Don't Be Strained: A Case Study and Lessons Learned on Comparing Multiple IMU Data

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Abstract

Many pipeline operators have performed bending strain assessments based on IMU data and received results that are challenging to interpret and properly sentence, especially if the assessment identified hundreds of features. These challenges can be compounded if the operator acquires a second IMU data set and elects to perform another bending strain assessment or a comparison assessment between the two data sets. In these situations, operators often observe significant variations in the number of reported bending strain features and the reported strain magnitudes associated with those features. These challenges can rarely be solved by comparing the final reports as the graphical information for the bending strain features is often rendered differently between vendors. This paper presents the results of a case study comparing four IMU data sets acquired over a decade on the same pipeline segment where the number of reported features varied from 195 to 384. The paper examines the causes of this variation in reported features including the influence of gage length, signal noise, and analyst judgement. The case study also identifies common challenges that occur when comparing multiple IMU data sets and provides strategies for recognizing and overcoming these challenges. The paper concludes by identifying how bending strain reporting requirements can be standardized and help operators minimize these challenges in future assessments.

Background

The geohazard threat has received increased attention from operators and regulators over the last decade. To borrow the words from Dave Johnson's introduction to the INGAA JIP on Landslide Management [1], there seem to be two kinds of pipeline operators when you discuss geohazards: those who know they must deal with the geohazard threat, and those who haven't realized they have to deal with the geohazard threat. The geohazard threat has also caught the attention of regulatory bodies in the United States as the Pipeline and Hazardous Materials Safety Administration (PHMSA) has released two separate bulletins in 2019 [2] and 2022 [3] addressing the geohazard threat. The 2022 bulletin identified seventeen pipeline incidents related to geohazards with nine of the incidents occurring in the time between the issuance of the two bulletins (2019 - 2022). The incidents identified by PHMSA occurred in liquid transmission pipelines, gas transmission pipelines, gas distribution pipelines, and even one C02 pipeline.

In response to the geohazard threat, operators have begun gathering and disseminating knowledge in the form of joint industry projects [1] and dedicating resources to stand-up geohazard programs. As discussed in a prior publication [4], geohazard integrity management programs most commonly rely on data collected from surface-based assessments and bending strain assessments based on data collected from inertial measurement units (IMU) on-board in-line inspection (ILI) tools. Bending strain assessments were first introduced in the mid-1990s [5] and have grown in popularity over the last decade. Recent publications have demonstrated bending strain comparison assessments to be highly repeatable and effective at identifying geohazard threats [6].

Despite the benefits from bending strain assessments, operators often encounter challenges and steep learning curves when performing bending strain or bending strain comparison assessments for the first time. A few common challenges are discussed herein: first, bending strain assessments can identify a significant number of sites, and many of these sites do not correspond to any type of geohazard threat [1]. These results often leave operators questioning the legitimacy or usefulness of the information from bending strain assessments. Second, the results from bending strain assessments may be communicated in the form of graphical plots that can be difficult to interpret

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without prior experience or adequate training. Third, the identified features are difficult to sentence as many operators do not have strain response criteria for bending strain features.

These issues may be compounded if an operator obtains a second IMU data set and elects to perform a comparison assessment with a different vendor. Previously identified bending strain features may disappear in the second report while new features may be identified. Features that are identified in both reports can have significantly different strain values raising concerns that an active time-dependent threat exists at the location. Attempting to compare the graphical information contained in the bending reports creates additional challenges. The graphical information may be presented differently in each of the reports, and it may be impossible to compare some features if the features were not identified as reportable features in both reports.

The objective of this paper is to present and discuss these typical challenges encountered by operators when performing bending strain comparisons and demonstrate how these challenges contribute to uncertainty in the analysis. The paper provides guidance on how to minimize the effects of these challenges through clear reporting requirements that operators can deliver to vendors.

Case Study Data

This paper considers a case study utilizing data collected on a 113-mile, nominal 8-inch diameter liquid pipeline. IMU data was available from inspections performed by different ILI vendors in 2013, 2018, 2021, and 2023. The first bending strain assessment was performed by an ILI vendor, noted as Vendor A, based on data collected in 2021. A bending strain comparison assessment was also performed by Vendor A in 2021 using the information from the 2018 and 2021 IMU data sets. The second bending strain analysis was performed by a different ILI vendor, noted as Vendor B, based on IMU data collected in 2023. The assessment performed in 2023 did not include a bending strain comparison as the previous IMU data was not made available to the vendor for the assessment. The analysis requirements and results of both assessments are summarized in **Table 1**.

