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Activity 4a: Enhancing the Reliability of Condition Assessment of Buried Large Diameter Water Mains

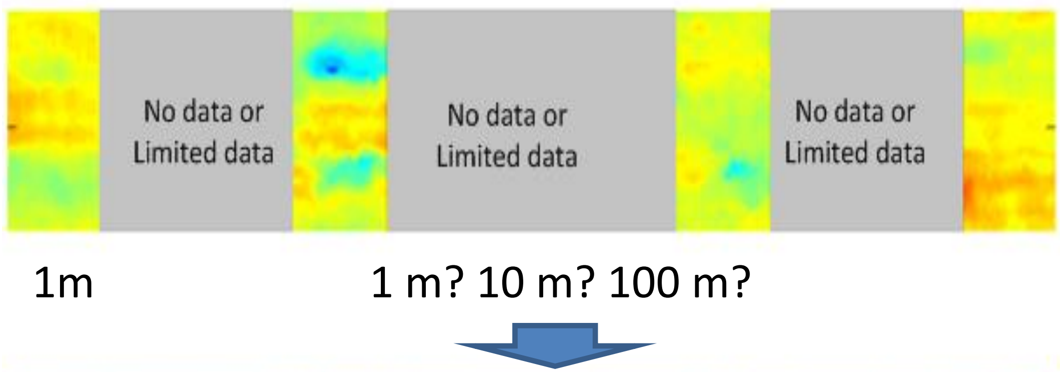
Activity Co-leaders: A/Prof. Jaime Valls Miro, Prof. Gamini Dissanayake

UTS

Scope Activities 4a: In-Between Interpretation

Key Expected Outcomes:

Framework to assess in-between interpretations of pipeline condition from limited inspections



Pipe Wall Thickness Map

* Approaches for 1 m and 100 m in-between are quite different

* Longer distance is more challenging. This is our target.

Activity 4 – 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 (x3):

- Dr Lei Shi (Leo)
  - In-between, Upcoming Technologies, LPR ML
- Ms Liye Sun (PhD candidate)
  - Multimodal Information Fusion for Advance Condition Assessment of Ageing Infrastructure
- David Hunt (Technical Assistant, Sept'15 – Dec'16)

Presentation Outline

1. Summary Current State of Affairs
2. In-Between Framework
   – Methodology
   – Interim Evaluation
   – Robust Evaluation Plan
3. Data Fusion
4. Stand-alone Applications Derived from In-Between Framework
   – Sampling Inspection
   – UTS EVA
5. Final Thoughts

Summary Current State of Affairs and Latest Progress

1. UTS has developed a methodology based on spatial statistics (Gaussian Processes) to estimate continuous geometry

2. A data fusion approach has been developed to combine different sources of information. The output is a robust common probabilistic representation of the pipe thickness

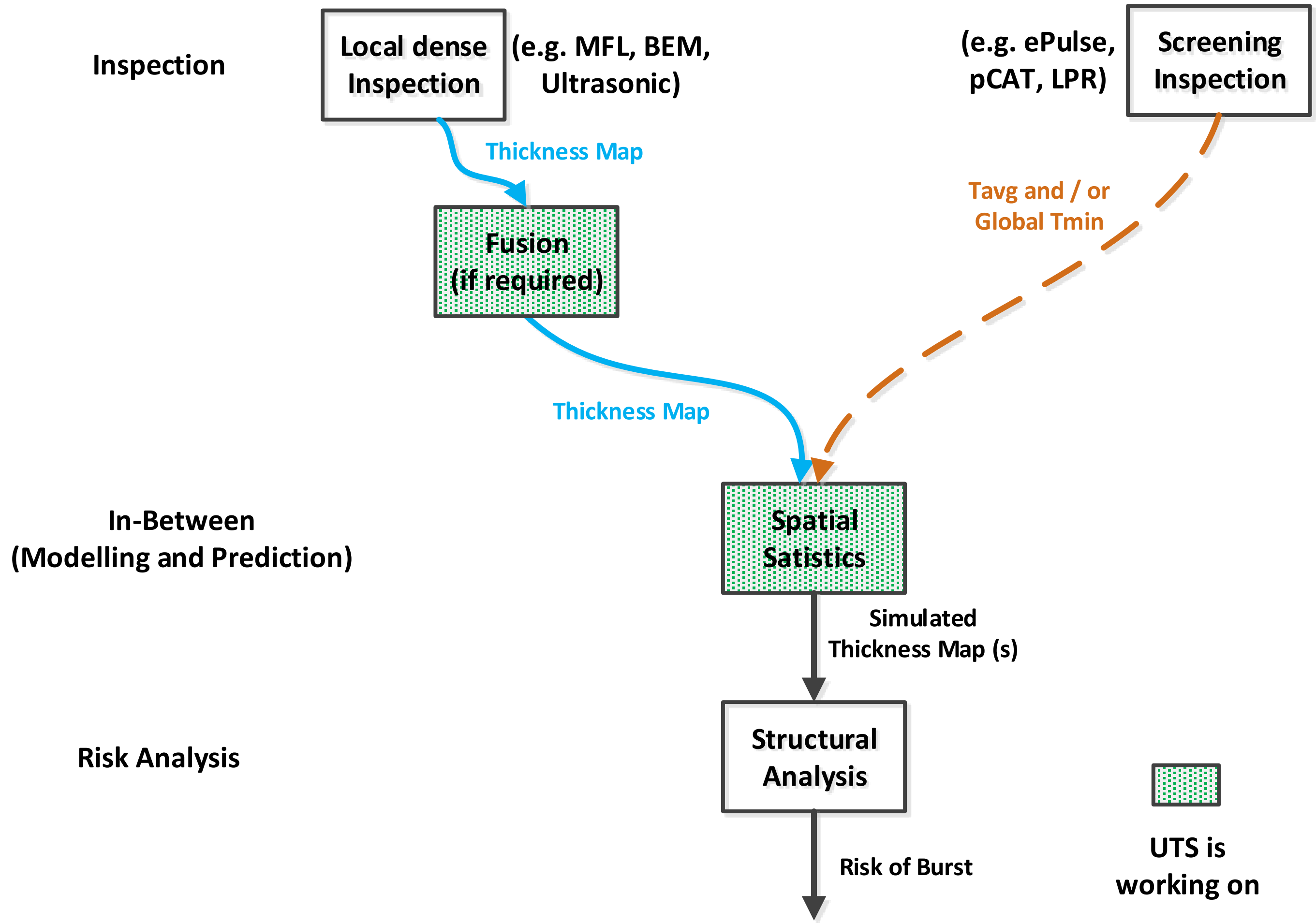
3. The link between the in-between framework and maximum pitting related corrosion modelling (e.g. from Activity 3) has been established

4. The link between the in-between framework and stress analysis (e.g. from Activity 1) has been established

5. Validation of the in-between framework has been conducted with limited data (12 one meter sections) collected from test bed

6. A validation plan has been developed and is being put into practice to further validate the in-between framework with sufficient data

The Big Picture



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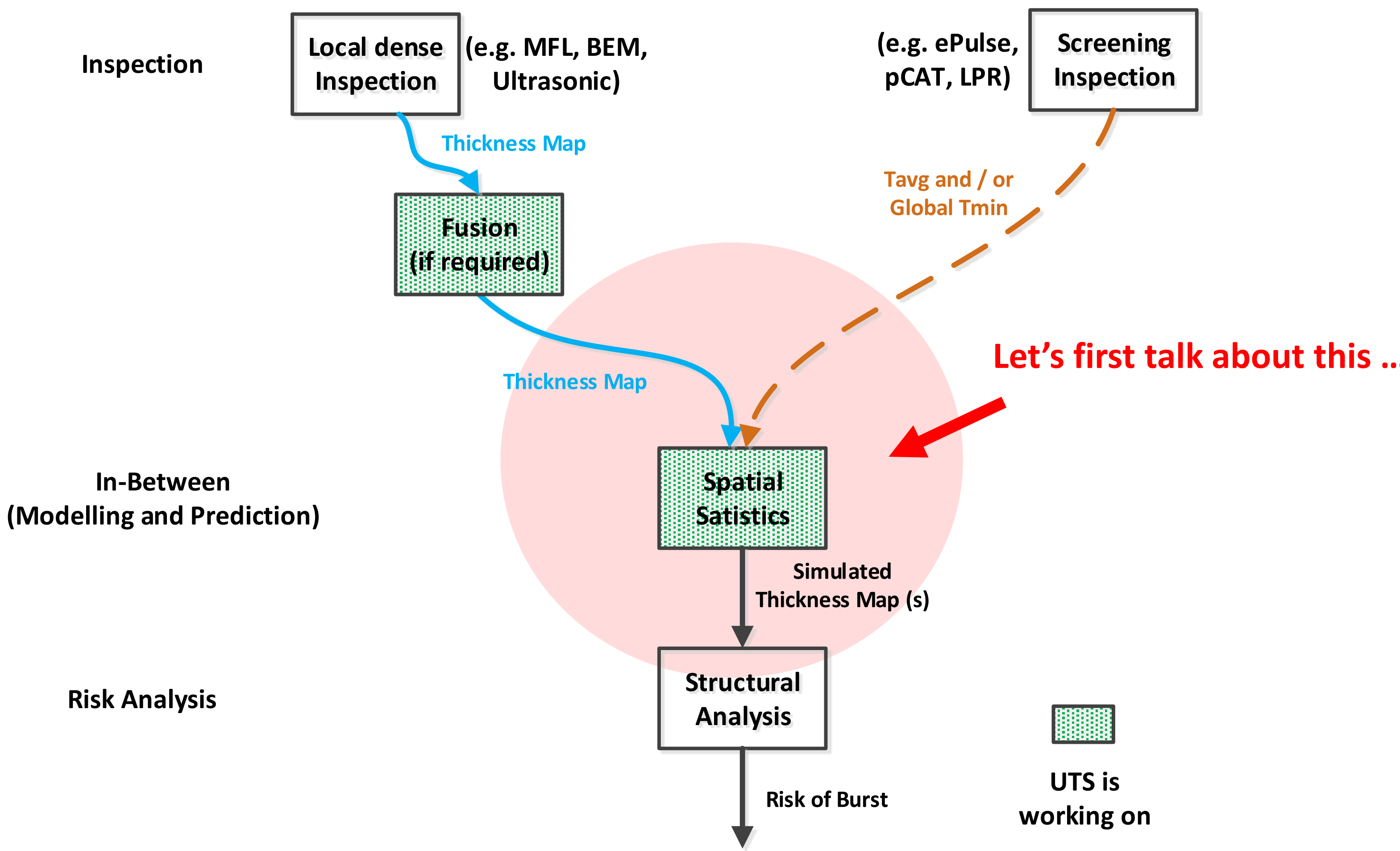
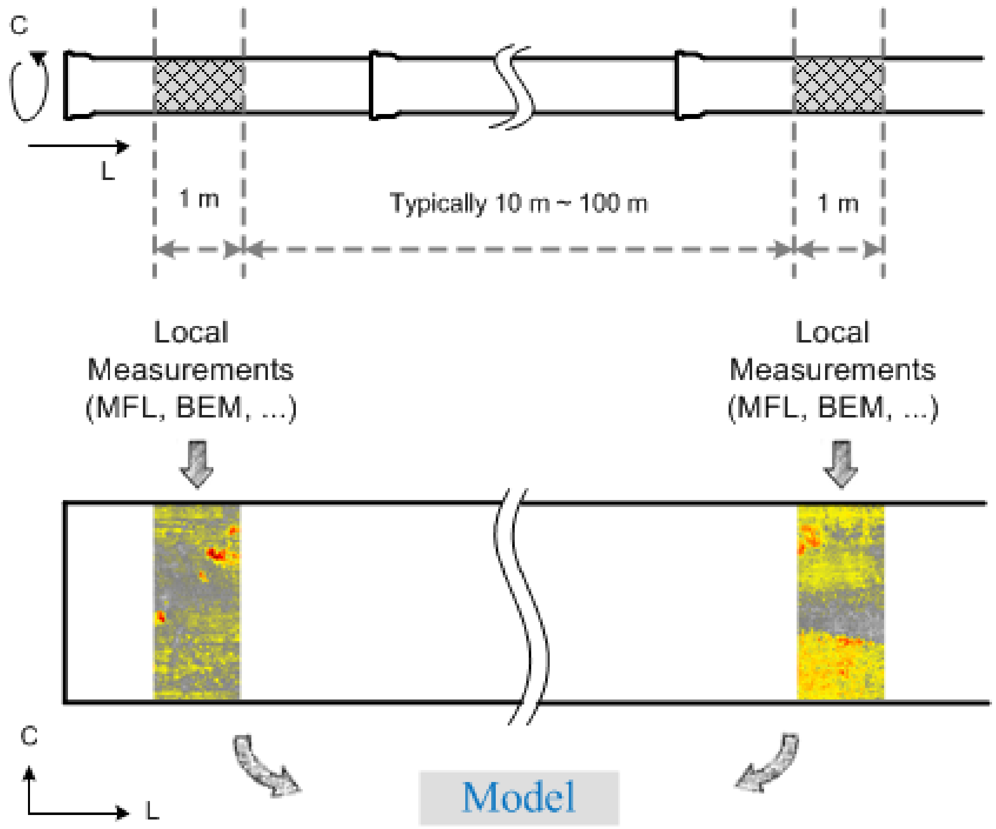
The Big Picture



