GEOPIG GEOMETRY SURVEY

of

NPS 20 Line 5 Straits of Mackinac (West)

MP 1475.64 to MP 1479.55

Inspection Date: April 12, 2005

FINAL REPORT

prepared for

Enbridge Pipelines Inc.

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1 EXECUTIVE SUMMARY

BJ Pipeline Inspection Services performed an Inertial Geometry Survey of Enbridge Pipelines' 3.9 mile NPS 20 light crude pipeline (Straits of Mackinac – West), running from MP 1475.64 to MP 1479.55 in Michigan. The successful run was performed on April 12. The purpose of the inspection was to determine pipeline geometry, which includes plan, profile, curvature, weld tally, pipe wall shape and deformations, as well as to identify and measure strain difference and pipe movement with respect to the 2003 Geopig survey.

The strain analysis identified 11 areas of pipeline movement. They are listed in Appendix 4 and illustrated on the plots included in Appendix 7. They are also described in detail in Section 2.5. The largest movement since the 2003 survey was 0.76ft in the vertical plane at chainage 8,043ft over a span of 691ft. The maximum strain difference was 0.02% in the vertical plane at chainage 9,244.8ft. Horizontal displacement was identified at only one location, at chainage 15,480.7ft where the pipeline moved 0.05ft in the horizontal plane and 0.14ft in the vertical.

The inertial data was used for reporting all bends with an angle exceeding 1.5° and a radius of curvature less than 100D. 23 such bends have been detected in this line and they are listed in Appendix 3. The tightest bend was found to have a radius of curvature of 21D.

The analysis of the caliper data has identified 1 pipeline anomaly greater than 2% O.D. It is a 0.6" (3.0 % OD) ovality at BJ chainage 15,479 ft. The size of this feature has not increased since the 2003 survey.

The pipe tally including girth welds and pipe fittings can be displayed in BJ's software together with the caliper and inertial survey data. The complete pipeline listing is also included in the Microsoft Excel spreadsheet "Enbridge_NPS20_MackinacWest_BJ_Survey_2005.XLS" on the CD-ROM submitted with this report. The CD also contains the survey data (from both 2003 and 2005) and the BJ software for viewing it.

2 SURVEY RESULTS

The Geopig inertial survey provides pipeline plan, profile and bending strain, allowing one to locate the pipeline in the UTM mapping projection, and to detect pipeline movement between runs. The positional information is derived from the onboard strapdown inertial unit, the odometer readings and the UTM coordinates of selected tie points obtained from a GPS survey.

The caliper survey provides the information on the internal diameter and shape of the pipe, allowing for detection and measurement of pipe wall anomalies (dents, ovalities and wrinkles), wall thickness changes, valves, tees and girth welds.

2.1 Chainage

The BJ chainage is the distance measured by the Geopig's odometers along the pipeline and is denoted as S Chain (Slack Chainage) on the plots. It starts from 0 ft at the pig launcher and ends at 21,898ft in the receive trap. This chainage has been matched to the chainage from the 2003 Geopig inspection. A separate client chainage that correlates the Geopig slack chainage to Enbridge's asbuilt chainage has been created and is denoted as "Enbridge chainage" on the plots. The correlation is based on the valve chainages provided by Enbridge. The horizontal chainage is also available, and it represents the true horizontal distance of the surveyed pipeline.

2.2 GPS Tie Points

The final pipeline position in the UTM mapping projection was obtained by translating, rotating and scaling the inertial survey data to the 2003 data. The tie-points were obtained every hundred meters (except for pipeline movement areas) from 2003 Geopig data, which was tied to the launch and receive coordinates provided by Axiom Pipeline Solutions Inc. The list of the GPS tie points is included in Appendix 1.

2.3 Pipe Anomalies

The caliper data was used for detecting and sizing diameter restrictions and pipe wall anomalies, such as ovalities, dents and wrinkles. The anomaly size definition is provided in Section 4.4.

The analysis of the caliper data has identified 1 pipeline anomaly greater than 2% O.D., which is listed in appendix 2. It is a 0.59" (3.0 % OD) ovality at BJ chainage 15,479 ft.

Appendix 6 contains inspection sheets for the one ovality greater than 2% O.D. There are three inspection sheets per anomaly: a dig sheet showing the position of the feature in a pipe joint together with the adjacent joints, a plot of pipeline plan and profile between the nearest u/s and d/s reference points, and a plot showing 3 views of the anomaly: 3-D view, pipe cross-section and diameter profile. The 3-D view scale is exaggerated 3 times. The pipe diameter profile consists of 16 lines showing the pipe internal diameter at different clock positions measured by the 16 pairs of opposite caliper arms. The clock positions of these caliper arms are colour-coded according to the spectrum displayed on the left side of the plot.

2.4 Bends

The inertial data was used for reporting all bends with an angle exceeding 1.5° and a radius of curvature less than 100D. 23 such bends have been detected in this line and they are listed in Appendix 3. The complete list is also available in the worksheet "Bends" in the MS Excel spreadsheet "Enbridge_NPS20_MackinacWest_BJ_Survey_2005.XLS". Each bend is described in terms of BJ chainage at its center, bend radius and angle, as well as change of direction in horizontal and vertical plane. The tightest bend was found to have a radius of curvature of 21D.

2.5 Pipeline Movement

The strain analysis identified 11 areas of pipeline movement, which are listed in Appendix 4. The pipeline profile and displacement between two inspections in horizontal and vertical plane are shown on the plots included in Appendix 7. The largest movement since the 2003 survey was 0.76 ft in the vertical plane at chainage 8,043ft over a span of 691ft. The maximum strain difference was 0.020% in the vertical plane at chainage 9,244.8ft. All areas of pipeline movement were found to be in the vertical plane with the exception of one location that had 0.05ft horizontal displacement associated with a 0.14ft vertical displacement at chainage 15,480.7ft.

2.6 Pipe Tally

The list of pipeline features, such as valves and tees are included in the worksheet "Valves and Fittings" and Appendix 5.

The Geopig has also detected all the girth welds in the pipeline. They are listed in the worksheet "Weld Log", which contains the information on the length and start chainage of each pipe joint. The weld log combined with all the other features in the pipeline (valves, tees, strains and bends) are listed in the worksheet "Pipe Tally" and in Appendix 8.

All the features included in the pipe tally can be displayed as "Client Inventory" in the GeminiView and GeoDisplay programs, as shown on the sample plot in Appendix 8.

All the listings included in the appendices were generated using the Access database "Enbridge_NPS20_MackinacWest_2005.mdb" and they are also available in the MS Excel spreadsheet "Enbridge_NPS20_MackinacWest_BJ_Survey_2005.XLS" provided on the enclosed CD.

2.7 Plan and Profile

The first plot in Appendix 9 shows the plan, profile, internal diameter, pig velocity and location of valves and AGMs for this section. The remaining 4 plots show the pipeline plan, profile, internal diameter, and location of selected features, such as valves, AGMs, tees, and anomalies at 5,000 ft per page.

3 GEOPIG DESCRIPTION

3.1 System Description

The Geopig is designed to meet a large variety of user requirements using a modular system that integrates a variable number of different sensors. The design of NPS 20 Geopig consists of two pig carriers, as illustrated below.



20" Mechanical Caliper Geopig

A Strapdown Inertial Navigation System is the heart of the Geopig and delivers position and attitude of the pig along its trajectory within the pipe. Due to the nature of inertial measurements regular "updates" of attitude, position, and velocity are required. External position and attitude are taken from GPS results or alignment sheets.

