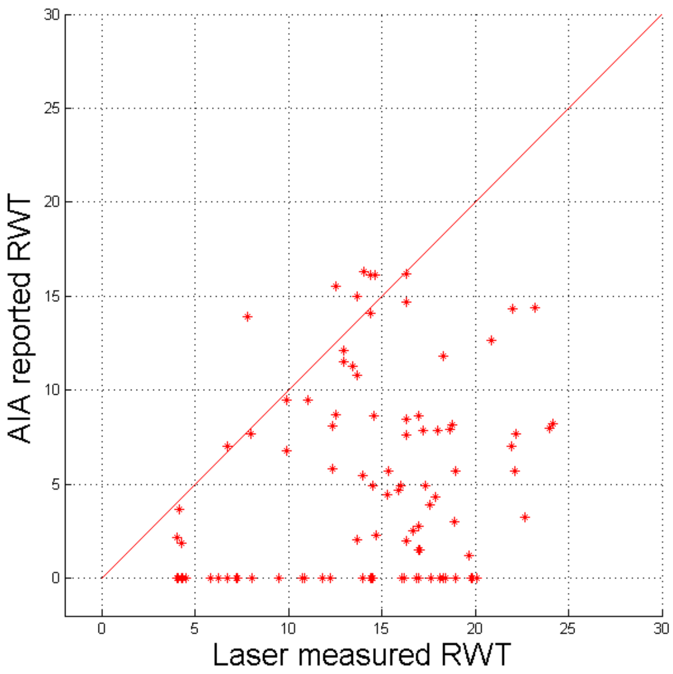
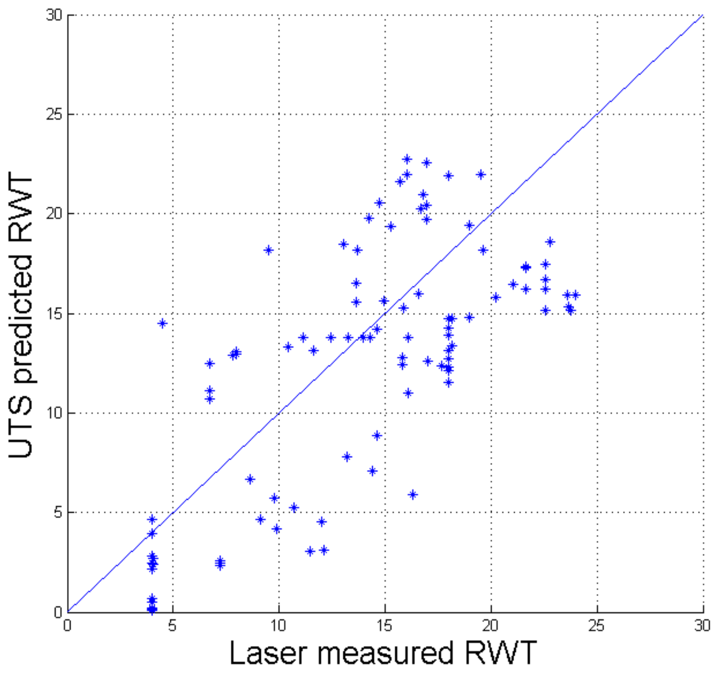
UTS Development: Overall Error Analysis from All Test-bed Trials



AIA vs. laser (GT) RWT
AIA Results RMS error : **11.20mm**



UTS vs. laser (GT) RWT
UTS Results RMS error : **4.79mm**

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Latest Progress

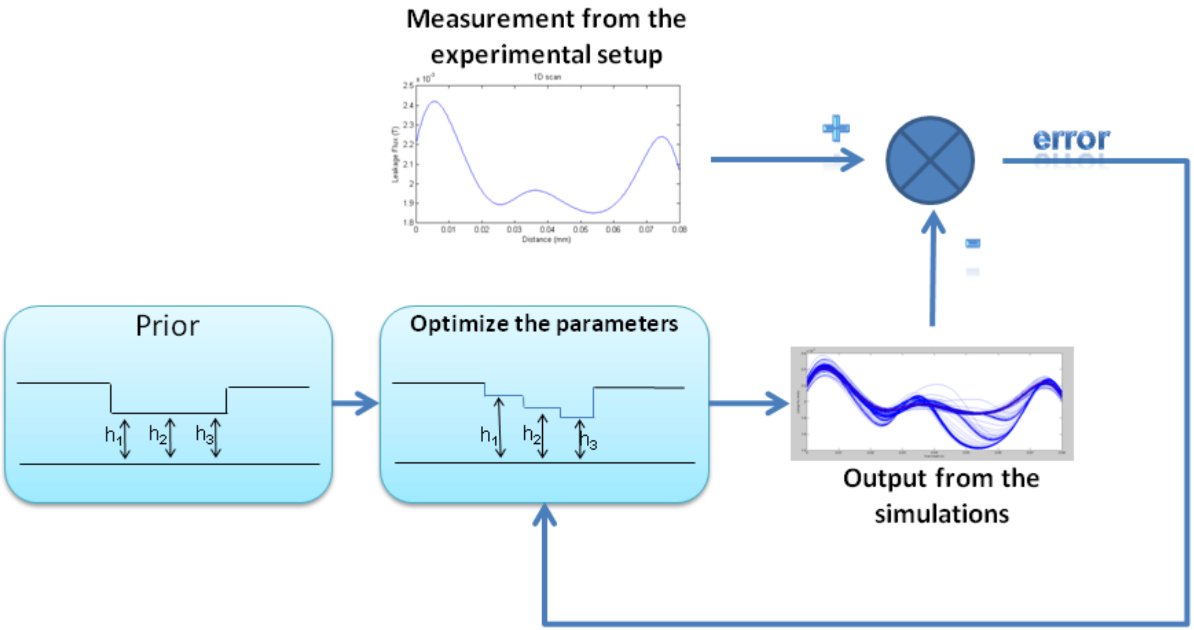
1. Investigate a close-to-optimal FEA sensor model through global optimisation methods

    - Complements current GP proposition for higher accuracy

2. Study suitability of ellipsoidal approximation from raw data on the basis of current learnings from relevant stress analysis (Monash)

Iterative Coarse to Fine Approach

- Investigated a close-to-optimal FEA sensor model through global optimisation methods
- It complements current GP proposition for higher accuracy
- The initial results are convincing yet computationally intensive



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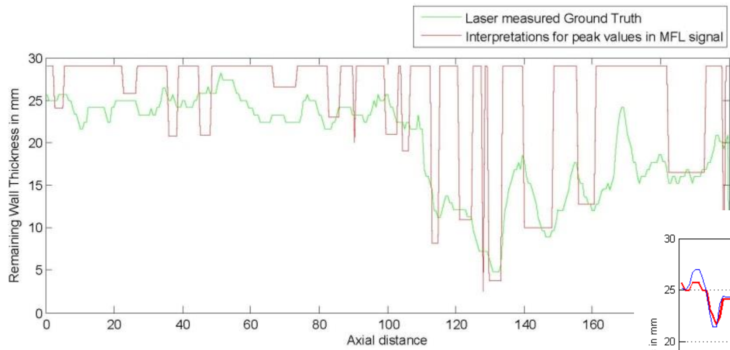
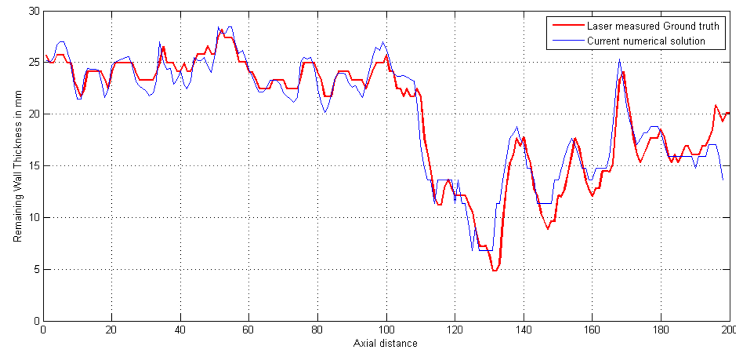
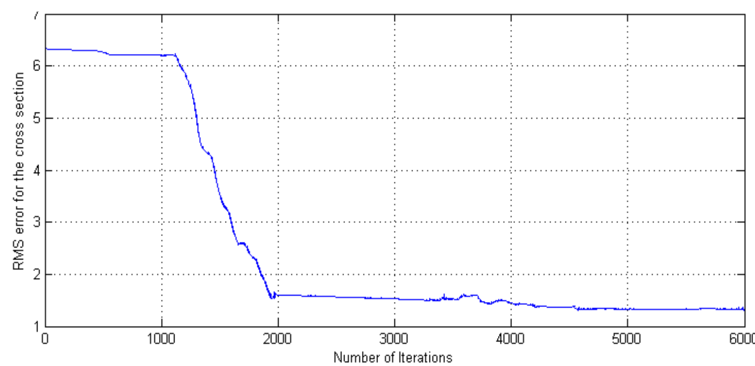
Iterative Coarse to Fine Approach: Results



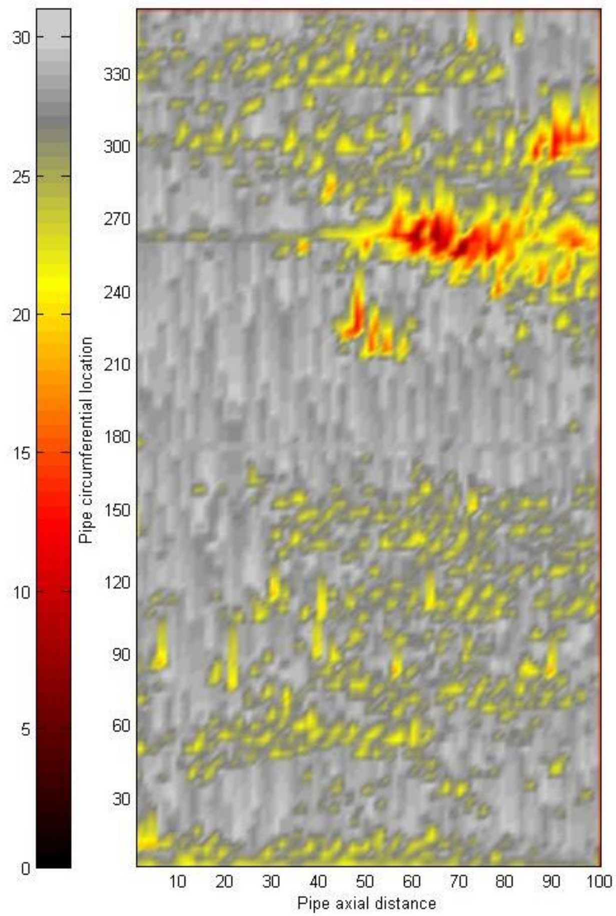


Coarse to fine iterative approach using GP – peak based result as the initial seed

