

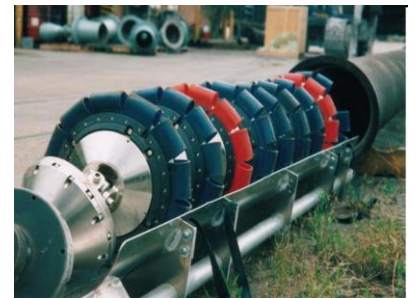
Activity 2: Direct Condition Assessment Methods

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



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 (x5):

- Buddhi Wijerathna (PhD candidate) – Thesis submitted Sept'15
 - Magnetic Flux Leakage modelling (AIA)
- Nalika Ulapane (PhD candidate) – Thesis submitted Sept'15
 - 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)
- David Hunt (Technical Assistant, Sept'15 – Dec'16)
- Interns

Note:

Buddhi Wijerathna and Nalika Ulapane have also been temporarily appointed as Research Associates for ~1 day/week since March 2015

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

Presentation Outline

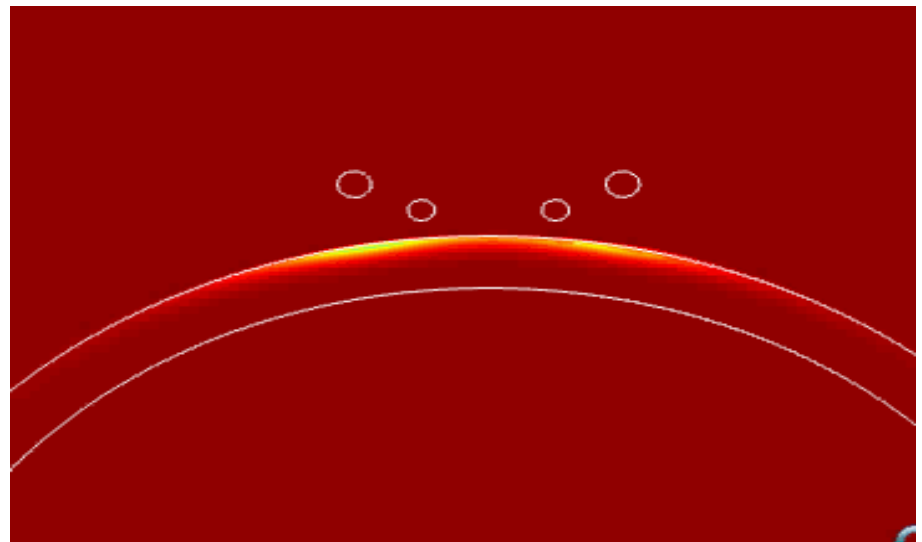
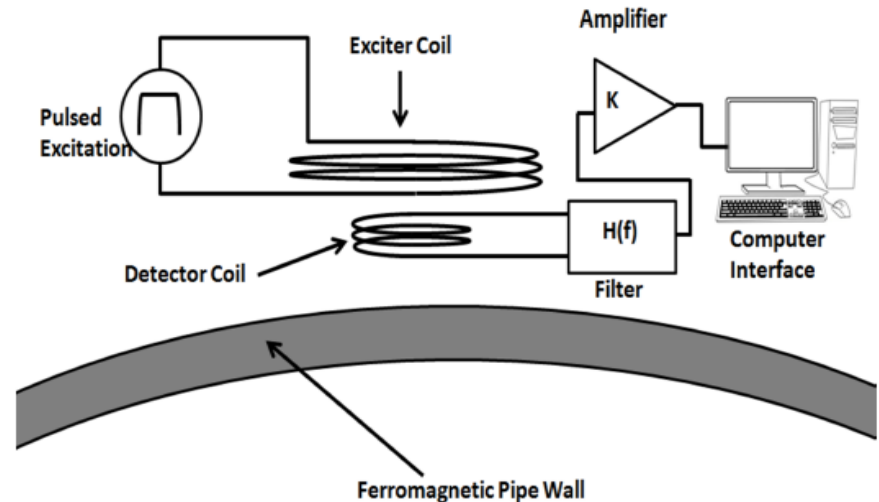
1. Research **findings**
 - Rock Solid Group (BEM)
 - Asset Integrity Australia (Advanced Engineering Solutions Ltd) (MFL)
 - Russell NDT Technologies/PICA (RFT SeeSnake)

2. What have we learned **so far** about MFL, BEM, RFT and Acoustic PWA for the purpose of CA

RSG (BEM): State of Affairs and Current Progress

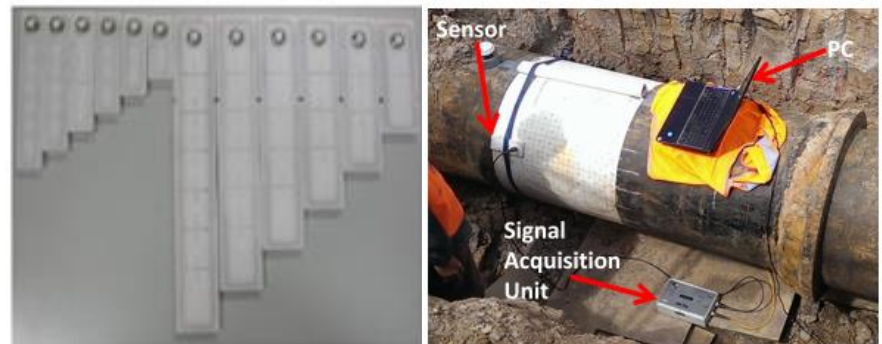
Broadband Electro-Magnetics (BEM): Brief Technical Description

- 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



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



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
5. Multiple **receiver** antennae (e.g. 6 way antennae) is less suitable to produce results of similar sensitivity to single **receiver** antenna sensor, RSG researching on a new multiple **sensor** antenna
6. Preliminary analysis indicate **suitability** for stress analysis, if **coarse**

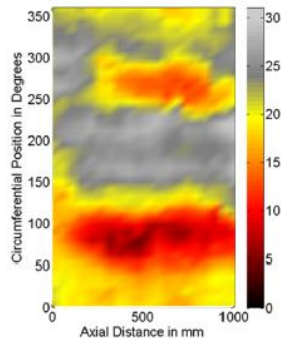
BEM and Material Property Calibration in CI

1. UTS work has shown that there exists a BEM signal feature β , which can be used to estimate average pipe wall thickness d localized to an area underneath the sensor (area = 50 mm x 50 mm) through a function in the form of

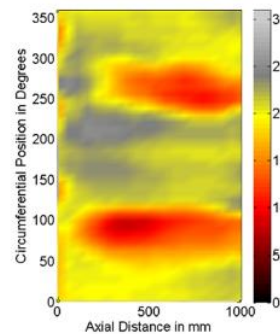
$$d = f(\mu, \sigma, \beta)$$

where μ and σ represent electrical and magnetic properties of a pipe.

