BENDING STRAIN REPORT
MFL-C

Marathon Petroleum

22” Crude Oil Pipeline
Roxanna to Patoka Woodpat

January 2018

Report Date	April 23, 2019
Revision Number	0
ROSEN Project Number	0-1000-14050
ROSEN Line Name	22” ROX-PAT

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report describes the bending strain analysis for the pipeline inspection carried out by ROSEN in the 22-inch 54.74-mile crude oil Roxanna to Patoka Woodpat pipeline segment inspected in January 2018.

The bending strain analysis was performed by analyzing curvature patterns recorded using an inertial measurement unit (IMU). The post run assessment indicated that the IMU data was of acceptable quality and the tool operated with the specified parameters. After calculating the bending strains along the length of the pipeline, any areas with a bending strain greater than 0.125% (i.e., 1250 microstrain) were identified for further review. It should be noted that pipeline features such as field bends, valve installations, or construction irregularities may also register bending strains greater than 0.125%. However, these features were specifically excluded from the bending strain assessment. More information on the appropriate identification of bending strain areas and anomalous locations can be found in Section 3.

The assessment described in this report identified **18** areas with total bending strains exceeding 0.125%. These areas and the associated bending strains are summarized in Section 4.1 and 4.2. More details on each of these areas are presented in the body of the report. Detailed plots for each of these locations are available in Section 5. The maximum total strain observed was **0.34%** at location **3**.

This report is divided into the following sections. The Introduction section provides some background on bending strain evaluation. Section 2 provides the pipeline data used in the assessment. Section 3 provides a summary of the rules used to discriminate actual bending strain areas from features that are not a concern. Section 4 presents lists of the following information:

- Up to 25 areas with the highest bending strains sorted according to highest strain (Section 4.1)
- All areas with bending strains greater than 0.125% sorted according to log distance (Section 4.2)

Section 5 provides a detailed description of the reported areas including graphs showing the line deviations and the bending strain components as a function of line distance. Finally, Section 6 closes with a discussion on the results and any areas that require additional information.

ROSEN would like to take the opportunity to thank **Marathon Petroleum** for the assistance and cooperation we received during the course of this project. ROSEN would also l ke to state that feedback from any site investigations of the areas mentioned in this report would be highly appreciated.

1 INTRODUCTION

This report describes the bending strain analysis for the pipeline inspection carried out by ROSEN in the 22-inch 54.74-mile crude oil Roxanna to Patoka Woodpat pipeline segment inspected in January 2018.

The objective of the bending strain assessment is to identify areas where the pipeline has experienced high strain resulting from bending induced by external loads or during construction. High bending strains may occur in the horizontal or vertical plane and can result in yielding (i.e. plastic deformation) or buckling of the pipeline. Typical examples of external loads that may affect onshore pipelines are:

- Pipeline spanning resulting from erosion or washout near streams
- Landslides
- Earthquakes or fault movement
- Frost heave
- Walking or buckling in heated lines
- Sand-dune movement.

The bending strain assessment is performed using specialized algorithms to assess the data collected from an inertial measurement unit (IMU) in a single run. The algorithms calculate the pipeline curvature which is directly proportional to the bending strain in the pipeline (i.e., higher curvature produces higher bending strains). The curvature patterns associated with each area are then analyzed to determine whether the curvature is associated with external loads.

Please note that the expressions “Strain” and “Bending Strain” are used interchangeably throughout this report and refer to strain that occurs as a result of pipeline bending. Membrane strains, which might be caused by thermal expansion or pressure elongation, are not accounted for in the reported bending strain values.

2 PIPELINE DATA

This information used in the bending strain assessment is based on the pipeline questionnaire received from the client prior to inspection and on the information collected by the ILI tool. A summary of the data used in the assessment is provided below.

nominal diameter (NPS) [inches]	22.00
type of pipe	SMLS, EFW, ERW-HF, ERW-LW, DSAW
grade	X-46, X-52, X-60
nominal wall thickness [inches]	0.281, 0.312, 0.344, 0.375, 0.500
MAOP [PSI]	939, 1036, 1104, 1225, 1276, 1473, 1505, 1702, 1964*
design pressure [PSI]	939, 1036, 1104, 1225, 1276, 1473, 1505, 1702, 1964**
SMYS [PSI]	46000, 52000, 60000
minimum bend radius	7D
length [miles]	54.74
built in	1949
pipeline product	Crude Oil
inspection history	TDW - 2012

*Note: *Per the request of Marathon Petroleum, MAOP and design pressures have been given equal values.*

*Note: **Design pressure have been calculated per ANSI/ASME B31.4.*

3 BENDING STRAIN ANALYSIS RULES

A description of the methodology used to determine bending strain is included in the Appendices. This section provides a description of the rules used to discriminate between actual bending strain areas and features that are not of a concern such as field bends or valve stations.

Bending strain reporting threshold
A total bending strain threshold of 0.125 % is used to identify any areas for further review. This strain value corresponds to a 400D radius of curvature. This strain value is less than the strain that would result in yielding or buckling for most pipelines.

Determining the beginning and end of a bending strain area
The start and end distances of a bending strain area are defined as the locations where the pipeline trajectory deviates from a plausible route. The selection of these points is based on the analyst’s review of the curvature patterns. External loads may affect a significant portion of a pipeline while producing high bending strains in excess of the threshold over a smaller location. The intent in reporting the extents of a bending strain area is to ensure that the entire affected area is identified in this report rather than only reporting the local area where the bending strain exceeds the reporting threshold.

Bends
The bending strain assessment will identify curvature (and hence high strain) associated with field bends although this curvature is a necessary part of the manufacturing process and is not indicative of an integrity issue. The bending strain analysis documented in this report seeks to identify bends in the system and ensure that they are not erroneously reported as high strain features. A high bending strain area is classified as a “bend” when any of the following criteria are met:

- The location corresponds to a given bend location provided by the client.
- The bending strain location affects only a single spool.
- The bending strain shows a pattern consistent with a field bend.

It should also be noted that “bends” may be identified within areas identified as having high bending strain. At these locations, it is not possible to separate the bending strain resulting from the manufacturing process and the bending strain resulting from external loads. Bends located within high bending strain areas are identified in the detailed descriptions provided in Section 5.

Exceptions
Not all areas with a calculated bending strain value exceeding the reporting threshold are classified as bending strain areas. As discussed previously, field bends are an example where curvature is a necessary part of the pipeline design and should not be identified as an area with high bending strain.

The following features are excluded from the bending strain evaluation:

- “Bends” as defined above.
- Installations areas, such as valve stations, are excluded and will be classified as “Other”.
- Localized signals clearly caused by anomalies, such as dents, are excluded and will be classified as “Other”.
- Signals interpreted as girth weld passage effects will be excluded.

4 BENDING STRAIN SUMMARY

The purpose of this section is to present a summary of the bending strain results. Detailed results of each high strain feature are provided in Section 5. Any feature with a bending strain greater than 0.125% and meeting the criteria outlined in the previous section is presented here. The results are divided into two subsections.

The first sub-section presents up to 25 locations with the highest reported bending strains with the features sorted according to highest strain. The second sub-section provides a comprehensive list of all the bending strain areas sorted by log distance.

The summarized findings are below:

- A total of **18** areas have been identified with a total bending strain greater than 0.125%. Bending strain area no. **3** at log distance 32604 – 32800 ft. has the highest reported maximum strain value. The maximum calculated total bending strain value in this area, disregarding peaks observed over girth welds, is **0.34%**.
- Of the **18** identified areas**,** there are **12** areas where the bending strain is primarily vertical. The maximum calculated total bending strain value in these areas, disregarding localized peaks observed over girth welds, is **0.28**%.
- Of the **18** identified areas, there are **6** areas with strain oriented in both the horizontal and vertical directions. The maximum calculated total bending strain value in these areas, disregarding localized peaks observed over girth welds, is **0.34%**.

All distances are expressed in feet [ft.] in this report. The center distance of the first valve in the launcher station has been set to **0.001** ft. This point is used as reference distance.

The following table provides a list of the locations having a bending strain greater than 0.125% and interacting with other features in the pipeline (i.e., dents, ovality, etc.). It should also be noted that these interactions appear within the comments section for each bending strain location.

OBJECT	AREA(S)
Casing	4, 8
Patch	4, 6, 7
Sleeve	3, 4, 6, 8
Wall thickness change	1, 2

4.1 List of Maximum Bending Strain Areas

This section presents up to 25 bending strain locations with the highest strain values sorted according to maximum strain.

The results are sorted based on maximum bending strain values. Areas that are classified as possible construction irregularities, known bends and installation areas have all been omitted from this list.

The “List of Maximum Bending Strain” can be found on the following page.

The information listed for each area is:

- Anomaly number
- Start log distance of the area in [ft.]
- End log distance of the area in [ft.]
- XYZ information of the max bending strain distance
- Maximum bending strain value in [%]
- Length of the bending strain area in [ft.]
- Comment

In total, **18** areas with bending strain were included in this list.

*Detailed information of these bending strain areas is given in section **5, “Detailed Description of the Reported Areas”**.*

Abbreviations possibly used in the “List of Maximum Bending Strain”:

Event	
BSTR	Bending Strain

Comment	
Component	The bending strain area contains one or more component(s) (other than girth welds)
ID anomaly	The bending strain area contains one or more ID anomalies. ID anomalies are dents, ovalities, buckles, wrinkles, misalignments, and bulges.

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22" Roxanna to Patoka Woodpat

List of Maximum Bending Strain

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Client: Marathon Petroleum
ROSEN Project No.: 0-1000-14050
ROSEN Line Name: 22" ROX-PAT
Inspection Type: MFL-C
Date of Inspection: January 5, 2018
Revision No.: 0

Bending Strain Anomaly No.	Start Distance ft	End Distance ft	Latitude °	Longitude °	Height ft.	Max. Bending Strain %	Length of Strain Area ft.	Comment
BSTR #003	[redacted]	[redacted]	[redacted]	[redacted]	440.697	0.34	196.00	bending strain, combined with sleeve and sleeved bend
BSTR #006	[redacted]	[redacted]	[redacted]	[redacted]	432.863	0.28	180.00	vertical bending strain, combined with patch and sleeves
BSTR #010	[redacted]	[redacted]	[redacted]	[redacted]	462.533	0.22	150.00	vertical bending strain
BSTR #011	[redacted]	[redacted]	[redacted]	[redacted]	517.887	0.22	87.00	bending strain
BSTR #007	[redacted]	[redacted]	[redacted]	[redacted]	542.252	0.21	113.00	vertical bending strain, combined with bends and patch
BSTR #008	[redacted]	[redacted]	[redacted]	[redacted]	553.306	0.21	240.00	vertical bending strain u/s of bend, combined with bends, casing, and sleeves
BSTR #014	[redacted]	[redacted]	[redacted]	[redacted]	484.096	0.21	65.00	bending strain d/s of bend
BSTR #013	[redacted]	[redacted]	[redacted]	[redacted]	482.422	0.20	70.00	vertical bending strain, combined with bend
BSTR #017	[redacted]	[redacted]	[redacted]	[redacted]	472.177	0.20	64.00	bending strain between bends
BSTR #009	[redacted]	[redacted]	[redacted]	[redacted]	537.157	0.19	243.00	vertical bending strain u/s of bend, combined with bends
BSTR #005	[redacted]	[redacted]	[redacted]	[redacted]	460.084	0.18	121.00	vertical bending strain d/s of bend
BSTR #002	[redacted]	[redacted]	[redacted]	[redacted]	424.752	0.17	105.00	vertical bending strain with wall thickness change
BSTR #004	[redacted]	[redacted]	[redacted]	[redacted]	447.104	0.16	120.00	vertical bending strain, combined with casing, patch, and sleeve
BSTR #012	[redacted]	[redacted]	[redacted]	[redacted]	502.498	0.16	61.00	bending strain
BSTR #015	[redacted]	[redacted]	[redacted]	[redacted]	443.722	0.15	90.00	bending strain
BSTR #018	[redacted]	[redacted]	[redacted]	[redacted]	481.505	0.14	80.00	vertical bending strain u/s of bend
BSTR #001	[redacted]	[redacted]	[redacted]	[redacted]	419.461	0.13	240.00	vertical bending strain d/s of bend with wall thickness change
BSTR #016	[redacted]	[redacted]	[redacted]	[redacted]	443.773	0.13	100.00	vertical bending strain

4.2 List of Bending Strain Areas

This section presents a summary for every area identified as having a total bending strain exceeding the threshold value of 0.125% sorted according to log distance.

The “List of Bending Strain Areas” contains the following information:

- Anomaly number
- Start log distance of the area in [ft.]
- End log distance of the area in [ft.]
- XYZ information of the max bending strain distance
- Maximum bending strain value in [%]
- Length of the bending strain area in [ft.]
- Comment

In total, **18** areas with bending strain were recorded.

Detailed information of these bending strain areas is given in section ***5, “Detailed Description of the Reported Areas”****.*

Abbreviations possibly used in the “List of Bending Strain Areas”:

Event	
BSTR	Bending Strain
Comment	
component	The bending strain area contains one or more component(s) (other than girth welds)
ID anomaly	The bending strain area contains one or more ID anomalies. ID anomalies are dents, ovalities, buckles, wrinkles, misalignments, and bulges.