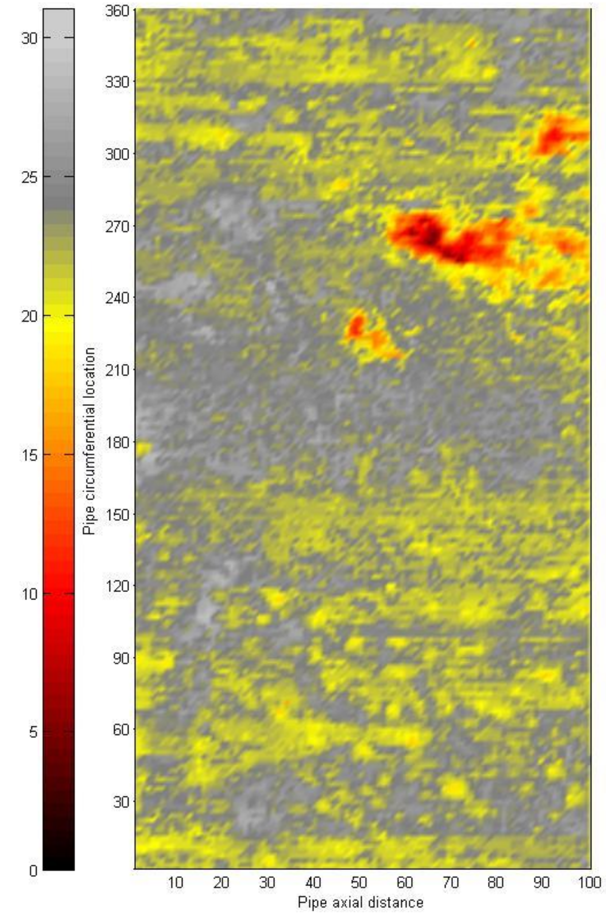


RMS error variation with number of iterations

Iterative Coarse to Fine Approach: Results



2.5D Optimized solution



Ground Truth

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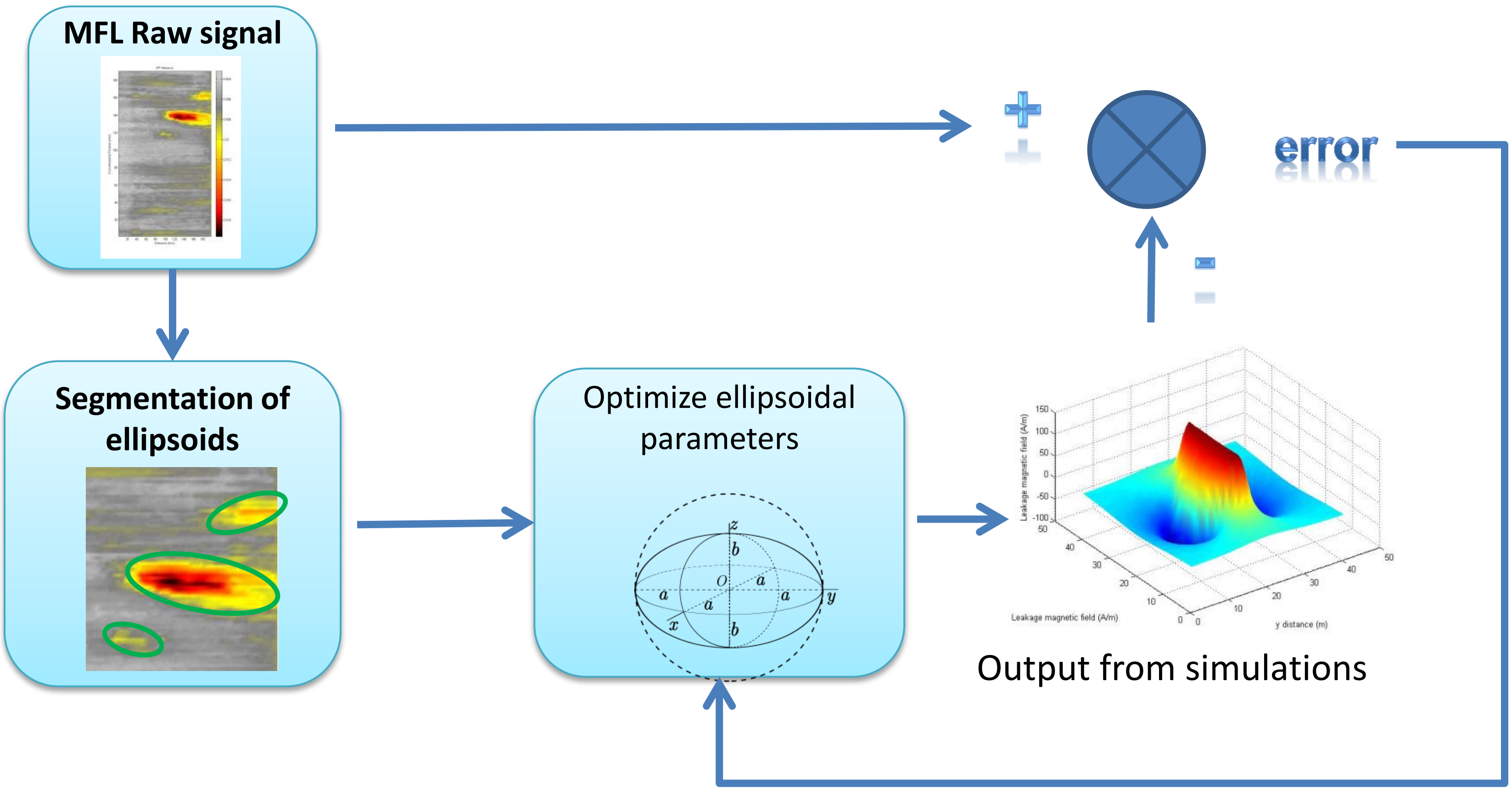
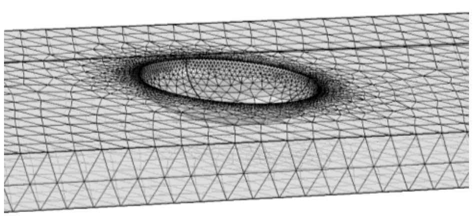
Iterative Ellipsoidal Approximation of Defects

- The importance of ellipsoidal approximation of defects has been identified for stress analysis purposes

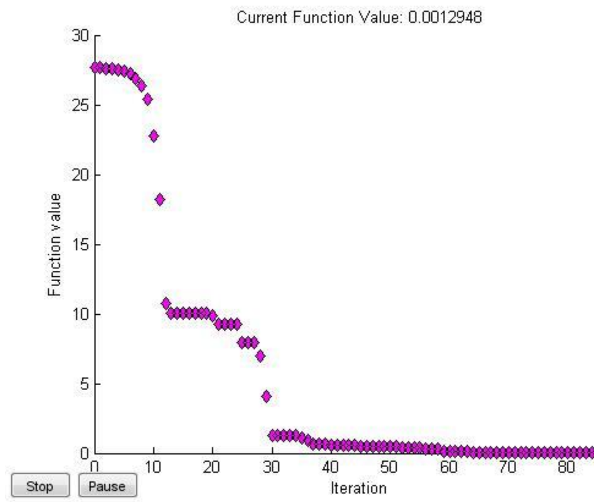


Proof of Concept Using Simulated Data

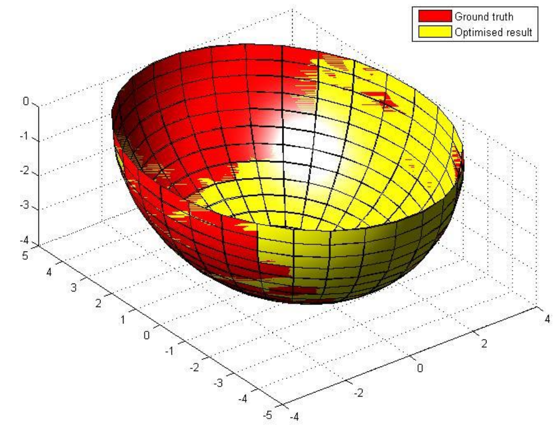
- An ideal ellipsoid defect was simulated using Comsol
- Dipole model based analytical model was used to optimise the ellipsoidal parameters
- Converges with ±0.1mm within ~8 seconds
- Encouraging results more relevant to stress analysis



FEA based ellipsoid simulation



Convergence of the optimization



GT vs. optimized result

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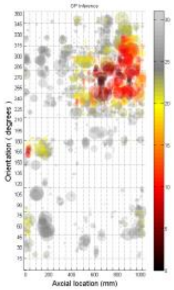
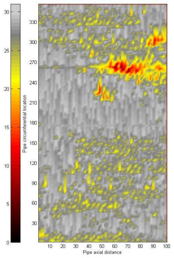
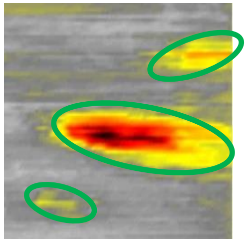
Modalities of UTS Interpretations from MFL Raw Signals

	Pros	Cons
Measles plot • Industry partner produces measles plots	• Fast generation of the plot (~ 5 minutes) • Can easily identify the sizes of defects	• Defects approximated to cylindrical defects • Cylinders overlap to each other • Needs pre trained models
2.5D thickness map • MFL signal has information to produce a thickness map	• Very high resolution 2.5D representation of the remaining wall thickness	• Computationally very expensive (~10 days of automated data processing) • Room for improvement
Ellipsoidal approximation • With feedback from Activity 1	• Can be used for stress analysis purposes • Fast computation (~7 minutes per ellipse)	• Not a very detailed representation of the remaining wall thickness







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MFL: Current Progress and Future Goals

Goal	Status
Use of Gaussian Processes to infer depth and width of isolated defects with FEA models	Completed (on MFL lab set-up)
Generation of 3D defect profiles using model outputs	Completed (on MFL lab set-up)
Preliminary data analysis of field runs	Completed (defect profile figures)
Design and prototype of a MFL lab setup	Completed (capacity to further improvements)
Development of a realistic simulation for UTS MFL lab setup	Completed
MFL Software interpretation tool development	Delivered Beta version to technology provider (AIA) and on-going improvements
Development of a realistic simulation model for the output of AESL tool	In-progress (in collaboration with AIA)
AIA prediction Vs Ground truth analysis	Completed (report sent to AIA)
UTS prediction Vs Ground truth analysis	Completed (report sent to AIA)
Further investigations of novel optimization methods for interpretation of MFL signals to enhance accuracy.	In-progress
Ellipsoidal approximation of real defects using optimization techniques	In-progress

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RFT (Russell NDT/PICA): State of Affairs and Current Progress

Remote Field Technology (RFT): Technical Description

- RFT technology detects changes in an AC electromagnetic field generated by the tool that interacts with the metal in the pipe, becoming stronger in areas of metal loss
- The electromagnetic field interactions are measured by on board detectors and processed on the tool
- Dedicated analysis software is applied to generate accurate information on the wall thickness

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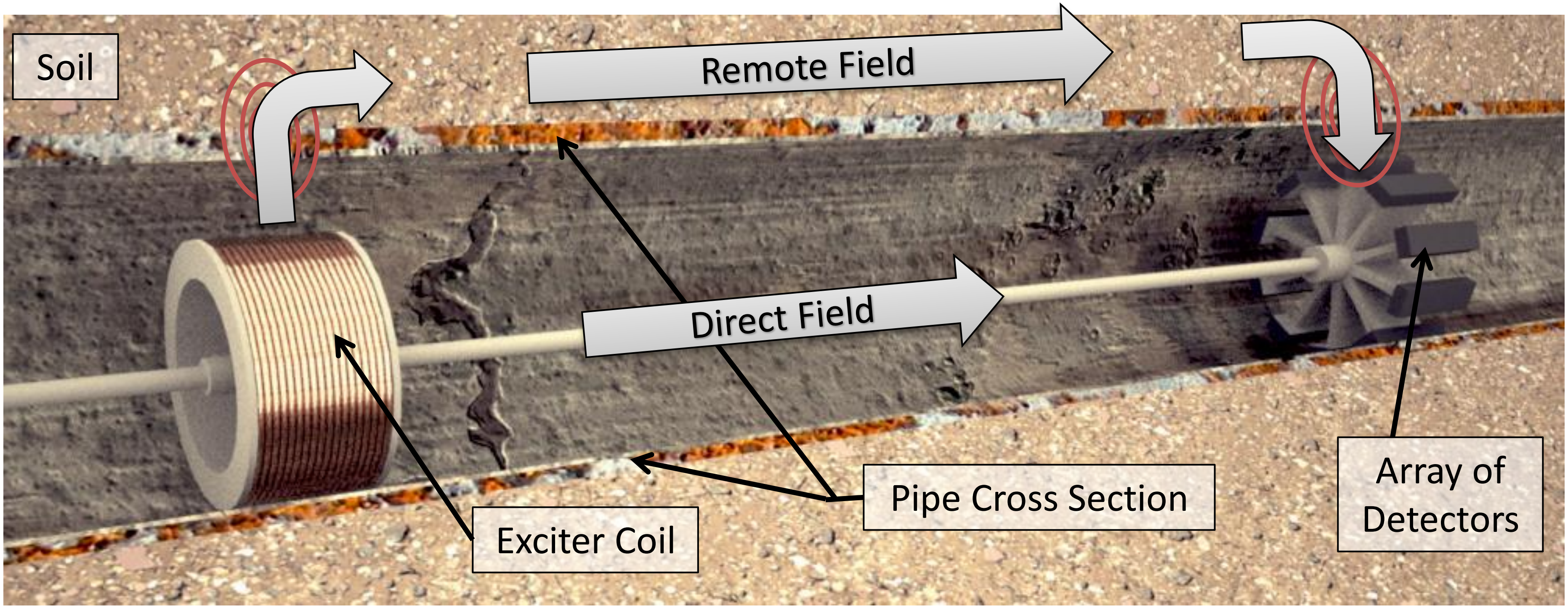
Remote Field Technology (RFT): Technical Description



Near Field Zone

Transition Zone

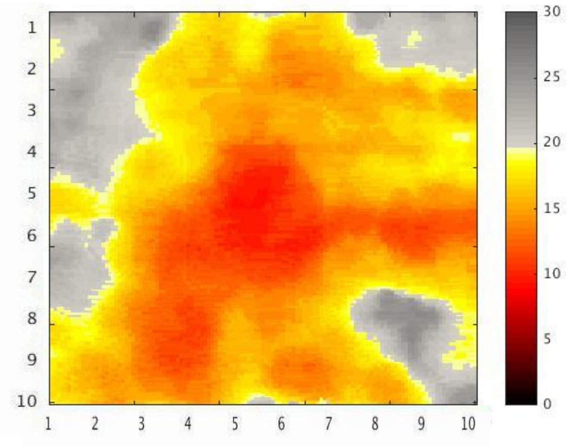
Remote Field Zone

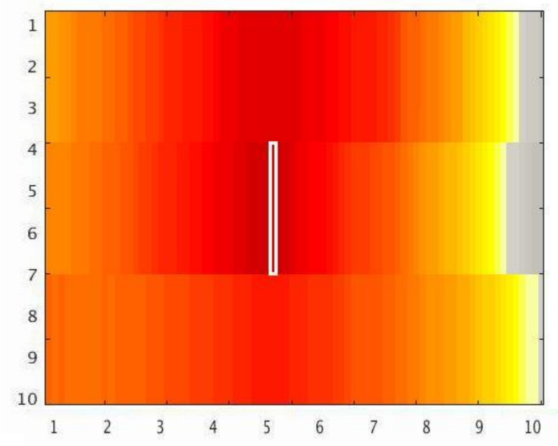
Reminder: Remote Field Technology in CI Data Example

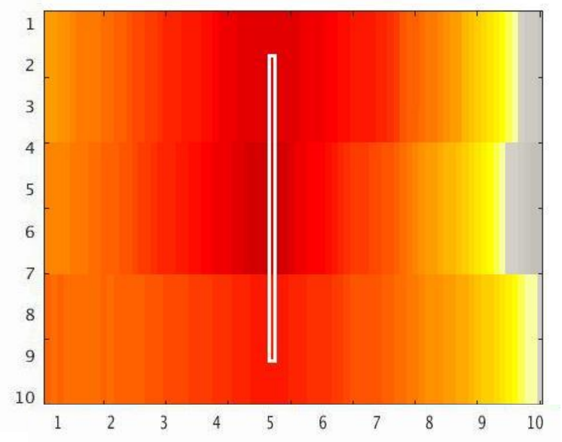
GT 10 x 10 cm

Raw RFT at the resolution of RFT tool

Raw RFT at the resolution reported by Russell







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Summary Current State of Affairs

1. UTS has performed FEA of the RFEC phenomenon
   - 2D axisymmetric simulation
   - 3D simulation using various symmetries
   - Realistic simulations with laser scanner data

