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Phase Sensitive Methods to Detect Cathodic Disbondment

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Table of Contents

Legal Notice ii
Table of Contents iii
Table of Figures iv
Abstract 1
Executive Summary 2
Task Work as Proposed 3
Task 1 - Parametric Studies 3
Task 2 - Prepare Representative Disbondment Samples 3
Task 3 - Construct a Breadboard Instrument 3
Task 4 - Test the Breadboard Instrument 4
Task 5 - Project Management 4
Technical Discussion and Accomplishments by Task 5
Task 1 – Parametric Studies 5
Task 2 - Disbondment Sample Preparation 6
Task 3 – Construct a Breadboard Instrument 11
Baseline Data 11
Lock-In Amplifier 12
Impedance Analyzer Chip 13
dsPIC Based System 13
Task 4 - Test the Breadboard Instrument 16
Facilities Preparation 16
Data Collection ..... **Error! Bookmark not defined.**
Business Status Section 22
Resource Status 22
Discussions with Operators or Potential Users 22
Quarterly Accounting 22
Payable Milestones (completed this reporting period) 22
Results and Conclusions 23
Accomplishments 23
Engineering Analyses and Conclusions 23
Issues, Problems or Challenges 23
Plans for Future Activity 23

Table of Figures

Figure 1 – Fabricated Disbondment Using Reversed Cathodic Protection 6
Figure 2 – Fabricated Disbondments on 20' Pipe Sections 7
Figure 3 – Fabricated Disbondments Prepped for Burial 8
Figure 4 – Fabricated Disbondment in Trench 8
Figure 5 – Fabricated Disbondment Test Station Detail 9
Figure 6 – Magnitude Data on Fabricated Disbondments 10
Figure 7 – Phase Data on Fabricated Disbondments 10
Figure 8 – 2250M Magnitude Data at Four Frequencies 11
Figure 9 – Lock-in Amplifier, Pick-up Coil and Support Equipment 12
Figure 10 – First dsPIC Based Breadboard Electronics 14
Figure 11 – Final dsPIC Breadboard Display View 15
Figure 12 – Final dsPIC Breadboard with Odometer Side View 15
Figure 13 – Test Pipe Complex Impedance 16
Figure 14 – Amplitude Data from Both Breadboards 17
Figure 15 – Phase Data from Both Breadboards 18
Figure 16 – Starting from Test Station on 30" Live Main 19
Figure 17 – Amplitude Data from 950 feet of 30" FBE Coated Steel 20
Figure 18 – Phase Data from 950 feet of 30" FBE Coated Steel 20

Abstract

The proposed work is to develop a phase sensitive technology that could detect coating disbondment on steel pipe from above ground, thus locating potential corrosion failure points. The system would consist of two components, a stationary signal generator that is attached to a test point and a detector that is carried along the pipeline. Sinusoidal or pulse excitation signals may be used. A wireless link between the generator and the detector provides accurate synchronization. An abrupt change of signal phase is expected at the disbondment.

There is currently no method to detect or locate a disbonded coating from above ground. Existing pipeline potential gradient surveys, both DC and AC voltage, make use of only amplitude data. While amplitude methods can detect an active holiday (break) in the coating, a disbonded coating can shield active corrosion from both detection and cathodic protection. Stated another way, the space between a disbonded coating and the pipe can house an active corrosion cell. Until there is an actual holiday in the coating, the corrosion cell cannot be detected with current technology. A holiday will allow increased cathodic protection current to flow to the pipe in the immediate vicinity of the holiday, but may not reach the extremities of a large disbondment.

A disbonded coating can contain an active corrosion cell that is undetectable until serious damage has occurred to the pipe wall. There is no exterior method that can reliably detect disbonded coating at this time. The coating effectively "shields" areas of active corrosion within the disbondment from DC or AC voltage gradient surveys. Internal methods, such as magnetic flux leakage (MFL) pigging may detect wall thinning but will not differentiate causes. MFL pigging is expensive and may not be possible on lines with bends or diameter changes. The proposed work is to provide a completely new method for surveying pipelines.

The object of the proposed work is to develop a technology that could detect coating disbondment on steel pipe from above ground, thus identifying potential corrosion locations before the pipeline fails. The deliverable would be prototypes of two components, a stationary signal generator and a hand carried detector. The signal generator would be attached to the pipeline at a test station. The hand-held device would be carried along the pipeline to acquire signal phase and amplitude measurements from the pipeline.

Executive Summary

This work was funded by DOT PHMSA and the GTI Sustaining Membership Program (SMP). The SMP is a consortium of natural gas distribution companies that collectively fund research. The input of the SMP members was actively solicited to guide the activities of this project. The entire membership was surveyed as to the types of pipe and coatings that they have in their systems that may be experiencing disbondment. A subset of the membership responded with pipe sizes, coatings, and number of feet in their systems. This provided guidance as to what materials and sizes to concentrate on.

A state of the art technology survey was carried out to identify prior and ongoing work relevant to this effort. An analysis of the pipe-coating-soil system was carried out in the context of the theory of electrical transmission lines. A number of bench top experiments were carried out to verify that the effects of magnetic properties of steels could be properly factored into the transmission line analysis.

One of the SMP member companies volunteered a test site that contained substantial amounts of pipe coated with coal tar enamel (CTE). This allowed GTI to concentrate the in house effort on fusion bonded epoxy (FBE) coatings. GTI used an existing FBE coated line to perform initial experiments. This line was used as is to provide baseline data and to verify that the prototypes constructed gave repeatable results. Additional 4” diameter FBE coated steel was obtained and specific disbondments and flaws were created. These sections were buried at GTI and used for testing.

Several iterations of the prototype disbondment detector were constructed. The initial version used several laboratory grade instruments to capture the magnitude and phase of a signal placed on the buried pipe. The magnitudes from this data were compared with data from a commercial pipe locating instrument to verify the system was operating reasonably. A battery powered prototype was constructed using an embedded DSP processor and its results compared with the lab instruments. These two compared very favorably. A third prototype combined the DSP unit with an odometer wheel and was capable of taking readings automatically as it was walked along the pipe. The repeatability of all three versions was verified on the GTI test pipe.

