

HIGH ACCURACY PIPELINE DEPTH OF COVER SURVEY IN CHANNEL CROSSING USING INERTIAL NAVIGATION

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ABSTRACT

A high accuracy pipeline position survey of a ship channel crossing was performed using an in-line inertial navigation survey combined with the GPS coordinates of the channel banks. Two independent inertial surveys were performed to confirm the required accuracy of 0.6 ft (0.2m). The results were overlaid with the channel bottom profile to determine the pipeline depth of cover. It proved that the planned dredging of the channel could be performed safely without compromising the integrity of the pipeline, and the expensive removal of the pipeline was not required. In addition the in-line inertial and caliper survey provided complete geometry data for the entire 12 mile (19km) line, including bending strain, caliper information, pipe tally and NAD27 coordinates that can be used for creating GIS database and anomaly location with GPS.

INTRODUCTION

While the US Army Corps of Engineers was planning in 1998 the dredging of the Houston Ship Channel they had to ensure that this procedure would not threaten the integrity of the pipelines crossing the channel. This required information on both the channel bottom profile and the position of the pipelines in 3-D space, which would allow them to determine the pipe depth of cover. The most difficult part was to obtain accurate position of the pipelines buried some 20 to 65 feet (6 to 20m) below the channel bottom at the water depth of up to fifty feet. The Reliant Energy NPS 12 fuel line operated by TEPSCO had been surveyed in the past using electromagnetic devices but those results were viewed with scepticism when compared with the existing as-built data. Electromagnetic surveys indicated that pipe depth of cover might have been insufficient, which would require removal of the pipeline before dredging the channel. Research into the original construction records did not provide a solid determination of the pipeline location.

Having reviewed all the available options it was concluded that the most accurate information on the pipeline position would be achieved by using an in-line inertial survey tied to the GPS coordinates of two points on each side of the channel. BJ Pipeline Inspection Services was contracted to provide the inertial and caliper survey using their geometry survey tool Geopig. For half a mile spacing between the two GPS tie points on the channel banks the specified relative inertial survey accuracy of 1:2000 would translate into 0.6 ft (0.2m) absolute pipeline position. Two inertial surveys were to be performed to confirm the repeatability of the results.

This paper presents the technology and methods employed in the survey, and discusses the obtained accuracy and benefits.

DESCRIPTION OF GEOMETRY SURVEY TOOL

The in-line inspection tool equipped with calipers and inertial system provides complete pipeline geometry data, including the mapping coordinates and curvature of pipe centerline as well as the internal pipe wall shape and diameter. It also delivers temperature and pressure profiling. The main sensors are the inertial navigation system and ultrasonic or mechanical calipers. They are complemented by other sensors and devices, such as odometers, temperature and pressure sensors, a data acquisition system with solid-state memory, a power supply and pig-tracking transmitter. The tool is suspended in the pipeline by urethane pig cups that maintain its movement close to the centerline of the pipe. NPS 8-16 tools are composed of four modules connected together, as shown on Fig. 1. Larger diameter tools consist of a single body carrier.

The purpose of the caliper survey is to measure the pipe internal diameter and pipe wall anomalies such as dents, ovalities and wrinkles. This is achieved by recording the distance from the caliper ring to the pipe wall using ultrasonic transducers or mechanical fingers that scan the pipe wall as the tool travels along the pipeline. The caliper sensors are spaced at equal angles around the ring; their number varies from 16 to 64 depending on the pipe diameter. The post-processing software calculates the radius and position of the circle that best fits the measured shape of pipe cross-section for every scan along the line. This produces the internal pipe diameter as well as allows for calculation of the anomaly size based on the deviation of the pipe wall cross-section from the circle. The calipers also detect welds, wall thickness transitions, valves, off-takes and other pipe installations.