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22" Roxanna to Patoka Woodpat

List of Bending Strain Areas

Client: Marathon Petroleum
ROSEN Project No.: 0-1000-14050
ROSEN Line Name: 22" ROX-PAT
Inspection Type: MFL-C
Date of Inspection: January 5, 2018
Revision No.: 0

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Bending Strain Anomaly No.	Start Distance ft.	End Distance ft.	Latitude °	Longitude °	Height ft.	Max. Bending Strain %	Length of Strain Area ft.	Comment
BSTR #001	[redacted]				419.461	0.13	240.00	vertical bending strain d/s of bend with wall thickness change
BSTR #002	[redacted]				424.752	0.17	105.00	vertical bending strain with wall thickness change
BSTR #003	[redacted]				440.697	0.34	196.00	bending strain, combined with sleeve and sleeved bend
BSTR #004	[redacted]				447.104	0.16	120.00	vertical bending strain, combined with casing, patch, and sleeve
BSTR #005	[redacted]				460.084	0.18	121.00	vertical bending strain d/s of bend
BSTR #006	[redacted]				432.863	0.28	180.00	vertical bending strain, combined with patch and sleeves
BSTR #007	[redacted]				542.252	0.21	113.00	vertical bending strain, combined with bends and patch
BSTR #008	[redacted]				553.306	0.21	240.00	vertical bending strain u/s of bend, combined with bends, casing, and sleeves
BSTR #009	[redacted]				537.157	0.19	243.00	vertical bending strain u/s of bend, combined with bends
BSTR #010	[redacted]				462.533	0.22	150.00	vertical bending strain
BSTR #011	[redacted]				517.887	0.22	87.00	bending strain
BSTR #012	[redacted]				502.498	0.16	61.00	bending strain
BSTR #013	[redacted]				482.422	0.20	70.00	vertical bending strain, combined with bend
BSTR #014	[redacted]				484.096	0.21	65.00	bending strain d/s of bend
BSTR #015	[redacted]				443.722	0.15	90.00	bending strain
BSTR #016	[redacted]				443.773	0.13	100.00	vertical bending strain
BSTR #017	[redacted]				472.177	0.20	64.00	bending strain between bends
BSTR #018	[redacted]				481.505	0.14	80.00	vertical bending strain u/s of bend

5 DETAILED DESCRIPTION OF THE REPORTED AREAS

For each bending strain area or poss ble construction irregularity, a separate page with a detailed description has been prepared. These pages consist of a header with general information, five graphs showing the strain situation and two pipeline representations in which the center of the bending strain events and the actual joint numbers are given.

The header consists of the following information:

Abbreviation	Description
Anomaly No	Anomaly ID number used in this report
Anomaly Type	Classification of the observed anomaly, according to rules mentioned in section 3
Distance Start [ft.]	Log distance of the start of the found anomaly
Distance End [ft.]	Log distance of the end of the found anomaly
Length [ft.]	Log distance based length of the found anomaly
Steel Grade	Type(s) of steel used in the specific anomaly area
WT_{nom} [in]	Wall thickness level(s) reported in the specific anomaly area
V_{avg} [ft/s]	Average velocity of the ILI tool, as recorded during passing the anomaly
$Coord_{Start}$ (Lon [°]| Lat [°]| Height [ft.]) resp. $Coord_{Start}$ (East [m]| North [m]| Height [ft.])	Coordinates of the start of the found anomaly, expressed in Longitude, Latitude and Height resp. in Easting, Northing and Height
$Coord_{End}$ (Lon [°]| Lat [°]| Height [ft.]) resp. $Coord_{End}$ (East [m]| North [m]| Height [ft.])	Coordinates of the end of the found anomaly, expressed in Longitude, Latitude and Height resp. in Easting, Northing and Height
Distance ε_{max}	Log distance where the maximum strain level was recorded within the anomaly
Direction [h]	Direction of the strain level, expressed in o’clock hours, where a 12:00 resp. 03:00 orientation represents a local pipeline curvature direction comparable with a vertical over bend resp. horizontal left bend
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	Strain level as recorded at log distance ‘Distance ε_{max}’, expressed in a horizontal component (ε_{hor}), vertical component (ε_{vert}) . The value ε_{total} represents the combination of the horizontal and vertical component.
Comment	Comments concerning the found anomaly

Explanation of comments:

Comment	Explanation
Bending strain u/s of bend	The spool(s) upstream of the bend are affected by bending strain. It is possible that the bending strain area ends in the bend.
Bending strain d/s of bend	The spool(s) downstream of the bend are affected by bending strain. It is poss ble that the bending strain area starts in the bend.
Bending strain between bends	The same as ‘strain u/s or d/s of bend’, but between two bends. It is possible that bending strain area starts and/or ends in a bend.

The graphs use the following legend:

Object	Explanation
	Value on left axis
	Bending strain value (%, right axis)
	Girth welds
	Other references (taps, clamps, supports, start of casing etc.)
	Bending strain areas > reporting threshold
	Field/factory bends within the strain location
	Areas with bending strain values > reporting threshold classified as ‘other’ (such as installation areas, dents, changes in wall thickness, etc.)
	Possible construction irregularity areas
	As a visual aid, the background in the ‘total bending strain’ graph is shown in grey above the threshold level

1: Top view graph
The black line in the “Top view” graph shows the horizontal distance between the actual pipe position and an imaginary straight line over the graph area. This view is also referred to as a “plan view or aerial view” Deviation is read on the left hand axis.

The red line shows horizontal bending strain [%]. Positive values represent right bends, negative values represent left bends. The horizontal bending strain is read on the right hand axis.

2: Side view graph
The black line in the “Side view” graph shows the height difference between the actual pipe position and an imaginary straight line over the graph area. This view is also referred to as an “elevation view.” The straight line is defined from the start and end points of the actual pipe height. Deviation is read on the left hand axis.

The red line shows vertical bending strain [%]. Positive values represent over bends, negative values represent sag bends. The vertical bending strain is read on the right hand axis.

3: Total bending strain graph
The “Total Bending Strain” graph shows the combined horizontal and vertical bending strain. The values represent the elongation at the outer side of the bend (which is equal to the compression at the inner side of the bend).

4: Direction of bending strain graph
The “Direction of bending strain” graph shows the o’clock position (h) of the total bending strain. The direction definitions are similar to the ones as described for the header info.

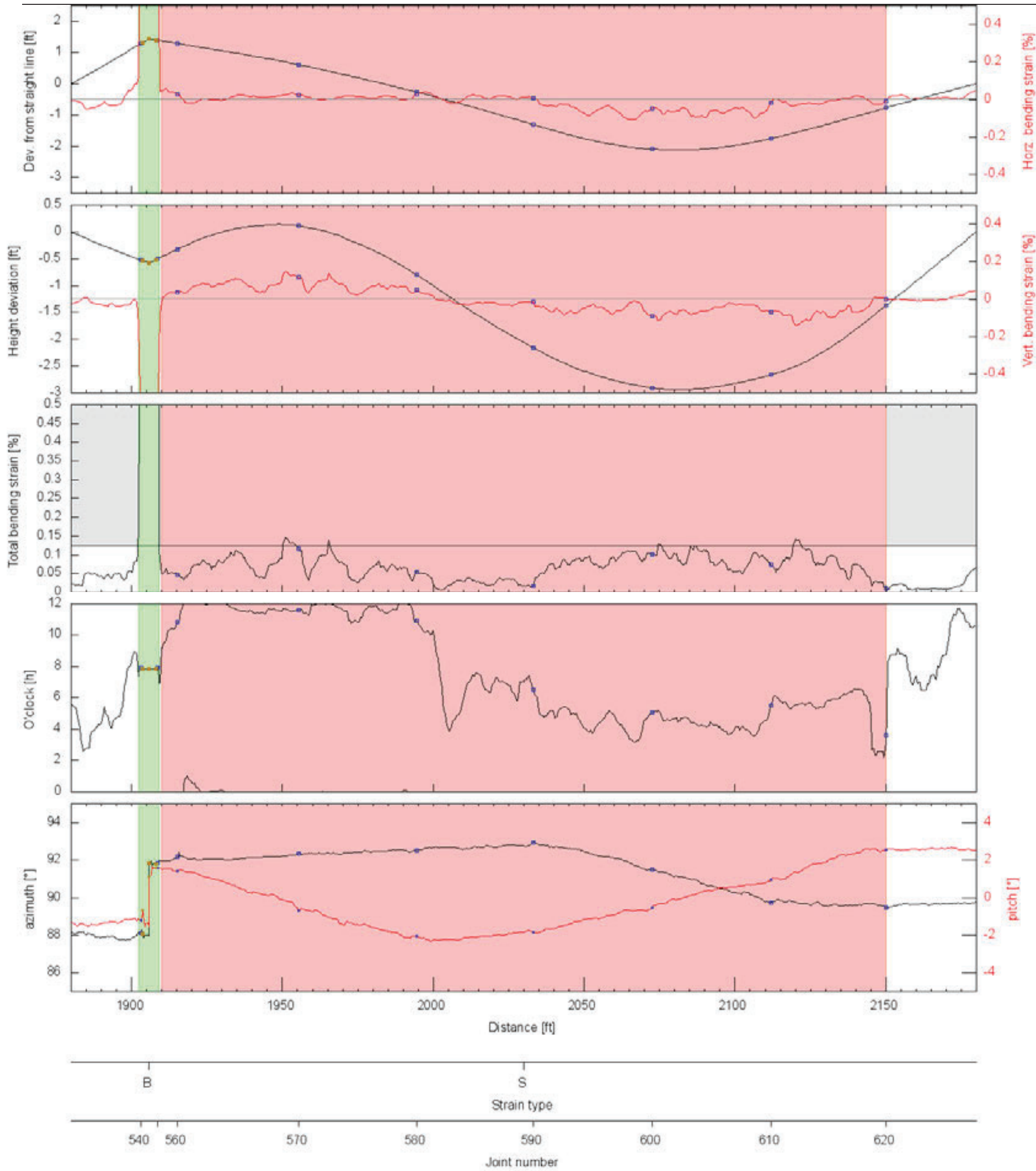
5: Azimuth and pitch graph
The “Azimuth and Pitch” graph shows the pipeline direction, expressed in azimuth and pitch, versus the log distance. The azimuth is defined as the direction of the pipeline in the horizontal plane, versus the north direction and increasing from north to east direction. The pitch is defined as the direction of the pipeline in the vertical plane, being 0 when pointing to the horizon and positive when pointing upwards.

Pipeline representations
At the bottom of each page, two pipeline representations are shown. The top pipe representation gives the center of the strain event. The following coding is used:

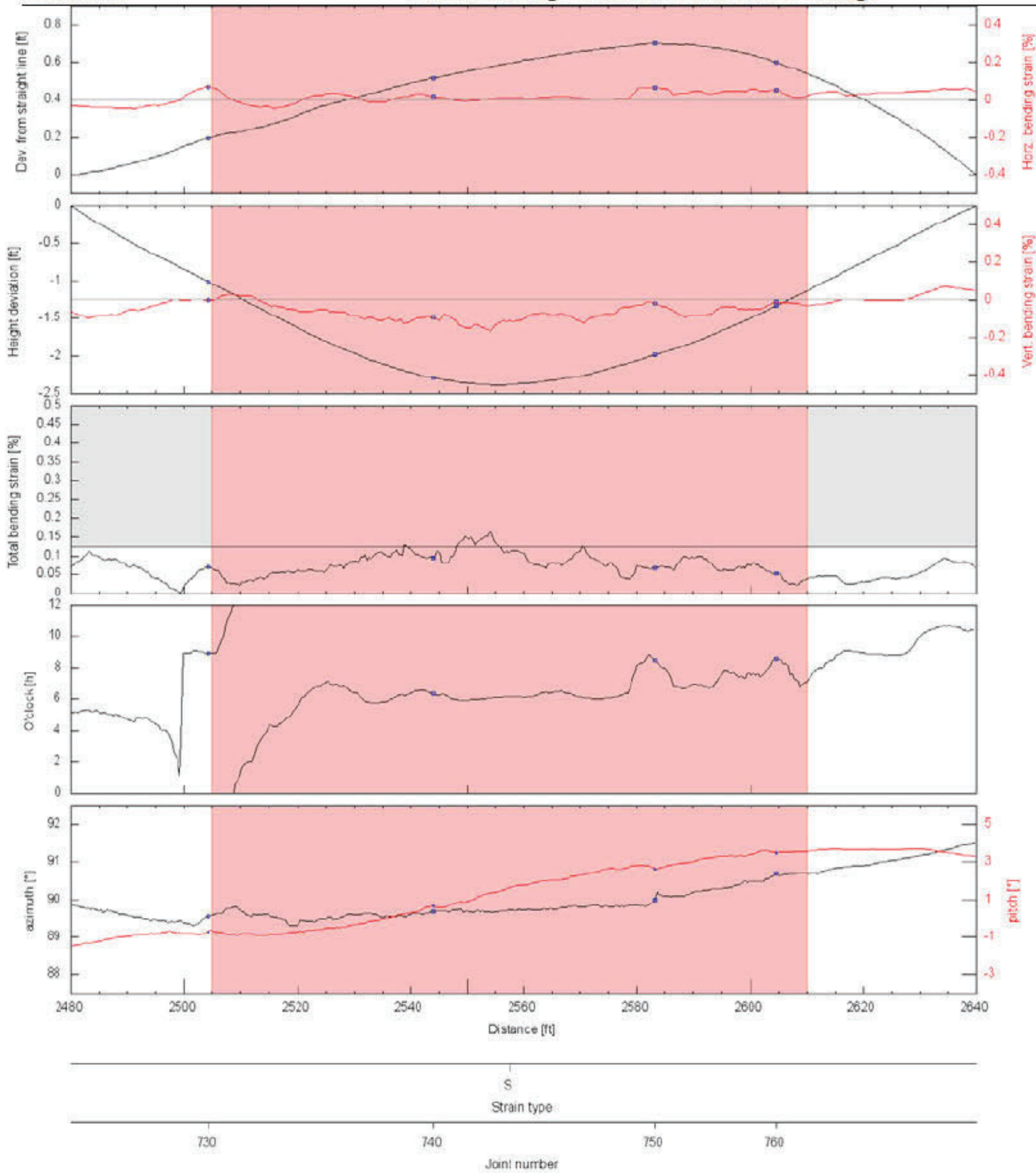
Code	Explanation
S	Bending strain (red areas)
B	Bend (green areas)
O	Other (yellow areas)

The bottom pipe representation shows the actual joint numbers which are also used in ROSOFT.

