ULTRASONIC GEOMETRY: PROVEN ACCURACY FOR RELIABLE ASSESSMENT

By: Dr. Henrik Witte, Roberto Yanez, Timo Schulten, Dr. Thomas Hennig
NDT Global
Germany, Ireland and Mexico

Abstract

State of the art and future assessment methodologies for geometrical defect types in pipelines benefit from superior inline inspection data. Post-inspection assessment of deformations such as strain, fatigue life, or finite element assessment require the most detailed, accurate and high-resolution data of the pipeline available. Therefore, NDT Global has developed and validated a fleet with a new, reliable, and robust technology for pipeline geometry measurement, based on the ultrasonic measurement principle with inherent advantages such as bidirectional capabilities and wall thickness data acquisition in one pass. Since the first successful commercial inspection in March 2016, the Atlas UG robot fleet has successfully conducted more than 4,000 km (2,486 miles) worldwide, achieving a 100% first run success rate and received positive feedback from operators. Extensive testing and field verifications prove the accuracy and reliability of ultrasonic technology as a basis for integrity assessment.

1 Motivation

Mechanical based callipers are robust geometry tools. Their typical high collapsibility allows them to pass diameter reductions of up to 30% Outer Diameter (OD). These tools are commonly used for exploration or passage proving before performing an intelligent inline inspection (ILI). Their second application is to detect dents and deformations. The capability to accurately detect, characterize and size dents is limited by the circumferential resolution and coverage of the sensing area [1]. The circumferential resolution depends on the number of sensors, the width of a single sensor and distance between them. Furthermore, the mechanical arm arrangement is in contact with the pipe wall and therefore susceptible to lift-off and overreaction at deformations and girth welds [Figure 1]. This can lead to misinterpretation of the actual depth and shade the real shape and local curvature of dents [2].

Regulations, codes and standards [3], [4], [5], [6], [7] demand operators take immediate action based on dent depth, orientation and/or association with secondary features such as welds. The use of the maximum depth as only criterion for the assessment can result in unnecessary digs and potential misinterpretation of severe dents. The pipeline industry welcomes different strain-based assessments that use the dent local radius of curvature to define severity [8]. Most of the fatigue life assessments are essentially depth-based or require complex finite element analysis [9]. The latter strongly benefits from accurate, high-resolution data.

Post-processing techniques such as de-noise, smoothing and/or interpolation, are typically used to prepare geometry ILI data for analysis and assessment. Unfortunately, the lack of circumferential resolution can only approximate the dent profile using interpolation techniques [8]. The distortion of the real shape due to the arm's behaviour and lift-off cannot be efficiently corrected or improved by post-processing algorithms.

The evolution of assessment methodologies relies on the continuous improvement and accuracy of ILI tools. NDT Global's new geometry robots are based on the ultrasonic technology, which provides an important enhancement of sizing accuracy.

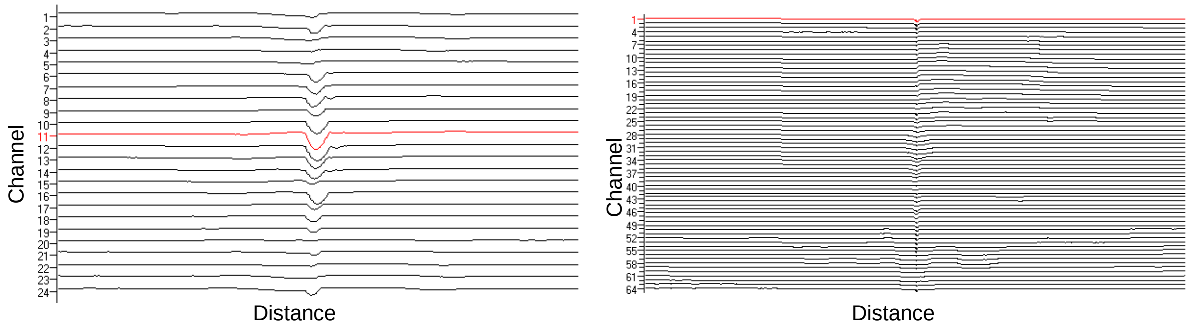


Figure 1: Mechanical caliper data (left) and ultrasonic robot data (right) from the identical girth weld (same scaling)

2 Theory of application

The ultrasonic geometry technique requires a suitable, single-phase liquid coupling medium. Depending on the nominal pipeline size, a certain number of sensors, arranged perpendicular to the pipe wall, covers the entire 360° circumference of the pipe. The transducer, operated in pulse-echo mode, emits a short pulse of ultrasonic energy, which is reflected by the internal (entry-echo) and external (back-wall echo) pipe wall and received by the same transducer. Combining ultrasonic technology with state of the art data storage and processors allows to collect the total amount of data of an entire inline inspection. The ultrasonic robot [10] measures the Time-of-Flight (ToF) of the ultrasonic signal. Using the speed of sound in the coupling medium (product) which is identified with real-time medium property monitoring, the distance from the sensor to the inner pipe wall is the calculated Stand-Off (SO) [Figure 2]. Deviations from the initial, cylindrical shape are identified, located, analysed and categorized.