The Geopig is suspended in the pipeline by urethane disks at front and rear of the carrier. This restricts the Geopig to move close and parallel to the pipe centre line. Mechanical callipers are mounted in the middle of the carrier, and they scan the wall of the pipeline and generate a full picture of the shape of the pipeline. Here the information on dents. ovalities, wrinkles and other features is extracted.

The Geopig is completed by some other sensors and devices: odometers, which measure he the distance travelled, tracking transmitter for location of the Geopig, and finally, storage device and power supply which allow independent operation for long measurement periods.

3.2 Strapdown Inertial Navigation System

The strapdown INS ultimately produces 3-dimensional measurement of inertial acceleration and angular rate directly from orthogonal triads of accelerometers, and single degree of freedom gyros. In the case of a pair of two degree of freedom gyros, a redundant or combined axis measurement is available, and is dealt with appropriately to produce 3 axis orthogonal angular rates. The strapdown accelerometers and gyros are complementary sensors which when coupled deliver the measurements for computing pipeline curvature, orientation of the curvature, and the positioning capability for location of the curvature or other detected features.

3.3 Caliper

One ring of mechanical calipers scans the wall of the pipe. The caliper arms are spaced at precisely machined constant angles around the ring on the pig. An accurate offset was added to these ranges to give the actual distance from the centre of the carrier to the pipe wall. There are 32 mechanical caliper arms mounted in the middle of the carrier.

3.4 Other Sensors and Components

Other sensors and components integrated in the Geopig are:

- Odometer wheels providing direct measurements of distance traveled (chainage). Velocity is derived from these time tagged distances.
- Temperature and pressure sensors
- A flash memory system, 640 Megabyte capacity
- Interface electronics
- Batteries
- Micro-processor controllers
- Power management module
- Pig Tracking Module (Electromagnetic)

3.5 Survey Accuracy Specifications

The accuracy of the Geopig measurements is as follows:

- Pipeline position 1:2,000
- Bending strain +/- 0.02%
- Bend angle +/- 0.1 °
- Anomaly size +/- 0.1”
- Temperature +/- 0.1 Deg C
- Pressure 0.1% or +/- 3 PSI (0.2 BARSG)

4 DATA ANALYSIS PROCEDURES

The primary function of the Geopig inertial survey is to determine the pipeline plan, profile and bending strain. This is achieved by computing the Geopig's trajectory during the run using the data collected by the onboard strapdown inertial unit and the odometers. Due to a tight fit of the Geopig cups into the pipe the tool rides practically along the pipe centerline. The only exception from this is the deviation of the tool trajectory from the pipe centerline due to serious pipe wall deformations, as well as "smoothing out the corners" over the transition length (equal to the distance between the cups) at the bend boundaries and at the girth welds exhibiting noticeable out-of-straightness, i.e. sudden change of direction due to the weld misalignment. That data it is then rotated into the GPS co-ordinates of the selected tie-points along the line (usually a few km apart) to obtain the desired location accuracy in a given UTM mapping projection.

The following paragraphs outline the methods used for processing the odometer and inertial data in order to obtain the pipeline slack and horizontal chainage, client chainage, pipeline position and bending strain.

4.1 Chainage

The following types of chainages are used for referencing the Geopig data:

- slack chainage - the distance measured by the Geopig's odometers along the pipeline.
- horizontal chainage - the true distance along the pipeline projection on the horizontal plane. Not required by the client in this survey.
- client chainage - the reference system used by the pipeline operator (e.g. station number used on the as-built drawings, or KP location from the ROV survey).

4.1.1 Slack Chainage

The Geopig slack chainage is the distance measured by the Geopig's odometers along the pipeline. It starts from zero at the reducer on the pig launcher and ends at the receive trap. The odometer accuracy is 0.1 %.

The chainage from the first run is used as the baseline for all the subsequent runs. The preliminary chainage from the subsequent runs derived from the odometer data is scaled to match the distance between the girth welds from the baseline survey. Therefore any change of pipeline length between runs, e.g. elongation due to temperature differential, is disregarded.

4.1.2 Horizontal Chainage

The Geopig horizontal chainage represents the true horizontal distance of the surveyed pipeline. It is computed from the slack chainage by projecting it on the horizontal plane first, and then scaling it to match the horizontal distance based on the GPS co-ordinates (Northing and Easting). The scaling is performed between the same tie-points that are used for rotating the inertial survey data into its final position.

4.1.3 Client Chainage

The purpose of a client chainage is to represent any one-dimensional information used by client that could be correlated to the slack chainage. Usually the client chainage corresponds to the chainage shown on the as-builts, or to the chainage recorded during another in-line inspection. It can be incorporated into the data at any time after the CD is issued to the client.

4.2 Pipeline Position

The pipeline position is provided in terms of Northing, Easting and Height as a function of the chainage, in a selected mapping projection (usually UTM) and a specified datum.

4.2.1 Tie Points

Inertial data is translated, rotated and scaled to the "tie points" with known co-ordinates. Those points are typically selected at traps, valves, welds, bends, wall thickness transitions, or any other pipeline features that can be detected directly or indirectly by the Geopig sensors. The co-ordinates of those points are usually obtained from GPS survey.

This procedure provides correction for long term drifts that can introduce an absolute position error in the inertial survey over time. By transforming the Geopig trajectory into the tie points, the Northing, Easting, and Height are obtained for any point along the pipe.

The specified accuracy of the inertial survey is 1:2,000 of the distance from the tie points, therefore for the following sample distances between the tie points the following absolute accuracy is obtained:

Distance Between Tie Points [m]	Absolute Accuracy [m]
20,000	5.0
10,000	2.5
5,000	1.25
3,000	0.75

For example, if the data from two Geopig run have been tied to the points that are 3 km apart, then the allowable error in-between the ties points can reach 0.75 m, which corresponds to up to 1.5 m difference between two runs. To reduce the relative difference between two runs, a procedure described in the next section is applied, which ensures that the actual pipeline movement is measured with centimeter accuracy. There is practically no difference in the pipeline position between the runs in the areas where the pipeline did not move.

4.2.2 Pipeline Movement

Once preliminary processing has been completed, the data from the current and the previous Geopig surveys are compared in order to identify the areas of strain differences associated with the pipeline movement. Then the current data is reprocessed using the coordinates of the tie points extracted from the baseline Geopig survey at 100 m intervals, except for the previously determined pipeline movement areas. This procedure improves the accuracy of the local pipeline movement measurement by reducing the relative error

between two runs. A noticeable error would result from the absolute position accumulation error when only the original tie points (from the GPS survey, at about 1 km spacing) were used for scaling and rotating the inertial survey data.

4.3 Bending Strain

The bending strain is computed directly from the curvature of the Geopig trajectory, typically averaged over the distance of three pipe diameters. The specification for the bending strain measurements from the Geopig survey is +/- 0.02% strain. When the strain difference between two runs is compared that specification is usually exceeded in the originally straight sections of the line, and the accuracy of +/- 0.005% strain is achieved. The following subsections contain the description of the bending strain measurement and general remarks on interpretation of strain data.

4.3.1 Computation Method

There are two main components of the strain tensor in a pipe wall: the longitudinal strain (in the direction of the pipe axis) and the hoop strain (in the circumferential direction). The longitudinal strain is further separated into the axial component and the bending component that changes linearly along the pipe cross-section (see Figure 4.1).