Table 1: Prior Bending Strain Assessment Results

	Vendor A	Vendor B
Bending Strain Reporting Threshold	0.125%	0.100%
Gauge Length	3 meters	1.5 meters
# of Bending Strain Features	81	338
Maximum Strain %	0.256%	0.409%
Maximum Reported GW Strain %	0.150%	1.18%
# of Horizontal or Combined Calls	16	n/a
Strain Change Reporting Threshold	0.1%	n/a
# Strain Change Features	7	n/a

A cursory comparison of the results between the 2021 and 2023 assessments indicates that the second analysis identified significantly more bending strain features and a higher overall maximum strain. **Table 1** also reveals that the two analyses were based on different gauge lengths and used different reporting requirements. As will be shown later, both the magnitude of the strains and the number of features are a result of the variations in reporting threshold and gauge length used in the two analyses. However, operators who are not familiar with these variables or their influence on a bending

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analysis are not likely to provide requirements to the vendor prior to the analysis or seek out the values used in the assessment, which often are not prominently shown in the reports. As a results, many operators who receive these results would be confused by the disparity in the two assessments. Alternatively, undue concern may be raised that substantial changes have occurred in the system. In this case study, all four data IMU data sets were provided to D2 Integrity (D2I) who was asked to perform a bending strain and comparison analysis using the available data.

Challenges

The bending strain reports provide valuable graphical descriptions of the identified bending strain features. A logical first step to understand the differences between the report would be to compare areas between the vendors. This creates multiple additional challenge and reveals reporting inconsistencies between the vendors. The first challenge involves the significant variations in the graphical representations of reported bending strain features between Vendor A and Vendor B. This is illustrated by comparing the same bending strain feature rendered by each of the vendors in **Figure 1** and **Figure 2** (note: the feature from Vendor A was recreated for clarity by D2I). Even to an experienced bending strain analyst, it is impossible to use this information to identify whether the features have changed. The plots are arranged differently with no consistent convention or scaling on any of the axes. While Vendor A provides a single panel for each data set, Vendor B groups multiple information sets onto a single plot. For instance, Vendor B shows the horizontal and vertical strains combined onto a single plot while Vendor A separates them. Out-of-straightness values cannot be compared between the two vendors because the plot extents do not align between the vendors.

Another common challenge in comparing results arises because the graphical bending strain results are typically only communicated at the reported locations. Unlike MFL and Geometry analysis where a viewer is provided that can permit signal interrogation at any location desired by the operator, many vendors only provide the bending strain signals at the reported locations. For example, in the current study, Vendor B identified 257 features that were not identified by Vendor A. However, Vendor A only provided images of the 81 reported locations leaving no way to review the data for the newly identified bending strain features. Additionally, Vendor B did not explicitly report on features identified by Vendor A. These variations render the plots provided in the reports as ineffective for comparisons. These issues could be improved by specifying common reporting requirements and by requiring reported features to be tracked in subsequent assessments.

Although not highlighted in this case study, comparing tabular strain results from different vendors can identify another common challenge arising from differences in sign conventions. While total strain is always positive in a bending strain assessment, both the horizontal and vertical component strains utilize a specified sign convention. This sign convention impacts the reported component strains and the graphical representation of the strains. Operators who encounter this will find it nearly impossible to identify whether any changes are present as both the magnitude and sign of the reported strains may vary between vendors.

Methodology

The specifics of identifying bending strain features and strain change features is outside of the scope of this paper and is discussed in more detail in previous publications [6]. However, the key steps are covered in this paper and briefly discussed in the paragraphs that follow.

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The first step of the comparison requires each of the IMU data sets to be aligned to a common reference system, typically based on the latest inspection odometer. This step often begins by using the girth welds to align the heading angles between two data sets. However, it is common for older IMU data sets to have offsets ranging from a few feet to over 30 feet that require local corrections along the entire line. It is also common for older IMU data sets to be misaligned with the girth welds in the feature lists. In these cases, the alignment is significantly more challenging and requires the alignment to use the heading angle signal patterns rather than the girth weld locations.

The second step of the comparison is to integrate additional data including repair history, known geohazard locations, and other known features into the assessment. This integrated data provides context and supplemental information for both bending strain and strain change analysis. Strain change signals interacting with repair sleeves and bending strain features interacting with cased crossings are common occurrences that can help with prioritization and reduce the effort required for the operator to sentence the features.

The third step requires the vendor to identify replacement sections between the various inspections. This step can be accomplished by the vendor through comparisons of heading angles and by comparing reported girth welds. Any replaced sections should be identified by the vendor and provided to the operator with the final report for confirmation.

After performing these steps, the bending strain and bending strain comparison evaluations can be performed. All data sets should be assessed using the same gage length as specified by the operator. Shorter gage lengths may be used to assist in the identification of manufactured bends and noise influences but should not be used for reporting. It is also important that any feature, once identified in an inspection, should be tracked across future inspections. This prevents features from disappearing in future analyses and ensures that features currently addressed in the operator's integrity management program continue to be tracked. It should be noted that this step requires the operator to provide a vendor with the extents of previously identified features.