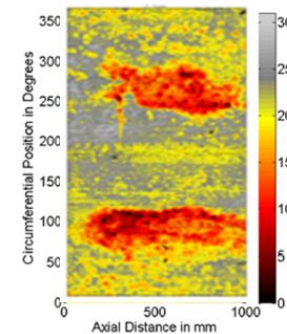
2. When μ and σ are known, our research showed that the BEM technology can estimate average pipe wall thickness in an area of 50 mm x 50 mm to an accuracy of over **92%** (tested on 12 CI pipe segments, 9 from Sydney Water test bed and 3 from Water Corporation pipes).



UTS estimated thickness map



Ground Truth
(averaged down to BEM resolution)



Ground Truth
(laser scanner - high resolution)

BEM and Material Property Calibration in CI

3. To estimate wall thickness with best accuracy calibration is essential. This can be done by means of:
 - estimating pipe electrical and magnetic properties
 - using accurately calibrated ultrasound measurements
 - performing BEM measurements on known thicknesses of the **exact** material being tested

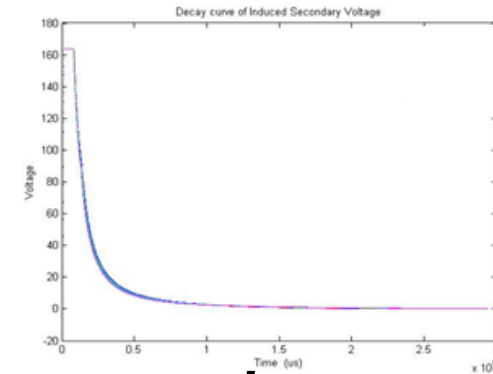
As mentioned in 2), **UTS interpretation** algorithms carried out with **calibration** done by the above means achieved accuracies up to **92%** in 9 pipe segments from the Sydney Water Test bed. Standard **RSG interpretation** procedures by means of their calibration blocks showed accuracies up to **85%** on the same pipe segments.

BEM and Material Property Calibration in CI

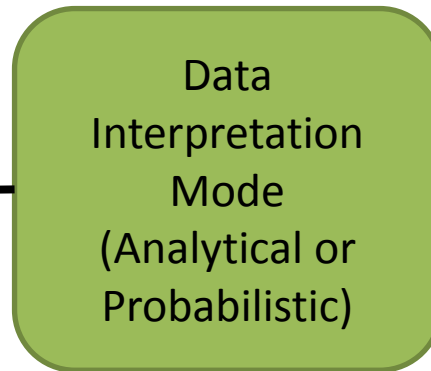
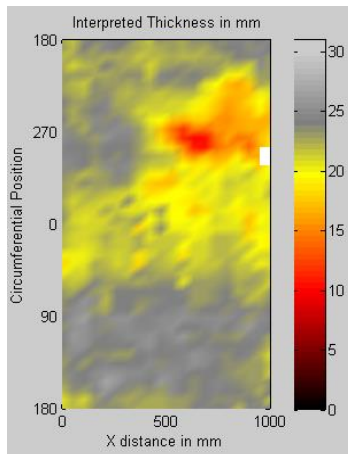
4. An error of up to **5%** in estimated thickness with BEM has been observed due to material property variations in Gray Cast Iron belonging to the same pipeline (as per Sydney Water test bed).
 - Variability of material properties was quantified via **PPMS** and **XRF** measurements using 12 specimens extracted from different locations on the test bed.
 - Measurements on more specimens are being performed to enhance confidence on variability.

UTS Development 1: BEM Data Interpretation Model based on Calibration Blocks

Obtain generic calibration data (RSG "Calibration Blocks")



