TEXAS
The University of Texas at Austin

PHMSA
Pipeline and Hazardous Materials Safety Administration

FINAL DE-BRIEF MEETING

Internal Corrosion Monitoring in Pipelines by using Helical Ultrasonic Waves

Contract Number: ***693JK31850004CAAP***

Principal Investigator: ***Dr. Salvatore Salamone***

August 30, 2022

Acknowledgements

Funding agency:

- US Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) under Contract No. 693JK31850004CAAP

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Industry Partners:

- Amerapex

Research team


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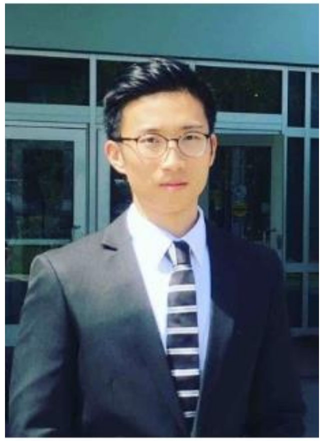
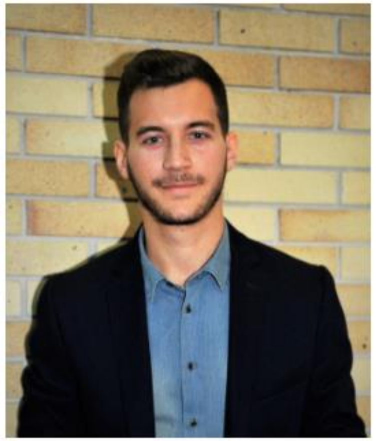

Tony Lee (Ph.D student)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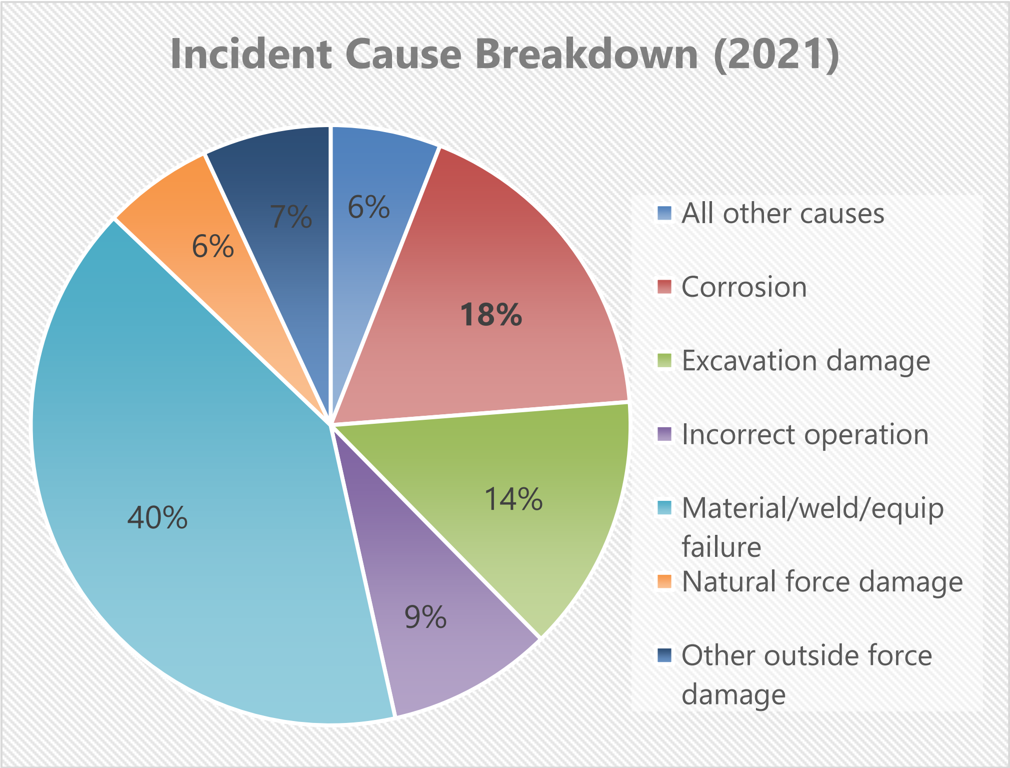
Motivation

According to the Pipeline and Hazardous Materials Safety Administration (PHMSA), during the past 20 years in the US there were reported:[1]

- 12,505 incidents
- 270 fatalities
- 1176 injuries
- Cost of $9.9 billion
- Environmental destruction

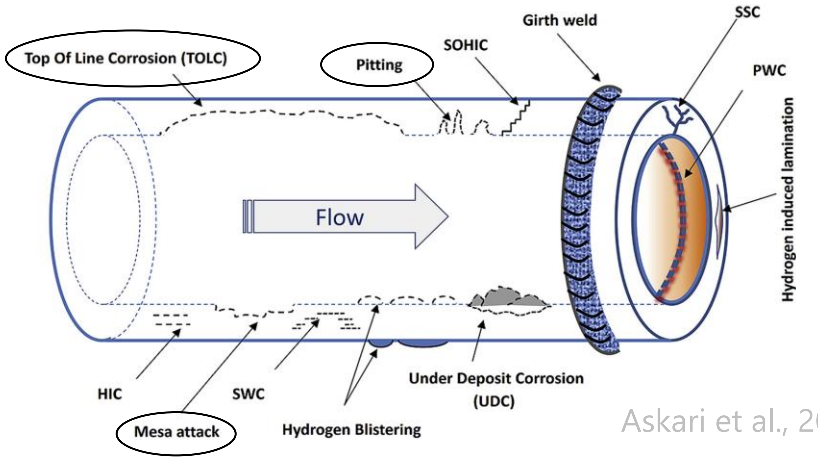


[1] from PHMSA website reports

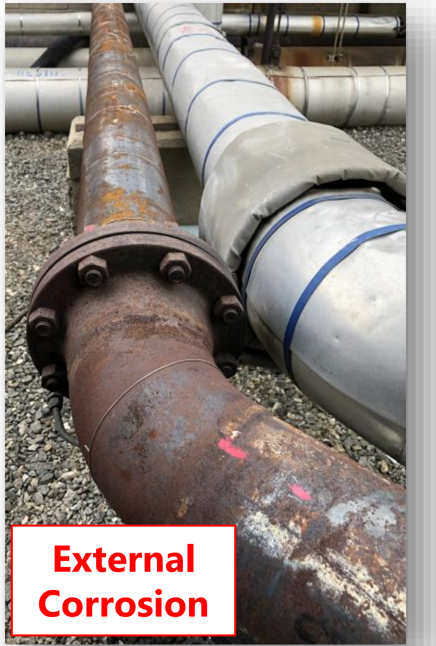
Motivation

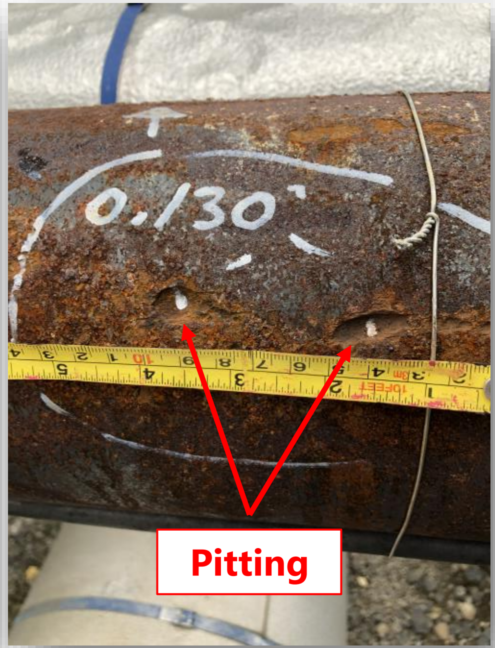
Corrosion in pipes

- Uniform, pitting, stress corrosion, erosion
- Internal/external
- Wall-thickness loss & loss of pressure



Askari et al., 2019



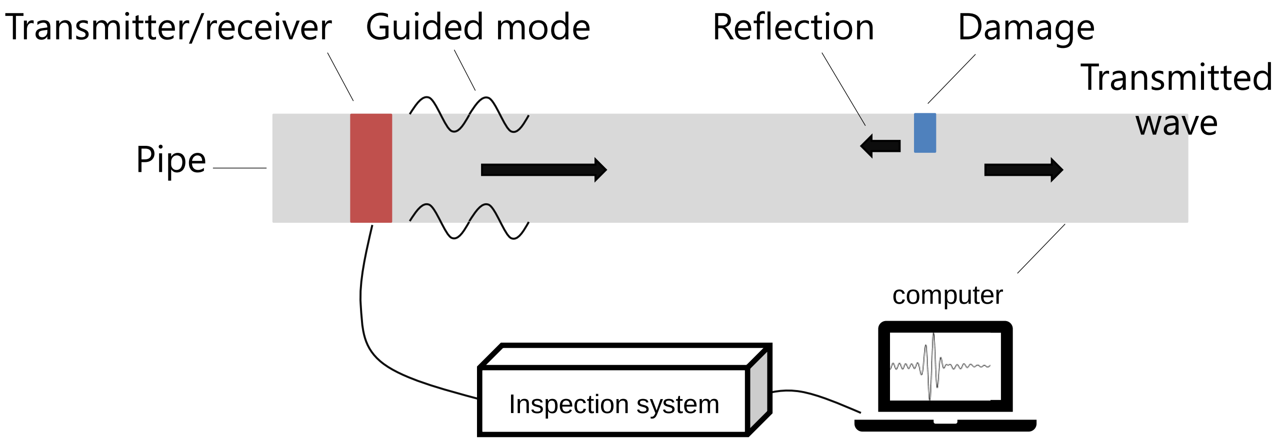


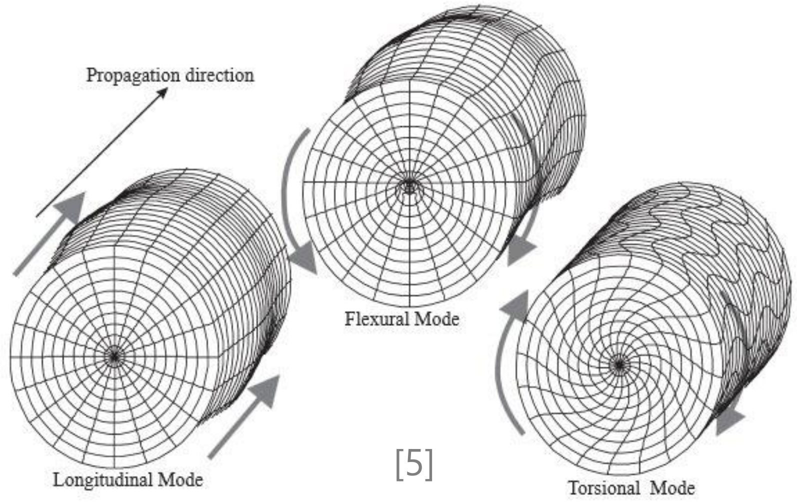
Mitigation strategies currently used in industry :

- Coatings, cathodic protection, corrosion inhibitors, pigging, visual inspections, and **non-destructive evaluation.**

Motivation – Nondestructive Evaluation (NDE)

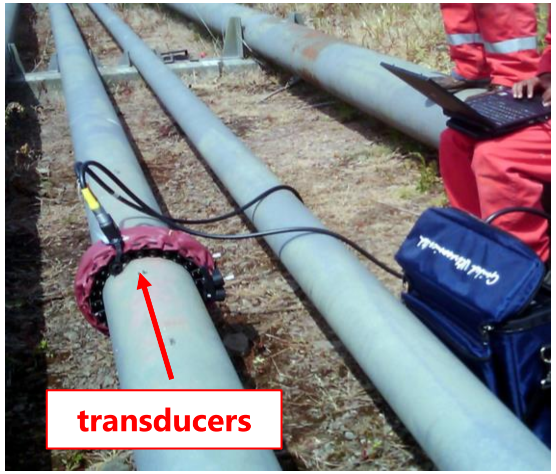
Conventional guided wave inspection (GUW) [3,4]





Major limitations

- Ineffective in screening the pipe for small defects
- No capacity for sizing the defects
- No tomographic capacity
- Requires large number of sensors



[3] Alleyne et al., 2004 , [4] Lowe et al., 2006, [5] Fong 2005

Motivation - SHM

Acoustic Emission (AE)

Different mechanisms → Acoustic energy

- Corrosion, internal pressure, cracking

Monitor AE features:

- Energy, Amplitude, Frequency.