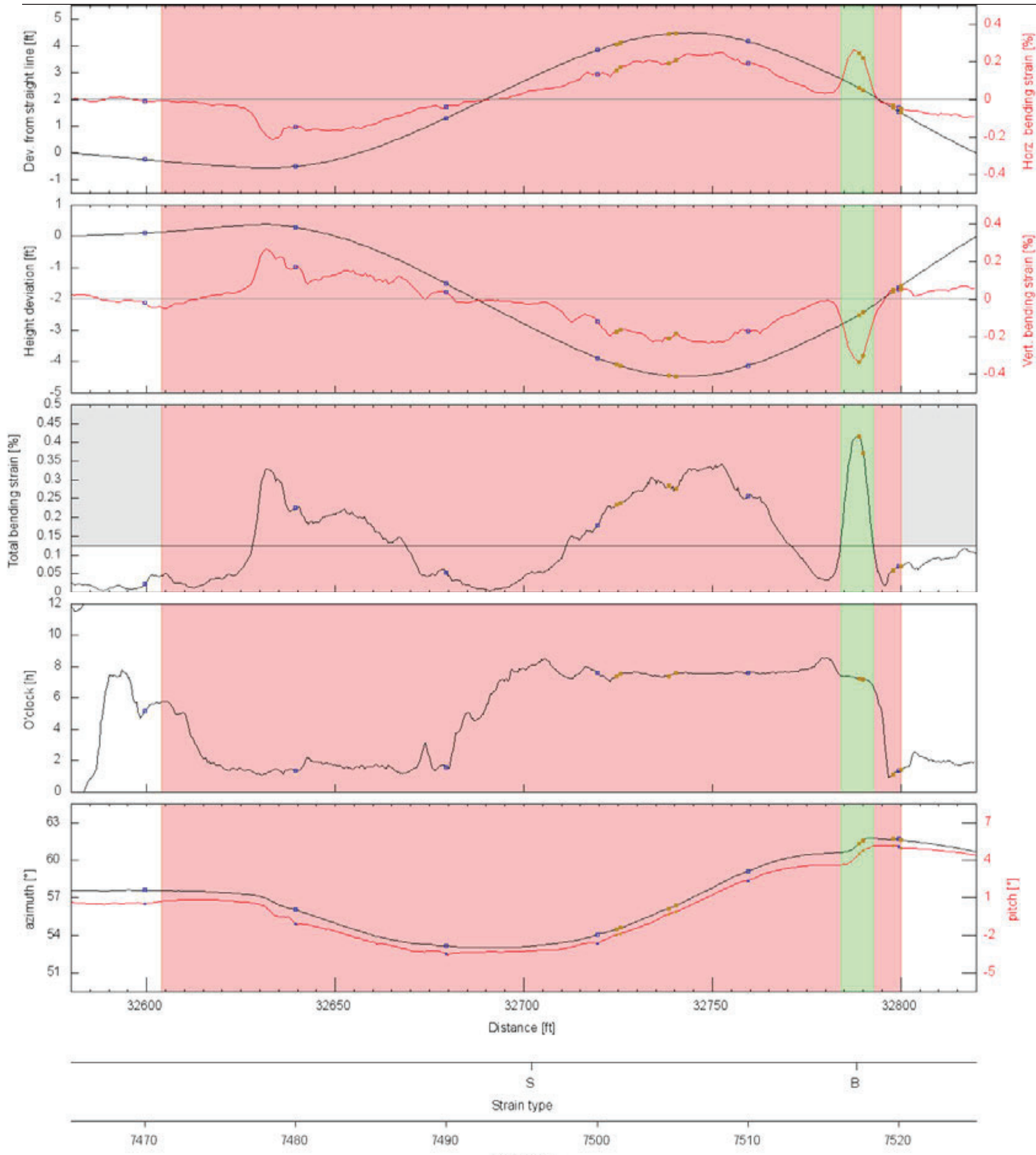
Anomaly No. | Anomaly Type	BSTR #001	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	240
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46 / X60	0.281" / 0.500"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	421.994
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	420.977
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	-0.06	-0.12	0.13
Comment	vertical bending strain d/s of bend with wall thickness change		



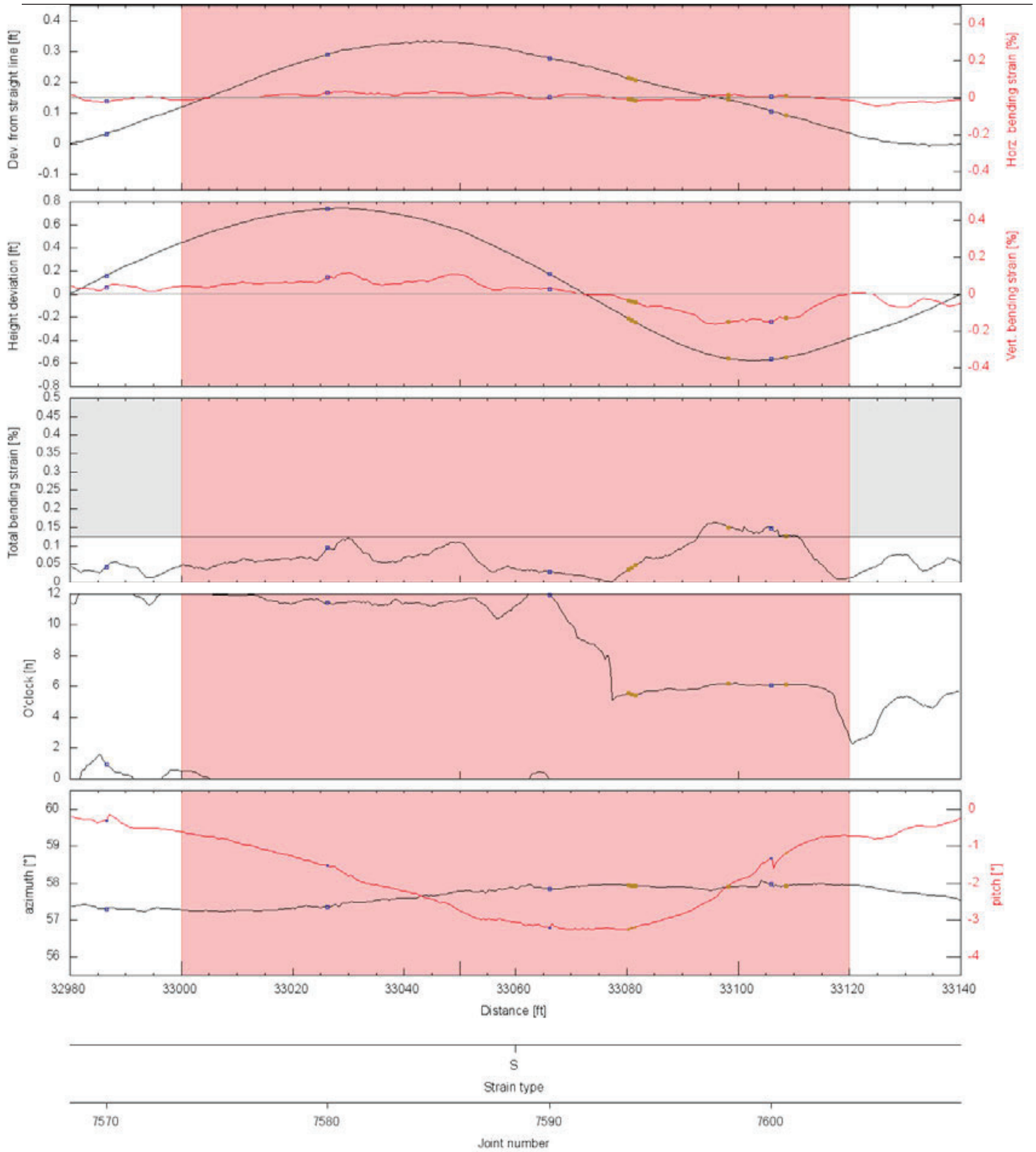
Anomaly No. | Anomaly Type	BSTR #002	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	105
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46 / X60	0.281" / 0.344"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	424.857
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	427.399
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.01	-0.17	0.17
Comment	vertical bending strain with wall thickness change		



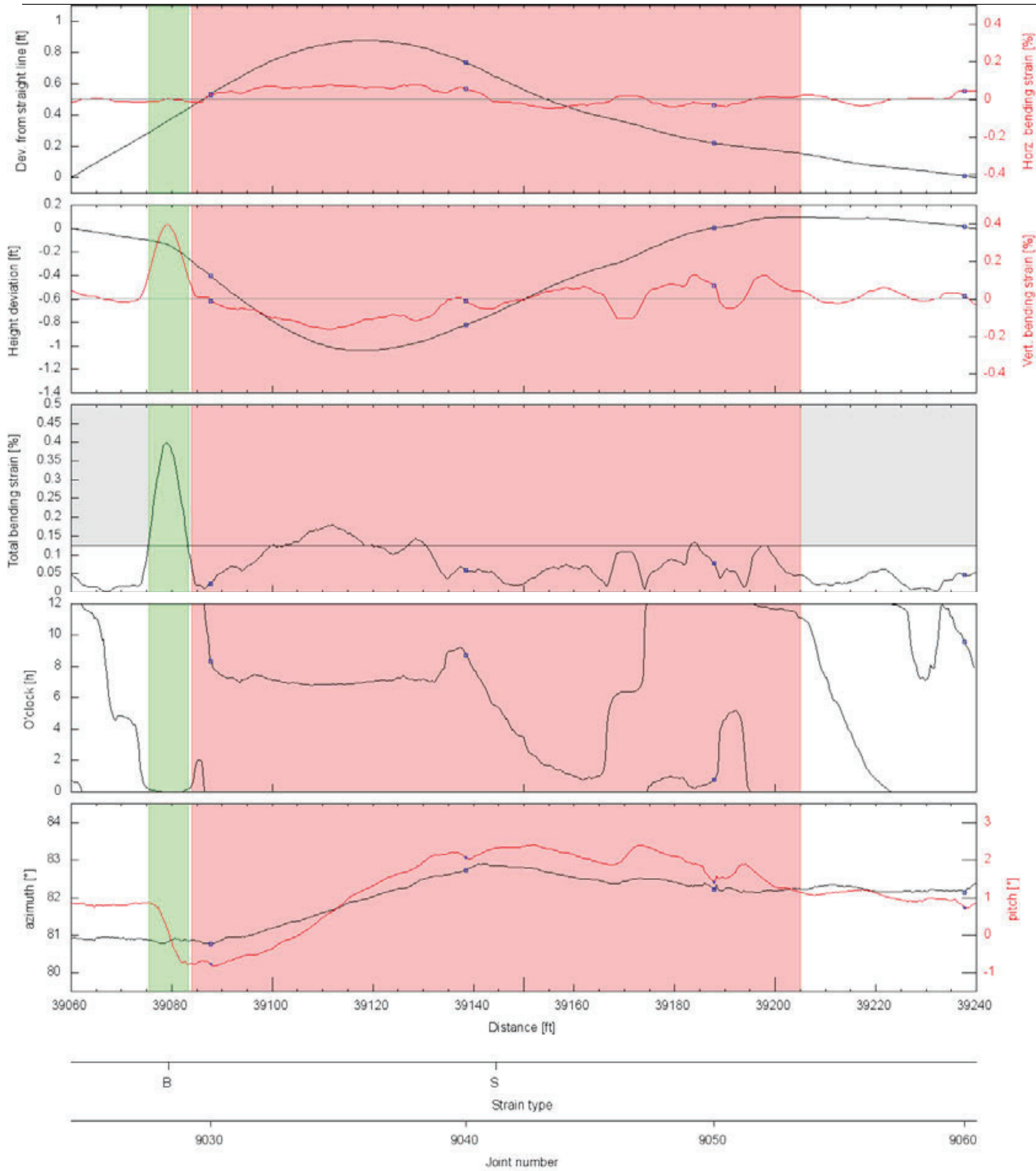
Anomaly No. | Anomaly Type	BSTR #003	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	196
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.344"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	444.571
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	443.665
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.25	-0.23	0.34
Comment	bending strain, combined with sleeve and sleeved bend		



