the Energy to Lead

gti

FINAL REPORT

GTI PROJECT NUMBER 21497

Above-Ground Detection Tools Including Disbondment and Metal Loss for all Metals Including Cast-Iron Graphitization

DOT Project # 500
DOT Agreement Number: DTPH56-13-T-000011

Reporting Period:
September 1, 2013 through August 31, 2016

Report Issued:
August 31, 2016

Prepared for:
Mr. Bill Lowry
PHMSA Technical Manager

Prepared By:
Gas Technology Institute
Mr. Christopher Ziolkowski
R&D Manager Information Ecosystem
chris.ziolkowski@gastechnology.org
847-768-0549

GTI Project Manager:
Gas Technology Institute
Dr. Kiran Kothari
Institute Engineer/Program Manager
kiran.kothari@gastechnology.org
847-768-0893

GTI Team Members:
Dr. Kiran Kothari, Christopher Ziolkowski, Robert Marros, Mike Mensinger Jr, Steven Blitzstein, Dr. Saurav Acharya

Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gastechnology.org

Legal Notice

This information was prepared by Gas Technology Institute ("GTI") for the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration.

Neither GTI, the members of GTI, the Sponsor(s), nor any person acting on behalf of any of them:

a. Makes any warranty or representation, express or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights. Inasmuch as this project is experimental in nature, the technical information, results, or conclusions cannot be predicted. Conclusions and analysis of results by GTI represent GTI's opinion based on inferences from measurements and empirical relationships, which inferences and assumptions are not infallible, and with respect to which competent specialists may differ.

b. Assumes any liability with respect to the use of, or for any and all damages resulting from the use of, any information, apparatus, method, or process disclosed in this report; any other use of, or reliance on, this report by any third party is at the third party's sole risk.

c. The results within this report relate only to the items tested.

Table of Contents

Page

Legal Notice i

Table of Contents ii

Table of Figures iv

Executive Summary 1

List of Deliverables during Reporting Period 2

Introduction 2

- Proposed Method of Flaw Detection 2
- Technology Approach 3

Initial Test Site 4

- Data Captured at Initial test site 4
- Results at Initial test site 4

Data Collection and Visualization 5

- Data Sources 5
- Data Processing Methods 6
- Data Processing with R Studio 8

Utility A Test Site 9

- Utility A Site Background Information 9
- Utility A Site Findings 12

Utility B Test Site 13

- Utility B Site Background Information 13
  - Test Site B Anomaly 2 13
  - Test Site B Anomaly 3 17
- Utility B Site Findings 20

Utility C Test Site 23

- Utility C Site Background Information 23
- Utility C Site Findings 26
  - Follow Up Survey 27

Investigation of Cast Iron Pipes 29

- Cast Iron Background Information 30
- Cast Iron Experimental Results 33

General Observations on Technique 35

- Requirements for a Successful Survey 35

Recommendations for Improvement 35
Conclusions 36

Table of Figures

Page

Figure 1 – Field Generated by Current on a Pipe 2
Figure 2 – Single Axis Prototype with Odometer Wheel 3
Figure 3 – Spar 300 Magnetometer with GPS Antenna 3
Figure 4 – Data from Initial Test Site 4
Figure 5 – FieldSens View Operator Panel 6
Figure 6 – Early Data Visualizations 7
Figure 7 – Current Map Produced with R Studio 8
Figure 8 – Current Plot Produced with R Studio 9
Figure 9 – Spars in use on Test Site A 9
Figure 10 – Current Map for Site A 10
Figure 11 – Normalized Phase Map for Site A 11
Figure 12 – Current Plot for Site A 11
Figure 13 – Normalized Phase Plot for Site A 11
Figure 14 – Steel Culvert Sections used to Protect Buried Pipe 12
Figure 15 – Exposed Pipe with Minor Gouges in Coating 12
Figure 16 – Phase Map 1 near Anomaly B-2 14
Figure 17 – Phase Map 2 near Anomaly B-2 14
Figure 18 – Current Plot 1 for Anomaly B-2 15
Figure 19 – Phase Plot 1 for Anomaly B-2 15
Figure 20 – Current Plot 2 for Anomaly B-2 16
Figure 21 – Phase Plot 2 for Anomaly B-2 16
Figure 22 – Rescaled Version of Figure 16 to Exclude Culvert 17
Figure 23 – Spar in use at Anomaly B-3 17
Figure 24 – Current Map for Anomaly B-3 18
Figure 25 – Phase Map for Anomaly B-3 18
Figure 26 – Current Plot 1 for Anomaly B-3 19
Figure 27 – Phase Plot 1 for Anomaly B-3 19
Figure 28 – Current Plot 2 for Anomaly B-3 20
Figure 29 – Phase Plot 2 for Anomaly B-3 20
Figure 30 – Location of Coating Flaws Found during Excavations 21
Figure 31 – Adjusted Current Map Data for Anomaly B-2 21
Figure 32 – Adjusted Current Plot for Anomaly B-2 22

Figure 33 – Adjusted Phase Plot for Anomaly B-2 22
Figure 34 – View of Electric Feeders in Manhole 23
Figure 35 – Current Map of Site C-2 West 24
Figure 36 – Phase Map of Site C-2 West 24
Figure 37 –Current Plot of Site C-2 West 25
Figure 38 – Phase Plot for Site C-2 West 25
Figure 39 – Disbonded Coal Tar Coating found in Excavation 26
Figure 40 – Projected Distance from Manhole to Flaw 27
Figure 41 – Current Plot with Old Coating 28
Figure 42 – Current Plot with New Coating 28
Figure 43 – Phase Plot with Old Coating 29
Figure 44 – Phase Plot with New Coating 29
Figure 45 – Samples of Graphitized Cast Iron 30
Figure 46 – Micro-Photograph of Cast Iron Graphitization 30
Figure 47 –Typical BEM Mapping of Apparent Wall Thickness 31
Figure 48 – Schematic Representation of Indoor Test Setup 31
Figure 49 – Indoor Cast Iron Testing with Spars 32
Figure 50 – New Ductile Iron Replacing Graphitized Sample 32
Figure 51 – Current Plot for Graphitized Cast Iron 33
Figure 52 – Phase Plot for Graphitized Cast Iron 33
Figure 53 – Current Plot for New Ductile Iron 34
Figure 54 – Phase Plot for New Ductile Iron 34

Executive Summary

This document is the Final Report for "Above-Ground Detection Tools Including Disbondment and Metal Loss for all Metals Including Cast-Iron Graphitization" covering the entire effort. As such, it will provide a high-level view of the project work. There are additional milestone reports that have been prepared over the course of the project that deal with specific sections of the work in detail. The goal is to present the reader with the accomplishments of the project and conclusions.

The overall objective of this project is to develop, test, and then commercialize a technology to detect coating disbondment, metal loss, and external corrosion on buried pipelines from the ground-level. This technique works by measuring pipe electromagnetic (EM) field signatures using an above ground tool. This Above-ground Detection Tool (ADT) leverages prior technology development by PHMSA, OTD, and the Gas Technology Institute (GTI) Sustaining Membership Program. These organizations have worked collaboratively in the areas of cathodic disbondment detection, cast iron feature location, and remote metal loss assessment. These various areas have been pursued in the past as stand-alone projects. The researchers have, over time, identified features common to these research areas and seek in this project to unify these approaches to detect flaws on metallic pipelines.

In order to accomplish the detection of flaws, a suite of sensors is moved along the pipeline route with stops at specific intervals to take readings. A pre-defined current excitation signal is placed on the metallic pipe in order to generate an external EM field that some of the sensors are tailored to receive. Measurements of this field allow the inference of the pipe location and orientation relative to the sensors. Other components of the sensor suite capture the geospatial location of the sensor package. Taken together, these data enable the absolute location of the pipe to be captured to a high degree of accuracy. The lesson of the past efforts is that locating the pipe properly within the measured EM field is critical to interpreting that field to determine flaw types and locations.

List of Deliverables during Reporting Period

Item # 31, Task # 8: Final Report for the Development of an Above-Ground Detection Tool, Report covering September 1, 2013 through August 31, 2016 (this report)

Introduction

The overall objective of this project is to develop, test, and then commercialize a platform to detect coating disbondment, graphitization, and external corrosion by measuring a magnetic field signature from above ground. The basics of the proposed technology and its implementation are briefly discussed to provide the reader insight into the various data that must be gathered and coordinated.

Proposed Method of Flaw Detection

The operating principle is to inject or induce a current on the pipe being surveyed that in turn generates an exterior electromagnetic (EM) field around the pipe. The next step is to carefully map the EM field around the pipe in 3 dimensions (Figure 1). The properties and curvature of the exterior field will be influenced by the path of signal current through the pipe metal, coating, and surrounding soil. Unlike standard pipe locators that infer the pipe location from the field magnitude only, the system being developed also captures the phase angle of the signal.

The fundamental premise for this work is that the signal phase and magnitude both will be influenced by the coating condition. In the instance where the coating is in good condition and the soil uniform it is anticipated that the phase and magnitude would vary gradually and monotonically as a function of location on the pipe. Experience with earlier, and less sophisticated, versions of the equipment have shown that coating holidays have signatures that are different from changes in "shape" of the pipe that do not involve breaks in the coating. Coating holidays are typically indicated by a change in the field magnitude that occurs over a small region rather than gradually. Distortions in the pipe surface or shape are indicated by highly local changes in the signal phase that are not associated with a change in magnitude. Examples of these indications will be covered in the body of the report.

The equipment used for this investigation captures the signal magnitude and phase at points along the pipe as well as the attitude, compass bearing, and geo-location of the sensor platform. The data is automatically captured, then stored for post-processing to locate pipe and coating features. An end goal is for visualizations of the data will be available in the field.

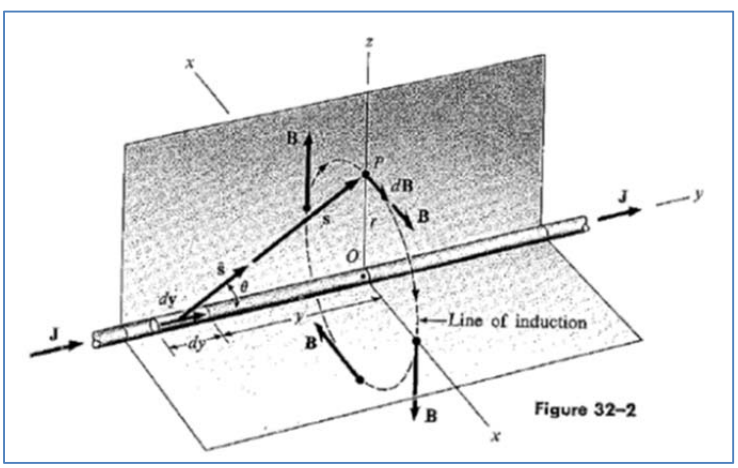

Figure 1 – Field Generated by Current on a Pipe

Technology Approach

Previous work in this area had been carried out using single-axis magnetometer sensors without built-in GPS. While several investigations were successfully carried out with these prototypes, the results were very dependent on having, a priori, an accurate location for the pipe being investigated. Unexpected, variations in the location of the pipe with respect to the sensor platform could cause changes in the data that can then be misinterpreted as pipe or coating flaws. In order to identify small flaws in the pipe coating the "noise" introduced by position error must be minimized.

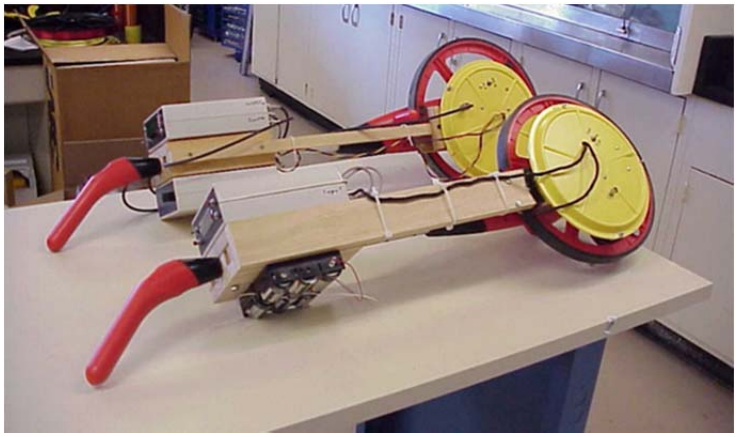

Figure 2 – Single Axis Prototype with Odometer Wheel

A commercially available (Figure 3) locating system, the Spar from Optimal Ranging Incorporated (ORI), was identified that addressed the location issue. In addition to having multiple magnetometers to locate the pipe, the Spar integrates GPS location and timekeeping. The external field observed can now be referenced to the true location of the pipe rather than one generated by a separate mark-out operation. Eliminating the separate step for the mark-out further streamlines the operation of any given survey.

Figure 3 – Spar 300 Magnetometer with GPS Antenna

A single Spar consists of a pair of 3-axis magnetometers separated by a known baseline. This allows the location of the pipe to be triangulated by measuring the radiated field of the pipe when excited with a

signal current. The curvature of the field as measured with the two sensors allows the system to infer where the current source generating the field is. Multiple Spars can be linked wirelessly when longer baselines are needed to triangulate deeper pipes. In the case of this application, two Spars are linked to determine the pipe signal phase shift between their relative locations. These locations are provided by GPS that can be augmented with Real Time Kinematic (RTK) correction for improved accuracy. The frequency of the pipe excitation current is pre-determined to a very high precision and shared amongst the components of the system for synchronization.