2. UTS has designed a filtering process to enhance the quality of the raw data for further interpretation of remaining wall thickness (RWT)
   - Interpolation of missing sensors
   - Alternative calibration of the sensors based on signal processing
   - Background removal algorithm to avoid a native source of noise from RFEC technology

Latest Progress

1. UTS has finalised a comparison of the pitting evaluation reported in Russell report with the actual GT when defects are reported at similar locations (following a similar approach to the one used for the assessment of the other technology providers)

2. UTS has used the filtering process to enhance the quality of the raw data for further interpretation of remaining wall thickness (RWT)
   - Simple standardisation has been applied to normalise the data
   - Investigations related to normalisation strategies, carried out - pursuing technology partner' advice in this regard

3. UTS has implemented a defect detection algorithm
   - Filtering process based on machine learning using manually labelled samples (1000+) -Still under development but shows promising results
   - Results has been shared with the technology partner for feedback (not forthcoming)

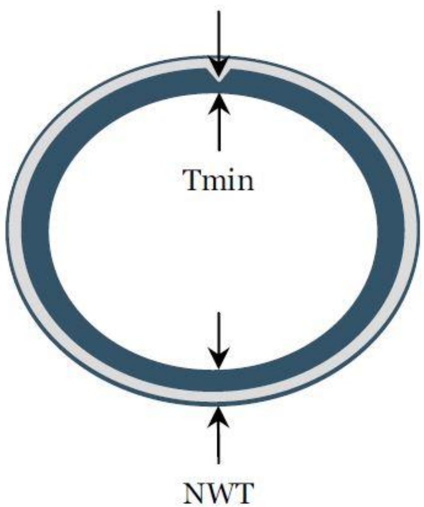
Information Reported by Russell NDE

TCircMin: Minimum circumferential value

RW: Average RWT for the full pipe segment (~3.6m)

TCircMax: Maximum circumferential value

Defect: Up to 3 defects are reported at a given location and point-wise minimum thickness



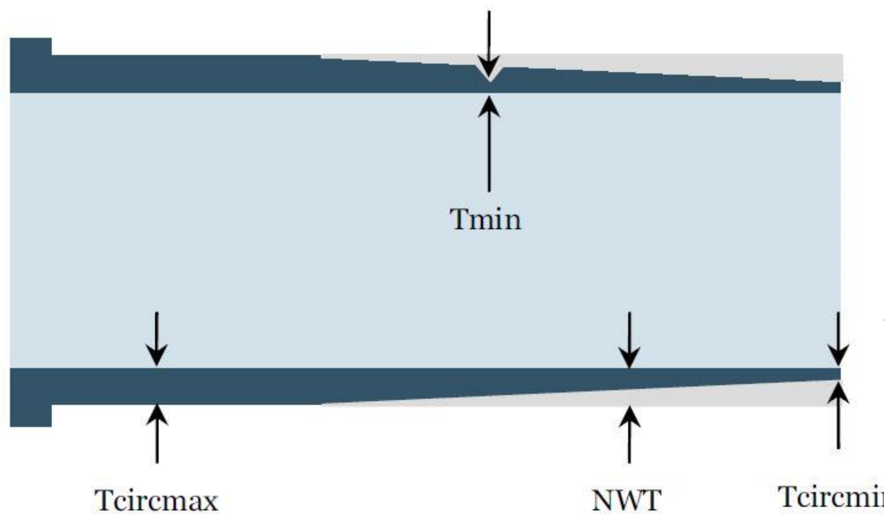
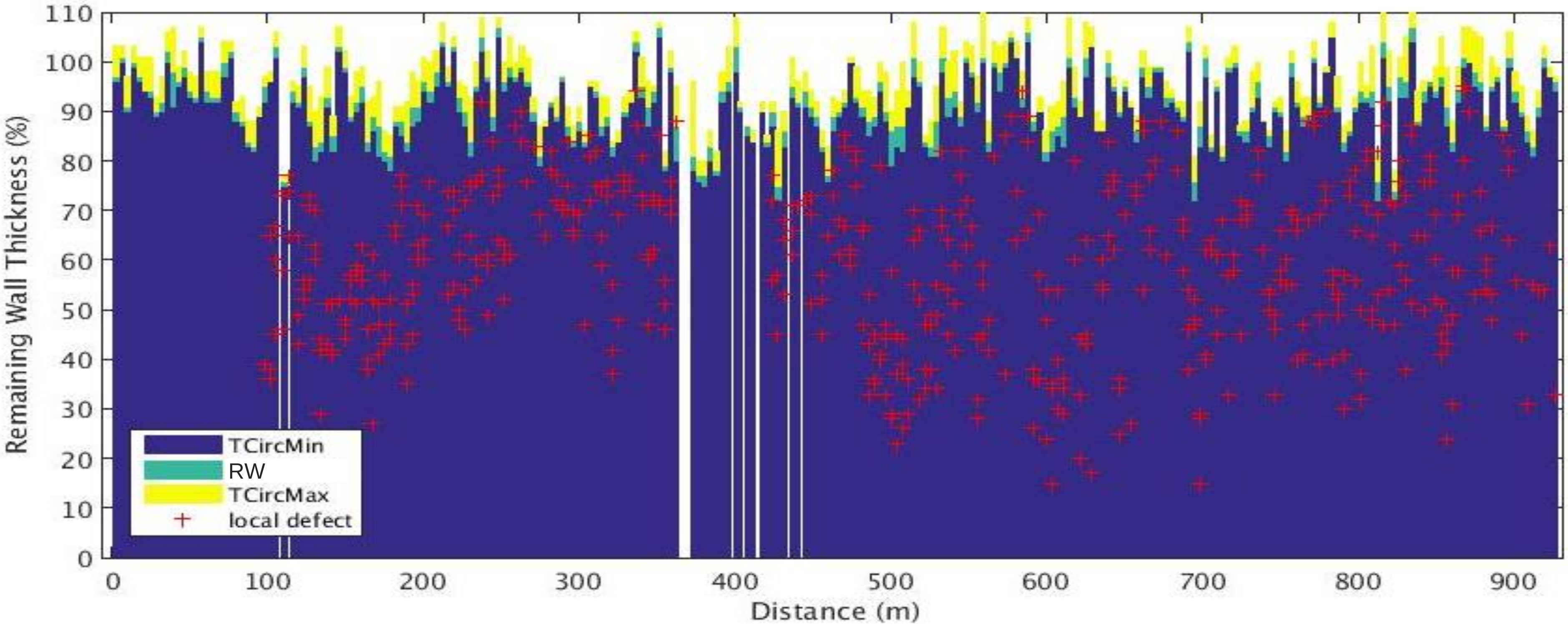


Image taken from Russell NDE Report 2012

Data Reported by Russell NDE

- Along the full pipe inspection



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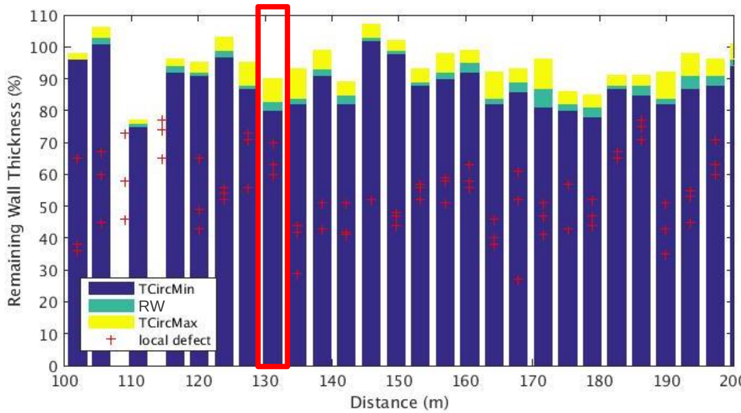
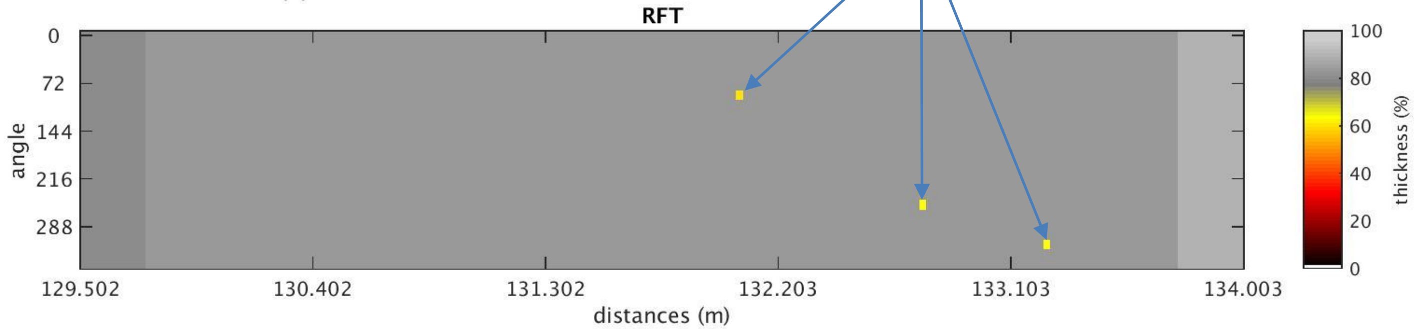
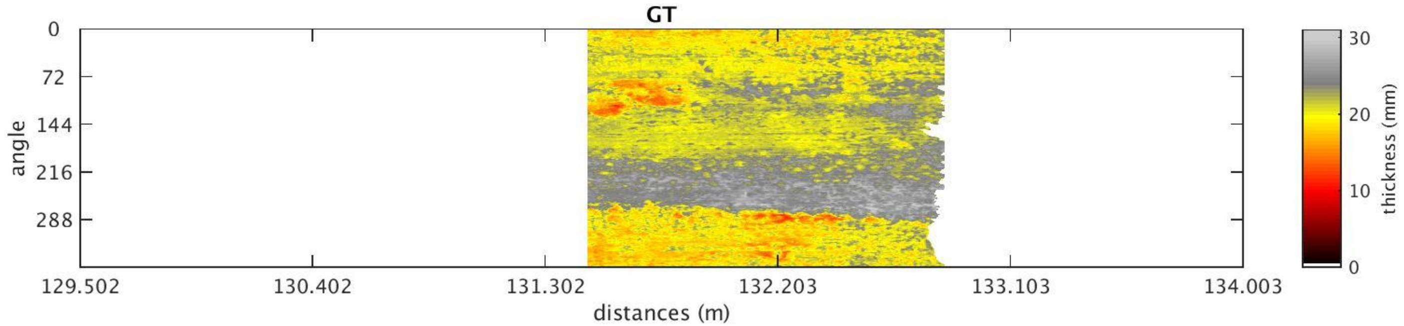
Data Reported by Russell and Ground Truth (GT) (Trial 3 – Pit 1)



RW = 83%
TCircMin = 80%
TCircMax = 90%
Defects





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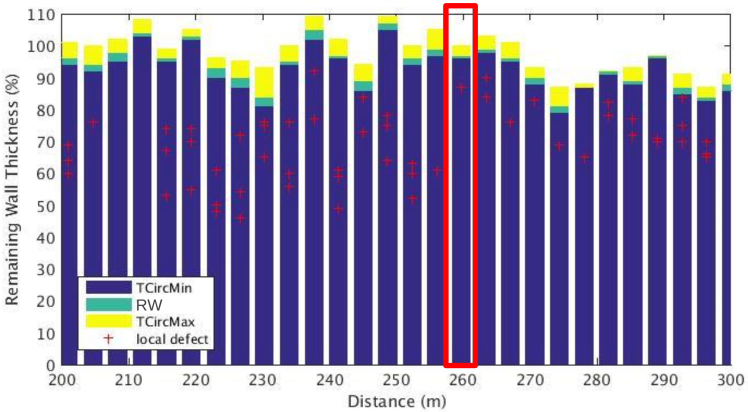
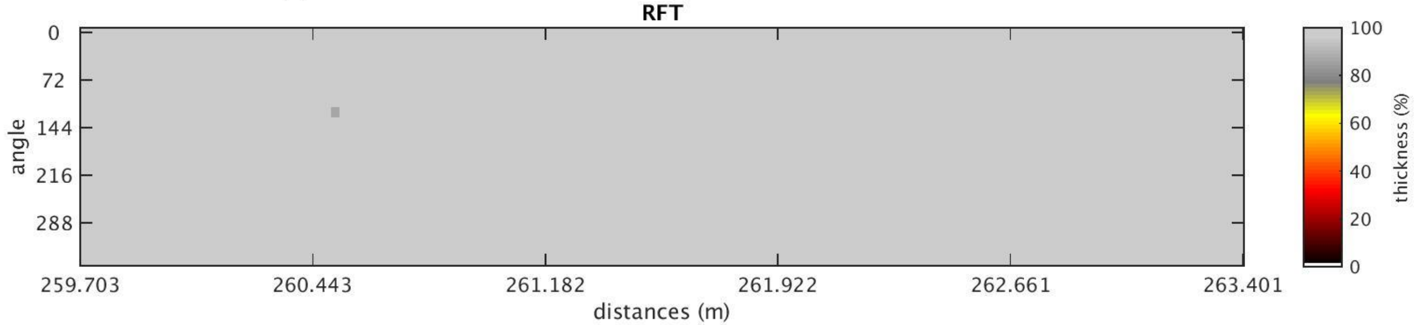
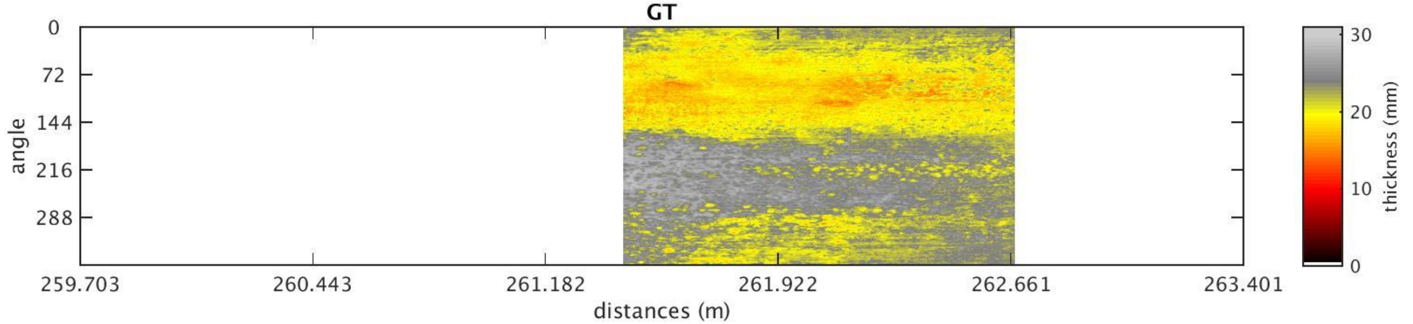
Data Reported by Russell and Ground Truth (GT) (Trial 2 – Pit 1)

