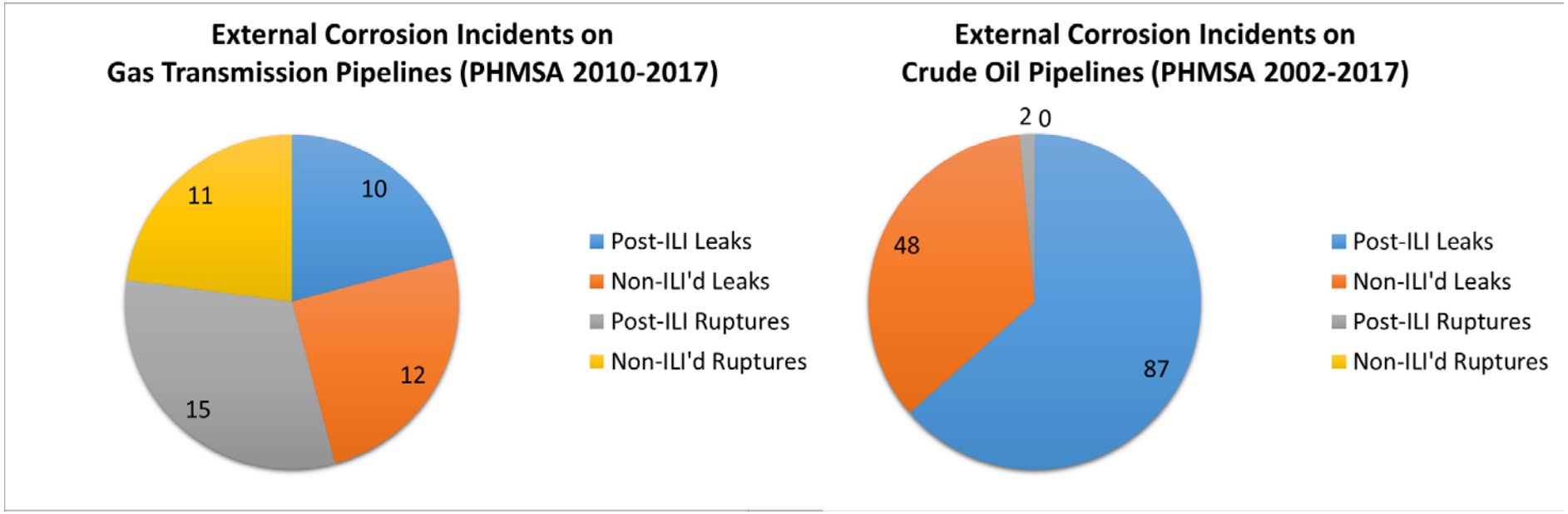
Background

MFL ILI is most effective in managing corrosion and reducing corrosion incident, yet still a few post-ILI incidents!

Industrial Post-ILI Corrosion Incidents – PHMSA Gas + Oil



For more details, IPC2018-78604 An ILI Based Program That Prevents Reoccurrence of Post ILI Failures Seen in Industry

Pipeline Research Council International

Quantification of ILI Sizing Performance for Severe Corrosion Anomalies

PRCI Project EC 4-6A

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LEADING PIPELINE RESEARCH

Introduction

- **Project Background:**
  - PRCI Project EC 4-6, *Improving Corrosion ILI Sizing Models for Long Complex Corrosion Anomalies,* focused on ILI performance in the presence of complex corrosion.
  - Complex corrosion identified based on high resolution laser scans
  - Data set consisted of 14 high resolution laser scans representative of complex corrosion – too small to quantify sizing errors with confidence

- **EC 4-6A Project Objectives:**
  - Develop criteria to identify severe corrosion anomalies from ILI data
    - *Anomalies that are likely to having sizing underestimated due to unique feature morphology*
  - Quantify ILI sizing errors for severe external corrosion as a function of feature morphology and dimensions
    - *For example, feature density, orientation, depth, length*

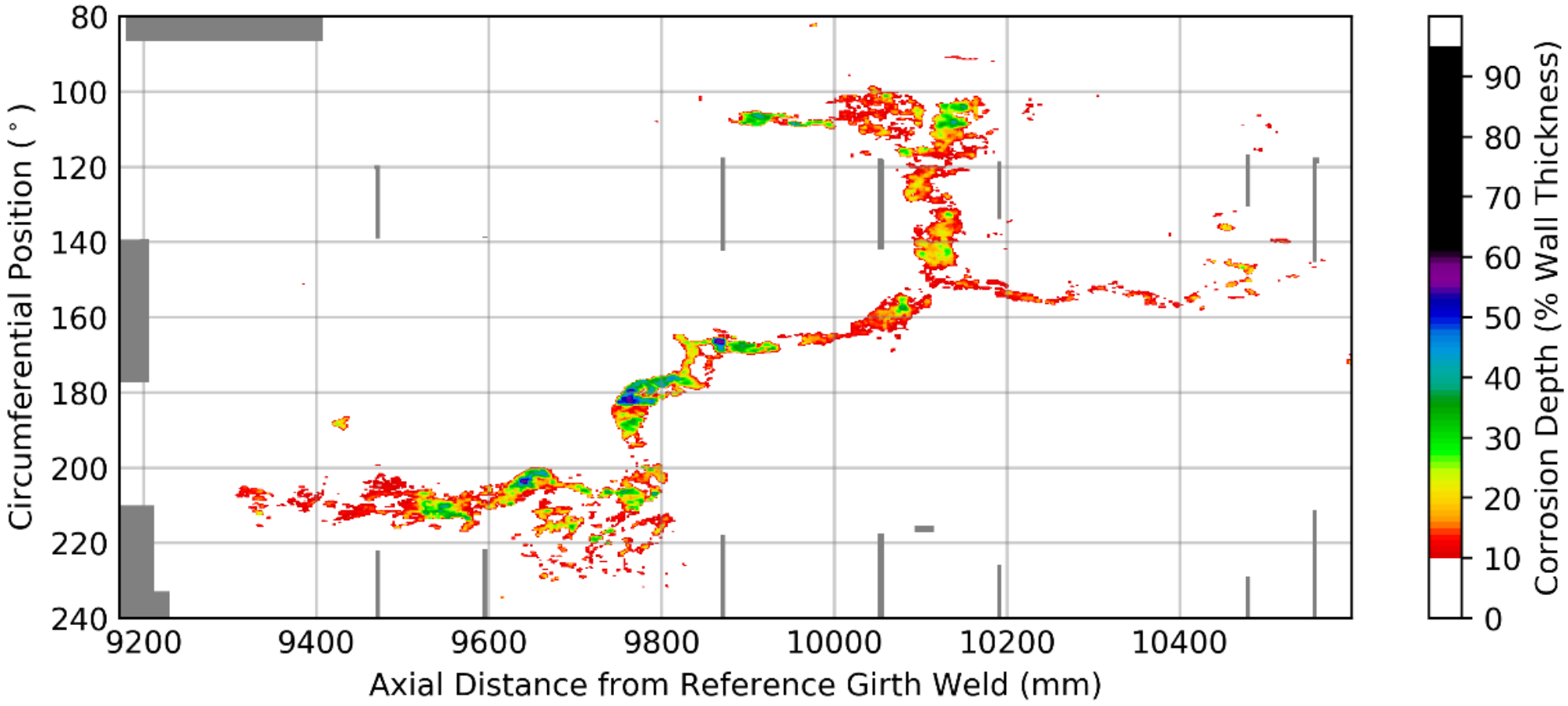
Project Tasks

- **Data Collection and Validation:**
  - Collection of high-resolution laser scan data and associated ILI data sets
  - Validation of the data collection against correctness, completeness and consistency
  - Storage in secure database
- **Severe Anomaly Identification**
  - Severe anomaly definition
  - Severity characterization using corrosion attributes such as orientation, density of features, depth gradient
- **ILI Sizing Error Modeling**
  - Quantification of ILI sizing errors
  - Sizing error modeling for correction of depth and length sizing, and validation of the model
- **Project Management and Reporting**