Reminder: In-Between Prediction

The Framework – Modelling



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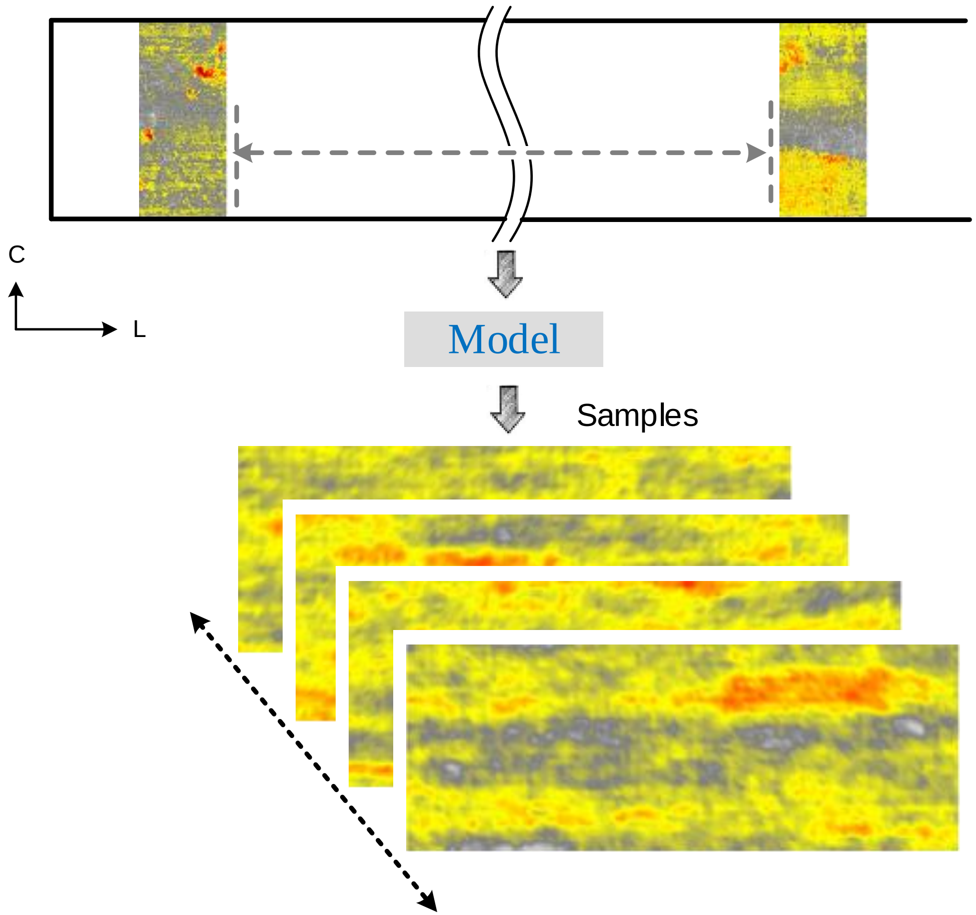
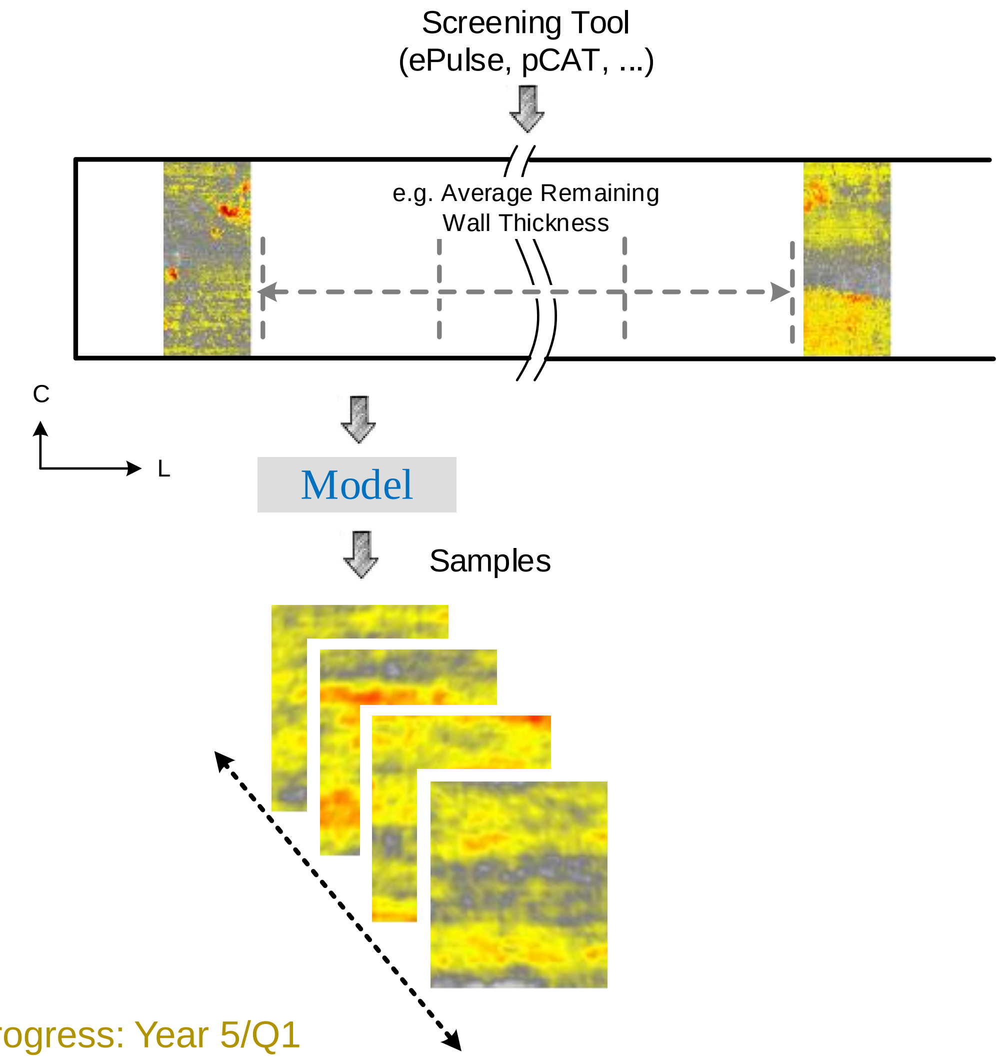
Reminder: In-Between Prediction

The Framework – Prediction
(without reliable screening input)



Reminder: In-Between Prediction

The Framework – Prediction
(with reliable screening input)



In-Between Prediction
Spatial Statistics Model – Advantages

In local inspections:

- Conventional statistical extrapolation looks for isolated pitting
- UTS in-between looks for data correlation:
  - How remaining wall thickness is spatially distributed

In unknown areas:

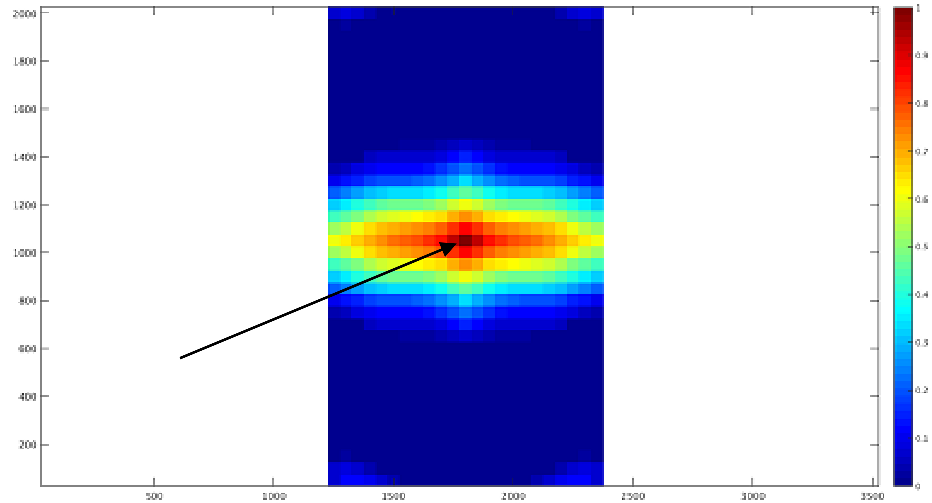
- Conventional statistical extrapolation aims to predict the most “serious” pitting
- UTS in-between predicts on the statistical representation of the geometry, which contains information about the most “serious” pitting, and more

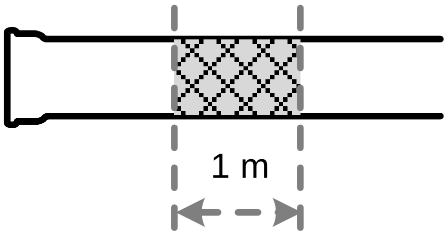
For risk analysis:

- Conventional statistical extrapolation aims at “time to penetration”
- UTS in-between prediction aim is structural analysis as advised by Activity 1 findings. It is also able to provide “time to penetration”

In-Between Prediction

Spatial Statistics Model – Correlation Maps





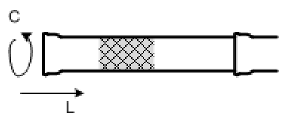
Correlation map from statistics

From 12 x one meter pipe segments collected from the SW testbed,

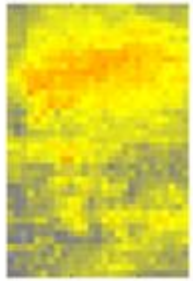
- Given any point, the strong correlation reaches 35 cm each way axially, 10 cm each way circumferentially
- Very weak correlation outside of this area
- The correlation range and pattern is what we aim to learn – pipe specific!!

Reminder: Case Study 1 from Last TAC

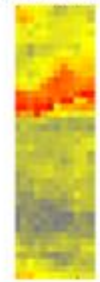
Training / Test Data



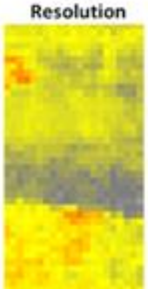
BEM Resolution



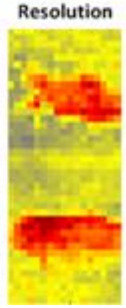
BEM Resolution



BEM Resolution



BEM Resolution



4 Pits labeled in RED: used for training (ideally given their relative condition attained from currently available screening results , e.g. Russell, ePulse, LPR)

8 Pits labeled in BLUE: used for testing

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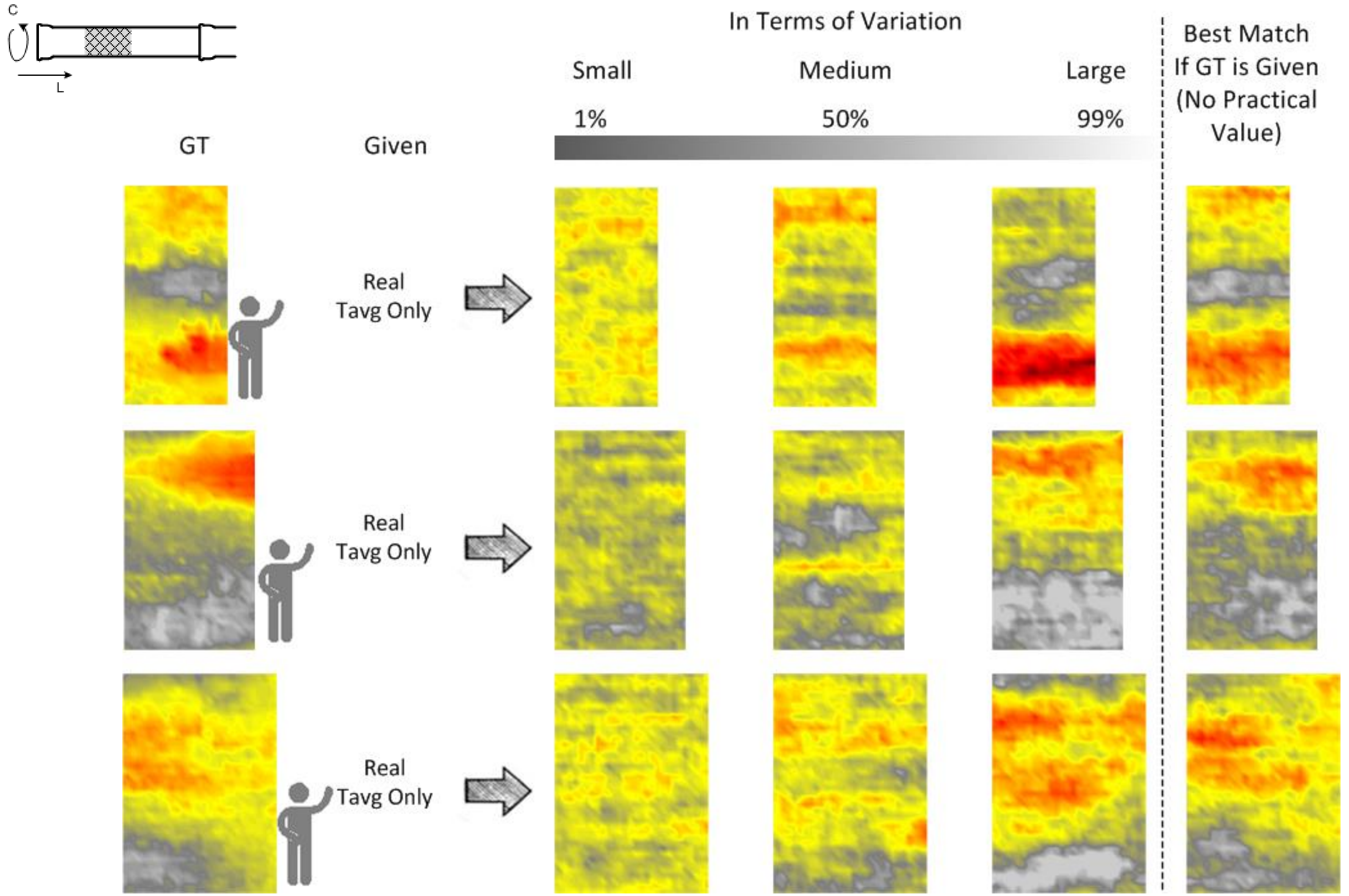
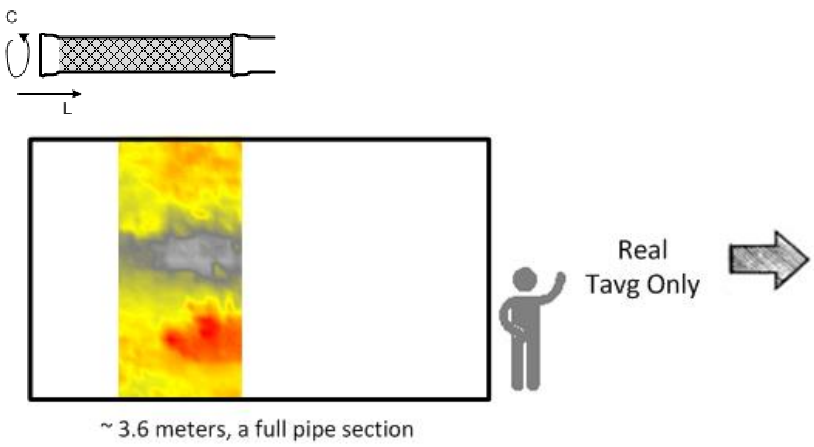
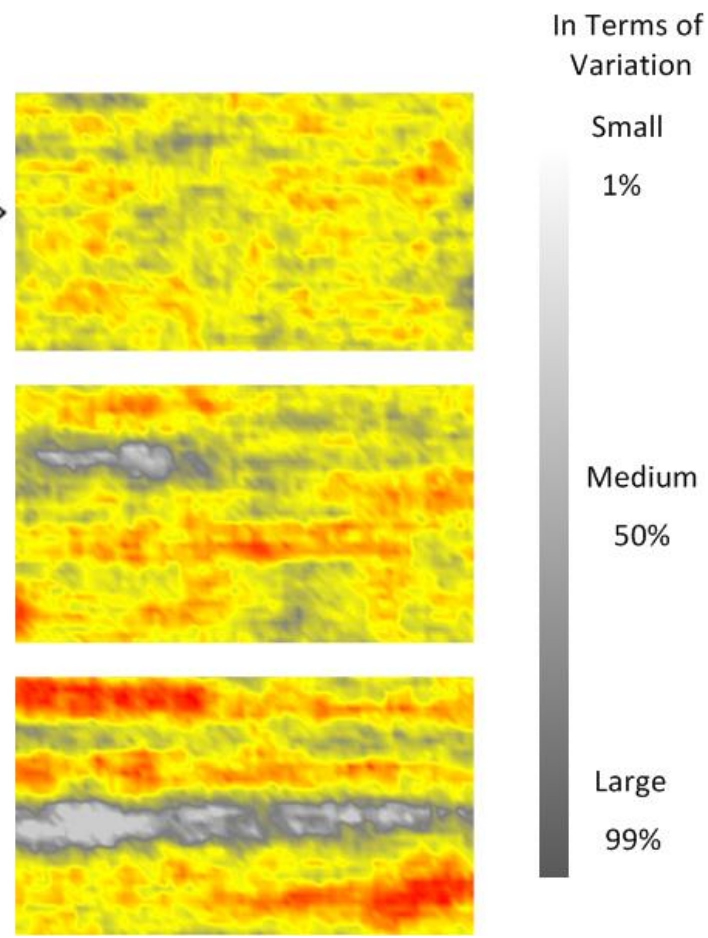
Reminder: Case Study 1 from Last TAC
Prediction Based on Tavg Only