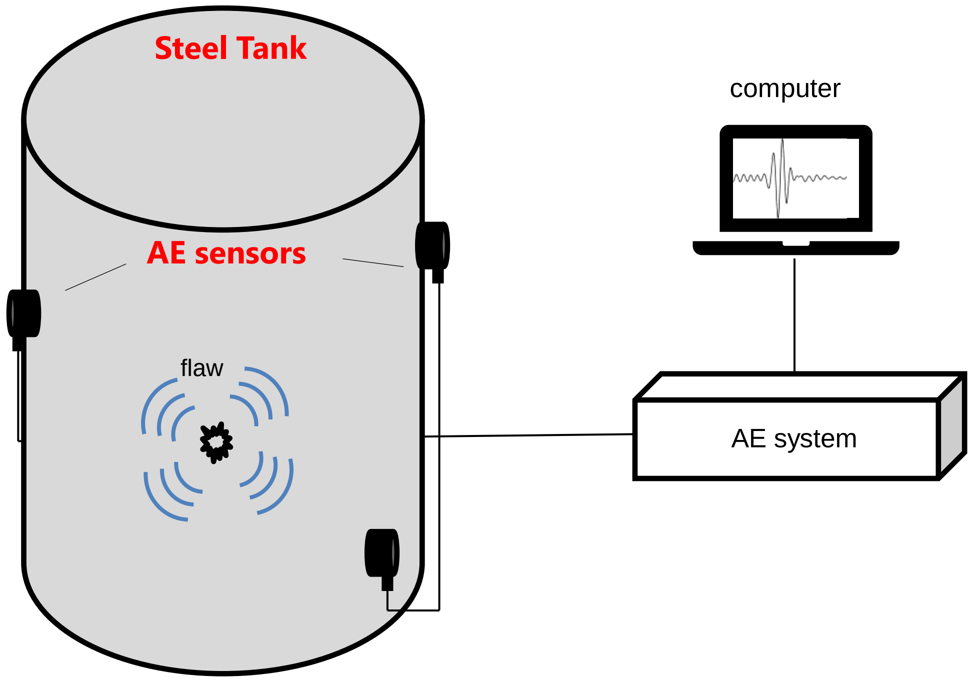
Distinguish between different forms of corrosion like:[5]

- Pitting, uniform, stress cracking

Gaps in knowledge

Using the HGUW AE for estimating:

- Estimate corrosion growth/intensity.
- Predict the corrosion



[5] Jomdecha et al., 2007, [6] Jirarungsatian et al., 2010

Research objective

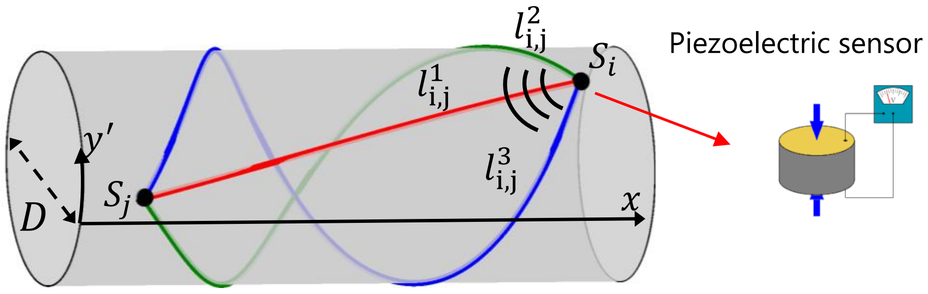
- The main objective of this work is to a develop a systematic approach by which the underlying structural health condition of steel pipes could be assessed using non-destructive methodologies.
- Overall, it is proposed to use a novel class of sensing system, helical guided ultrasonic waves (HGUW) and advanced data processing techniques for supporting corrosion diagnosis and decision-making.

Project timeline

Task Description	Year 1				Year 2				Year 3				Extension			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Task 1: Development of numerical model to predict HGUW																
Task 2: Development of algorithms for corrosion damage assessment by HGUW																
Task 3: Experimental Tests																
Task 4: Deliverables																
Quarterly Status Report																
Kick-off Meeting																
Mid-term Summary																
Final Report																

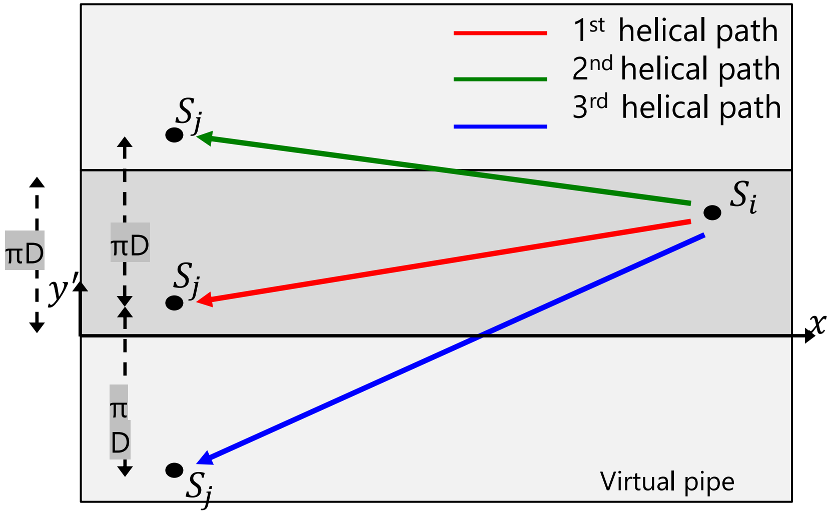
- **Original Award: $299,686.00**

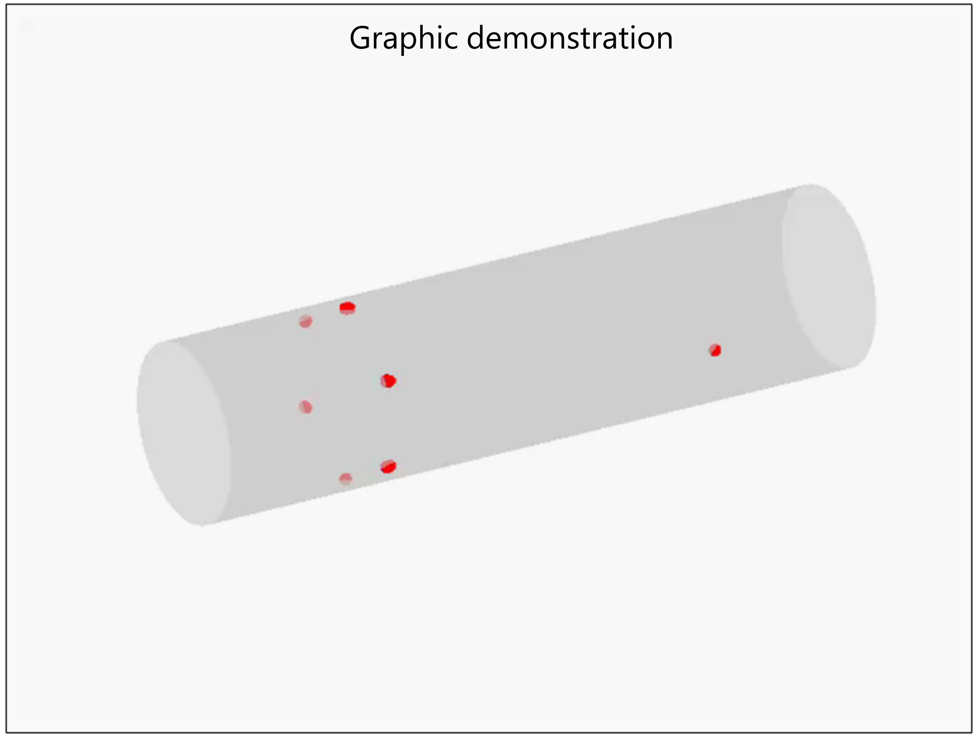
Helical Guided Ultrasonic Waves - Background



Equivalent plate

2D (x, y')





Task 1

Development of numerical model to predict HGUW

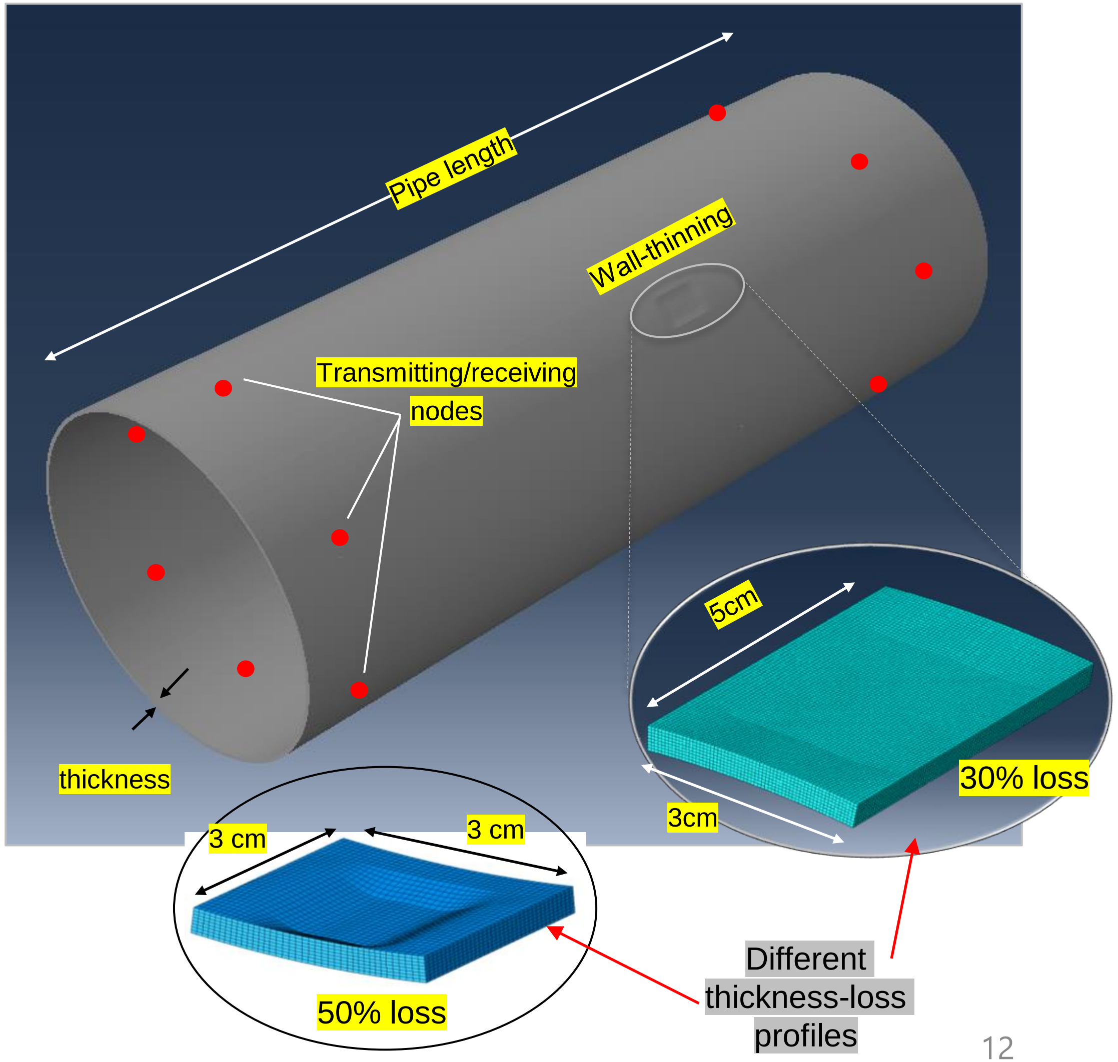
Task 1: Development of numerical model to predict HGUW

Finite-Element (FE) modeling details

- ABAQUS commercial FE software
- 3-dimensional modeling

Methodology

I. A segment of the pipe was modeled based on the actual dimensions.
II. Corrosion was modeled by means of pipe wall-thinning (both internal & external).
III. Helical waves were generated using an appropriate force configuration at different nodes.
IV. Time-domain waveforms were collected at nodes of interest.
V. Waveforms processed for identifying features of the HGUW that correlate with the different thickness-loss.