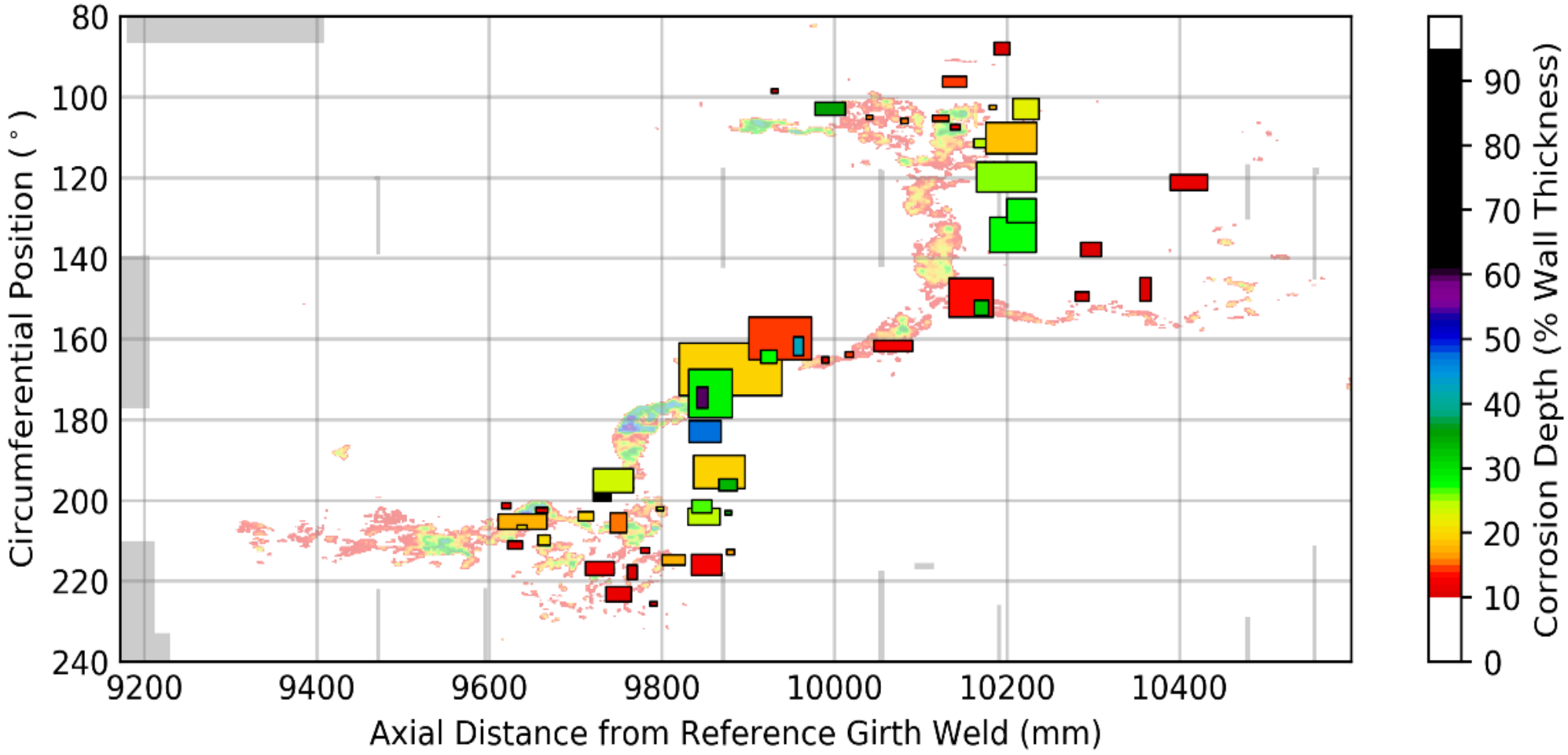
Project Outcomes

- A secure SQL database with 121 high-resolution LS and associated ILI datasets.
- Cluster length, average depth and maximum depth threshold criteria were developed to identify severe corrosion clusters.
- Run-specific ILI performance in the dataset meets the typical depth sizing specifications of +/-10%WT tolerance, when factors related to corrosion growth and sample size are removed.
- Correction models for maximum depth and length were developed and validated
- Applying sizing corrections was shown to reduce the error in estimated burst pressure capacity for severe clusters.