Reminder: Case Study 1 from Last TAC Prediction Based on Tavg Only (arbitrary length*)





- Actual maximum length of a single instance only limited by available computer memory
- Note: it is not recommended to make one continuous prediction on a length longer than a pipe segment (joint-to-joint). Instead, break down target length into pipe segment lengths

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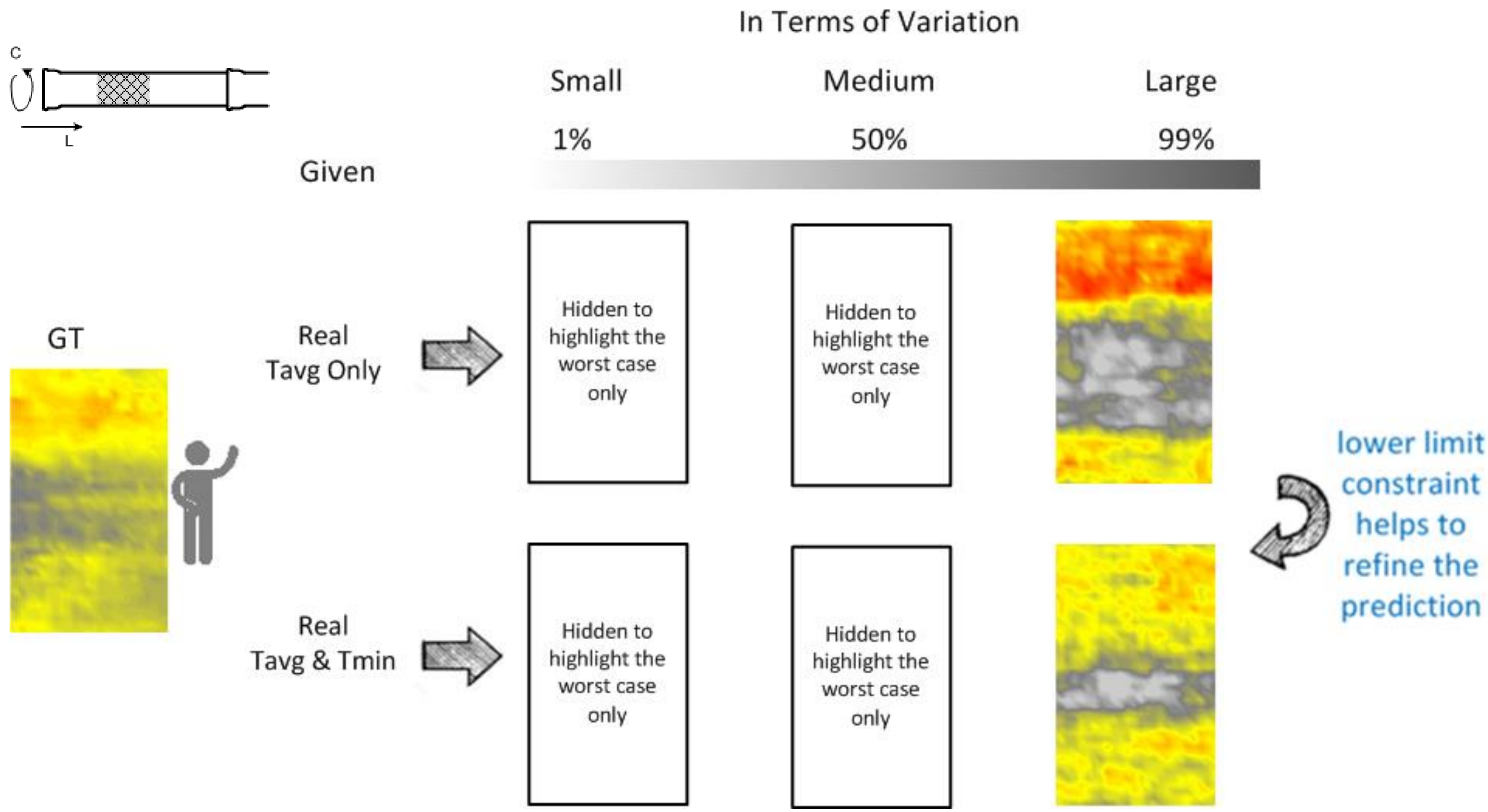
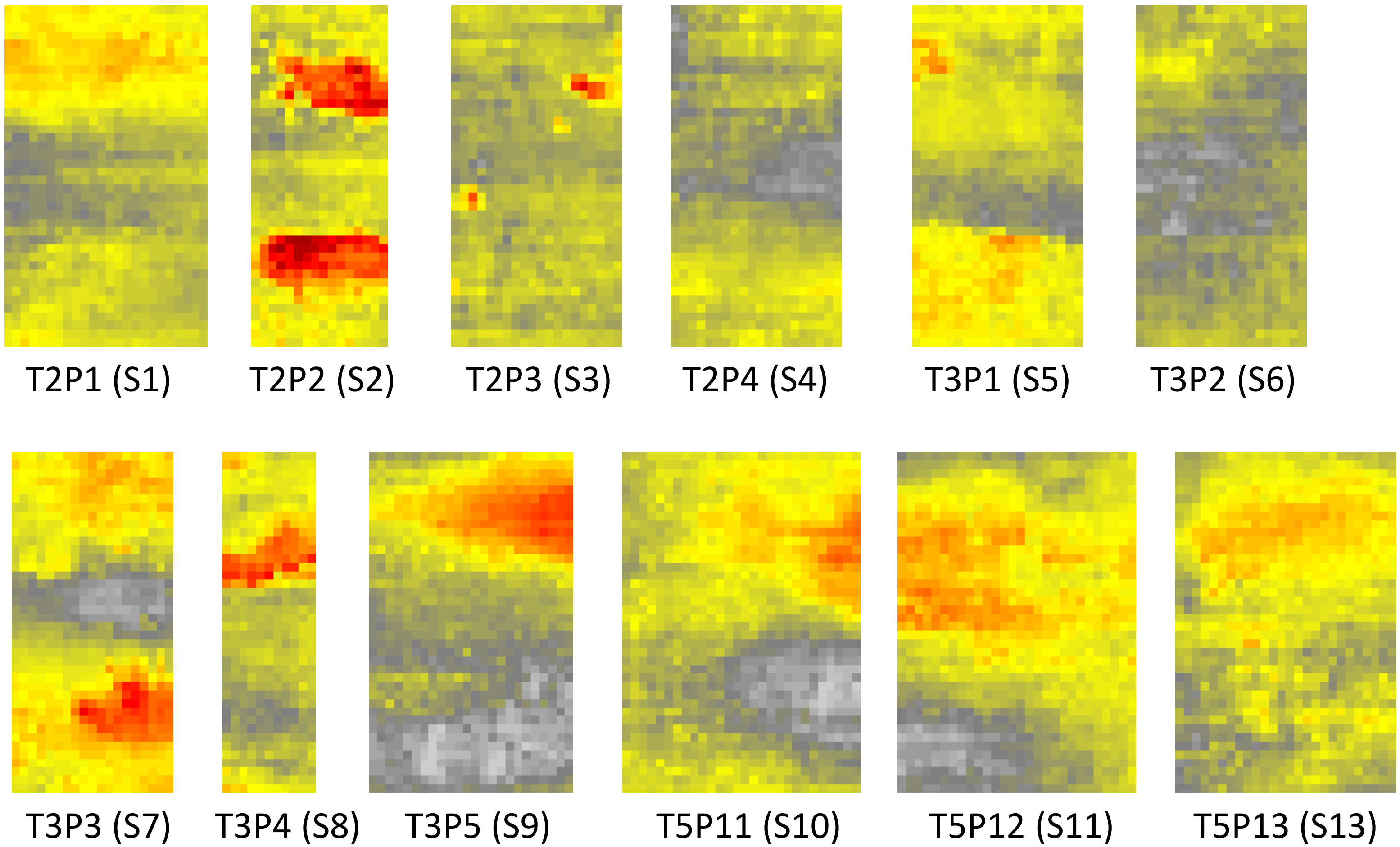
Reminder: Case Study 1 from Last TAC Prediction Based on Tavg and Tmin



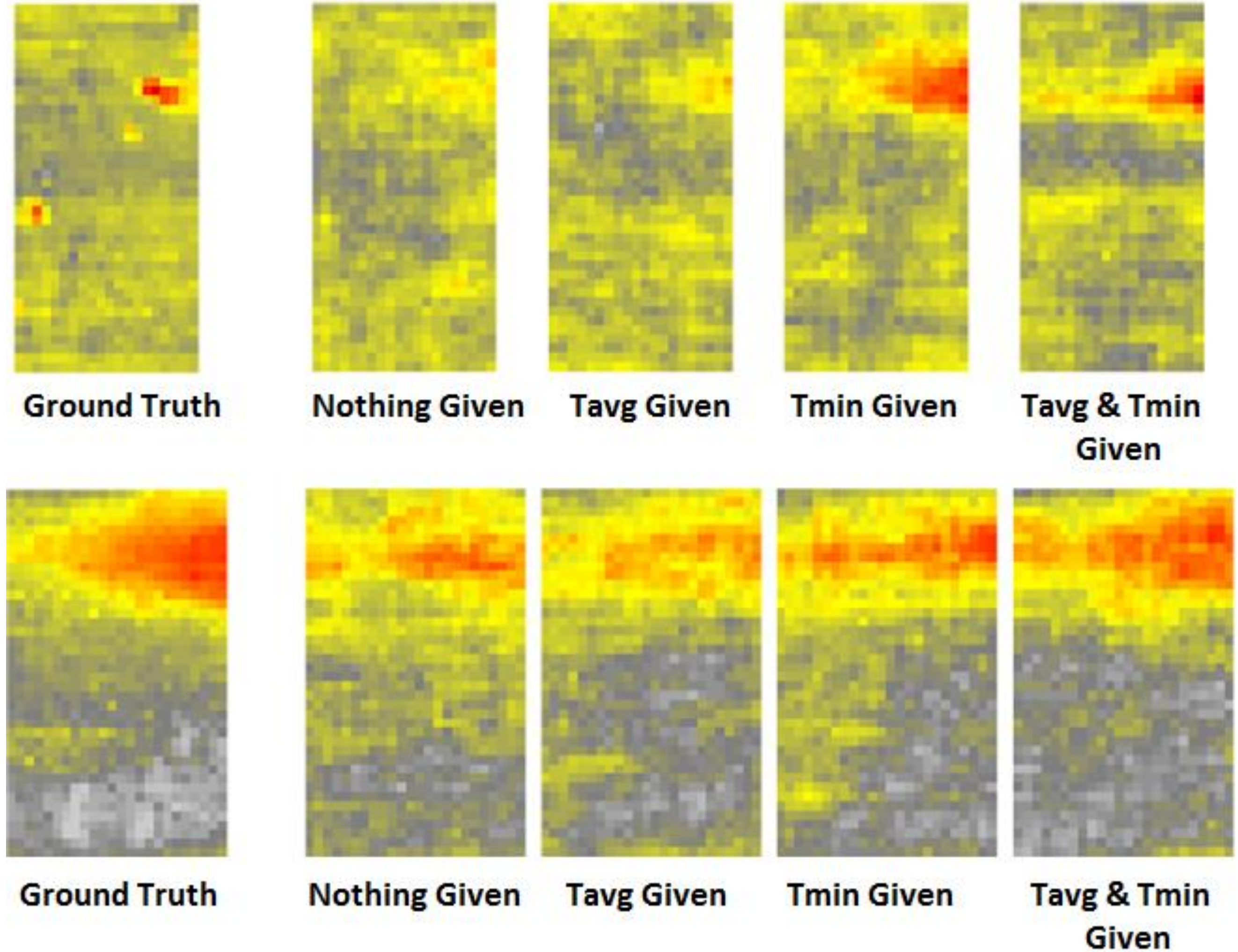
Quantitative Evaluation of In-Between Framework

Leave-one-out - More Comprehensive Experiments



Quantitative Evaluation of In-Between Framework

Experimental Results: 2 Examples



Quantitative Evaluation of In-Between Framework
Conclusions So Far

- Performance evaluated in terms of RMSE:

  Mean Given > Nothing Given

  Min Given > Nothing Given

  Mean and Min Given > Nothing Given

- The framework has been proven to be able to meaningfully incorporate mean/min/mean+min as constraints

- Generally speaking, more information gives more reliable prediction

- **The above findings are based on the assumption that the screening tools can provide what the framework needs**
  Q: how much trust can we put on available screening tools?