The prototypes were also tested on field sites with a local utility. This data is still is included in the final report. The data acquired with the DSP showed anomalies at locations on the pipe in agreement with those found by the utility during a DCVG survey. Due to schedule and budgetary considerations, the host utility was unable to excavate the field sites as during 2008. GTI will endeavor to provide an addendum to this report as soon as the excavations are possible.

Task Work as Proposed

The following section contains the work task descriptions as provided in the original proposal.

Task 1 - Parametric Studies

A number of theoretical issues will be addressed during this task. When the materials to be tested are established, calculations of their characteristic impedance will be performed. Simulations of various disbondment geometries will be performed to estimate how these will change the characteristic impedance. Electrical impedance data for the chosen soil type will be gathered. These activities should establish the limits of sensitivity required for the Breadboard Instrument to be constructed in Task 3.

Task 2 - Prepare Representative Disbondment Samples

A set of Representative Disbondment Samples will be produces and buried on the GTI Pipe Farm. The electrical impedance properties of these samples will be accurately measured and recorded. These will provide standard targets to calibrate and verify the Breadboard Instrument. Samples of the pipe materials selected in Task 1 will be obtained and inspected for pre-existing disbondments. Samples of pristine pipe will be buried and placed under cathodic protection.

A methodology for fabricating disbondments of known geometry will be developed. Disbonded samples will be fabricated and tested with an impedance analyzer prior to burial. This will establish that the disbondment does not create a breach in the coating: that it is a disbond not a holiday. All the pipe samples will be measured with the impedance analyzer after they are buried. The empirical values will be compared to those calculated in Task 1.

The buried samples will also be tested using time domain reflectometry (TDR). The object of the TDR testing is to determine if the technique is of any value in refining the location of disbondments. If the results of these measurements are positive, some elements of TDR may be factored into the breadboard instrument.

Task 3 - Construct a Breadboard Instrument

A Breadboard Instrument will be constructed using the data generated during Tasks 1 and 2 as guidance. The envisioned instrument will consist of two components: a stationary signal generator and a hand-carried detector. The signal generator will be connected to the pipe under test using a wire at a test station or other convenient point. The operator will walk the hand carried device along the pipe under test. A wireless link will pass control information between the two components.

The signal generator injects an electrical current into the pipe under test. The form and frequency content of the signal will be chosen based on data gathered in the first two Tasks. The simplest signal would be a sinusoid; the phase shift of a sinusoid per meter of coated pipe is readily calculated from transmission line theory. The use of more complex signals, such as UWB pulses or chirps, will be considered insofar as they can augment the location of disbondments.

The expectation is that a disbondment will produce a phase shift anomaly not seen on well-bonded coatings. It has been demonstrated with standard pipe location technologies that an actual breach in the coating causes a drop in the magnitude of the signal. Anomalies in the coating will cause deviations in phase, magnitude, or both.

The hand-held device will detect the field radiated from the buried pipe when the excitation signal is present. The device will measure both the amplitude and phase of the radiated field at that location along the pipe. Current pipe tracing technologies use magnitude information only. There are two methods of extracting phase information proposed for investigation. One is local, or short baseline, phase comparison. In this case there are two detectors on the hand held device separated by a known baseline. This baseline is parallel to the direction of the pipe. The phase difference between the lead and lag detectors should be uniform so long as the coating is uniform. A disbondment will change the phase difference. The extent of the change is proportional to impedance of the disbondment and the baseline length.

The other phase measurement technique under investigation is long baseline. In this case the phase shift from the signal generator to the current location of the hand held detector is measured. The wireless link between the generator and detector is instrumental in accuracy of this phase measurement. In this mode the phase difference between the wireless signal and the signal on the pipe can be compared. Again, the expectation is a uniform phase shift per meter of distance traveled down the pipe unless a coating anomaly is encountered.

The wireless link between the two devices also allows signals of several types to be utilized on the fly. The instrument can adapt to various pipe and soil conditions by modifying the excitation signal to suit. The long and short baseline measurements can be used in concert so as to improve the location of coating anomalies.

Task 4 - Test the Breadboard Instrument

The breadboard instrument will be tested on both the GTI Pipe Farm and one test site provided by a utility. The pipe farm tests provide a reasonable calibration of the instrument's sensitivity on pristine pipe and known disbondments. The field experiment will provide data under field conditions and test longer baseline operations than are possible at the GTI Pipe Farm.

After initial testing at the GTI Pipe Farm the results will be evaluated and modifications made to the breadboard instrument as indicated. The Pipe Farm results will also be correlated with the impedance data collected on the standard samples in Task 2. There are sufficient resources proposed for a small number of such iterations. The goal of this activity is to bring the Breadboard Instrument to readiness for testing at a field site. The advisory group will be kept apprised of the tests at the Pipe Farm and the field experiment scheduled for a mutually agreeable time

The Breadboard Instrument will be tested at a utility test site. The advisors will be given sufficient notice that they will be able to witness the test if so desired. The test is regarded as a field experiment to gather data under more realistic conditions. It is not intended as a demonstration of a pre-commercial prototype.

Task 5 - Project Management

Appropriate quarterly updates and status reports will be prepared. Annual peer reviews will be presented. The results will also be presented at the annual meetings of the SMP and to the SMP Technical Guidance Committee. A technical paper will be presented at a public forum.

Technical Discussion and Accomplishments by Task

This section contains the work performed on each task in detail, presenting experimental data and results.

Task 1 – Parametric Studies

The first work performed under this task was the preparation of a state of the art assessment of technologies that could be similar this effort. The draft state of the art was submitted in November of 2006. There is some germane subject matter that was found but none that is directly applicable to coatings on buried pipes.

An experimental test plan was formulated during this task to establish reasonable boundaries. A large number of pipe materials and coatings are currently used in the transmission and distribution of natural gas. It is beyond the scope of the proposed work to exhaustively test these. Early in the proposed work, an advisory group was formed to select a reasonable subset of pipe and coating materials to test. This advisory group was formed from utilities within the GTI Sustaining Membership Program (SMP).