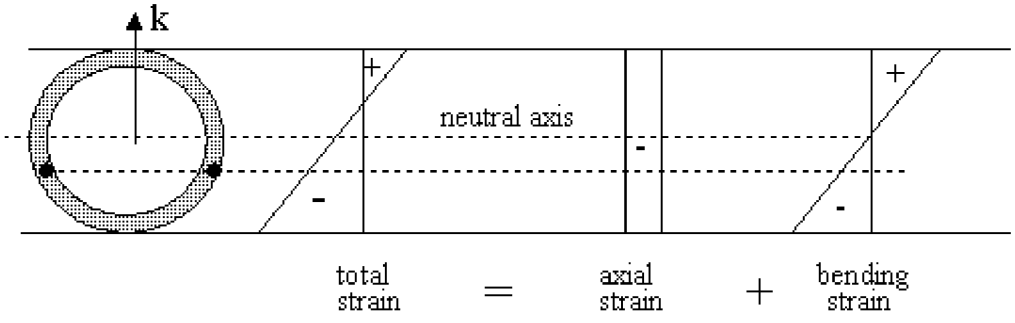


Figure 4.1 Distribution of Axial and Bending Components of Longitudinal Strain in Pipe Cross-section

The bending component of the longitudinal strain at any location in the pipe cross-section can be computed based on the bending strain at two points, e.g. at the top of the pipe (0 o'clock position) and on a right side (3 o'clock position). The bending strain at the bottom of the pipe is called the vertical strain ε_v, because it is induced by bending in the vertical plane (the bending strain at the top of the pipe has the same absolute value, but the opposite sign, i.e. $-\varepsilon_v$). For a similar reason the bending strain on the right side of the pipe is called the horizontal bending strain ε_H (the bending strain on the left side is equal to $-\varepsilon_H$). The maximum bending strain ε in the entire pipe-cross-section is equal to:

$$\varepsilon = \sqrt{\varepsilon_v^2 + \varepsilon_h^2} \,. \qquad (4.1)$$

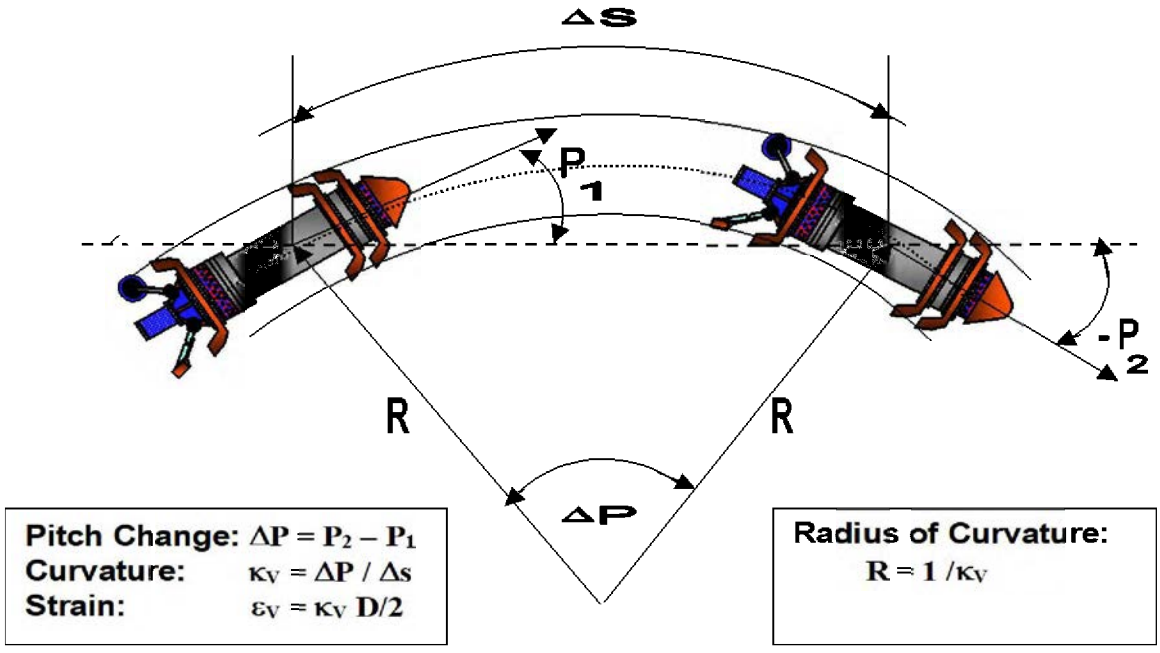


Figure 4.2 Computation of Pipeline Vertical Curvature and Strain from Geopig Pitch

Both the vertical and horizontal bending strains are computed from the Geopig survey using the measurements of the pipe centerline curvature. The curvature of a line in a 3-D space is defined as the change of direction (in radians) over the distance. The distance is measured by the odometers, and the direction of the pipe centerline is computed from the inertial system in terms of azimuth and pitch. The pitch P(s) describes the pipeline tilt with respect to the horizontal plane at chainage s, while the azimuth A(s) specifies the angle between the pipe direction and the north. The horizontal component of the curvature is proportional to the change of the azimuth, and the vertical component is proportional to the change of pitch. The following formulas are used for computation of the pipeline total curvature κ and its vertical κ_V and horizontal κ_h components based on the changes ΔP and ΔA of pitch and azimuth over a distance Δs along the pipe centerline:

$$\kappa = \sqrt{\kappa_v^2 + \kappa_h^2}\,, \qquad \kappa_v = \frac{\Delta P}{\Delta s}\,, \qquad \kappa_h = -\frac{\Delta A}{\Delta s}\cos(P) \qquad (4.2)$$

The relationship between curvature and bending strain is as follows:

$$\varepsilon = \frac{D}{2}\kappa \qquad \varepsilon_v = \frac{D}{2}\kappa_v \qquad \varepsilon_h = \frac{D}{2}\kappa_h \qquad (4.3)$$

where D is the pipe outside diameter.

The curvature radius is the inverse of the curvature. The BJ software reports strain in percents and the radius of curvature in pipe diameters. Strain is a unitless value that can be expressed in percents by multiplying it by 100%; e.g. 0.45% corresponds to 0.0045 strain.

4.3.2 Smoothing Curvature Data

The curvature can be computed according to formula (4.2) using the change of azimuth or pitch over the chainage increment as small as the distance between two inertial samples. The inertial data is collected at the rate of 100 samples per second. If the tool travels at the speed of 2 m/s then the distance between two samples is only 2 cm. The raw curvature computed this way would exhibit a significant level of noise, e.g. due to tool vibrations. In order to reduce that noise the curvature is typically averaged over a distance of 3 – 5 pipe diameters, i.e. 3 m for 30" diameter pipe. For computational efficiency, instead of calculating the actual average, the curvature is computed using formula (4.2), where the increments ΔP and ΔA of pitch and azimuth are taken over a distance of 3 m. This is practically equivalent to averaging curvature over the same distance - if the data are equally spaced, i.e. when the tool velocity is stable. The longer is the averaging length the smoother are the results.

Another smoothing technique is a regression line fit to the pitch or azimuth considered as functions of chainage. That method fits a line to all of the pitch values (or azimuth) over a specified length. This is practically equivalent to fitting a circle to all of the points along the Geopig trajectory over the specified length, but again much more computationally efficient than actually doing it. The radius of that circle is equal to the radius of curvature of the pipeline. The regression line fit produces smoother results than a regular moving average applied over the same length.