Further Evaluation of In-Between Framework

Do We Use Screening Tools?

The validation of the screening technique is **INTRINSIC** to in-between validation

1. If technique goodness is proven <u>insufficient</u>

- Guidance for local inspections for model building **X**
- Constrained sampling **X**

2. If technique goodness is proven <u>sufficient in relative terms</u>

- Guidance for local inspections for model building ✓
- Constrained sampling **X**

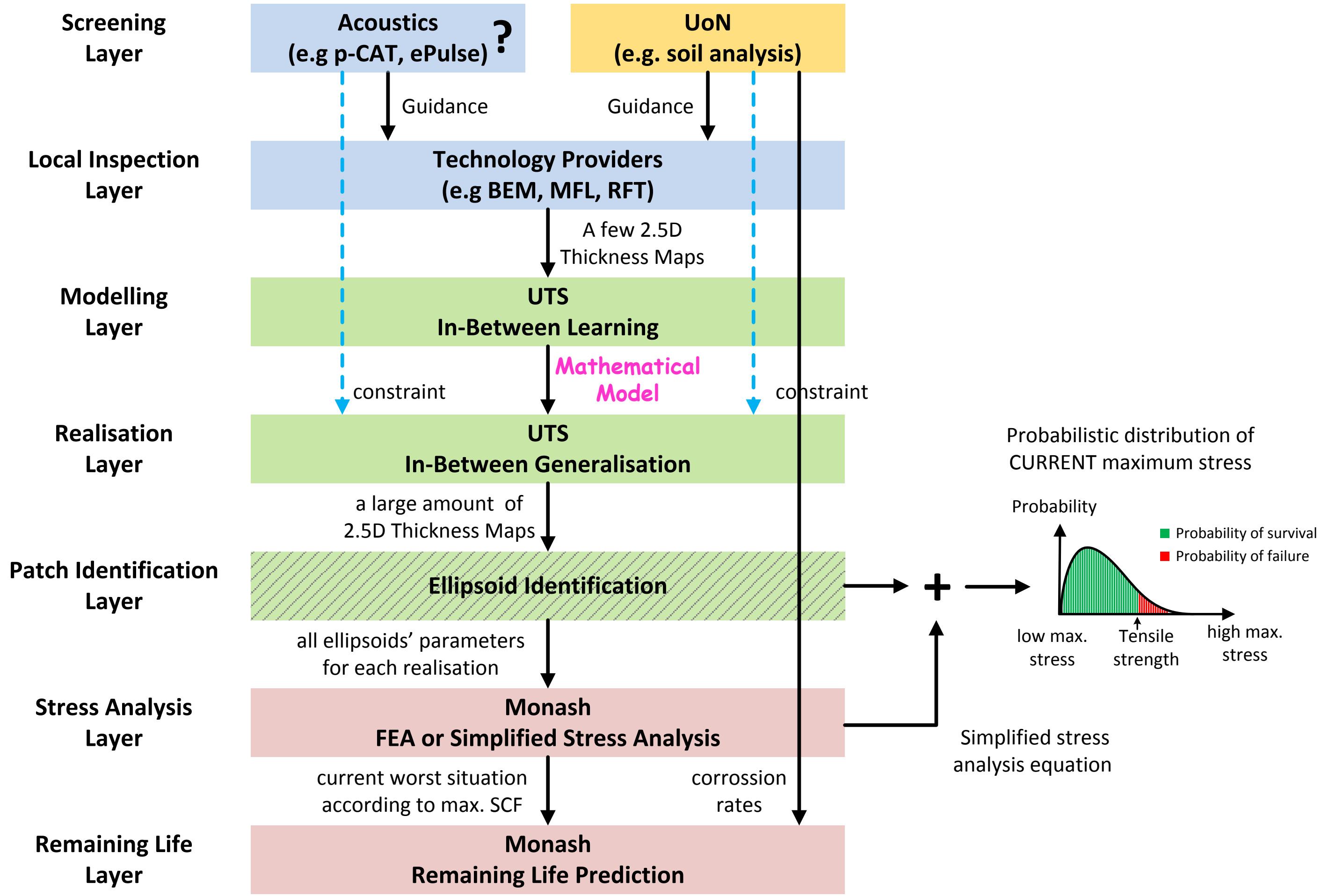
in-between framework prediction "with no reliable screening input"

3. If technique goodness is proven <u>in absolute terms</u>

- Guidance for local inspections for model building ✓
- Constrained sampling ✓

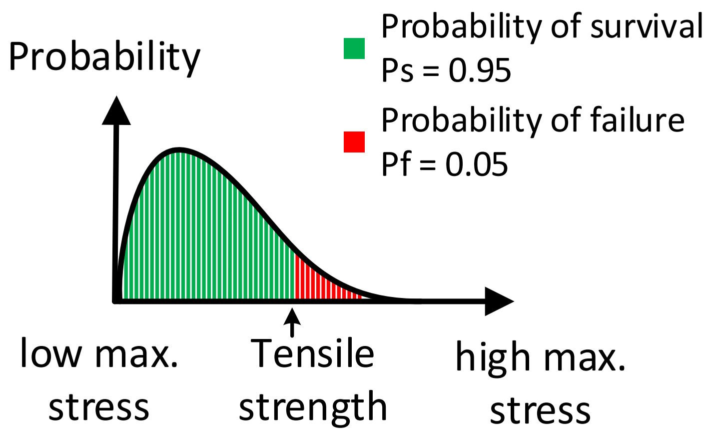
Evaluation of In-Between Framework

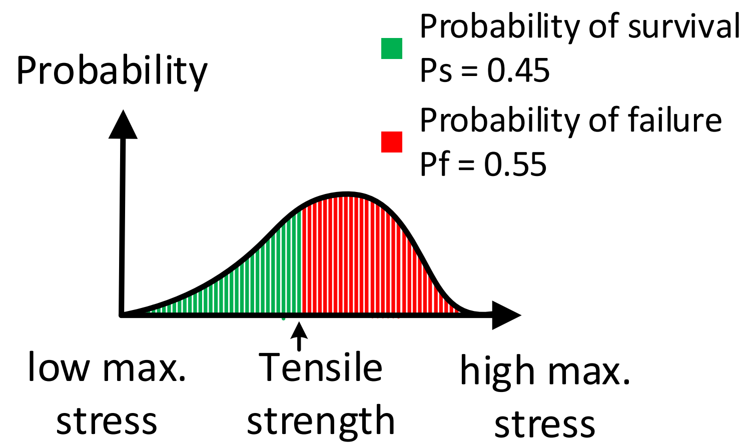
From Geometry to Stress Analysis



Evaluation of In-Between Framework

Probabilistic Distribution of Maximum Stress - Examples





What the above tells you:

The probability of survival/failure of any targeted length (e.g. 10 m) of pipe under the specified constraints

(Note: "no constraint" is a special example of the specified constraint)

What else can it also tell you? A "fun" probabilistic game ….

e.g. if Ps = **0.95** and Pf = **0.05** (high!!) for ANY 10 m, what can you say about 1000 m?

Probability ALL survive: Ps_1k = 0.95 ^ 100 = **0.0059** (Low!)

thus, probability at least one will fail: Pf_1k = 1 – Ps_1k = **0.9941** (Large!)

Evaluation of In-Between Framework

Preliminary Results from Test Bed

- A very recent draft version of an ellipsoid identification algorithm has been developed to extract all possible ellipsoids from a thickness map and incorporated into the framework
- Needs further verification particularly in integration with Activity 1

In-between Model

Realisations for Length = 1m

Ellipsoids

a1,b1,c1	a1,b1,c1	a1,b1,c1	a1,b1,c1	a1,b1,c1	a1,b1,c1	a1,b1,c1	a1,b1,c1	a1,b1,c1	a1,b1,c1
a2,b2,c2	a2,b2,c2	a2,b2,c2	a2,b2,c2	a2,b2,c2	a2,b2,c2	a2,b2,c2	a2,b2,c2	a2,b2,c2	a2,b2,c2
a3,b3,c3	a3,b3,c3	a3,b3,c3	a3,b3,c3	a3,b3,c3	a3,b3,c3	a3,b3,c3	a3,b3,c3	a3,b3,c3	a3,b3,c3
:	:	:	:	:	:	:	:	:	:
an,bn,cn	an,bn,cn	an,bn,cn	an,bn,cn	an,bn,cn	an,bn,cn	an,bn,cn	an,bn,cn	an,bn,cn	an,bn,cn

$$SCF = 1 + \frac{\sqrt[4]{3(1-\nu^2)}}{2}\left\{\frac{\alpha_1\left(\frac{a}{\sqrt{RT}}\right)^{\beta_1} + \alpha_2\left(\frac{b}{\sqrt{RT}}\right)^{\beta_2} + \alpha_3\left(\frac{c}{\sqrt{RT}}\right)^{\beta_3}}{\alpha_4\left(\frac{a}{\sqrt{RT}}\right)^{\beta_4} + \alpha_5\left(\frac{b}{\sqrt{RT}}\right)^{\beta_5} + \alpha_6\left(\frac{c}{\sqrt{RT}}\right)^{\beta_6}}\right\}\alpha_7\left(\frac{c}{T-c}\right)^{\beta_7}$$

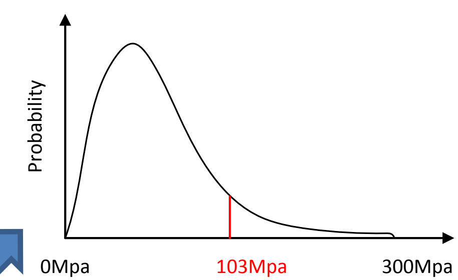
Dimensionless parameters

α_1	0.820415	β_1	0.780791
α_2	0.094409	β_2	3.844334
α_3	0.029142	β_3	1.39904
α_4	0.001069	β_4	0.299967
α_5	0.782993	β_5	0.498019
α_6	4.975226	β_6	2.854115
α_7	1.560761	β_7	0.581137

$$\sigma_{actual} = \sigma_{nominal} . SCF$$

Actual Stress	50Mpa	80Mpa	30Mpa	110Mpa	130Mpa	70Mpa	99Mpa	40Mpa	60Mpa	750Mpa

Distribution



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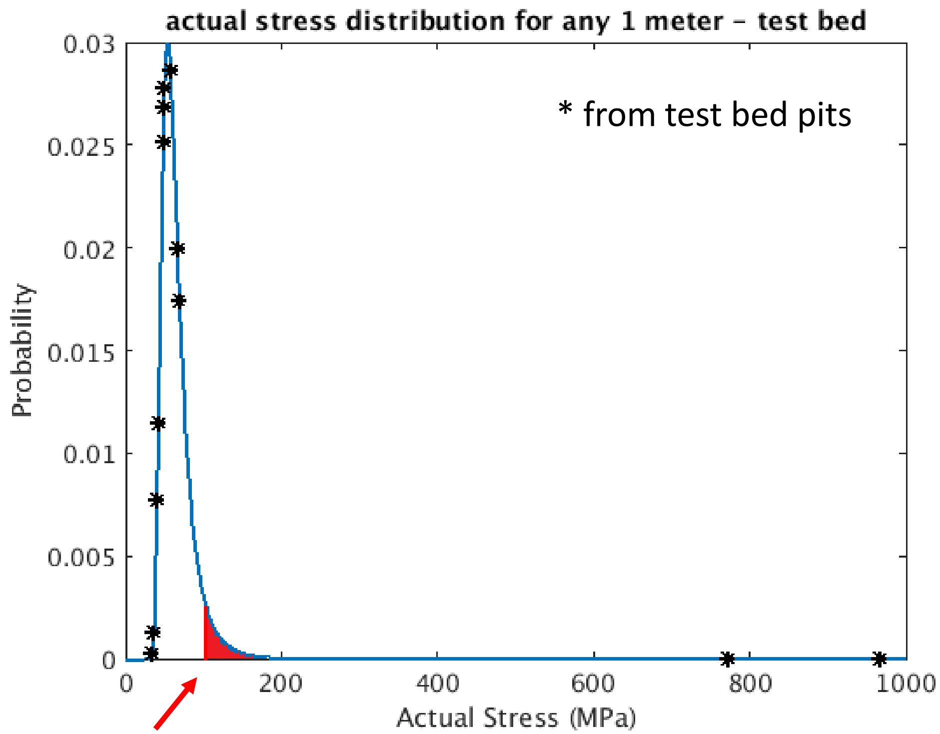
Evaluation of In-Between Framework