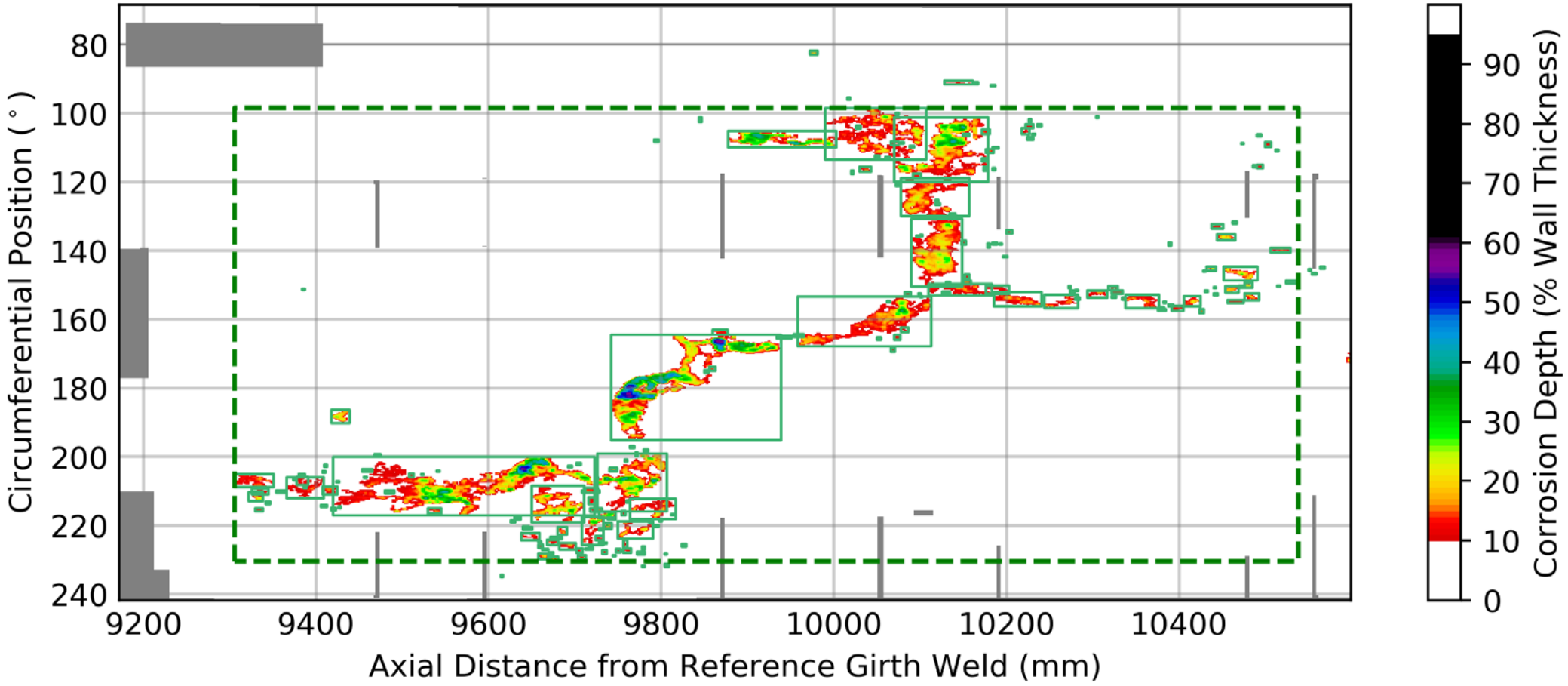
Data – High Resolution Laser Scan



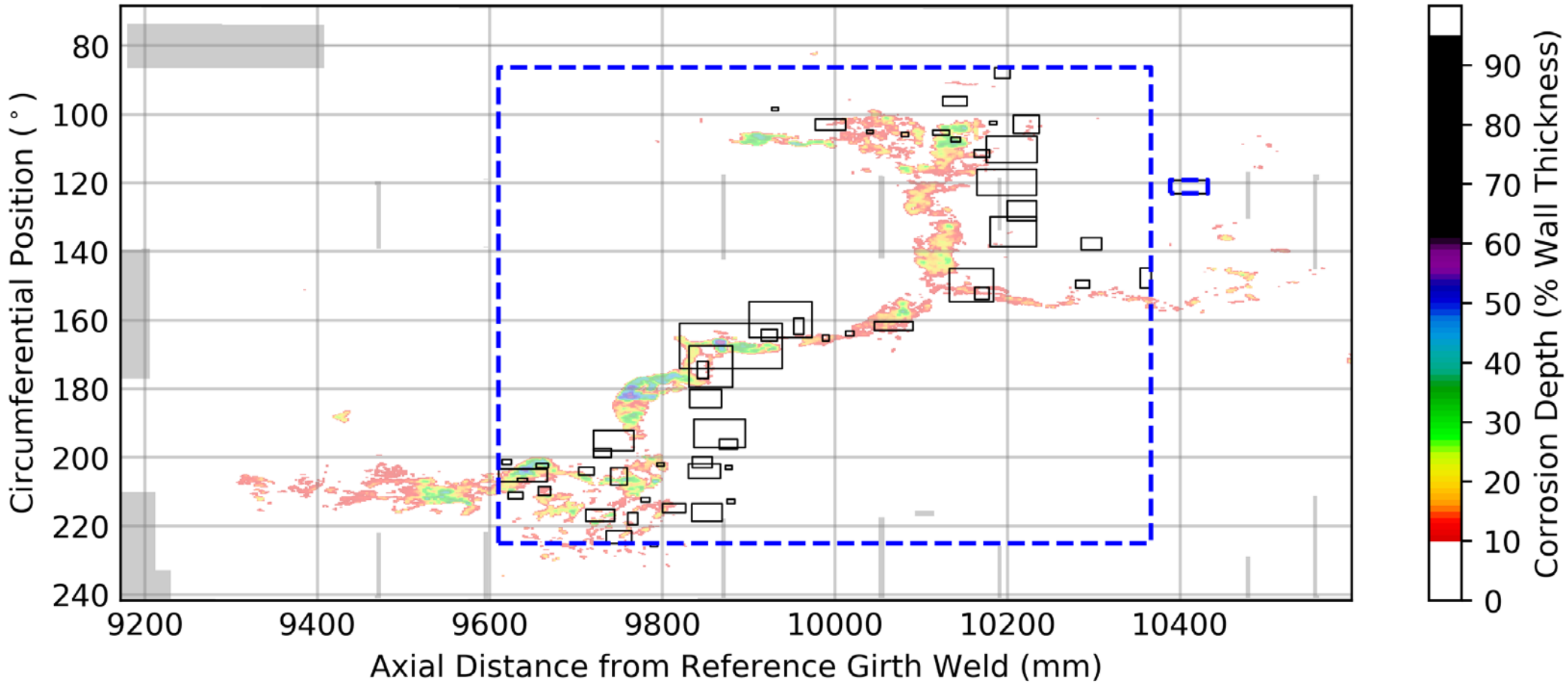
Data – Inline Inspection



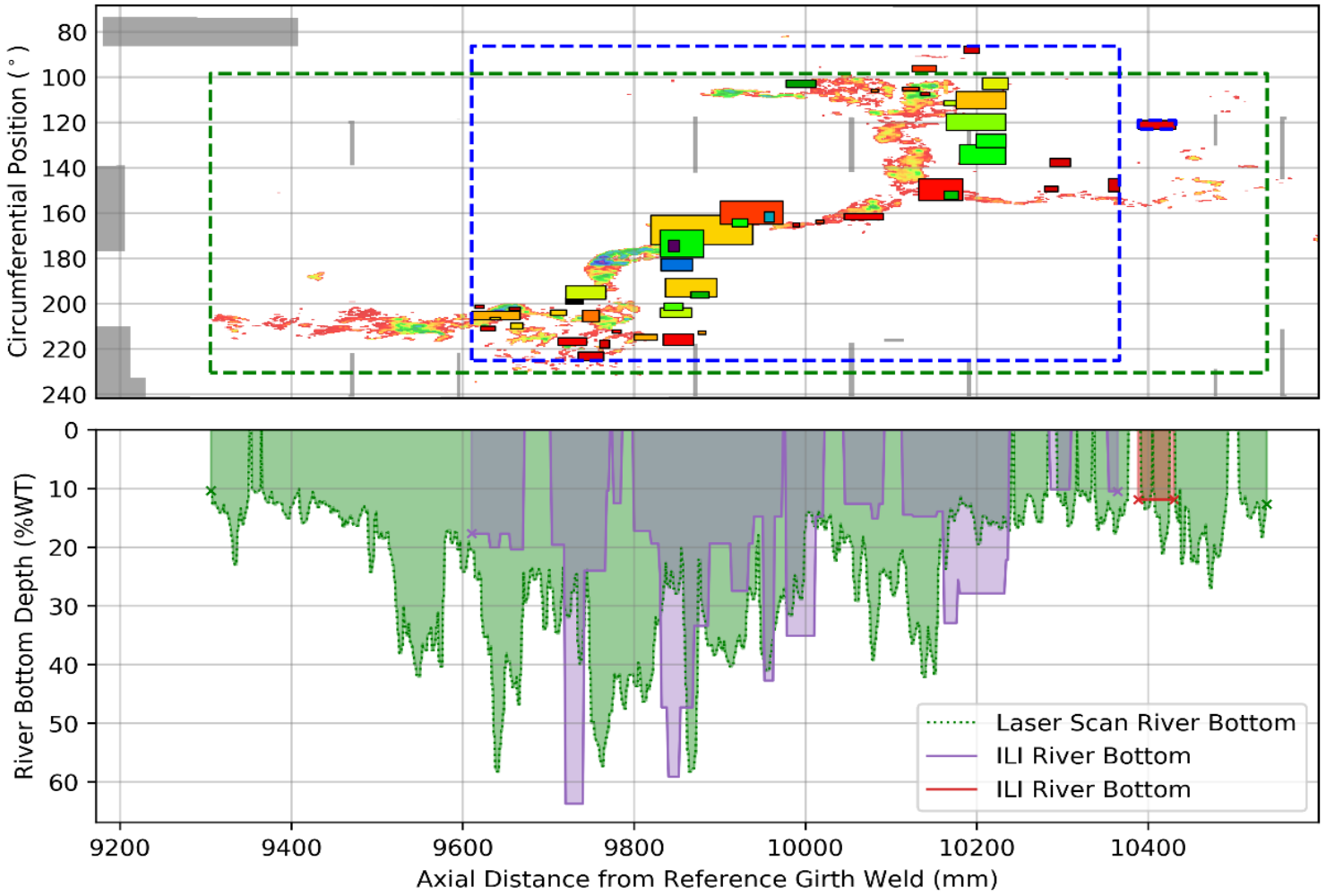
Identifying Features and Clusters – Laser Scans