A survey was submitted to the SMP membership to gather feedback on the project direction and to form an advisory group. Four utilities responded with substantial information about their systems. One of these companies volunteered to provide a test site. The prevalent coating types that are in use with the survey group are coal tar enamel (CTE) and fusion bonded epoxy (FBE). The vast majority of pipe currently being sold has FBE coating. There is a large installed base of CTE coated pipe in place. There is also a small amount of X-Tru Coat (XTC) in use, also referred to as "yellow jacket" because of its color. The table below summarizes the data collected during the survey.

A	B	C	D	Company / Question
9300	440	7343	5640	Miles of coated steel in service
30	0.6	20	25	New miles per year
CTE	XTC	CTE	CTE	Prevalent type of coated pipe
CTE	XTC	FBE	FBE	Highest coating failure type
B	A	B	I	Is CP Anodic, Impressed, or Both
yes	no	no	yes	Willing to host field test
yes	yes	yes	yes	Are surveys scheduled in 2007-2008
			CTE	Coal Tar Enamel
			XTC	X-Tru Coat or "yellow jacket"
			FBE	Fusion Bonded Epoxy

Table 1 – Survey Responses of Four Gas Utilities

A review of basic electrical transmission line theory was carried out during Task 1. Bench top experiments were carried out to determine the propagation velocity of electromagnetic waves in steel pipe. Theory predicts that the magnetic properties of steel will lead to a predominately

inductive transmission line and a propagation velocity lower than a non-magnetic material. This was verified on the bench.

Task 2 - Disbondment Sample Preparation

The objectives of Task 2 were to establish a set of standard disbondment targets to provide a calibration for the instrumentation developed in other tasks. The pipe acquired for the test targets was 4" diameter steel with FBE coating. The decision to use FBE was driven by the difficulty of purchasing new CTE coated pipe and also by the availability of CTE coated pipe already in the ground at a local utility.

The process of preparing the samples and burying them required more time than anticipated. Several attempts were required before arriving at the correct technique to create a reasonable disbondment. Two test sections, each 60' in length, were buried at GTI during the last project quarter. These efforts are covered in the following section.

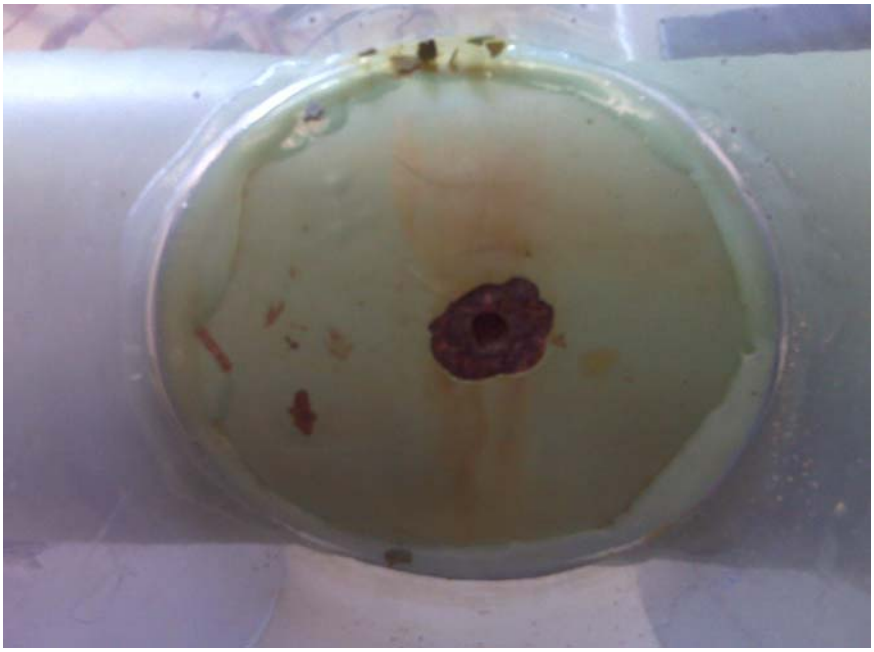

Figure 1 – Fabricated Disbondment Using Reversed Cathodic Protection

The coating disbondment was initially attempted by the methods called out in the ASTM G95-87 specification. Two small pipe sections were set up in the laboratory to test the procedures before attempting them on the larger pipes. After one month, the process was stopped and one of the samples tested.

The test for the extent of disbondment called out in the specification is to pry the coating around the puncture in the coating with an exacto knife or dental pick. There was no detectable disbondment at this point. Given the time constraints another method was applied to accelerate the process. One of the samples was restored to the ASTM G95-87 test. The other sample was placed in reverse polarity: the pipe was made positive with respect to a copper electrode placed in the bath. This polarity is the opposite of normal cathodic protection and will induce corrosion.

The test section was subjected to reverse polarity for roughly 36 hours and then tested as before. As can be seen in Figure 1 – Fabricated Disbondment Using Reversed Cathodic Protection, the coating was significantly undermined. An area around the initial drill point on the coating was

easily removed. It is also arguable that disbondments that contain corrosion are of more concern to utilities than "dry" disbondments.

Figure 2 – Fabricated Disbondments on 20' Pipe Sections

With the methodology established, fabrication of disbondments on the large pipe sections for burial was carried out. Six sections of 20' length were obtained with the ends stripped and chamfered for welding. Two of the six 20' sections were prepared in the following fashion. A circular pattern of 7 small holes were drilled through the coating so as to fit within the saddles. The saddles were mounted to the pipes with silicone adhesive. The saddles were filled with salt solution and a copper electrode inserted into the solution. A power supply applied a constant 3 volts to the steel with respect to the copper and the process monitored.

The process was carried on for approximately 48 hours of total run time. The salt solution was changed several times to inspect the progress. The solution rapidly becomes clouded with corrosion products. The final result can be seen in Figure 2 – Fabricated Disbondments on 20' Pipe Sections. This shows the sections after the saddle fitting has been removed. Note that the coating is not peeled as it is desirable to maintain the undermined space for this test.