Initial Test Site

Very early in the project, a test site was offered by Utility A. At this early stage many of the hardware features and software analysis tools developed later in the project were not available. Nonetheless, this site was valuable in acquainting the operators with the characteristics of the equipment and getting early utility exposure for the project.

Data Captured at Initial test site

The initial site at Utility A was visited as a "shakedown test" of the Spar equipment under real world conditions.

Figure 4 – Data from Initial Test Site

Results at Initial test site

Several features were not working properly at this test site. One of the Spar devices was malfunctioning so the dual Spar locate mode was not available. All the data at this location was taken with a single Spar in the line locating mode. The signal current values are shown as color-coded dots shown on the map. This site was excavated and spent anodes were found at locations that correspond to drops in current seen in the Spar data.

This site showed a number of issues to be resolved with respect to the Spar system. In order to determine the change in magnitude and phase during a survey, a two Spar system with custom software from ORI was required. The use of two Spars with the standard ORI software enables long baseline triangulation for the accurate location of deep utilities. The requirements of gathering condition assessment data are different than that of generic location. The custom software for condition assessment uses one of the Spars to find the location of the pipe, signal magnitude, and phase. The second Spar captures the magnitude and phase to allow a differential measurement between the two Spars. RTK correction for high GPS accuracy was added later in the project.

Data Collection and Visualization

Inferences on the pipe and coating condition are made by post-processing the Spar survey data; the ORI FieldSens View software is only used during the survey for the location and mapping of the facility. All of the data generated by both Spars are saved to a file during the survey of a pipe. No real time field display of anomalies or suspect coating problems were developed during this project.

Data Sources

There are two complete subsystems within each Spar that generate data to be stored. First, the Spar processor that was developed by ORI uses the EM field data to estimate the current on the pipe and the location of the pipe relative to the Spar. Second, a GNSS board from Ashtec produces the geo-location and timestamp data for the system. The following block of text is typical of the data generated during a few seconds of Spar run time.

```
GNSS! 3086424,$PASHR,DDM,Y,RT3,1004,4959,0333,144538.00,1.5,*59
GNSS! 3086434,$PASHR,DDM,Y,RT3,1012,4960,0333,144538.00,1.5,*54
GNSS! 3086454,$PASHR,DDM,Y,RT3,1004,4961,0333,144539.00,0.5,*52
GNSS! 3086474,$PASHR,DDM,Y,RT3,1012,4962,0333,144539.00,0.6,*55
GNSS! 3086834,$GNGST,160844.00,0.21,,,,0.126,0.099,0.267*5D
GNSS! 3086874,$PASHR,POS,2,15,160844.00,4143.8434278,N,08733.6038321,W,147.154,
1.0, 296.6,1.191,+0.038,1.5,0.8,1.3,0.8,Hm26*05
FSS! 3087064,$IIRAW,48948,57891,2825,2075,19299,36289,-52202,-59019,337,-339,
-30318,-52729*6c
FSS! 3087064,$IIRAW,27862,-63487,4931,-9088,32001,-50808,-28412,57588,6263,
-9979,-38151, 74620*4c
FSS! 3087074,$IINAV,-8124,-614,344825,0*59
FSS! 3087074,$IINAV,522,4273,334523,0*5e
FSS! 3087074,$IISOL,342,65,1643,254,25304,32768,37332,6209,-2807,22,
-5345,255,19506,257,19081025,8192,155,22,125,1,344825*47
FSS! 3087074,$IIENU,0,0,0,102,0,432*58
FSS! 3087074,$IIENU,-2969,4488,-23,359,452,401*62
```

The strings prefaced with GNSS are generated by the Ashtec boards embedded within each Spar and attached to the GNSS antenna at the top of the unit. GNSS coordinates are provided in the DDMM.MM format with N and W labels to differentiate latitude and longitude. The strings prefaced with FSS are produced by the ORI subsystem that measures the electromagnetic field strengths and estimates the pipe location. The number preceded by a * at the end of each record is a checksum that is added for error correction, not data.

Of interest to our application are the contents of the RAW strings generated by the Spar subsystem. The first string is associated with the "leading" or primary Spar and the second string is with the "trailing" or secondary Spar. The values in the string are the 3-axis data from the top magnetometer followed by the 3 axes from the bottom magnetometer. The values are expressed as real-imaginary pairs so there are a total of 12 values to encode 6 axes. The magnitude, phase, and direction of the field can be calculated from these data. The second RAW string repeats these values for the trailing Spar.

The SOL string contains the location "solution" calculated internally by the Spar using the RAW field data. The first four fields give the offset from the Spar to the pipe, the offset error, the depth of pipe, and the depth error all in millimeters. The offset and depth values must be used in conjunction with GNSS to estimate the true geo-location of the pipe. The seventh and eighth fields in the SOL string are an estimated signal current on the pipe and its error both in microamps. This current is a good indicator of the signal magnitude in general.

It is important to note that the GNSS coordinates given in the PASHR-POS string are the location of the Spar sensor not the pipe itself. The GNSS has an error associated with it that can be improved using RTK correction. The depth and offset numbers have errors that are caused by interferences with the tracing signal or the radiated EM field of the pipe. The GNSS and the magnetic pipe location errors are quantified by the Spar and are independent of one another.

The ENU strings provide the relative location of the two spars by providing the East, North, and Up offset in millimeters. Note the first ENU string has three zero values that indicate that this string is from the leading or "origin" Spar. The second ENU string can be used to calculate the distance between the two. This distance between the two Spars is the baseline over which our phase difference is calculated.

Figure 5 is a screen shot of the FieldSens View Operator dashboard that is used by the operator in the field. It provides a graphical view of the pipe survey data that incorporates many of the data items that have been discussed in this section. The left hand pane shows a top down view of the pipe (blue line) location relative to the center of the Spar (yellow triangle). The right hand pane provides a cut away view displaying the depth of the pipe (blue dot) relative to the Spar (yellow cross). The depth and the offset are provided both graphically and numerically, as are the error estimates (red square). The estimated signal current is shown in milliamps.

The quality of the GNSS fix is provided both in terms of number of satellites and horizontal/vertical error estimates. In this particular example, real time kinematic (RTK) correction for location is being applied to improve the GNSS location. The application of RTK correction does require that there be a hotspot or other internet connection available and a local RTK server. Many states are now providing free RTK service; it is also available on a subscription basis.

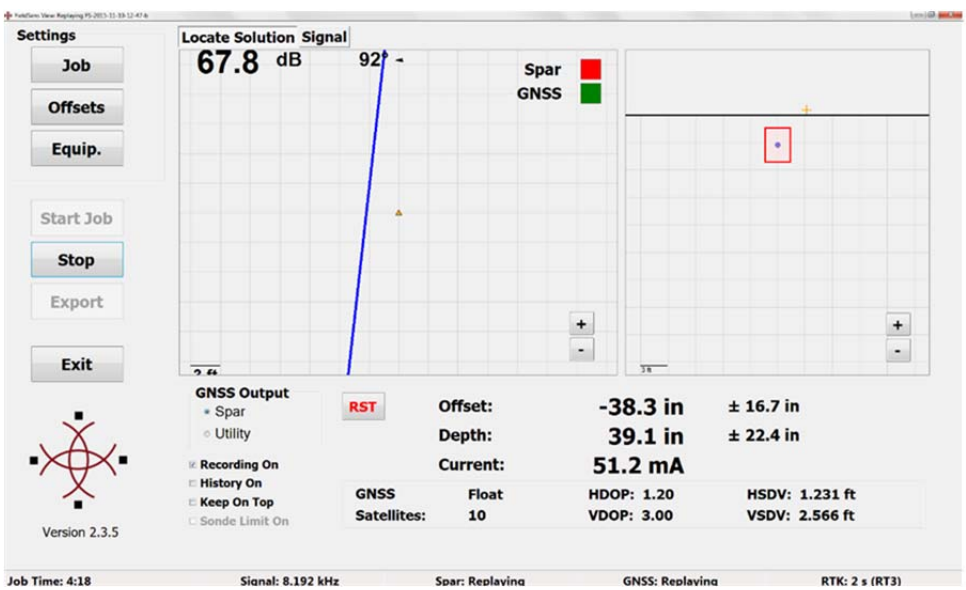

Figure 5 – FieldSens View Operator Panel

While the FieldSens View software provides sufficient operator feedback to allow the survey to track the centerline of the pipe, it does not provide any insight into the pipe/coating condition. Assessment of the pipe condition requires significant additional processing.

Data Processing Methods

The original thinking was that the RAW signals would need to be processed to determine the signal phase and magnitude at each Spar. The difference in these parameters between the Spars with be captured for each point in the survey. It was noted there is a phase measurement from the leading Spar and from the trailing Spar (in milliradians) already embedded in the SOL string. Initially this phase value was divided

by the ENU distance between Spars to provide a phase shift in degrees per meter. This approach is not technically correct; it was the result of a miscommunication between GTI and ORI, the manufacturer of the Spar system. The clarification was that the value embedded within the IISOL string is actually the relative drift between the phase clock in each Spar rather than the magnetic field phase change.

The current method makes use of the RAW sensor signals in conjunction with the phase clock drift to provide the estimate of the phase shift between Spars. The phase angle at each individual Spar is calculate by using the real and imaginary parts of a RAW sensor reading to calculate a phase angle. The difference between the phase angles is taken and the clock drift between the Spars is applied as a correction. This phase shift is still divided by the ENU distance between Spars to normalize the data to degrees per meter. The normalized phase shift between the two Spars is calculated as follows.

$$\frac{Phase\ of\ Spar1 - Phase\ of\ Spar2 + Phase\ Drift}{ENU\ separation\ of\ Spars}$$

The initial site data analysis method involved the use of Python and MATLAB both in order to produce mapped and graphed data (Figure 6). Partway through the project a shift was made to R Studio as the primary method to visualize the captured data. While the earlier methods were functional, there were several issues that needed addressing before it could be a path forward to commercial deployment of this technology:

- The processing of the data needs to take place within a single environment. The end user must not be required to access multiple applications to visualize survey data.
- The end user must not be required to perform any extensive cleanup of the raw data provided by the Spar prior to visualization.
- The number of manual steps required to prepare graphics must be minimized.
- There must be simple means of scaling visualizations to allow direct comparisons between multiple data sets.
- There must be simple means to define the geographic extent of a visualization to include/exclude specific data.
- The user interface should be simple and intuitive.

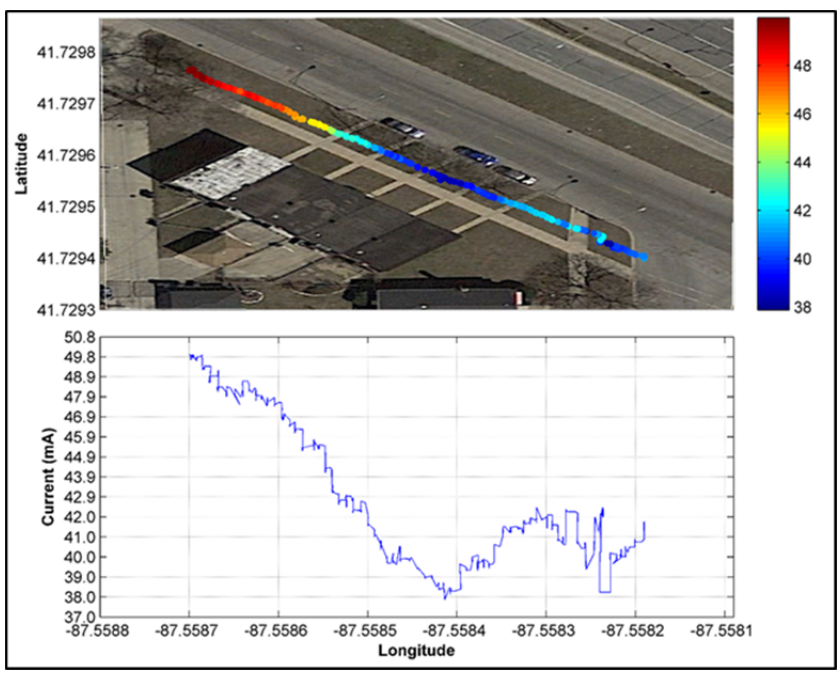

Figure 6 – Early Data Visualizations

Data Processing with R Studio

The R programming language was initially developed for statistical computing and display of data. The features that lead to its adoption by GTI for this application were the extensive graphics capability and the built in functionality for associating data sets with geographic locations. In the earlier version of the software it was necessary to manually pull a site map from an online service and then overlay the data. The mapping libraries available in R allow maps and imagery to be automatically acquired from on-line sources as shown in Figure 7.

Another data display features enabled by R was the color coding of data points. The Figure 7 map of current displays the magnitude by color coding. This allows the visual association of possible flaws or interferences to geographic features. The color coding also allows one to make use of the parameter error estimates provided by the Spar. Figure 8 shows a plot of current magnitude versus longitude with the estimated error displayed as point color. Overlaying the error estimate onto a parameter plot enables one to quickly identify probable outliers in the data. The spikes in the data in Figure 8 would be a source of concern if they appeared in a simple line plot.