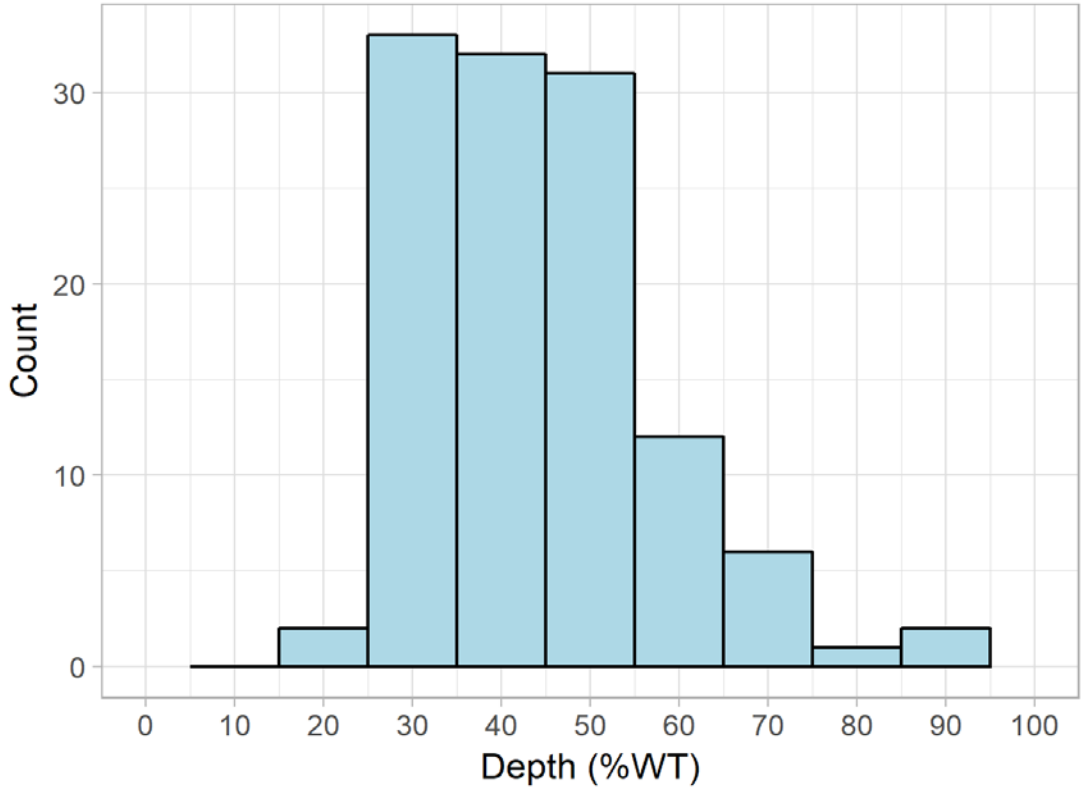
Identifying Clusters – ILI Anomalies

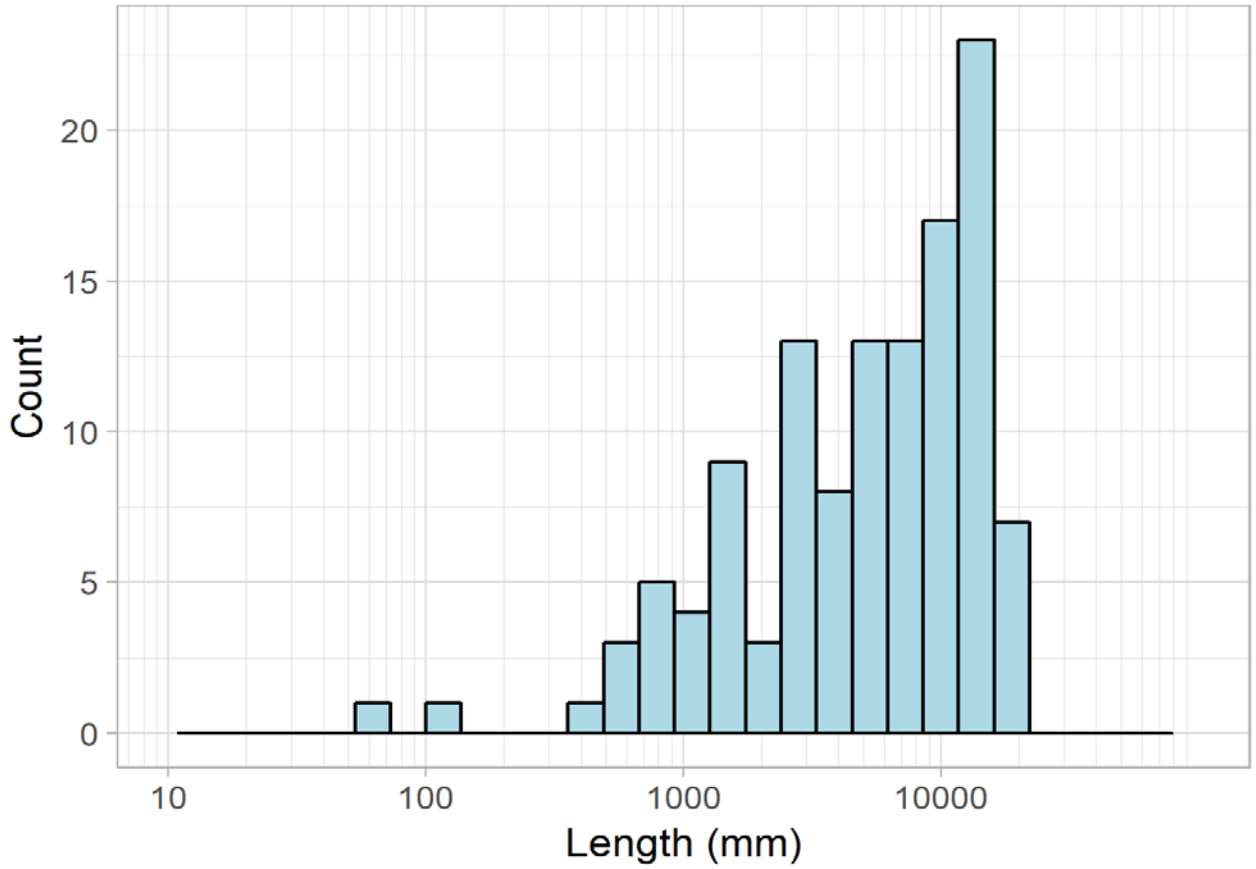


Data Processing – River Bottom Profiles



Data Summary – All Laser Scans



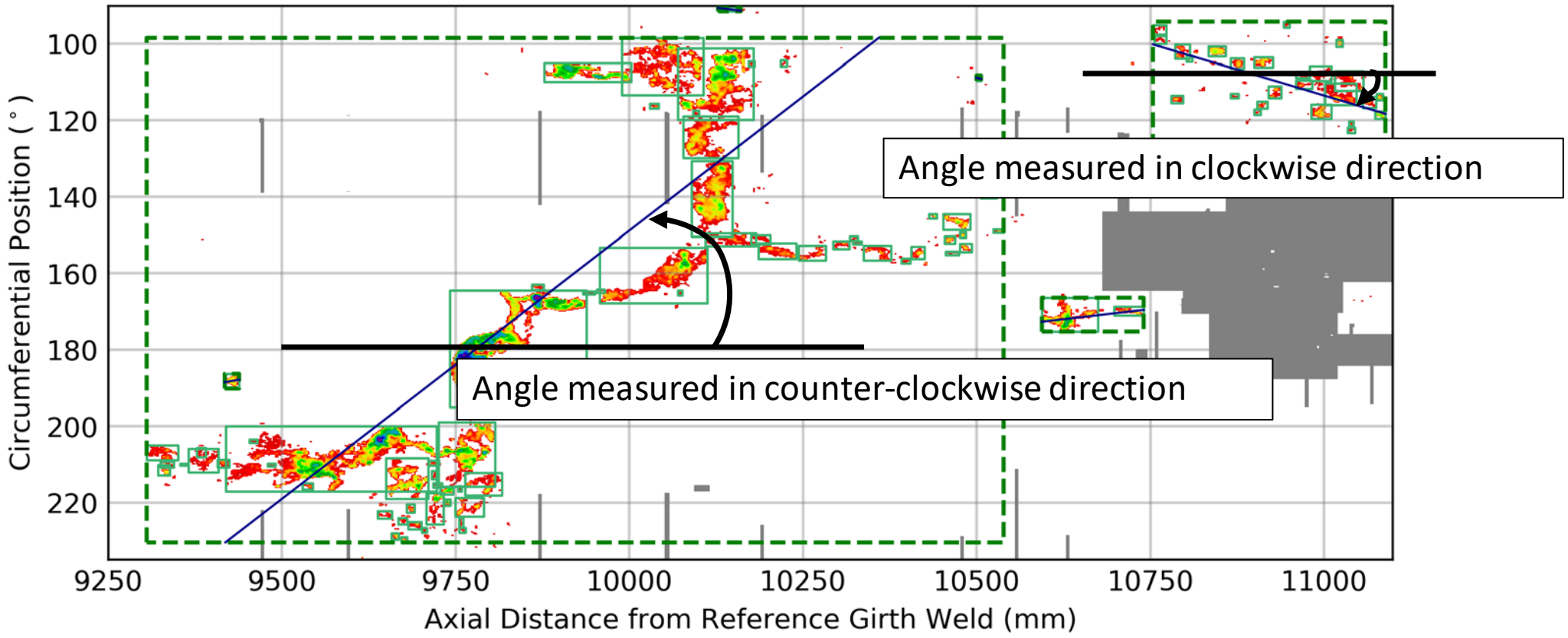


Severity Criteria Development

- **Severe Corrosion:**
  - Clustering of anomalies by 6t interaction distance – axially and circumferentially
  - Burst pressure capacity assessed by Effective Area method < 100% SMYS

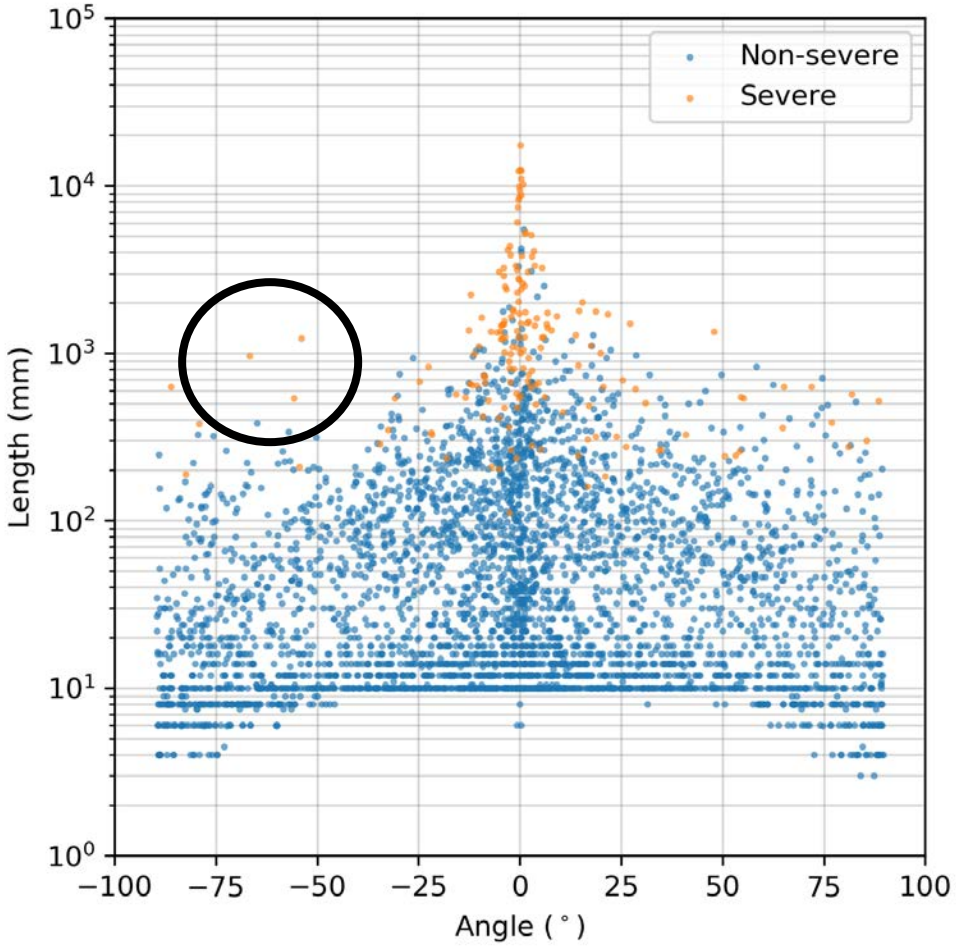
- **Cluster Attributes:**
  - Maximum depth: Maximum depth of a cluster
  - Length: Maximum length of the cluster
  - Average depth: Average of depths in a river bottom profiles
  - Density: Density of features within a corrosion cluster
  - Angle: Angle between the primary orientation of the corrosion cluster and the pipe longitudinal axis
  - Gradient: Ratio of maximum depth to length
  - Profile factor: Ratio of average depth to length