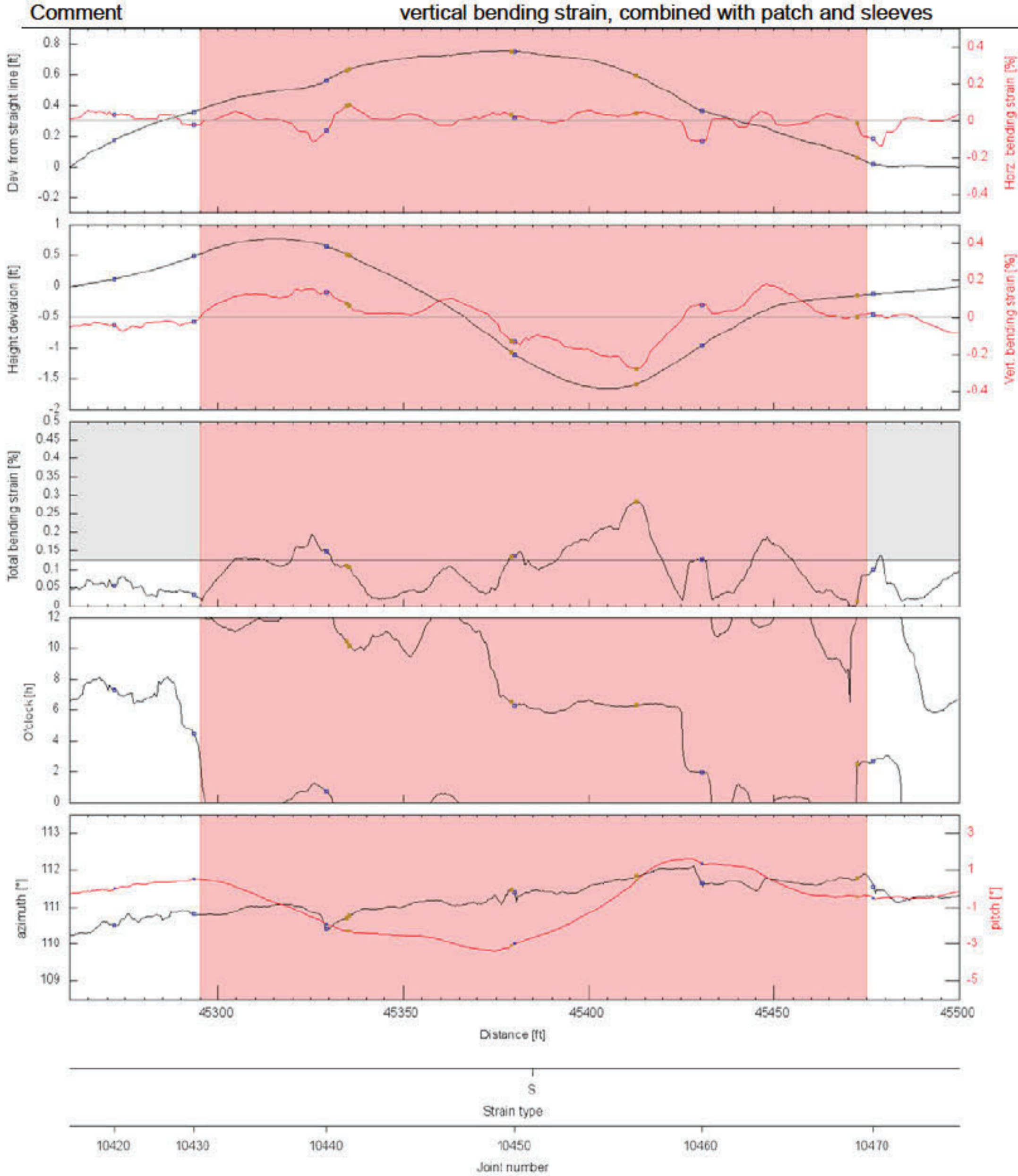
Anomaly No. | Anomaly Type	BSTR #004		bending strain
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	120
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.344"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	450.900
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	446.557
Distance ε_{max} [ft.] | Direction	[redacted]		various
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.01	-0.16	0.16
Comment	vertical bending strain, combined with casing, patch, and sleeve		



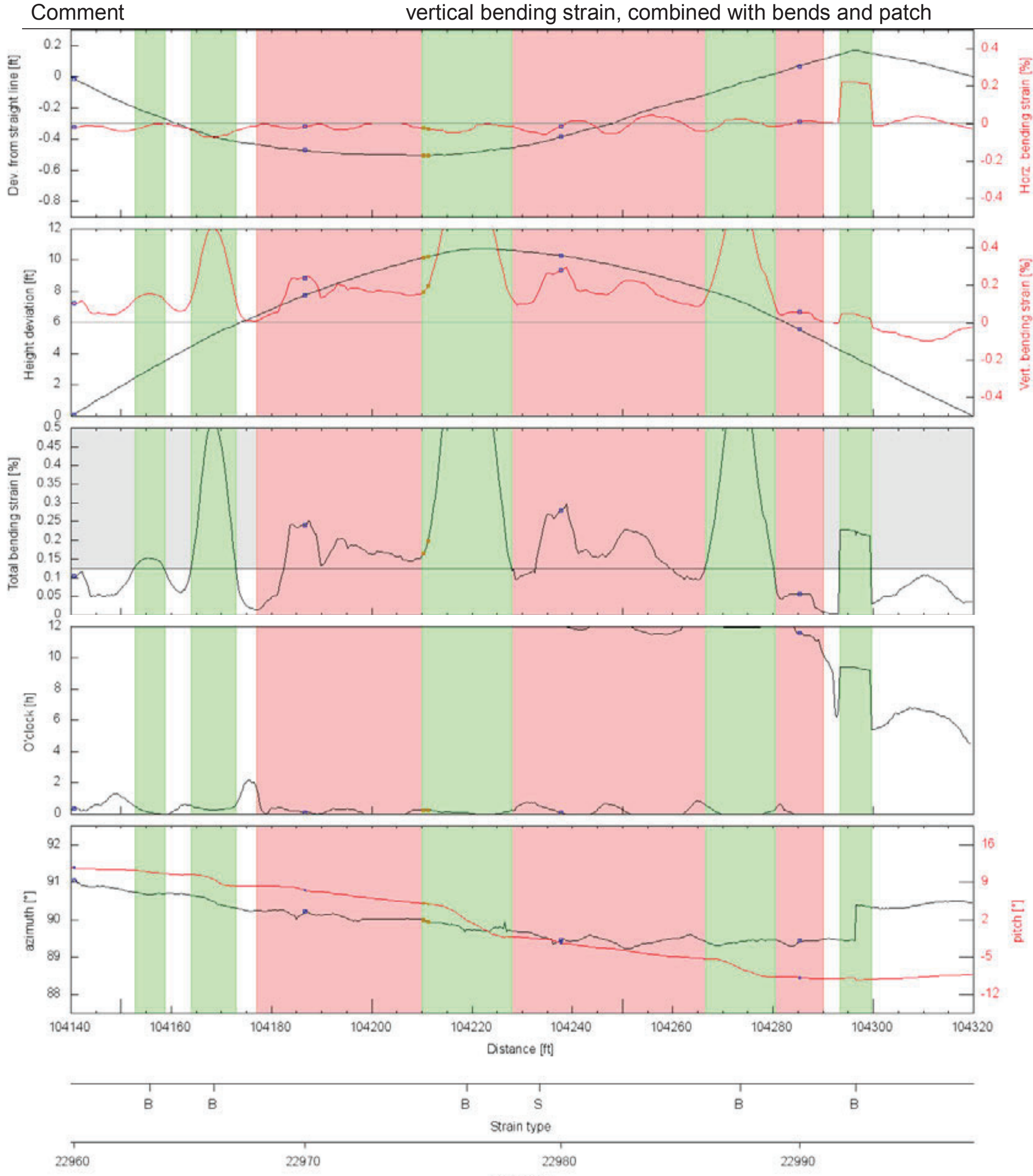
Anomaly No. | Anomaly Type	BSTR #005		bending strain
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	121
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.344"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	460.230
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	463.122
Distance ε_{max} [ft.] | Direction	[redacted]		various
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.08	-0.16	0.18
Comment	vertical bending strain d/s of bend		



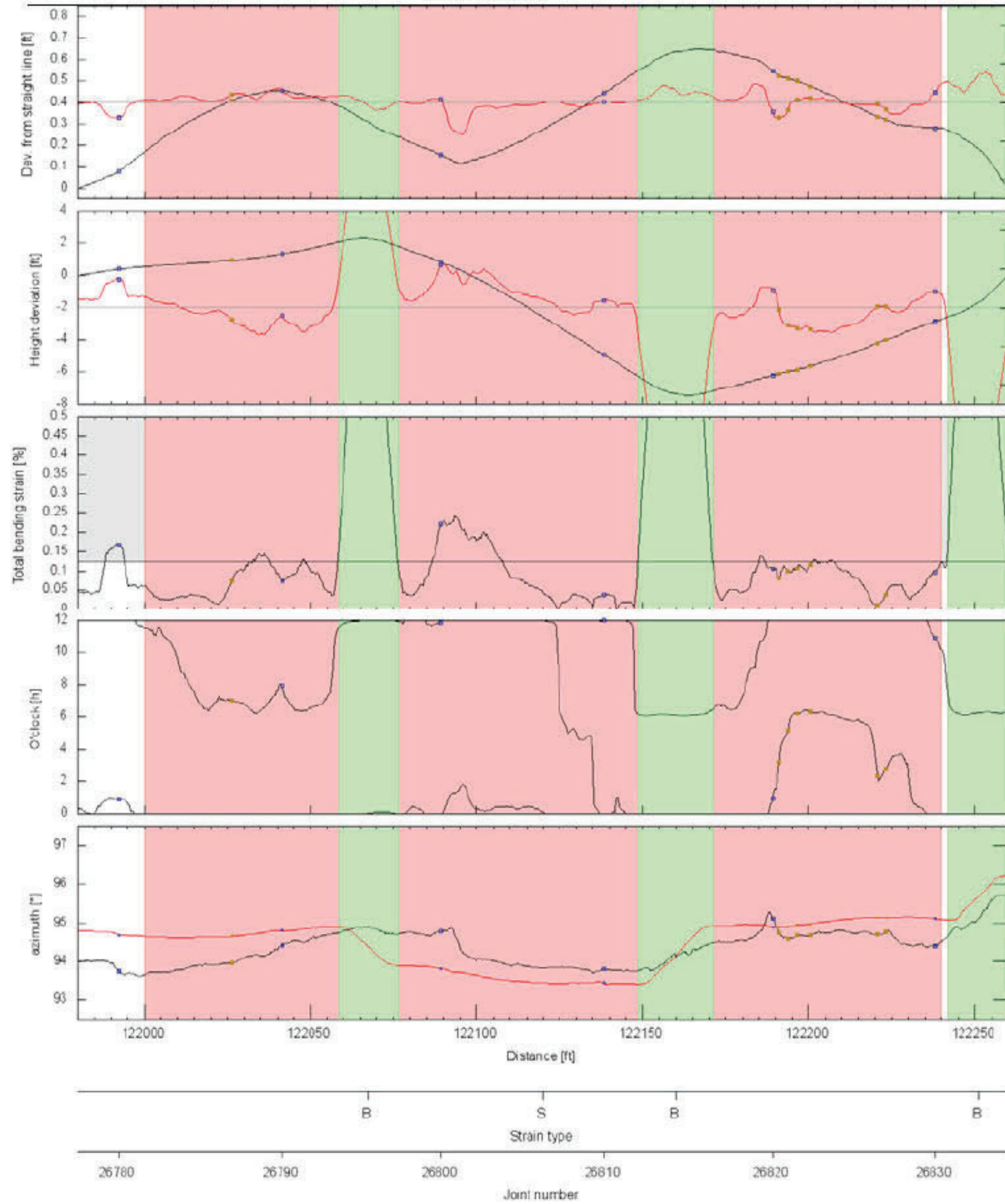
Anomaly No. | Anomaly Type	BSTR #006		bending strain
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	180
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.344"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	436.452
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	433.510
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.05	-0.28	0.28
Comment	vertical bending strain, combined with patch and sleeves		



Anomaly No. | Anomaly Type	BSTR #007	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	113
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.344"	5.2
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	540.070
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	539.197
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	-0.03	0.2	0.21
Comment	vertical bending strain, combined with bends and patch		