The value of the R environment is greatly enhanced by the libraries available. It may have been possible to reproduce these same results by continuing effort with the Python language; Python has its own ecosystem of libraries. However, the existence of the extensive R mapping libraries and of a readily available means of generating a web interface greatly accelerated results for this project. The actual algorithmic approach to the data was reasonably well defined prior to shifting to R. A more in depth treatment of the web user interface and its features can be found in report Item 25, "Algorithm Improvement".

Figure 7 – Current Map Produced with R Studio

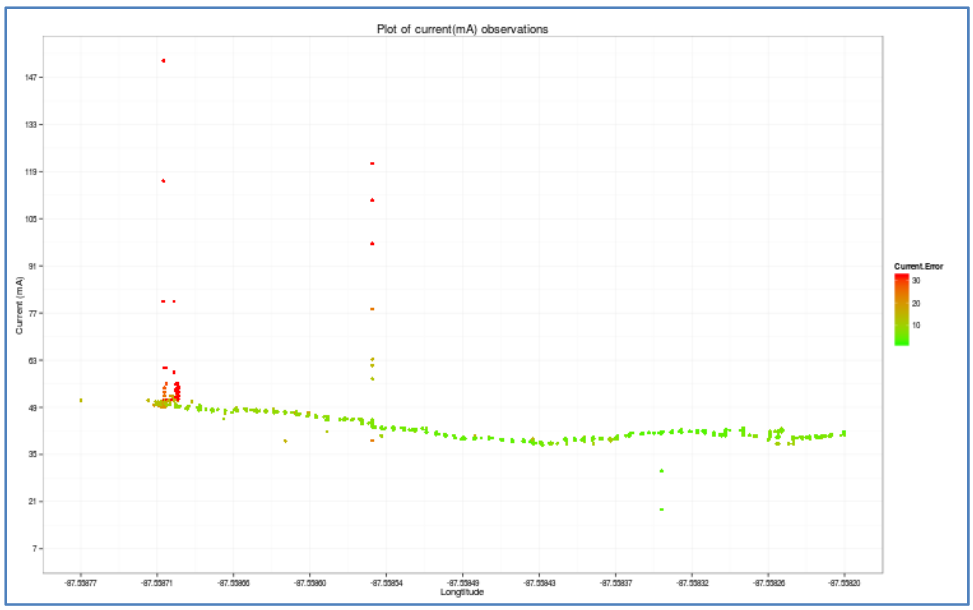

Figure 8 – Current Plot Produced with R Studio

Utility A Test Site

This section gives a high level view of testing conducted at Utility A. Several areas were surveyed but not all were excavated; the final choice on which locations to excavate were at the discretion of the hosting utility. This section focuses on a survey that concluded with a confirming excavation. The full text describing all of the various site surveys at Utility A can be found in report Item 8 "Initial Field Testing".

Utility A Site Background Information

The site consists of several miles of inter-station 36" steel main with coal tar enamel coating. GTI was provided information on specific areas where three anomalies were identified using ACVG surveys. The survey was carried out over several days and the data is in several segments rather than as a monolithic data map. A single segment was excavated and is discussed in this section. The main lay primarily within a parkway (Figure 9) and did not require any special traffic control during the surveys. A cathodic protection test station was available on the site to allow the hookup of the signal generator.

Figure 9 – Spars in use on Test Site A

A phase anomaly was located on the site that coincided with an anomaly identified during the ACVG and DCVG survey. Figure 10 and Figure 11 provide map imagery views of the site with the current and phase data overlaid respectively

The phase date from the Spar (Figure 13) shows an abrupt change over one portion of the survey. In previous work these changes have been found to indicate changes in "shape" to the pipe exterior. This can be caused by an attachment to the pipe such as an appurtenance or a change in the coating such as a bubble or blister. The phase measurement is normalized: the phase shift between the two Spars is divided by the distance between them to give degrees per meter. The expectation is that a featureless pipe would provide a constant rate of change over its length.

The change in current over the same area (Figure 12) is not large. The scaling of the plot is somewhat exaggerated in order to expose detail; the total span is only about 10 mA. Also note that the current level does not drop off at the location coinciding with the phase anomaly. The expectation from this data is that the coating is intact in this area. This is supported by earlier work in this area: coating holidays are indicated by a drop in the current level with no subsequent recovery. Shielding features, such as casings may cause a drop in the observed current over an area with a rise in the current at points beyond the shielding feature. The expectation for a featureless pipe is that the current would decay at a steady rate as the Spar sensor is moved away from the signal injection point.

Figure 10 – Current Map for Site A

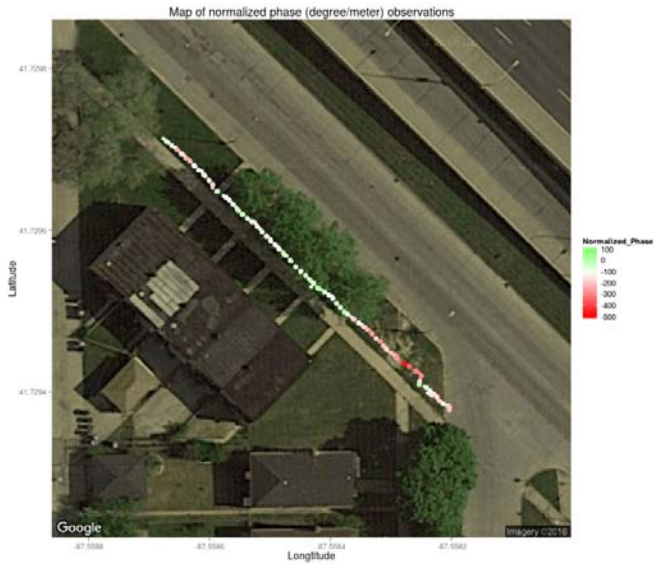

Figure 11 – Normalized Phase Map for Site A

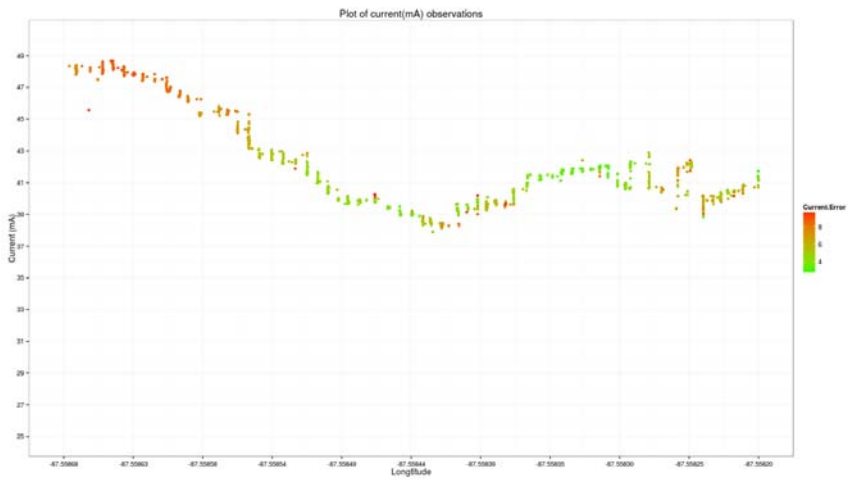

Figure 12 – Current Plot for Site A

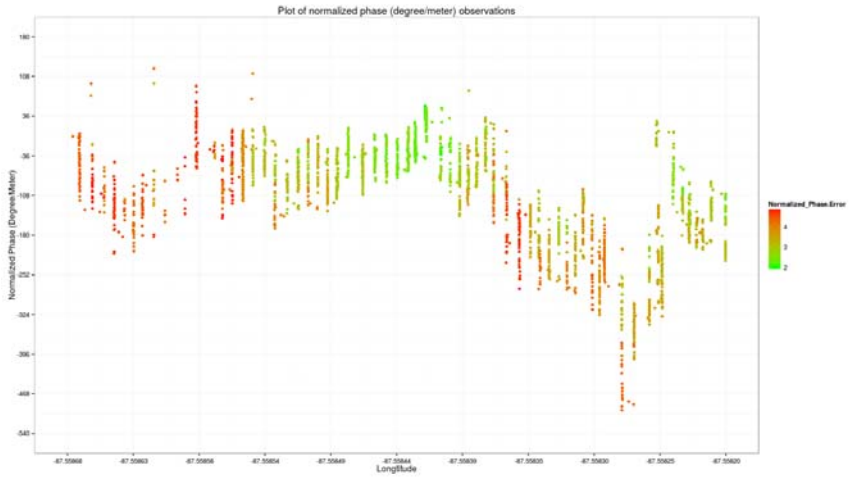

Figure 13 – Normalized Phase Plot for Site A

Utility A Site Findings

Upon excavation it was found that the buried pipe had been covered with half-sections of steel culvert at the location indicated by the phase shift plot (Figure 13). These, shown in Figure 14, had been put in place as protection against accidental dig in at the point where the pipe was shallowest. The pipe coating, when uncovered, showed minor dents and gouges but no exposed metal as shown in Figure 15. This agrees with the signal current plot for the same area: indicating very little change in current over the same area. A large change in signal current over a small area would indicate that a coating flaw or other exposed metal draining the signal.

Figure 14 – Steel Culvert Sections used to Protect Buried Pipe

Figure 15 – Exposed Pipe with Minor Gouges in Coating

Utility B Test Site

This section gives a high level view of testing conducted at Utility B. One length of pipe was surveyed that contained three areas of interest; all three areas were ultimately excavated. The full text describing the entire survey at Utility B can be found in report Item 21 "Initial Field Tests - Site 2 Results".

Utility B Site Background Information

Utility Company B provided access to the site and substantial support of GTI test activities during August of 2015. The site contained an 8" diameter high pressure steel line with a coal tar enamel coating. The site had been previously assessed by indirect survey techniques and three anomalies identified; these were designated for excavation in early September. The data presented here covers Anomalies 2 and 3 along with the subsequent excavation results. All three anomalies were excavated, however the Spar data gave no indications of a flaw at Anomaly 1, as verified by the excavation.

An initial visit to the area was carried out to verify that it was suitable and to determine the location of an appropriate signal injection point in proximity to the anomalies. The pipeline is located in a green space between two roads; traffic control was not an issue. It was determined that the closest metallic access point was a valve box at the extreme north end of the site being surveyed. It was possible to make contact with the valve and inject a signal by placing a digging bar into the valve box. The contact was serviceable but somewhat intermittent. The hosting utility volunteered to install a new test station the following morning in order to better facilitate the testing.

The new test station was complete by the following morning allowing testing to proceed. The injected signal was in excess of 150 mA which was a factor of 3 better than what was achieved through the valve box. The three anomalies were surveyed over the next two days, allowing two complete sets of data to be captured across the site. As noted, three anomalies had been identified by ACVG and DCVG surveys and were clearly marked with stakes. Overall, there were very few interfering facilities in the area.

Test Site B Anomaly 2

The second anomaly marked out has several physical features that must be noted. The location is substantially downhill from the first anomaly. There is a drainage culvert nearby that did cause some interference with the signal that shows up in the data. The interference is probably due to rebar embedded in the concrete structure. The culvert is not immediately adjacent to the marked location of Anomaly B-2 but its presence must be noted when interpreting the data. The stakes indicating the suspected location of the anomaly are just visible in the upper right of the picture.

Figure 16 and Figure 17 show phase data, taken on two consecutive days, superimposed on geospatial imagery. The outlet of the drainage culvert is near the top (north) end of the image. Slightly different areas were included in the surveys on each day. This introduces offsets in the data which must be accounted for in the interpretation. In Figure 17 one can discern the location of the marked out anomaly by the increased density of the mapped points in the middle of the picture. The personnel conducting the test decreased the spacing between readings in the area close to the anomaly.

Figure 16 – Phase Map 1 near Anomaly B-2

Figure 17 – Phase Map 2 near Anomaly B-2

The following current and phase plots were also taken on two consecutive days. Figure 18 and Figure 19 must be interpreted differently because they contain the data from the drainage culvert. There is a distinct upward change in the current level in Figure 18 near the right edge of the graph. Figure 19 shows a change in the normalized phase shift slope close to this same location. When one examines the latitude associated with this change it aligns well with one edge of the culvert. The data from that point continuing to the right edge of the graph is strongly affected by the presence of the culvert and not likely to be indicative of a flaw in the pipe.