The next step was to weld the 20' segments together. Two 60' test sections were prepared, each containing three segments and two welds. The order of each test segment was one clean segment, one containing a fabricated disbondment, and one clean segment. A flat plate cap was welded onto each and a wire bonded onto each cap.

When the welding was completed, the drill openings and welds were covered with a field applied coating. This is an epoxy preparation that is typically used on welds and is compatible with the FBE coating on the pipe. Figure 3 – Fabricated Disbondments Prepped for Burial shows the two 60' sections welded and re-coated. The light green area on one pipe is the field applied coating over the disbondment.

Figure 3 – Fabricated Disbondments Prepped for Burial

The two test sections were buried in parallel trenches on GTI property. It was found at this time that the actual length of the test sections was close to 66' long. The length of each segment provided by the mill is in excess of 20'. Figure 4 – Fabricated Disbondment in Trench shows one test section. The soil in the area is a mixture of small stone and fines with good drainage. The area also has a sump pit to allow control of moisture in the soil.

Figure 4 – Fabricated Disbondment in Trench

Four test stations were installed; one at each end of a pipe section. Figure 5 – Fabricated Disbondment Test Station Detail shows one of these. The wire bonded to each end of the test pipe is brought up through the white PVC pipe into the terminal block, housed in the yellow enclosure. A magnesium anode was placed at both ends of each pipe and its wire also brought up to the terminals. The anodes are used both to provide cathodic protection and a ground return for the signal generator. A permanent reference cell was installed at one end of each pipe and its lead wire brought up to the terminals to allow the pipe-to-soil potential to be monitored.

Figure 5 – Fabricated Disbondment Test Station Detail

The installation of the two test pipes with disbondments was completed in early November of 2008. A small amount of phase and magnitude data was taken on these pipes. Representative data is shown in Figure 6 – Magnitude Data on Fabricated Disbondments and Figure 7 – Phase Data on Fabricated Disbondments. The exact methods used to acquire this data are dealt with in detail in the sections on Task 3 and Task 4.

The important features to note are that the location of the fabricated disbondment is clearly visible in the magnitude data near the middle of the span. There are also slope reversals in the phase plot at the same location. Another interesting feature in the phase plots are ripples near the 22 and 44 foot marks; close to the locations of the welds. In this case the feature only shows up in the phase data.