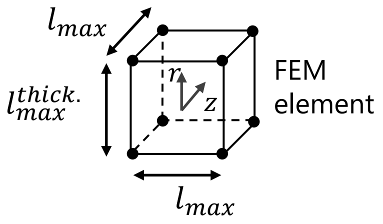


Task 1: Development of numerical model to predict HGUW

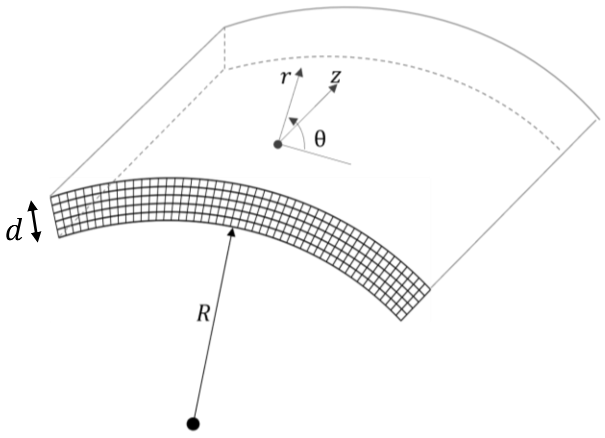
Modeling considerations

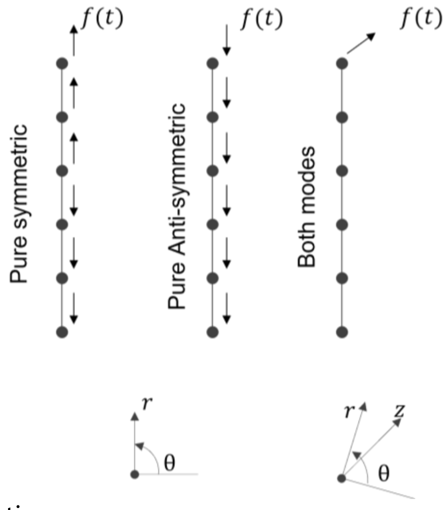
(1) Spatial & temporal resolution:

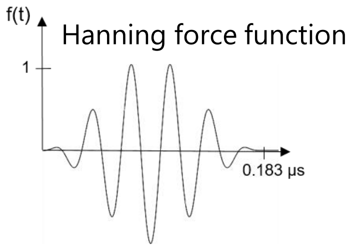
$$l_{max} = \frac{\lambda_{\min}}{15} \qquad l_{max}^{thick.} = \frac{d}{10} \qquad \Delta t = \frac{1}{20 f_{max}}$$



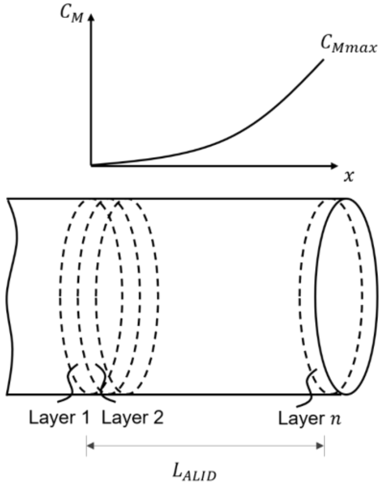
(2) Nodal forces for Lamb wave excitation:







(3) Absorbing layers with increased damping:

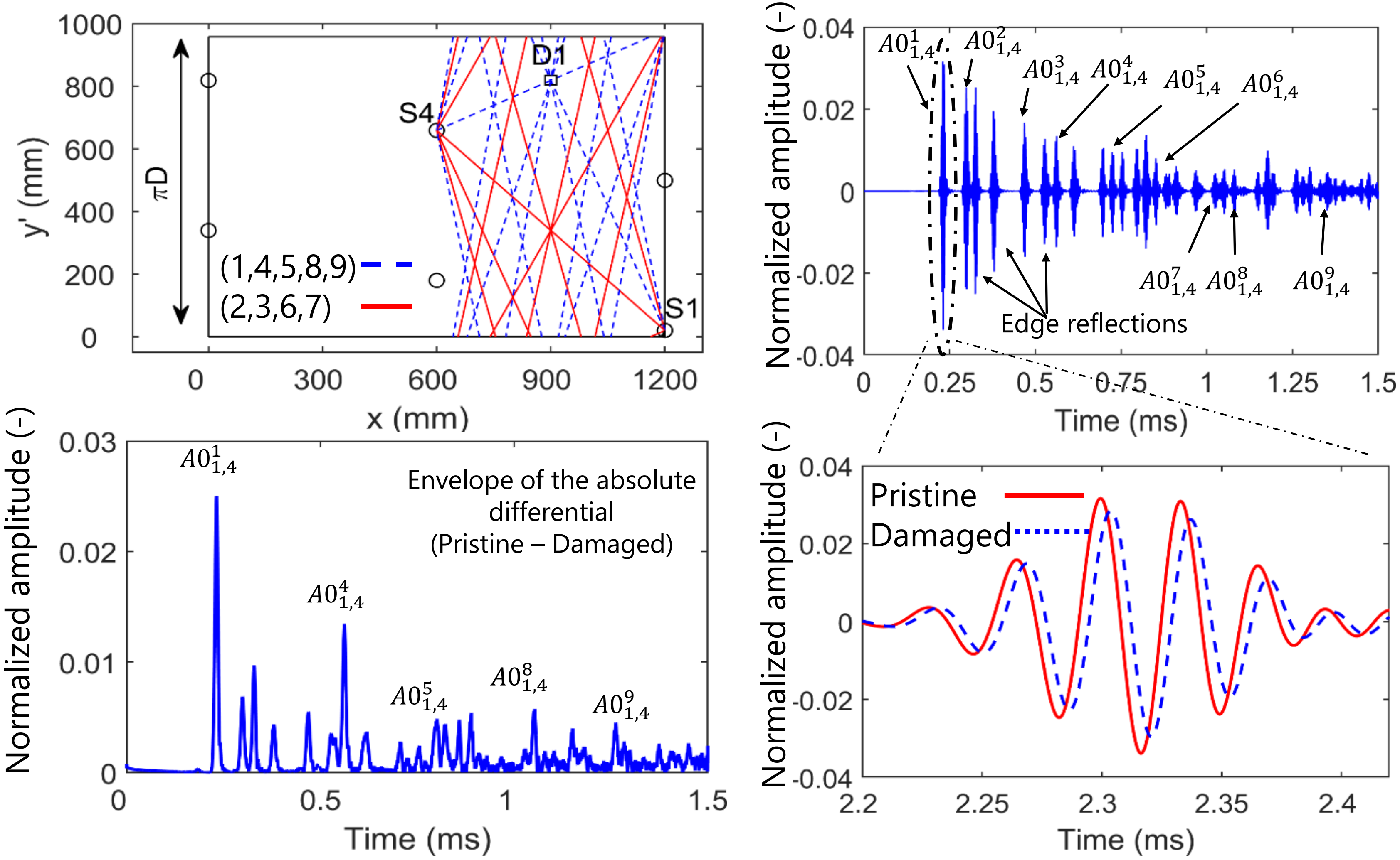


$$L_{alid} = \lambda_{\max} \times 3 \longrightarrow (\sim 10 \text{ cm})$$

$$C_M(x) = C_{Mmax}\left(\frac{x}{L_{alid}}\right)^3$$

Task 1: Development of numerical model to predict HGUW

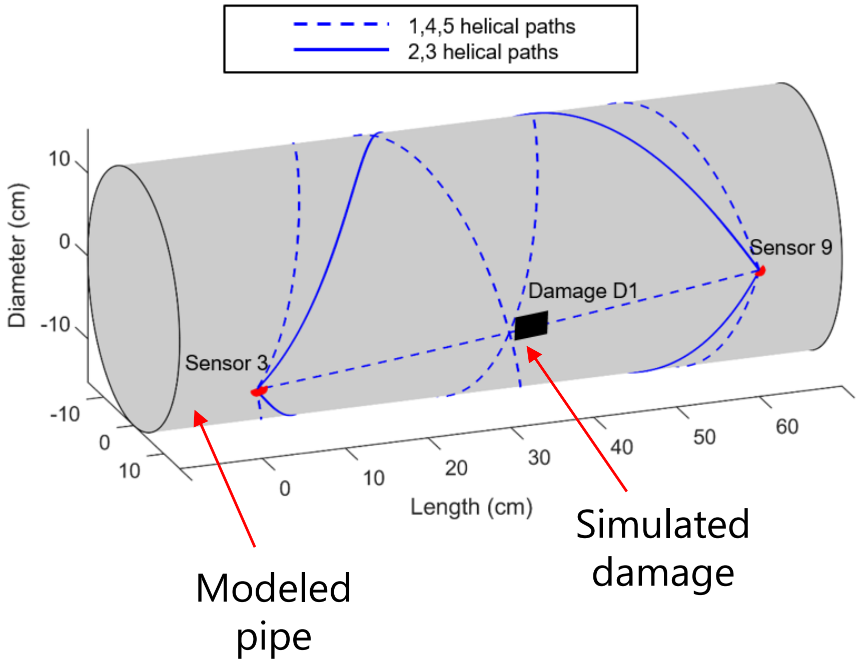
- Comparison of models with (damaged) & without (pristine) a wall-thinning