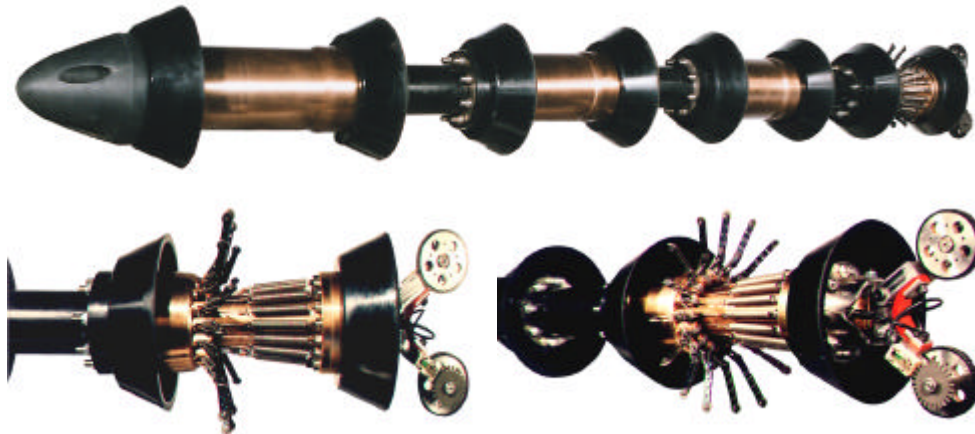


Fig. 1 NPS 8-16 Mechanical Caliper and Inertial Survey Pig

The primary function of the inertial survey is to determine the pipeline plan, profile and curvature (bending strain). This is obtained by computing the trajectory of the pig traveling inside the pipeline using data collected by the onboard strapdown inertial unit and odometers. The inertial system produces three-dimensional measurements of inertial acceleration and angular rate directly from orthogonal triads of accelerometers and gyroscopes. The geometry tool uses systems built by Litton Industries, containing three fiber optic gyroscopes and three single-axis accelerometers. The output from these are typically sampled at 50 or 100 times per second. In this line, with the data acquisition rate of 50 Hz and the average speed of 6 ft/s (1.8m/s) the distance between the inertial data samples was 1.5 in (3.8cm)

An accurate plan and profile database containing three dimensional coordinates for every point along pipe centerline is obtained by integrating the inertial data with the GPS coordinates of selected tie points along the line.

INTEGRATION OF INERTIAL AND GPS DATA

In order to improve the absolute position accuracy the inertial data is translated, rotated and scaled to the tie points with known co-ordinates, 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 tool trajectory into the tie points, accurate Northing, Easting, and height can be obtained for any point along the pipe. The tie points are typically spaced at several km intervals, however the smaller the distance the better the absolute pipeline position accuracy between them. Those points are selected at traps, valves, welds, bends, wall thickness transitions, take-offs or any other pipeline features that can be detected directly or indirectly by the pig's sensors and can be readily identified in the field when performing the GPS survey. The coordinates of the tie points must correspond to the centre of the pipe, therefore a proper offset has to be applied from the GPS antenna location to the pipe centre. When the pipe is buried the depth of cover has to be determined from the available records or measured in the field using pipe locators or probes.

Traps, valves and take-offs are the best features to be surveyed as they can be accurately identified in the inertial /caliper data and are easy to locate, access and occupy in the field. Bends are also often used as the tie points, because they can be clearly seen in the inertial data. However, more effort is required to physically pinpoint them in the field using pipe locators. The higher the curvature of the bend the easier it is to locate in the field and the more accurate the determination of its centre point. Thickwall pipe transitions, insulating joints and girth welds are also detected by the calipers, but they

are useful only if they are marked in the field, or the as-built plans detail their accurate distance to a terrestrially observable features such as a road centreline or a permanent pipeline marker. Cathodic protection installations are not detected directly by the geometry tool, but can be utilised if their location in a weld log is known from the construction records or previous corrosion in-line surveys. Matching the weld log from the geometry survey with this data allows for identification of the CP points in the inertial data.