Results

After aligning each of the four bending strain data sets and applying a bending strain reporting criteria of 0.125% with a 3-meter gage length, the 2023 data set identified 259 unique features with a combined bending strain greater than the reporting threshold from any of the inspections. 125 of the previously reported features were below the reporting threshold in every inspection but were tracked for comparison purposes after being identified by Vendor B in the previous assessment. This resulted in 384 unique features that were reported on from each IMU data set. A summary of the reportable and non-reportable bending strain features is provided in **Table 2**. It should be noted that eight of the reportable features from the 2013 IMU data set and two of the reportable features from the 2018 IMU data set were located within replaced sections of pipe as noted in **Table 2**. Even when applying the same reporting threshold to each data set, it is common for the number of reportable bending strain features to vary between inspections due to features near the reporting threshold or replacement areas.

With regards to the reporting threshold, 0.125% is the most common reporting threshold in the industry. It is the level where noise can be discriminated from true signal patterns in most pipelines. The 0.125% reporting threshold is also conveniently located near 80% SMYS for mild steel grades (i.e., Grade B – X52), which is the maximum axial stress that should be reached in most pipelines under normal operating conditions. However, for pipelines constructed form higher steel grades such as X70, it is possible for elastic construction stresses to exceed that limit resulting in a larger number of reportable features that are associated with construction.

Table 2: Bending Strain Feature Summary

	2013	2018	2021	2023
Reportable Strain Features	217	200	205	195
Non-Reportable Strain Features	34	57	54	64
Features <0.125% from Vendor B	125	125	125	125
Replaced Features	8	2	0	0

A breakdown of the strain features by strain range from each inspection is shown in **Table 3**. When all data sets are summarized according to the same methodology, the results show better agreement, and the agreement typically improves at higher strains. The variation in the number of features between 0.125% and 0.2% in each inspection is primarily a result of features near the reporting threshold. These results agree with the conclusions of prior publications [6] and demonstrate the repeatability of bending strain based on IMU.

Table 3: Summary of Reportable Bending Strain Features by Strain Range

	2013	2018	2021	2023
Reportable Strain Features	217	200	205	195
Features with 0.125% <=Strain <0.20%	192	179	185	175
Features with 0.20% <=Strain <0.30%	24	20	19	19
Feature with 0.30% <=Strain <0.40%	1	1	1	1
Maximum Bending Strain (%)	0.311%	0.307%	0.307%	0.314%

The strain comparison was performed using a strain change reporting threshold of 0.06%. This strain change reporting threshold was chosen as it is the most appropriate threshold for identifying legitimate areas of change based on previous publications [6]. Larger thresholds may be required in situations where noise in the IMU data cannot be adequately smoothed through the gage length or other means.

A summary of the strain change features identified from 2013 to 2023 is provided in **Table 4**. The comparison identified 118 reportable strain change features occurring between 2013 and 2023. Based on the author's experience, this is an unusually high number of strain change features. This number is notably larger than the seven strain change features identified by Vendor A who sed a higher strain change threshold of 0.1%. Fortunately, data integration offers some clarity on the number of the reported strain change features. Seventy-one (60.1%) of the strain change features were associated with repair sleeves. The significant number of strain change features associated with repair sleeves presents an opportunity to review excavation and backfill procedures to reduce strain from backfilling. Seven additional features were adjacent to replacement sections where construction fit-up offers a likely cause for the observed change.

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Table 4: Strain Change Summary

	2013 - 2023
Reportable Strain Change Features	118
Strain Change Features Interacting with Sleeve	71
Strain Change Features Adjacent to Replacements	7
Maximum Strain Change	0.229%
Horizontal Strain Change Features	3
Replacement Areas	17

After accounting for prior repairs and replacements, 40 strain change features remain to be addressed. Of these 40 strain change features, only 11 were associated with reportable bending strain features. This provides a manageable number of features to address in the near term (i.e., 3 to 6 months). The initial response to these strain change features should seek to positively identify or rule out an active geohazard through additional data integration, consistent with the recommendations from previous publications [4]. The additional data integration may include a review of construction records, interviews with field personnel, or a Level 2 field assessment with qualified geotechnical personnel [1].

A few of the reportable bending strain features are presented here to demonstrate the influence of gage length and illustrate how bending strain assessments are highly repeatable when they are performed using the same assessment methodology. A comparison of the gage lengths is shown in **Figure 3** and **Figure 4** using data from the 2023 inspection. In each figure, the green lines show the calculated strains using a 1.5-meter gage length. The red and blue lines show the calculated strains using a 3-meter gage length. **Figure 3** demonstrates the influence of gage length at girth welds. The results show that most of the strains have excellent agreement including the location of the peak strain denoted by the vertical purple line with a "T". In fact, the strains only diverge at the three weld locations. At these locations, the calculated strain appears as much as 50% higher (0.06 % strain). However, these higher strains are not representative of the actual strain at the girth welds. Instead, the narrowing of the signal pattern and increased strains at the girth welds indicates misaligned joints rather than true strain patterns. The three joints showing the increased strains have angular misalignment of slightly less than 1-degree which is common in pipelines.