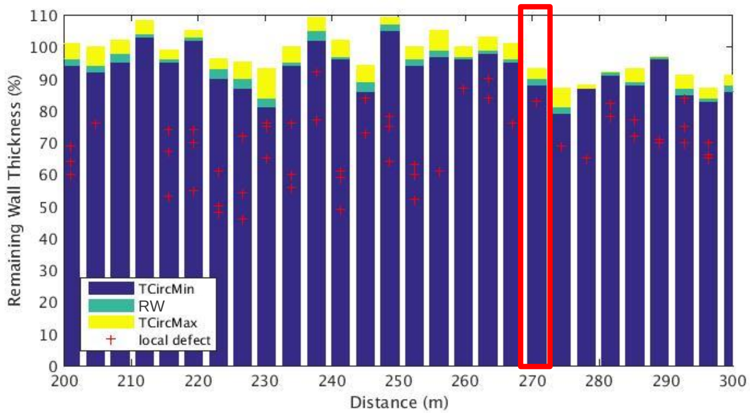


RW = 97%
TCircMin = 96%
TCircMax = 100%

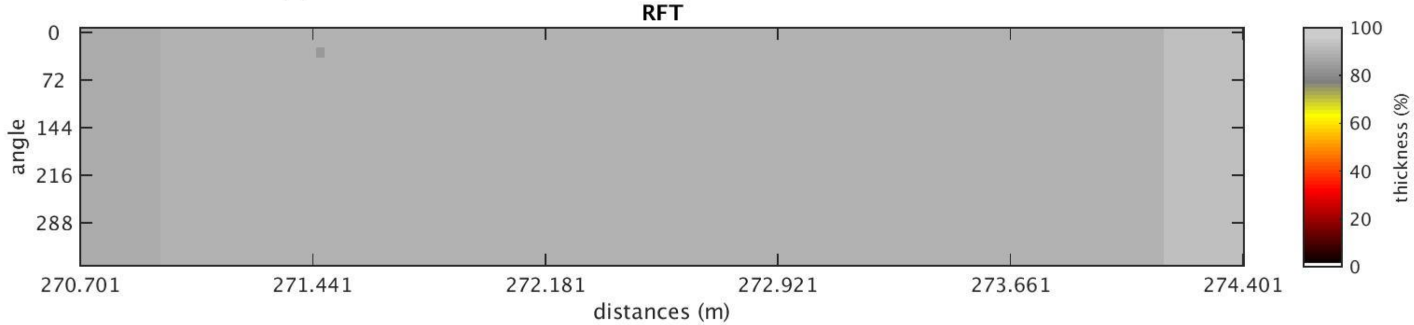


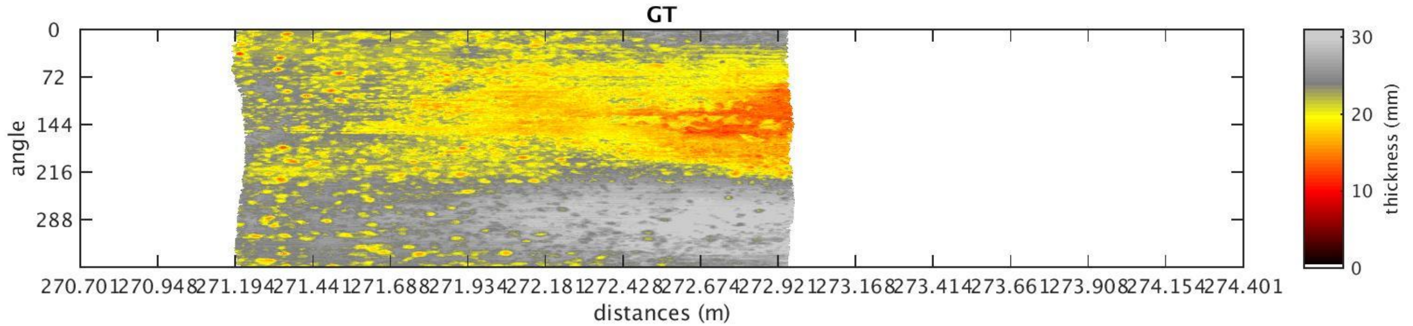


Data Reported by Russell and Ground Truth (GT) (Trial 5 – Anomaly 1)

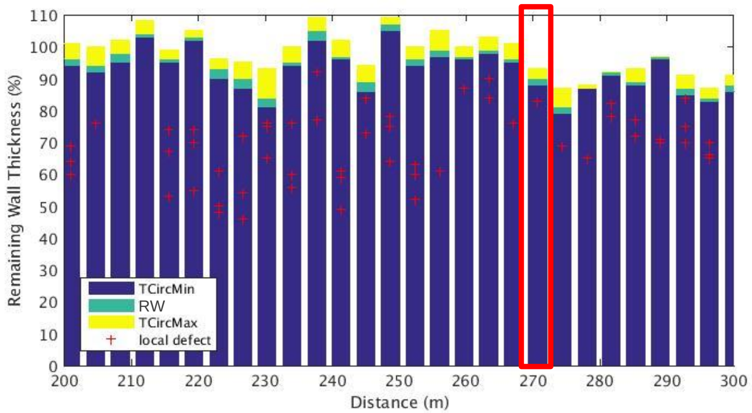


RW = 90%
TCircMin = 88%
TCircMax = 93%

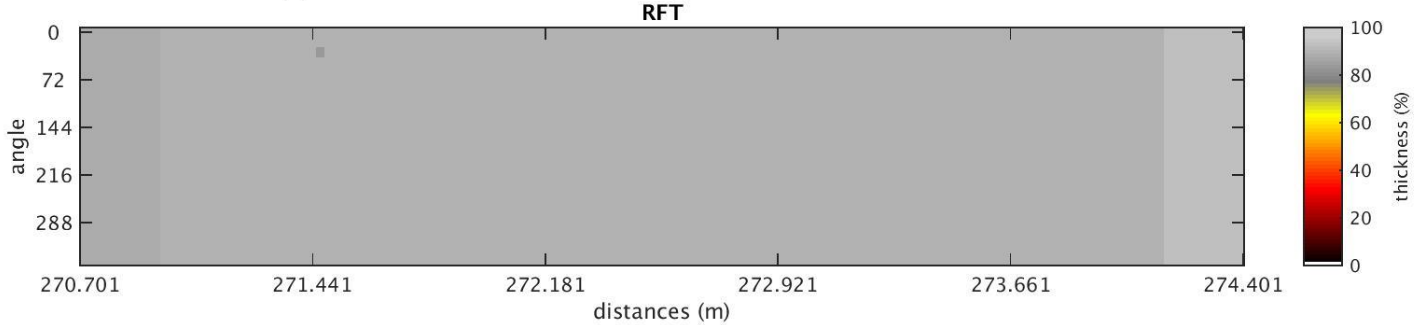


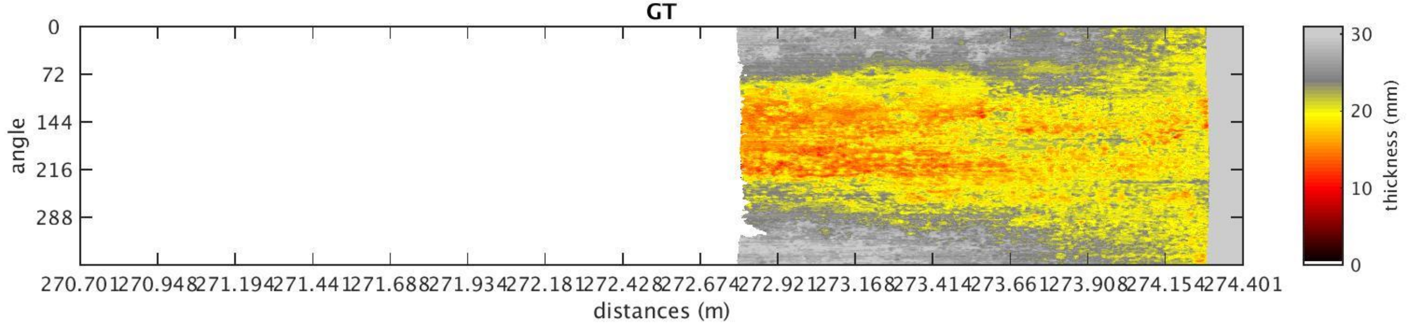


Data Reported by Russell and Ground Truth (GT) (Trial 5 – Anomaly 1)

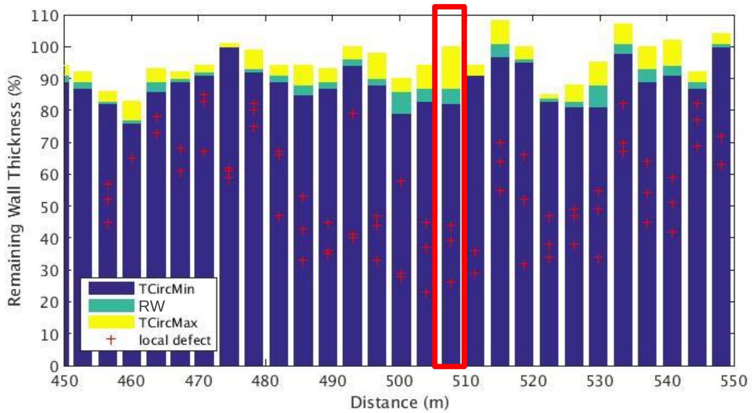


RW = 90%
TCircMin = 88%
TCircMax = 93%

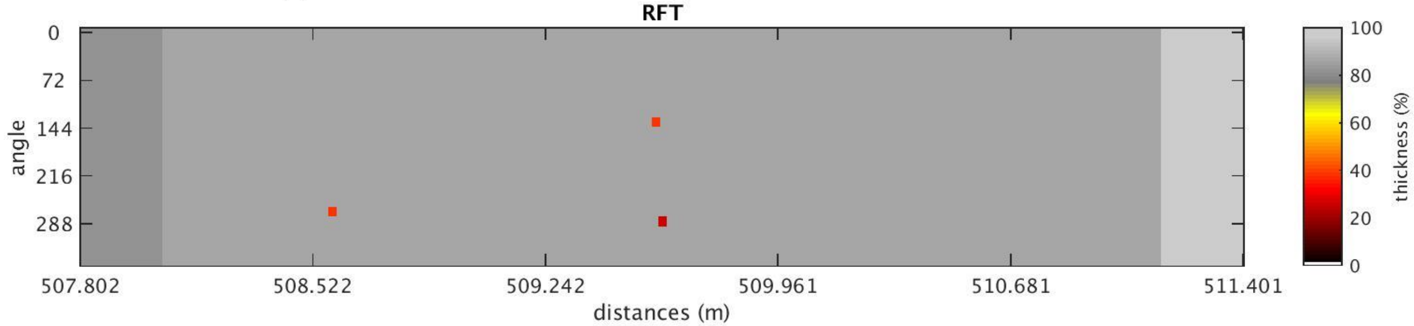


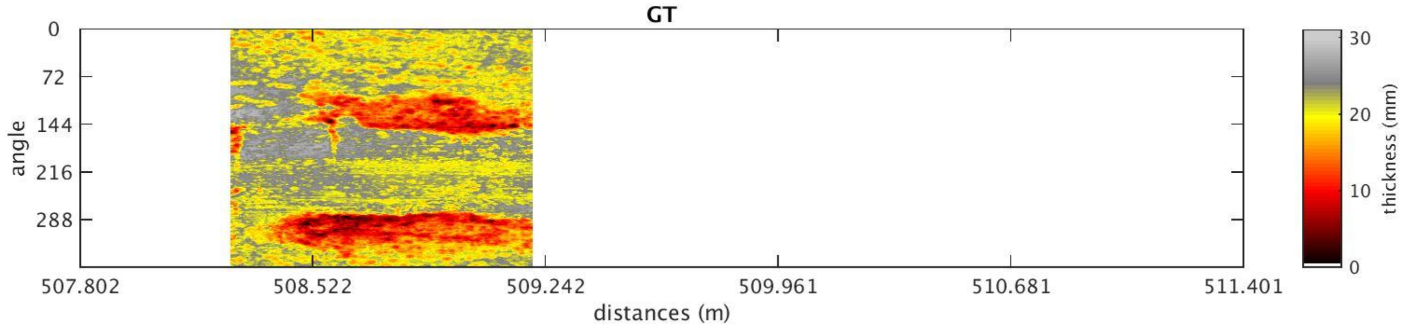


Data Reported by Russell and Ground Truth (GT) (Trial 2 – Pit 2)