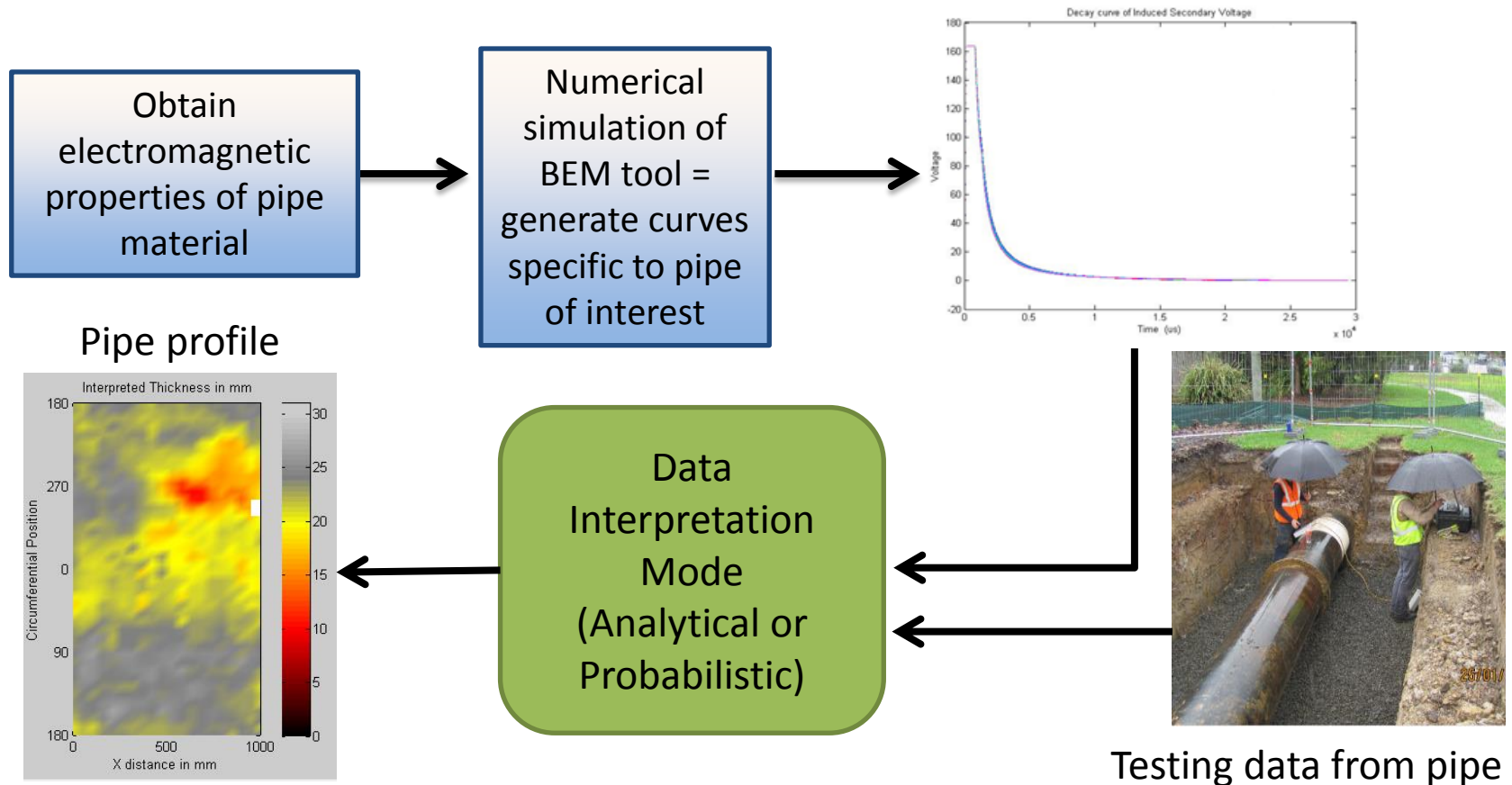
Pipe profile



Testing data from pipe

UTS Development 2: BEM Data Interpretation Model based on Numerical Simulations

To account for possible effects from variations in material properties



Summary Current State of Affairs

1. UTS has delivered preliminary software to RSG for enhanced estimation of thickness from BEM data from their **Single Receiver Antenna** design
 - Readily available for use by Technology Provider
 - Probabilistic interpretation provides an estimate of uncertainty
 - The **Multi Receiver Antenna** design often used commercially by RSG at present was not incorporated in this research, in accordance with the agreed project schedules
2. Software performs estimation of thickness on-the-spot
 - 16ms per measurement, including obtaining measurements from HSK Kit (~14.4s)
3. The approach exploits the discriminative features found in the BEM raw data and machine learning algorithms to provide more accurate estimates

Pending

1. Estimation of electrical and magnetic properties of 30+ already extracted pipe wall specimens to further ascertain variability in properties.
2. If RSG is forthcoming, liaising with them to validate and advance their latest multi antennae sensor where findings from this research work can be readily incorporated for field deployment.

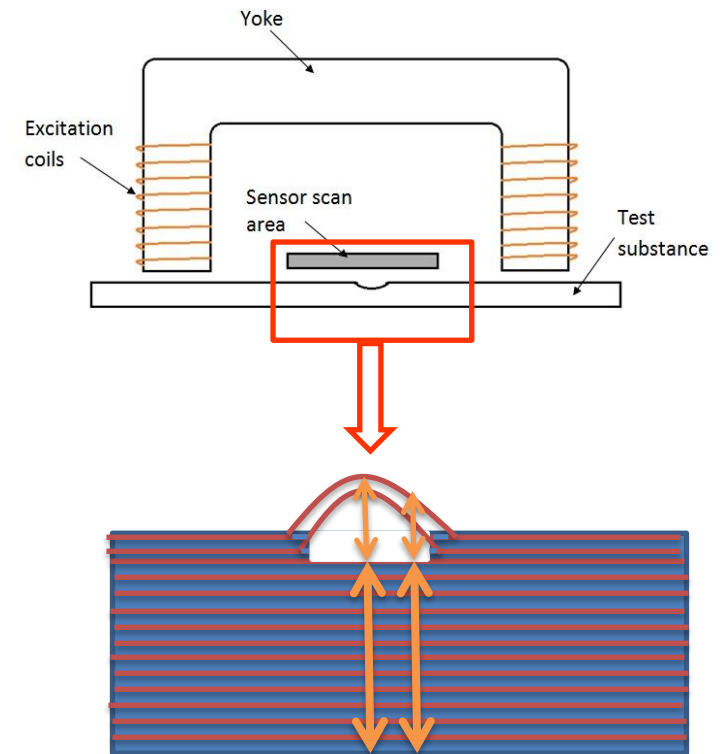
BEM: Current Progress and Future Goals

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
Studying the effect of lift-off on the BEM antenna to evaluate the capability of scanning through cement lining	Completed
Trial 6 Data Analysis	Completed
Developing BEM laboratory setup	Completed
Quantification of variation in material properties	Completed (Additional measurements being performed)
If RSG is forthcoming, liaising with them to validate and advance the multi antennae sensor for field deployment	In progress

MFL (AIA): State of Affairs and Current Progress

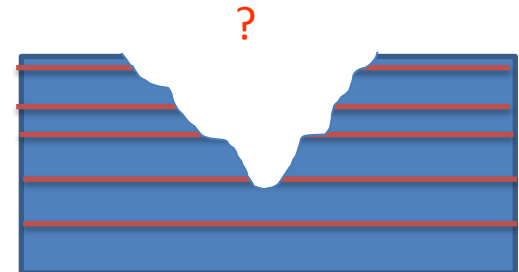
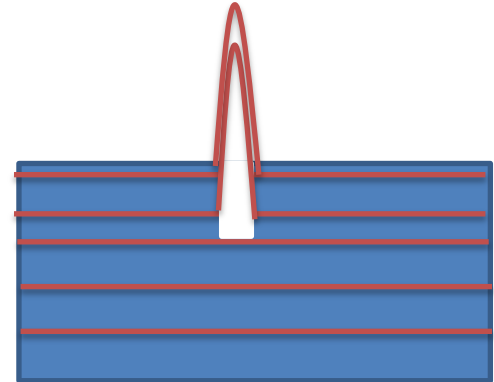
Magnetic Flux Leakage (MFL): Brief Technical Description

- 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, state of the art MFL technologies provide measles plots(not 3-dimensional reconstruction of pipes and defects)



Magnetic Flux Leakage (MFL): Challenges

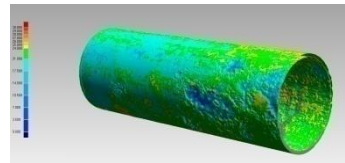
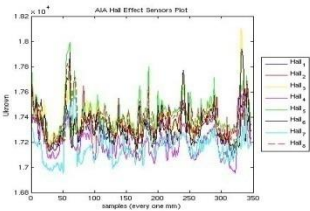
- MFL signal is affected by (not exhaustive)
 - Variations in the air gap - needs to be kept constant
 - Variations in the pipe materials – inhomogeneous
 - Variations in pipe thickness - in manufacturing
 - Shape of the defects – Cylindrical, conical etc
 - Distribution of the defects
- Combination of above and possibly others can contribute to prediction errors