Cluster Attributes: Angle

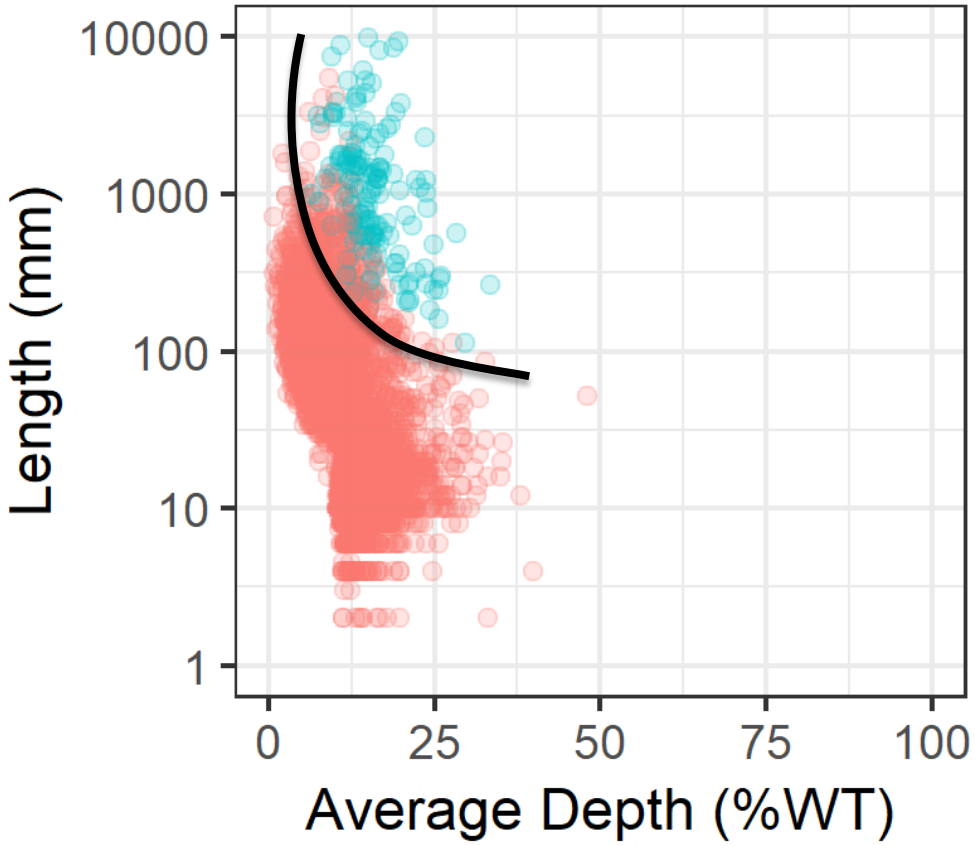


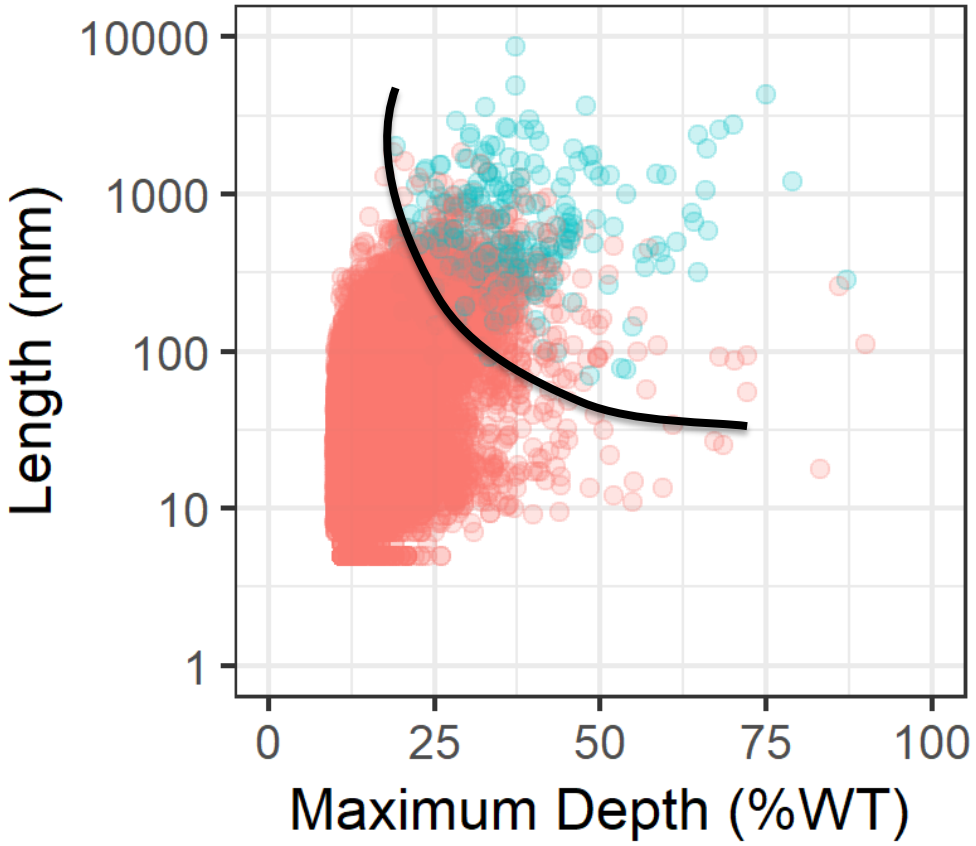
Exploratory Data Analysis

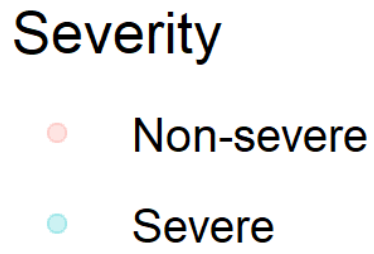
- **Relationships between all cluster attributes explored to identify “severe” clusters**
- **Most influential cluster attributes are related to burst pressure models**
- **Primary cluster attributes:**
  - Length
  - Average depth
  - Maximum depth



Severity Criteria Selection – Laser Scan Clusters







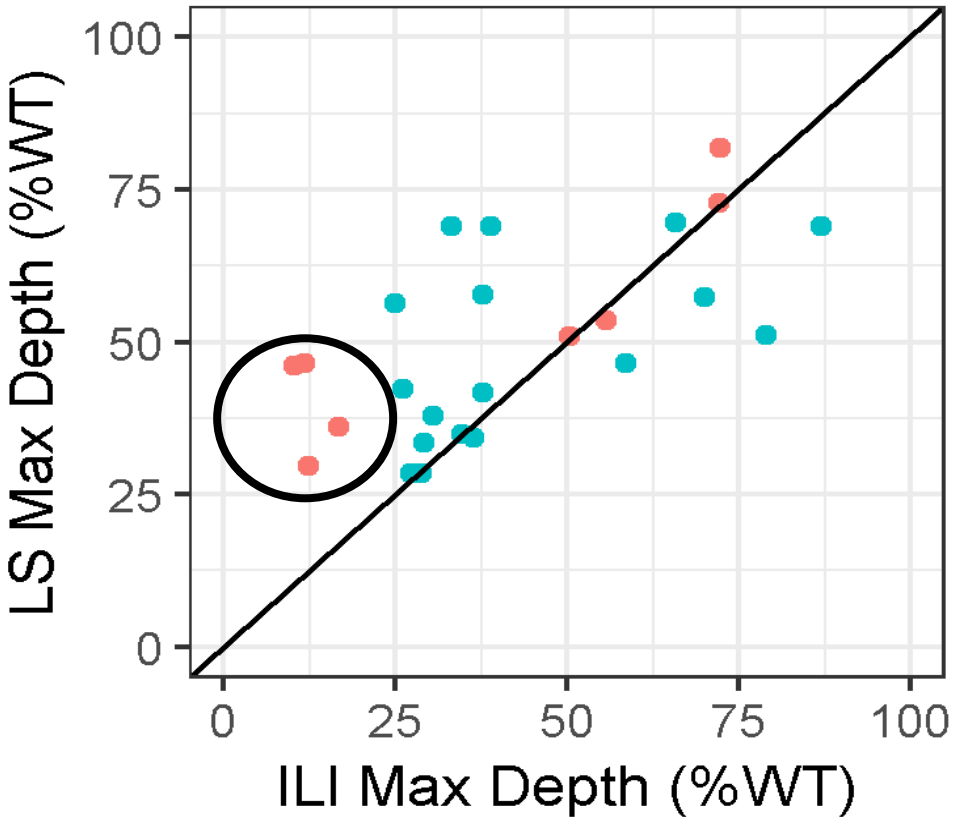
Severity Criteria Development – Laser Scan Clusters