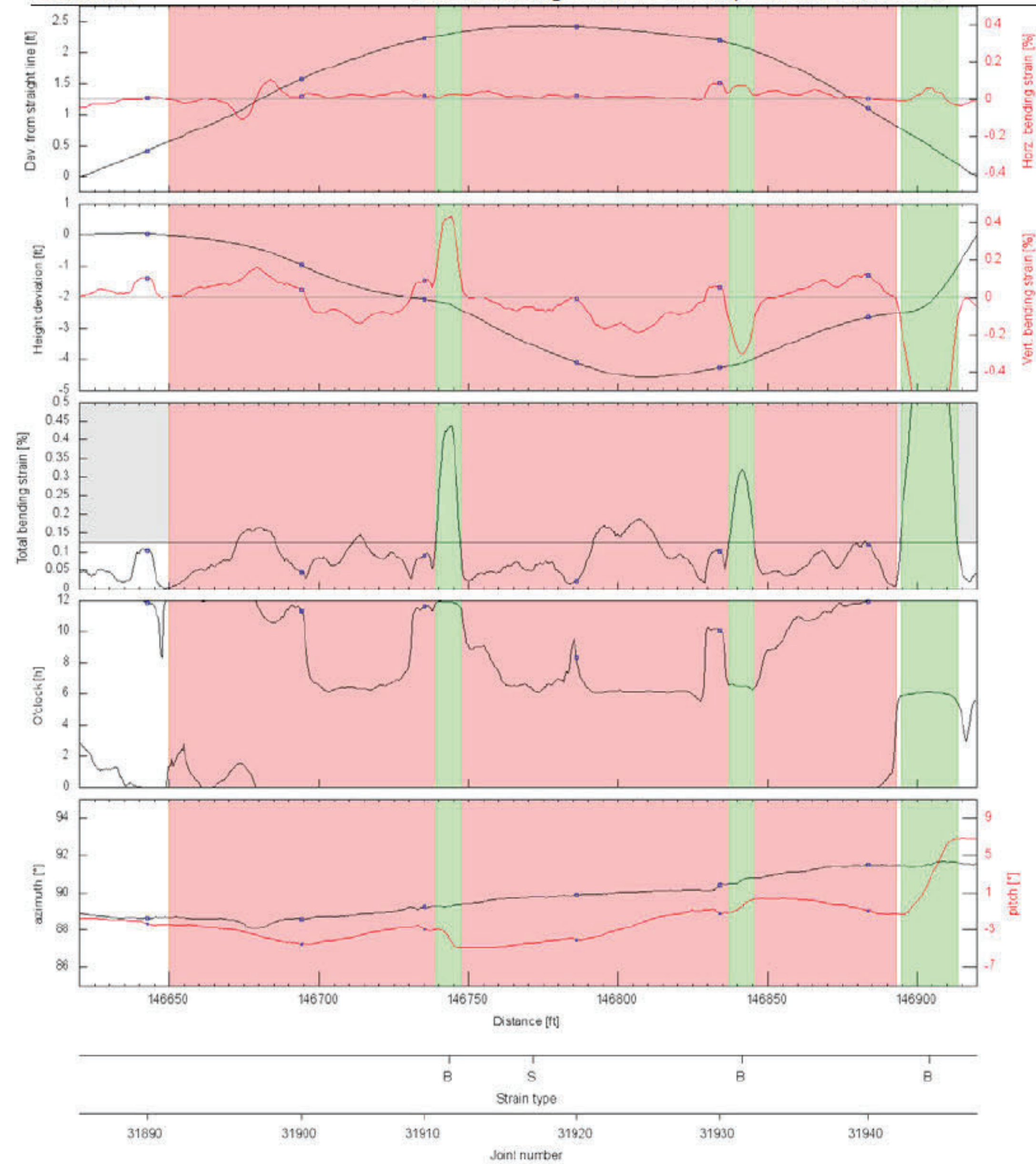


Anomaly No. | Anomaly Type	BSTR #008		bending strain
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	240
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	556.179
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	546.615
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	-0.17	0.13	0.21
Comment	vertical bending strain u/s of bend, combined with bends, casing, and sleeves		



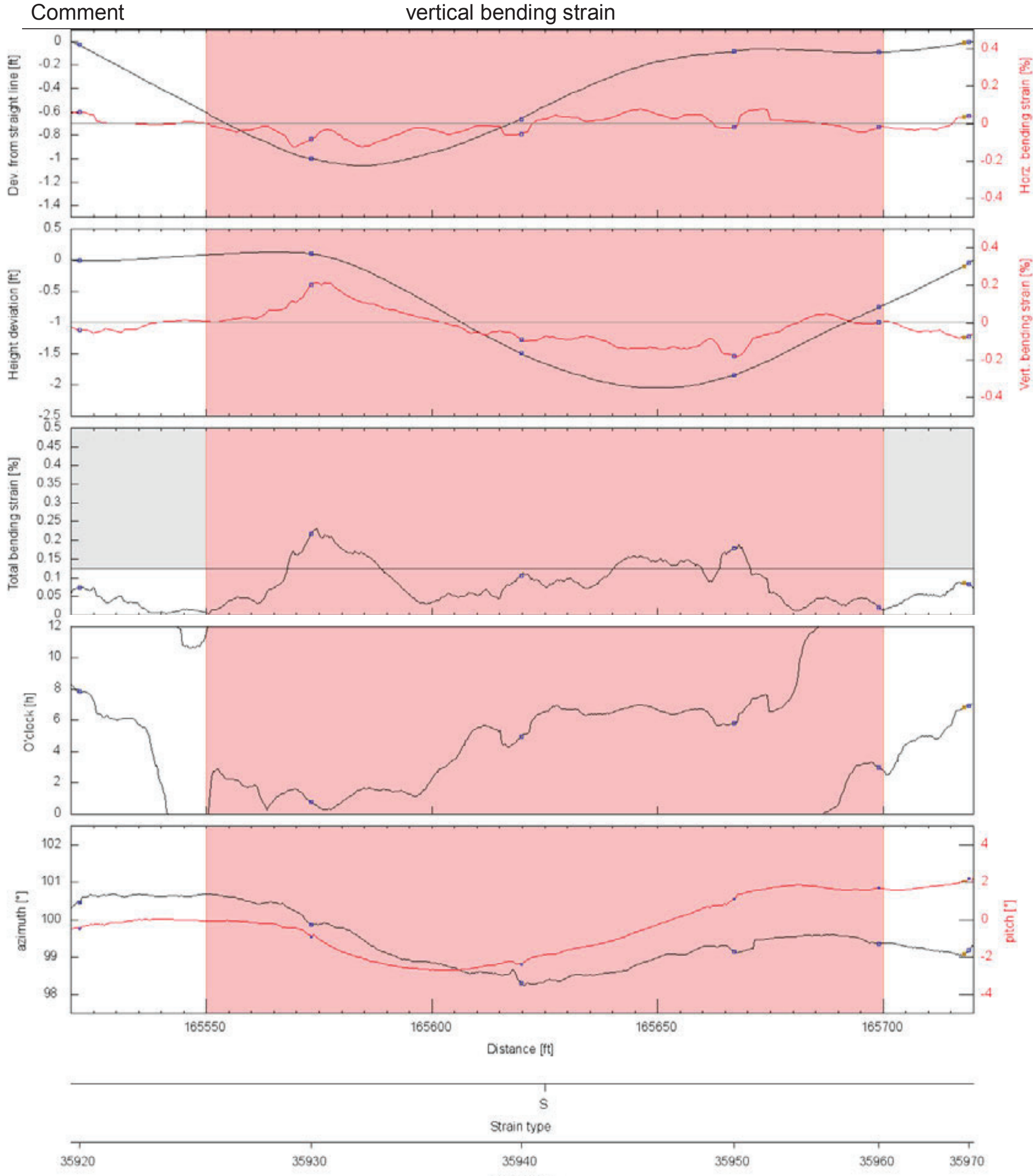
Client: Mara hon Petroleum
ROSEN Project No.: 0-1000-14050
ROSEN Line Name: 22" ROX-PAT
Inspection Type: MFL-C
Date of Inspection: January 5, 2018
Revision No.: 0

Anomaly No. | Anomaly Type	BSTR #009	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	243
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	547.249
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	536.168
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.01	-0.19	0.19
Comment	vertical bending strain u/s of bend, combined with bends		

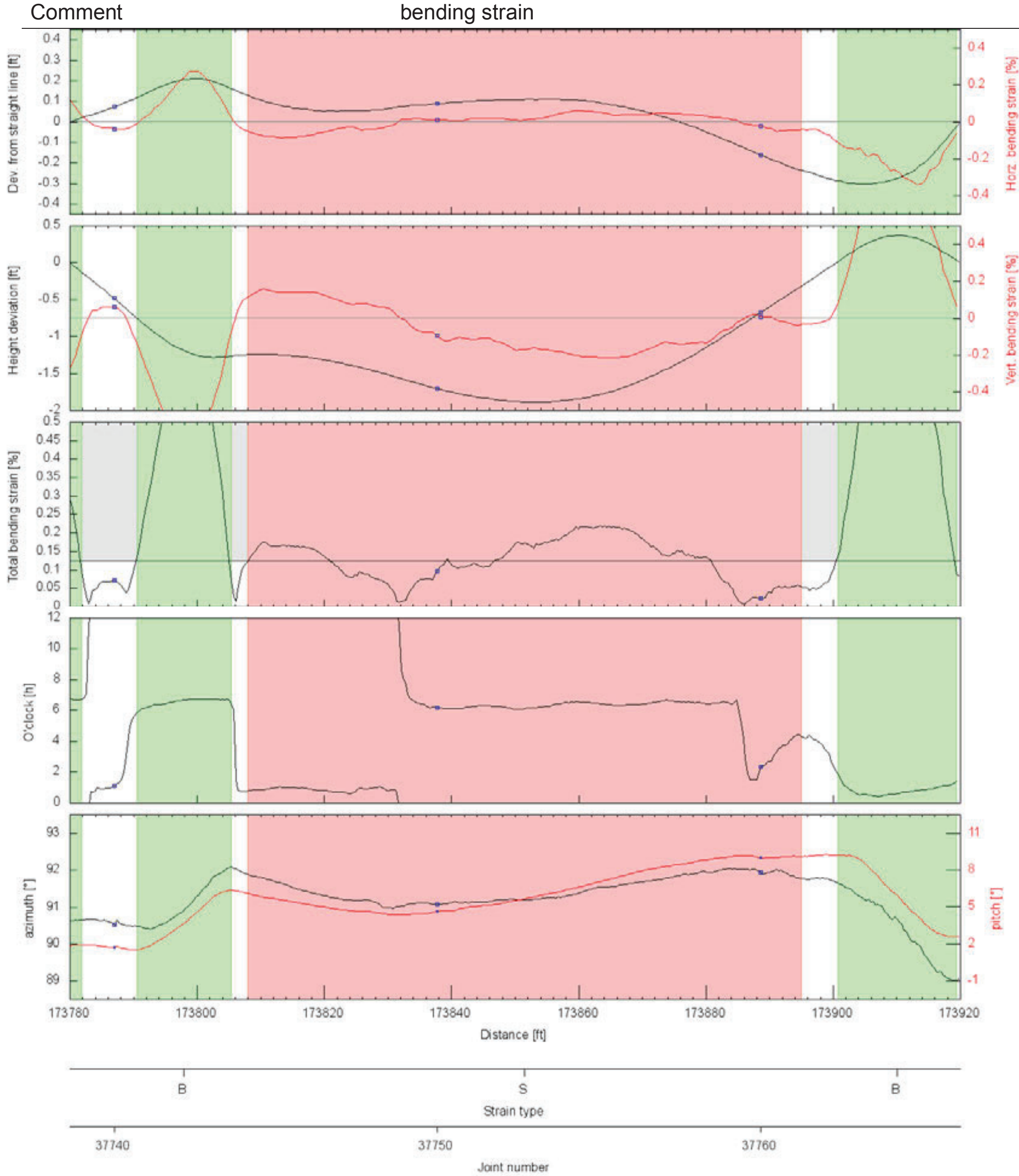


Client: Mara hon Petroleum
ROSEN Project No.: 0-1000-14050
ROSEN Line Name: 22” ROX-PAT
Inspection Type: MFL-C
Date of Inspection: January 5, 2018
Revision No.: 0

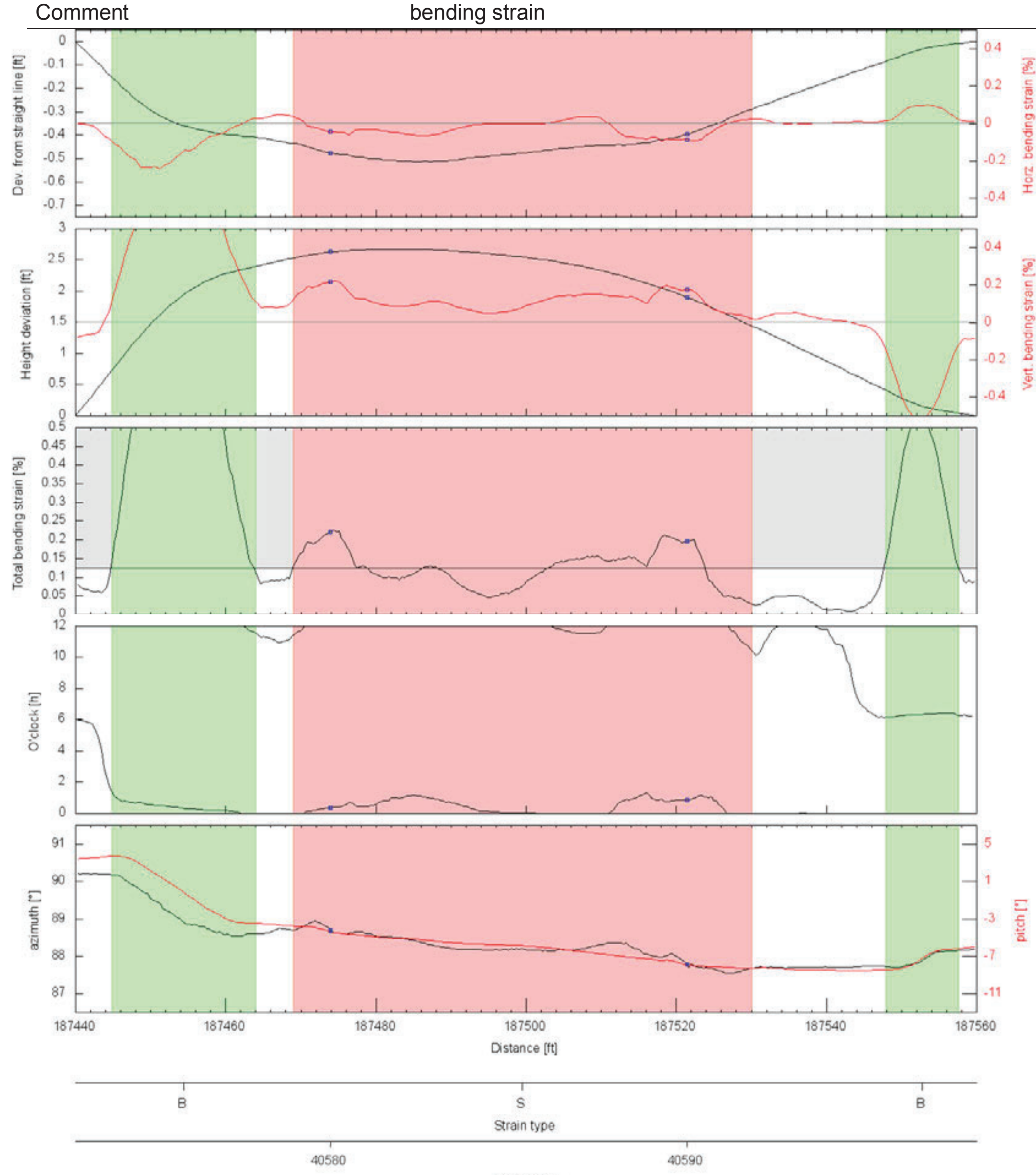
Anomaly No. | Anomaly Type	BSTR #010		bending strain
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	150
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	462.685
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	461.130
Distance ε_{max} [ft.] | Direction	[redacted]		various
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	-0.03	0.21	0.22
Comment	vertical bending strain		