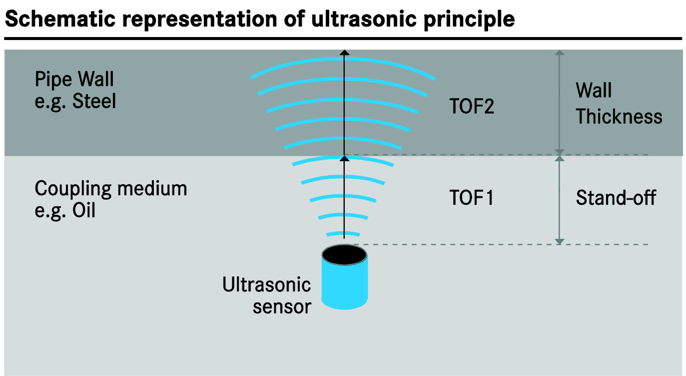


Figure 2: Schematic representation of ultrasonic principle

Additionally, a portion of the ultrasound signal enters the pipe wall and is reflected at the rear wall of the pipe, delivering a wall thickness reading: This is an inherent advantage from the ultrasonic technology, which is not provided on conventional geometry tools [11].

2.1 Atlas UG mechanical setup

Ultrasonic transducers are mounted in a cylindrical module body forming rings of sensors [Figure 3, left]. These rings form the entire sensor setup for 360° circumferential coverage. In addition, the setup and design ensures there is no risk of damage to the transducers and allows the flexibility to perform bi-directional inspections.

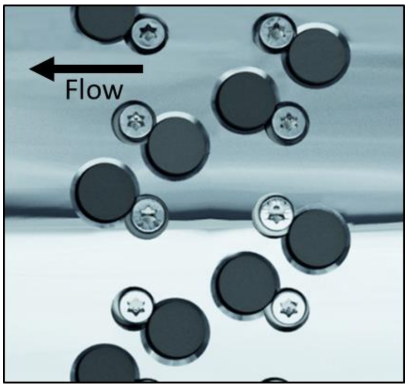


Figure 3: Atlas UG assembled module[1] (left) and detailed view of sensor alignment (right)

2.2 High-resolution build up

The accuracy of a geometry tool has been reported to depend on resolution, which is directly related to the number of sensors that cover the pipeline circumference [2] and the axial sample rate. If the geometry tool resolution is insufficient, true and reliable axial and circumferential profiles cannot be produced [9]. The axial and circumferential resolution offered by Atlas UG, allows operators access to detailed and accurate geometry information that directly translates to reliable input, used for further integrity assessment, regardless of depth, estimated curvature or detailed shape.

2.2.1 Circumferential resolution

In contrast with conventional calliper tools, the increased number of sensors results in a much higher spatial resolution. Ultrasonic sensor technology allows an overlap [Figure 3, right] delivering a circumferential resolution down to 8 mm (0.31 in).

2.2.2 Axial Resolution

Axial resolution of geometry tools are directly related to the sample rate [12]. The Atlas UG robot is integrated with a state of the art acquisition system [10] that achieves an axial sampling and resolution down to 1.5 mm (0.06 in). Atlas UG is compatible with the existing NDT Global inline inspection solutions, a combined inspection with crack or metal loss technologies is possible. When combined as a multi-technology inspection robot, data analysis teams have access to fully aligned data sets and perform an online anomaly correlation.

2.3 Deformations measurement and sizing

Industry codes and standards acknowledge the sizing accuracies and measurements for deformation features, defining a dent by its depth, length and width is a common practice.

Deformation depth is measured by reference to the original outside contour of the undamaged pipe. Length and width however, have been defined as the damaged pipe surface deviant from the undamaged pipe, but this is sometimes difficult to determine. An alternative definition of length and width is given by the full width at half maximum (FWHM) [13] [Figure 4].

[1] Module size availability from 6" to 38"

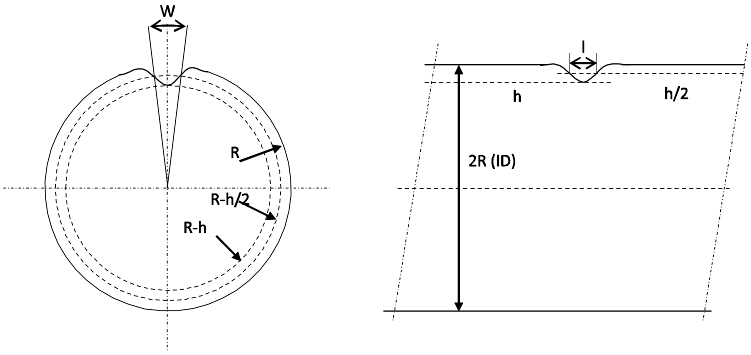


Figure 4: POF 2016 dent definition

2.3.1 Depth measurement

Signals from a single sensor are used to acquire the nominal position of the pipe wall (baseline) to measure the depth [Figure 5]. Measurements include a degree of ovality or flattening of the pipe surface as an unavoidable component of the depth [2].