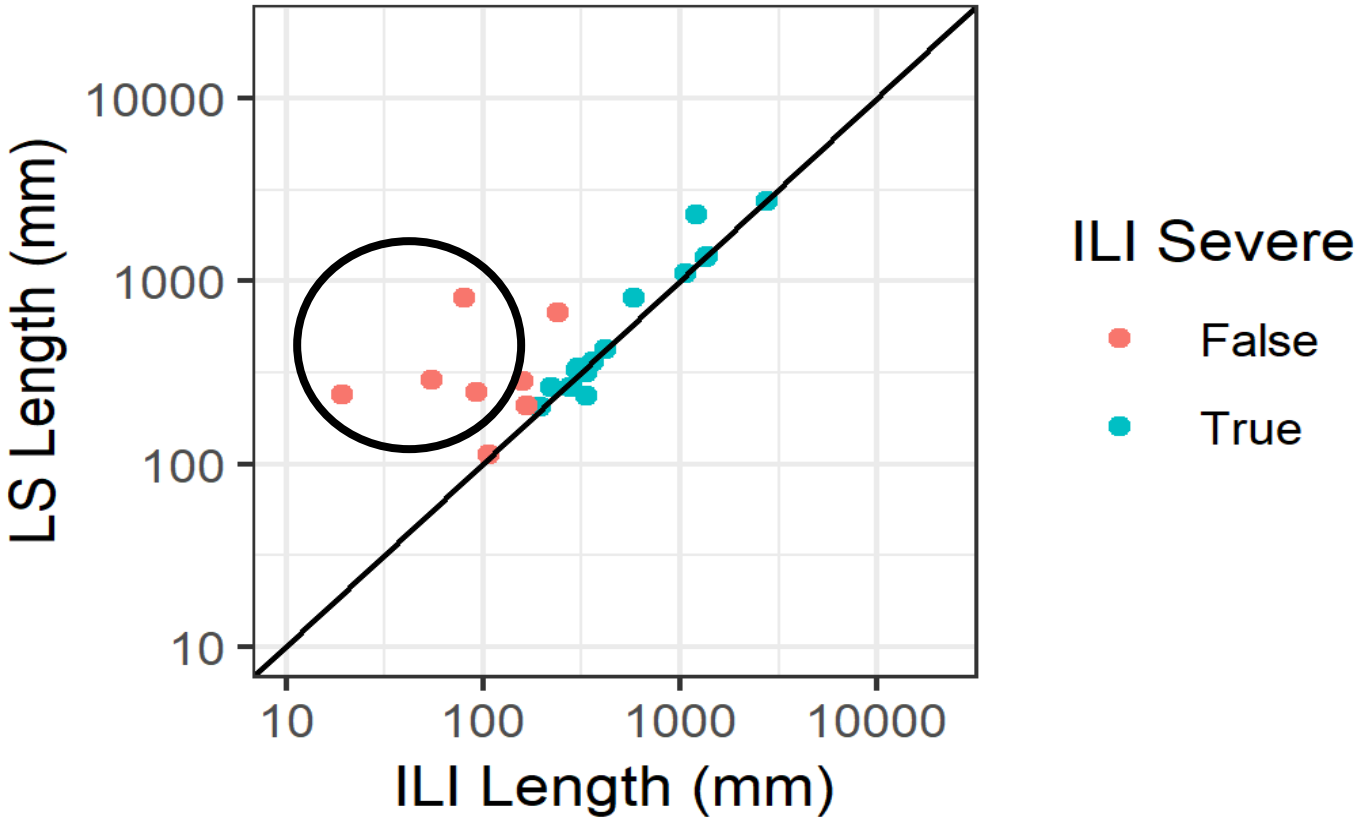
- ***Length*: Corrosion cluster length greater than 200 mm (7.87 in).**
- ***Average Depth*: Average depth greater than 10%WT**
- ***Maximum Depth*: Maximum depth greater than 25%WT**

- **Selected for balance between**
  - True positive rate (TPR): Ratio of correctly identified severe clusters to the total number of severe clusters – 88%
  - False discovery rate (FDR): Ratio of non-severe clusters incorrectly identified as severe to the total number of severe clusters – 38%

- **High TPR reduces the likelihood of severe clusters being misclassified as non-severe**
- **Low FDR reduces the likelihood of non-severe clusters being misclassified as severe**

Severe Cluster Identification – Validation





Validated for 25 ILI-LS matched severe clusters considering ILI depth and length sizing tolerances

ILI Depth Sizing Performance by ILI Run

ILI run date	Number of One ILI to One LS matched clusters	% of clusters within 10%WT	95% confidence interval	
			Lower bound	Upper bound
2013	66	94%	85%	98%
2013	26	96%	81%	99%
2014	44	59%	44%	72%
2014	29	41%	25%	59%
2016	58	86%	75%	93%
2016	46	80%	67%	89%
2017	87	75%	65%	83%
2017	65	71%	59%	80%
2017	48	88%	75%	94%
2017	28	86%	68%	94%

10 out of 28 ILI runs listed that have more than 15 one-to-one matched clusters

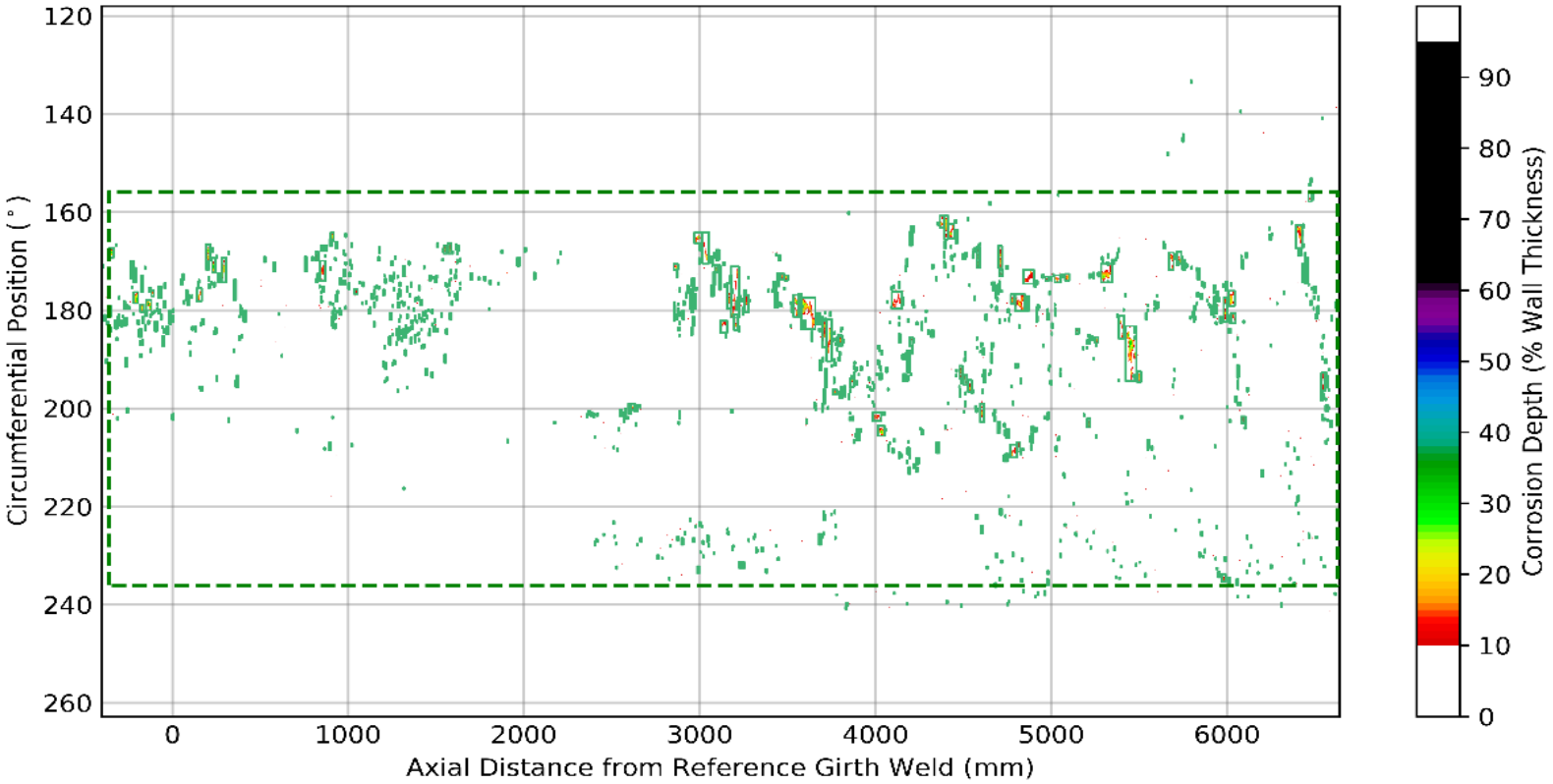
Corrosion growth could affect sizing error quantification for ILI runs earlier than 2017

ILI Sizing Performance - Severe Corrosion

- **Only 25 one-to-one matched severe corrosion clusters with 6t x 6t interaction distance**
- **“Scan-wide” clusters matched based on the entire laser scan area**
  - 121 laser scans matched all ILI anomalies within the scanned area

ILI run date	Number of scan-wide clusters	% within 10%WT tolerance	% within 15%WT tolerance	%within 20%WT tolerance
2013	32	84%	94%	97%
2014	17	41%	59%	65%
2015	2	100%	100%	100%
2016	18	28%	44%	44%
2017	51	75%	82%	90%
2018	1	0%	100%	100%