If there is an area along the pipeline that requires GPS survey but has no feature that the geometry tool can detect then “timer boxes” can be deployed during the run. They are placed on the ground above the pipeline so that they can record the time of the passage of the tool. The location of the timer boxes can be surveyed with GPS at any time (before, during or after the run).

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

Distance Between Tie Points [ft]	Absolute Accuracy [ft]
15,000	3.7
5,000	1.2
2,500	0.6
1,200	0.3

PIPELINE GEOMETRY SURVEY APPLICATIONS

The pipeline plan and profile in UTM projection is used primarily for creating as-builts and Geographic Information Systems, as well as location of anomalies using GPS (including corrosion anomalies from a metal loss survey)⁽¹⁾. The inertial data also provides angle, curvature and orientations of bends, measurements of bending strain and geometrical imperfections, such as buckles, out-of-straightness, weld misalignment and mitre bends. Comparison of multiple surveys allows for detection of pipeline movement between runs, usually caused by oil and gas field subsidence, permafrost thaw, slope instability, dyke settlement, riverbed erosion or lateral buckling of unrestrained pipe under temperature and pressure changes. The pipe centerline shape and bending strain can also be used for structural analysis using FEM and fitness-for-purpose assessment.

On many occasions the geometry tool has been used for surveying water crossings, such as ship channels, rivers, lakes, bays and canals. Example applications of such surveys performed in the past are ⁽²⁻⁵⁾:

- out-of straightness and depth of cover survey for upheaval buckling analysis of offshore pipelines
- pipe centerline shape and bending strain for assessment of impact of dyke settlement on pipeline integrity
- monitoring bending strain, pipewall deformations and pipe movement between runs for assessment of impending buckling and wrinkling due to permafrost settlement
- position survey of pipeline river crossing for planning the construction of a new bridge running along the pipe
- curvature survey of a pipeline bay crossing for planning pipe in pipe insertion

- pipeline shape and bending strain for fitness-for-purpose assessment and planning stabilization of underwater free spans
- multiple surveys for monitoring an impact of rock dump on pipeline settlement and integrity
- detection of wrinkles in pipeline river crossing caused by strong currents and riverbed erosion
- detection of buckles caused by offshore field subsidence

PIPELINE SURVEY OF HOUSTON SHIP CHANNEL CROSSING

A total of 15 points were surveyed with GPS in order to tie the inertial position of the entire 12 mile line to Texas Plane Coordinates, NAD27 Projection, Texas South Central Zone. The points were selected at traps, valves, bends and two pipeline markers (surface monuments) located above girth welds on both sides of the ship channel. One of the surface monuments, located on Barnes Island, corresponded to weld number 101 in the construction records, and the point on Goat Island was above weld 106 (the weld numbering was not consecutive). Those two welds were positively identified in the inertial data data by comparing the geometry inspection weld log with the construction records. In addition, they were adjacent to the insulating couplings that were also detected by the calipers. One of them was close to a horizontal bend that can be seen in the inertial survey data presented on Fig.2. Those two tie points provided the position control for the inertial survey of the entire ship channel crossing.