Preliminary Results from Test Bed



Tensile Stress: 103 MPa

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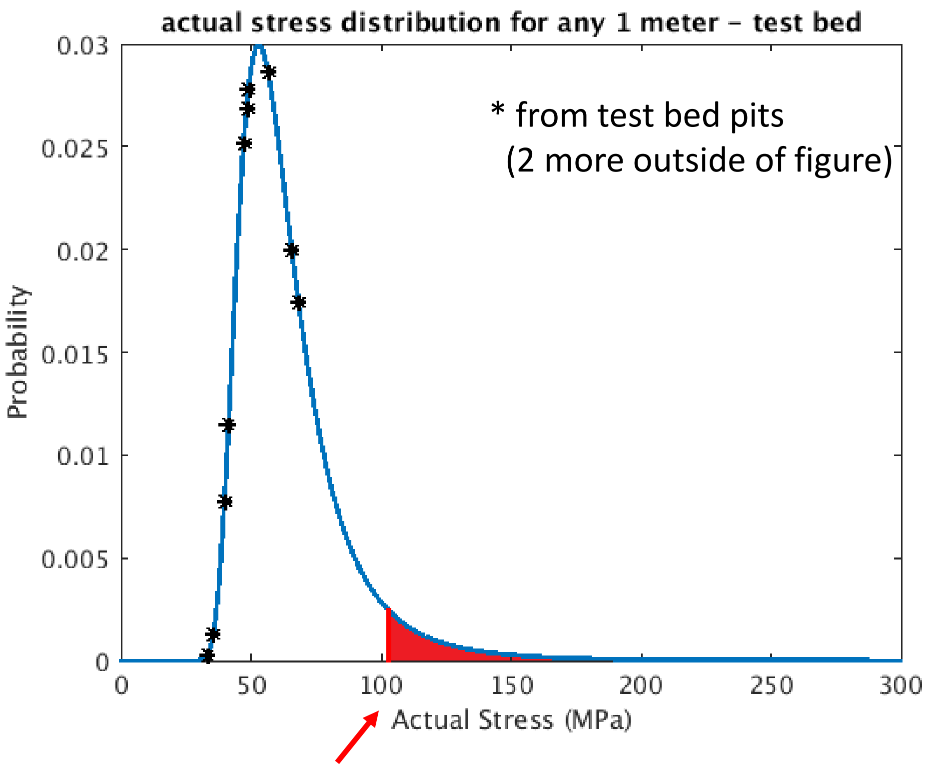
Evaluation of In-Between Framework

Preliminary Results from Test Bed



Tensile Stress: 103 MPa

Probability of failure for any 1 meter: 0.053 (red area)

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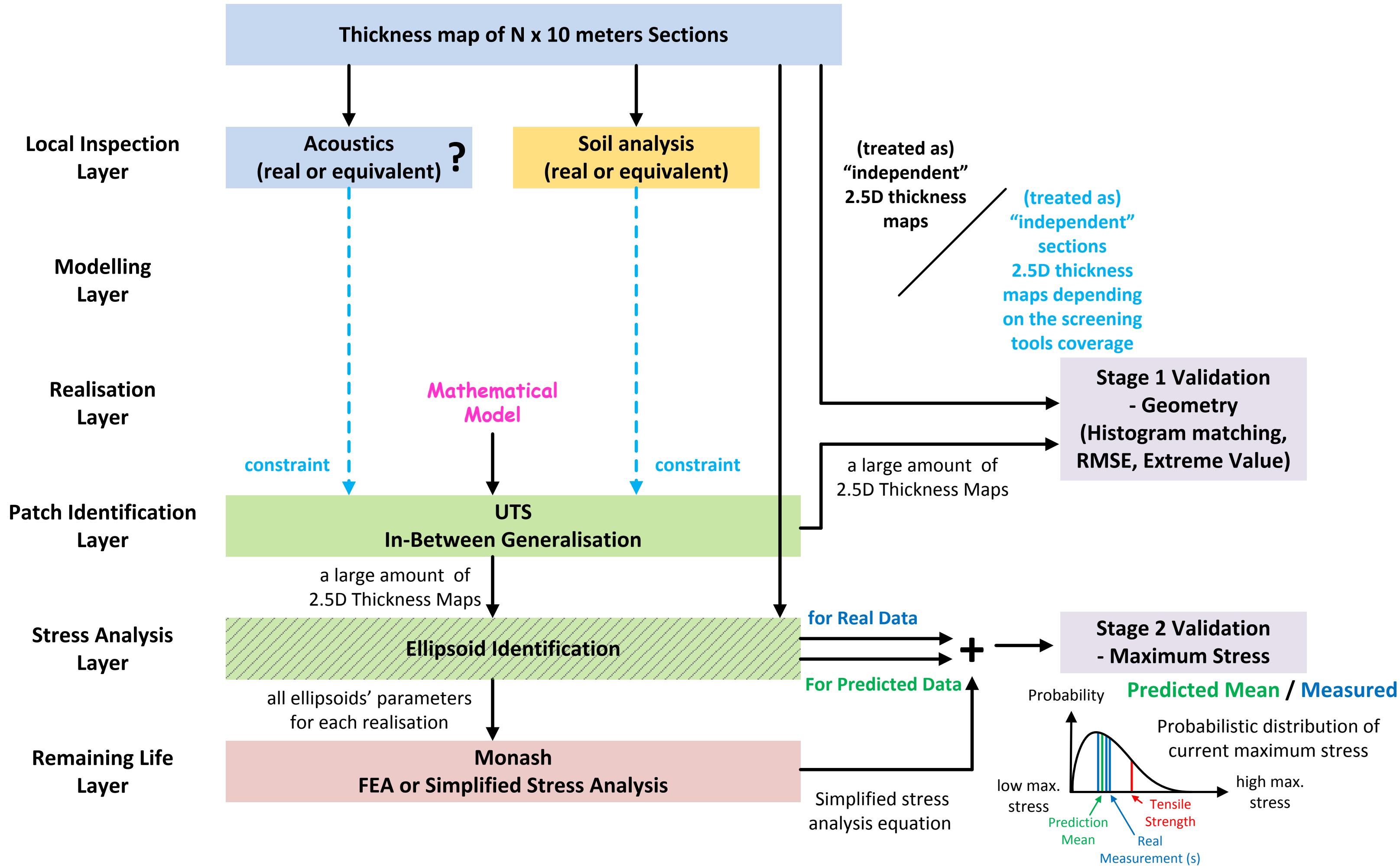
Evaluation of In-Between Framework

Validation Plan With/Without Constraint



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Evaluation of In-Between Framework

The Challenge of Validation

- Given multi-variate information (e.g. a pipe segment with very many lengthwise and circumferential thickness measurements) validation is not straightforward to calculate/visualise
- For uni-variate information (e.g. current maximum stress, or minimum wall thickness) it is more straightforward

↓

Transform “information” to facilitate validation.

Do it “probabilistically” as it involves “samples”.

Evaluation of In-Between Framework
The Challenge of Validation

A simple scenario:

- 100 students in a class, so that there are 100 marks after an exam.
- Take e.g. 10 random students' marks and build a distribution
- How good is that so it can be assumed to represent the whole class?

- Student ***Sa*** (one of the rest 90 students) comes and shows his/her mark, e.g. 85, *how does this number validate our 'representative' distribution?*

- Another student ***Sb*** (one of the rest 90 students) comes and shows his/her mark, e.g. 70, *how does this additional value further validate our distribution?*

- Another student ***Sc*** (one of the rest 90 students) comes and shows his/her mark, e.g. 90, *how does this additional value further validate our distribution?*

Evaluation of In-Between Framework
The Challenge of Validation

Options:

a) Compare realisations

- Generate 10,000 representative (realistic) marks from our proposed distribution
- When a student (one of the remaining 90 students available to 'test' the goodness of the distribution) shows his/her mark, check the probability of this mark in our representative marks distribution

b) Compare the consequences (e.g. mark -> pass/fail)

- Convert our distribution to probability distribution of pass/fail
- When a student (one of the 'test' 90 students) shows his/her mark, check where this mark is in our pass/fail distribution

To validate the model, we need to sample a few students from the remaining 90 students, and not just one or two!!

Evaluation of In-Between Framework
Stage 1 Validation

Stage 1 validation – purely geometric analysis (compare "realisations")

How close a dug-out pipe geometry is to the realisations used to build the model?

- Metric 1a: Histogram (of thickness) Matching - disregards spatial correlations
- Metric 1b: Average RMSE of thickness maps - somehow disregards the spatial correlation
- Metric 1c: Extreme case – minimum wall thickness

Evaluation of In-Between Framework
Stage 2 Validation

Stage 2 validation – stress analysis (compare “consequences”)

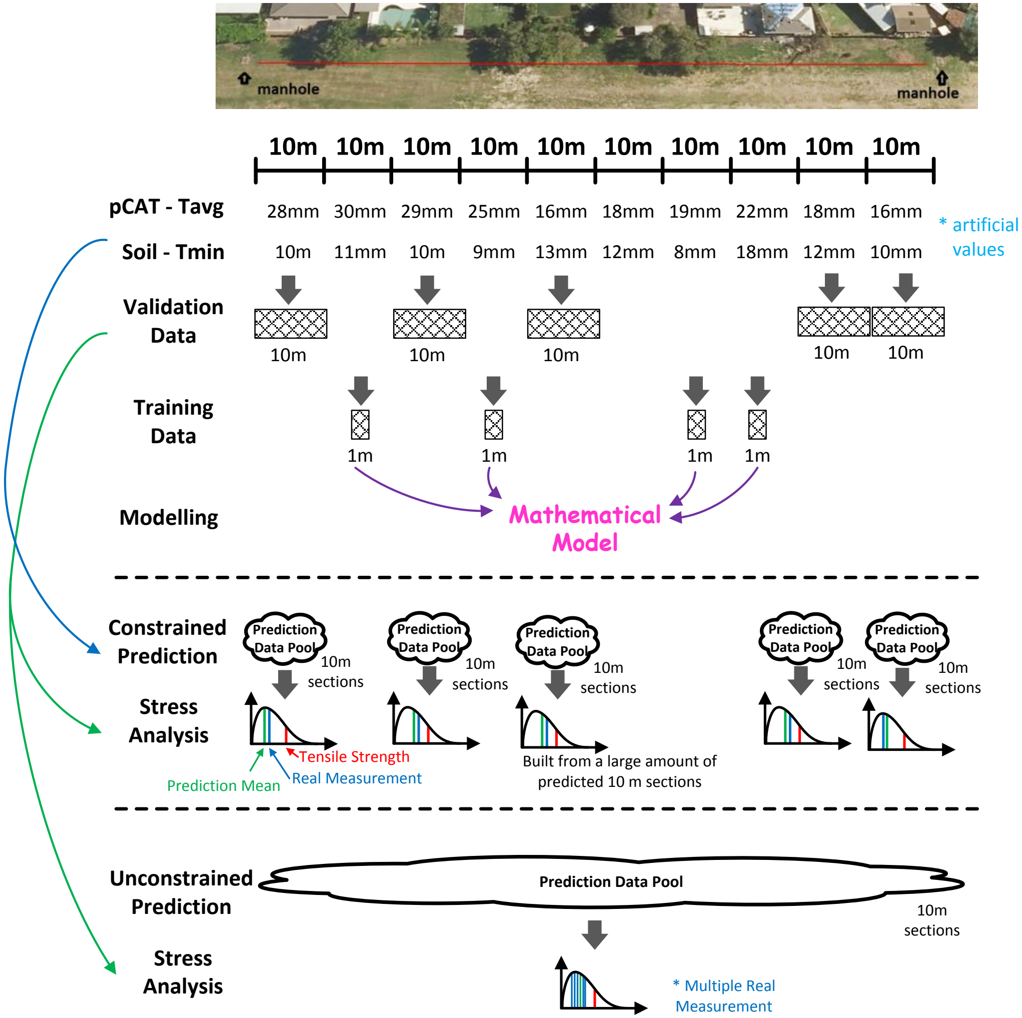
Build distribution of survival/failure based on maximum stress, then see the predicted probability of the maximum stress of the real dug-out pipe

- Metric 2a – FEA analysis on each realisation. Ideal but not currently feasible
- Metric 2b – Monash’s model as an approximation of FEA analysis