ILI Sizing Performance - Outliers

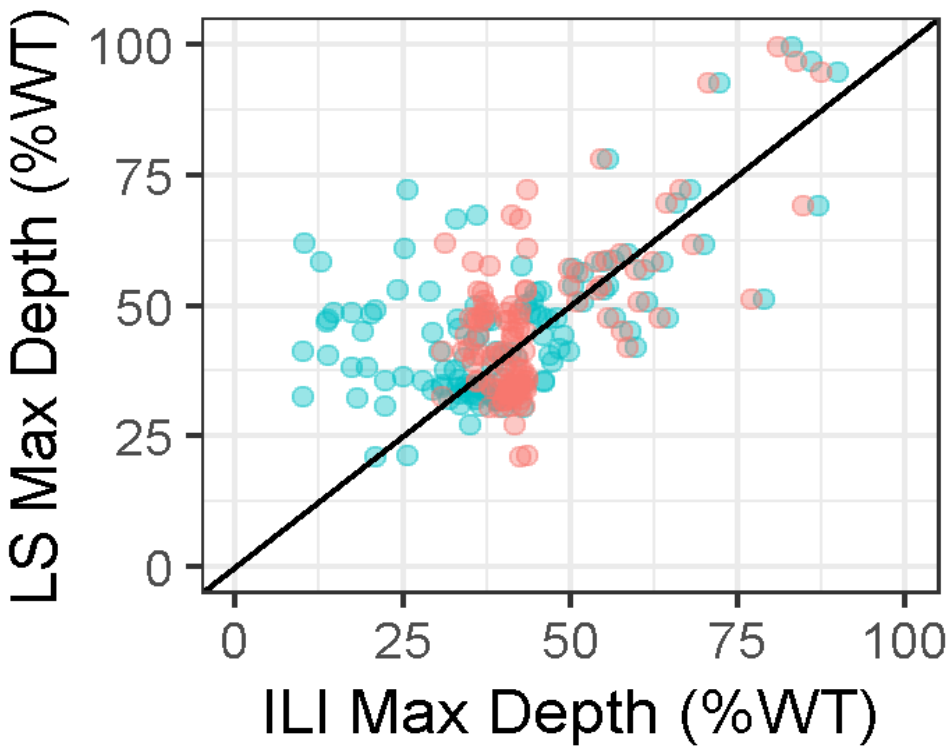


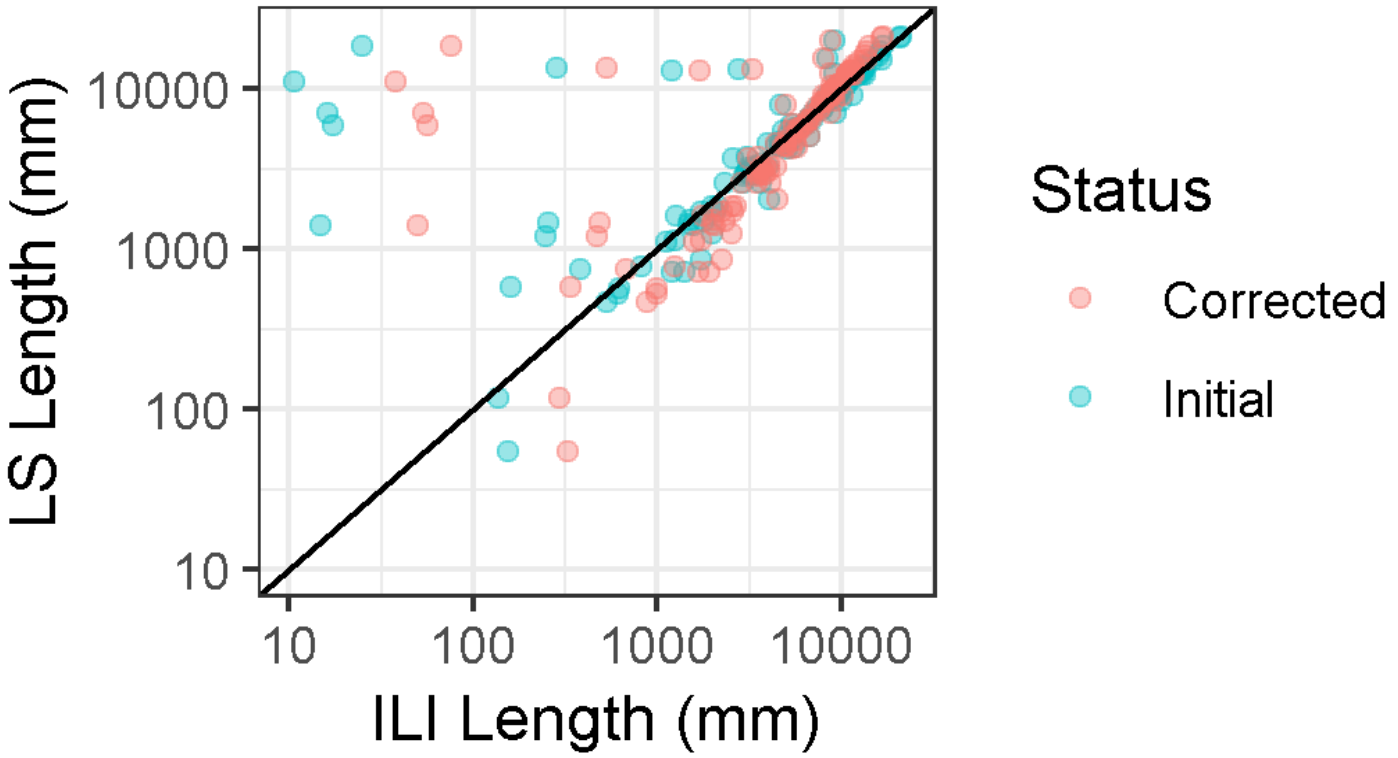
Sizing performance in 2016 ILI run data influenced by undetected pinhole features

ILI Sizing Correction Models

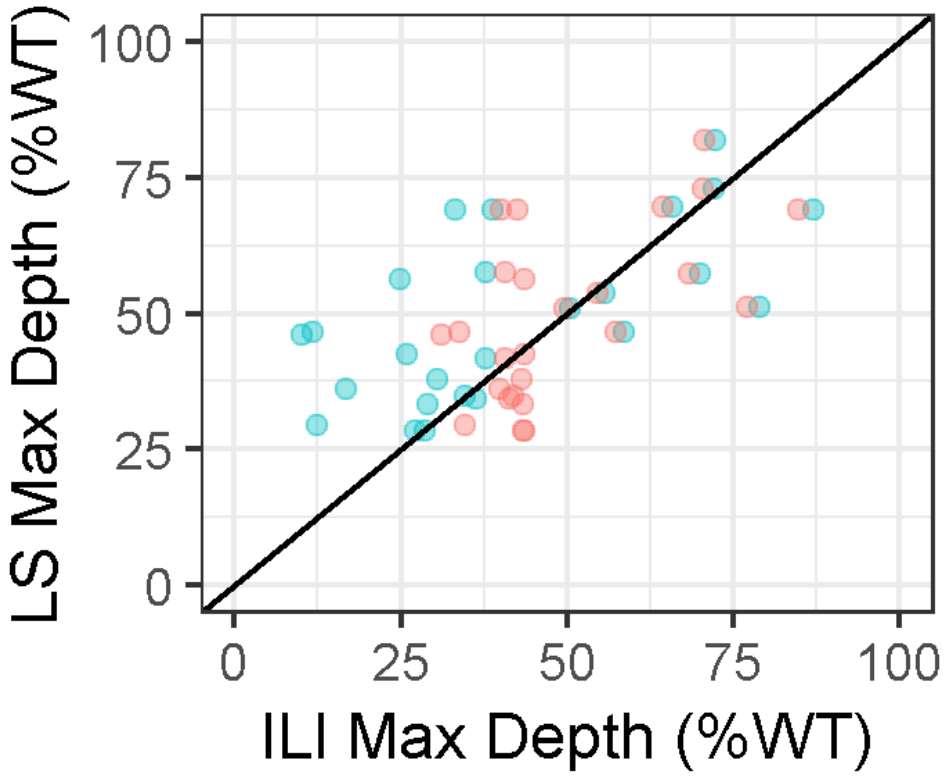
- **Maximum depth sizing:**
  - Maximum ILI depth > 50% WT
    - *Likely sizing error less than 50% WT for under-calls*
    - $D_{ILI_{corrected}} = m_D \cdot D_{ILI_{raw}} + b_D$
  - Maximum ILI depth < 50% WT
    - *Likely sizing error greater than 50% WT for under-calls*
    - *Nonlinear correction model needed for large corrections of under-calls*
    - $D_{ILI_{corrected}} = D_{ILI_{raw}} \cdot \exp(m_D \cdot D_{ILI_{raw}} + b_D)$
- **Length sizing:**
  - Linear model for length converted to log-scale in base 10
  - $L_{ILI_{corrected}} = m_L \cdot L_{ILI_{raw}} + b_L$