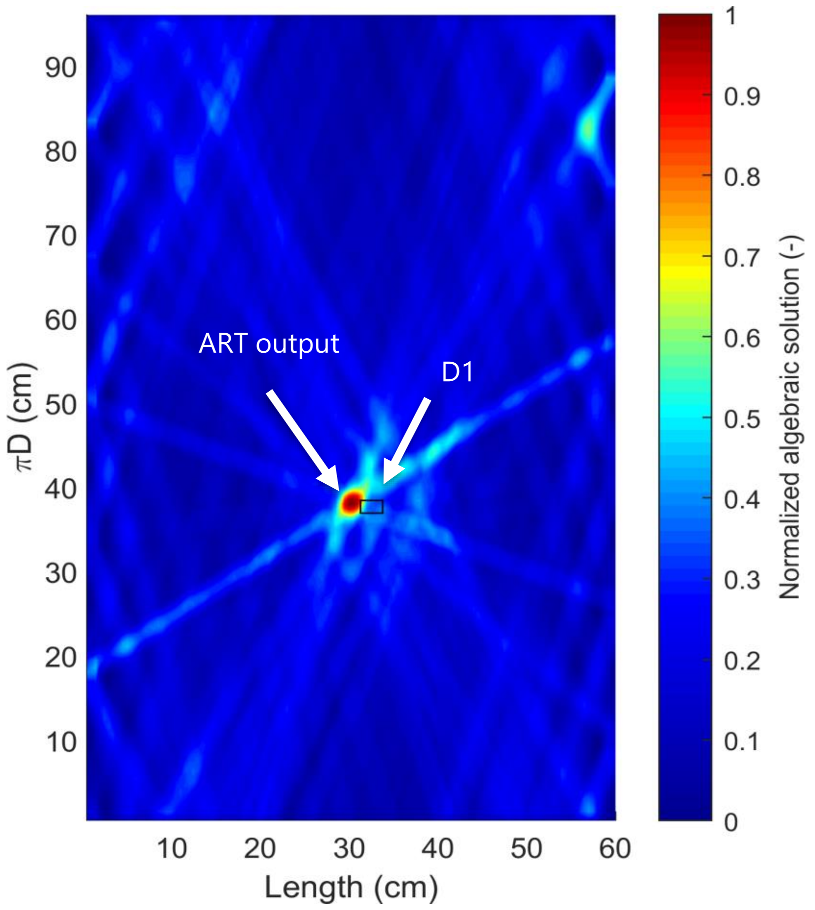
Task 1: Development of numerical model to predict HGUW

Modeling objectives

- Use of the FEM models to assess the efficacy of the corrosion assessment algorithms developed in Task 2



Example of damage localization using ART algorithm



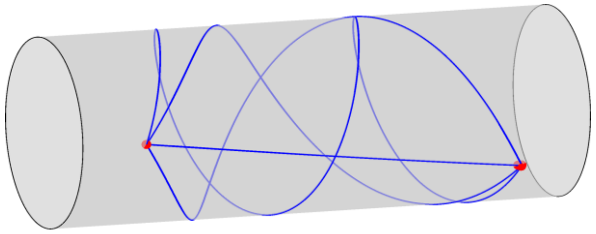
Task 2

Development of algorithms for corrosion damage assessment

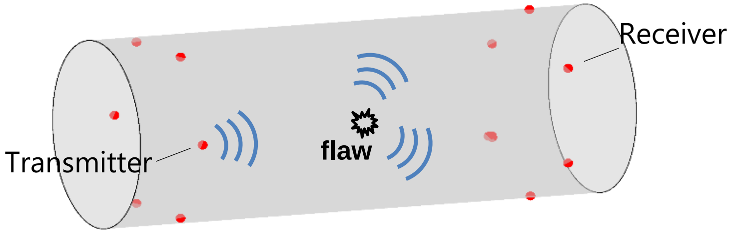
Task 2: Development of algorithms for corrosion damage assessment

- 2 different approaches have been investigated:

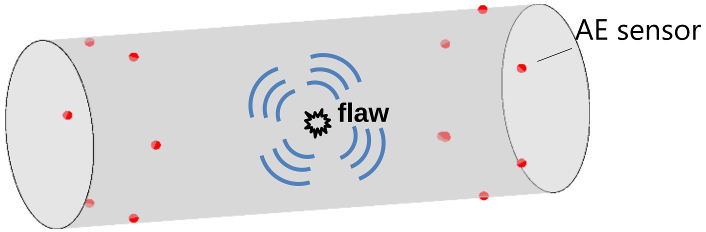
Helical guided waves



Active monitoring



Passive monitoring



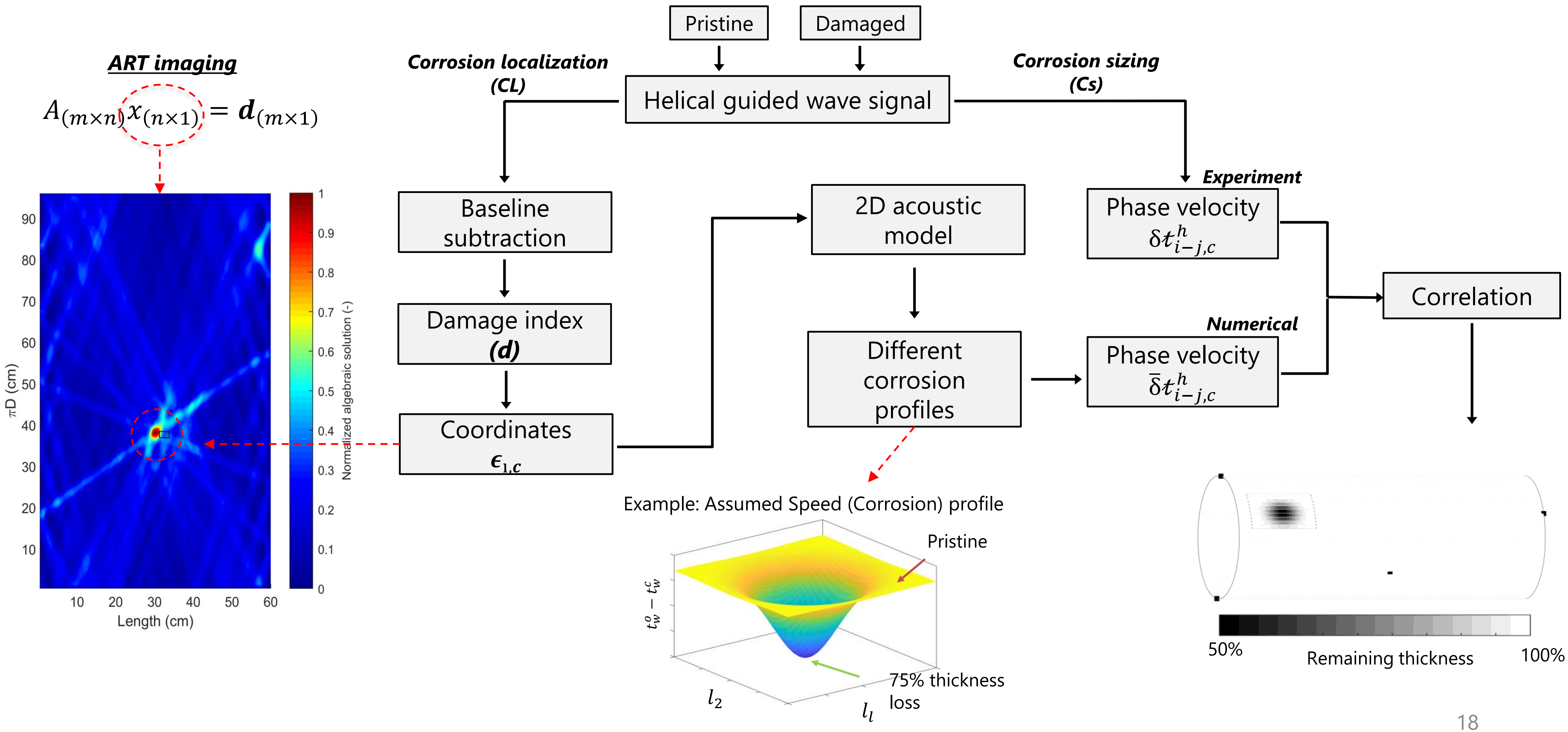
Advantages

Few sensors
Increase inspected area

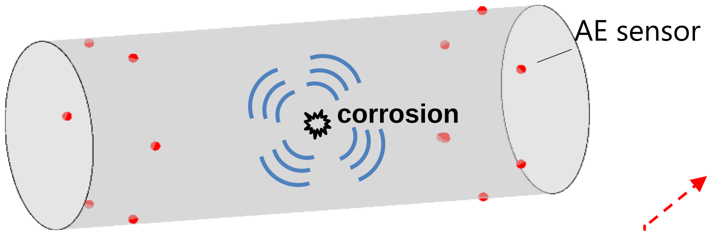
- Localize defects
- Estimate of the defect’s size
- Estimate the remnant wall-thickness

- Identify critical stages of corrosion
- Distinguish corrosion mechanisms
- Predict corrosion rate

Task 2: Active pipeline health monitoring-(2step approach)



Task 2: Passive pipeline health monitoring – (AE)



Corrosion

↓

Helical guided wave Acoustic Emission

↓

***b*-value**

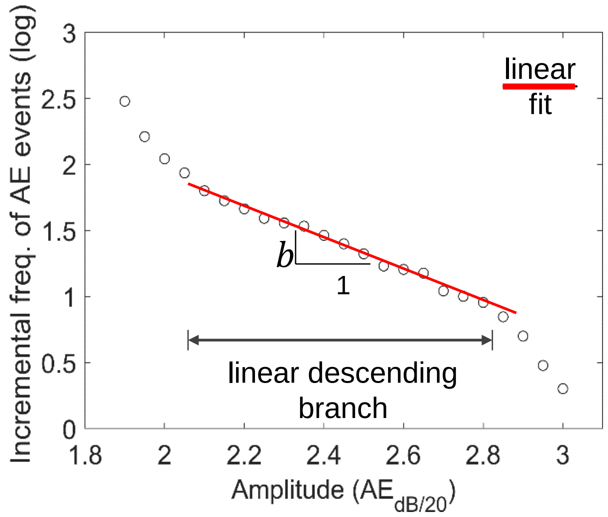
↓

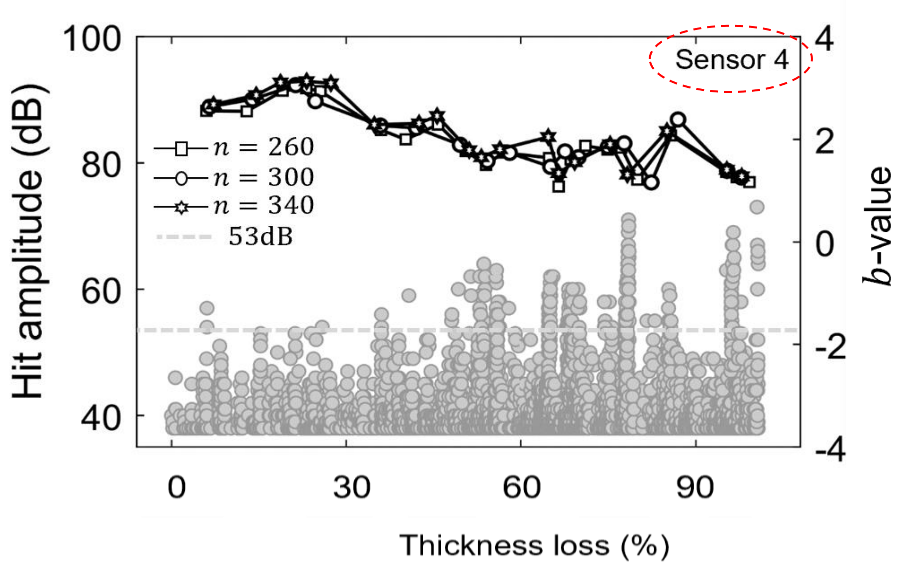
Qualitative estimation of corrosion evolution