Figure 4 shows a similar comparison of gage lengths at a location with horizontal strains and slightly higher strain magnitudes that would likely warrant more attention from an operator. Similar to the previous example with the girth welds, the strains compare well throughout the bending strain area except at the locations identified as manufactured bends, denoted by the red shading in the images. At these locations, the calculated strains show sharp disagreement. Again, the shorter gage length shows a narrowing of the signal pattern and increased strains at the manufactured bends. However, the calculated strains within the manufactured bends are excluded from the assessment as they are intentionally introduced into the pipeline. The reported strains in the manufactured bends do show a difference between the 1.5 and 3-meter gage lengths, but the different gage lengths are useful for characterizing manufactured bends and do not influence reporting.

With respect to gage lengths, some operators elect to use different gage lengths depending on the diameter of the pipe being assessed. In the author's experience, the most common choice among these operators is to use 2 meters for pipe diameters less than 12-inch NPS and 3-meters for pipe diameters greater than or equal to 12 NPS. There is some merit in this as smaller diameter pipes can

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be bent to higher curvature. However, as shown in this publication, the variation in reported strain for most areas of concern in an 8-inch pipeline is not significant as the overall signal length is much longer than 2 or 3 meters. It is important to understand that shorter gage lengths will be more sensitive to noise potentially resulting in unnecessary calls or unrealistically high strains. It is also important to recognize that any comparison between two data sets must be performed using the same gage length. It is the author's opinion and recommendation that a 3-meter gage length is sufficient for analysis and reporting, and other gage lengths should be used for bend identification or additional information.

Figure 5 provides an example demonstrating the repeatability of IMU when properly aligned and assessed using the same criteria. The out-of-straightness and calculated bending strains are presented from each of the four inspections. At this reportable feature, the calculated bending strains are identical from each of the 4 data sets throughout the entire 345-ft long feature. This presentation of the strains in a multi-run view is useful for demonstrating the stability of bending strain features across the duration of the IMU data.

The last example presented in this study demonstrates the benefits when additional data is integrated into the bending strain assessment. **Figure 6** shows a comparison of all four IMU data sets at one of the seventy-one strain change locations interacting with a repair sleeve. The comparison of all four IMU data sets shows that the change occurred between the 2021 and 2023 inspections. The location shows a textbook example of a strain change feature characterized by an 8-inch vertical downward movement and a clear "W"-shaped oscillating pattern in the vertical strains. The vertical strain change at this location is 0.14%, equivalent to a longitudinal bending stress increase of 42,000 psi. The cause of the strain change is clearly associated with the repair sleeve which is located near the center of the strain change pattern. Integrating this information at the time of the bending strain assessment streamlines the process of identifying the cause for the operator and properly sentencing the feature.

While the previous example is shown for repair sleeves, information from other types of data integration can provide insight into the assessment. For instance, if data integration shows a wrinkle or a dent that is coincident with a peak bending strain, it may increase the attention given to an area as these features reduce the compressive strain capacity or could indicate that a buckle has already formed. Similarly, if a known geohazard overlaps with a strain change area, it may warrant a quicker response as it could indicate movement happening within a known geohazard area.

Lessons Learned

The assessment conducted in this study highlighted common issues that operators may encounter when performing bending strain assessments or comparisons based on multiple IMU data sets. This section summarizes the lessons learned and provides recommendations to operators performing these assessments.

First, operators need to develop reporting specifications for IMU data and bending strain. These specifications should be developed and given to vendors prior to performing the bending strain assessments. At a minimum, the reporting specifications should address the following requirements.

- Whenever an ILI tool is equipped with an IMU, a high-resolution report should be delivered to the operator at the time of the final report. This IMU report should contain the navigation heading angles (pitch, azimuth, and roll) with the pipe centerline coordinates (latitude, longitude, and elevation) on a 4-inch (0.1 m) odometer interval, or less. Having this

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information will permit the operator to perform a bending strain assessment in the future whenever the need arises.

- When a bending strain assessment is performed by a vendor or consultant, the analysis should be performed to a specified gage length. It is the opinion of the authors that a 3-meter gage length is sufficient for most pipelines. Additional gage lengths can be integrated into the results for feature identification.
- When a bending strain assessment is performed by a vendor or consultant, the analysis should identify features with a combined strain greater than a specified threshold. It is the opinion of the authors that a reporting threshold of 0.125% is capable of discriminating noise from actual bending strain patterns and is appropriate for most assessments. Reducing the reporting threshold will result in a significant increase in the number of reported features.
- When a bending strain change is performed by a vendor or consultant, the analysis should identify strain change features with a change in strain in the horizontal, vertical, or total strain that exceeds 0.06%. Previous studies have demonstrated that this threshold is slightly larger than twice the real-world repeatability of IMU tools [6]. Larger reporting thresholds may be used when pipe-tool dynamics result in higher levels of noise, but this change should be clearly communicated and agreed upon with the operator.

If these minimum requirements are implemented by operators, they will observe greater consistency in the reported results independent of the vendor or consultant performing the analysis. However, the industry currently has significant disparity in the presentation of bending strain features and the delivery of information to operators. It is the opinion of the authors that additional consistency and program improvements can be achieved if the following requirements are also addressed in their reporting specifications.