When estimating the bending strain induced by pipe-soil interaction the curvature can be smoothed out over a length longer than 5 pipe diameters, usually over 5 - 10 m. This approach significantly reduces the effect of weld misalignment, pipe wall imperfections and tool dynamics on the computed curvature, and at the same time it doesn't underestimate the bending strain induced by pipeline movement. This approach is particularly suited for calculation of strain difference between two runs. However, averaging over too long distance is not proper for computation of curvature of short features, such as bends or buckles. The bending strain of a feature would be underestimated if the feature was shorter than the effective averaging distance, which includes both the length used in curvature computation and the tool length, i.e. the distance between the cups supporting the pig body (i.e. the inertial canister in case of multi-body tools).

4.3.3 Interpretation of Bending Strain Data

The Geopig measures the total pipeline bending strain at the time of inspection, which includes strain induced during manufacturing, construction and operation. While pipeline is in operation the strain may be caused by the operating conditions (temperature and pressure differential) or by the external forces affecting the pipeline as the results of sea-bottom scouring, sub-sea currents, slope instability, soil settlement and erosion, etc. As the Geopig measures the total bending strain, including the plastic component induced during the whole history of loading, the current shape of the pipe and its bending strain can not be fully explained by taking into consideration only the forces acting on the pipe during the inspection, e.g. the gravity, buoyancy and support reaction.

The Geopig measures the curvature of the pipe centerline with all its imperfections, including the out-of-straightness at welds that is theoretically described by infinite curvature, although it does not correspond to any bending strain in the pipe wall. When such curvature is measured by the Geopig is obviously not infinite due to the finite length of

the tool and some additional smoothing applied during data processing, but it may still show up as spikes of significant amplitude in the curvature data.

When analyzing the bending strain induced during operation the high residual plastic strain present in the field bends should be disregarded. The main features distinguishing the bending strain induced during operation from the field bends are briefly discussed below. The bending strain in the field bends is usually in the range from 1 to 2 % strain, is confined to one pipe joint and is characterized by an abrupt change of strain at the beginning and the end of a bend. The bending strain induced during operation is usually of smaller amplitude, spans more than one pipe joint and undergoes gradual change over longer transition sections.

4.4 Pipewall Anomaly Calculation

The caliper information is processed to provide the internal shape and diameter of the pipeline.

The anomaly size D (depth) is calculated as follows:

$$D = D_{Rstr} - O_V$$

$$D_{Rstr} = D_{Nom} - D_{Min}$$

$$O_V = (D_{Max} - D_{Nom})/2$$

where:

D_{Rstr} - total diameter restriction
O_V - pipe ovality
D_{Nom} - inner nominal pipe diameter
D_{Min} - inner pipe diameter at the feature
D_{Max} - inner pipe diameter 90° from the feature

The anomaly length is calculated as the axial distance over which the feature depth exceeds 50% of its peak value.

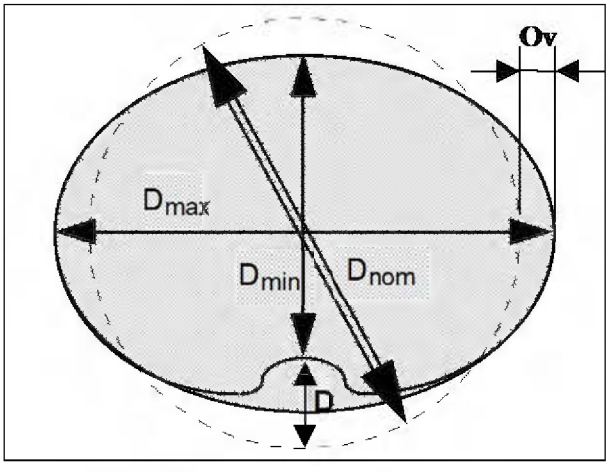


Figure 4.3 Anomaly Sizing

5 BJ Software Installation

The report is accompanied by a CD-ROM containing the BJ display software and the data from the present survey. The data can be viewed using the GeoDisplay and GeminiView programs running in Microsoft Windows operating system. GeoDisplay is used for displaying the inertial, odometer, weld, caliper, and other data bases (if available). GeminiView is used to display the inner pipe wall shape measured by the calipers and 3-D view of the pipe.

The directory structure on the CD is as follows:

\BJ\NPS20_Mackinac_Straits_West\2005_GEOPIG, which contains:

- several subdirectories with the Geopig data from the run
- environment file J918West.env with the information on the location of the data files for each section. (%RootDir% specifies the path, and %BaseName% - the name)
- configuration file GD.cfg for Geodisplay

\BJ\BJ_Software with the software stored on two subdirectories:

- \GD with the GeoDisplay program (GDWIN.EXE)
- \GeminiView with the GeminiView program (GEMINIVIEW.EXE)

The simplest way to launch GeoDisplay from the CD is to double click on the application program (GDWIN.EXE) using Windows Explorer.

The entire content of the CD can be copied to a network drive, or a local hard drive for faster access of the data and the ability to save configurations files with customized displays. The programs can be also stored on the local hard drive while the data is accessed from the CD or a network drive. In this case only the \BJ directory needs to be copied on the local hard drive.

The recommended way to launch Geodisplay is to copy the "Geodisplay NPS20 Mackinac West" icon onto the computer desktop using the procedure outlined below. It is assumed that the directory \BJ_Software is stored on the **C:** drive, and the data directory \BJ\NPS20_Mackinac_Straits_West\2004_GEOPIG is on the **D:** drive. However, the proper drive letters for the CD, network or hard drive corresponding to the actual location of those directories have to be used.

1) Go to directory C:\BJ\BJ_Software\GD using the Windows Explorer and drag the shortcut icon "GeoDisplay NPS20 Mackinac West" (with the blue and white BJ logo) to the desktop.
2) Right click on this new icon and left click on "Properties".
3) Click on the "Shortcut" tab and make sure the "Target" and "Start in" are set to C:\BJ \GD\Gdwin.exe and D: \BJ\NPS20_Mackinac_Straits_West\2004_GEOPIG, respectively.
4) Click on the "General" tab and uncheck the "Read-only" box.
5) To start the program, double click on the icon.

To setup the GeminiView program for the first time on a computer:

- Run the setup.exe program in the \GeminiView directory.