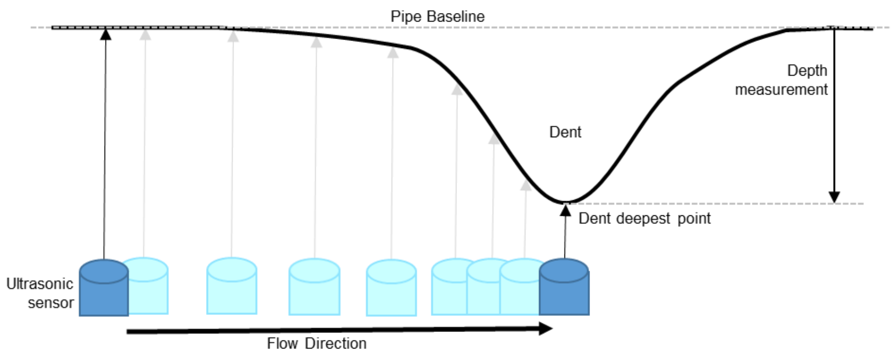


Figure 5: Dent depths are measured from the pipe baseline to the deepest point.

An inherent advantage of Atlas UG module is the capability to accurately measure the internal diameter (ID) of the pipe, without the need of a reference such as OD and nominal wall thickness (WT). By knowing the Atlas UG module's diameter, and therefore the distance between opposite sensors, ID measurement is straightforward. The sum of the measured SO on opposite sides of the pipe and module diameter are the only required parameters to know the ID of any feature in the pipeline [Figure 6].

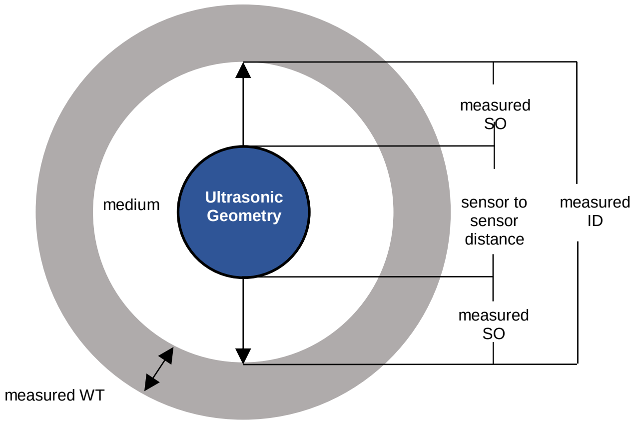


Figure 6: Atlas UG Internal Diameter calculation; SO is the distance between sensor and pipe wall.

Wall thickness measurement is also available and the outer diameter is derived from Atlas UG measurements. Wall thickness changes are easily identified, and can be used for further assessment if required.

2.3.2 Data Post-Processing

Using the readings of all circumferential sensors the shape of the internal bore can be easily reconstructed. Off-centred module position (e.g. caused by vibration) does not affect the measurement and can be subtracted using geometric calculations [Figure 7], without any loss of information such as dent ovality or pipe flattening.

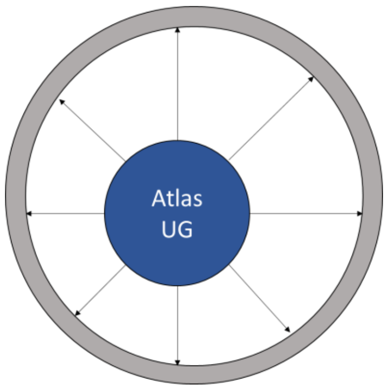


Figure 7: Off-centred tool position can be corrected by geometric calculations

Module tilt can be derived from the readings of different sensor planes, which sequentially observe the same geometry of the pipeline. In some isolated cases, the ultrasonic beam does not fully return the sensor. This can be due to inspection speed, medium properties or debris. As a result, the entry-echo is not properly selected and the SO is not accurately measured. In the Atlas UG dataset, this effect is represented as a spike (not a gap).

Atlas UG robots, offer many benefits from the high-resolution data acquisition (axial and circumferential), the resulting spikes are located and removed using data point interpolation without influence the actual profile of the pipeline (or deformations), delivering a smooth, accurate and continuous data set [Figure 8].