- When a bending strain or strain change analysis is performed, operators should specify the requirements of the graphical images. These requirements should address the information contained in each of the panels and the sign convention used in the assessment. While the presentation of the graphs does not impact the results, the most common sign convention specifies sag bends as having positive strain in the vertical direction and left turns as having positive strain in the horizontal direction.
- Operators should require the ability to view and interrogate completed bending strain analyses along the entire analysis segment as opposed to only reported features. This requirement could be met through graphical images included as part of a report or a software delivery system. The software delivery system is preferred as inclusion in a report will lead to cumbersome deliverables for longer segments.

It is relatively straightforward for operators to develop the work instructions and requirements to meet the first set of objectives. The second set of requirements would impose challenges on some vendors and may be best suited for an industry consortium such as API or PRCI.

The authors also feel that this study demonstrated the value of integrated data in the bending strain and strain change assessments. While this information can be integrated after the fact, it is more efficient and produces a better product if the data is integrated during the analysis and presented to the operator with the final report. This workflow would require operators to have the data prepared beforehand and provided to the vendors. At a minimum, operators should include features identified from other ILI technologies. Additional information from repair records or surface-based geohazard assessments is also recommended.

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Conclusions

The adoption of bending strain and strain change assessments based on IMU data has increased steadily over the last decade. This paper examined a case study based on an operator's experience with performing bending strain and bending strain comparisons assessments with multiple data sets across different vendors. The results from each of the vendors showed significant disparity because of different analysis and reporting requirements. The case study demonstrated how the results can be aligned when the analysis and reporting requirements are aligned. The lessons learned provide operators with guidance for developing reporting specifications to ensure consistent results.

References

1. INGAA Foundation, Geosyntec Consultants, Inc. Guidelines for Management of Landslide Hazards for Pipelines, Version 1, August 17 2020.
2. Pipeline and Hazard Materials Safety Administration, Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards, PHMSA-2019-08984, May 1, 2019.
3. Pipeline and Hazard Materials Safety Administration, Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards, PHMSA-2022-00063, June 2, 2022.
4. Dotson, R., McKenzie-Johnson, A., How Should we Respond to Geohazards, Pipeline Pigging and Integrity Management Conference, February 6-10, 2023.
5. Czyz, J., Adamas, J., Computation of Pipeline Bending Strains Based on Geopig Measurements, Pipeline Pigging and Integrity Management Conference, February 14-17, 1994.
6. Dotson, R., et. al., Beware the Shapeshifter: A Repeatability Study on Pipeline Movement and Bending Strain Assessments, Pipeline Pigging and Integrity Management Conference, February 24-25, 2021.

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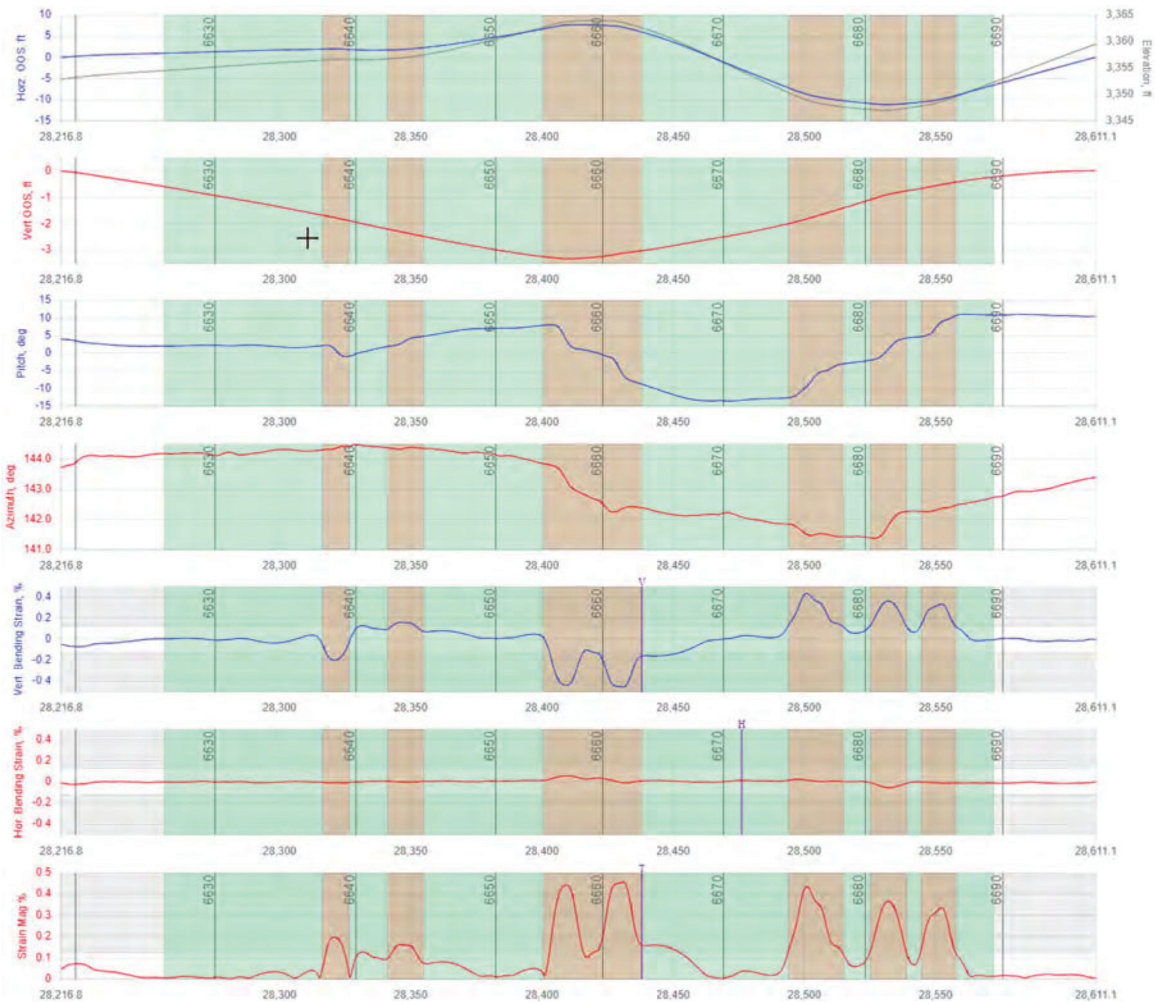