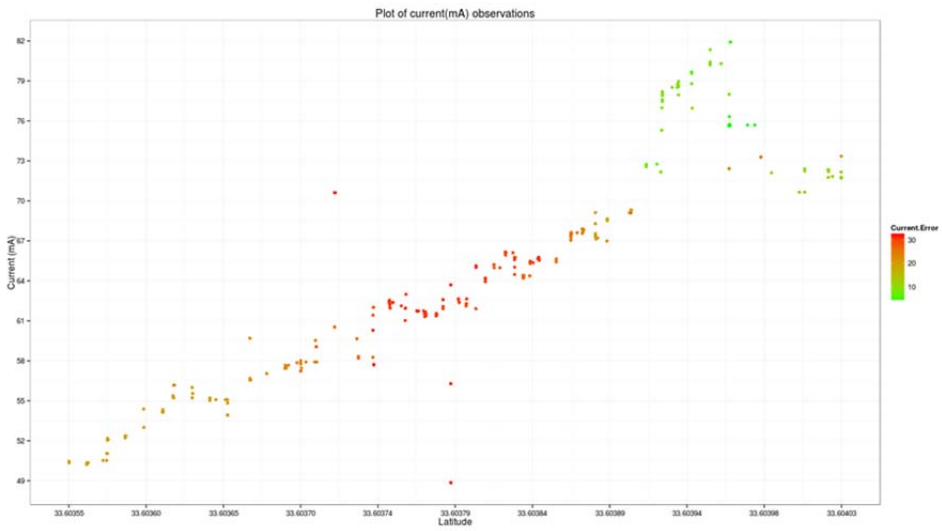

Figure 18 – Current Plot 1 for Anomaly B-2

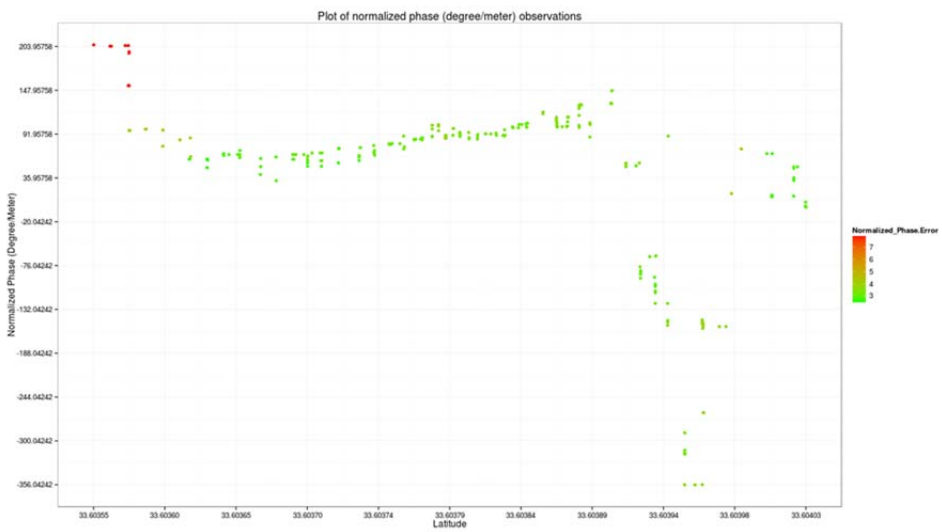

Figure 19 – Phase Plot 1 for Anomaly B-2

An upward trend in the current and corresponding change in the phase slope can be seen in Figure 20 and Figure 21 on the following day. This case the feature is located toward the center of the graphs; there is no data from the culvert area in these two plots. There is also a difference in the acquired latitude and longitude coordinates between the two days; a longer path was captured in the first data set.

The experience with the Spar system thus far is that abrupt changes in the current slope are indicative of coating holidays. GTI has received verbal indication that there was a small flaw in the coating in this vicinity when the excavation took place. Figure 22 is a version of Figure 18 that has been rescaled to exclude the culvert data and allow a better direct comparison with Figure 20. There is similarity between the current slopes on different days but at this anomaly it is somewhat weak.

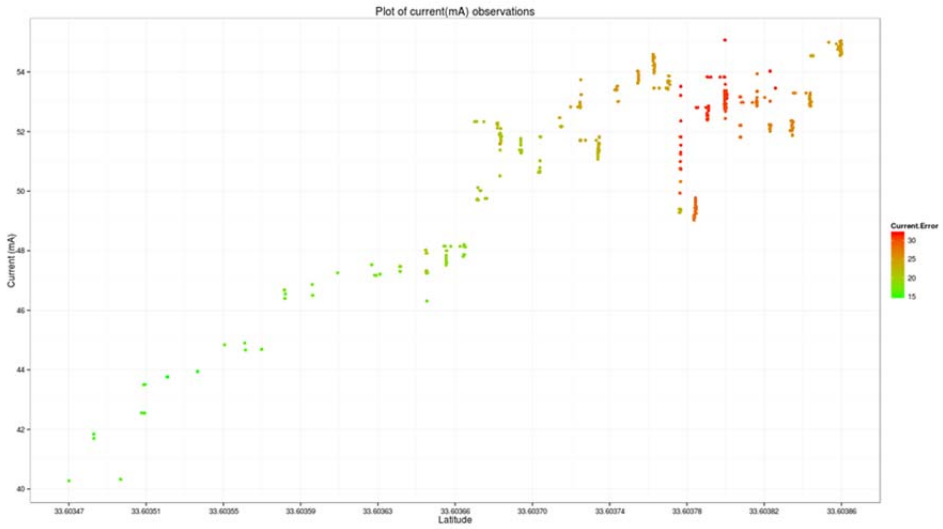

Figure 20 – Current Plot 2 for Anomaly B-2

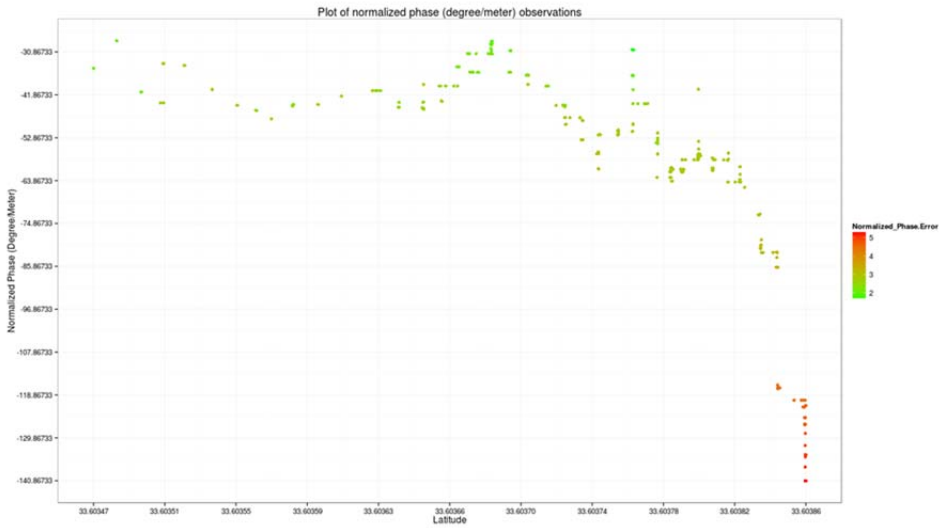

Figure 21 – Phase Plot 2 for Anomaly B-2

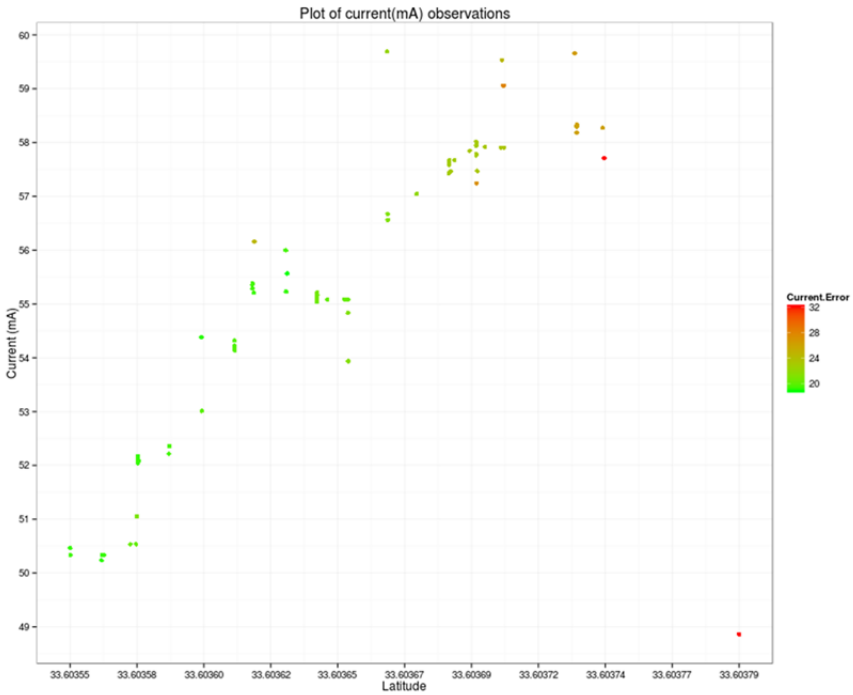

Figure 22 – Rescaled Version of Figure 16 to Exclude Culvert

Test Site B Anomaly 3

Anomaly B-3 is the most southern and furthest removed from the point of signal injection of the three. One consequence of this location is that the injected signal level was the weakest at this point in the survey. In spite of location of the pipe, the` acquisition of data was reasonably straightforward. Figure 23 shows the staked location of Anomaly B-3 as indicated by standard survey techniques. Anomaly B-2 and the culvert structure are in the far background of the picture.

The initial interpretation of the data was that there may be a coating flaw in this location. The data shows a structure that is repeated at the same location on two subsequent days. Figure 24 and Figure 25 show current and phase data projected onto the map. The horseshoe shaped structure on the right of the picture is a flag emplacement that is at the same level as the roadway; these are elevated above the location of the pipe. Note that there is street lightning at the left side of the picture that aligns with the flag emplacement; there is a possibility that electrical conduits perpendicular to the pipeline connect these.

Figure 23 – Spar in use at Anomaly B-3

Figure 24 – Current Map for Anomaly B-3

Figure 25 – Phase Map for Anomaly B-3

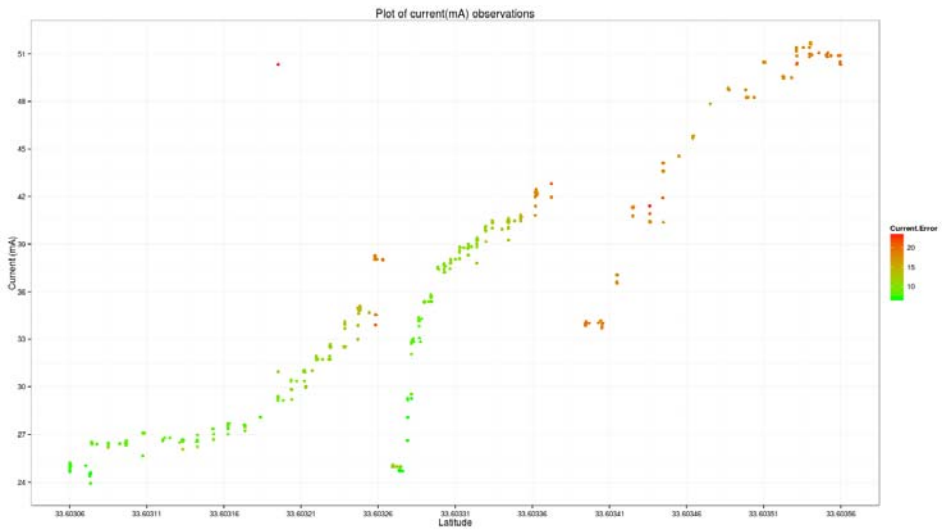

Figure 26 – Current Plot 1 for Anomaly B-3

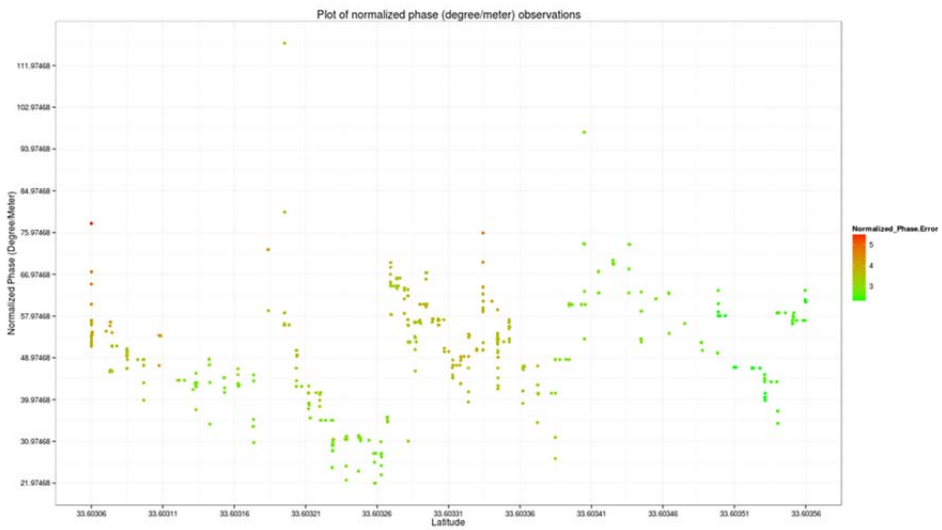

Figure 27 – Phase Plot 1 for Anomaly B-3

Figure 26 and Figure 27 show current and phase data respectively. There is a discontinuity in the current plot that corresponds with a dip in the phase plot. The discontinuity in the middle of the plot aligns roughly with the staked location of Anomaly B-3. One can get a rough idea of the location on the mapped points from the data point density; again, the operators took closer readings when traversing this area. There is another smaller discontinuity to the north of this.

Figure 28 and Figure 29 show current and phase plots for Anomaly 3 taken from a different day. The large current discontinuity is repeated in this data at the same geospatial location. In this case the second current discontinuity to the north is less pronounced. The changes in the phase plot correspond well with those in the current.