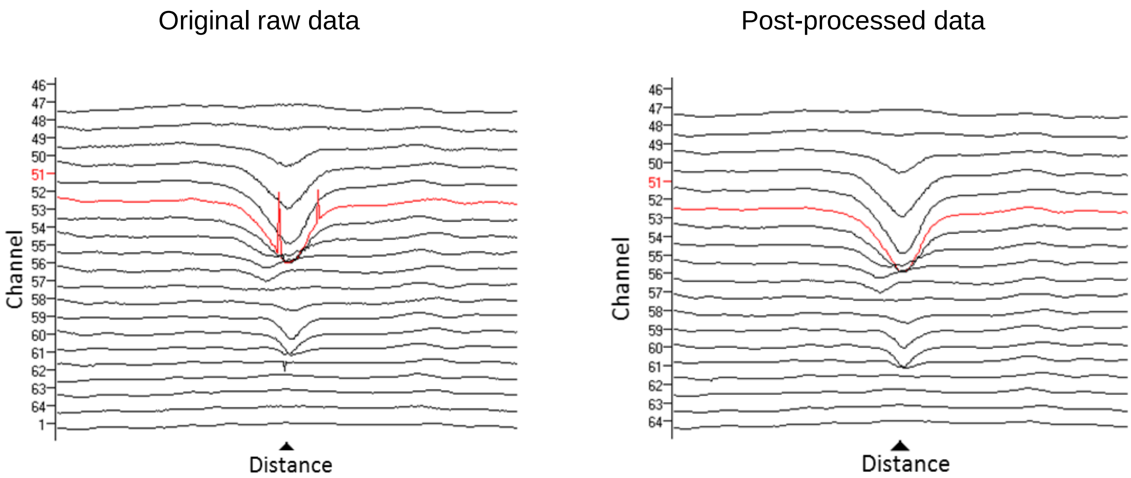


Figure 8: Comparison of original and post-processed data

3 Module test and validation

For ILI providers, a 100% First Run Success Rate (FRS) is paramount. Of course, testing is critical for successful product development, rollout and market introduction. Thorough testing of all hardware and software components is performed. Finally, the entire ILI robot is assembled and a factory acceptance test completed. For full-scale testing of the latest generation of ultrasonic robots, NDT Global designed and built a looped pipeline [Figure 9] equipped with automatic valves and control stations, enabling fully automated monitoring and operation.

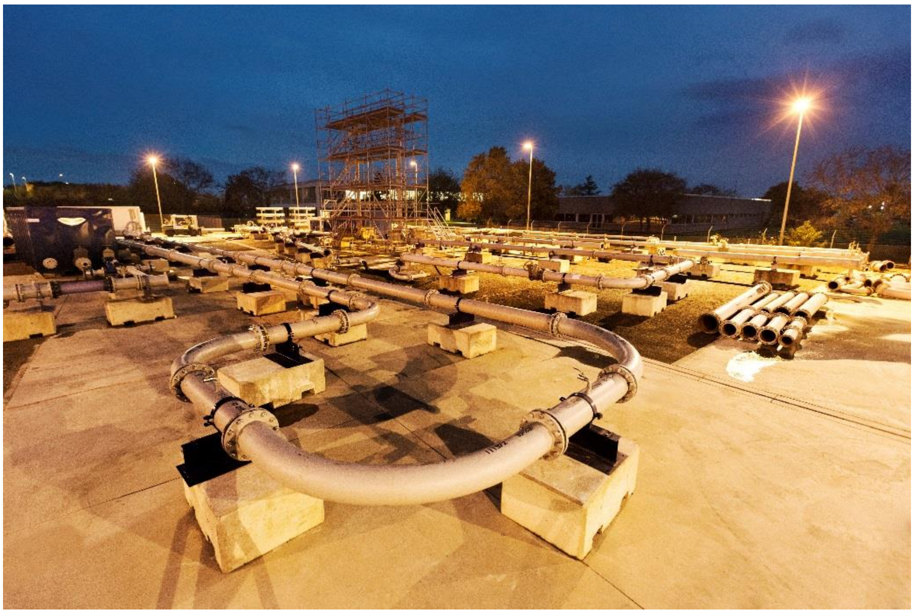


Figure 9: Loop test setup at NDT Global testing yard, Germany

Test spools contain manufactured flaws with known dimensions below and above the specified minimum feature dimensions. Several test runs are completed using different essential variables and configuration settings. After successful checks and analysis of several datasets, the optimum settings and configurations are defined to achieve and exceed the testing requirements and performance objectives.

3.1 Performance specifications

NDT Global's testing program consists of small-scale lab testing, full-scale tests using extensive loop testing and field verification information from actual inline inspections. Published values (cf. Table 1 & Table 2) are derived from such processes in accordance with requirements stated by international standards [14] [15].

Minimum depth for deformations, dents and ovalities at a POD[2] ≥ 90%			
Certainty		**80%**	**90%**
Detection threshold deformations, dents and ovalities	Depth (mm) Depth (in)	2.0 0.079	2.5 0.098

Table 1: Ultrasonic Geometry POD for deformations, dents and ovalities

Depth sizing accuracy for dents and ovalities		
Accuracy at 90% certainty (mm)[2] Accuracy at 90% certainty (in)[2]	±1.0 ±0.039	
Length sizing accuracy for dents and deformations[3]	**Axial sampling 3 mm (0.12 in)**	**Axial sampling 1.5 mm (0.06 in)**
Accuracy at 90% certainty (mm) Accuracy at 90% certainty (in)	±10.0 ±0.39	±6.0 ±0.24
Width sizing accuracy for dents and deformations[3]	**Circumferential resolution 30 mm (1.18 in)**	**Circumferential resolution 15 mm (0.59 in)**
Accuracy at 90% certainty (mm) Accuracy at 90% certainty (in)	30 1.18	15 0.59

Table 2: Sizing Accuracies for deformations, dents and ovalities

3.2 Validation through Field Verification

Field verification is a key part of validation of ILI performance and analysis process [14] [13]. In accordance with the continuous improvement of processes for hardware, software, algorithms, analysis and reporting, NDT Global conducts a detailed review of any inspection project. This allows for the identification of potential enhancements for future ILI developments. Likewise, the NDE verification results from pipeline operators will enable ILI companies improve their tools and data analysis procedures. For some of the verification tasks, NDT Global has been invited to participate "in the ditch", performing their own measurements. All results shown in this section have been performed by an independent, third party company and not by the pipeline operator or NDT Global.

[2] POD - Probability of detection
[3] Atlas UG is combined with UC/UMp technologies and inherits configured axial and circumferential resolution, contact your KAM for details

The unity plot [Figure 10] shows the absolute depth comparison between the NDE results and the ILI measurements. One of the advantages of using a direct measurement inspection methodology is the possibility to measure and report absolute values instead of relative depth values for the comparison.