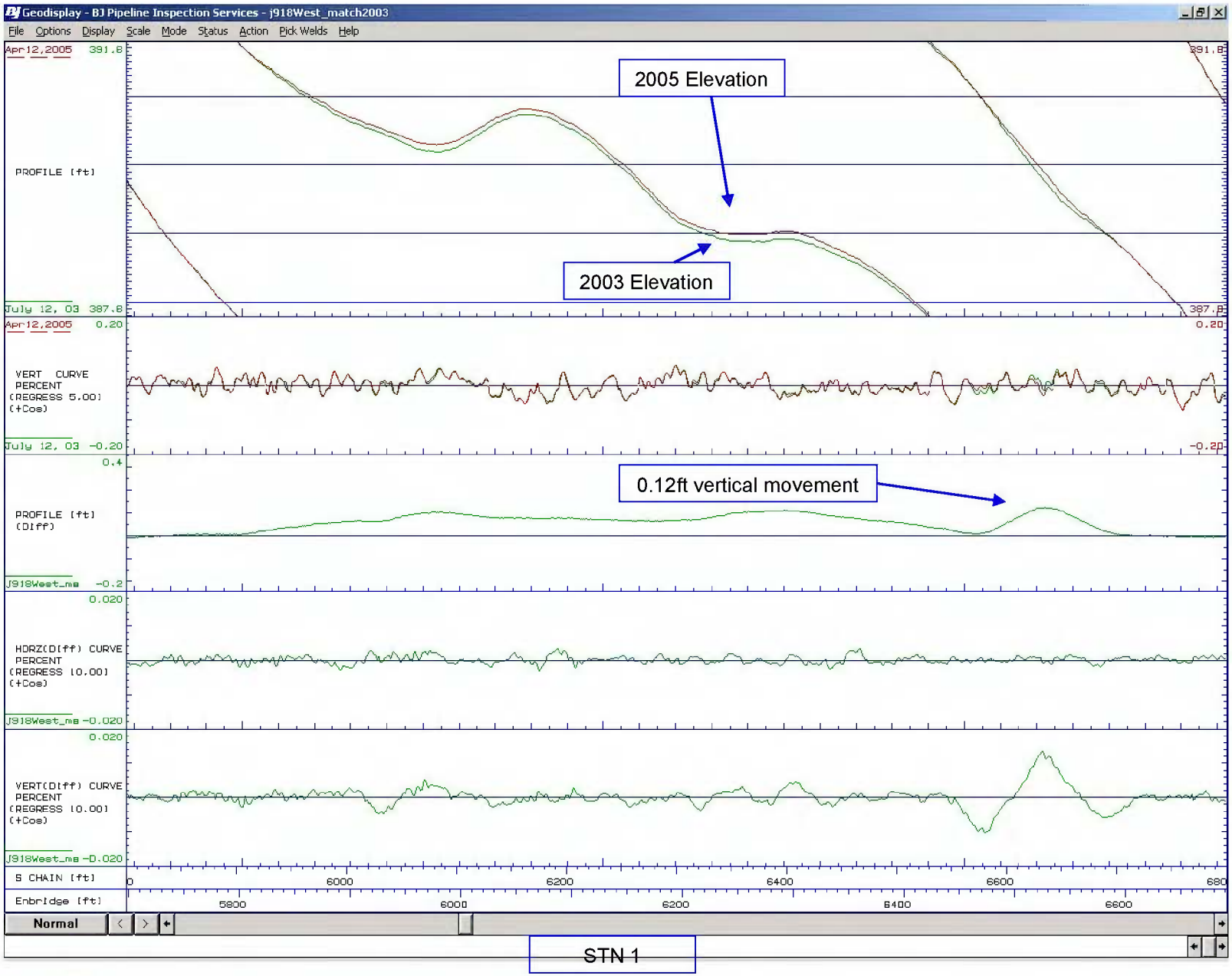
To launch the GeminiView program:

- Double click Geminiview_3.1.0.0.exe

Jobs can then be loaded using the File ⇒ Open menu

Login name = "BJ" Password = *blank* ""