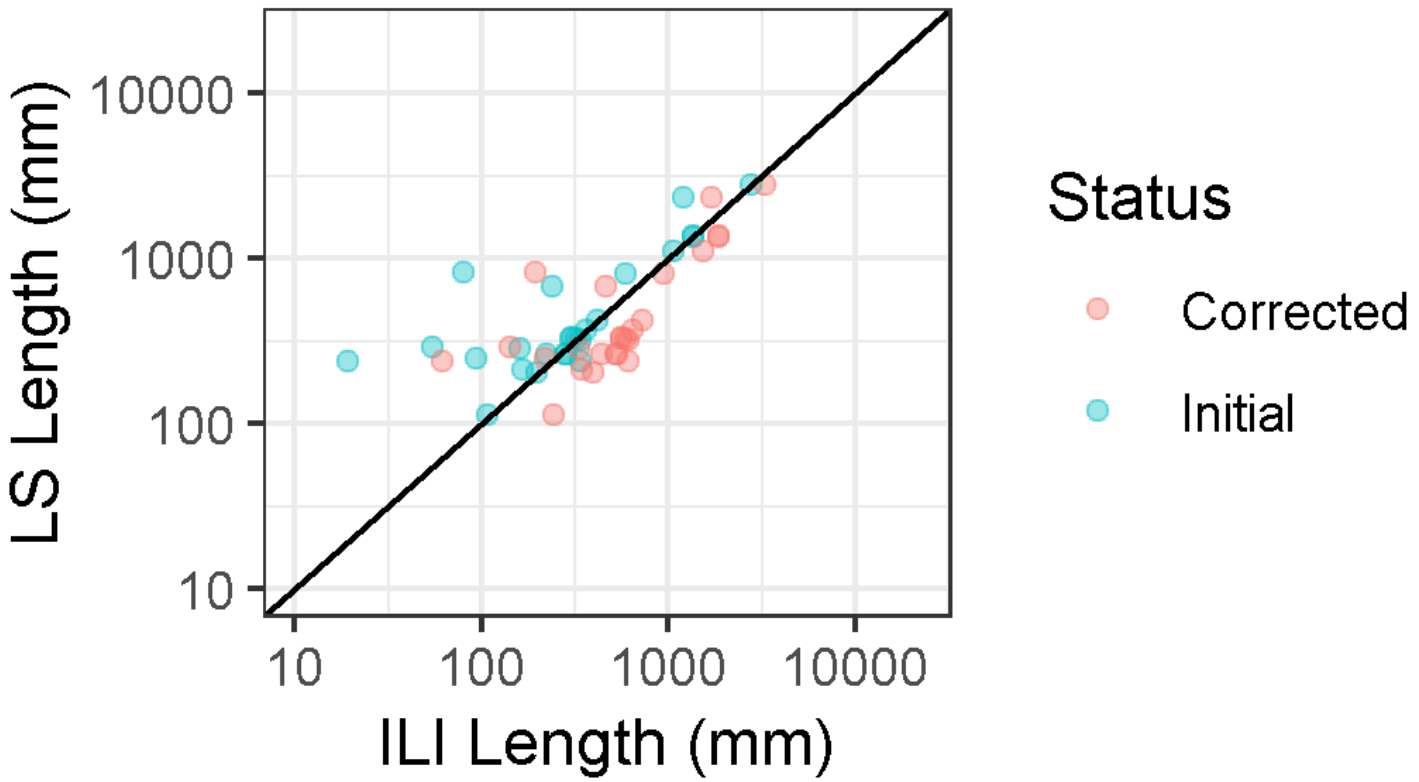
Sizing Correction – Scan Wide Clusters





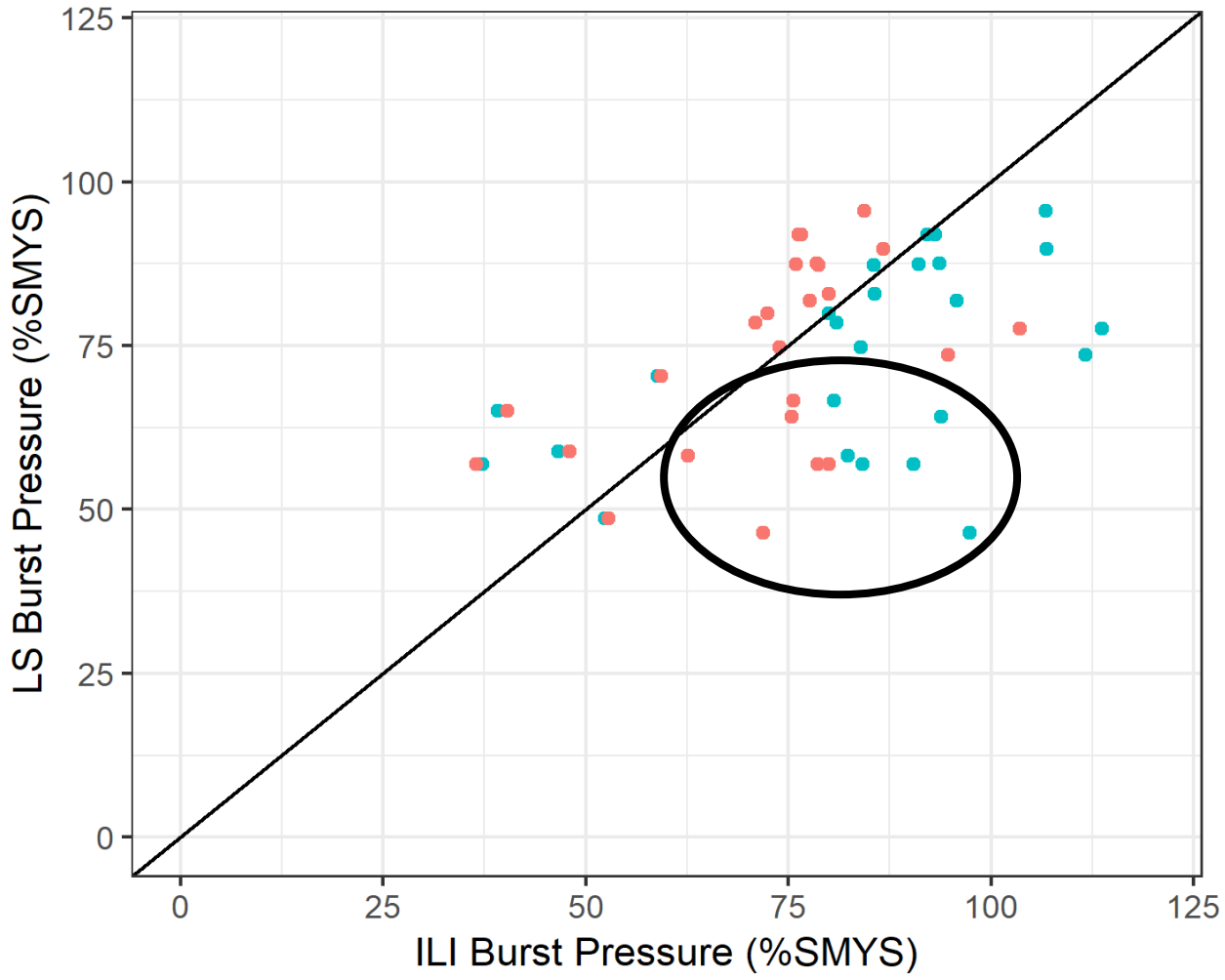
Sizing Correction





Sizing correction improved maximum depths by 1% to 23%WT, and lengths by 14% to 51% length.
As correction models are nonlinear, improvement in sizing estimates is not uniform.

Sizing Correction Effect



Sizing correction improved burst pressure estimates by 5% to 25% SMYS for all ILI burst pressures overestimated by more than 10% SMYS

Conclusions

- **Develop criteria to identify severe corrosion anomalies from ILI data**
  - Severity criteria developed based on
    - *Length: Corrosion cluster length greater than 200 mm (7.87 in).*
    - *Average Depth: Average depth greater than 10%WT*
    - *Maximum Depth: Maximum depth greater than 25%WT*
  - Severity criteria is highly dependent on severity definition and burst pressure assessment model
  - Corrosion attributes such as angle did not correlate to the corrosion severity definition that was based on Effective Area burst pressure model

- **Quantify ILI sizing errors for severe external corrosion as a function of feature morphology and dimensions**
  - Sizing errors were uncorrelated to the attributes of severe corrosion clusters
  - Sizing errors were driven by undetected features
  - Correction models were developed for severe corrosion as a function of cluster depth and length

Lessons Learned

- **Feature Matching**
  - Alignment of high-resolution LS and ILI data sets is a critical step that affects the available sample size for data analysis
  - There are multiple approaches available for feature matching such as,
    - *pattern matching techniques through machine learning algorithm*
    - *constrained optimization of the matched metal loss volumes*
  - All approaches require significant effort to match the corrosion features identified from multiple sources such as high-resolution LS and ILI data sets
  - Matching error may have to be explicitly quantified to improve confidence in results of aggregated data sets as different matching approaches result in different types of errors

- **Feature Severity Definition**
  - Approach selected to define the severity of corrosion affects which feature attributes could be used to identify severe corrosion

Summary

- **Value to Industry**
  - A secure database of more than 100 high resolution laser scans of external corrosion was developed, which can be used by operators and vendors to drive ILI tool technology improvements.
  - Attributes to quantify corrosion morphology were developed, which can be used to compare different corrosion geometries.
  - Sizing correction models were developed for improved confidence in estimated burst pressure capacity of corrosion clusters that meet severity criteria.

- **Challenges**
  - Location and detection errors in ILI features reduced the number of validated one-to-one matched severe corrosion clusters
  - Longer duration between an ILI run and field measurements meant direct comparison between the measurements may not be accurate due to corrosion growth

Recommendations for Future Work

- Develop optimization algorithms for aligning ILI and LS clusters considering location and detection errors in the ILI data.
- Further develop corrosion cluster definitions for ILI and LS alignment and error treatment.
- Leverage multiple ILI measurements associated with high-resolution LS data to develop corrosion growth models.
- Develop approaches to improve the accuracy of ILI sizing using multiple ILI measurements that are unlikely to be affected by corrosion growth.
- Compare the predicted burst pressures from ASME B31G models to the burst pressure predictions obtained from other models.

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Thank you for joining today's presentation