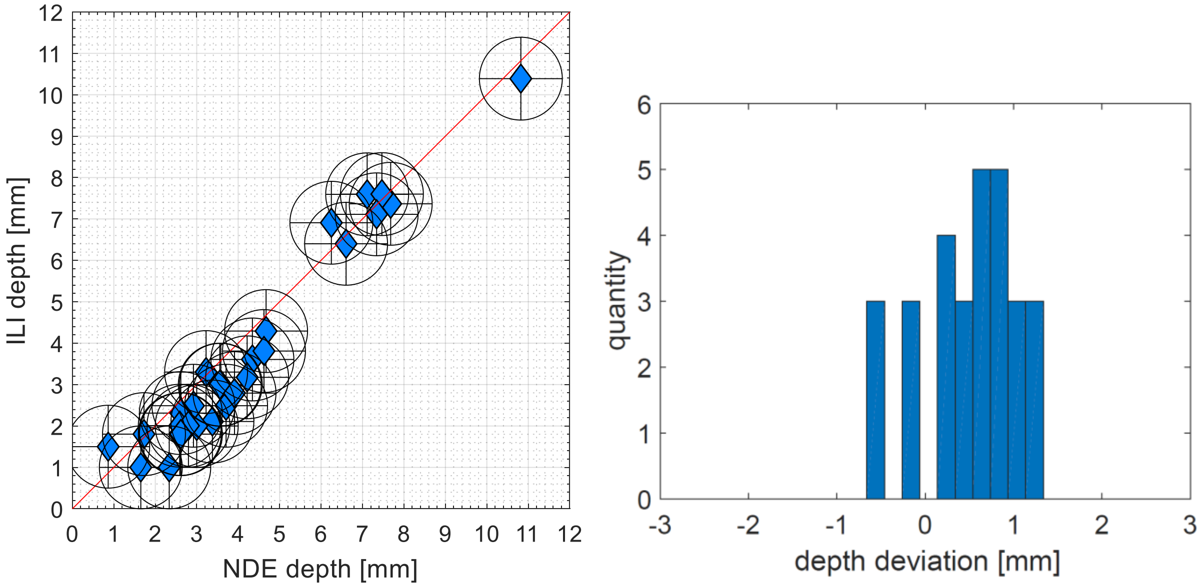


Figure 10: Field verification results Unity Plot (left) and histogram of measurement deviation

For now, 29 verification results are part of the confirmation of the Atlas UG performance. Depth measurement correlation is consistent between the ILI and NDE. The largest depth deviation shown is 1.3 mm (0.05 in). The performance specification of Atlas UG states a depth tolerance as 1.0 mm (0.04 in) at 90% certainty. For proposes of this paper, the depth tolerance for NDE results also have been set to 1.0 mm (0.04 in). A histogram of measurement deviation between NDE and ILI results is given in Figure 10.

NDT Global reported more than 20,000 deformation features based on Atlas UG inspections. Of these, 90% were dents. In addition, several types of deformation features such as ovalities, wrinkles, buckles, bulges and pipeline expansions have been successfully detected, analysed and reported. Exemplary data is given in chapter 7. Moreover, the combination of an Atlas UG robot with ultrasonic crack or metal loss measurement, results in a reporting of more than 280 dents interacting with a secondary feature. Out of those dents, 21 were verified and successfully found, 17 had a secondary feature associated, delivering an 81% confidence level on combined anomalies [Figure 11].

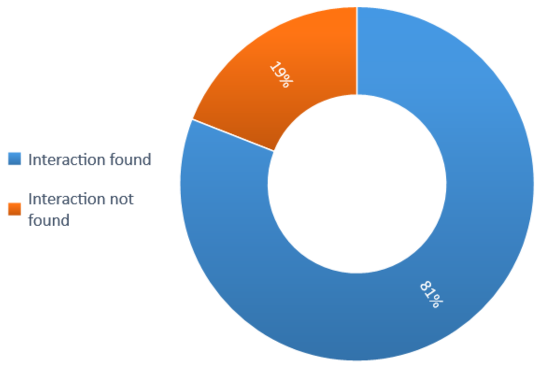
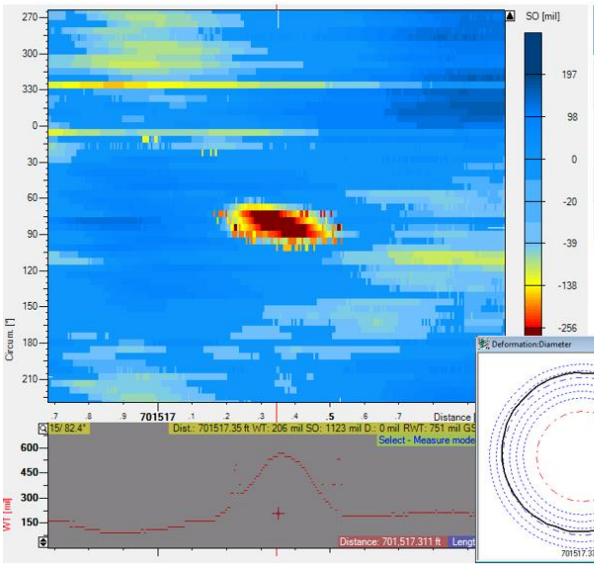


Figure 11: Dent interaction reported and successfully verified

In most cases, dents reporting thresholds are depth-based and usually given in percentage of OD [3], [4], [5], [7]. A common dent reporting threshold for calliper tools, are those with a depth greater or equal to 2% OD. With this in mind, it should be noted 97% of dents reported by the Atlas UG robot have a depth below 2% OD. Of the 17 dents with interactive features successfully found, 15 of them were dents below 2% depth. If a conventional calliper tool had been used, those dents with interacting features would have been missed and the threat would remain without attention.