Gutenberg-Richter empirical equation:

$$\log_{10} N = \alpha - \boldsymbol{b}(M)$$

Number of events greater than M — Constant — Amplitude of 1dB



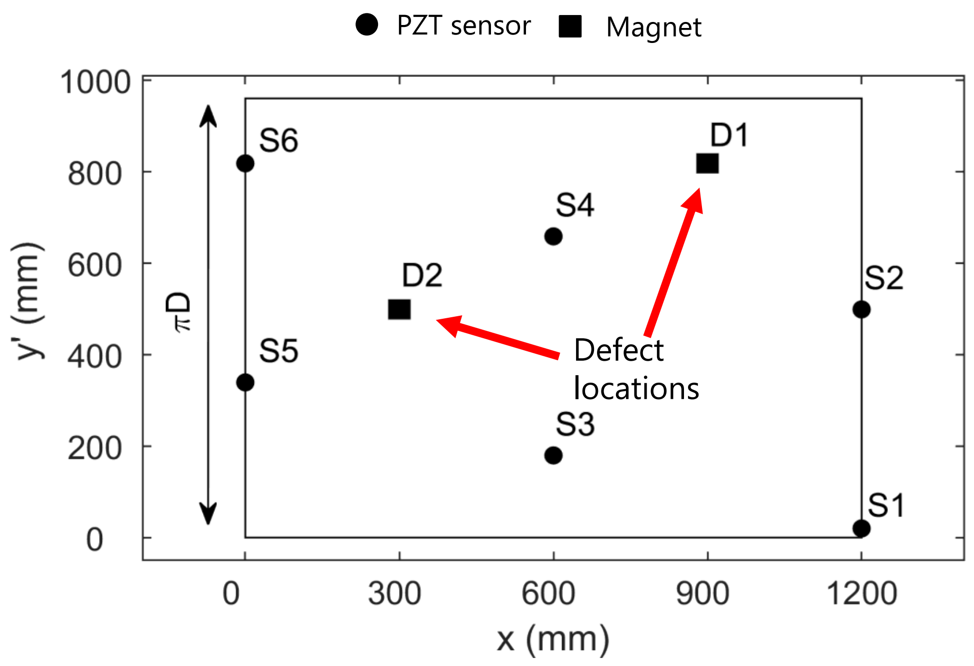


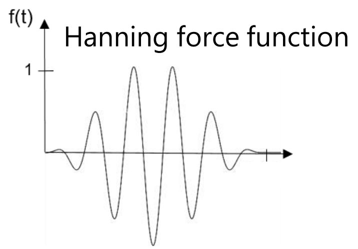
Task 3

Experiments

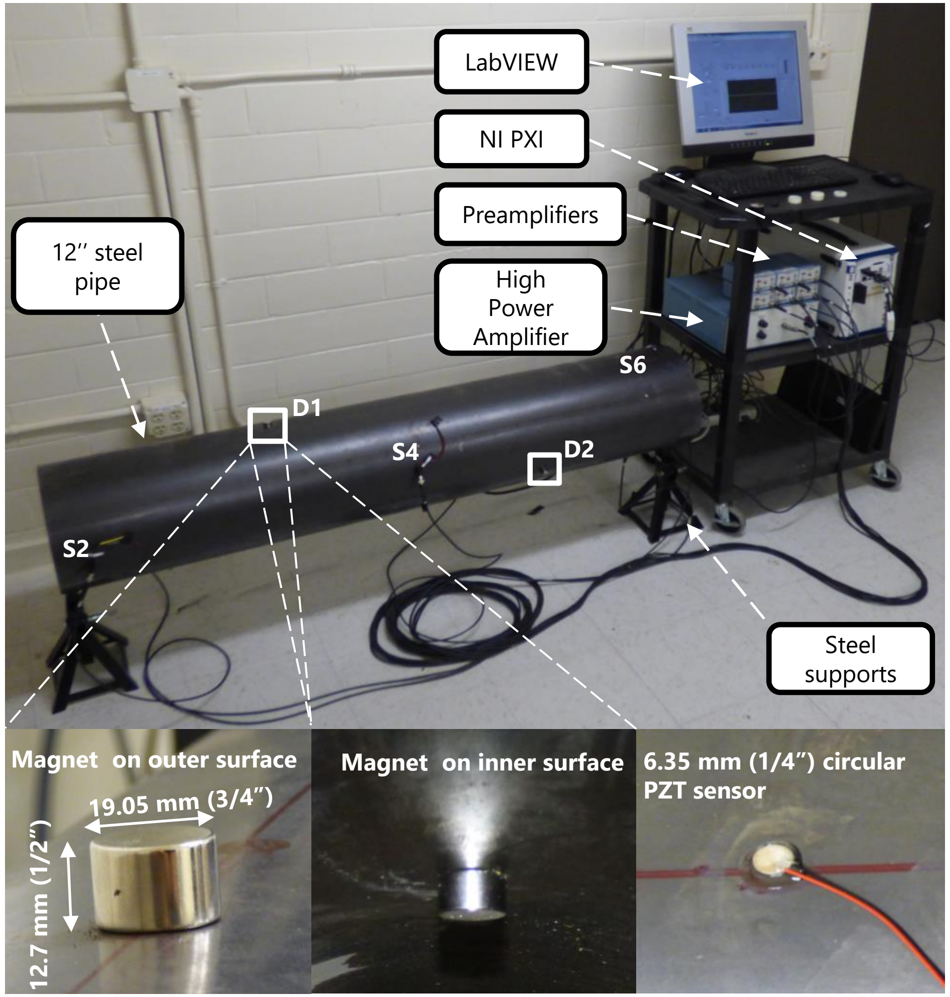
Task 3: Active pipeline health monitoring

Experimental setup





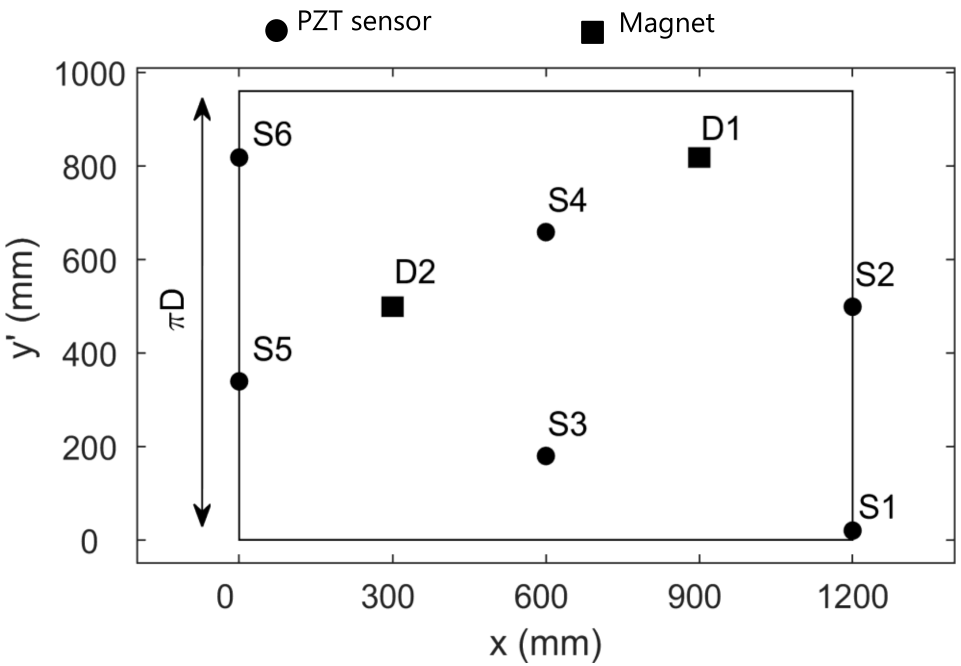
5.5 cycle Hanning profile burst
(300 - 400 kHz, < 1.5 MHz-mm)

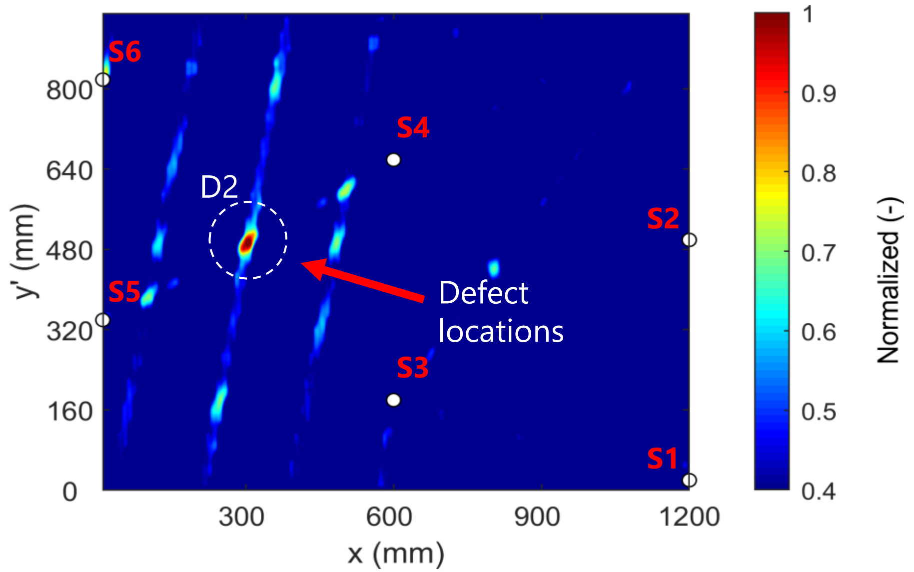


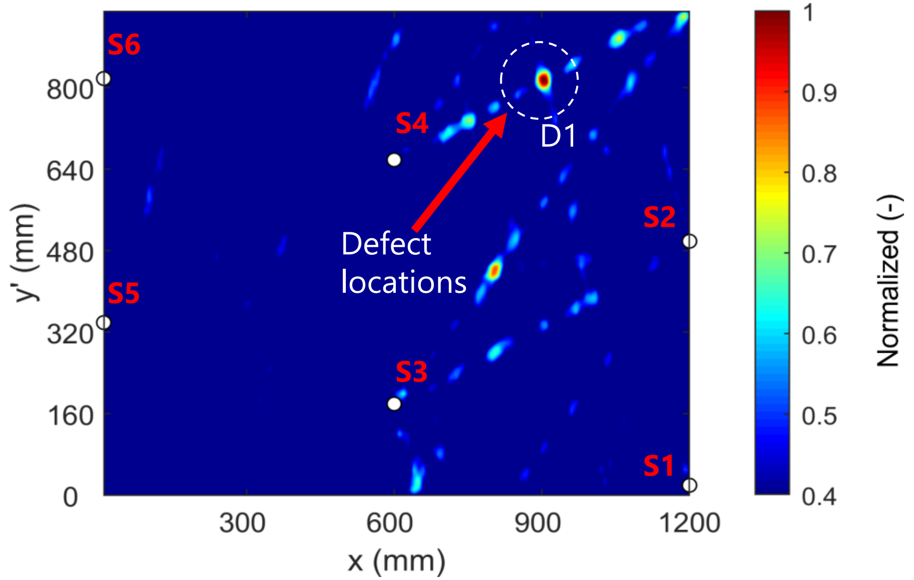
Task 3: Active pipeline health monitoring

Results

- Each magnet was localized accurately
- 9 helical orders were considered
- 6 PZT sensors to cover 120 cm
- Artifacts at least < 12% smaller than the peak indication