Figure 1: Vendor A Graphical Feature Near Odometer 28300 ft (recreated by D2I).

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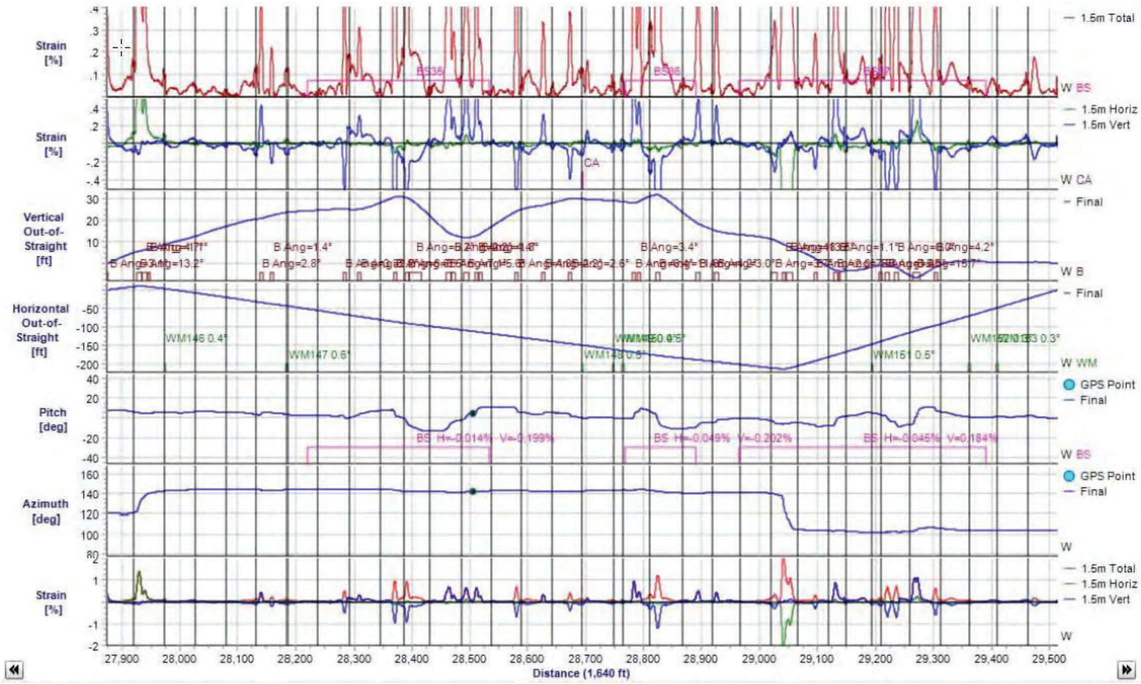

Figure 2: Vendor B Graphical Feature Near Odometer 28300 ft.