Two possible explanations for these features in the data suggest themselves. The first is that there is a coating flaw on the pipeline at this (or both) locations. This explanation was refuted when the excavations took place; no coating flaws were found in the location that had been marked out.

The other possibility is that there is another buried structure in the area that is causing these features. The presence of the flag emplacement and highway lighting may indicate buried power conduits. The locations of other facilities in the area should be evaluated in light of this data.

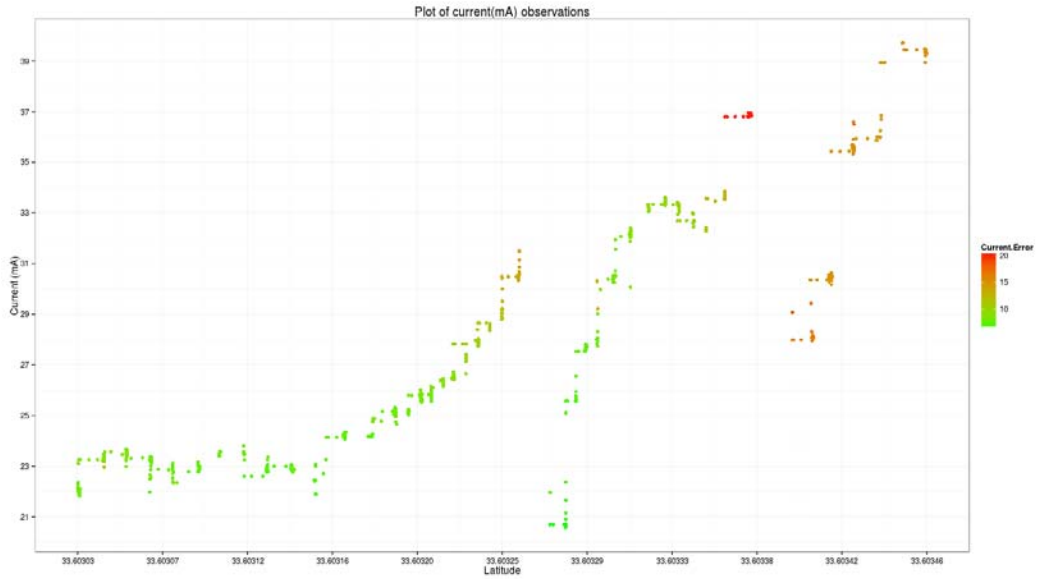

Figure 28 – Current Plot 2 for Anomaly B-3

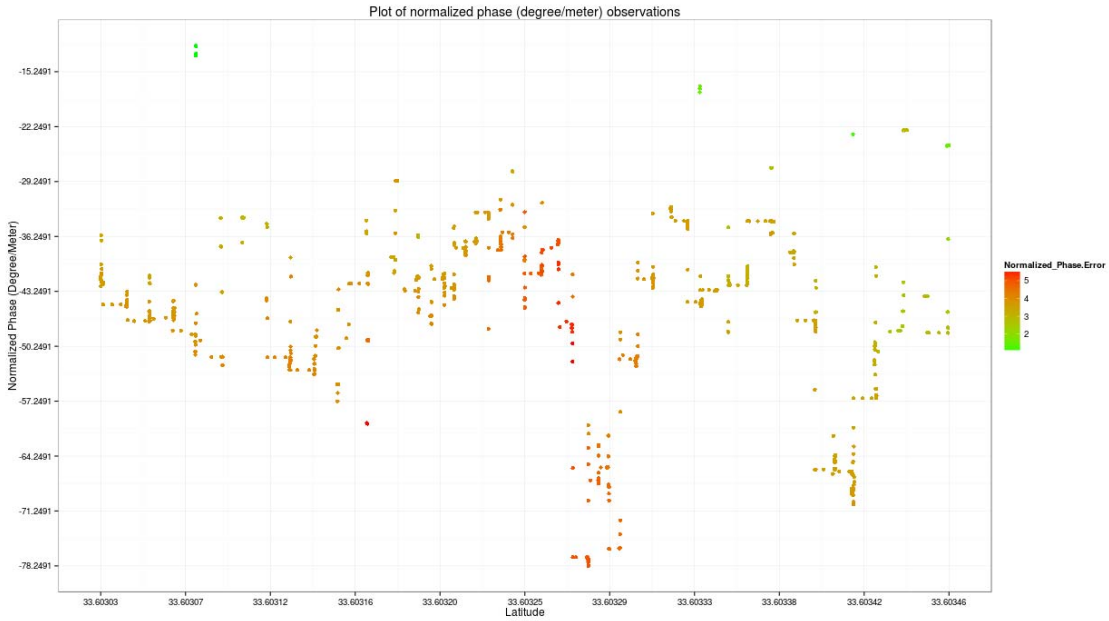

Figure 29 – Phase Plot 2 for Anomaly B-3

Utility B Site Findings

The site was excavated shortly after the surveys carried out by GTI. There was a delay of several months before documentation of the sites was provided to GTI. The contractor performing the work for Utility B needed to complete many other sites as well and submitted this data as a single report. After receiving the contractor's report, Utility B needed to review and extract the appropriate data to provide to GTI. All three anomalies were excavated. Only Anomaly B-2 showed any coating holidays.

Figure 30 shows the location of the holidays at Anomaly B-2. There were two small holidays, one at the 11 o'clock and one at the 8 o'clock location. The lateral separation between the two was roughly one foot. The contractor report indicates that the coating was well bonded and the holidays were small gouges in the absence of any widespread corrosion.

Figure 30 – Location of Coating Flaws Found during Excavations

Figure 31 – Adjusted Current Map Data for Anomaly B-2

Figure 31 shows the Spar current data for Anomaly B-2 projected onto a map. In this mapping the data in the vicinity of the culvert has been omitted for clarity. One can see from the color coding that there is a shift in the current level that coincides with the holidays found in the excavation. Figure 32 represents the same data versus latitude. The contractor report places the holidays at 33.60377 latitude; this does correspond to point in the plot where there is a shift in the slope of the current curve. Although less obvious due to the scatter, Figure 33 shows the median of the phase shift changes depending on which side of the anomaly the data is. There is reasonable correlation between the Spar data and the small

holidays found in the excavation. The exact size of the holidays was not provided in the contractors report but the change in current would indicate they were quite small.

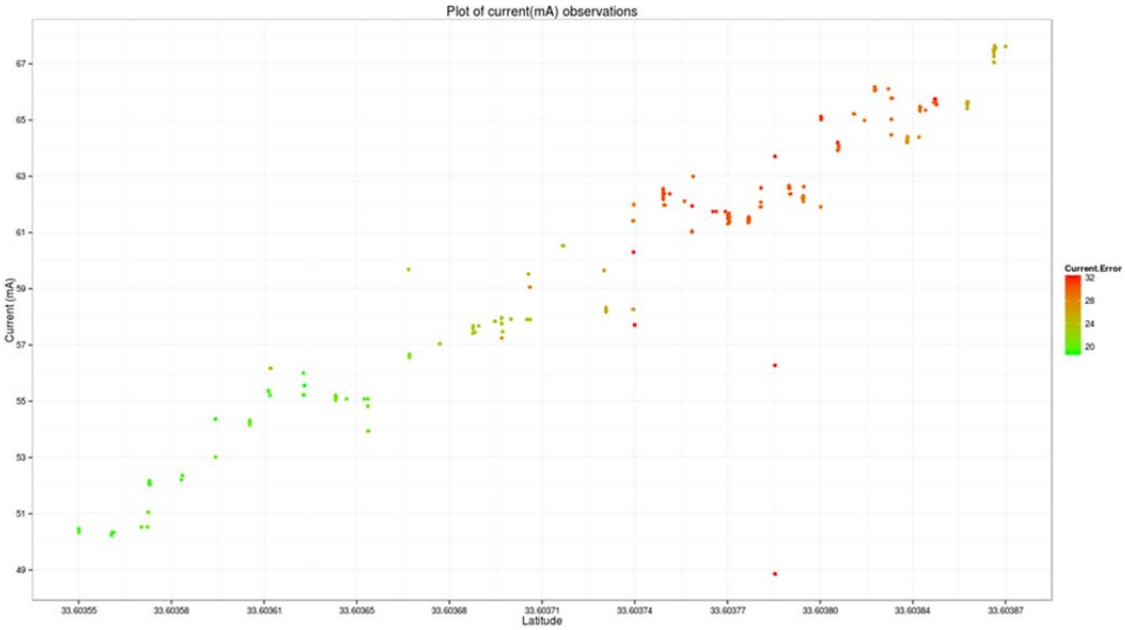

Figure 32 – Adjusted Current Plot for Anomaly B-2

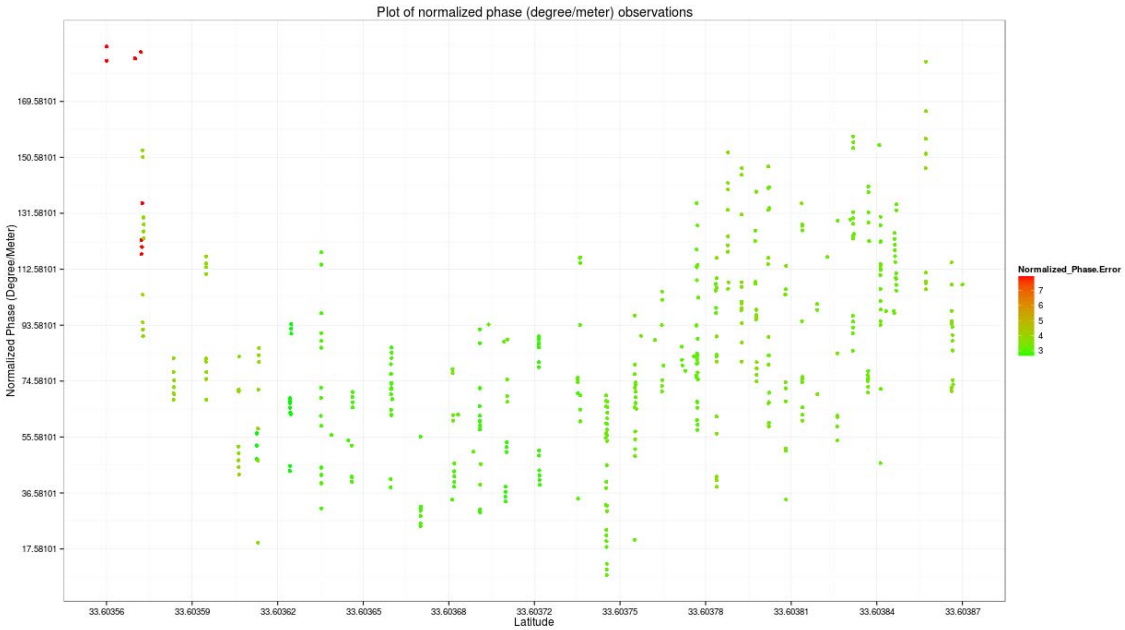

Figure 33 – Adjusted Phase Plot for Anomaly B-2

GTI's initial analysis of the data was that there is a strong and repeatable indication at Anomaly B-3 that may be indicative of a coating flaw. No flaw was found when excavation was carried out. The source of the perturbation in the current curves still remains unknown at this time. The best possibility is that another infrastructure crosses the gas line at that point. A deeper metallic facility could drain some of the signal current and produce the changes in the data indicated. It is interesting to note, however, that both the Spar technology and the standard survey technique found indications at B-3. If there is no underlying cause, then both methods produced false positives.

Utility C Test Site

This section gives a high level view of testing conducted at Utility C. Several areas were surveyed at this utility but not all were excavated. One particular length of pipe surveyed had been scheduled for in service replacement of the coating; all of this was ultimately excavated. This section focuses on the area excavated. The full text describing the entire survey at Utility C can be found in two reports; Item 18 "Initial Field Tests –Site 3 Results" and Item 27 "Follow up Field Testing".

Utility C Site Background Information

Utility Company C provided access to two test sites and substantial support of GTI test activities during November of 2015. The Spar hardware was used to capture survey data at both of these sites. This data was post-processed and an assessment of potential flaws was provided to the utility. Only the second site (C-2) was excavated subsequent to the Spar survey.

The C-2 site contained two side by side buried electric feeders. These are 3 phase power lines enclosed in 10" diameter steel pipe with 5" diameter re-circulation lines for cooling oil. The electric site was volunteered in response to GTI expressing an interest in disbondments. The utility indicated that coating at this site was due for renewal in spring of 2016, providing an opportunity to capture results.

On November 11, 2015 GTI met with the utility at test site C-2. The test subject was a pair of parallel underground electric feeders under a residential street. These are 10" diameter steel lines with 3-phase conductors inside as shown in Figure 34. Proceeding south from the manhole, steel pipe is coated with coal tar enamel for several hundred feet at which point it transitions to newer tape wrap coating. The feeders are oil-cooled and have 5" diameter steel recirculating lines parallel to the feeders. The reasons for including this site in the study is that the hosting utility indicated the probability of finding disbondment on the electric feeders was much higher than on similar gas systems.