NDT Global's standard analysis procedure requires all deformations above or equal to minimum detection threshold (2.0 mm / 0.08 in), must be analysed, identified and classified accordingly. This procedure ensures that all deformations detected by the Atlas UG inspections, will be comprehensively correlated with available metal loss or crack inspection data sets to locate interacting anomalies threatening the integrity of the pipeline. Different kinds of deformation anomalies have been detected, analysed and reported by the Atlas UG robot [Figure 12].



Dent value	ILI	NDE
Depth (mm)	10.4	10.8
Length (mm)	116	149
Orientation	02:34	02:10
Type	w/ Crack Field	w/ Axial Gouge

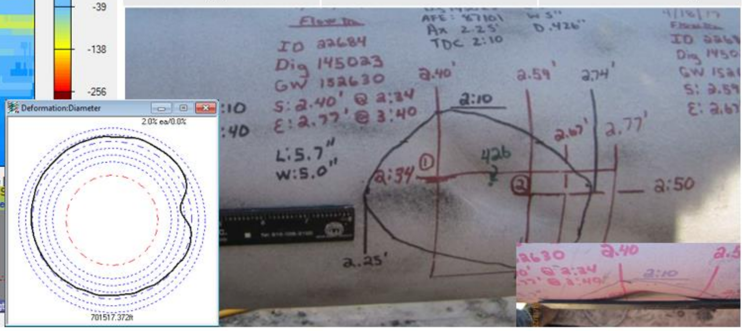


Figure 12: Dent interaction reported and successfully verified. Axial oriented gouges were present in the dent.

4 Prospects

4.1 Dent Fatigue Life Assessment

A new dent assessment approach has been developed in a Pipeline Research Council International (PRCI) research project [16] that uses the detailed axial and circumferential profile [Figure 13], operating pressure spectra and pipeline material grade. This methodology identifies three possible approaches to fatigue life estimation based on the shape of the dent. The assessment level selection and accuracy of the results are based upon the complexity of the features, the availability of required data, level of detail and certainty in the input data. ILI data representing the true pipe geometry deformation should be used to carry out the calculations. Behaviour of dents is exceptionally complex and lack of circumferential resolution can only approximate the dent profile using interpolation techniques. Furthermore, the real dent shape could be hidden due to mechanical arm behaviour or lift-off, which cannot be efficiently corrected using post-processing algorithms. Proven accuracy and performance provided by the Atlas UG module, will improve the input data used in the assessment calculations, offering pipeline operators reliable and accurate results for decision-making.

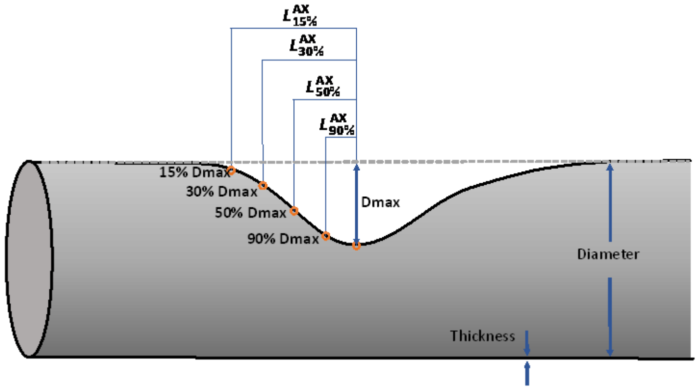


Figure 13: PRCI Dent fatigue life assessment, dent axial lengths required for computation

5 Summary

Accurate pipeline geometry measurement is essential for integrity assessment. Strain-based assessments have focused on how to accurately determine the axial and circumferential radius of dents [8] using ILI geometry data to calculate. A new dent assessment approach developed by a PRCI research project uses true pipe geometry deformation to carryout fatigue life assessment. It should be noted that accuracy of the results is based on certainty of the input data [16].

Multiple aligned data sets gathered by combined high-resolution ultrasonic inspection technologies allows an online correlation of anomalies that enhance identification of combined defects.

Atlas UG robots reliably perform precise, direct measurement of dents with depth resolution down to 0.1 mm (4 mil). The increased number of sensors and overlap, along with state of the art data acquisition systems, deliver higher spatial resolution that can be exploited in the computation of assessment methodologies such as the PRCI dent fatigue life assessment or finite element modelling that require specific and rigorous geometric data input.