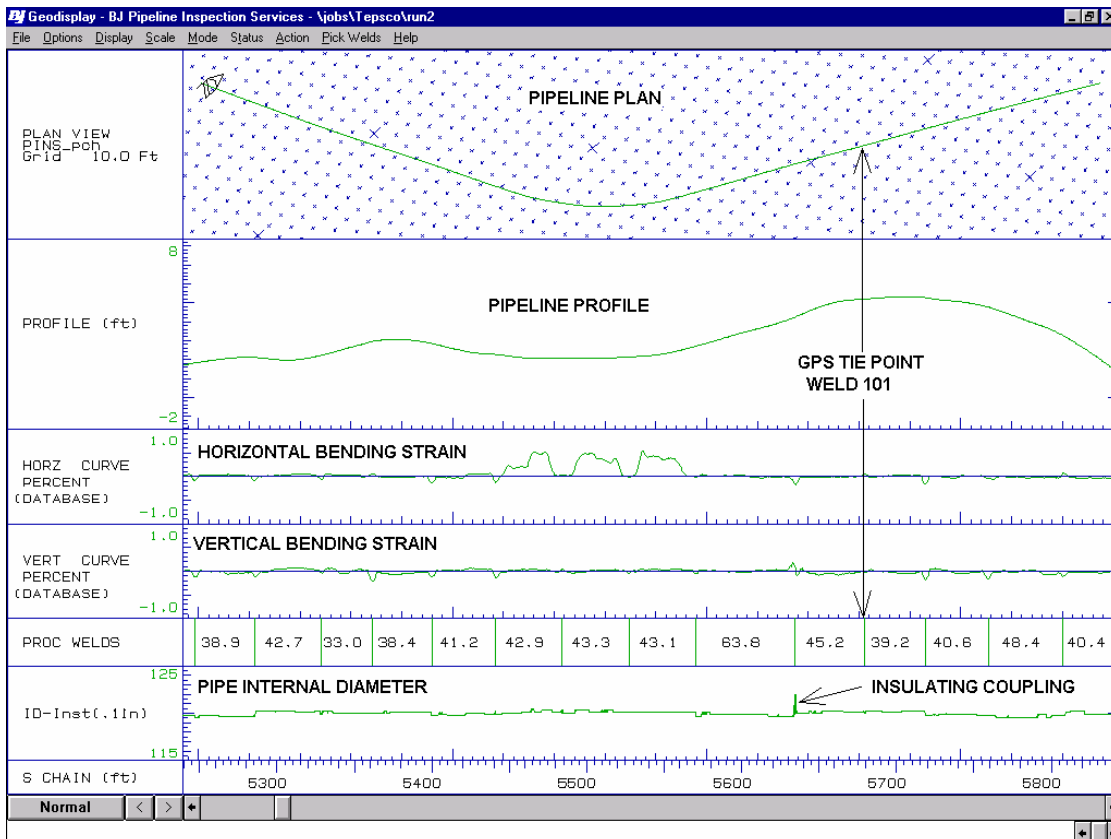


Fig 2 Location of GPS Point on Barnes Island

A static GPS survey network provided horizontal and vertical control for the project. Coordinates for the surface monuments above the pipeline on each side of the Houston Ship Channel were referenced to NGS published data. Houston Galveston Coast Subsidence District monuments and NGS Vertical Benchmarks were held to control the vertical measurements. The baselines were short, 6000 to 20000 feet; the occupations were long, 45 min to 4 hours; and the two points above the welds were occupied on separate days at different times to provide for a different satellite constellation. From the least squares adjustment of the network, the error in the vertical component of adjusted coordinates was 0.08 feet.

The surface elevations above welds were transferred to the pipe center by hand probing to determine the depth-of-cover to top-of-pipe, and then adding the design dimensions for the pipe, concrete cover, and insulation. Clearly, the error in the depth-of-cover measurement contributed the greatest amount to the total error of the derived elevation for the center-of-pipe. The assumed error estimates for the independent measurements of elevation-at-surface, the depth-of-cover measurement and the as-built verses design dimensions for the pipe, concrete cover, and insulation are listed as follows:

Measurement	Estimated Error	Remarks
Surface Elevation	0.1'	Conservative Rounding
Depth-of-cover	0.2'	Subjective Assumption
Insulation	0.02'	2" Nominal; Assumed 1/4"Error
Concrete Cover	0.02'	2" Nominal; Assumed 1/4"Error
Radius Pipe	0.02'	12.75"OD; Assumed 1/4"Error