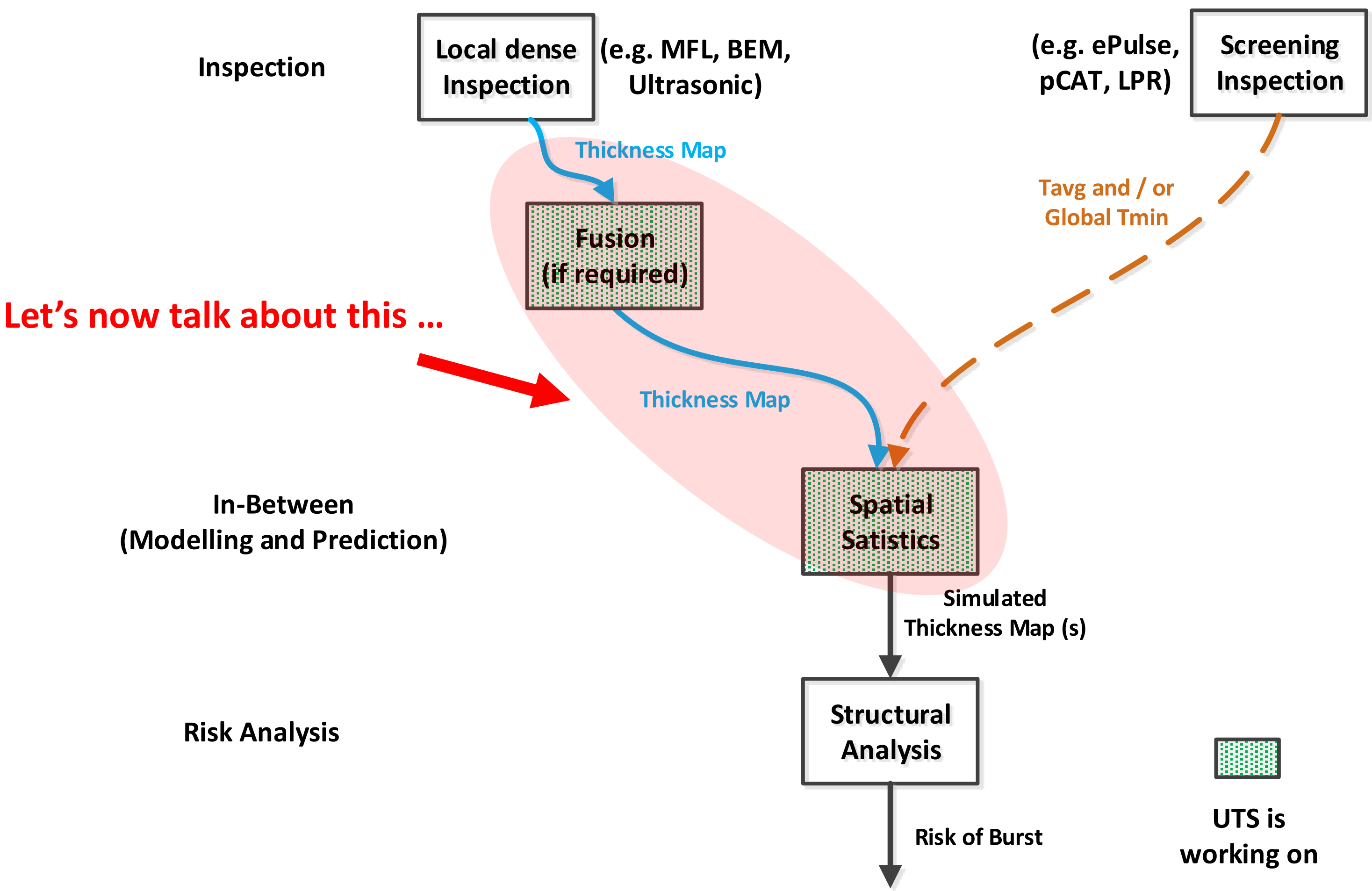
BOTH levels of validation require a small, representative number of real dug-out pipe samples

Evaluation of In-Between Framework

Example

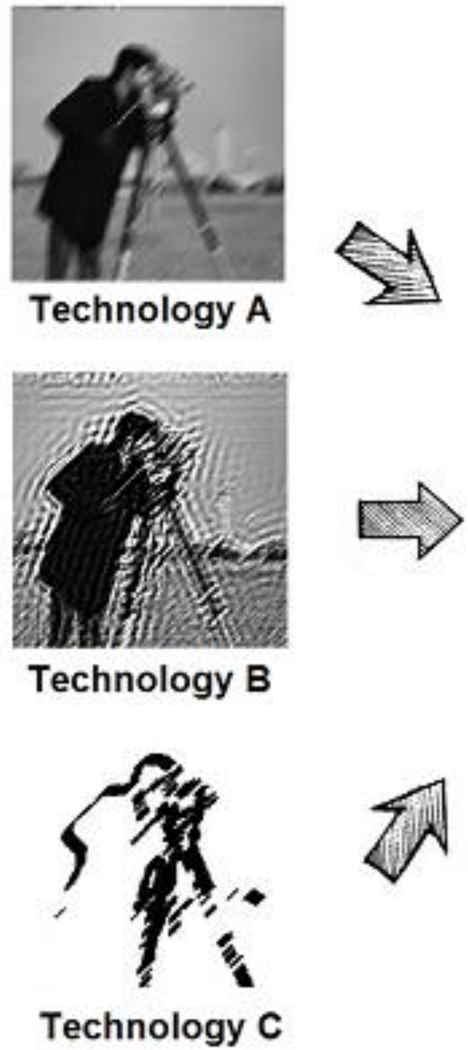


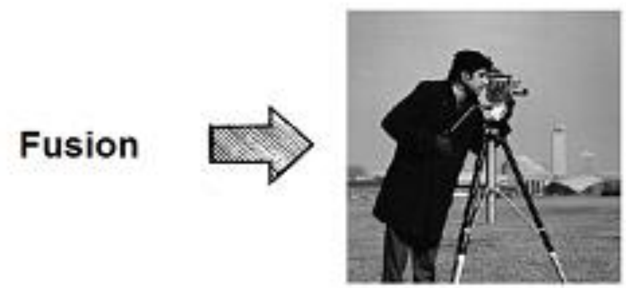
The Big Picture



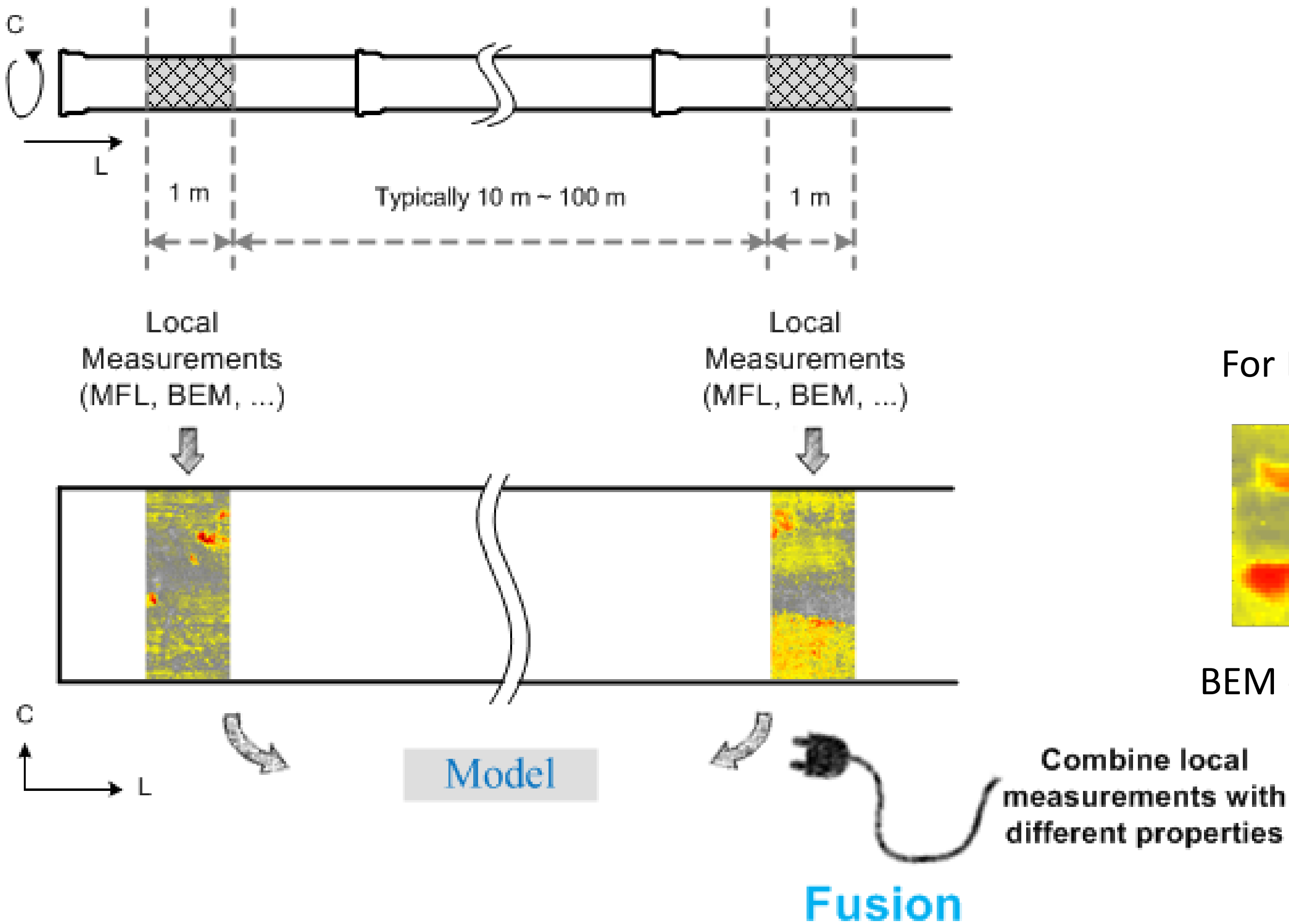
Data Fusion

- It deals with different resolutions
- It combines different modalities
- It reduces uncertainty
- It can improve the output resolution

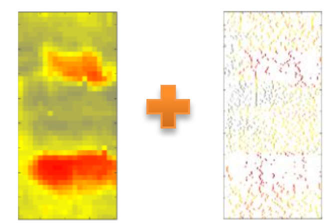




Reminder: In-Between Prediction



For Example:



BEM data MFL data

Important Challenges

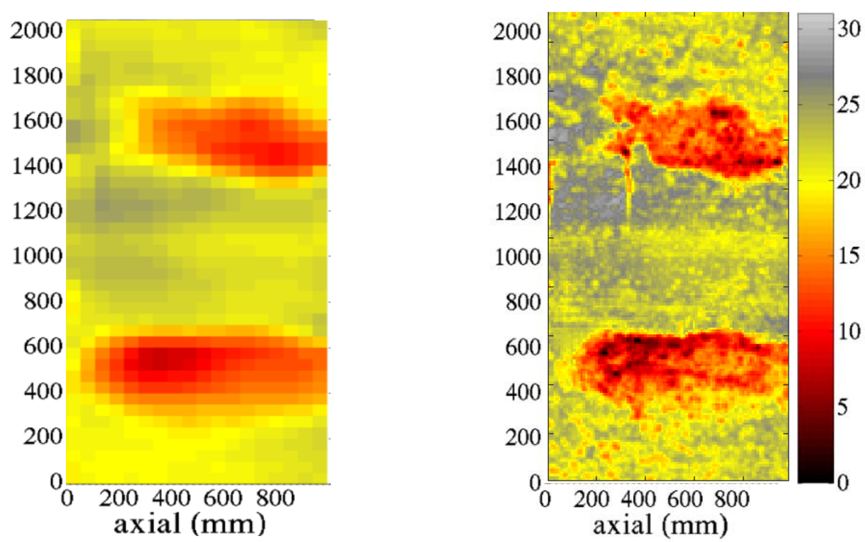
1. Spatial Statistics and Data fusion can be a **computationally expensive** process in that relations between all the data points needs to be calculated and maintained throughout for most accurate results

2. UTS is working towards developing more efficient and reliable solutions for dealing with big data in **capturing data points relationships** and **fusing multiple sensor interpretations**

Processing Large-scale Data

1. Large-scale data includes both high-resolution data and the extensive amount of sensor data required to inspect a sizeable area

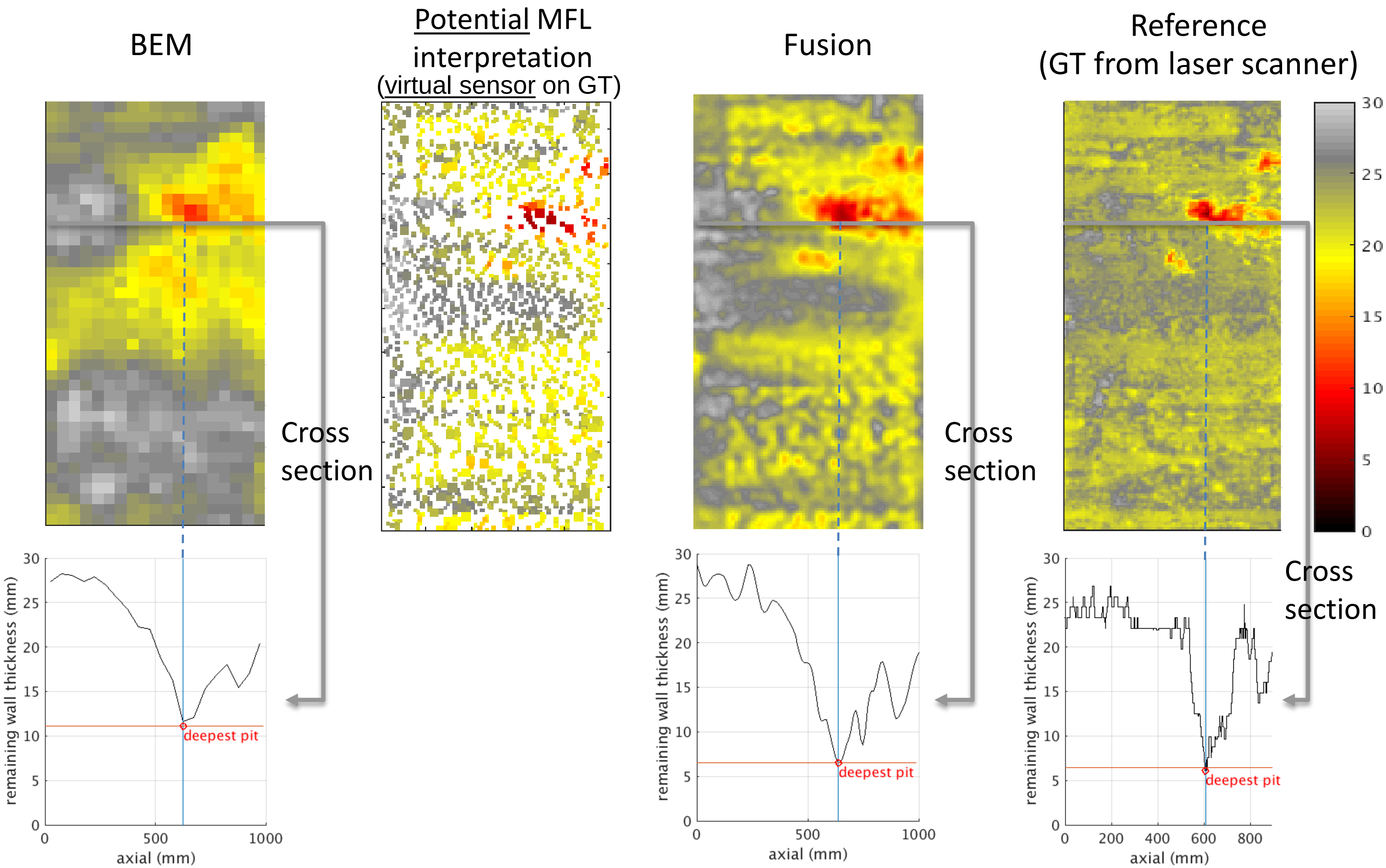
2. Current in-between methods use a matrix of BEM resolution (42X20) to do the sampling, but how can we deal with MFL resolution (192X198) to even allocate the memory?