RW = 87%
TCircMin = 82%
TCircMax = 100%





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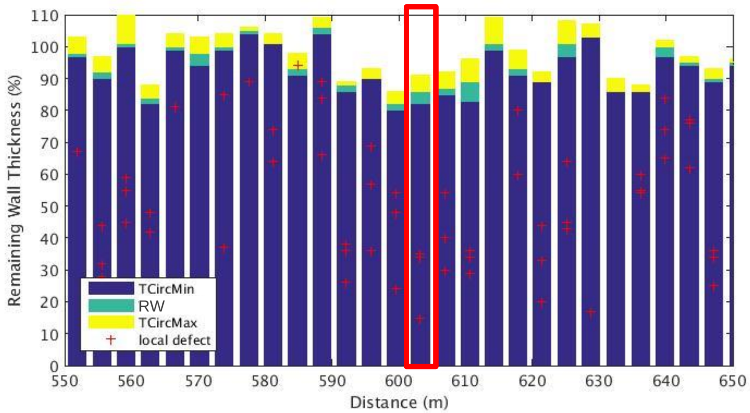
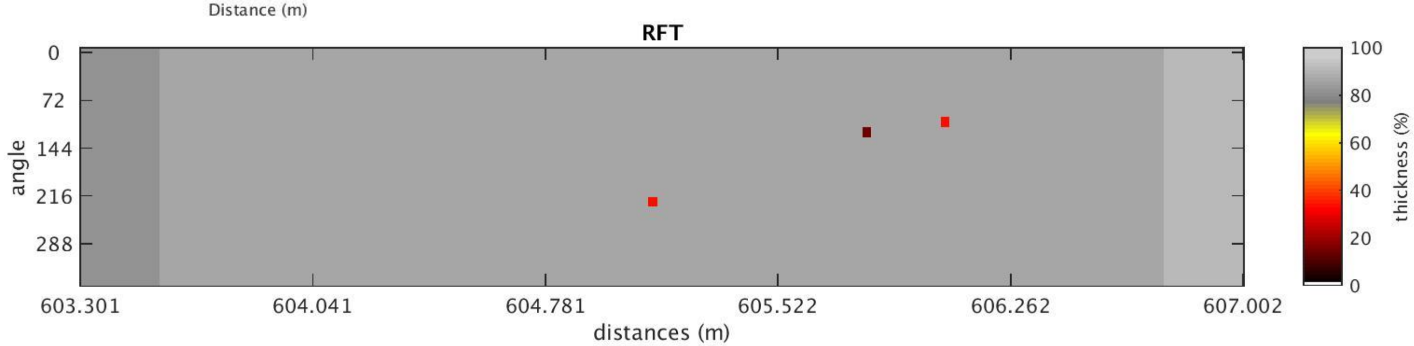
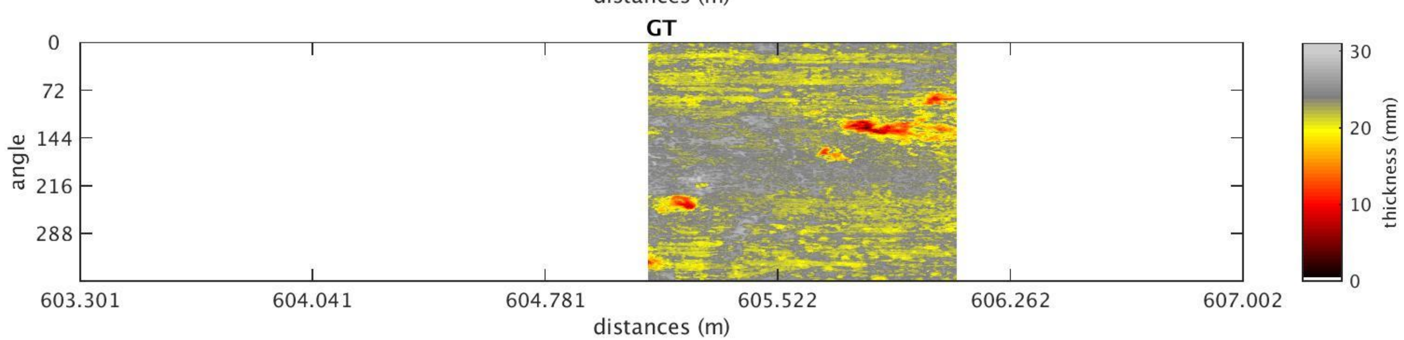
Data Reported by Russell and Ground Truth (GT) (Trial 2 – Pit 3)



RW = 86%
TCircMin = 82%
TCircMax = 91%





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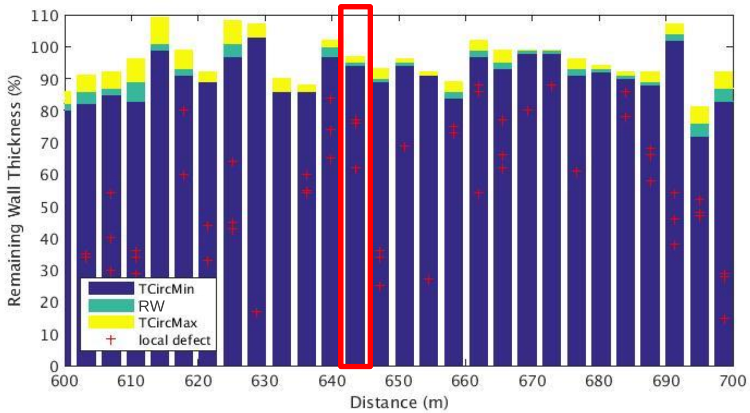
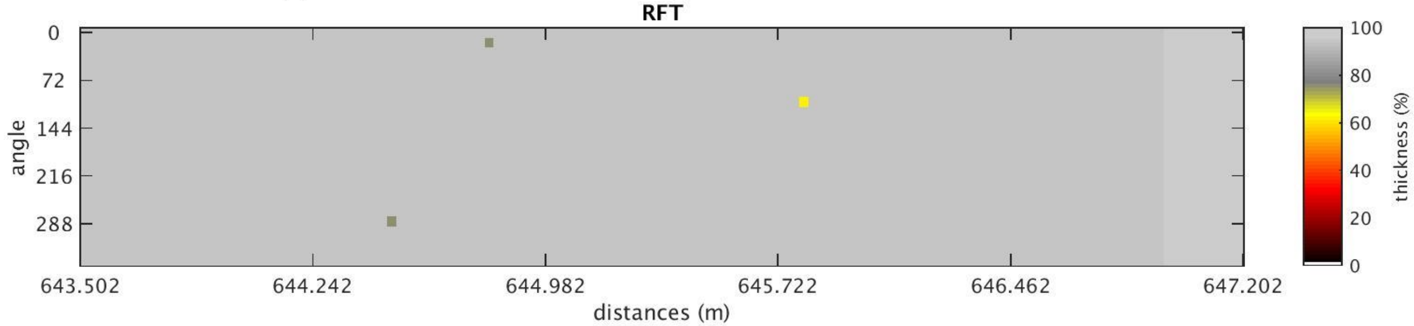
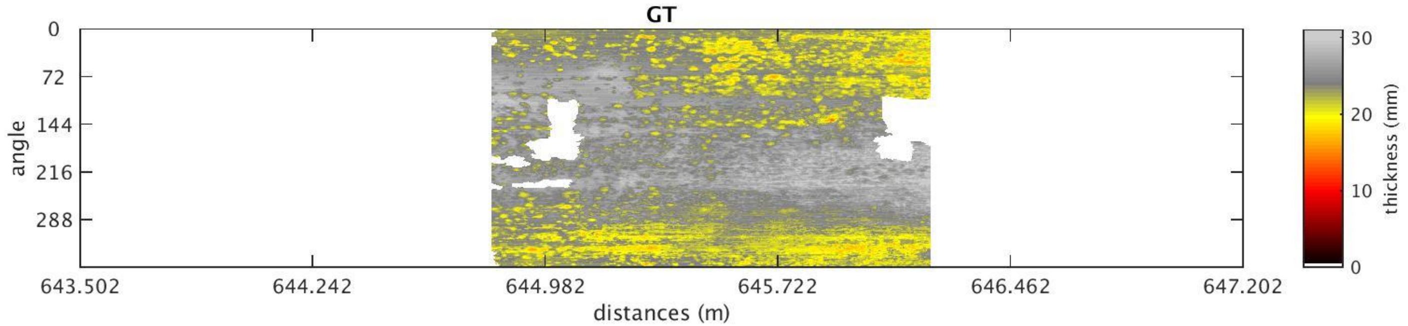
Data Reported by Russell and Ground Truth (GT) (Trial 2 – Pit 4)



RW = 95%
TCircMin = 94%
TCircMax = 97%





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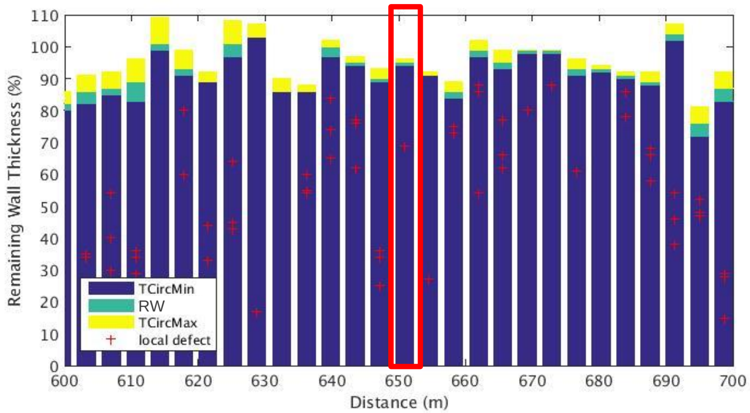
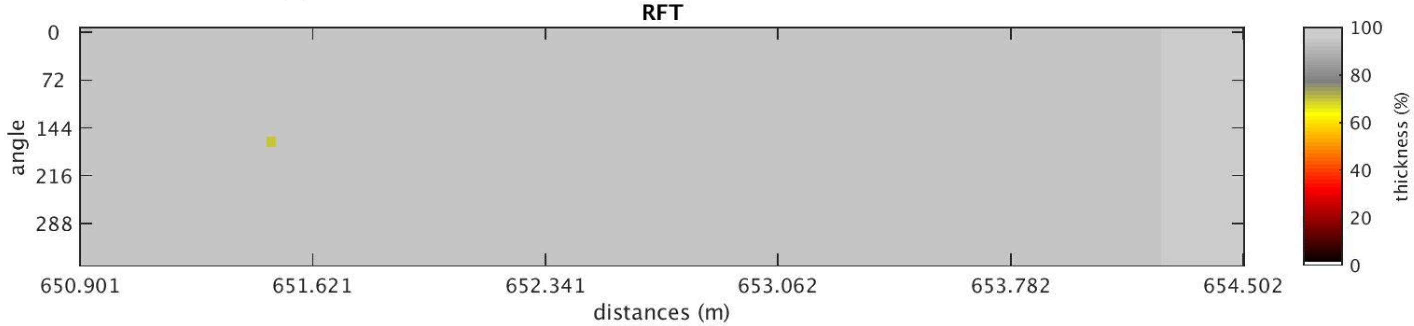
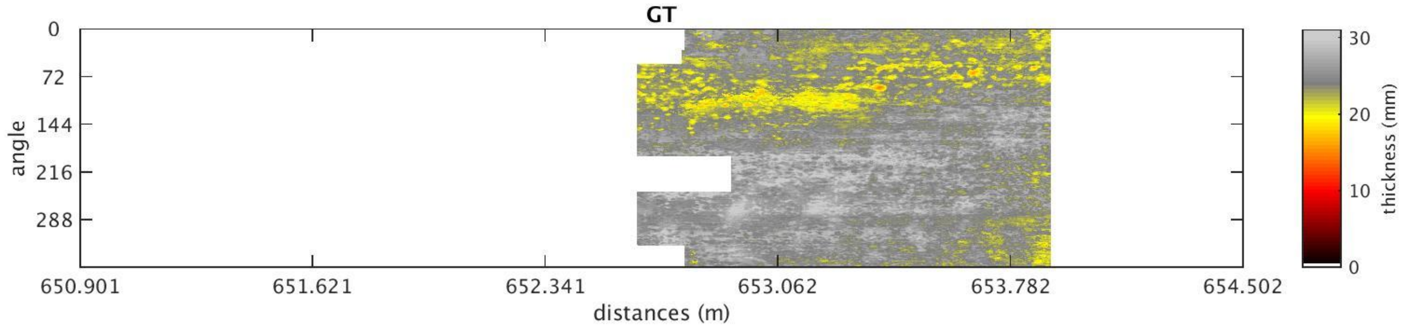
Data Reported by Russell and Ground Truth (GT) (Trial 3 – Pit 2)