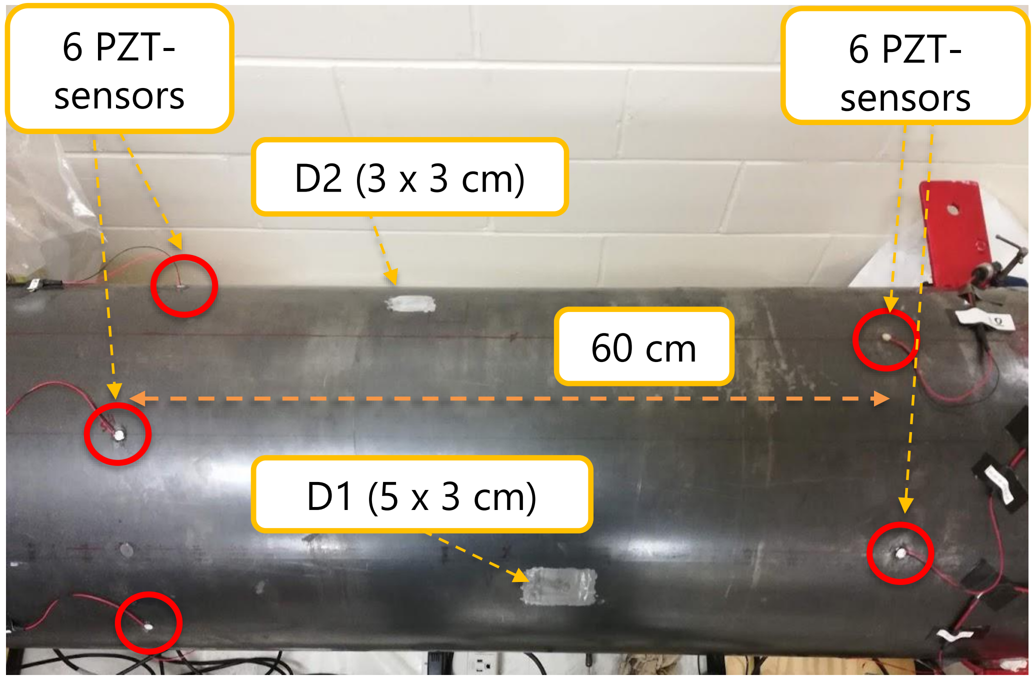




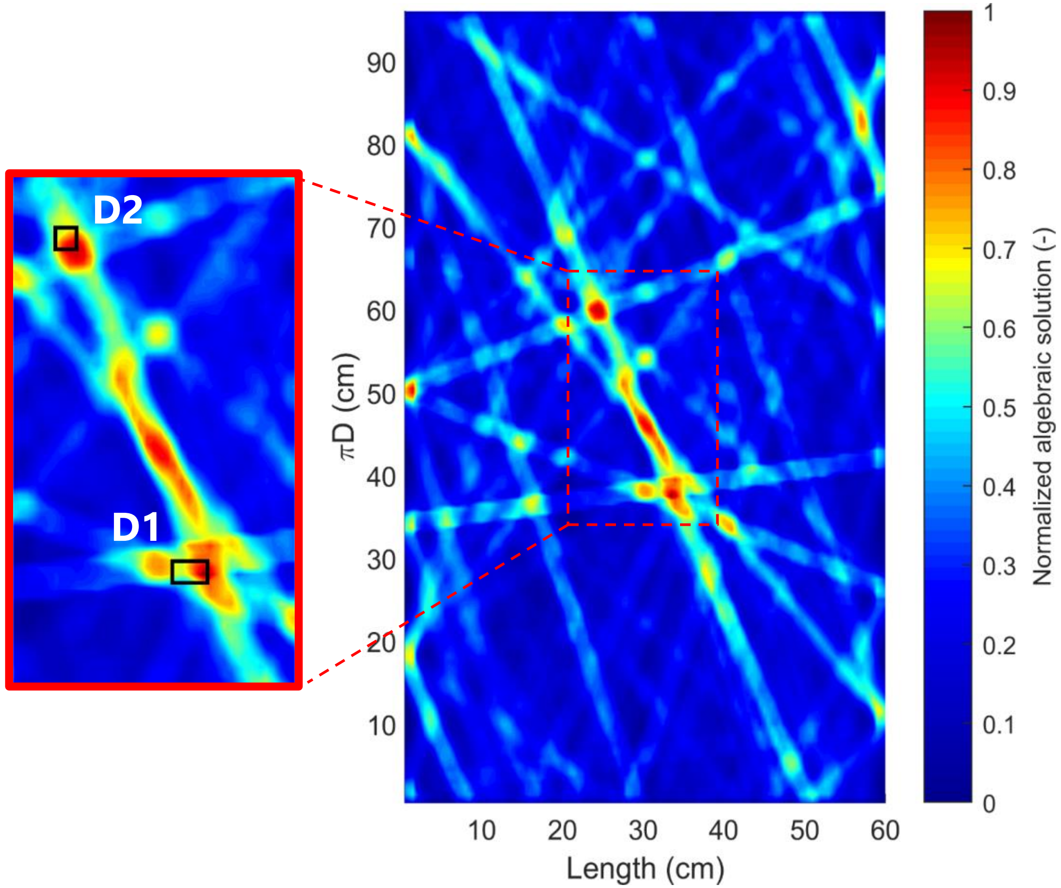
Task 3: Active pipeline health monitoring

Results

- Accurate localization on realistic damages (D1,D2), **simultaneously**
- 5 helical orders were considered
- 12 PZT sensors to cover 60 cm.