The first step was to enter the electric manhole and pump out the excess water. After this the CP bond wire connecting the feeders together was separated to allow the tracing signal to be injected on one feeder at a time. The West line was traced first using the signal generator with the standard ground rod provided; only 60 mA of signal could be obtained in spite of re-positioning the ground rod several times. The utility then provided a digging bar that was hammered into the ground about 20' East of the manhole to provide better contact. With this arrangement 150-170 mA was obtained; the test run was started with this current level.

Figure 34 – View of Electric Feeders in Manhole

Figure 35 and Figure 36 show the current and phase maps respectively for site C-2 West. The signal injection point is via the manhole in the upper right of the area shown. The utility provided guidance as to the location of the boundary between the older coal tar coating and the newer tape wrap; the survey data does include some of the tape wrapped pipe in the lower left of the area.

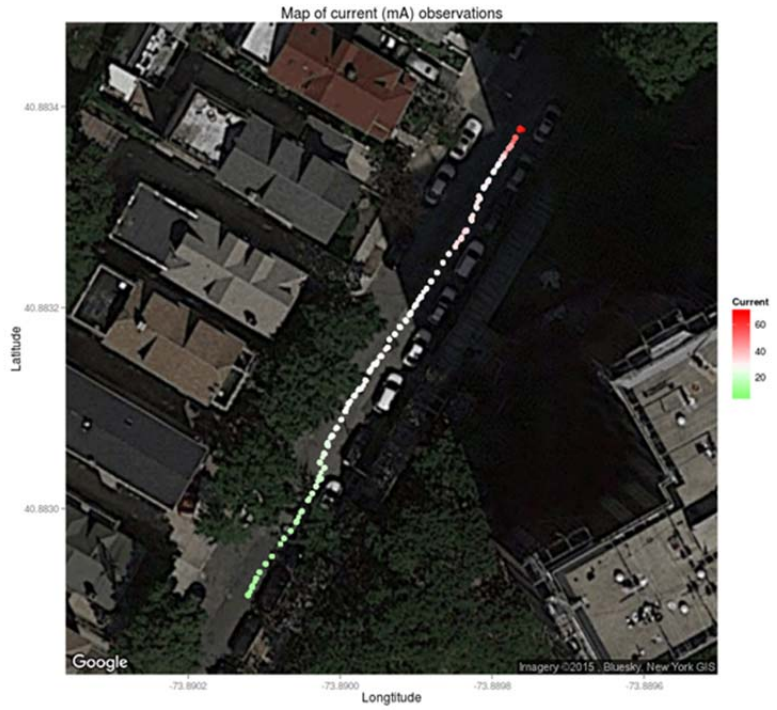

Figure 35 – Current Map of Site C-2 West

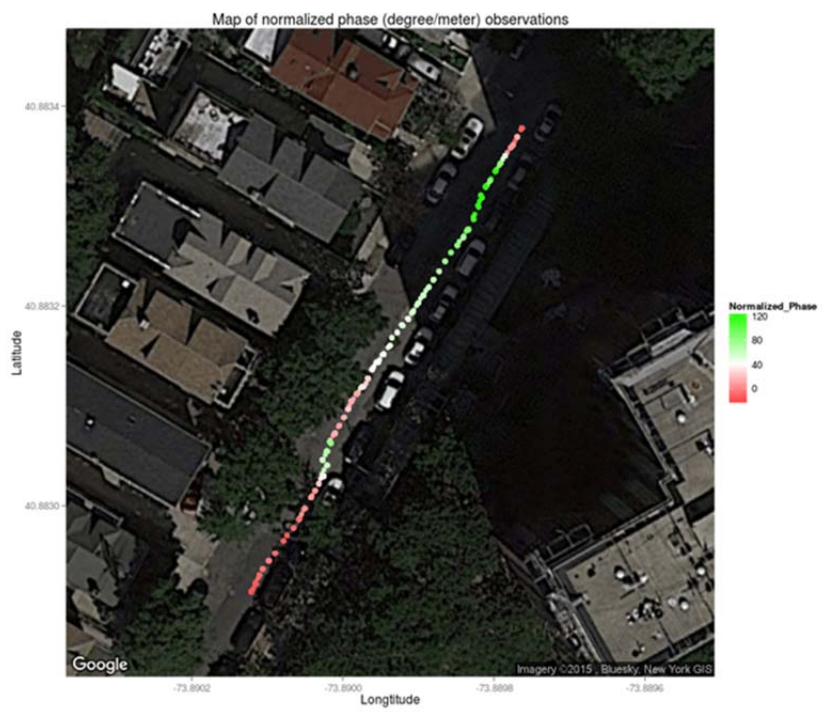

Figure 36 – Phase Map of Site C-2 West

Figure 37 and Figure 38 are the current and normalized phase shift plots versus latitude over the same area. The current plot does show a slight disturbance at the location of the feature of interest but returns to the trend-line of increasing current approaching the source. The phase plot shows a large disturbance at the same location and then returns to the original trend-line. The fact that the current does not show an abrupt and persistent change in magnitude over the feature of interest would tend to rule out any significant hole in the coating. The large phase deviation is indicative of a change in the "shape" of the pipeline coating. These data taken together indicate a likely coating disbondment at this location (40.88305 latitude).

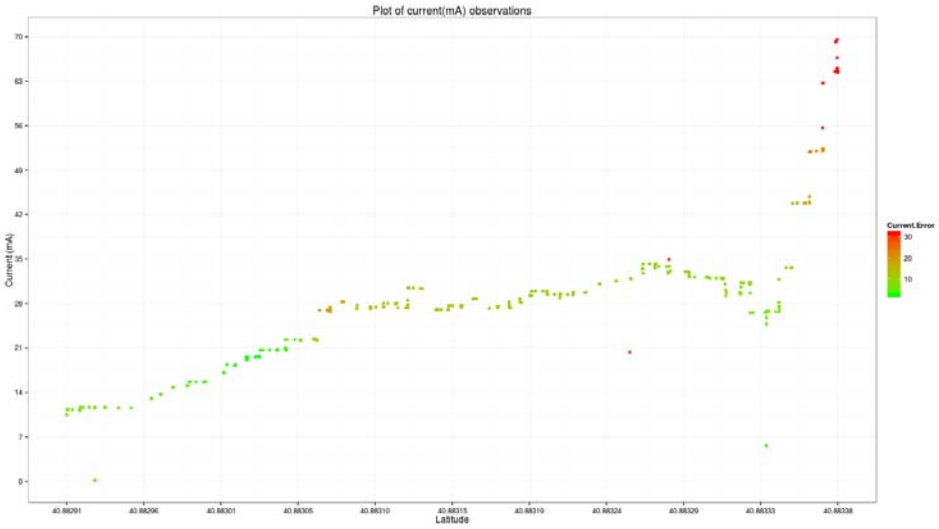

Figure 37 –Current Plot of Site C-2 West

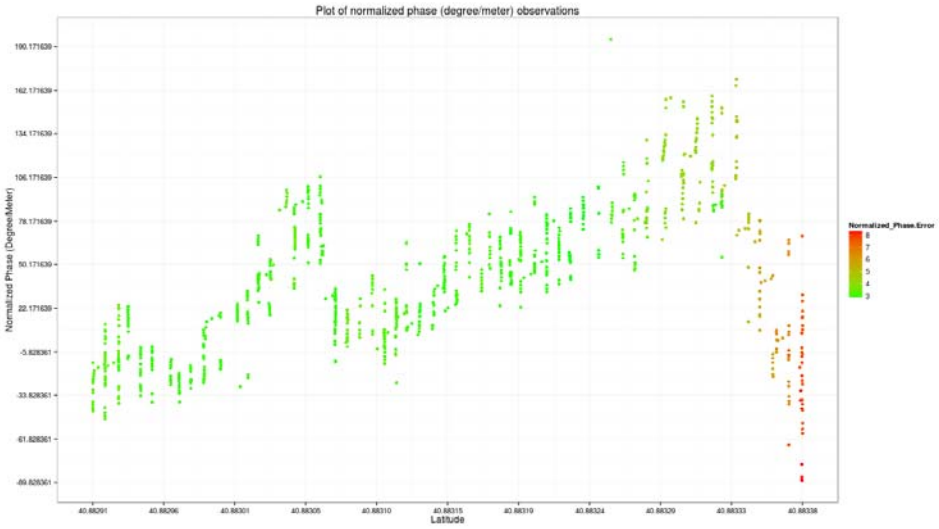

Figure 38 – Phase Plot for Site C-2 West

Utility C Site Findings

The C-2 site was excavated and the coating renewed during March of 2016 as planned by the hosting utility. This involved exposing the pipe to remove the existing coal tar enamel and replacing it with tape wrap. Figure 39 shows the exposed pipes and an area of disbonded coal tar enamel that coincides with the features in Figure 37 and Figure 38. The photo has been rotated such that North is at the top of the frame. The report from the excavation indicates the area of significant disbondment on line C-2 West began 181 feet south of the manhole. Figure 40 shows that this distance is an extremely good match for the estimated location of the flaw one would expect from Figure 36.

Figure 39 – Disbonded Coal Tar Coating found in Excavation

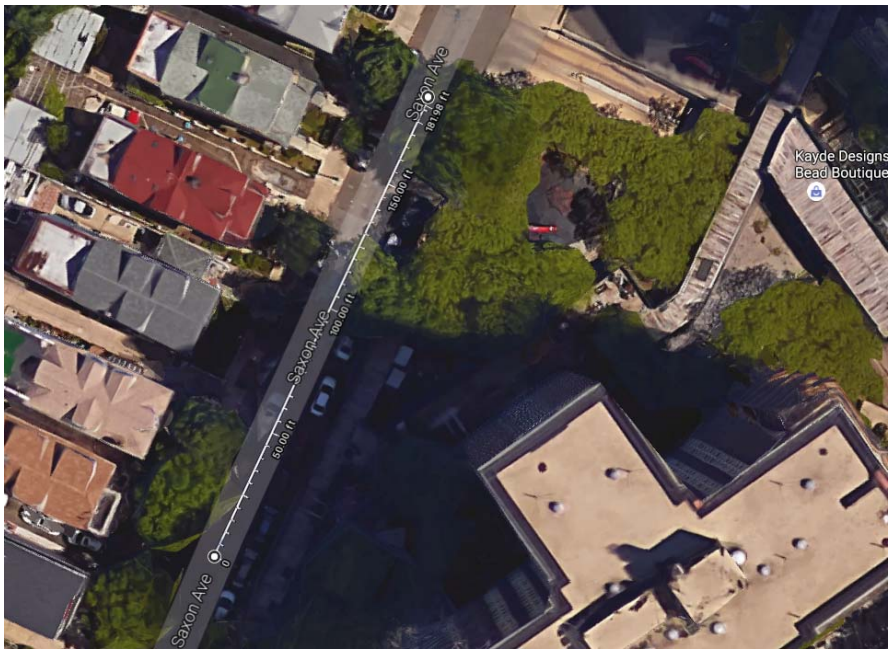

Figure 40 – Projected Distance from Manhole to Flaw

Follow Up Survey

During July of 2016, GTI was given the opportunity to return to this site and run a second survey on the line C-2 West with the new coating in place. This second survey provides a before and after comparison of the Spar signal data relative to the coating condition. Based on the previous experience with interference caused by parked vehicles, no attempt was made to survey the line C-2 East.

The second survey did meet with a number of challenges. For reasons that are still not clear, it was not possible receive RTK corrections to the GPS. The data points collected have standard GPS accuracy. Given that this is a second survey, the current and phase measurements were more important than the absolute position. When the manhole was opened to apply a signal to the pipe, it was discovered that the bonding wire had broken loose from the pipe. In order to inject the signal, a magnet with the signal wire connected was placed on the pipe; this provided an intermittent connection. As with the first survey, a digging bar was driven into the soil to the side of the pipe to provide a ground. Several signal wires were tried and the ground rod repositioned in an attempt to remedy this. Water was applied to the soil around the ground rod to improve contact; the soil was much dryer than at the time of the original survey. The contact point on the pipe was cleaned several times with a file and a wire brush before a reliable signal of 140 mA was established.

Figure 41 and Figure 42 show the observed signal current plotted versus distance along the line for the old and new coatings respectively. For these plots, the max and min currents and the latitude range have fixed to allow direct comparison. It is obvious that the new coating is retaining more signal current than the old; the overall signal level is higher and has less loss as one moves away from the injection point. The signal level with the new coating still has ripple in the values; some of the variations coincide with those from the first survey. Given that the entire coating has been replaced, these variations may be caused by service lines or other metallic features native to this site.