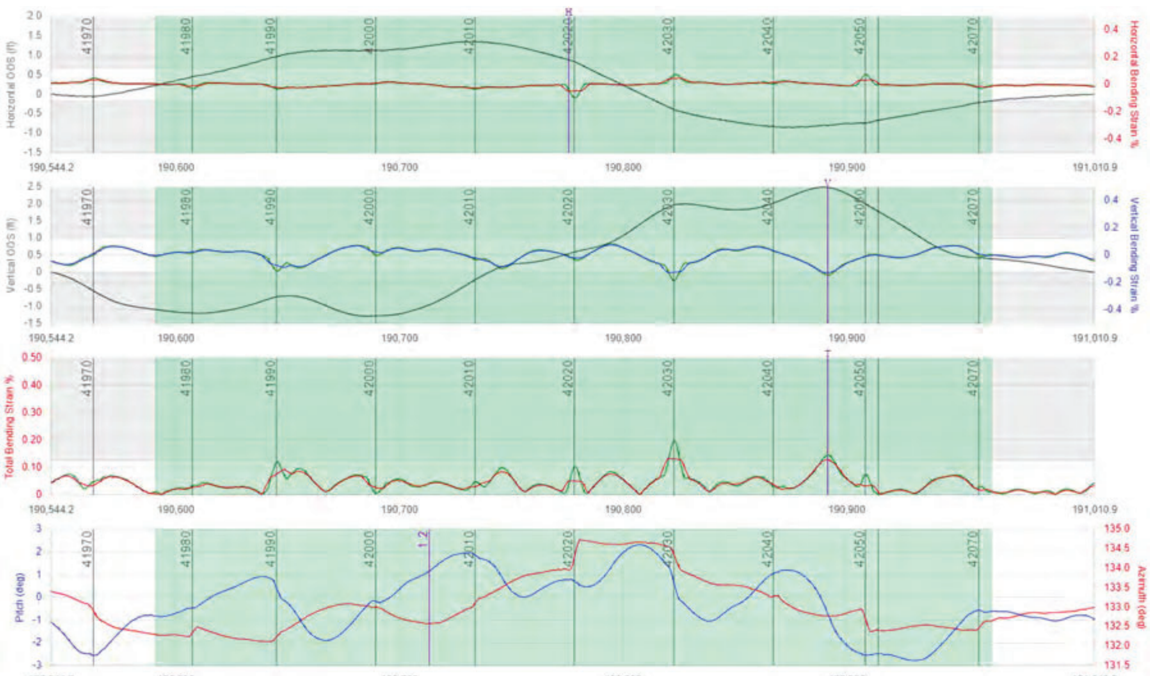

Figure 3: Comparison of 1.5 and 3m Gage Lengths at Girth Welds

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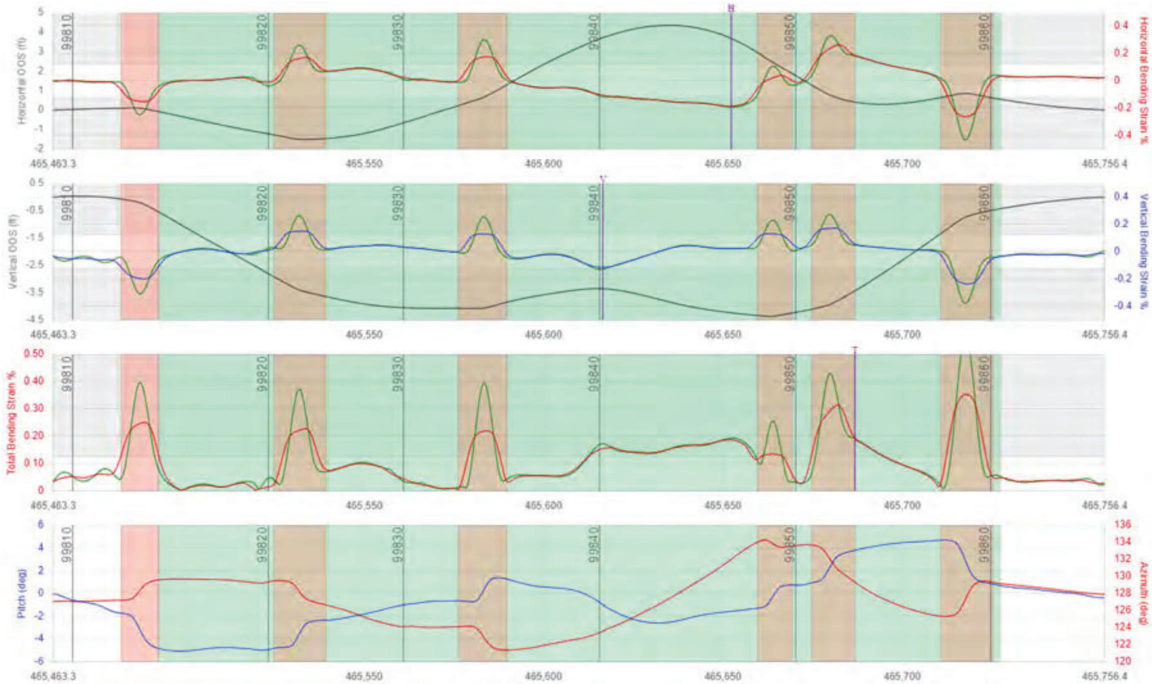