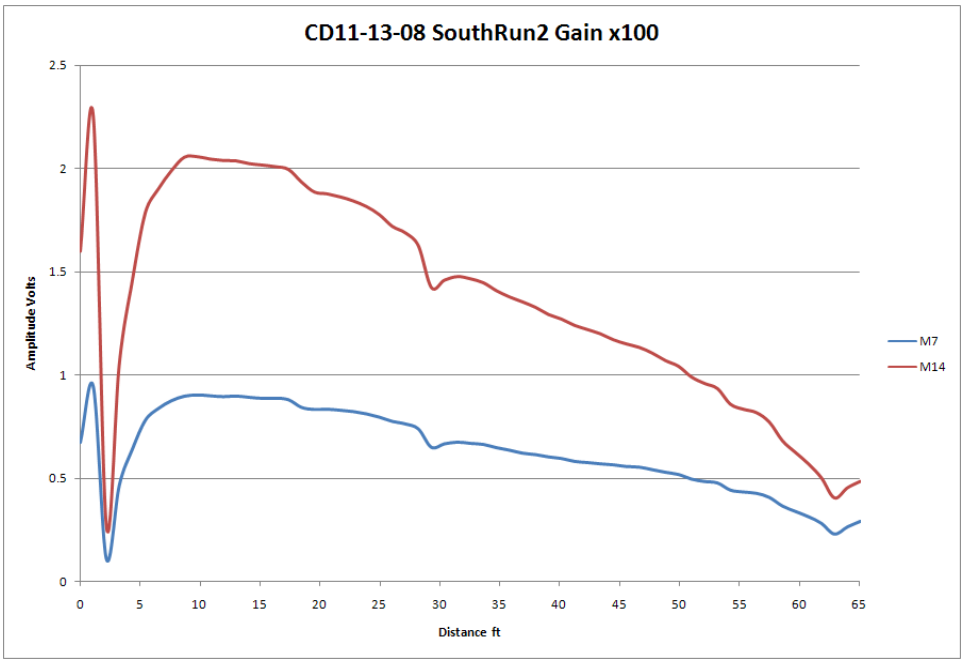

Figure 6 – Magnitude Data on Fabricated Disbondments

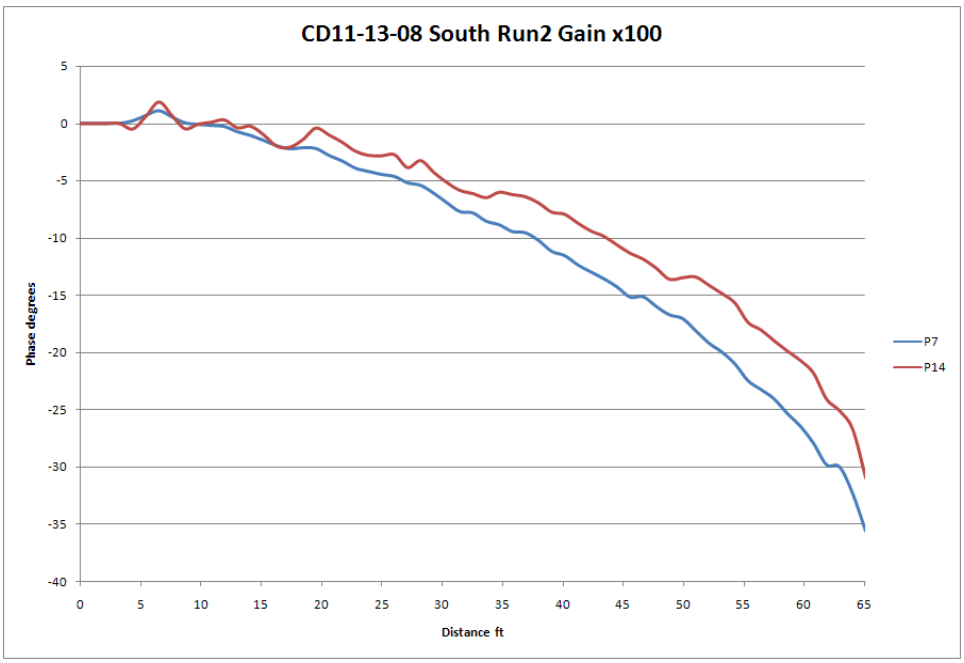

Figure 7 – Phase Data on Fabricated Disbondments

Task 3 – Construct a Breadboard Instrument

The apparatus used to capture the phase and magnitude data was developed in several stages. An existing section of 4" diameter pipe at GTI was used as a baseline to verify the functionality of the breadboard. Every iteration of the instrument was run on the same test pipe and the data compared for repeatability. The progression of the breadboard technology is as follows.

1. A Dynatel 2250M Locator was used to gather magnitude only data
2. Laboratory grade SR7265 Lock-In amplifier gathered magnitude and phase data
3. AD5934 impedance analyzer chip was tested as a substitute for SR7265
4. dsPIC30F4013 processor and CODEC was tested as a substitute for the SR7265
5. An improved dsPIC breadboard was constructed and used on the field sites

Baseline Data

The Dynatel 2250M Pipe and Cable Locator is an industry recognized instrument. It consists of a hand carried locator with readout and a stationary signal generator that is attached to the pipe at a test station. Both components are battery operated and field hardened. The signal generator can be set to four standard frequencies: 577 Hz, 8 kHz, 33 kHz, and 33 kHz. The locator is set to the same frequencies and can be used to locate the pipe and capture the relative magnitude of the signal at that location.

The baseline data captured with the 2250M provided several insights. First, it indicated the relative effectiveness of the various frequencies in propagating along the pipe. As can be seen from Figure 8 – 2250M Magnitude Data at Four Frequencies, 33 kHz and 8 kHz provided the highest signal strength over the distance. The "posts" on the distance axis are fence posts that were used to provide a repeatable location for successive runs; they are on roughly 8' centers.

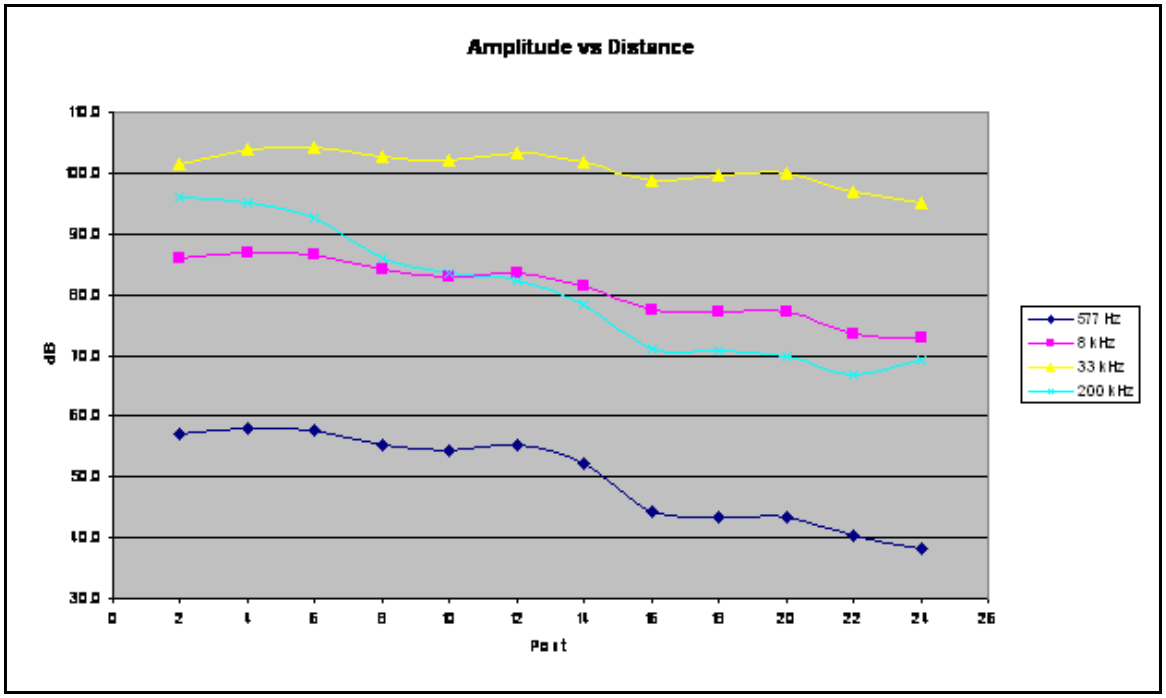

Figure 8 – 2250M Magnitude Data at Four Frequencies

Lock-In Amplifier

Some of the baseline experiments were repeated using a Princeton Research SR7265 Lock-In Amplifier. This device is a laboratory grade instrument that can capture very precise magnitude and phase data. The SR7265 can generate the sinusoidal excitation frequency up to 160 kHz. A power amplifier was used to boost this signal before applying it to the pipe. A laptop running a LabVIEW program was used to capture the data from the SR7265. These pieces of equipment all required AC power, and so were stationary at one end of the test pipe.

A pick up coil with a preamplifier was constructed that could be hand carried along the pipe. All of the equipment with the exception of the laptop is shown in Figure 9 – Lock-in Amplifier, Pick-up Coil and Support Equipment. The coil and preamplifier were mounted on a wooden frame that allowed them to be set on the ground in the proper orientation to the pipe. The preamplifier is battery powered but still required a coax cable to convey the signal back to the SR7265.