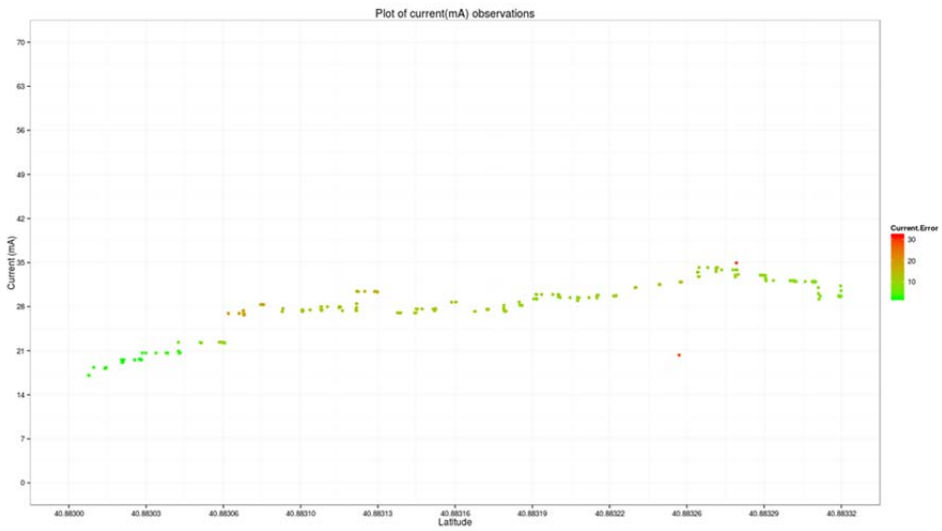

Figure 41 – Current Plot with Old Coating

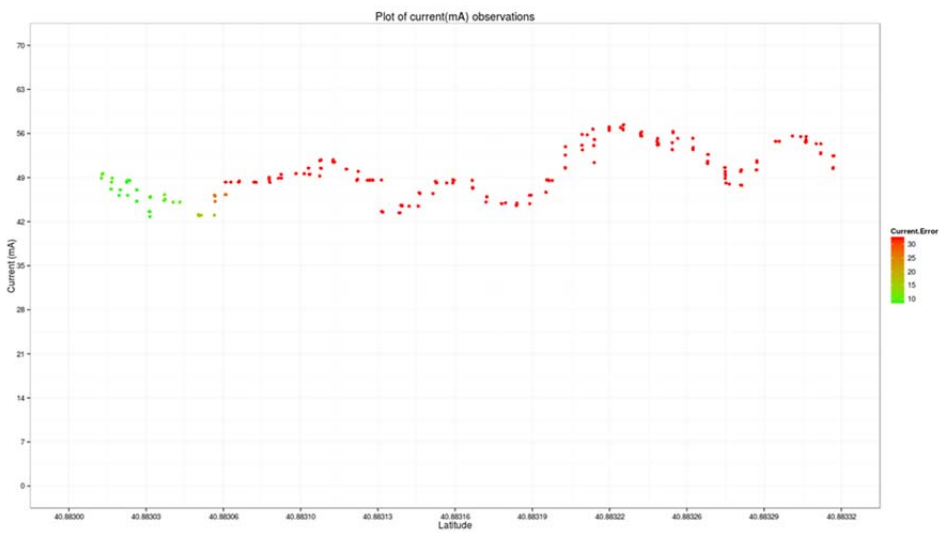

Figure 42 – Current Plot with New Coating

Figure 43 and Figure 44 show the phase plots over a common range before and after re-coating. As with the current plots, the overall range and scatter of the phase values has been reduced by the new coating. Also, the new phase plot has some features that were present in the old, albeit less pronounced. There is still a transition in the new phase plot near where the disbonded coating was found and subsequently repaired; the magnitude is smaller than before. This, in conjunction with the current data, leads to the speculation that there may be some sub-structure to this site that is not associated with the electric feeder lines but still is interacting with the signal current.

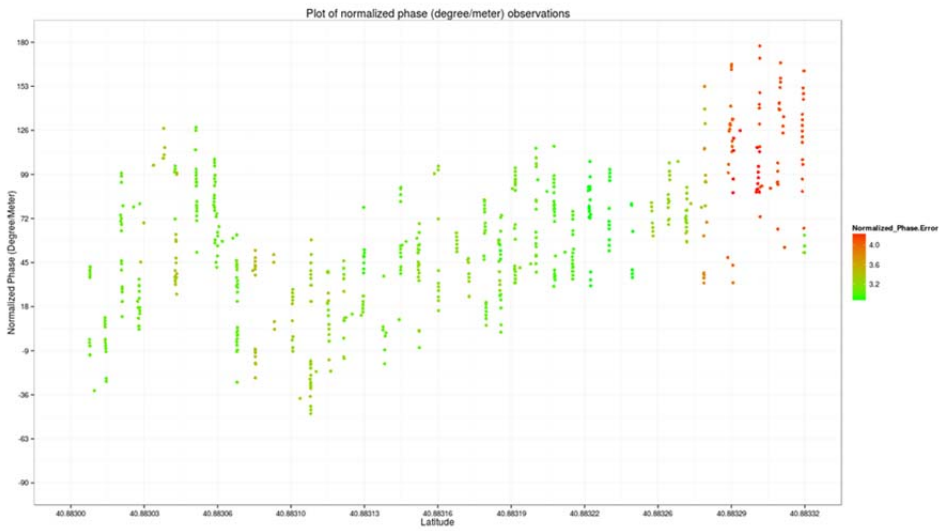

Figure 43 – Phase Plot with Old Coating

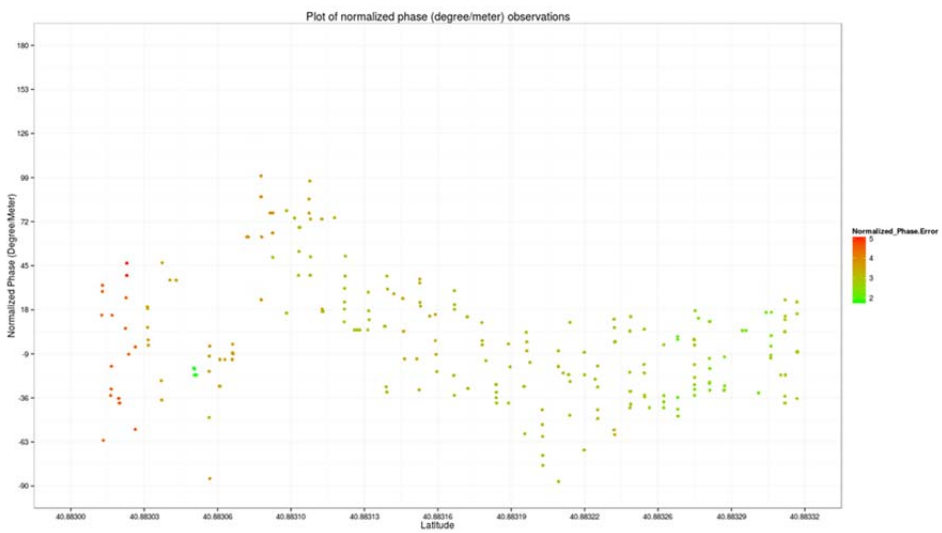

Figure 44 – Phase Plot with New Coating

Investigation of Cast Iron Pipes

This section will describe the experiments specific to assessing the condition of cast iron piping. There will be discussion of the reasoning for setting up an indoor test facility with known cast iron samples rather than depending on what could be found "in the real world". It will also provide justification for abandoning this line of research and focusing on coated steel facilities. A complete treatment of the cast iron investigations can be found in report Item 11, "Test Results of Graphitized Cast Iron Pipe".

Samples of graphitized cast iron were obtained and characterized. An indoor test facility was constructed to obtain measurements of the signatures under controlled conditions. A small number of outdoor measurements were made on utility owned cast iron mains to determine an order of magnitude for the current that could be induced. These items are explained in greater detail in the following section.

Cast Iron Background Information

All of the utility test sites offered during this project have been on coated steel lines and not cast iron pipes. Given this lack, GTI constructed several cast iron test strings in order to gather baseline data. Several samples of 6" cast iron (Figure 45) with varying degrees of graphitization were on hand. The extent of graphitization (Figure 46) was verified for each sample by cutting sections for micro-photography. The goal was to install these in line with sections of new ductile iron pipe to form the in-ground test strings. Ultimately, the experimental data from the above ground testing did not support proceeding with burial of the samples.

Figure 45 – Samples of Graphitized Cast Iron

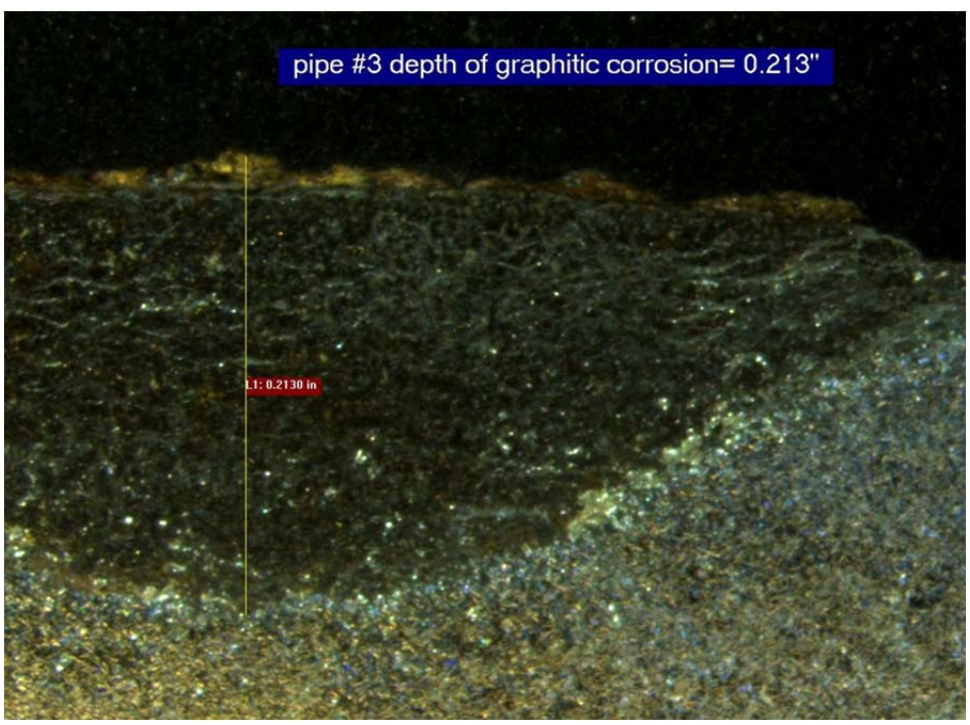

Figure 46 – Micro-Photograph of Cast Iron Graphitization

Several preliminary steps to verify that the accuracy of the Spar survey technique for cast iron were carried out. One of these preparatory steps was to accurately measure the degree of graphitization on the sample pipes using a non-destructive evaluation technique called Broadband Electromagnetic (BEM) scanning. The Australian contractor, Rock Solid, was engaged by GTI to perform BEM testing of the cast iron samples. The result of the BEM test is a map of the apparent wall thickness for each of the three samples; this mapping has been shown in previous work to correlate well with the metal loss caused by graphitization. Figure 47 shows a typical output map from the BEM process.

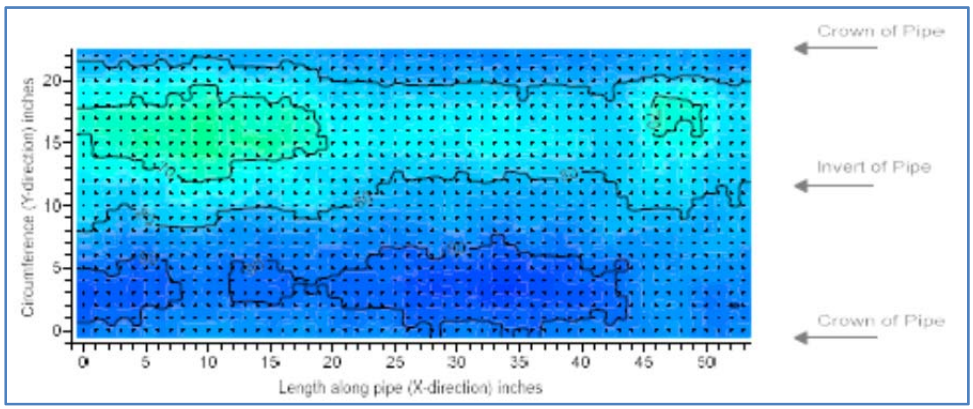

Figure 47 –Typical BEM Mapping of Apparent Wall Thickness

The actual BEM measurement is carried out using an antenna that must be in close proximity with the pipe wall. BEM does not require removal of the coating on a pipe and can tolerate an air gap of a few inches; the range is not sufficient that it can scan a pipe from above ground. The detail level of a scan is set by the size of the scanning antenna. The antenna used for the GTI testing provided resolution of 1 square inch; this is the finest pitch available. All three cast iron samples were processed in this fashion. The full BEM test reports for the three samples are included in report Item 11.

GTI then set up an indoor test facility to calibrate the response of the cast iron specimens to the Spar survey under controlled conditions. The various test specimens are inserted in series with two new sections of ductile iron pipe. Ductile iron is used because its magnetic properties are identical with cast iron gas pipe, which is no longer manufactured. The graphitized samples are roughly 5' in length and the new ductile iron section are 20' in length. The extended length will help ensure that magnetic measurements on transition from new to graphitized pipe sections will be far from any end effects where the signal current is placed on the pipe.