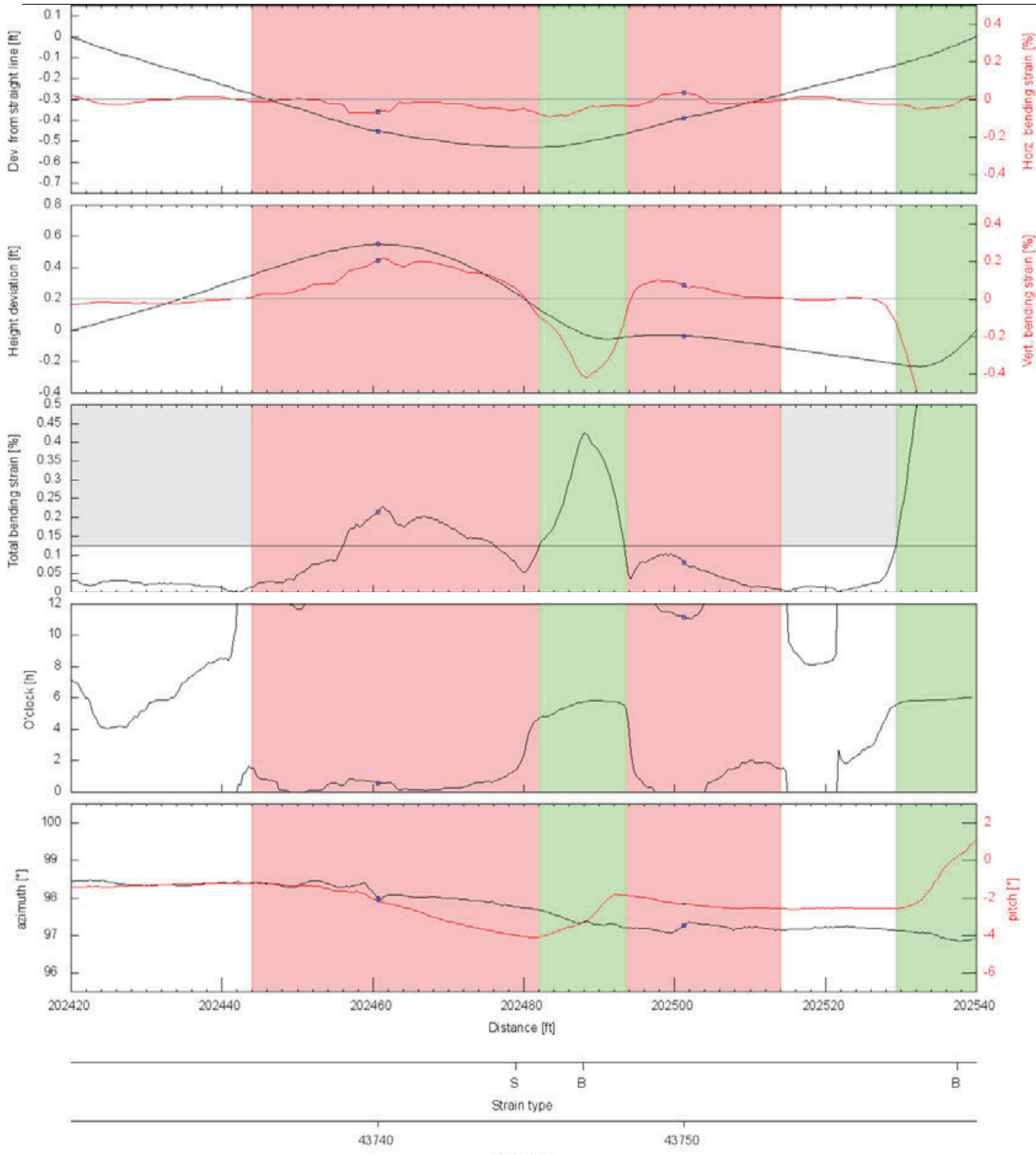
Anomaly No. | Anomaly Type	BSTR #011	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	87
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	512.672
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	522.498
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.05	-0.21	0.22
Comment	bending strain		



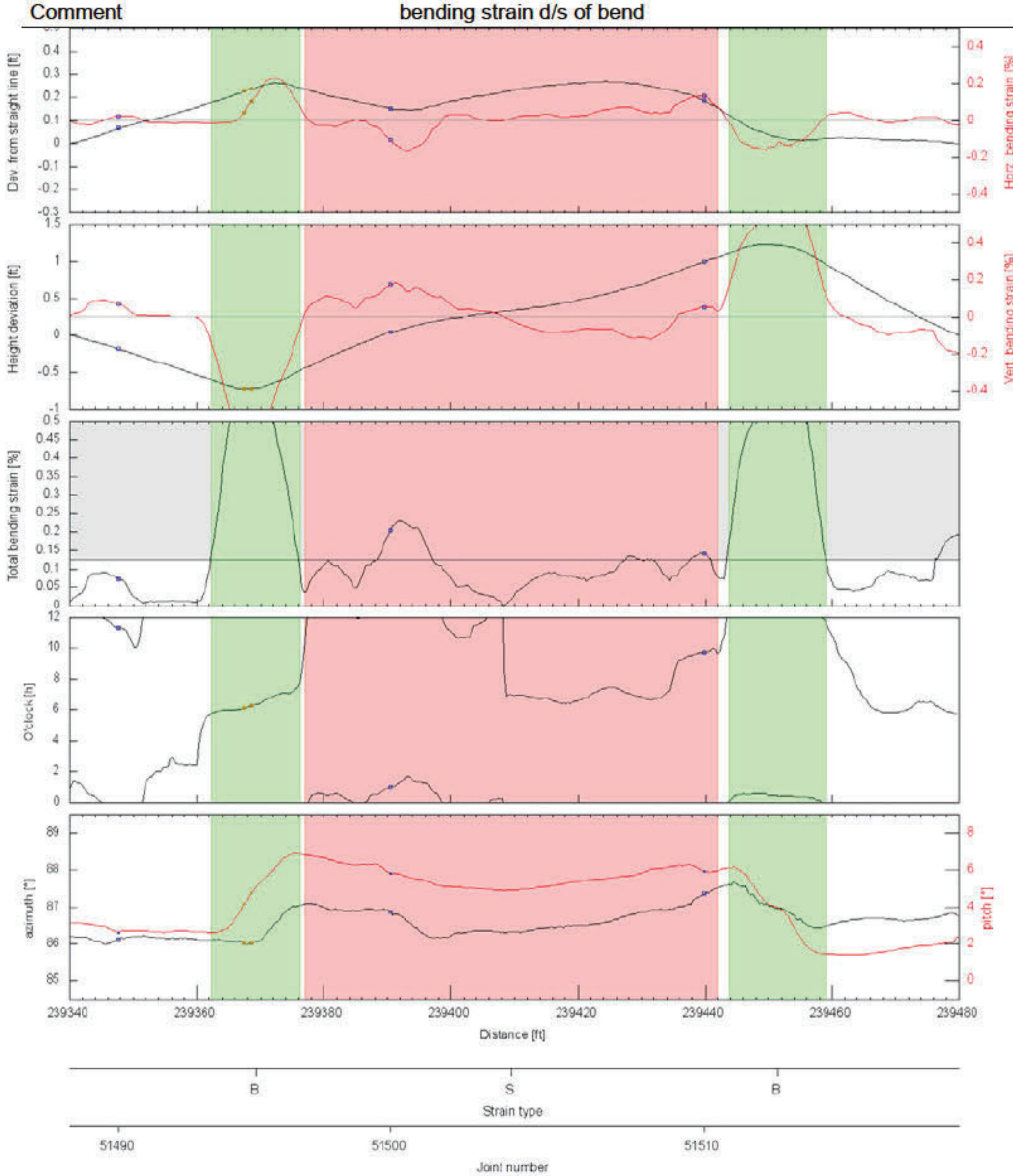
Anomaly No. | Anomaly Type	BSTR #012	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	61
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	506.278
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	499.786
Distance ε_{max} [ft.] | Direction	[redacted]	00:30 h	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.03	0.15	0.16
Comment	bending strain		



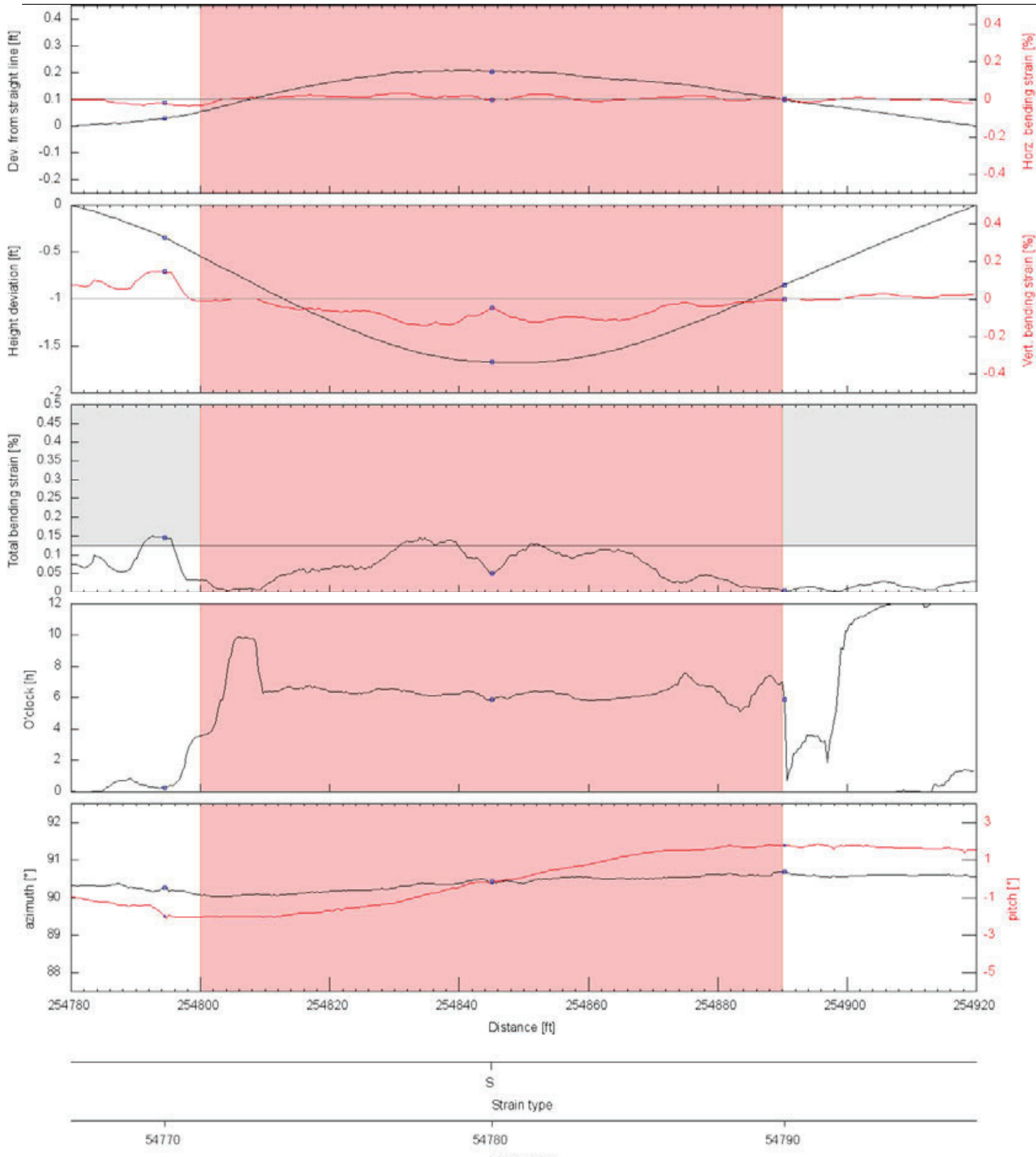
Anomaly No. | Anomaly Type	BSTR #013	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	70
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	483.124
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	480.025
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	-0.01	0.2	0.2
Comment	vertical bending strain, combined with bend		