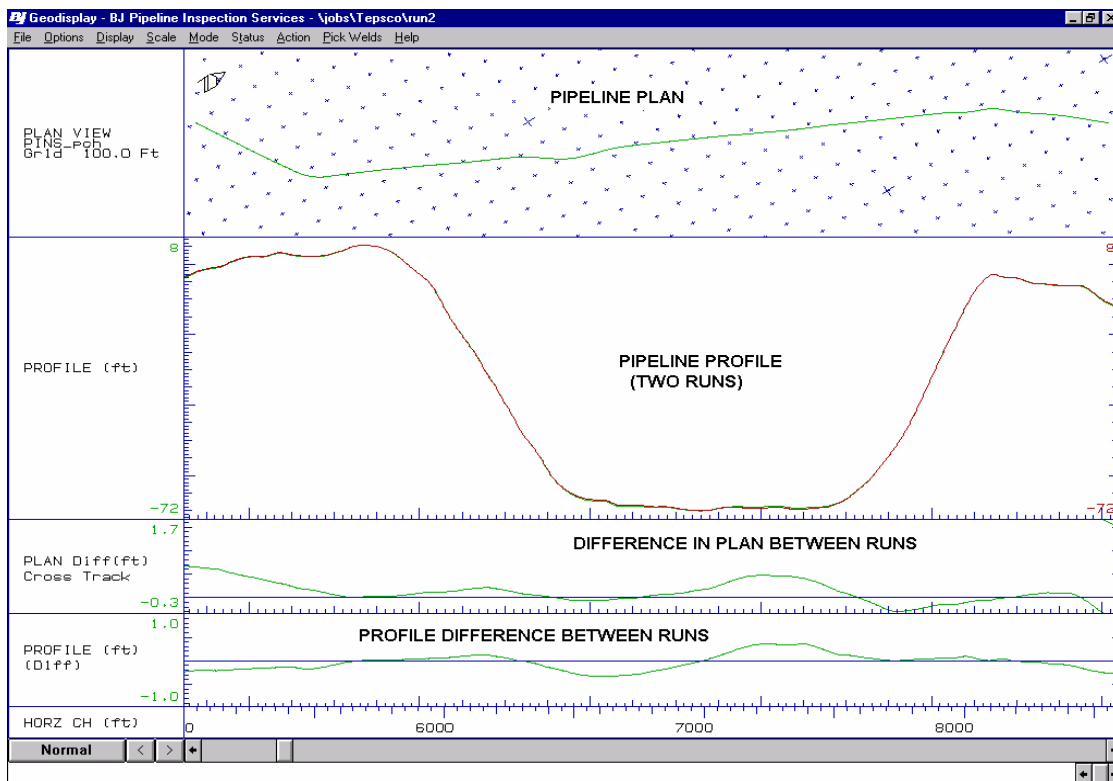


Fig. 3 Pipeline Plan, Profile and Difference between Two Inertial Surveys of Channel Crossing

The inertial survey data from two runs tied to the GPS points were compared for repeatability. The data for the Houston Ship Channel crossing from two Geopig run were tied to the points that are 2500 ft (760m) apart, therefore the allowable error in-between those points could reach 0.6 ft (0.2m), which corresponds to up to 1.2 ft (0.4m) difference between two runs. Fig. 3 shows the overlaid pipeline profile from two runs as well as the difference in plan and profile between the runs. It can be seen that the difference both in plan and profile is below 0.5 ft (0.15m), which exceeded the specifications.