Plots of Areas of Pipeline Movement

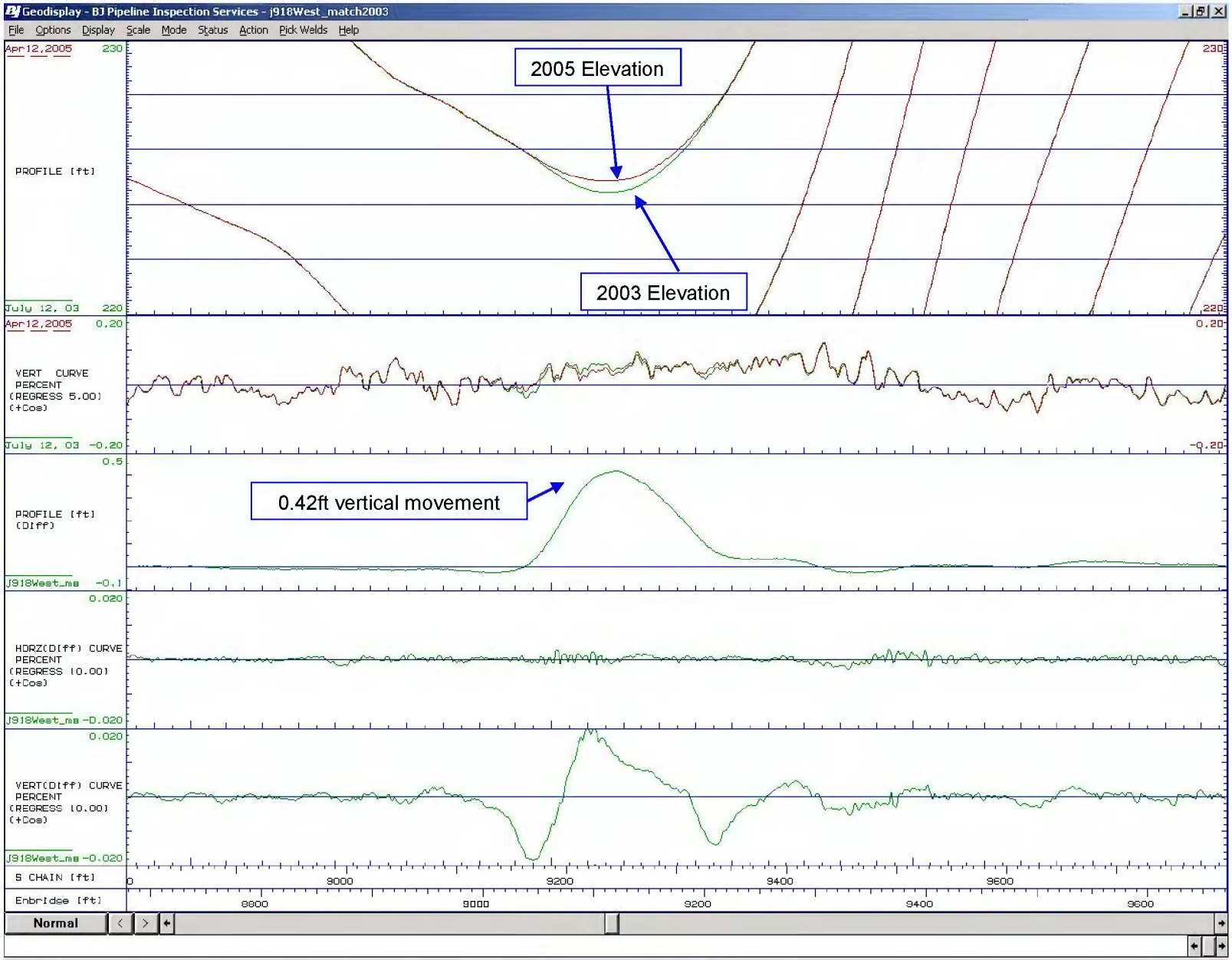


Plots of Areas of Pipeline Movement



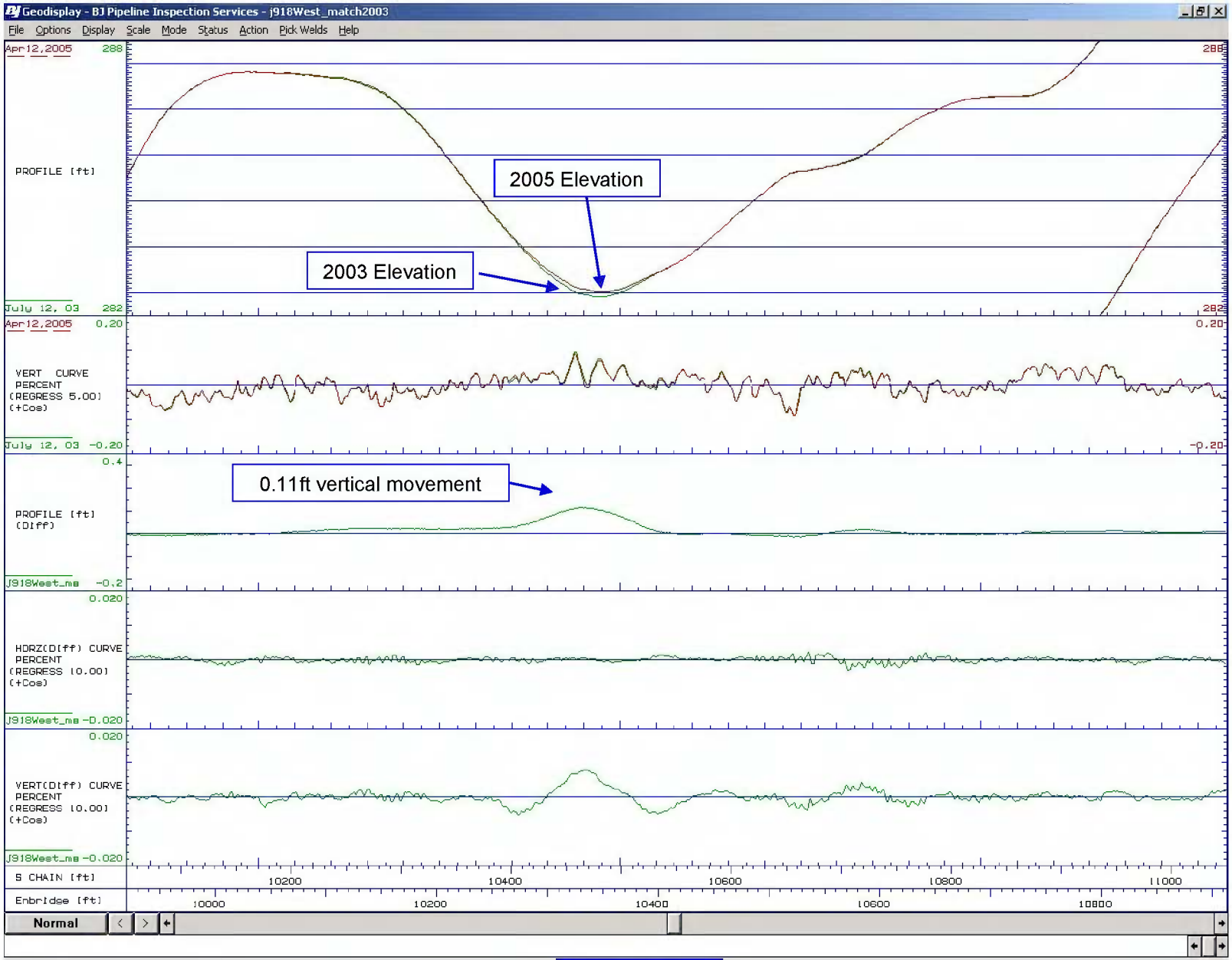
STN 2

Plots of Areas of Pipeline Movement



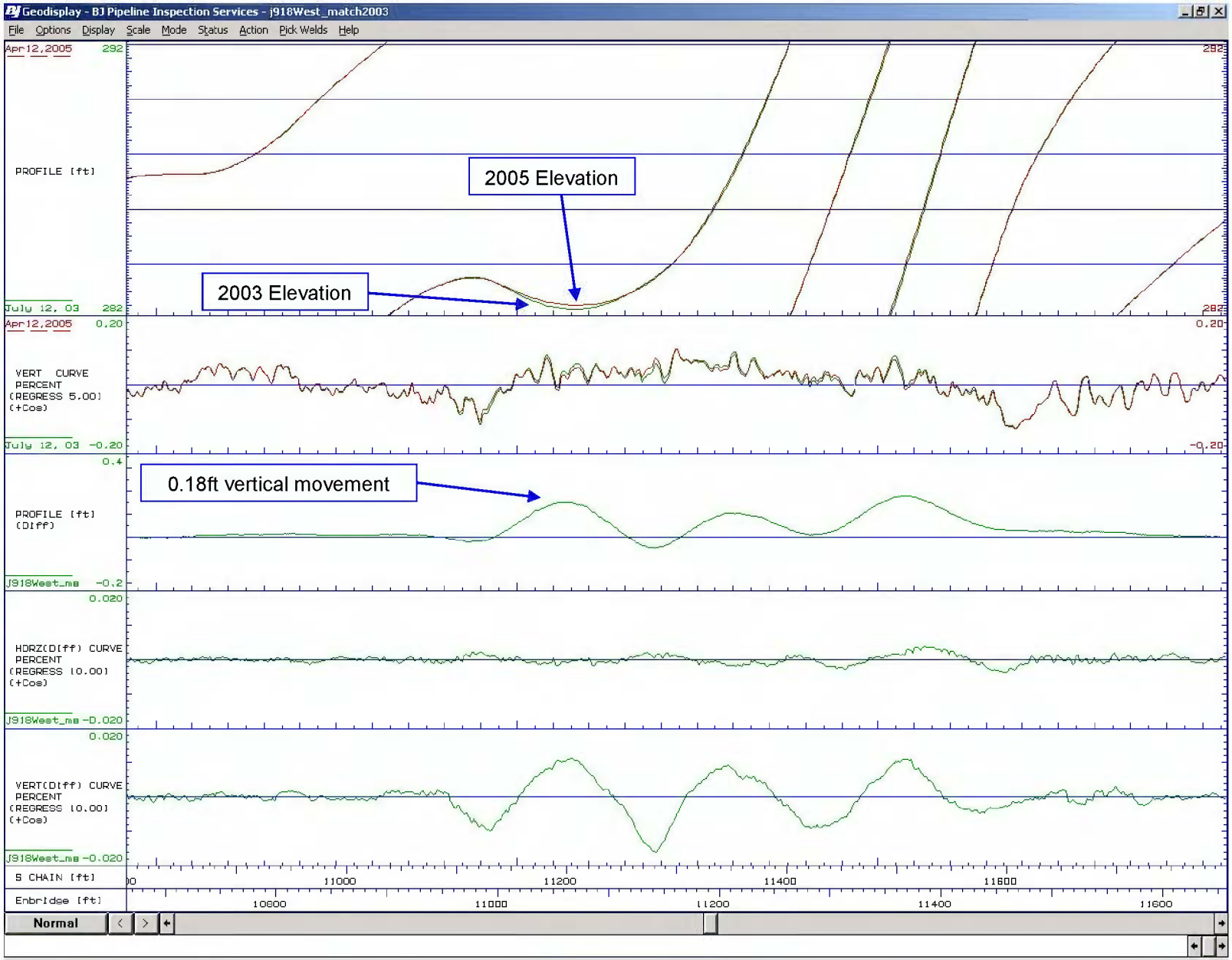
STN 3