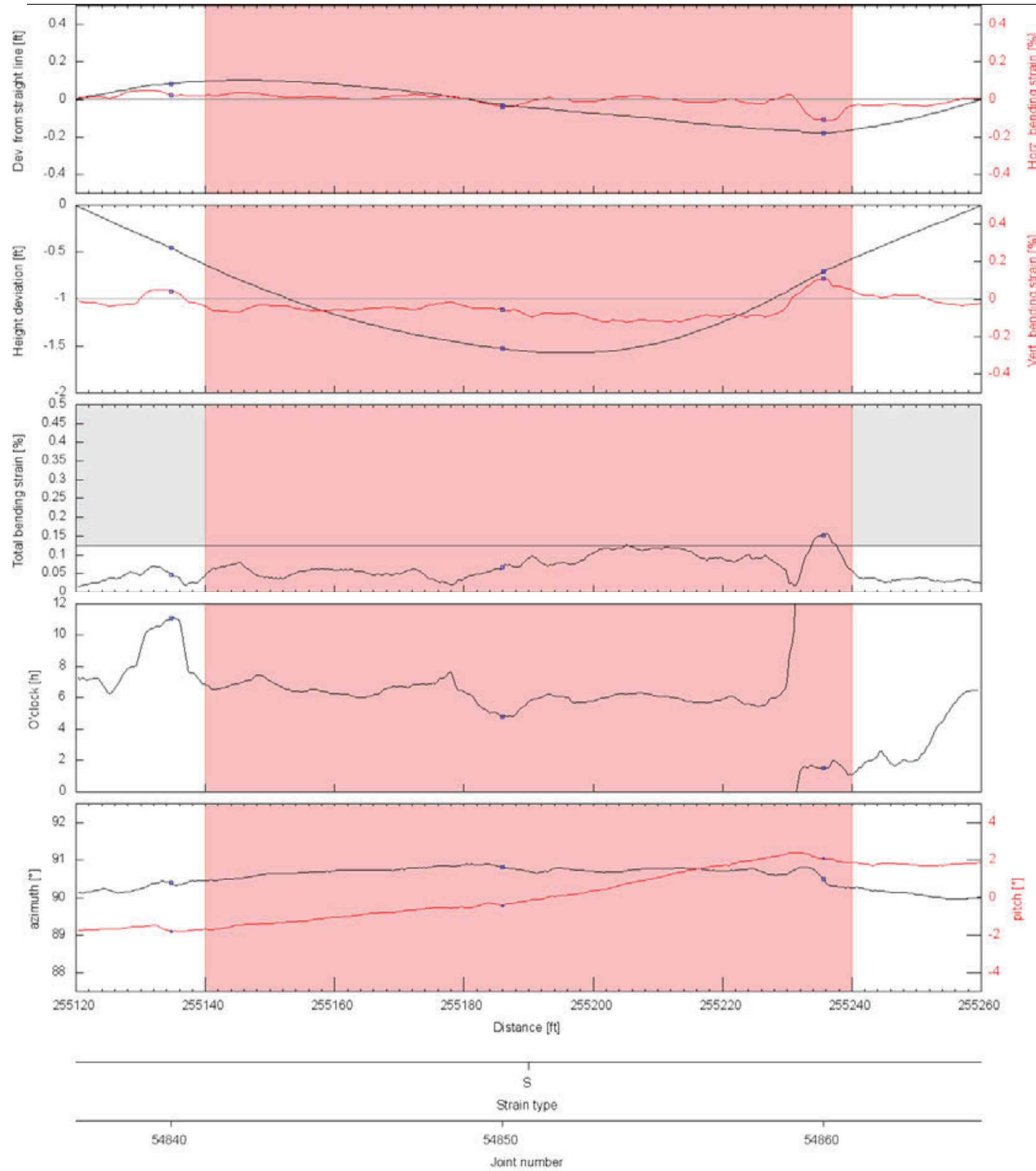
Anomaly No. | Anomaly Type	BSTR #014		bending strain
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	48
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	482.181
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	486.846
Distance ε_{max} [ft.] | Direction	[redacted]		various
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	-0.14	0.16	0.21
Comment	bending strain d/s of bend		



Anomaly No. | Anomaly Type	BSTR #015	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	90
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	444.725
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	444.464
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.02	-0.15	0.15
Comment	bending strain		

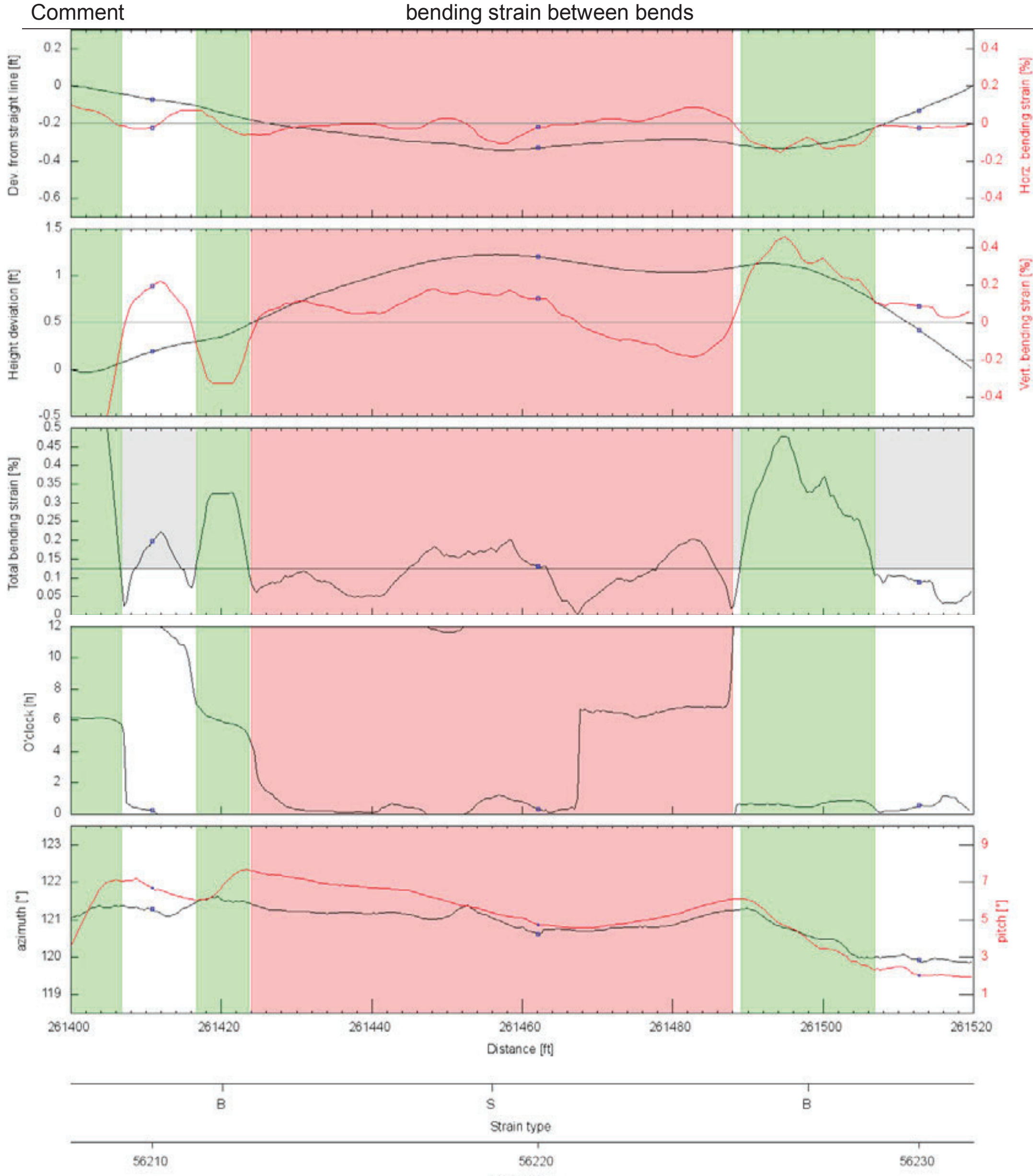


Anomaly No. | Anomaly Type	BSTR #016	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	100
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	444.503
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	444.824
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.02	-0.12	0.13
Comment	vertical bending strain		



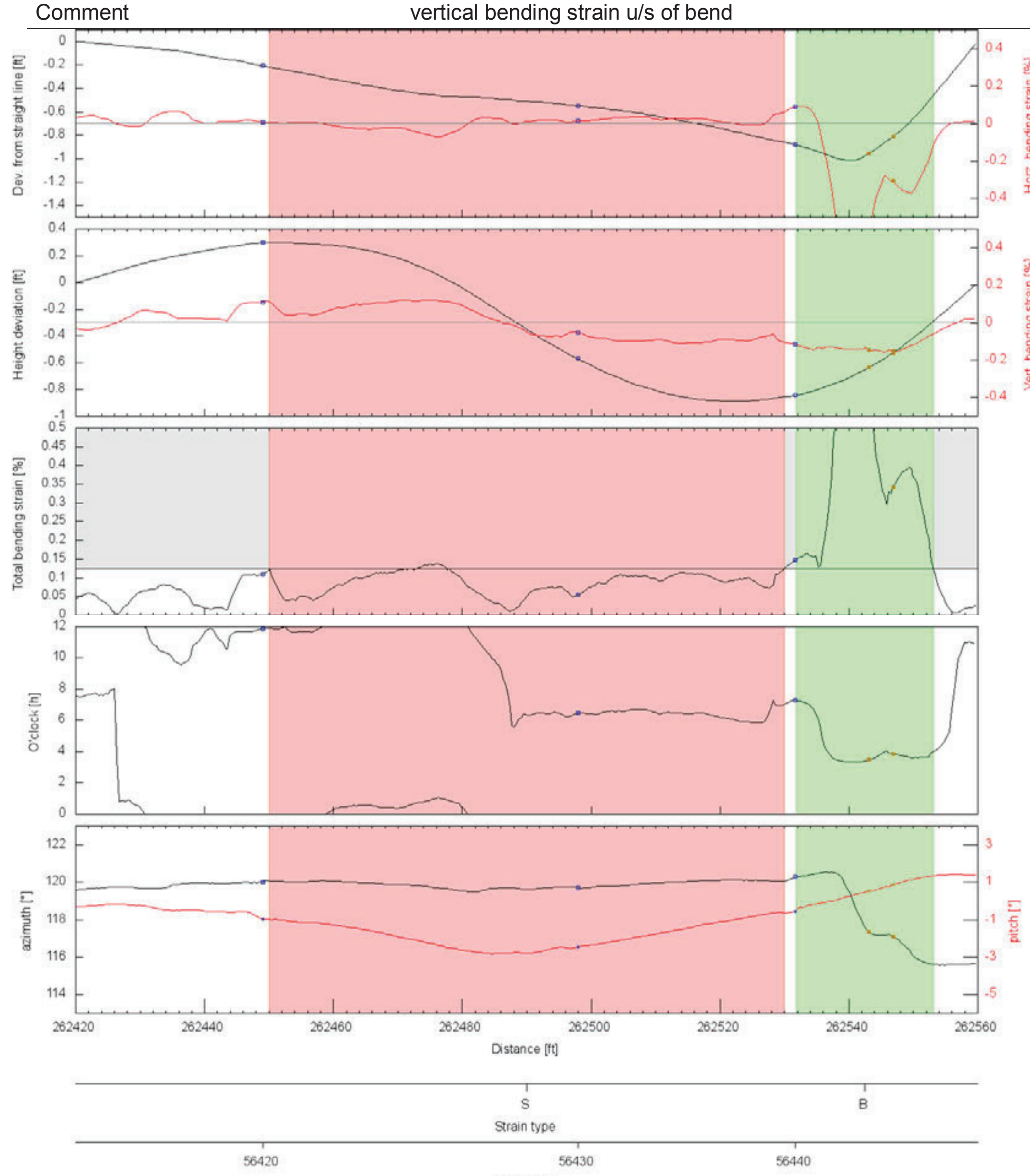
Client: Mara hon Petroleum
ROSEN Project No.: 0-1000-14050
ROSEN Line Name: 22” ROX-PAT
Inspection Type: MFL-C
Date of Inspection: January 5, 2018
Revision No.: 0

Anomaly No. | Anomaly Type	BSTR #017		bending strain
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	64
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	466.157
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	472.718
Distance ε_{max} [ft.] | Direction	[redacted]		various
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	0.09	-0.18	0.2
Comment	bending strain between bends		



Client: Mara hon Petroleum
ROSEN Project No.: 0-1000-14050
ROSEN Line Name: 22” ROX-PAT
Inspection Type: MFL-C
Date of Inspection: January 5, 2018
Revision No.: 0

Anomaly No. | Anomaly Type	BSTR #018	bending strain	
Distance (Start | End | Length) [ft.]	[redacted]	[redacted]	80
Steel Grade | WT_{nom} [in] | V_{avg} [ft/s]	X46	0.312"	5.1
$Coord_{Start}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	482.191
$Coord_{End}$ (Lat [°] | Lon [°]| Height [ft.])	[redacted]	[redacted]	479.646
Distance ε_{max} [ft.] | Direction	[redacted]	various	
Strain Level (ε_{hor} | ε_{vert} | ε_{total}) [%]	-0.07	0.12	0.14
Comment	vertical bending strain u/s of bend		



6 DISCUSSION

The acceptance of bending strain values at each reported location is dependent on numerous factors including the cause, the pipe diameter to wall thickness ratio, and material properties (including pipe grade and material fracture toughness). There is no single bending strain limit that is applicable for each circumstance. Any acceptable value should consider the age of the pipeline, the quality of the welds, the cause of the bending strain, and any interacting anomalies.

When evaluating bending strain, it is necessary to determine the cause of the bending strain and the impacts of any potential future movement. Mitigation may include finite element assessments, in-situ strain monitoring, stress relief, additional IMU runs accompanied by a pipe movement assessment, or pipeline replacement. For each reported location, ROSEN can provide guidance on managing these potential integrity threats through our Integrity Solutions Group. The Integrity Solutions group can evaluate the cause of the bending strain, evaluate the fitness for purpose, and/or make recommendations for future inspections or repair. These assessments will involve the expertise of an engineer familiar with geotechnical considerations.