(a) 42X20 (b) 192X198

Down-sampled ground-truth for Trial 2 Pit 2 at:
BEM resolution (a) and MFL resolution (b)

Case Study : More Detailed Fusion Models



Deep pits found !

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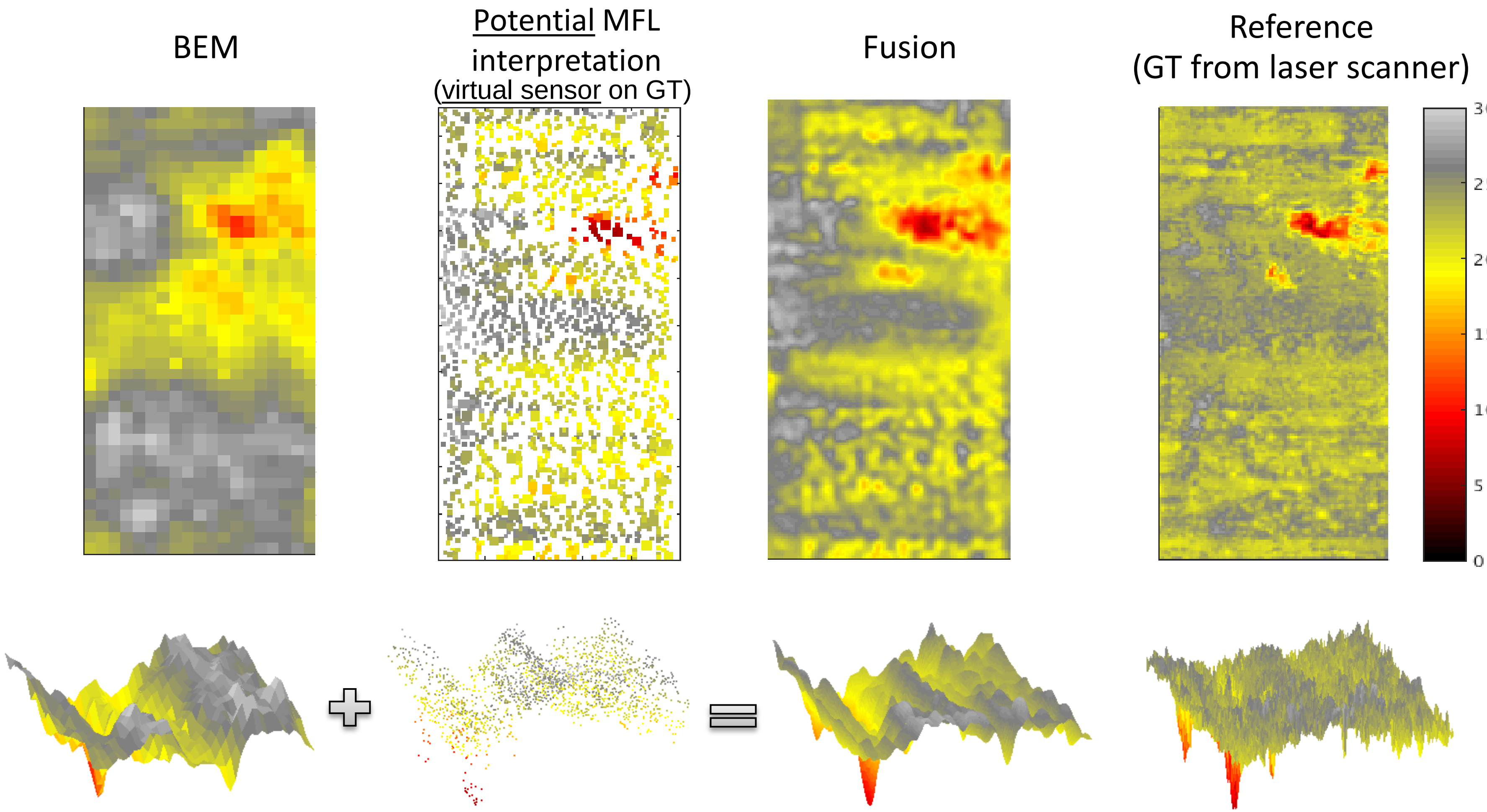
Case Study : More Detailed Fusion Models



	BEM	MFL	Fusion
RMSE(mm)	3.45	2.87	2.20

* Root Mean Squared Error

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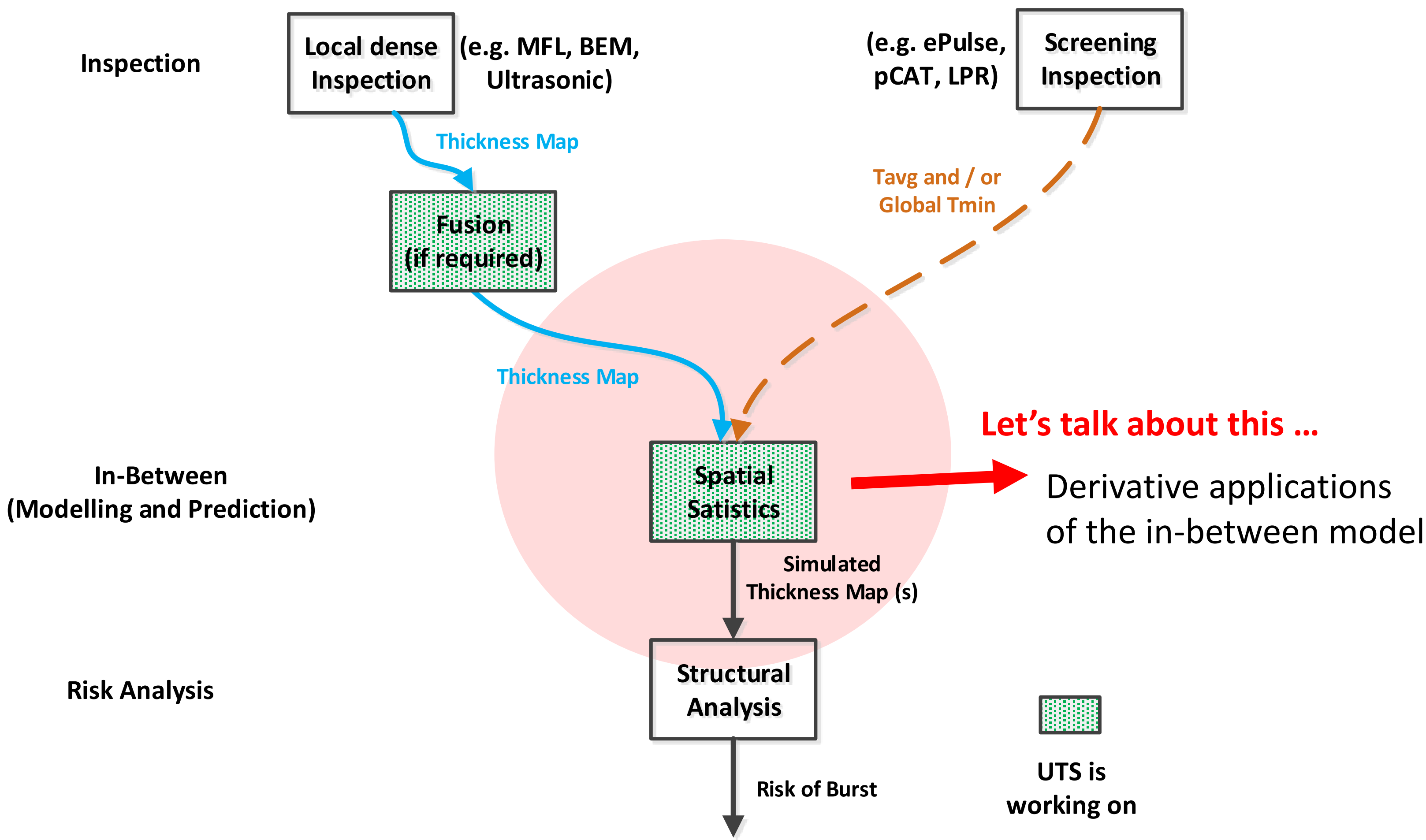
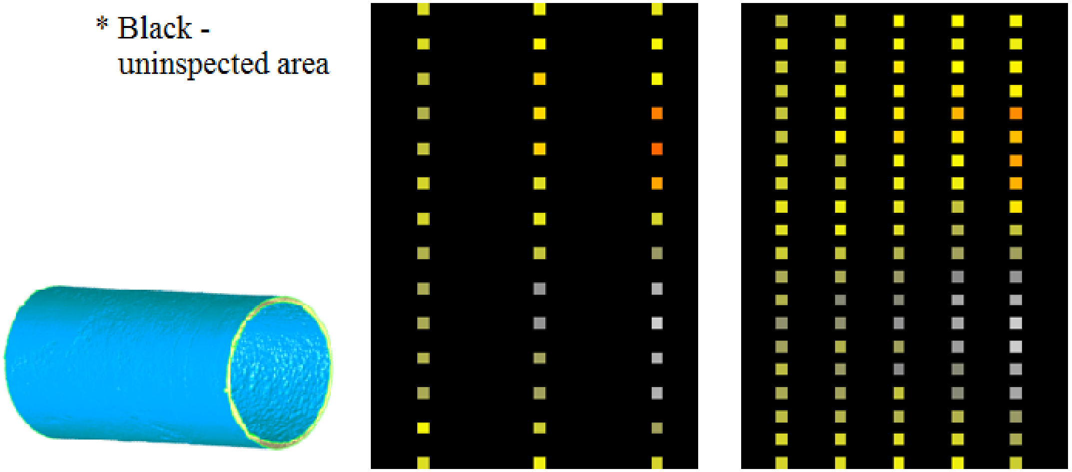
The Big Picture



Sampling Inspection

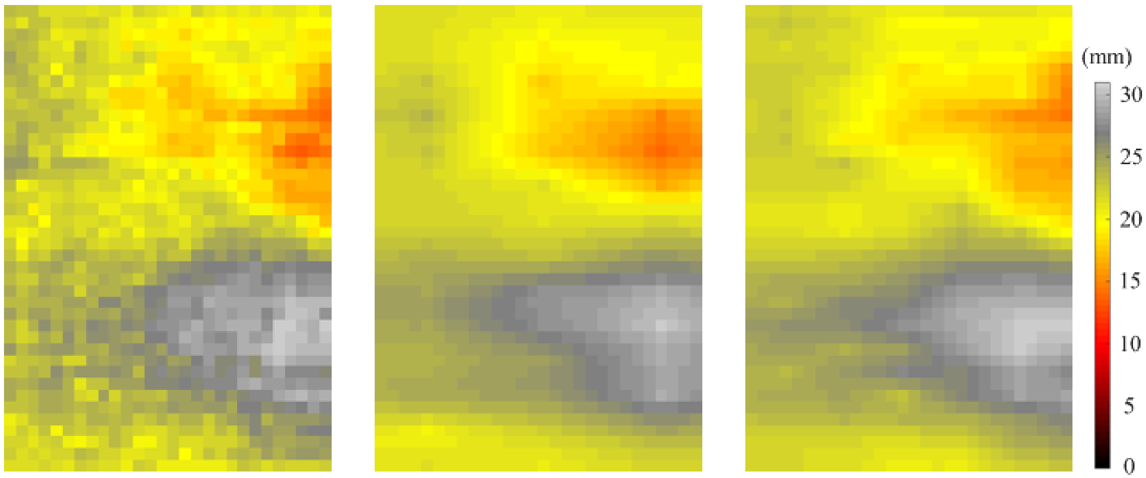
Experimental Results

* Black - uninspected area



Inspection Pattern A (r > 0.7, use 3.33% of data)

Inspection Pattern B (r > 0.8, use 10% of data)