Plots of Areas of Pipeline Movement



STN 4

Plots of Areas of Pipeline Movement



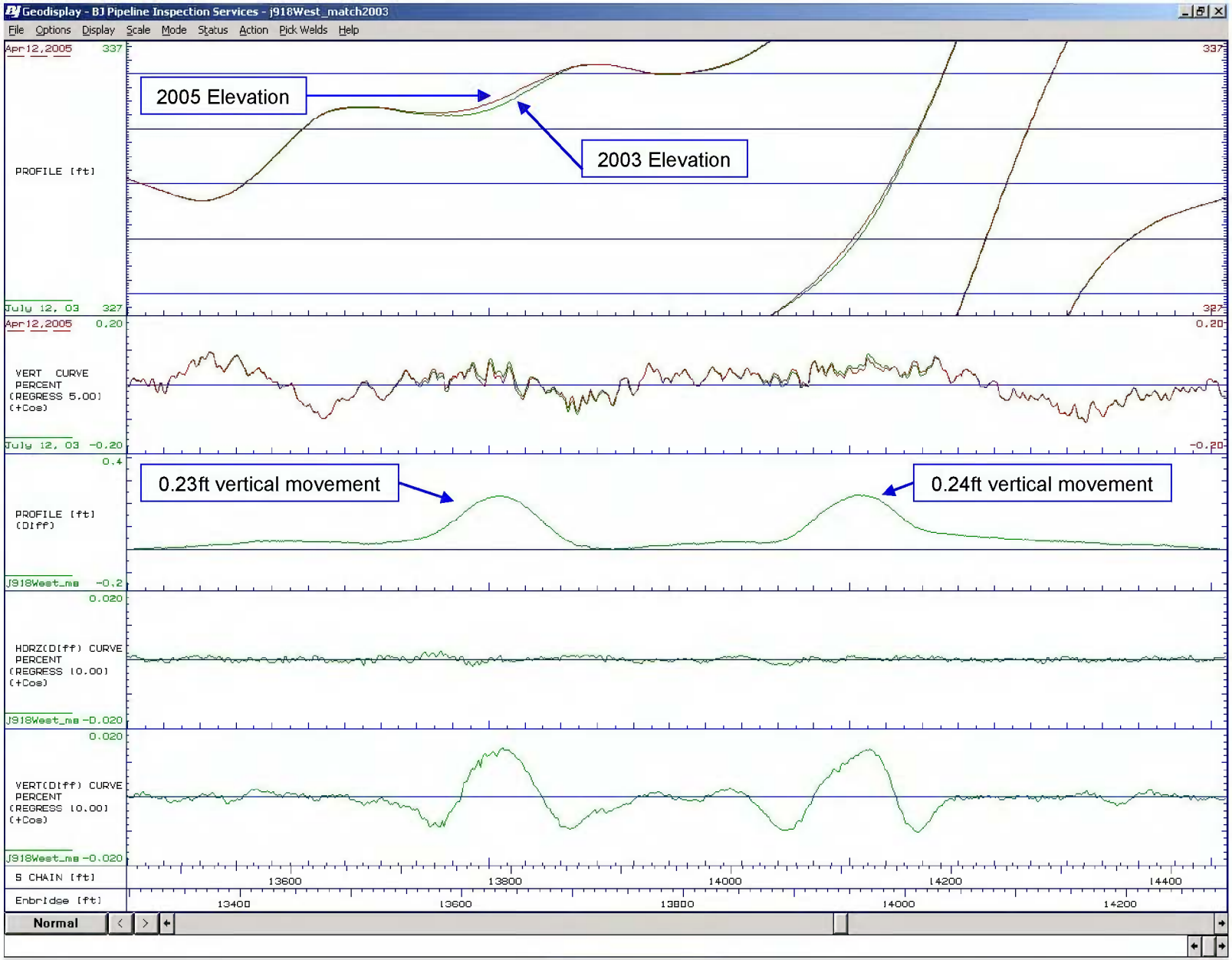
STN 5

Plots of Areas of Pipeline Movement



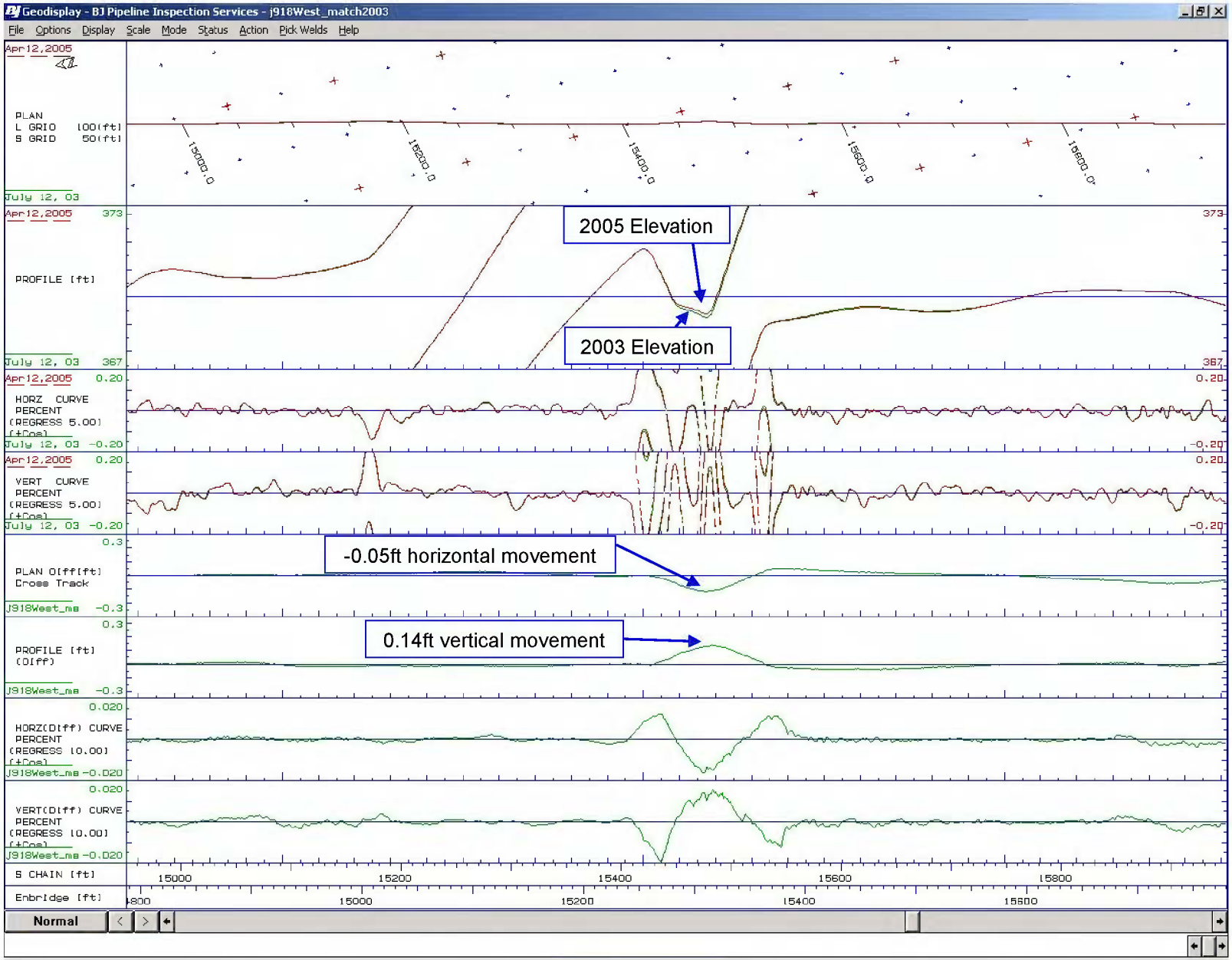
STN 6 & 7

Plots of Areas of Pipeline Movement