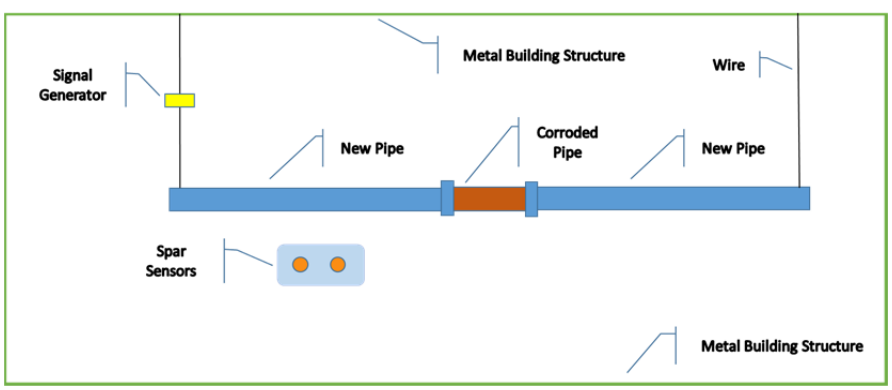

Figure 48 – Schematic Representation of Indoor Test Setup

These tests were carried out above ground to facilitate the quick change out of the test section that is sandwiched between two new pieces of ductile iron pipe. The test area had an overhead hoist that allows the samples to be easily moved. Because there is no soil to complete the circuit for the signal current, the building structure was used as the return path (Figure 48). The indoor tests represent ideal current injection into the test specimen through direct metallic contact.

The Spar equipment being tested on the indoor pipe string is shown in Figure 49. After the three graphitized samples were tested in this fashion, the test was repeated with new ductile iron (**Figure 50**) to determine any significant change. There are a number adjustments made to the test procedure necessitated by working indoors. The GPS antennae for the Spars are located outside of the facility using extension cables. The GPS with RTK correction is still required to maintain the accurate timing for phase measurements. This necessitates using a different procedure to determine the location of the two Spars relative to the pipe. This was accomplished with an odometer wheel in direct contact with one of the cart tires. This allowed reasonably precise locating of the sensors relative to the specimen for indoor testing.

Figure 49 – Indoor Cast Iron Testing with Spars

Figure 50 – New Ductile Iron Replacing Graphitized Sample

Cast Iron Experimental Results

The following plots are extracted from report Item 11 and represent a small subset of the test runs made during the course of indoor cast iron testing. Three replicate runs were made for each of the graphitized cast iron sections and also for the new ductile iron section. Figure 51 and Figure 52 show typical results for a graphitized cast iron test specimen, Figure 53 and Figure 54 for a clean ductile iron specimen.

There is little apparent difference in the data between the graphitized and the new test specimens. The data presented is taken from the middle portion of the test run such that the end effects of the new pipes bracketing the test specimen are minimized. The inflection points in the phase data curves provide a good visual indication of where the bell and spigot joints are located. If there were any distinguishing characteristics of the sample material, it would be seen in the region between these; none were identified.

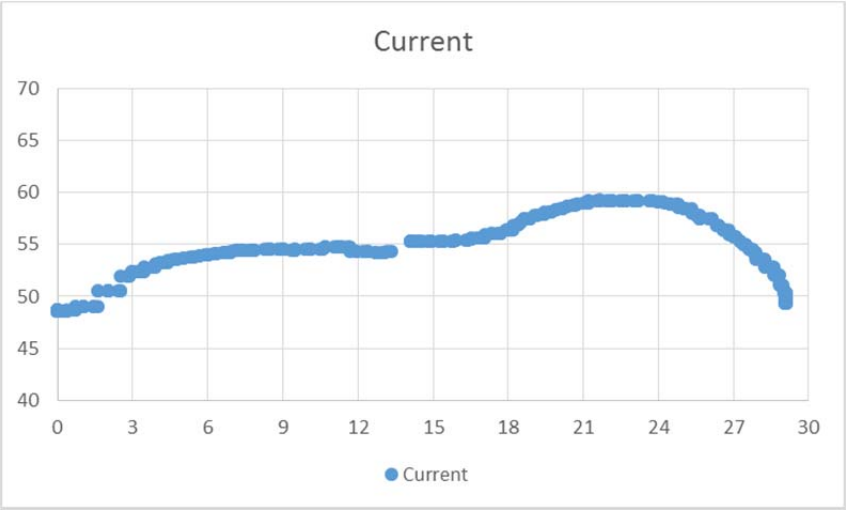

Figure 51 – Current Plot for Graphitized Cast Iron

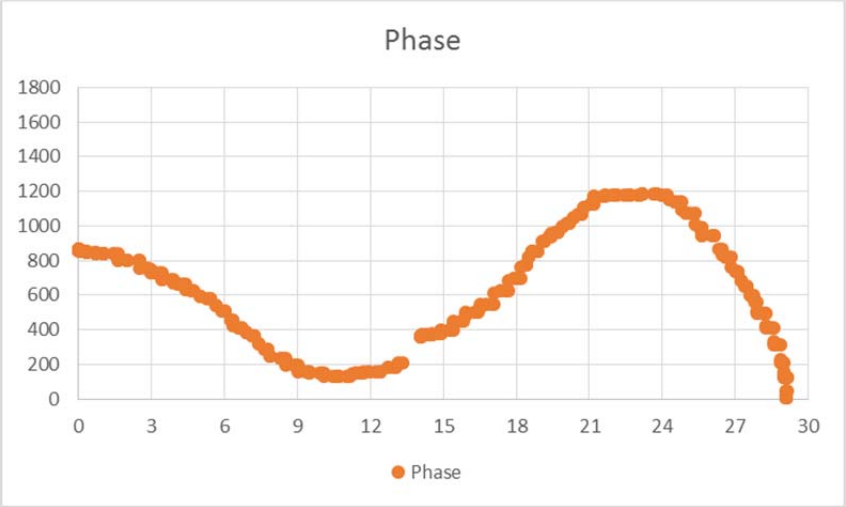

Figure 52 – Phase Plot for Graphitized Cast Iron

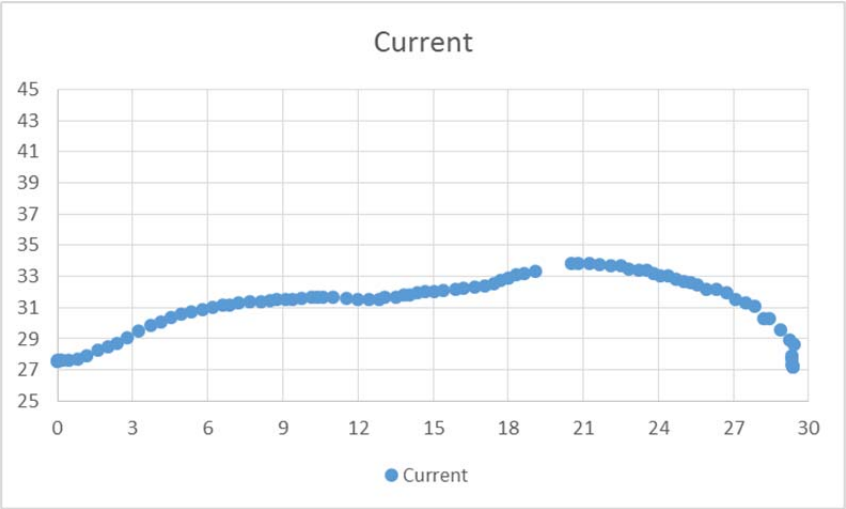

Figure 53 – Current Plot for New Ductile Iron

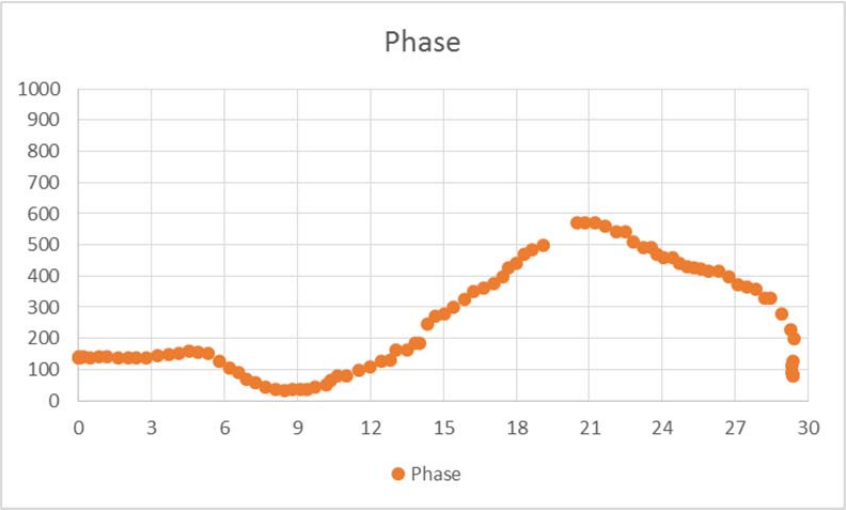

Figure 54 – Phase Plot for New Ductile Iron

A small amount of outdoor testing was carried out at a site known to contain a cast iron main. In this case the inductive coupling mode of the signal generator was used as there was no accessible point of attachment. It proved very difficult to perform a reliable locate of the cast iron main in spite of a priori knowledge of its location. In order to eliminate direct interference between the Spar and the signal generator a separation spanning several CI joints was required. The variable conductivity of the intervening joints did conduct sufficient current to the Spar location for proper operation.

The overall finding is that the application of the Spar-ADT technology to cast iron is, at best, problematic. The effectiveness of the technique on any pipe material is dependent on the level of signal current that is present on the pipe. The use of induction to inject the current is influenced by the conditions of the soil, adjacent facilities, and cast iron joints, making it difficult to achieve a consistent signal current. In those cases where sufficient current is attained, the metallic mass of the bell and spigot joints dominate the magnetic field data. The magnetic field effects expected from graphitization metal loss will be several orders of magnitude smaller than these secondary effects. It is not recommended that the application of this technology to cast iron be pursued.

General Observations on Technique

This section describes the lessons learned from the application of this technique at multiple field sites. The various strengths and weaknesses of the method will be described here.

Requirements for a Successful Survey

The primary requirement for conducting a successful survey with the Spar equipment is to place an adequate signal onto the facility being surveyed. Although the a priori knowledge of pipe location is less problematic than other methods, there is still a need to consider probable locations of other facilities when interpreting the data. Large masses of metal in the survey area, such as cars parked over the facility, were definitely seen to cause interference.

The first step in any site survey using the Spar technology is to establish the signal injection point. This requires a good metallic contact with the pipe under survey and an adequate ground for signal return. The amount of signal current placed on the survey pipe is a primary influence on the data quality. This will establish the signal to noise ratio (SNR) for the entire survey. A high SNR enables the Spar technology to function well, even in the presence of interferences.

If a reasonable SNR is established, the Spar equipment will provide an accurate mapping of the pipe under survey and indications of coating damage. Coating holidays are unambiguous: they express as drops in the current level that do not recover as the survey moves past them. Changes in the signal phase have consistently indicated some change in the "shape" of the pipeline system. In this case they correlated well with the location of coating damage. At other sites, phase changes have been associated with other buried appurtenances that were in contact with the pipe under survey.

Proper attention to GPS/GNSS factors is also required. The antennae need acquire sufficient satellites; a reasonable start-up time must be observed to acquire a location fix. The RTK correction is valuable in improving the fix but requires a hotspot connection and an RTK server within reasonable distance of the area being surveyed.

Recommendations for Improvement

There are areas in the mechanical set up of the Spar that could be improved in terms of the fixed height above the ground and levelling. The "known" height of the Spar over the ground is factored into the pipe depth calculation and can be a source of error if the height is inadvertently changed or the Spar is set on uneven ground.

Software improvements for obtaining RTK correction in Windows 10 are needed. More automation of the software initialization for RTK and other advanced features are needed to eliminate operator error.

The ability of the system to find buried appurtenances requires some additional consideration. There is not sufficient data in hand to allow these to be readily distinguished from disbonded coating. The signatures are very similar. Several operators have indicated the desire to locate buried repair clamps and other such hardware. This "bug" could be made into a feature if handled properly.

With additional effort, the analysis software could create a sub-surface "3D image" of the pipe referenced to geo-spatial location. The various errors from the Spar and the GPS could be built into this image to allow operators to visualize the confidence in the location and sources of interference.

Conclusions

The site data in-hand demonstrates that the Spar-ADT technology in combination with appropriate analysis software can locate several categories of features on coated steel pipelines. Coating holidays, loose/disbonded coating, and attached appurtenances have been found during this study. The data set is limited to a small number of sites at three utilities. A broader set would allow the development of a library of flaw signatures against more varied background interferences. GTI recommends that the Spar be tested with a larger audience and will propose this to its member companies.

The current mapping function of the equipment provides a straightforward means of determining where there are holidays and other metallic interferences. The signature of the current being drained from the system by a coating flaw or a contact is fairly easy to interpret.

The phase data does indicate a change in the pipe and coating parameters. It must be carefully interpreted in conjunction with the current signal data and with the location of other buried metallic facilities. Phase discontinuities in the absence of current changes indicate a change in the "shape" of the pipe/coating system. In this investigation, at least one coating disbondment was positively identified by the technique.

Utility personnel reaction to the system and the post processed data was overall positive. They found the FieldSens View operator interface easy to interpret. The ability to work alongside a facility rather than always having to be directly above it is useful. The automatic correlation of the signals to GPS locations in the post processed data was also appreciated by the operators. The general comment was that the Spar system may be easier to use overall than the current standard locate and survey equipment. The initial set up effort of adequate signal injection and grounding is no greater than what is currently done for pipe locating activities.

END OF REPORT