Figure 9 – Lock-in Amplifier, Pick-up Coil and Support Equipment

The procedure was to apply the signal to the test pipe and move the pick up coil along the pipe, stopping at the same locations as were recorded in the previous experiments. Given the frequency range of the various pieces of equipment and the performance during the baseline testing, the 577 Hz and 200 kHz frequencies were eliminated. The data collected using this apparatus was in good agreement with the baseline data.

The Lock-in amplifier apparatus was also used to test several radio links that were intended to replace the coaxial cable. The major requirement of the radio link was to have an extremely stable phase delay so as to not introduce error into that portion of the measurement. The procedure for testing these links was to attach the transmitter directly to the SR7265 signal output and the receiver to the signal input through a fixed coaxial cable. The transmitter and receiver were then separated and the magnitude and phase data recorded. The cable provides a constant phase delay so any change in phase is due to the separation of the transmitter and receiver.

No radio link tested during the project had sufficient stability to be useful. Radio links in the 2.4 GHZ, 900 MHz, and FM bands were tested. A set of 900 MHz Yagi directional antennae were obtained and that test repeated. In all cases the phase stability decayed rapidly as a function of distance. Based on this negative result, coaxial cable was used exclusively for all field data collection to maintain the integrity of the data.

Impedance Analyzer Chip

The Lock-In amplifier had verified that it was possible to gather phase and magnitude data over reasonable pipeline lengths. It also gave a reasonable estimate of the frequency range and power requirements. It was then necessary to develop a more portable version of the instrumentation in order to conduct testing at utility provided sites. This exercise would also give some indication of the component costs of a commercial version of a phase sensitive instrument.

The first device that was tested as a functional replacement for the lock-in amplifier was an impedance analyzer chip: the Analog Devices AD5934. This device can measure the complex impedance of a system it is connected to. It accomplishes this by generating a sinusoidal signal at several frequencies that is applied to the system being tested as a voltage. The AD5934 then measures the complex current through the system under test. The data is captured as real and imaginary components that are easily converted to phase and magnitude.

The AD5934 was abandoned after several experiments. The reason for this is that the device did not perform well when the impedance of the system under test was below 100 ohms. The test pipes on GTI property and those encountered in the field all were of relatively low impedances. Using external amplification to scale the currents and voltages into a range usable with the AD5934 turned out to be quite cumbersome.

dsPIC Based System

The next battery operated system tested to replicate the functionality of the SR7265 Lock-In amplifier was a microcontroller with digital signal processing (DSP) capabilities. The capabilities required were the ability to generate an excitation signal at one or more frequencies and to capture an input signal that can be precisely compared to the excitation signal. The experience with the AD5934 had demonstrated that using a Discrete Fourier Transform (DFT) method to capture the real and imaginary components of the signal was functionally equivalent to the lock-in approach.

Reduced to its simplest form, a narrowband DFT compares a captured signal to two sinusoids of identical frequency that are 90 degrees out of phase with one another. The captured signal is correlated with each sinusoid resulting in two outputs, an in-phase and a quadrature value for the signal. These are also referred to as “real” and “imaginary” parts of the signal and are easily transformed to phase and magnitude values.

A Cirrus Logic CS4270 CODEC was interfaced to a dsPIC30F4013 microcontroller to provide a means of generating a sine wave of known frequency and to analyze signal acquired by the pickup coil and preamplifier from the buried pipe. Figure 10 – First dsPIC Based Breadboard Electronics shows this arrangement. The CODEC provides analog output and input within the audio frequency band. The dsPIC provides sufficient processing power to simultaneously generate a sine waveform and perform a narrowband DFT on the captured signal.

A number of improvements to the dsPIC breadboard were required. One was to the software: only one channel of the stereo CODEC is now being used, allowing a longer sample of the data

of interest to be obtained. Prior to this, both channels were taken so that one half of the available memory was effectively wasted. The longer sample of data allows much better resolution of the magnitude and phase. Another improvement to dsPIC software was the generation and analysis of two frequencies simultaneously. The signal that is generated is a mix of 7 kHz and 14 kHz sinusoids. The DFT process returns the real and imaginary process of both signals. The use of a two frequency excitation signal provides additional data about the pipe impedance without requiring two passes to acquire it.

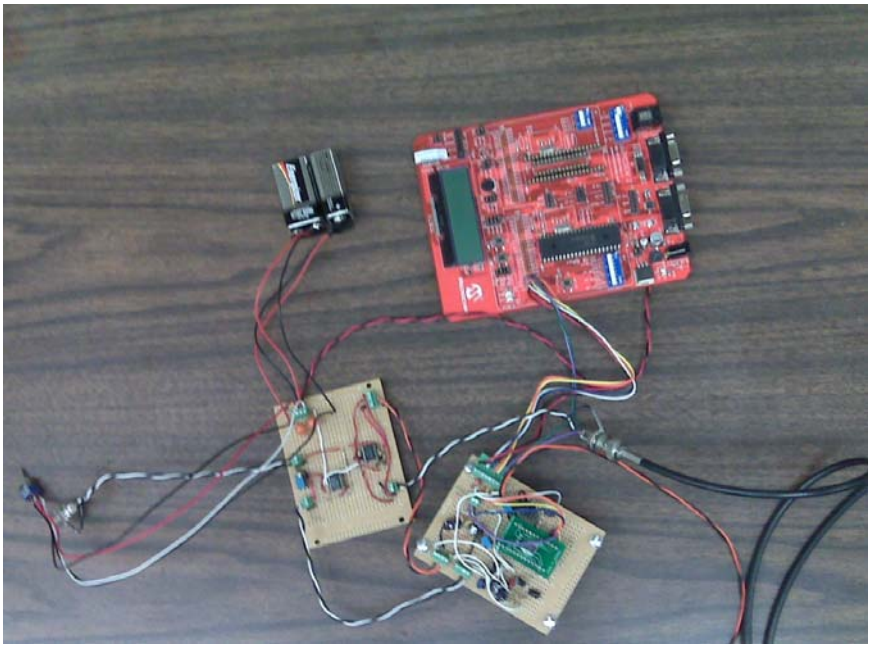

Figure 10 – First dsPIC Based Breadboard Electronics

The dsPIC breadboard electronic hardware was improved. A larger LCD display is now being used to improve the operator interface. This is shown in Figure 11 – Final dsPIC Breadboard Display View. An EEPROM and associated code was added that greatly extends the amount of data that can be logged. Previously the data needed to be recorded by hand from the LCD display, now 8,000 data points can be stored internally. The EEPROM contents can be electronically transferred to a laptop for analysis and display.