RW = 95%
TCircMin = 94%
TCircMax = 96%





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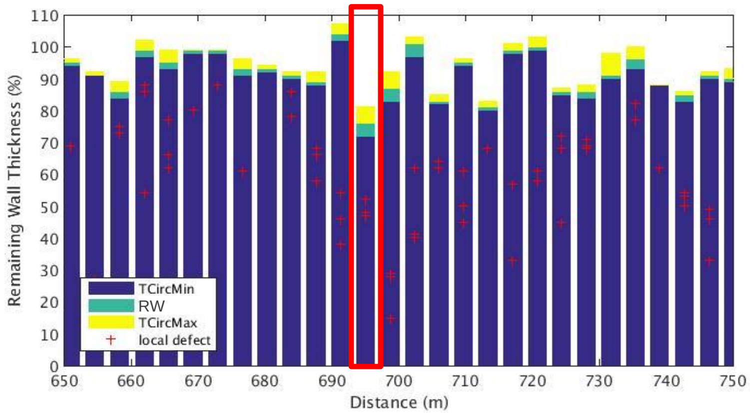
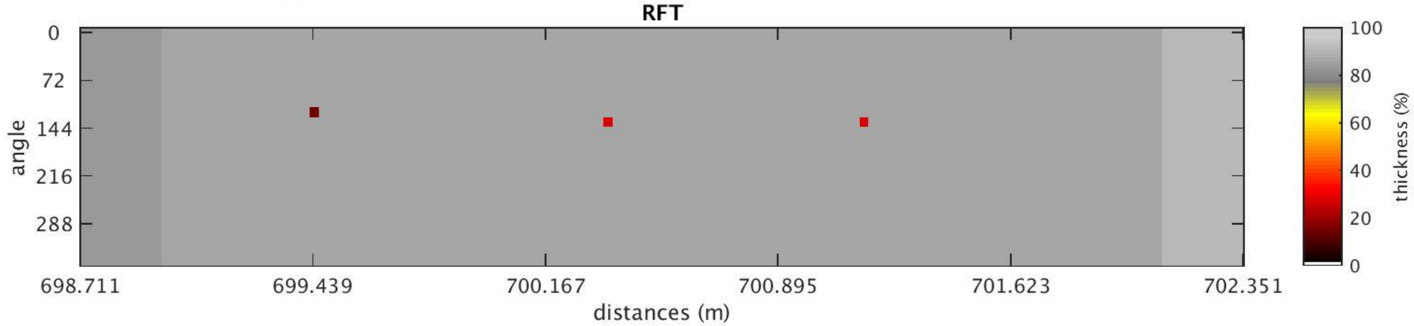
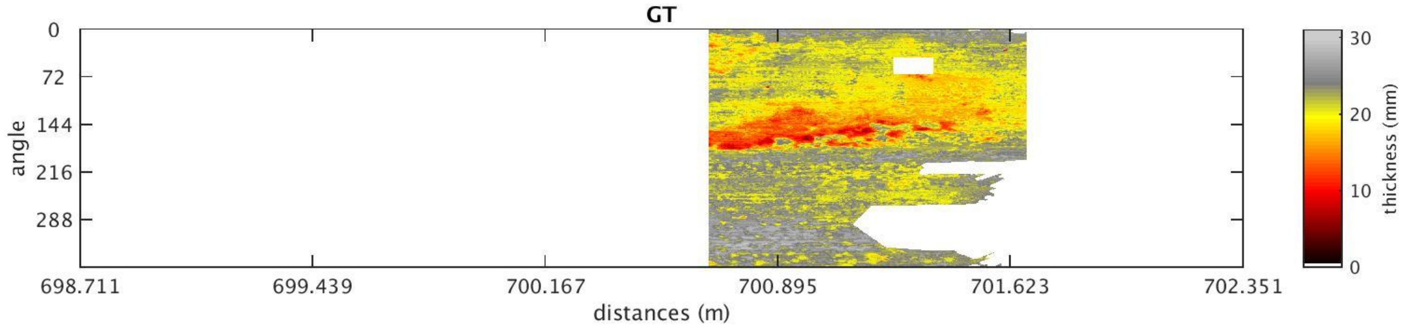
Data Reported by Russell and Ground Truth (GT) (Trial 3 – Pit 4)

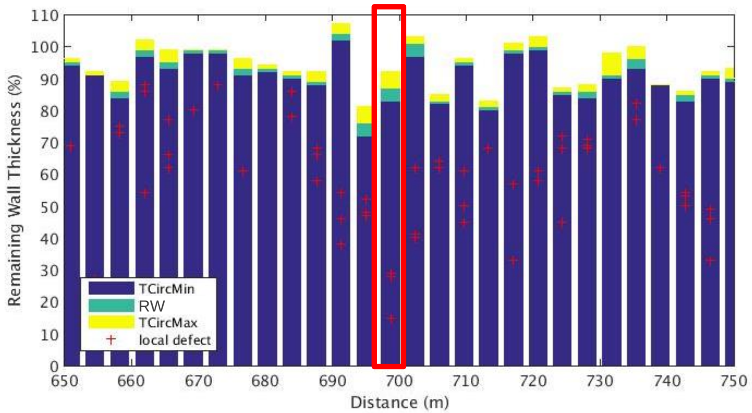


RW = 76%
TCircMin = 72%
TCircMax = 81%

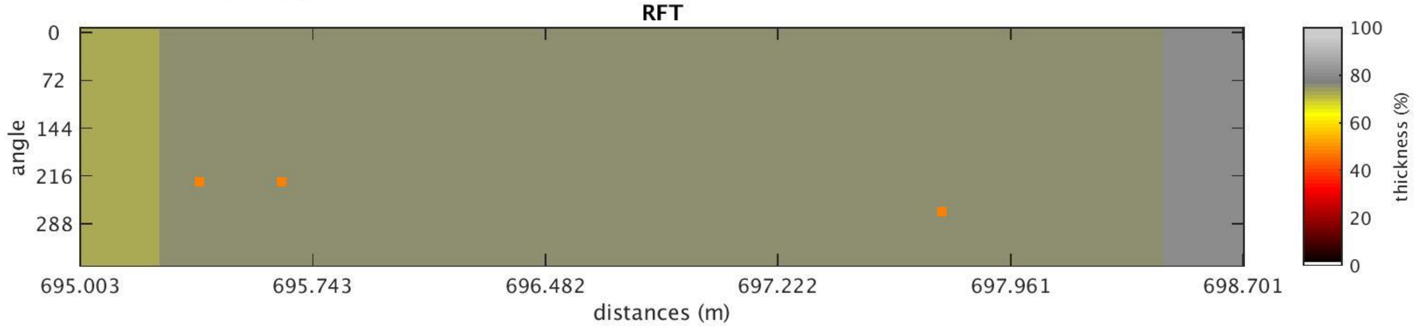


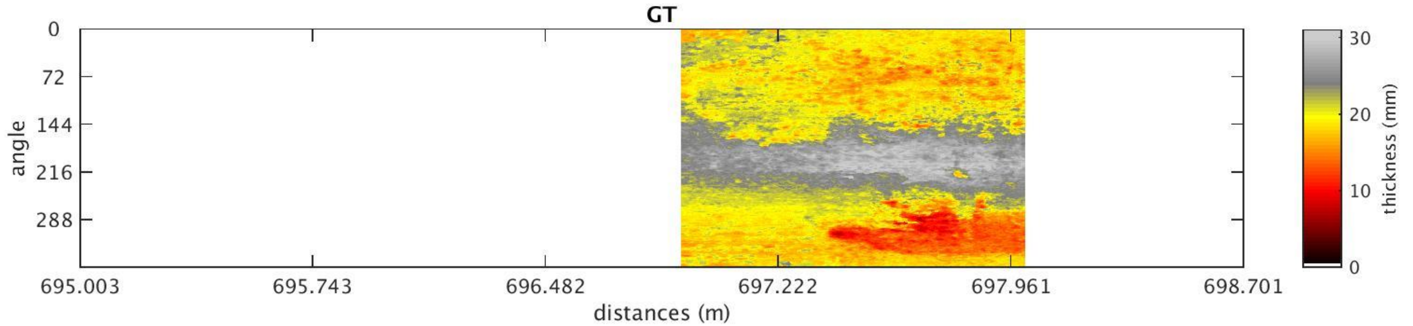


Data Reported by Russell and Ground Truth (GT) (Trial 3 – Pit 3)



RW = 76%
TCircMin = 72%
TCircMax = 81%





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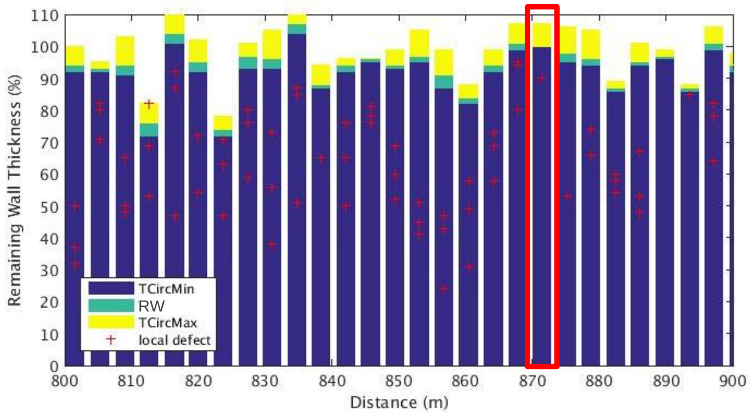
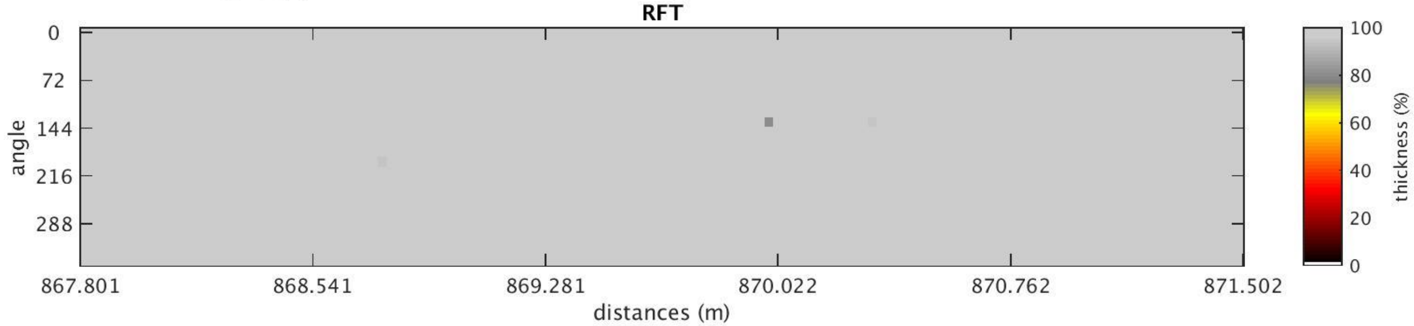
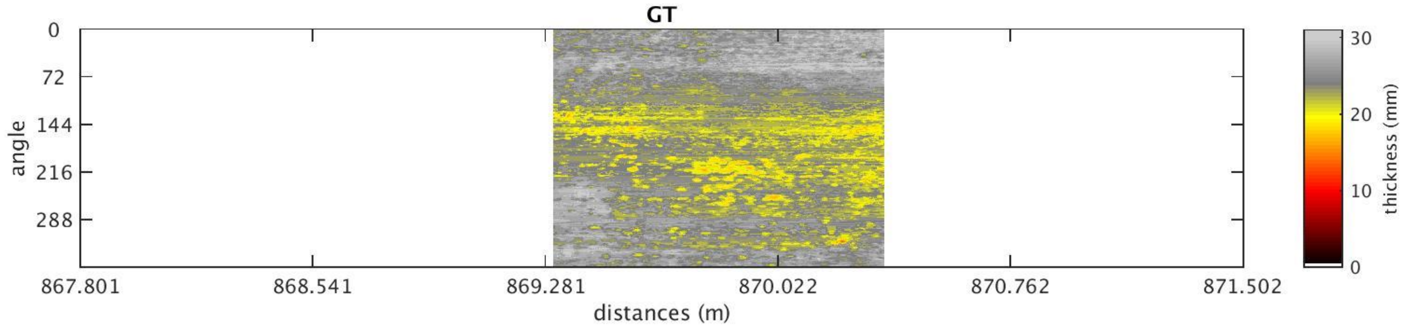
Data Reported by Russell and Ground Truth (GT) (Trial 2 – Pit 5)



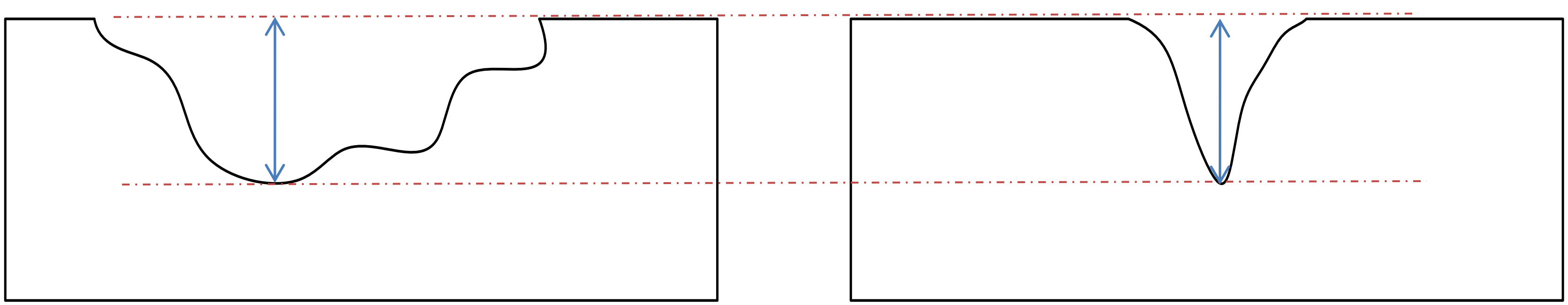
RW = 101%
TCircMin = 99%
TCircMax = 107%





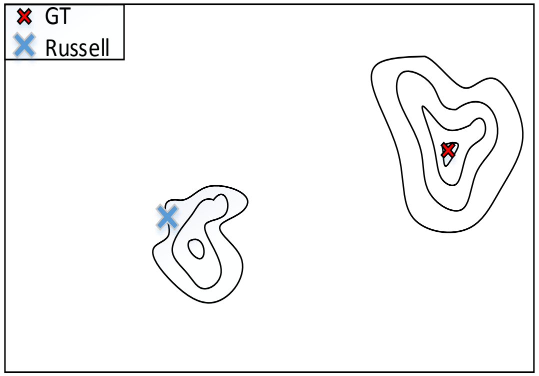
Data Reported by Russell and Ground Truth (GT)