What Have We Learned About MFL in CI

1. MFL signals can approximately **REPRESENT** a point measurement: it measures the material under the tool
2. MFL **CAN** detect pitting
3. AIA Interpretations are **idealised shape defects**
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
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. MFL data can be interpreted in **ellipsoidal large defect** form to assist the SCF equations for **stress analysis**, and/or for gaining more pipe detail from sparse data (see Activity 4a)

UTS Development 1: Modelling Sensors Through Bayesian Learning: Non-linear Regression



Simulation/
real data

x

Ground
truth

y

Machine
learning
algorithm

$$y = f(x) + \epsilon$$

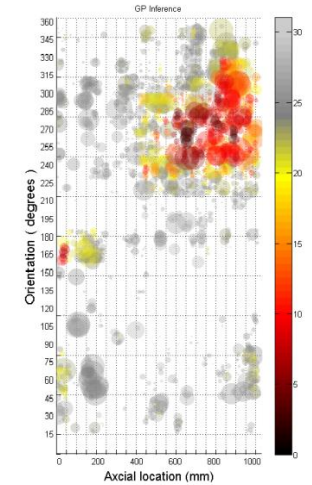
new (real)
sensor
data

x^*

Non-parametric
model with
uncertainty



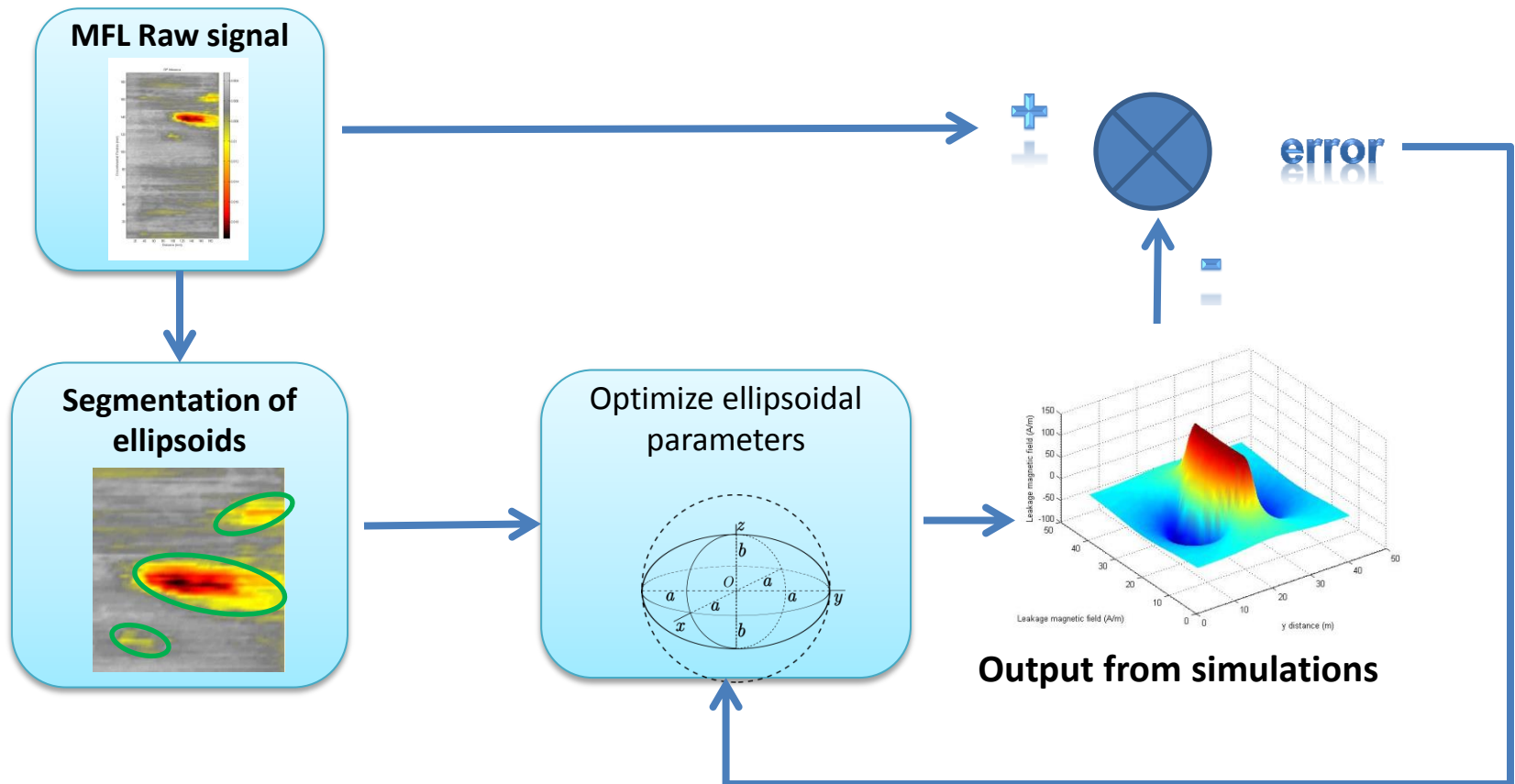
Estimated
condition +
uncertainty



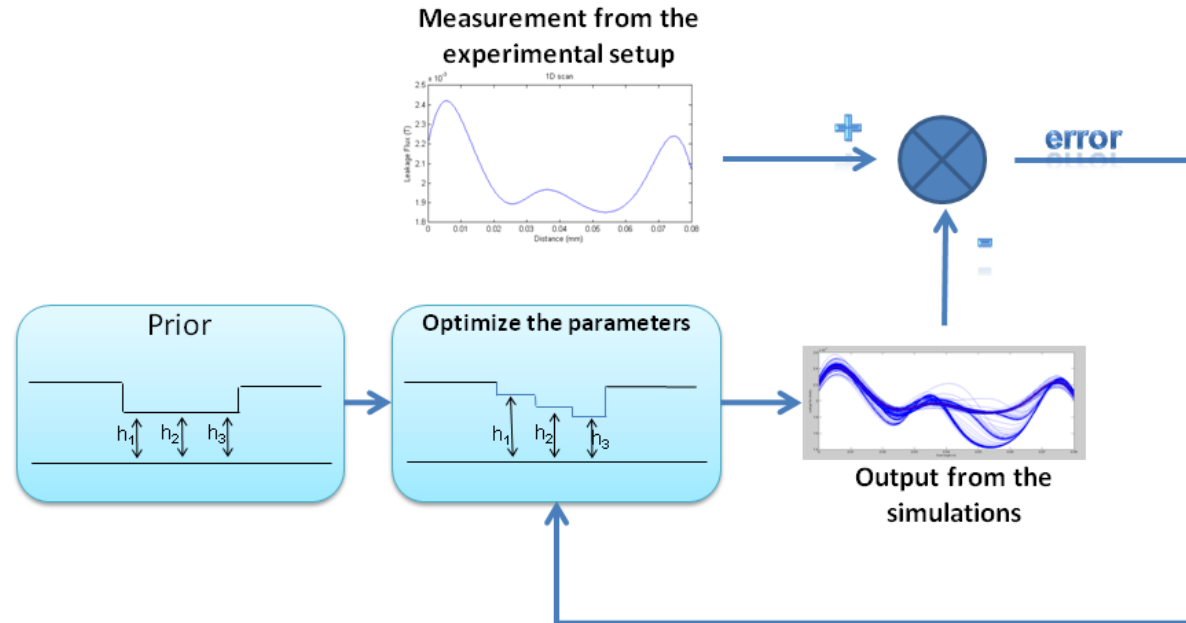
$$y^* = f(x^*)$$

UTS Development 2: Iterative Ellipsoidal Approximation of Defects

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

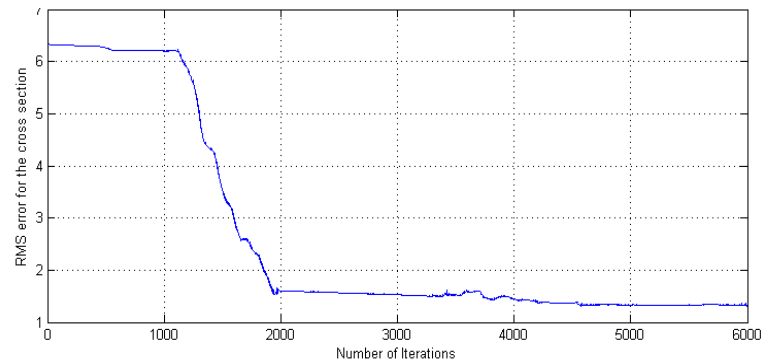
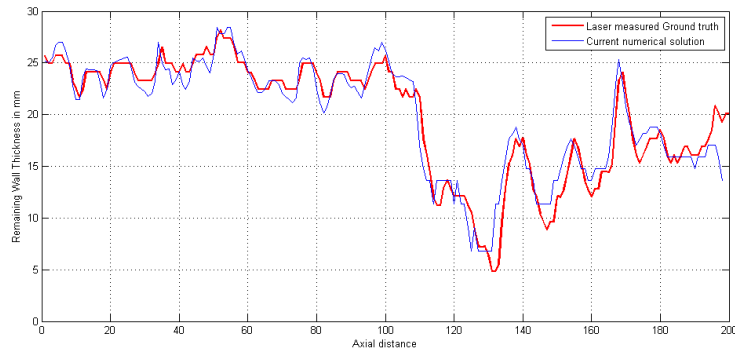
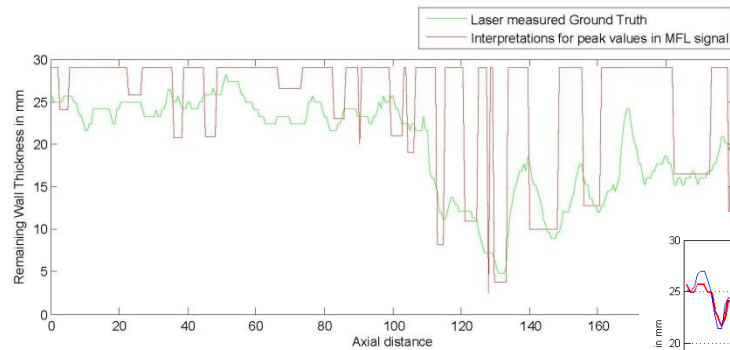


UTS Development 3: Iterative Coarse-to-Fine Approach



- 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 however it is computationally intensive

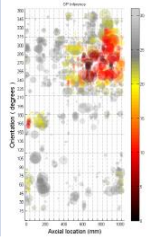
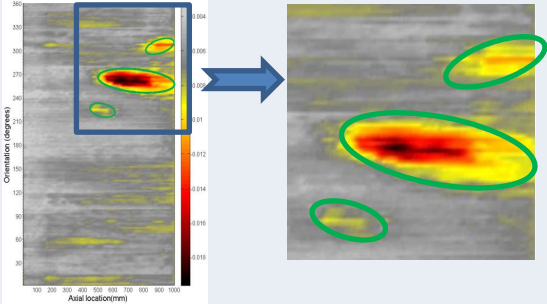