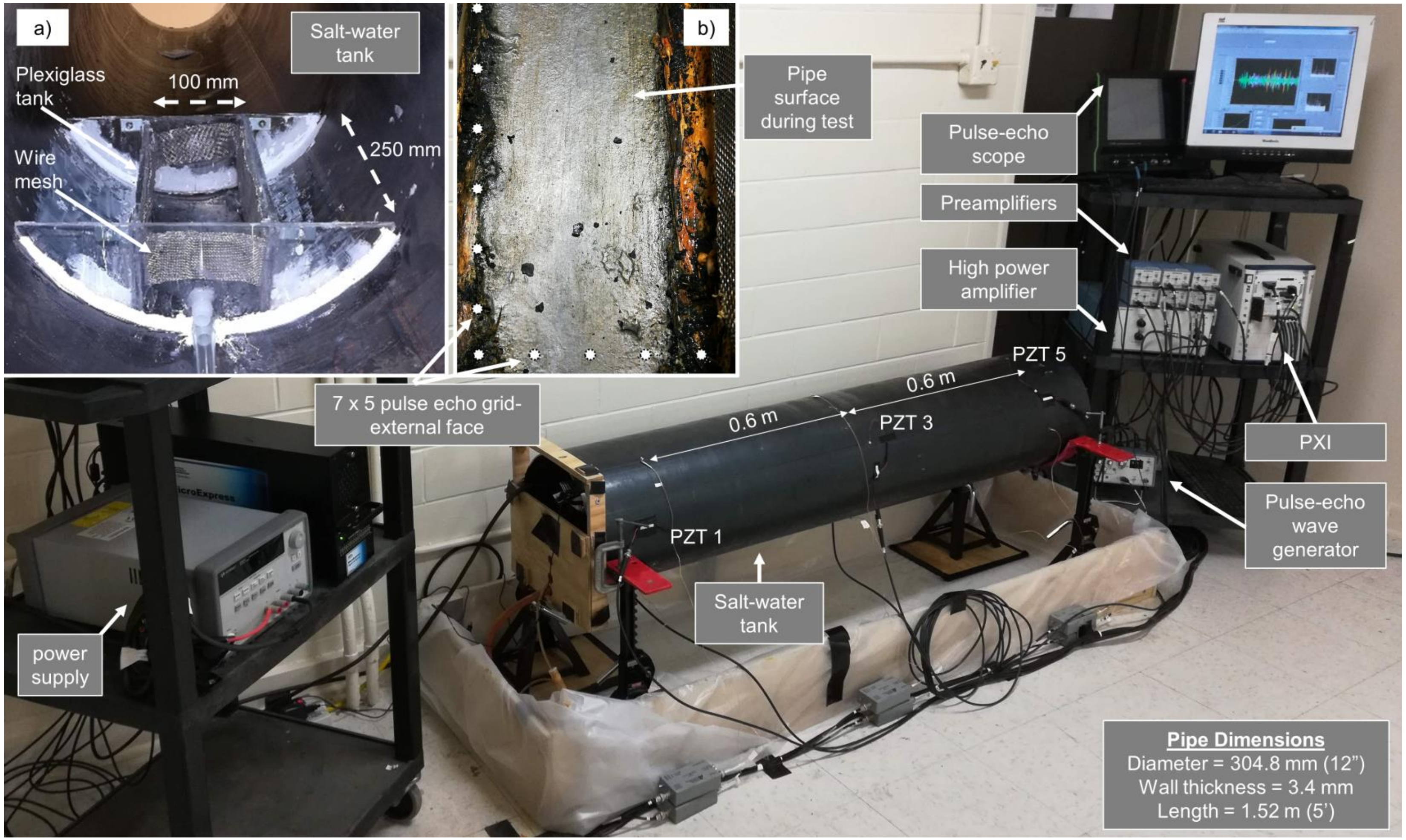


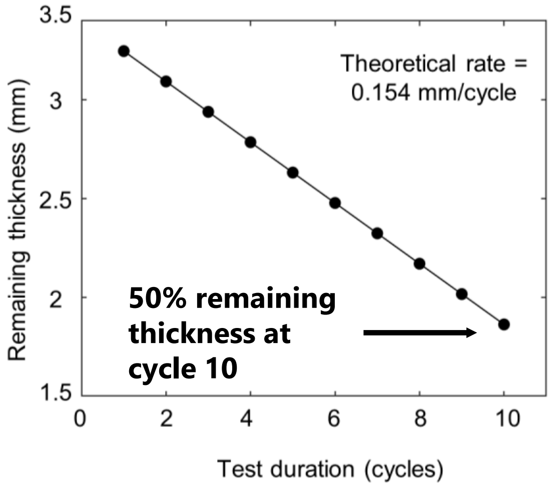
ART imaging

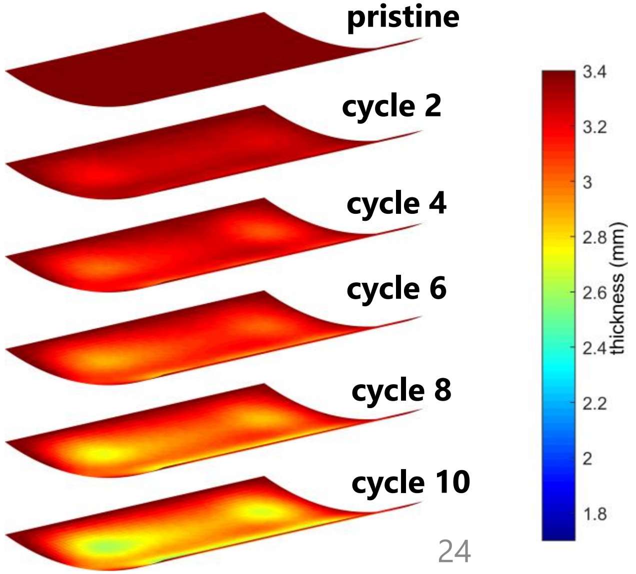


Task 3: Active pipeline health monitoring

Accelerated corrosion setup





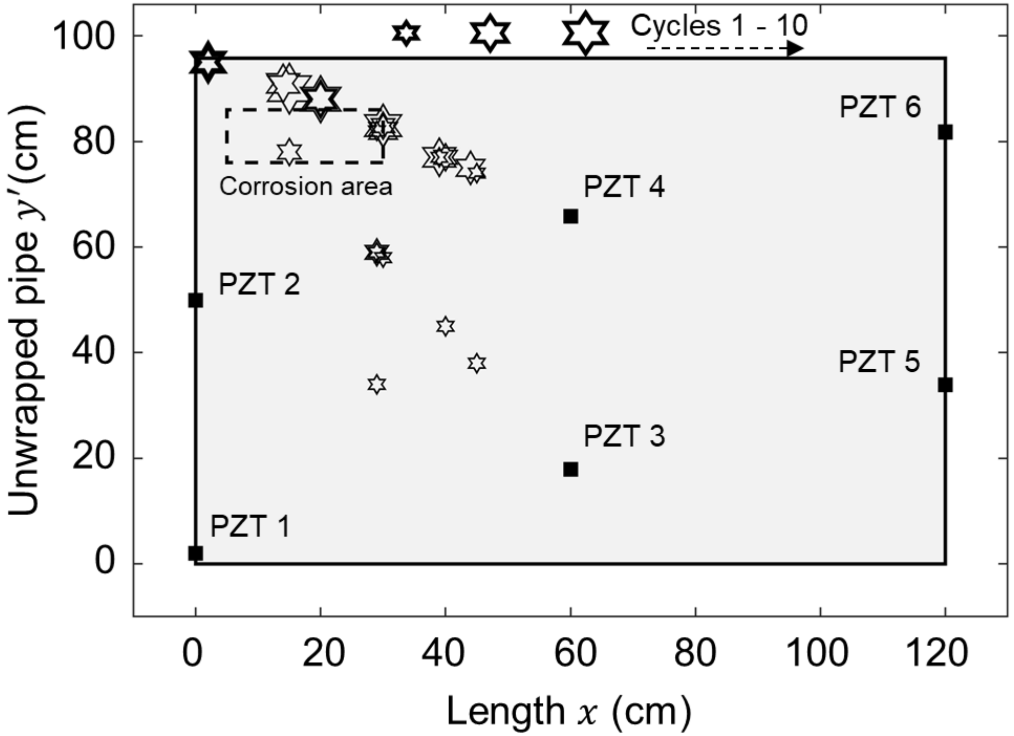


Task 3: Active pipeline health monitoring

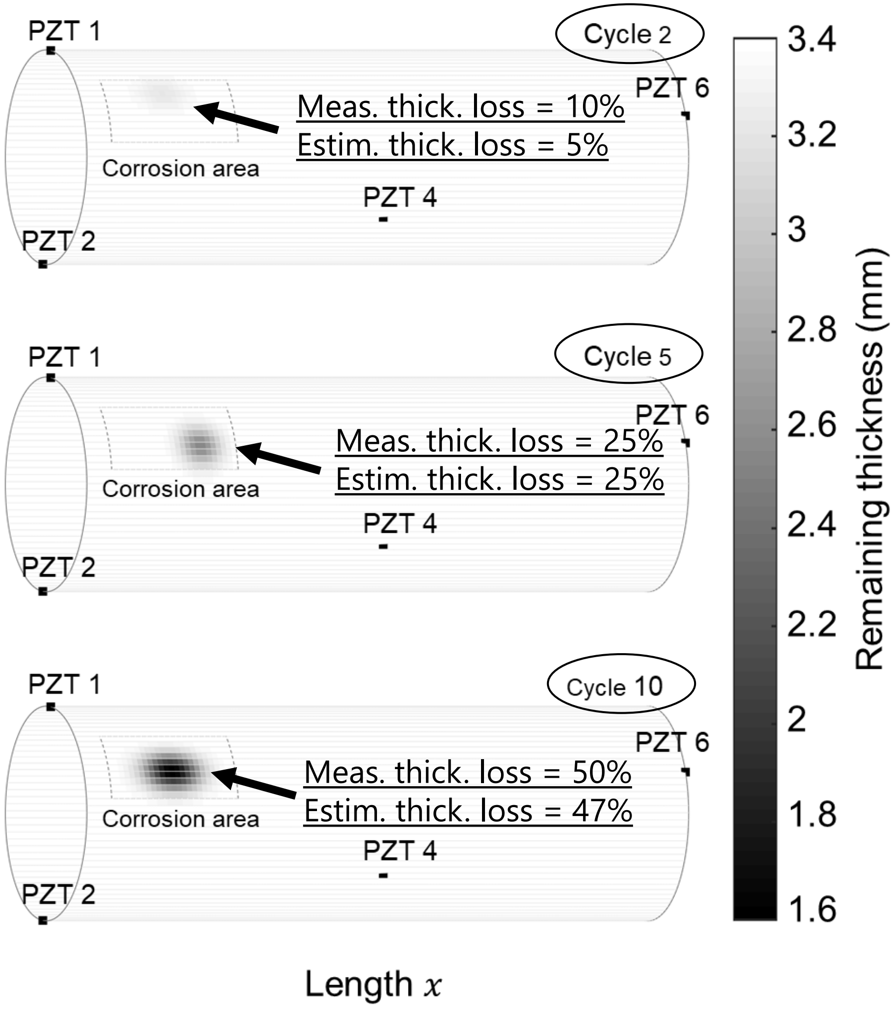
Results

- 5 helical orders were considered
- ***CL*** output typically > 2 coordinates locations
- Through ***CS*** the most accurate localization is chosen
- ***CS*** yields accurate results for thickness loss > 10%

Corrosion localization for cycles 1-10 (***CL***)



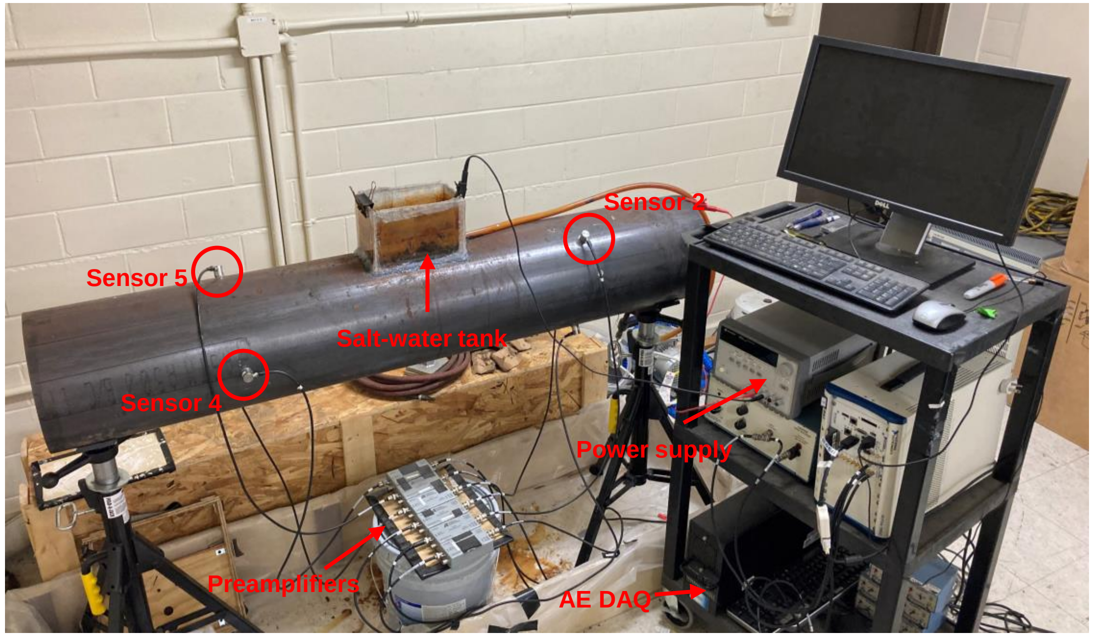
Tomographic results (***CS***)

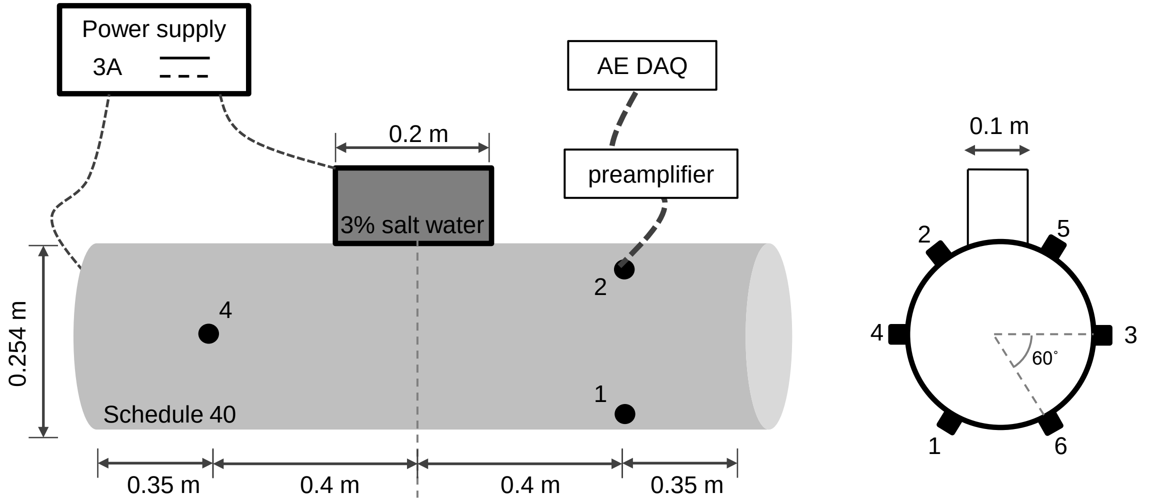


Task 3: Passive pipeline health monitoring

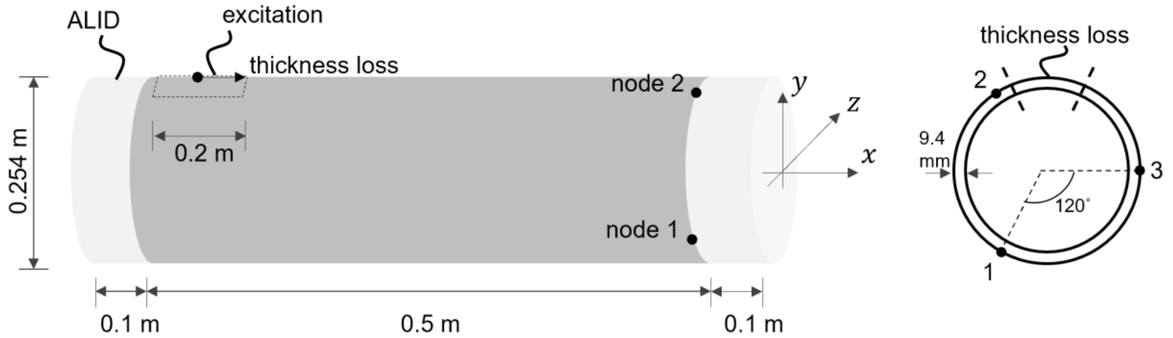
Test details

- Threshold = 38 dB
- 35 cycles (~ 160 hours)
- 6 × AE sensors (R15a)