6 References

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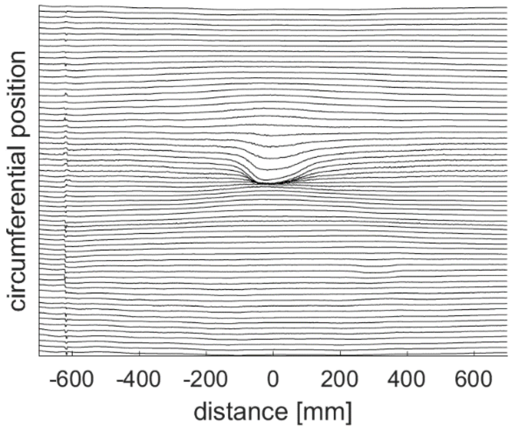
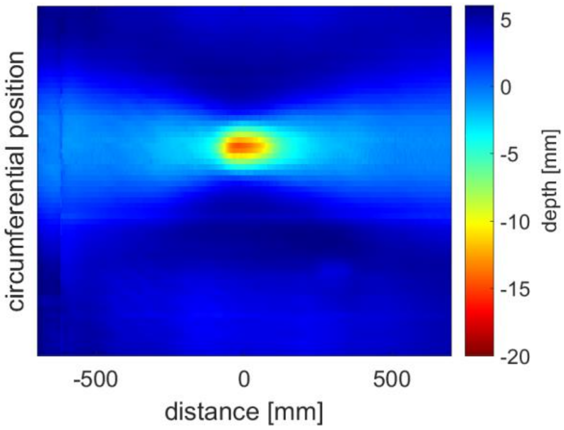
7 Annex A – Exemplary Data

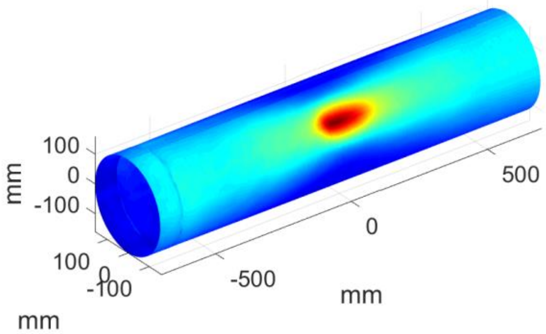
Data and images presented were selected from actual Atlas UG inspections, as examples of the data, and visualization of deformation features already detected, sized, and reported by the Atlas UG robots. Data is scaled and rotated for better visualization.

7.1.1 Dent

A local plastic or elastic deformation of the pipe wall resulting in a change of the internal diameter caused by an external force [15].