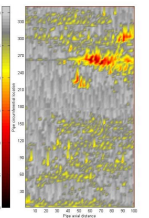
UTS Development 3: Iterative Coarse-to-Fine Approach



RMS error variation with number of iterations

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

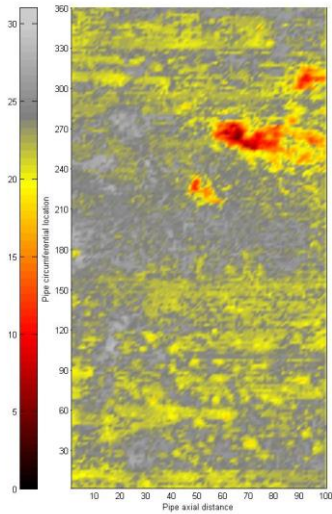
Current UTS Interpretations from MFL Signals

	Pros	Cons
<p>UTS Measles plot</p> <ul style="list-style-type: none"> Industry partner produces measles plots 	<ul style="list-style-type: none"> Fast generation of the plot (~ 5 minutes) Can identify defect sizes as individual pits 	<ul style="list-style-type: none"> Defects approximated to cylindrical defects Cylinders overlap to each other Needs pre-trained models
<p>UTS Ellipsoidal approximation</p> <ul style="list-style-type: none"> As per feedback from Activity 1 	<ul style="list-style-type: none"> Can be used for stress analysis purposes Fast computation (~7 minutes per ellipsoid) 	<ul style="list-style-type: none"> Does not produce a detailed dense representation of the pipe section remaining wall thickness
<p>UTS 2.5D thickness map</p> <ul style="list-style-type: none"> MFL signal has information to produce thickness map 	<ul style="list-style-type: none"> High resolution 2.5D representation of the remaining wall thickness 	<ul style="list-style-type: none"> Computationally very expensive (~10 days of automated data processing)

Current UTS Interpretations from MFL Signals

AIA Measles plot
(10 worst defects)