FE model

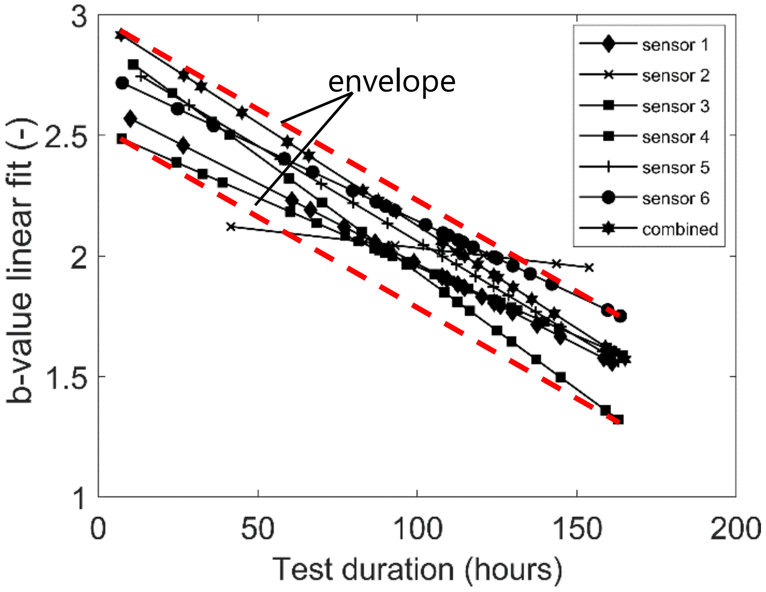


Task 3: Passive pipeline health monitoring

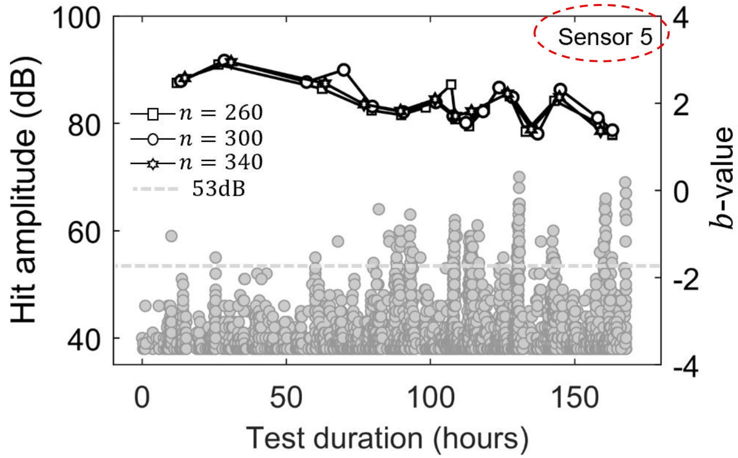
Results

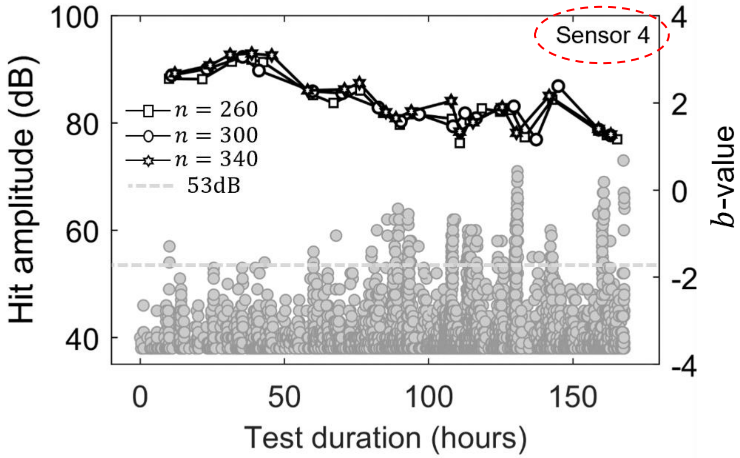
- *b*-value estimated individually for each sensor
  - Approximately 300 events/sensor for each *b*-value calculation
  - 1.5 < *b*-value < 3
  - Decreasing *b*-value
- A combined *b*-value from all the sensors
  - Linear interpolation of the *b*-values
  - Provide an envelope that characterizes the rate of corrosion

Combined *b*-values



Number of events and *b*-value for individual sensors





Task 3: Field testing

Location

- Monroe Energy – Philadelphia PA

Pipe dimensions

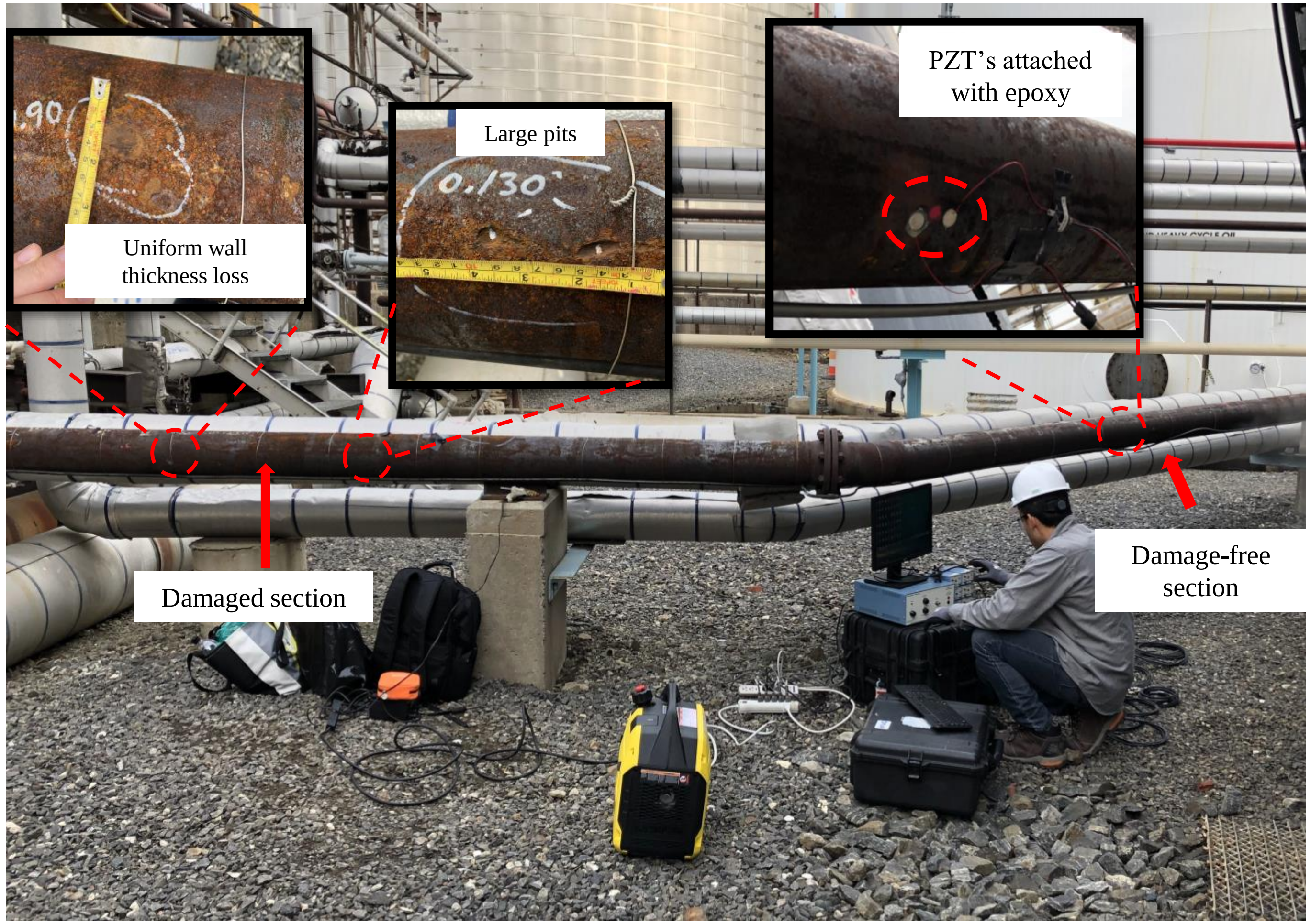
- Diameter = 6 in
- Thickness = 0.3 in
- Fluid filled (type unsure)

Findings

- High temperatures & rough surface led to weak bonding of the PZT to the structure.

↓

- Poor signal-to-noise ratio



Summary of findings & contributions

Helical Guided Ultrasonic Waves (HGUW)

Numerical modeling
- Guidelines for efficient modeling of HGUW using Finite Element methods
- FE modeling can estimate the interaction of HGUW with a variety of defects (e.g., corrosion, cracks)

Active Method
- Permanently attached, long-term monitoring system
- Reduced the number of sensing units
- Localization of corrosion-like defects in steel pipelines (internal & external, 10%CSA)
- Thickness reconstruction (tomography)
- Algorithms effective for small & low-contrast defects

Passive Method
- Qualitative monitoring of corrosion is steel pipes by monitoring the HGUW Acoustic Emission
- *b*-value methodology for corrosion
- Assist the early diagnosis of corrosion in pipes
- Identify critical stages of the corrosion progression

Recommendations for future work

Active method

- Establish confidence intervals or probability of detection (POD) for variety of defect sizes.
- Introduce additional corrosion profile parameters in 2D acoustic modeling.
- Extent the active monitoring algorithm to complex geometries.
- Investigate baseline-free alternatives.

Passive method

- Investigate pressurized pipes.
- Use the HGUW-AE for distinguishing different forms of corrosion.
- Investigate the HGUW-AE method for estimating the remnant thickness.

For both methods

- Field testing to study the influence of noise and vibrations during data collection.

Summary of accomplishments

Degrees awarded

• S. Livadiotis, "Pipeline health monitoring using helical guided ultrasonic waves", PhD thesis, 2022

Peer-reviewed journal publications

• S. Livadiotis, K. Sitaropoulos, A. Ebrahimkhanlou, and S. Salamone, "Acoustic emission monitoring of corrosion in steel pipes using Lamb-type helical waves", *Structural Health Monitoring*. June 2022. doi:10.1177/14759217221105644

• S. Livadiotis, A. Ebrahimkhanlou, and S. Salamone, "Monitoring internal corrosion in steel pipelines: A two-step helical guided wave approach for localization and quantification," *Structural Health Monitoring*, Nov. 2020, doi:10.1177/1475921720970139.

• S. Livadiotis, A. Ebrahimkhanlou, and S. Salamone, "An algebraic reconstruction imaging approach for corrosion damage monitoring of pipelines," *Smart Mater. Struct*., vol. 28, no. 5, p. 055036, 2019. doi:10.1088/1361-665X/ab1160

Conference papers & Presentations

• S. Livadiotis, A. Ebrahimkhanlou, and S. Salamone, "A helical-based ultrasonic imaging algorithm for structural health monitoring of cylindrical structures," Proc. SPIE. Denver, 2019, vol. 1, no. 1, pp. 2–8, 2019.

• S. Livadiotis, A. Ebrahimkhanlou, and S. Salamone, "Structural health monitoring of pipelines by means of helical guided ultrasonic waves and an algebraic reconstruction technique," Struct. Heal. Monit. 2019 Proc. 12th Int. Work. Struct. Heal. Monit., vol. 2, no. December, pp. 1885–1892, 2019.

• S. Livadiotis, A. Ebrahimkhanlou, and S. Salamone, "A helical-based ultrasonic imaging algorithm for structural health monitoring of large-diameter metallic pipelines" (presented at the Structures Congress 2019, Structural Engineering Institute (SEI) of ASCE, Hyatt Regency, Orlando, Florida April 24–27, 2019

Posters

• S. Livadiotis, A. Ebrahimkhanlou, and S. Salamone, "Internal Corrosion Monitoring in Pipelines by using Helical Ultrasonic Waves," (Presented at the Government/Industry Pipeline R&D Forum, Arlington, Virginia, US, February 19, 2020).

• S. Livadiotis, A. Ebrahimkhanlou, and S. Salamone, "An Integrated Corrosion Monitoring System for Pipelines," (Presented at the University of Texas at Austin Energy Research Expo, Austin, TX, US, October 2, 2019).

Student Engagement

• Tony Lee (PhD student in Civil Engineering) – 3rd and 4th year of the project

• Konstantinos Sitaropoulos (PhD student in Civil Engineering) – 3rd and 4th year of the project

Community Outreach

• Pipeline and Research Council International – (PRCI)

• ROSEN group

Final report and presentation available at:

https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=782

Thank you !

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https://sites.google.com/view/ssrg/