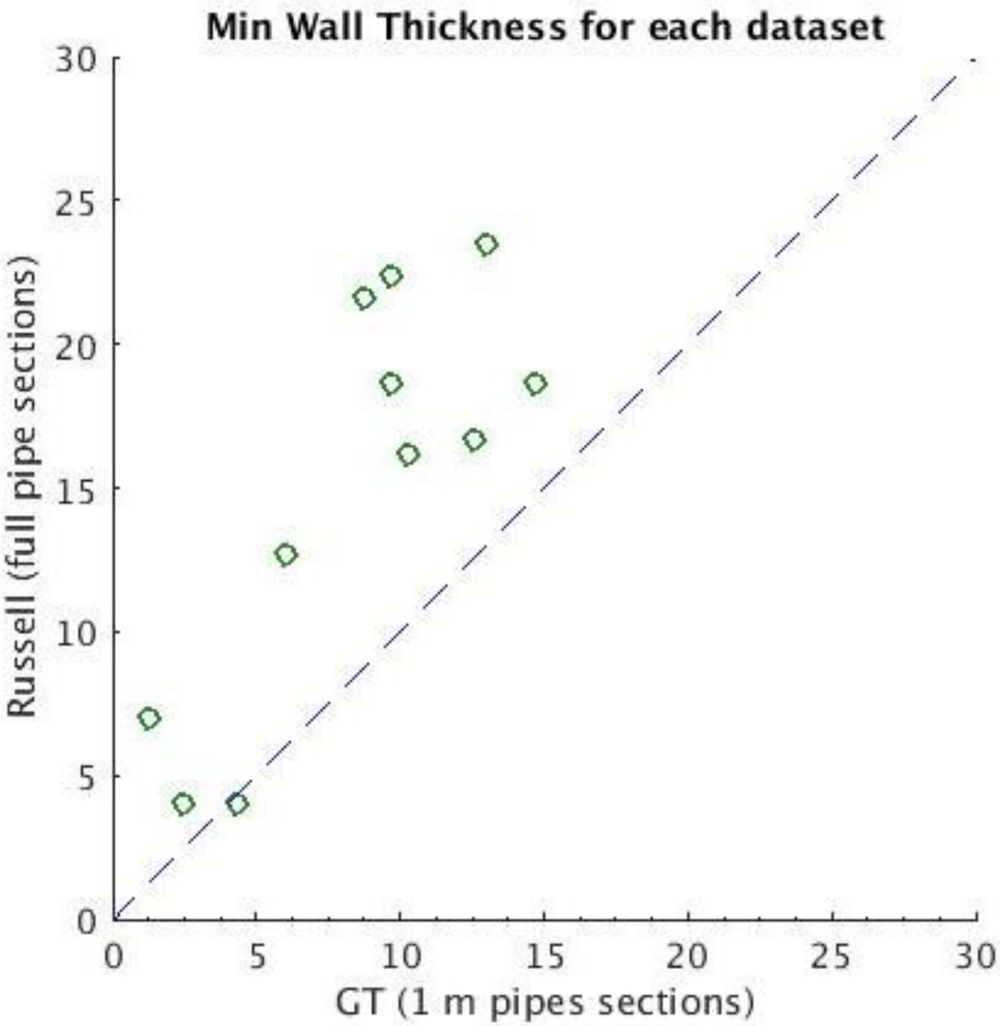
- With the methodology currently used by the technology provider, this two single defects would be reported equally



Defects: Minimum Pitting

- Thickness of the worst defect reported by Russell vs. actual worst RWT in the 1 m pipe segment (GT brought to RFT resolution by averaging)
- In some cases, there are worst defects than those reported by Russell as worst





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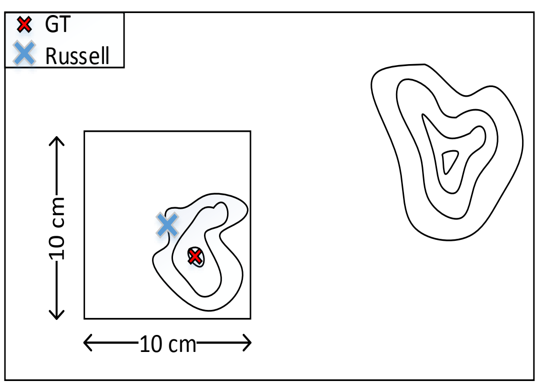
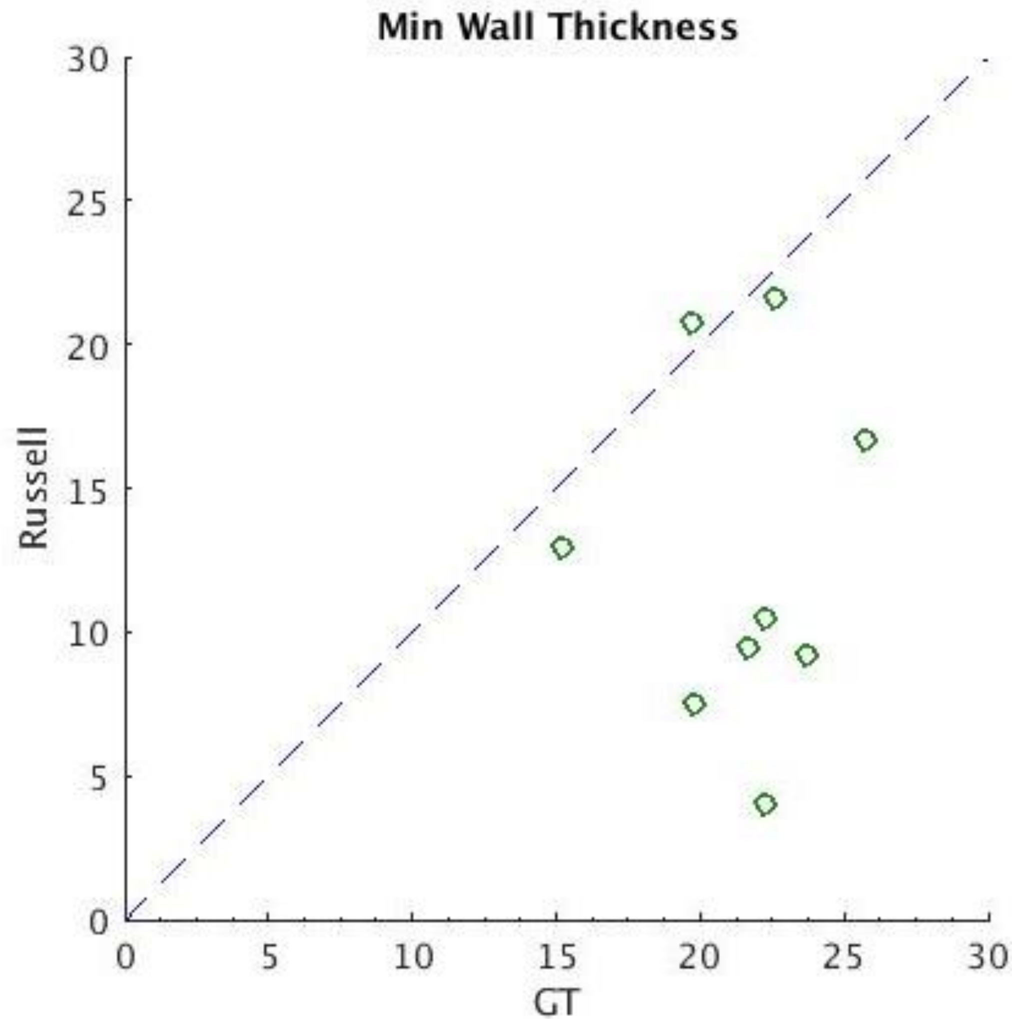
Defects: Minimum Thickness at the Same Location

- Russell estimation vs. actual RWT
  - Search window of 10 cm square for the worst defect in the GT centred on the location reported by Russell
  - Averaging of an area of 3.7 cm square
- RFT tends to underestimate the thickness of pipe's defect





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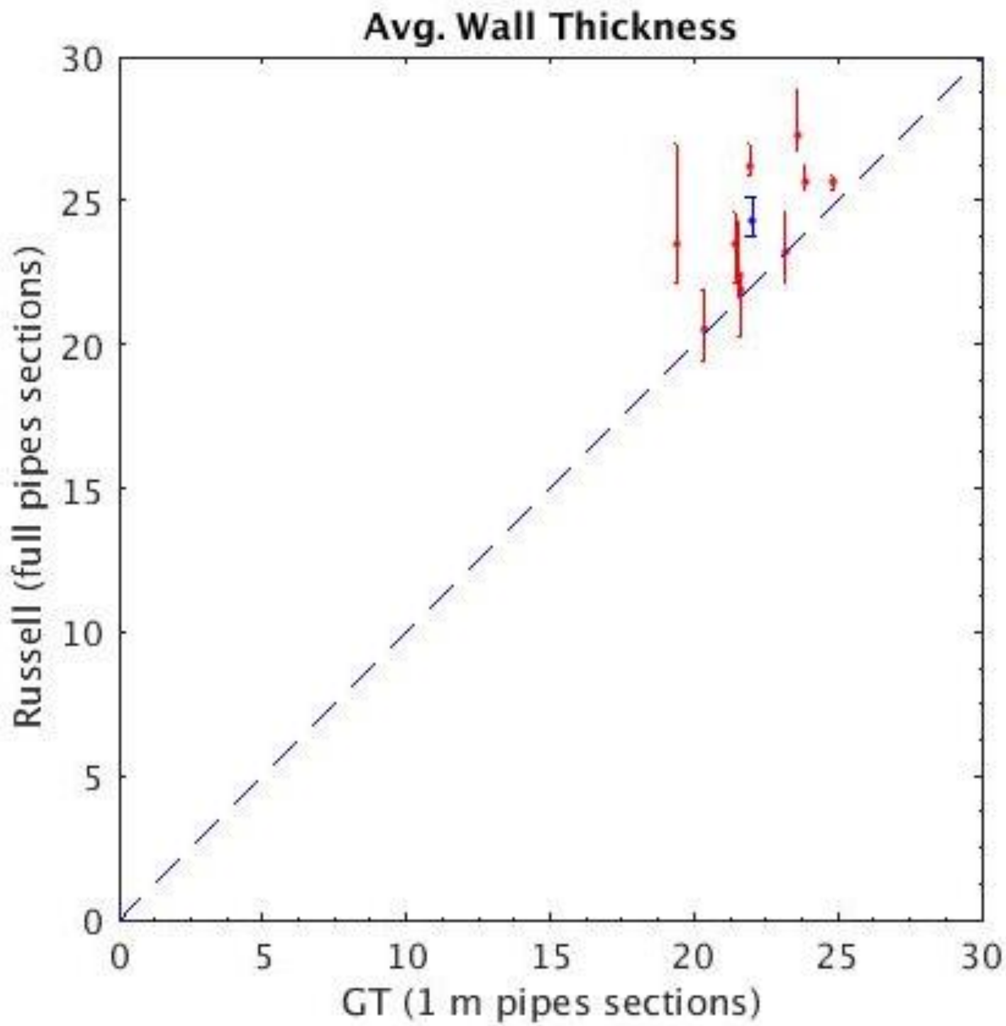
Average RWT

- Average RWT after blasting
- Average RWT error: 1.83 mm
- RFT tends to overestimate the global thickness of the pipes

Note: Results from ~3.6m pipe are being compared with available ~1m GT, so analysis remains indicative

1 measurement (in blue) does however represent the whole pipe segment which was extracted as part of GT



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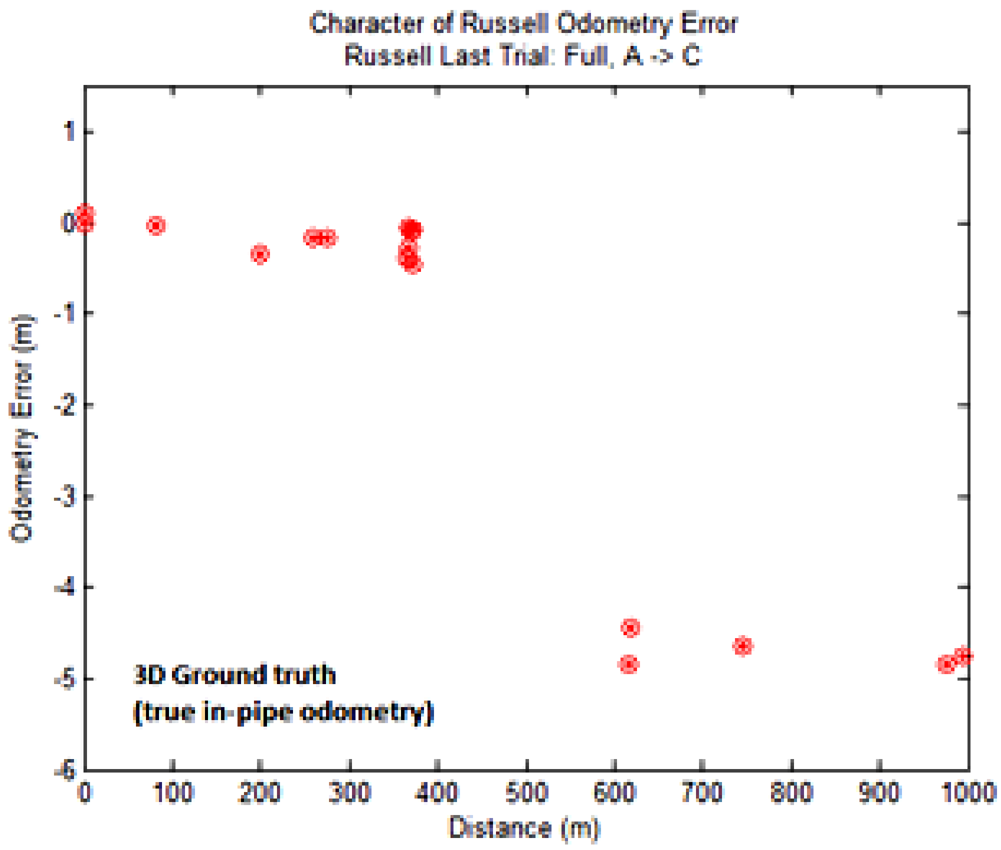
RFT Tool Localisation Issues