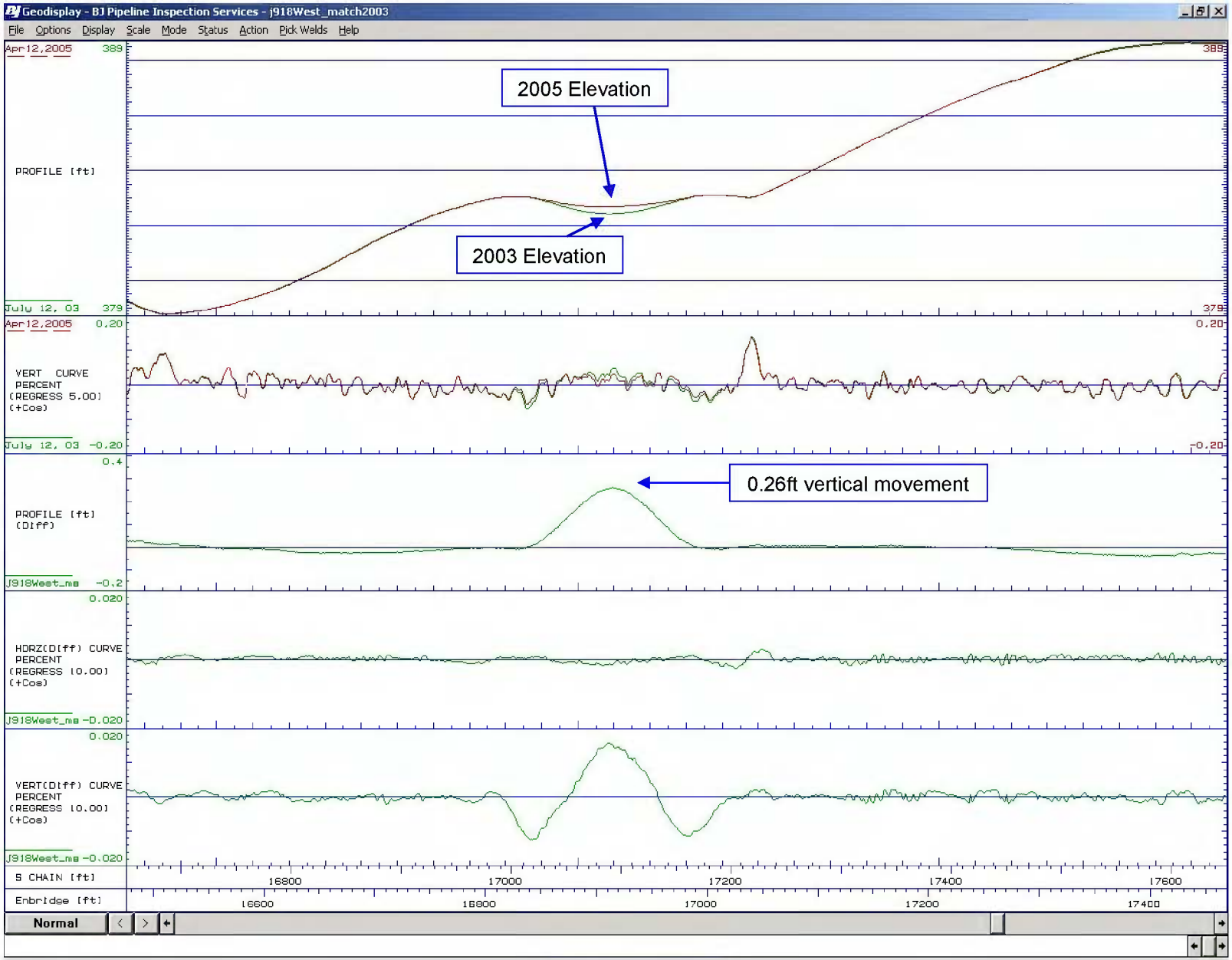
STN 8 & 9

Plots of Areas of Pipeline Movement



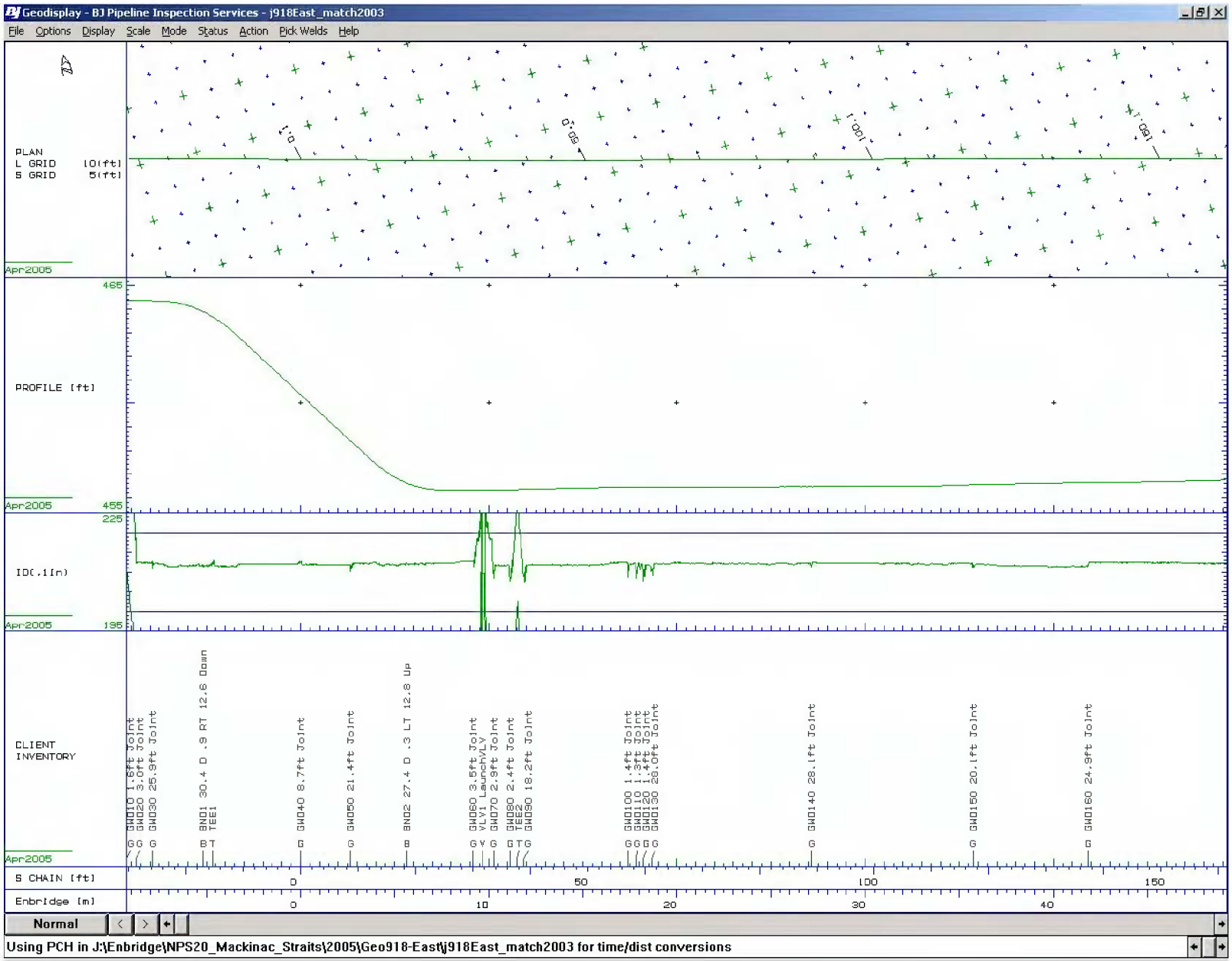
STN 10

Plots of Areas of Pipeline Movement



STN 11

Pipe Tally - Sample Plot and Listing



Plots of Pipeline Plan, Internal Diameter and Features