7 APPENDIX

7.1 Terms and Definitions

The “Terms and Definitions Details for bending strain and pipeline movement analysis” are attached hereafter.

TERMS AND DEFINITONS

XYZ MAPPING

BENDING STRAIN AND PIPELINE MOVEMENT

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TABLE OF CONTENTS

1 DEFINITIONS

Anomaly	An indication, generated by non-destructive examination of an irregularity or deviation from sound weld or base pipe material, which may or may not be an actual flaw
Azimuth	Angle in flat plane related to the north direction, counting clockwise
Buckle	A partial collapse of the pipe due to excessive bending, or compression associated with soil instability, landslides, washouts, frost heaves, earthquakes, etc.
Factory bend	Induced bend during joint manufacturing
Field bend	Induced bend during pipeline construction
Hot bend	Special factory bend
Inspection	Inspection of a pipeline from the interior or exterior of a pipe
Joint	Single section of pipe that is welded to others to make up a pipeline
Left bend	Bend to the left when looking downstream into the pipe
Mapping inspection	An in-line inspection with a tool that uses inertial sensing or other technology to collect data that can be analyzed to produce an elevation and plan view of the pipeline route
Over bend	Vertical bends downwards
Pipeline	A system of pipes and other components used for the transportation of products between plants. A pipeline extends from pig trap, or, if no pig trap is fitted, to the first isolation valve within the plant boundaries or a more inward valve if so nominated.
Pitch	Angle of inclination to a flat surface
Right bend	Bend to the right when looking downstream into the pipe
Sag bend	Vertical bend upwards
Strain	Geometrical measure of deformation representing the relative displacement between particles in a material body, i.e. a measure of how much a given displacement differs locally from a rigid-body displacement
Stress	The average amount of force exerted per unit area. It is the internal resistance a material offers to being deformed and is measured in terms of the applied load.
Tool	Device that is driven through a pipeline for performing various internal activities (depending on the pig type) such as separating fluids, cleaning or inspecting the pipeline
Trajectory	The path a tool follows through space
Wrinkles	Ripples or smooth localized bulges that occur on the inner radius of a pipe when the pipe is constructed with cold bents
XYZ inspectio	Determining 3D geographical pipeline coordinates using an inertial navigation unit
Y p i g	e XYZ ction

2 ABBREVIATIONS

RoGeo	ROSEN Electronic Geometry Tool
RoGeo Xt	ROSEN Extended Geometry Tool

3 APPLIED METHODOLOGY

3.1 Bending strain and curvature

A detailed description for this method will be described below. The equations for calculating bending strain are derived and all definitions concerning this method are described. In addition, the way of detecting bending strain and reporting of suspicious areas are defined.

3.1.1 Bending strain model

A pipeline is a system that might consist of a huge variety of components, such as joints, bends and traps. For bending strain analysis, the pipeline is modeled as straight tube which can be bent under an external force. Factory and field bends are assumed to exist. Bending strain areas are places where bends go over welds. Installation areas are outside the scope of bending strain analysis. The calculated bending strain values are based upon linear elongation of the material.

3.1.2 Bending strain

When a pipeline is bent, the outer side of the pipe will be longer than the central axis of the pipeline and the inner side of the bend will be compressed. There is a relation between the maximum elongation or compression and the amount of bending of a pipe [2]. In figure 3.1 a bent pipeline is shown. The bending part can be estimated by analyzing the curvature of this tube. Assuming the neutral axis is located at the axial centerline of the tube, it has a length of

$$l_o = \theta R$$

Curvature equivalent radius is defined as

$$R[m] = \frac{1}{\kappa} \qquad \textbf{(3.1)}$$

Curvature is defined as

$$\kappa = \sqrt{\kappa_v^2 + \kappa_h^2} \qquad \textbf{(3.2)}$$

The total curvature can be separated in a vertical and a horizontal curvature

$$\kappa_v = -\frac{d\varphi_{pitch}}{ds} \qquad \kappa_h = -\frac{d\varphi_{azimuth}}{ds}\cos(\varphi_{pitch}) \qquad \textbf{(3.3)}$$

Bending strain is defined as

$$\varepsilon_b = \frac{D}{2} k \cdot 100\% \quad \textbf{(3.4)}$$

This results in a vertical and horizontal strain

$\varepsilon_v = \kappa_v \frac{D}{2}$ and $\varepsilon_h = \kappa_h \frac{D}{2}$. **(3.5)**

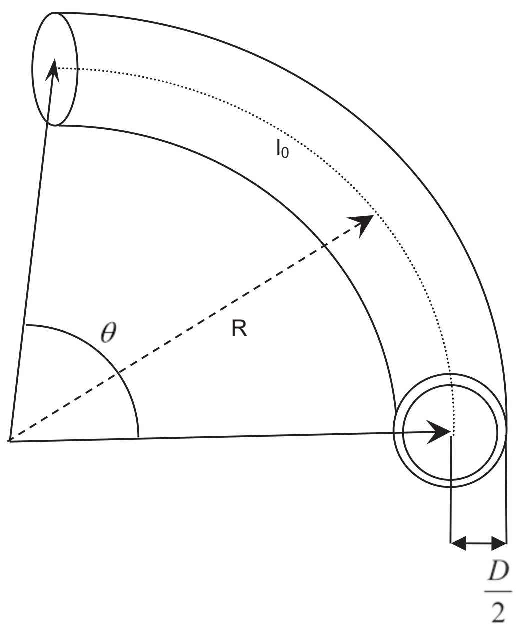

Figure 3.1: A bent tube

Positive vertical and horizontal strain values respectively mean over- and right-bends and negative values sag- and left-bends. When that bending strain area is expressed in total strain and o'clock position, then the time points to the elongated part of the strain which is opposite of the bend direction.

3.1.3 Elongation strain

The result of pipeline movement is a change in trajectory. This results in bending strain areas and into a difference between original and current trajectory length. When the elongation is assumed to be uniformly distributed over the moved section, then the strain can be calculated via:

$$\varepsilon_e = \frac{l_{new} - l_{old}}{l_{old}} \cdot 100\% \quad \textbf{(3.6)}$$

3.1.4 Total strain

Bending and elongation strain are both defined in longitudinal direction. Assuming elastic conditions, these two corresponding values can be combined to yield

$$\varepsilon_t = \varepsilon_b + \varepsilon_e \qquad \textbf{(3.7)}$$

For bending strain analysis only the bending strain are calculated. In a pipeline movement area both bending and elongation strain are calculated.

3.2 Pipeline movement

Pipeline movement assessment is a method to determine the change of trajectory between two mapping inspections. This can be a comparison between the reported as built trajectory and the first XYZ inspection or a comparison of two successive mapping inspections performed with several years between inspections. This comparison shows the changes in direction between the two moments of inspection. Ongoing movement will not be detected.

3.3 Parameters

l_o	Length of the centerline of the affected trajectory
$\theta[rad]$	Angle which is formed by the bent tube
$R[m]$	Radius of the curvature
κ	Curvature
κ_h	Horizontal curvature
κ_v	Vertical curvature
D	Outer diameter of the pipeline
$s[m]$	The tool log distance
$\varphi[rad]$	The tool heading
$\varphi_{azimuth}[rad]$	The tool azimuth heading
$\varphi_{pitch}[rad]$	The tool inclination
ε_b	Bending strain
ε_e	Elongation strain
ε_h	Horizontal bending strain
ε_v	Vertical bending strain
l_{new}	Length of the affected trajectory after pipeline movement
l_{old}	Length of the affected trajectory before pipeline movement
ε_t	Total strain

4 REFERENCES

[1] API RP 1117, Movement of In-Service Pipelines, Third edition, July 2008
[2] Dimitrios K. Karamitris, George D. Bouckovalas, Stress analysis of buried steel pipelines at strike-slip fault crossings, August 2006

7.2 Performance Specifications

The “Performance Specifications for bending strain and pipeline movement analysis” are attached hereafter.

ROGEO XYZ

IN-LINE PRECISION PIPELINE ROUTE MAPPING AND STRAIN ANALYSIS

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TABLE OF CONTENTS

1 INTRODUCTION

This document defines the ROSEN accuracy specifications for the in-line inspection (ILI) with the ROSEN XYZ Mapping Tool. It follows well established definitions applicable specifically to pipeline inspection, mainly found in "Specifications and Requirements for Intelligent Pig Inspection of Pipelines" formulated by the Pipeline Operators Forum (POF), version 2.1 (November 1998), version 3.2 (January 2005) and version 2009 (January 2009).

Further information about a particular in-line inspection tool can be provided as part of a particular inspection project. This information will be compliant with POF 2009 and will be derived from the specific pull-test certificate and the individual tool data sheet.

2 XYZ MAPPING

2.1 Accuracies

Accuracies for Differing Tie-Point Distances and Velocities

Values are given for a certainty level of 80%		**Tie-Point-Distance**					
		1000 m (3300 ft.)	**2000 m (6500 ft.)**	**4000 m (13 000 ft.)**	**10 000 m (33 000 ft.)**	**25 000 m (82 000 ft.)**	**50 000 m (164 000 ft.)**
Velocity	0.5 m/s (1.6 ft./s)	0.7 m (2.3 ft.)	1.0 m (3.3 ft.)	2.0 m (6.6 ft.)	5.0 m (16.0 ft.)	15 m (49.0 ft.)	30 m (98.0 ft.)
	1.0 m/s (3.2 ft./s)	0.5 m (1.6 ft.)	0.7 m (2.3 ft.)	1.0 m (3.3 ft.)	5.0 m (16.0 ft.)	15 m (49.0 ft.)	30 m (98.0 ft.)
	3.0 m/s (9.8 ft./s)	0.5 m (1.6 ft.)	0.7 m (2.3 ft.)	1.0 m (3.3 ft.)	5.0 m (16.0 ft.)	15 m (49.0 ft.)	30 m (98.0 ft.)

3 BENDING STRAIN / CURVATURE DETERMINATION

3.1 Accuracy

Bending strain accuracy (for strain values < 2%) 0.02%

3.2 System Sensitivity

Strain	Strain equivalent radius	Curvature	Curvature equivalent radius
0.02%	2500 D	0.0007 rad/m (0.023 rad/ft.)	1400 m (4593 ft.)

4 PIPELINE MOVEMENT

External influences, for example landslides or earthquakes, can cause the pipeline to move from its original position. This change in position can be detected by comparing the pipeline trajectory from previously acquired inspections and the current XYZ in-line inspections. In these areas bending strain will appear. The bending strain indication is an important contribution to the pipeline movement detection and sizing.

4.1 Accuracy

Minimum pipeline movement detection threshold: 0.2 m (0.66 ft.)

Tie-in point distance	Accuracy
1000 m (3281 ft.)	0.40 m (1.31 ft.)
500 m (1640 ft.)	0.30 m (0.98 ft.)
250 m (820 ft.)	0.20 m (0.66 ft.)
100 m (328 ft.)	0.15 m (0.49 ft.)

Minimum Tie-in point distance for pipeline movement detection is 50 m (164 ft.)

5 LOCATION AND ORIENTATION CAPABILITIES

Log distances are determined based on direct measurements by an odometer system on the tool. Further corrections e.g. using marker locations may apply.

Axial position accuracy from reference marker	1:1000
Axial position from closest weld	±0.1 m (±4")
Circumferential position accuracy	±5°

The axial positioning accuracy is based on following conditions:
- Distance between u/s and d/s marker/reference point < 2000 m (6560 ft.)
- Actual above ground distance to both u/s and d/s marker/reference points to be measured and correlated
- Negligible difference between pipeline and soil contour

6 SYSTEM CAPABILITIES

6.1 IMU Specifications

	Gyro	Accelerometer
Bias	1°/h	300 µg
Random walk	0.3°/sqrt (h)	40 µg (0.5 sec)
Scale factor error	300 ppm	500 ppm
Misalignment	0.25 mrad	0.25 mrad
Resolution	0.005°/s	100 µg

7 IDENTIFICATION OF FEATURES

Probability of Identification (POI) in accordance with XYZ Mapping unit.

Feature		Yes POI > 90%	No POI < 50%	May be 50% ≤ POI ≤ 90%
Out of straightness / bending strain		X		
Pipeline movement		X		
Bends		X		
Weld	bend start and -end	X		
	girth welds	X		

8 NOTES CONCERNING PERFORMANCE SPECIFICATIONS

8.1 Notes

The specifications provided for the ROSEN XYZ Mapping Tool are applicable where run conditions, tool velocity, pipe grade, pipe cleanliness, sensor operation, and data recorded are within the established parameters for the specific XYZ Mapping Tool used in each inspection survey. These parameters are provided in the Tool Data Sheet included in each Final Report. Variations from the established parameters may result in reduced data quality or modification of the performance specifications. Also the tie-in point DGPS coordinate accuracy as well as coordinate transformations (to special coordinate systems) may affect the XYZ data accuracy due to error propagation. A minimum of two tie-in points between launcher and receiver site are required. Additionally, launcher and receiver themselves must be used as tie-in points.

8.2 Comparison with other ILI results

Based on the location, identification and sizing performances specified for each system, inspection results can be compared to repeat runs with the same tools or other supplier's tools as outlined in the American Petroleum Institute, Pipeline Segment, Standard 1163, In-line Inspection Systems Qualification Standard, Appendix E, First Edition, August 2005.

9 ABBREVIATIONS

d/s	Downstream
ILI	In-Line Inspection
IMU	Inertial Measuring Unit
POI	Probability of Identification
SI	International System of Units
Tie-Point	Used reference/marker point with XYZ co-ordinates
u/s	Upstream
XYZ	Easting, northing, height; latitude, longitude, height co-ordinates