The housing of the dsPIC breadboard was improved by incorporating a commercial odometer wheel. This arrangement allows accurate measurement of the distance covered and normalizes the distance between the ground and the pick up coil. This is shown in Figure 12 – Final dsPIC Breadboard with Odometer Side View. The pickup coil and preamplifier located inside the yellow plastic housing alongside the wheel. The use of the wheel enables a reading to be automatically taken for every foot of linear travel. This form of the breadboard was used for the utility field test. No further modifications to the hardware have been made.

The power amplifier used to drive the pipe excitation signal for some of the field tests was an automotive unit that could run on 12 volts DC. This was powered from a deep cycle lead acid battery. For some of the field tests a generator was available, allowing an AC powered amplifier to be used.

Figure 11 – Final dsPIC Breadboard Display View

Figure 12 – Final dsPIC Breadboard with Odometer Side View

Task 4 - Test the Breadboard Instrument

Facilities Preparation

At the time the project started the buried pipe facility at GTI contained 270 feet of 4-inch diameter steel with FBE coating. This line was cleaned, pigged, and pressurized for this project. It has been kept continuously pressurized since that time. The line has intentionally fabricated leaks and areas where it is known the coating is in poor condition. Initially, the manholes at either end of the line were partially filled with water. The manhole at the East end of the line is used for signal injection, as it is more accessible to the laboratories. The electrical power to this manhole was restored and it is kept pumped clear. The West manhole is not pumped continuously; it is cleared as needed or allowed to dry on its own.

This line was used for all of the early breadboard development activities. Some of the test data generated within Task 4 has been shown in the Task 3 section. This was done when showing data collected with a particular version of the breadboard would add to the clarity of the text. Experimental data collection on this facility started in March of 2008.

GTI was able to collaborate with a local utility and survey live pipelines with the disbondment breadboard. This provided a much broader range of targets than could be installed at GTI. These tests were carried out in October and November of 2008.

An additional two 60' test pipes with intentional disbondments were completed in November of 2008. A limited amount of data was collected on these.

Tests at GTI Facilities

The complex impedance of the 270 foot pipe was taken. This was performed with an HP4194A impedance analyzer. This was attached to the pipe itself and the steel manhole that the East end of the pipe resides in. The two structures are electrically isolated from each other by the coating on the pipe. These attachment points are consistent for all of the experiments in this set: the manhole shell provides the ground return for the pipe signal.

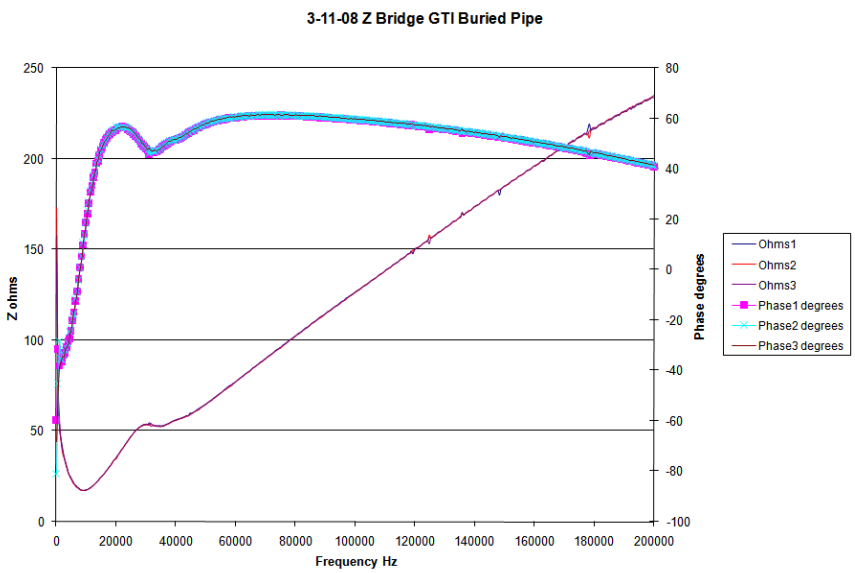

Figure 13 – Test Pipe Complex Impedance

This data is shown in Figure 13 – Test Pipe Complex Impedance. The magnitude is in ohms and the phase angle in degrees. The frequency range over which the impedance was tested is from 100 Hz to 200 kHz. These bounds were set by the other instruments used. The SR7265 works in the range from 1 Hz to 160 kHz, the 2250M from 577 Hz to 200 kHz. The general trend of the magnitude and phase is that the inductance of the pipe becomes dominant at higher frequencies. This agrees with the analysis and bench experiments of Task 1.

A number of tests were carried out to verify that the performance of the SR7265 based breadboard and the dsPIC battery powered breadboard track one another closely. The SR7265 is considered the standard that the dsPIC breadboard is judged against. These tests were carried out on several days with differing soil moisture conditions. Excitation signals of 7 kHz and 14 kHz sine waves were used in all tests. These frequencies are easily generated by the CODEC; the SR7265 can be arbitrarily set for any frequency. An amplifier that runs from AC was used in the tests that generated the following data.