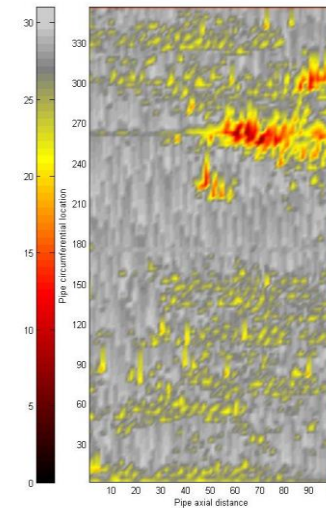
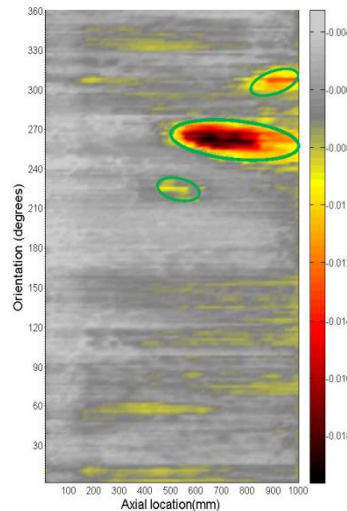
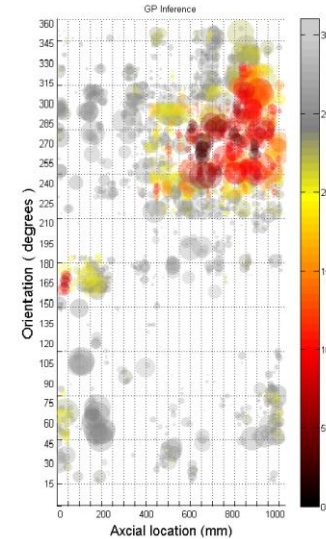
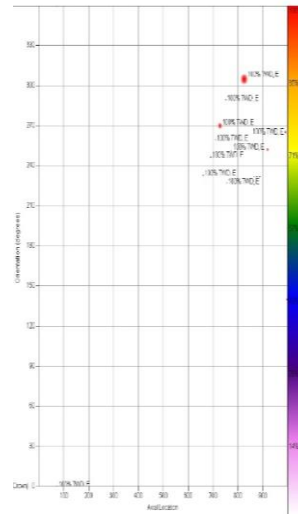
UTS measles plot
analysis



Ground Truth



UTS ellipsoids
approximation
approach on
simulated MFL
signal



UTS 2.5D
optimized solution

Summary Current State of Affairs

1. UTS has delivered a preliminary Software Module for MFL data interpretation and received feedback
2. AESL personnel (Ewan McDonald) spent a week (From 1st December 2014 to 5th of December 2014) at UTS - technology transfer
3. A comprehensive document ('AIAResultsEvaluation_20141107.pdf') illustrating the accuracies of the AIA/AESL predictions (RWT) and UTS prediction (RWT) on Trial inspections was sent to AIA/AESL on 07/11/14 and received feedback on 21/04/2015
4. A semi-automatic lab set up was developed
5. A framework for estimating ellipsoidal defect profiles is proposed and tested
6. A framework for continuous defect profiling is proposed through global optimisation methods
7. PhD candidate has completed his study and awaiting graduation

Pending

MFL: Current Achievements

Goal	Status
Generation of 3D defect profiles using machine learning	Completed (published at SIPE conference)
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 (to AIA). Improvements are possible if AIA is interested
Development of a realistic simulation model for the output of AESL tool	Completed (based on limited available feedback and contrasted data)
AIA /UTS predictions Vs Ground truth analysis	Completed (Report sent to AIA)
Analytical Model-Aided Optimisation for Ellipsoidal Defect Approximation	Completed
Reconstruction of Dense 2.5-D Thickness Maps using MFL Measurements	Completed
Buddhi Wijerathna PhD thesis on “Magnetic Flux Leakage Based Advanced Condition Assessment for Aged Cast Iron Pipes”	Completed (under review)

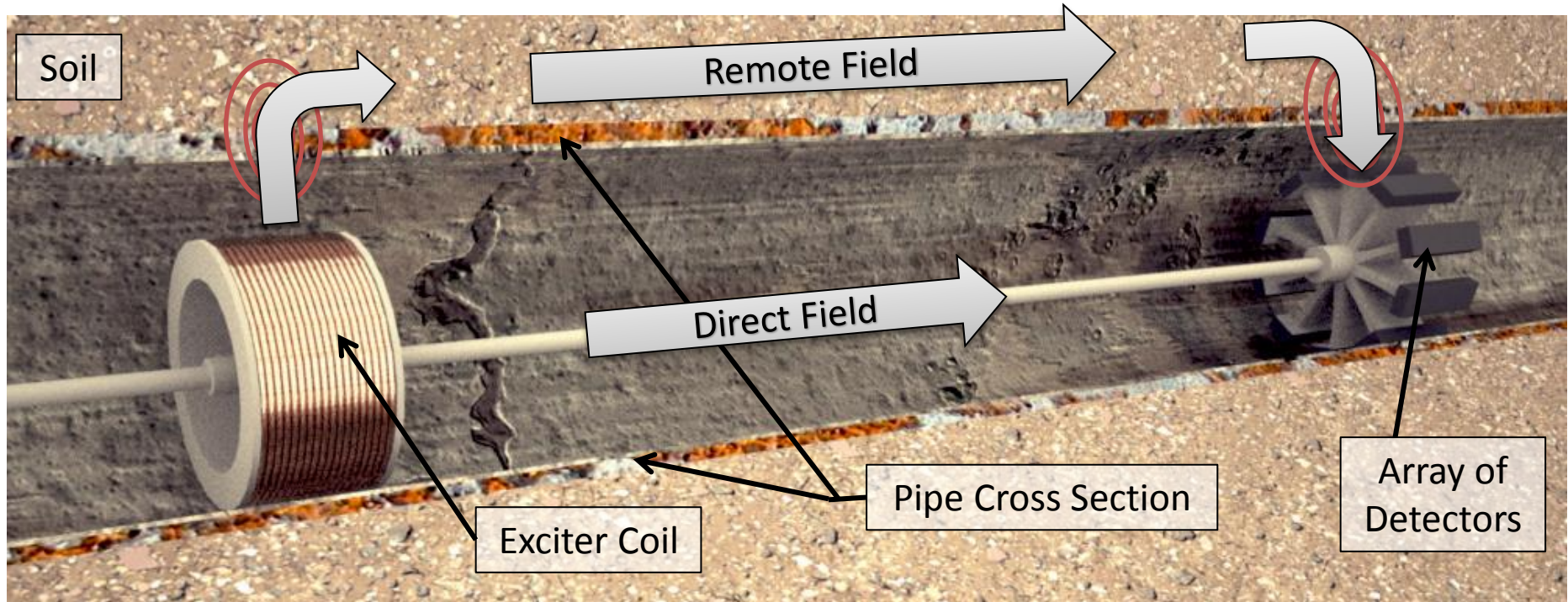
RFT (Russell NDT/PICA): State of Affairs and Current Progress