- As tool moves inside the pipe there is location inaccuracies, characterised as:
  - About -5 meters at the river crossing area
  - ± 1 meters error everywhere else



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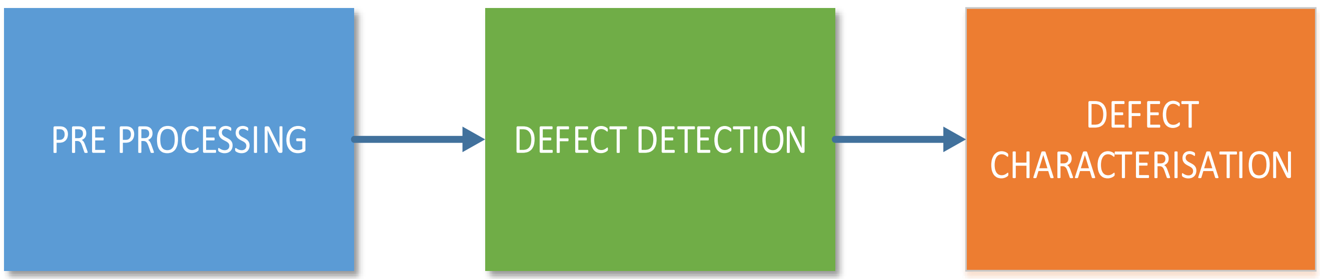
UTS Processing of RFT Data for Defect Detection

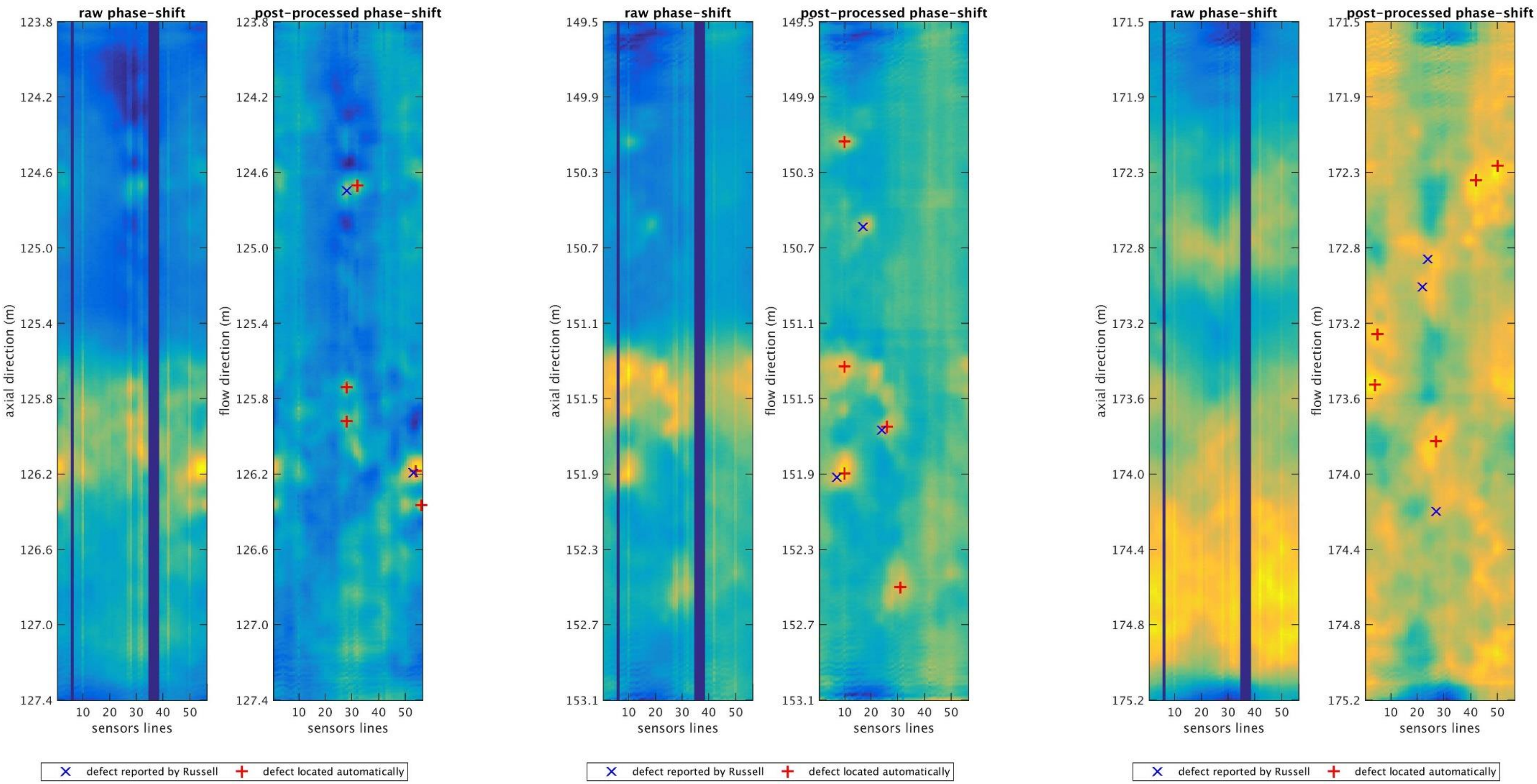
- The pre processing of the RFT data has already been implemented including:
  - background removal algorithm and
  - further filtering process able to remove most of the noise sources



- Focus on the defect detection …

Results from Defect Detection

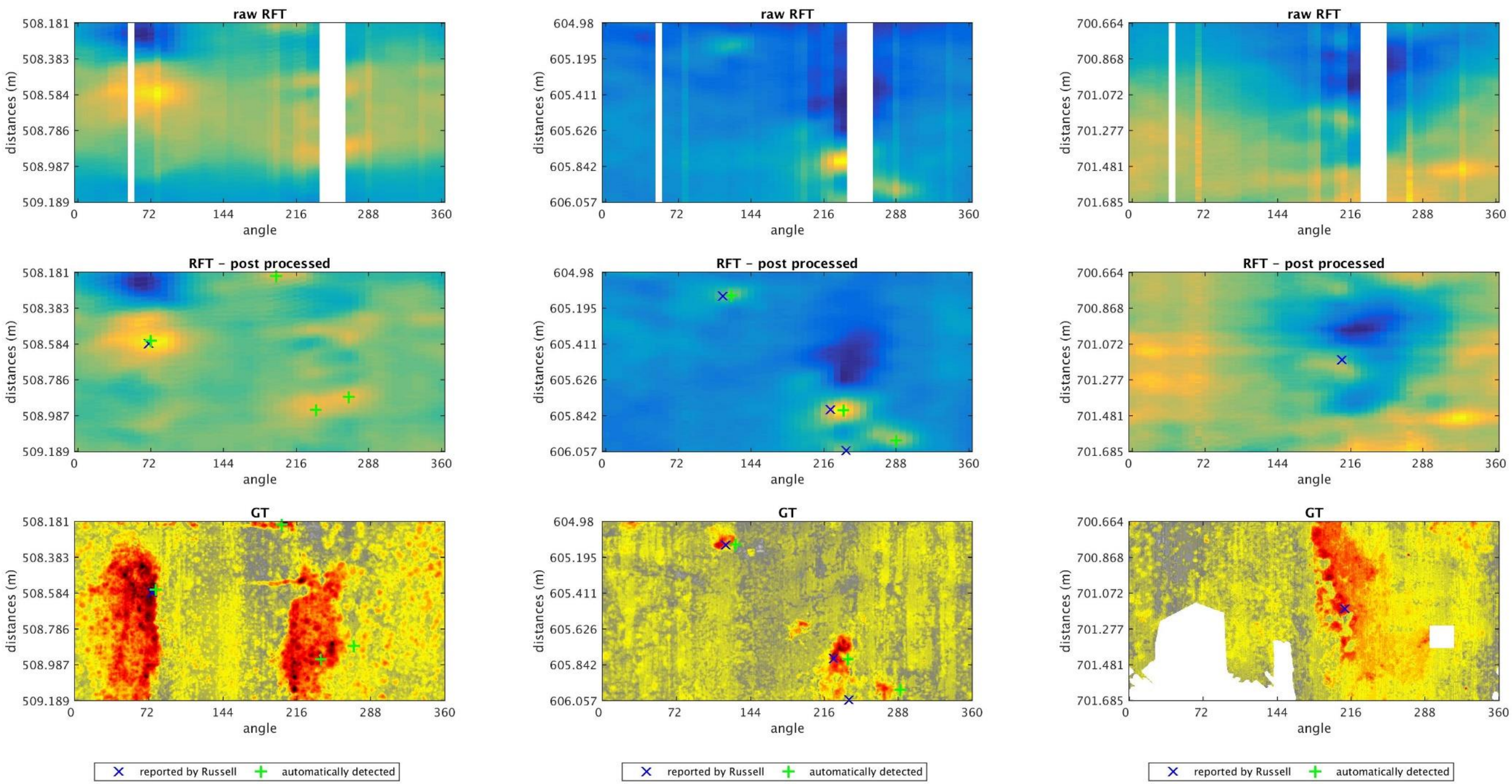
- Comparison of raw and processed data



* Examples of these results have been shared with Russell NDE

Results from Defect Detection (cont.)

- Comparison of the raw and processed data with the ground truth



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RFT : Current Progress and Future Goals

Goal	Status
Numerical simulation of the RFT tool interacting with pipe materials	Completed
Pre processing pipeline implemented	Completed [ACRA Paper - Published]
Implement a defect detection algorithm for significant defect in RFT data	Completed
RFT interpretation vs. Ground truth comparison (Trial 2,3,5)	Completed
Implementation of a shape detection algorithm for defect characterisation in raw RFT data	In-progress
Feature analysis on the RFT raw signal to characterise isolated defects (in terms of extension and thickness)	In-progress
Further analysis on data normalisation for thickness interpretation (hopefully with the engagement of Russell NDE)	In-progress

What Have We Learned About BEM in CI

1. A BEM signal does **NOT REPRESENT** a point measurement of wall thickness, it measures **AVERAGE VOLUME** of material under the sensor antennae
   - A single BEM measurement represents an area of 50mm x 50mm
2. BEM **CAN NOT** detect pitting
3. In CI pipes, RSG interpretations seems to relate well to actual volumes of pipe thickness
4. Pipe ferromagnetic properties (e.g. conductivity, permeability) affect results
   - Good estimations of these properties produce best interpretations of remaining wall thickness
   - If not considered, there exists an offset between interpreted and real wall thicknesses
5. Multiple antennae sensor (e.g. 6 way antennae) is less suitable to produce results of similar sensitivity to single antenna sensor
6. Preliminary analysis indicate suitability for stress analysis, if coarse

What Have We Learned About MFL in CI

1. MFL signals **REPRESENT** a point measurement: it measures the material under the sensor antennae

2. MFL **CAN** detect pitting

3. AIA Interpretations are <u>idealised shape defects</u> (perfect cylinders of a given depth and diameter)

4. AIA reports a plot locating 10 worst (depth) defects per 1m axial inspections

5. A nominal value (e.g. utility supplied info, average ultrasound spot measurements) is needed as a reference to measure leakage/defects against

6. In CI pipes, AIA interpretation does **NOT SEEM** to relate well to actual pipe profiles of wall thickness in relation to defect depth or location

7. Preliminary analysis indicate unsuitability for stress analysis from supplied idealised pitting defects. However, it may be more suitable for stress analysis when raw data is studied in ellipsoidal large defect form, and/or for gaining more pipe detail from sparse data (see Activity 4a)

What Have We Learned About RFT in CI

1. An RFT signal does **NOT REPRESENT** a point measurement of wall thickness, it measures volume of material under the receiver coil antennae
   - The location of defects is given according to their centre with an accuracy of 2mm along the axial direction, and 82mm along the circumference

2. RFT can not detect high-resolution pitting (it depends on the size of the receiver coil, which remains unknown)

3. Russell NDE's RFT implementation is an in-line Inspection pig with an array of receiver antennae around the circumference of the pipe

4. In CI pipes, Russell's interpretations seems to relate to actual average volumes of pipe thickness

5. Pipe ferromagnetic properties (e.g. conductivity, permeability) induce a source of noise in both components of the signal (amplitude and phase shift)

6. Current analysis indicate unsuitability for stress analysis from supplied defect and average RWT. However, like MFL, an analysis of larger ellipsoidal shape defects from raw data is possible, and sparse defects can contribute to information gain in a fusion step (see Activity 4a)

What Have We Learned About Acoustic PWA in CI

1. Acoustic PWA detects anomalies on pipe wall through acoustic wave propagation

2. Pure's Acoustic PWA is an In-line Inspection technique

3. Measurements represent pressure waves which could be related to **AVERAGE** pipe thickness. This is not straightforward

4. Pure's Acoustic PWA appears to **LACK** the sensitivity for detecting pipe wall losses/defects in large metallic pipes

5. Preliminary results appear more promising in non-metallic AC pipes

6. Sahara PWA remains a technique under development

What Have We Learned So Far about CA in CI

1. All techniques have got shortcomings in being able to provide an accurate picture of pipe wall thickness

2. From a qualitative point of view of CA, all techniques provide some information relevant to the CA processes carried out by utilities – as it is being done today

3. From a quantitative point of view of CA, the interpretations provided in the inspection reports by most technologies (i.e. MFL, RFT, Acoustics) are unsuitable for the purposes of stress analysis and failure prediction. In most cases though, the raw data does have the potential to do so

4. Establishing the perceived limitations, reported accuracies and errors of the various techniques pose significant challenges, and overcoming them within the limitation of the sensing principles, for the purpose of failure analysis in conjunction with Activity 1 and 3 constitutes the next and final phase of this project