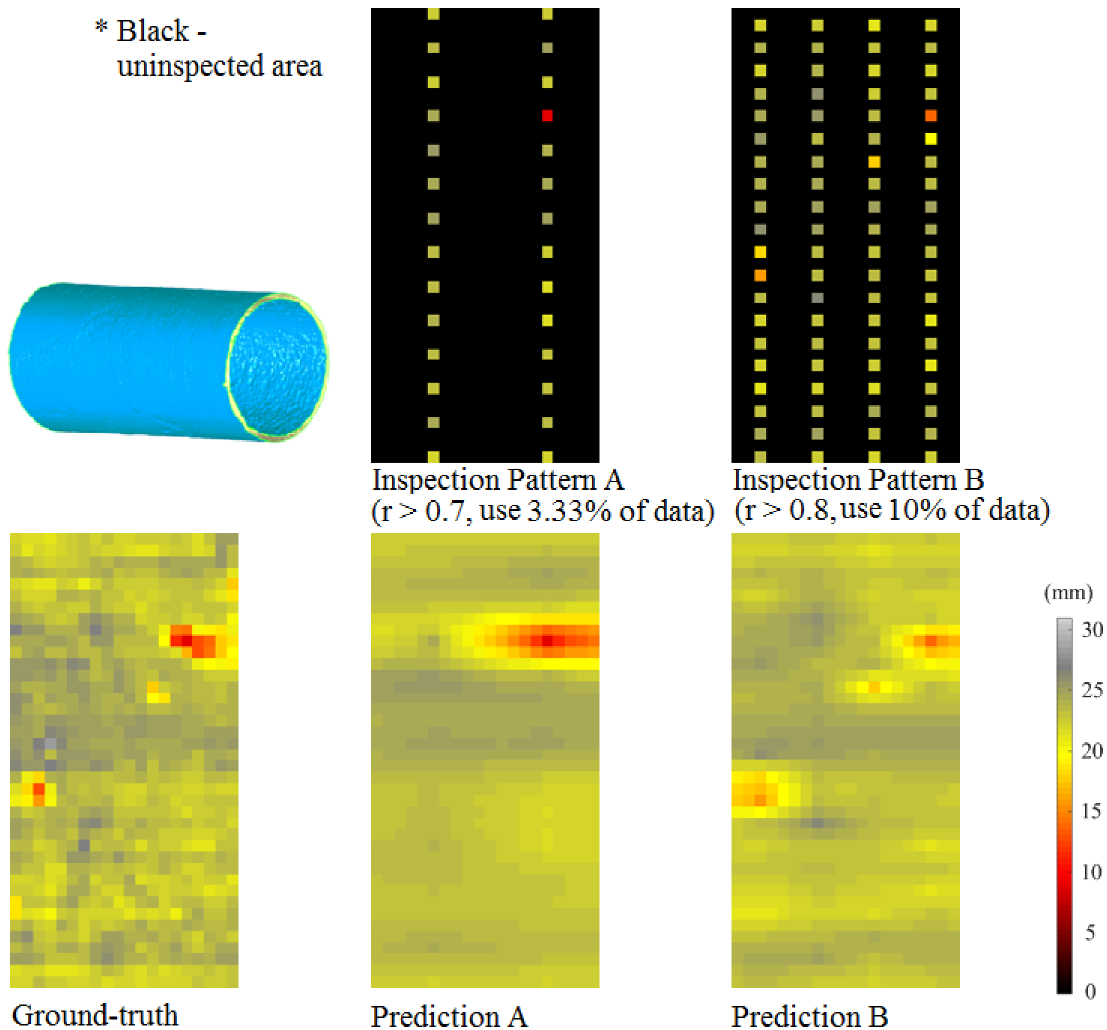
Ground-truth

Prediction A

Prediction B

Sampling Inspection

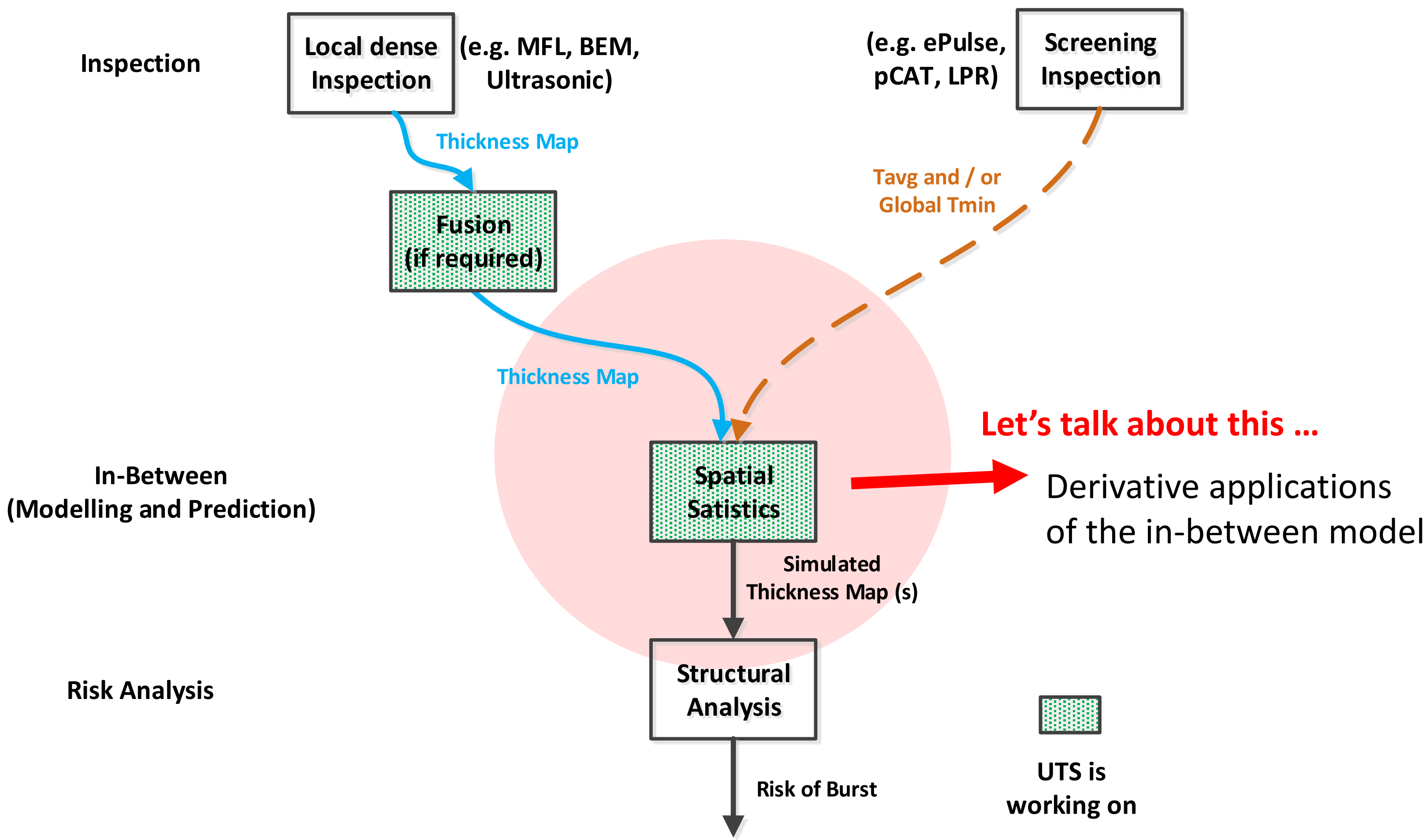
Experimental Results



Sampling Inspection
Conclusions

- Correlation pattern is anisotropic
- 10% of samples appear to represent the full thickness map “well”
- Extreme values could be missed out in the sampling, but prediction can mitigate this if distribution data is representative

The Big Picture



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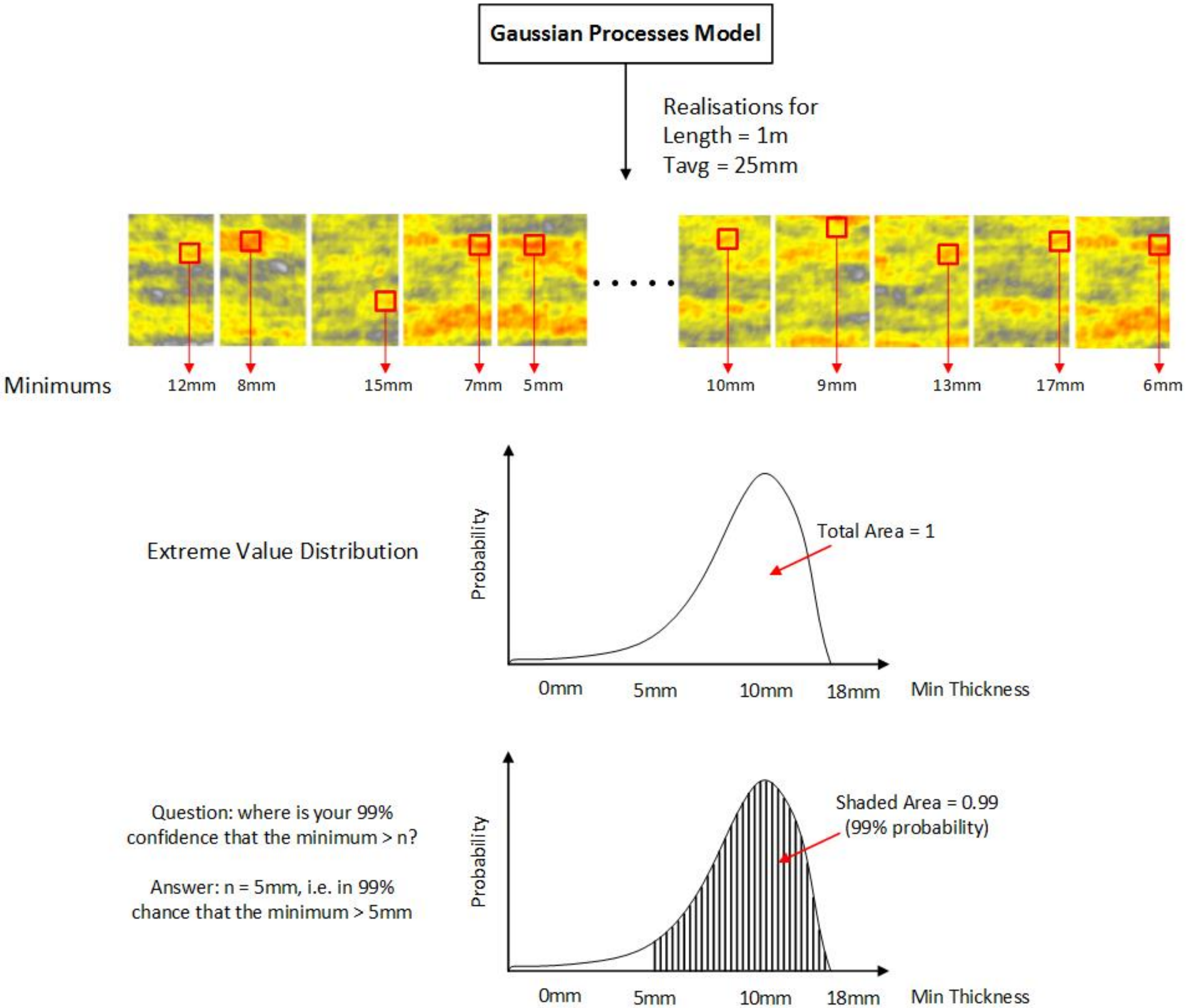
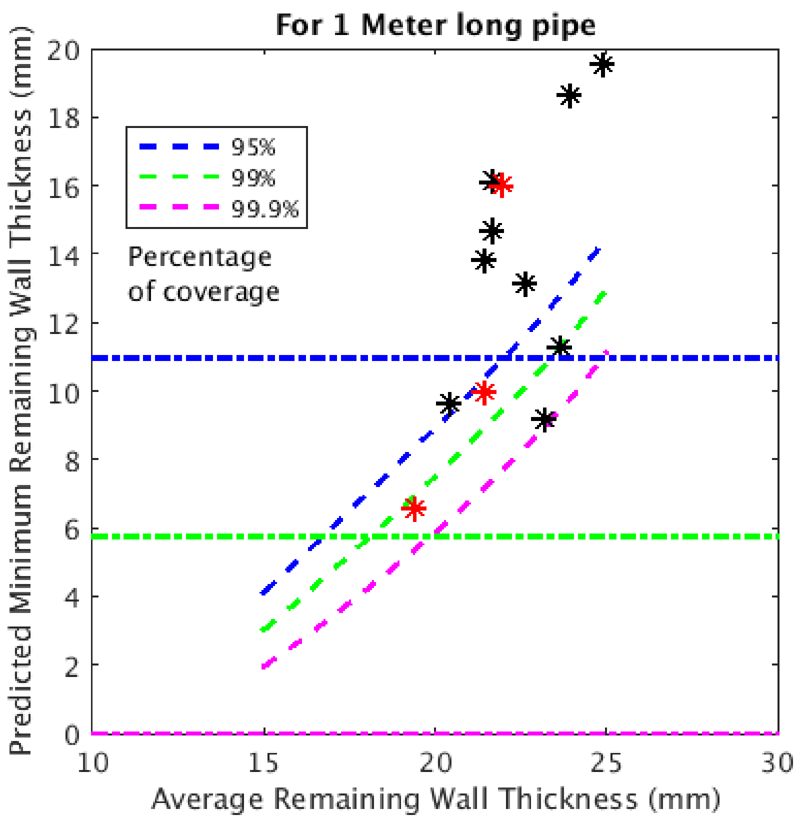
UTS EVA – Ideally with Accurate Tavg Constraint



UTS EVA – Ideally with Accurate Tavg Constraint
Validation and Conclusions



- UTS EVA considers data correlation and can incorporate constraints
- On limited available validation data, UTS EVA analysis improves accuracy

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Final Thoughts

1. The proposed framework is flexible to allow for a variety of scenarios drawn from current CA techniques to be readily incorporated

2. Understanding what current technologies not researched in Activity 2 (screening!) and their interpretations can provide **remains paramount** for success and it is a key objective of the on-going efforts from this activity

3. The framework has been put into practice on limited test-bed data, more evaluation is needed prior to adopting it

4. Robust validation currently means digging up long sections of pipe, under planning and discussion. Alternative in-pipe validation tool also being developed to aid with this.

Pending

1. A validation plan for both the in-between framework and suitable screening technologies has been proposed. Negotiations started with SW and Water Corporation regarding the implementation of this plan

2. Execution of the proposed validation plan mentioned in 1) with realistic simulated data being currently worked on

3. Continue investigations on dealing efficiently with big data for in-between interpretation, so as to be able to generate model realisations of longer pipe sections and/or high resolution

Current Progress and Future Goals

Goal	Status
Appointment of personnel and training Review of current practices and literature Signing agreements with technology providers/partners Establish framework to fuse data at varying resolutions Establish protocols for data collection	Completed
First pass at data fusion framework with simulated/numerical sensor data; Data collection runs completed; Preliminary evaluation of framework with real sensor data	In progress (85%)
Robust validation of framework with real data; Training (SWC/industry partners) and reporting	In progress (50%)

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