Remote Field Technology (RFT): Brief 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 off-line to generate information of the wall thickness



Remote Field Technology (RFT): Brief Technical Description



Near Field
Zone

Transition
Zone

Remote Field
Zone

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 a resolution 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 provider analysis (pitting defect and average RWT) appears unsuitable for stress analysis. Like MFL, **larger ellipsoidal** shape defects from raw data appears **promising**. Moreover, sparse defects can **contribute** to information gain in a **fusion** step (see Activity 4a)

Summary Current State of Affairs

1. UTS has developed and shared with Russell NDE a software to automatically detect joints using raw data
2. UTS has performed FEA of the RFEC phenomenon
 - 2D axisymmetric simulation
 - 3D simulation using various symmetries
 - Realistic simulations with laser scanner data
3. 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
4. UTS has implemented an algorithm to improve the localisation of the ground truth within the RFT data
5. UTS has implemented an automatic defect detection algorithm
 - An outlier removal algorithm to ignore the effect of the signal near the joints based on machine learning
6. Engagement with Russell NDE has been revised to advance outcomes more effectively
 - Semi-simulated data using FEA will be used to advance the project instead of See Snake data

Pending

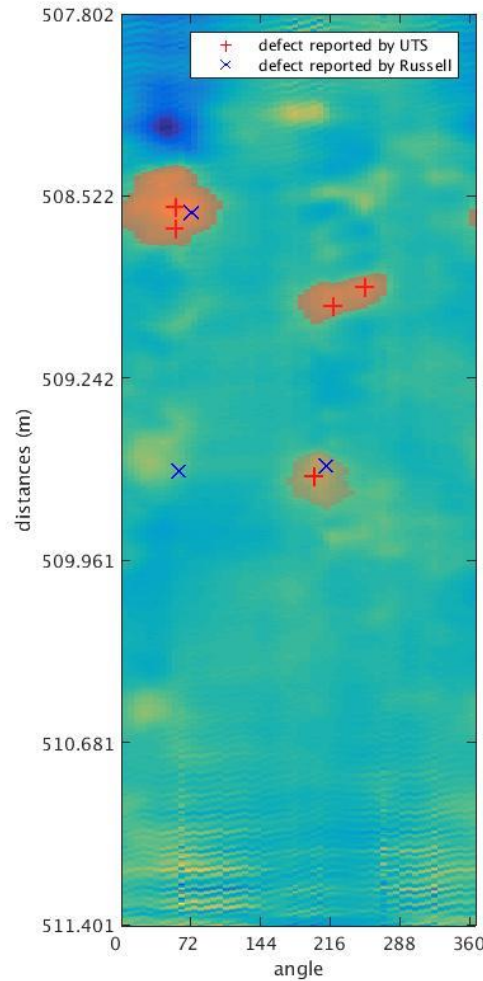
1. Development of a methodology to recover the shape of large defects (in-progress)
 - Implementation of image segmentation techniques commonly used in computer vision
 - Use of supervised learning to automatically segment the shape of large defects
 - Manual labelling is required to perform correct training
2. Using pre-selected data to characterise isolated defects
 - Utilise the given distance between receiver and emitter in a standard RFT tool
 - Realistic RFT FEA simulations on ground truth
3. Sizing of the remaining wall thickness (using the fact that phase-shift of RFT signal appears ~ linear with respect to thickness)
 - To generate pipe profiles with continuous data for in between validation
 - To size large defects

Shape Segmentation of Defects

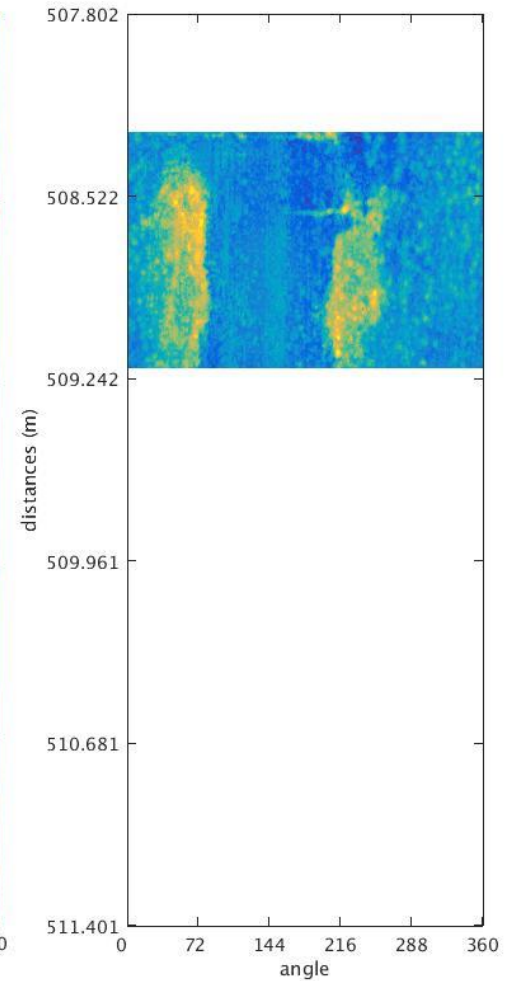
RFT (naïve method)



RFT (advanced method)



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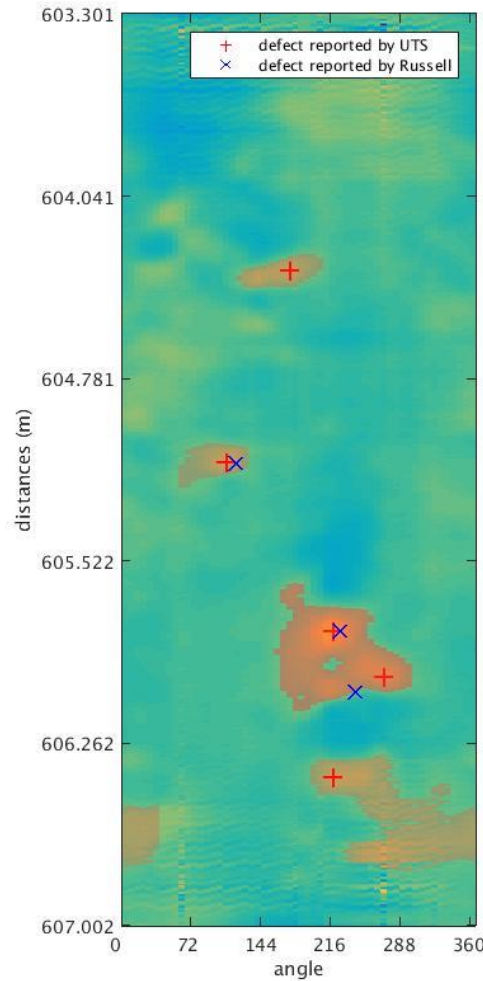