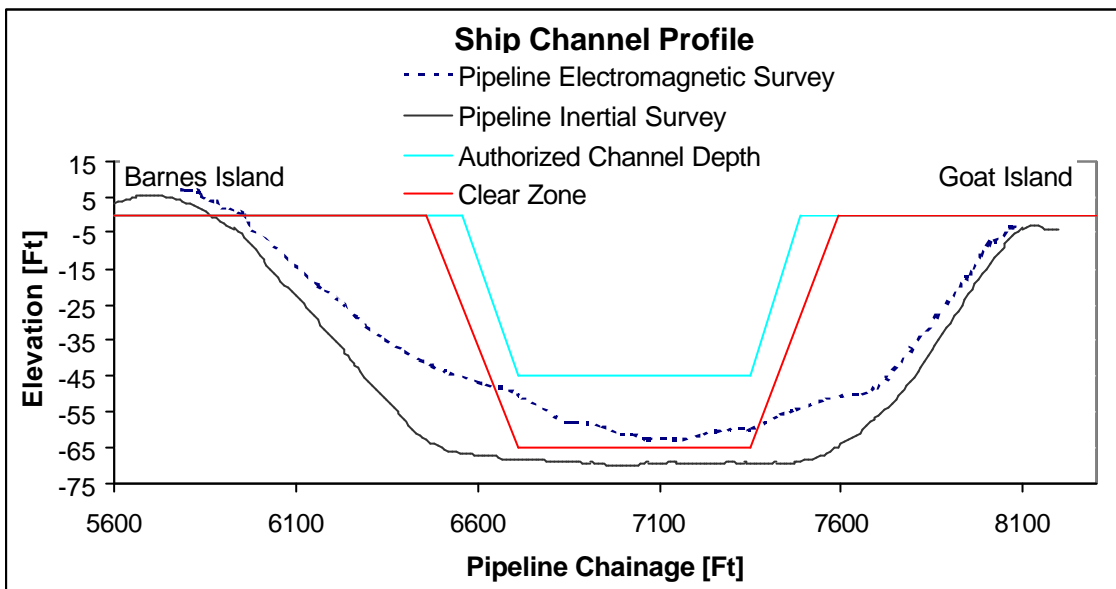


Fig. 4 Pipeline Position from Electromagnetic and Inertial Surveys Overlaid with Channel Bottom Profile

Fig. 4 shows the pipeline profile from the electromagnetic and inertial surveys overlaid with the authorized ship channel depth and the required clearance 20ft (6m) below it. The Geopig survey indicates that the pipeline profile is just below the authorized clear zone, while the electromagnetic survey showed the pipeline position encroaching that zone by up to 15ft (4.5m).

CONCLUSIONS

Two independent inertial surveys of the Houston Ship Channel crossing were performed to confirm the specified accuracy of 0.6 ft (0.2m) that allowed for the maximum difference of 1.2 ft (0.4m) between two data sets. The results from two surveys were only 0.5 ft (0.15m) or less from each other in both vertical and horizontal plane, which was well within the specifications. They indicated that the channel dredging could be performed without a need to remove the pipeline, which resulted in the savings of millions of dollars. In addition the in-line inertial and caliper survey provided complete geometry data for the entire 12mile (19km) line, including pipe centerline coordinates, bending strain, caliper information and girth weld locations (pipe tally) that can be used for creating GIS database as well as anomaly location with GPS.

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BIOGRAPHICAL NOTE ABOUT AUTHORS

Dr. Jaroslaw (Yarek) Czyz has been with BJ Pipeline Inspection Services since 1990, starting at the positions of Structural Engineer, then Senior Structural Engineer, and currently working as a Team Leader of the Geometry Analysis group, supervising data processing and software development. In 1989-1990 he was a Research Associate at the Mechanical Engineering Department at the University of Saskatchewan and the University of Calgary, where he was doing research on optimization of structures for stability and vibrations, non-linear viscoelastic models of material and analysis of structures by Finite Element Method. Prior to that he was an Assistant Professor at the Industrial Institute of Construction Machinery in Warsaw, Poland. He obtained his Ph.D. in Mechanical Engineering from the University of Warsaw in 1985, and M.Sc. in Applied Mathematics and Mechanics in 1979. He has published over 20 papers on pipeline inspection surveys and numerical methods in mechanics.

Curtis Cole is Project Surveyor with Reliant Energy where he has worked for the past 20 years. He is a Registered Professional Land Surveyor in Texas. He received a Bachelor of Science degree in Land Surveying from Purdue University, and Associate of Survey Technology from Pennsylvania State University.