Figure 4: Comparison of 1.5 and 3m Gage Lengths at Horizontal Feature

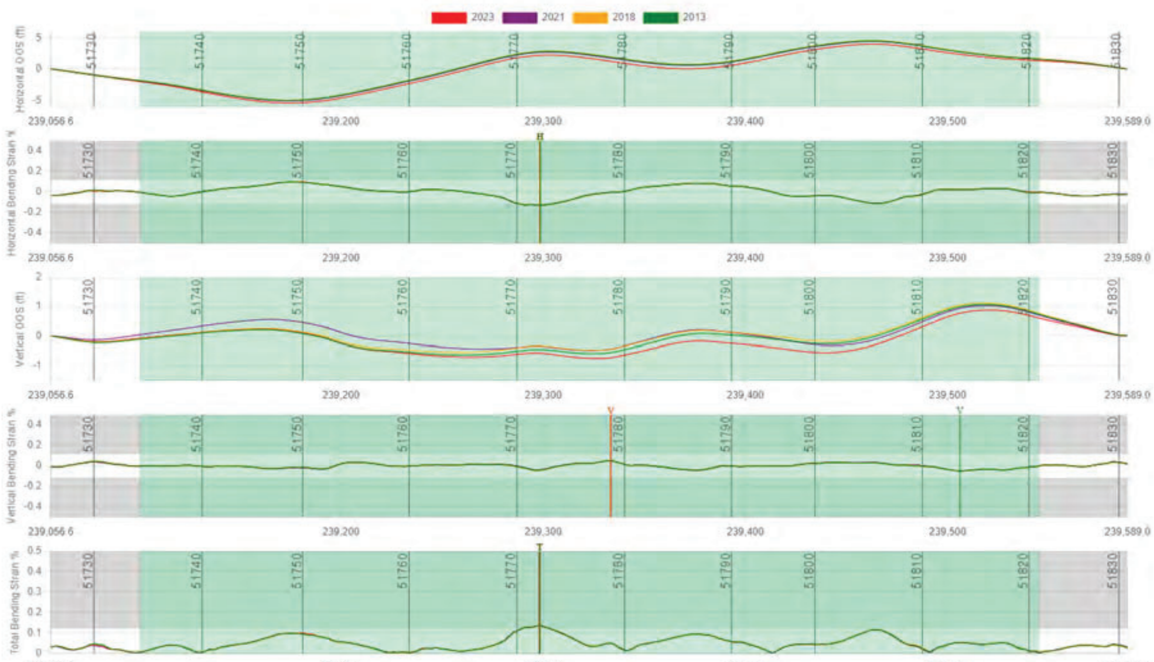

Figure 5: Multi-Run Comparison of 4 IMU Data Sets

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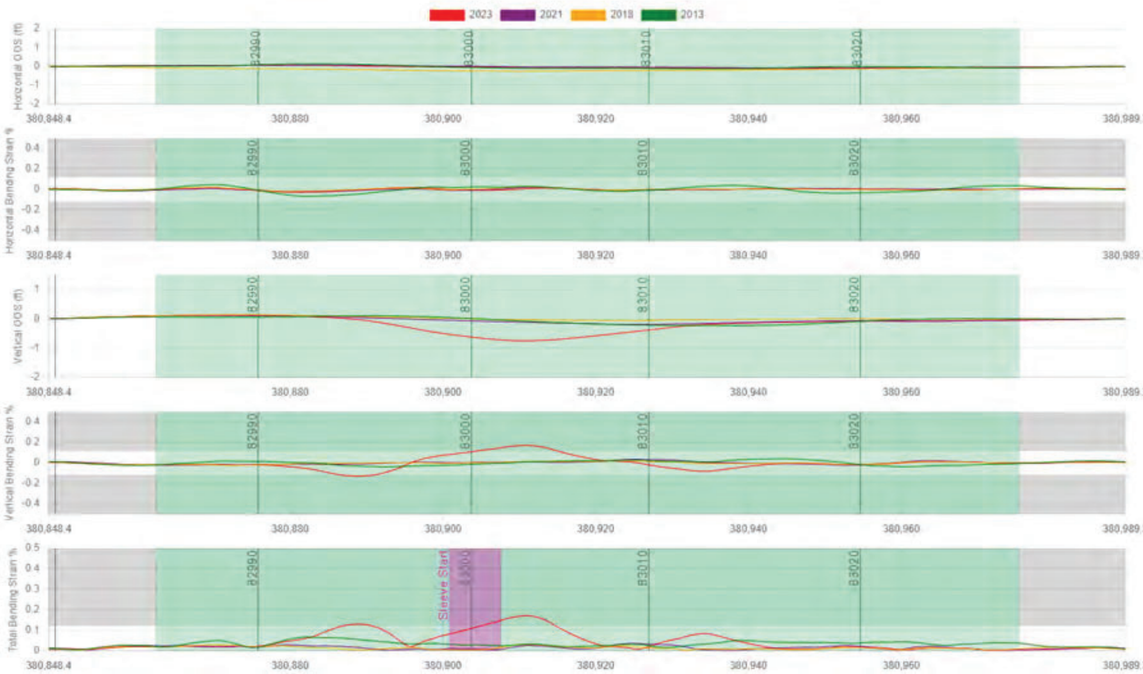

Figure 6: Multi-Run Comparison at Repair Location

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