Shape Segmentation of Defects

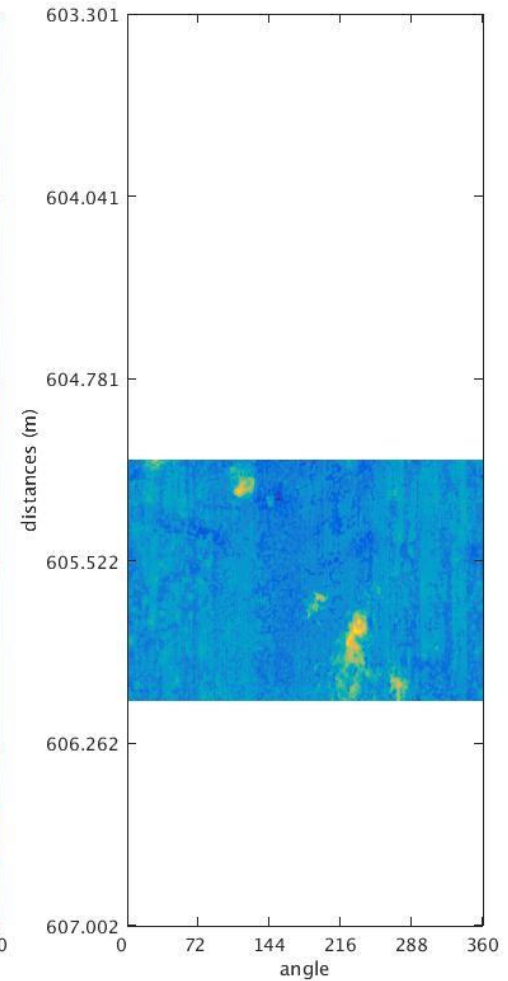
RFT (naïve method)



RFT (advanced method)



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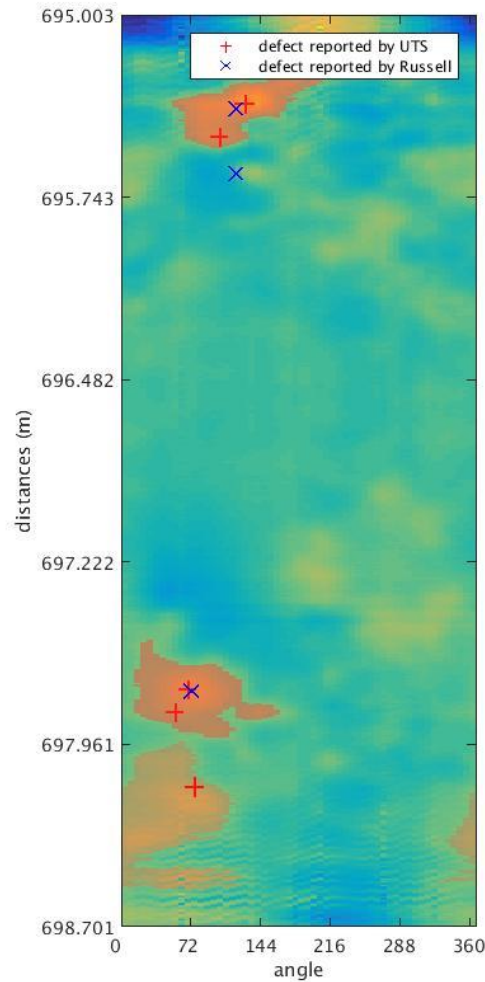


Shape Segmentation of Defects

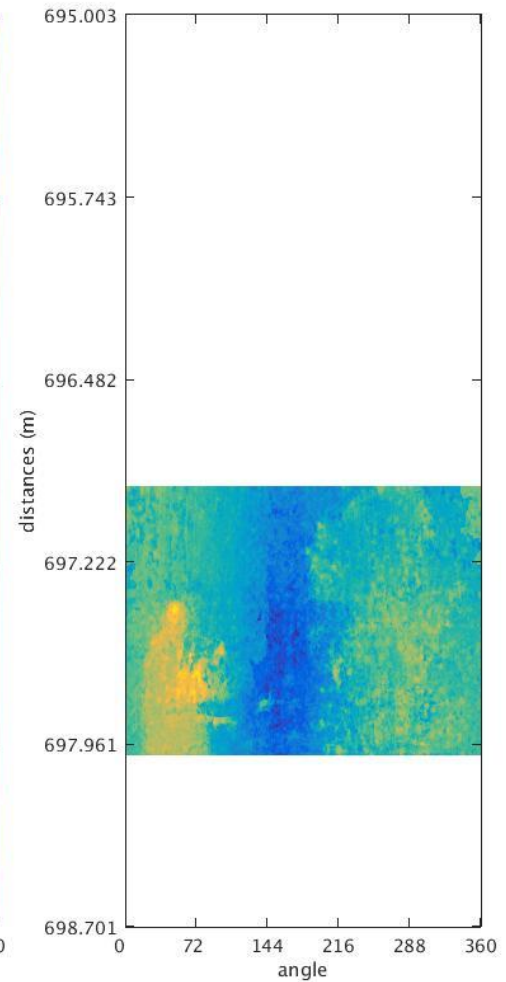
RFT (naïve method)



RFT (advanced method)



GT



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
Improvement in the localization of the ground truth within the RFT data	Completed [IROS Paper - Published]
RFT interpretation vs. Ground truth comparison (Trial 6)	In-progress
Implementation of a shape detection algorithm for defect characterisation in raw RFT data	In-progress
Feature analysis on the RFT raw signal to characterise defects (in terms of shape and size)	In-progress
Further analysis on data normalisation for thickness interpretation	In-progress

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. As per guidance from Activity 1, from a quantitative point of view CA interpretations provided in current inspection reports by most technologies (i.e. MFL, RFT, Acoustics) today might not be fit for the purpose of stress analysis and failure prediction. However, in most cases the raw data is being proven to be able to do so
4. The CA research findings from Activity 2 have produced advanced interpretations strategies for the various sensing technique studied – an analysis of their suitability as building blocks towards the remaining life prediction of long sections of pipeline being developed in Activity 4 is underway