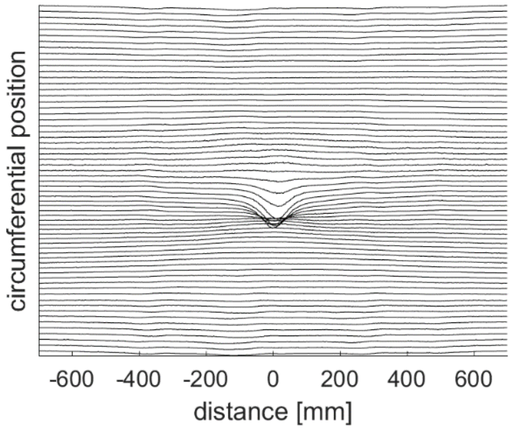


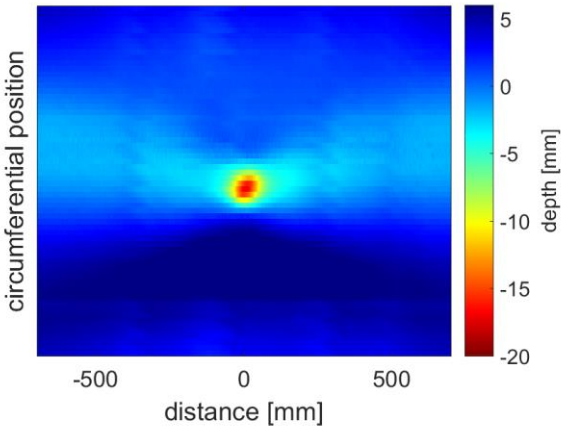


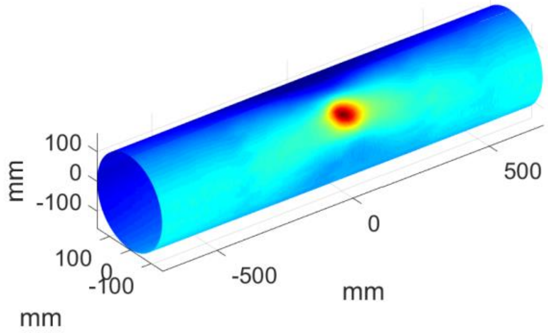


NPS	12"
type	dent
depth	14.0 mm
length	343 mm
width	144 mm
o'clock position	5:55

Figure 14: Asymmetric bottom-size dent reported in 12" pipeline





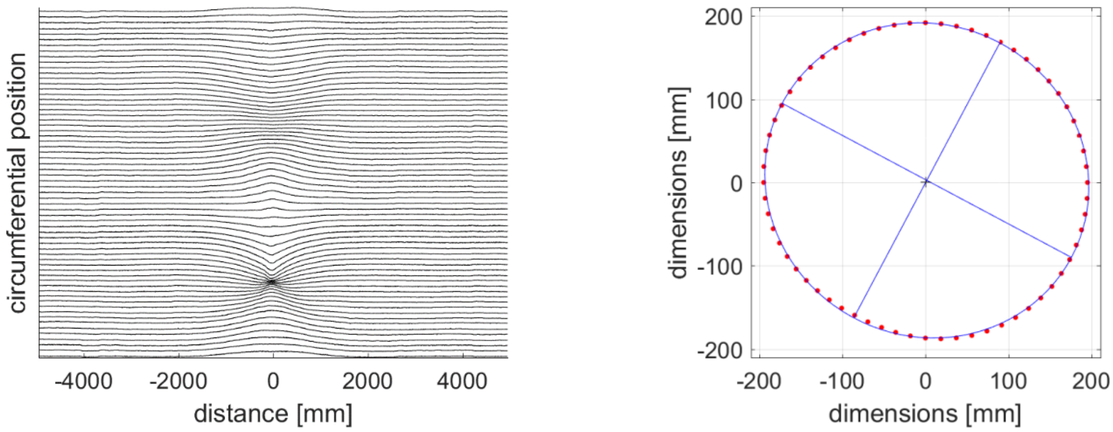


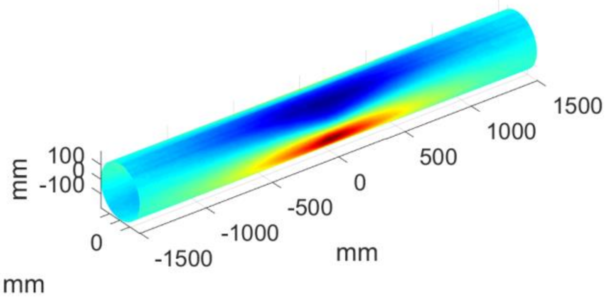
NPS	12"
type	dent
depth	16.5 mm
length	273 mm
width	144 mm
o'clock position	7:30

Figure 15: Sharp symmetric dent

7.1.2 Ovality

Out-of-roundness of the pipe joint, defined in terms of the difference between the maximum and minimum internal diameter of the pipe joint [15]. It can occur during pipe manufacturing, transportation or through incorrect storage. Like dents, it can also occur through bending or pressure from external loads.





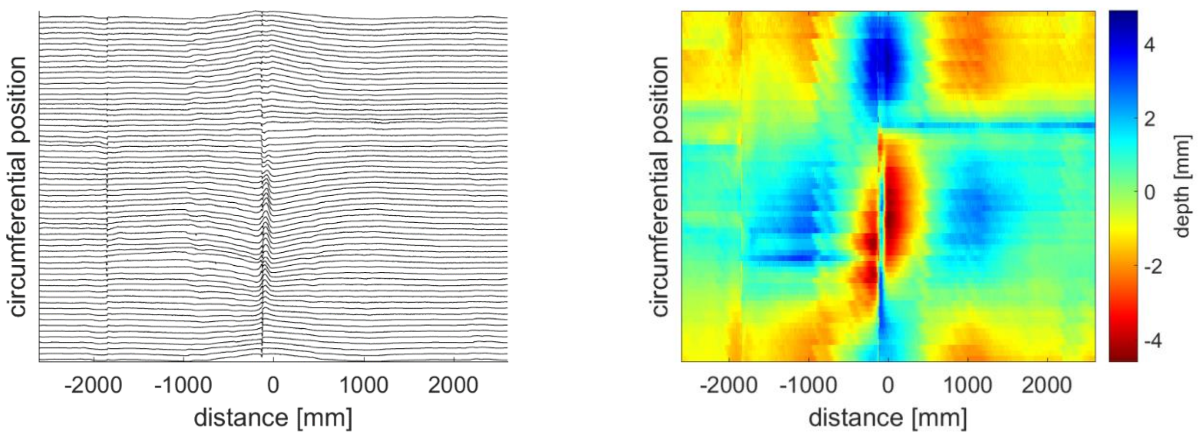
NPS	16"
type	ovality
length	922 mm
max ID	394 mm
min ID	373 mm
Ovality [15]	2.6 %

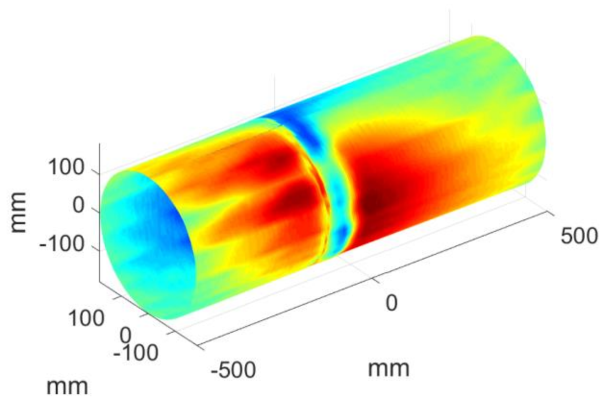
Figure 16: Ovality

7.1.3 Buckle

A wrinkle is a localized deformation of a pipe wall, which is usually in high strain areas and could be an indicator of imminent pipeline buckling.

A local geometric instability causing ovalization and flattening of the pipe as a result of excessive bending or compression with possibly abrupt changes in the local curvature, which may or may not result in a loss of containment [15]. Usually described as imminent failure of wrinkles that are located in high-strain areas.





NPS	12"
type	buckle
depth	---
length	118 mm
width	---
o'clock position	---

Figure 17: Buckle affecting girth weld, only length was reported