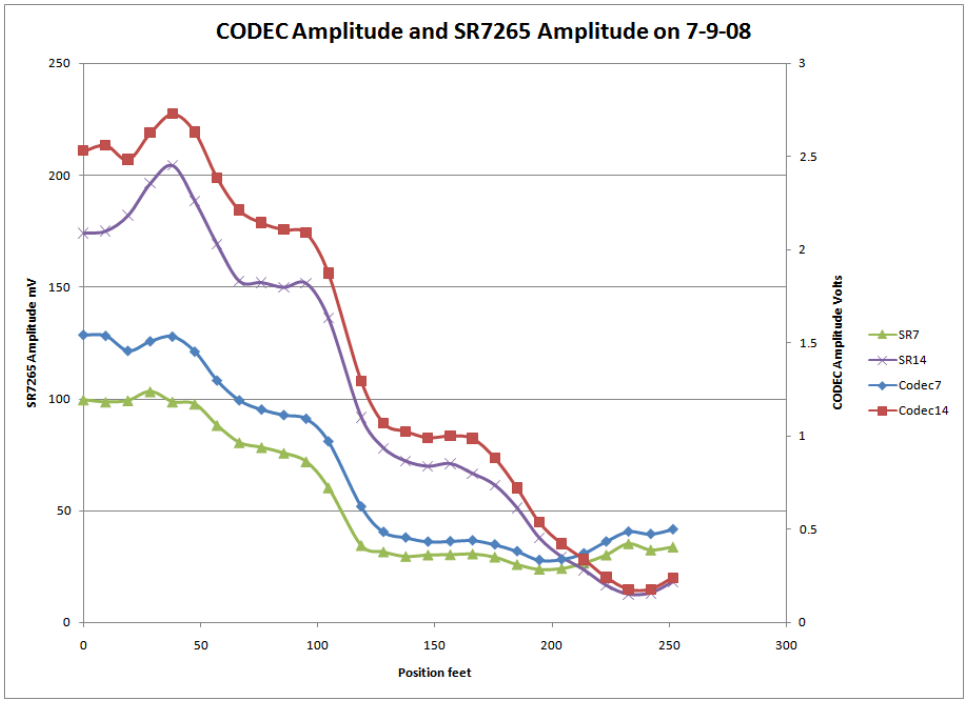

Figure 14 – Amplitude Data from Both Breadboards

The data shown in Figure 14 – Amplitude Data from Both Breadboards, shows a very good correlation of results between the SR7265 based breadboard and the one constructed from the dsPIC and CODEC.

Some features are extremely repeatable with either breadboard. The 14 kHz signal propagates more readily than the 7 kHz signal. There are several flaws in the pipe coating that were intentionally fabricated; the signal dip at 50 feet corresponds to one of these. A water main transects the pipe at right angles near the 100 foot mark and there are some coating flaws in the same area. This accounts for the large drop in signal strength at this point. The signal drops again as the dead end of the pipe is approached. The end effect is caused by the signal going to ground through the metal manhole that the pipe is connected to. The higher concentration of ground currents begins to cancel the field of the pipe currents.

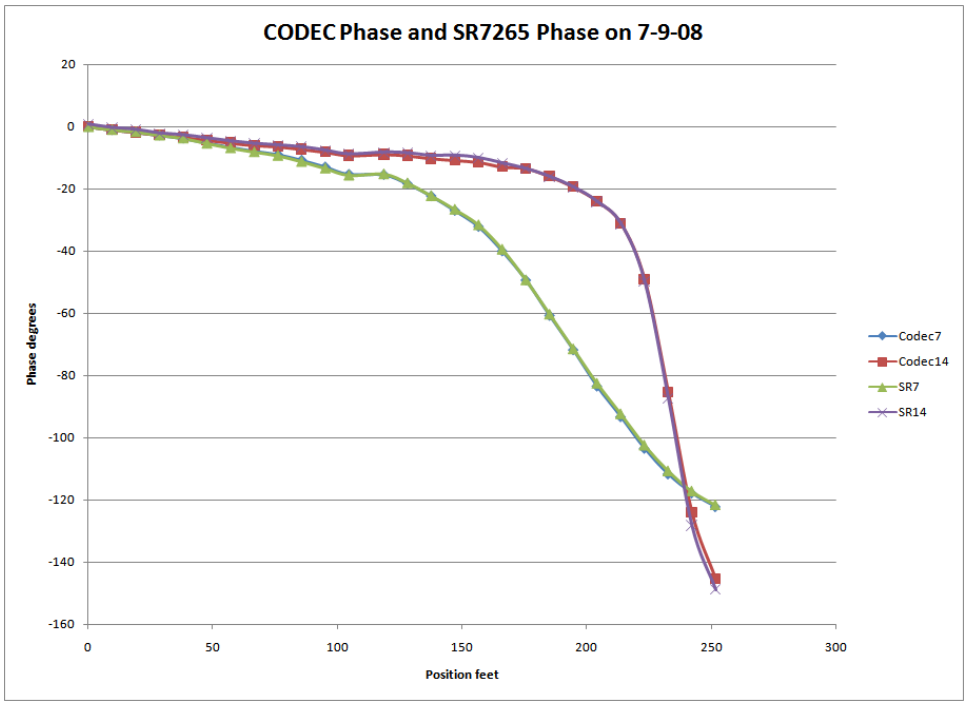

Figure 15 – Phase Data from Both Breadboards

The data shown above in Figure 15 – Phase Data from Both Breadboards, shows a similarly high correlation in the phase data acquired with both breadboards. Once again, the 14 kHz signal shows better propagation on the test line. A small phase deviation is apparent in both traces at 100 feet where there is a known interference from a water main. The major phase shift appears to be from the end effects. Testing the breadboards on longer lines provided by field testing should show a much more gradual change in phase versus distance.

Tests at Utility Sites

A local utility provided GTI with the opportunity to test the breadboard on live pipes in the field. Two pipelines were provided: a 30” diameter line with FBE coating and a 22” diameter line with CTE coating. The utility had recently performed a direct current voltage gradient (DCVG) survey on these lines and intended to excavate several anomalies during 2008. This provided an opportunity to verify the phase sensitive technique alongside standard survey techniques. For schedule and budgetary reasons, the local utility was not able to perform the excavations during 2008.

Several positions along the two lines provided were surveyed with the GTI breadboard. The most accessible of these was where the 30” line was in the shoulder of a road. The majority of the 22” line was under grass or rough ground which tended to cause errors in the distance recorded by the odometer wheel.

Figure 16 – Starting from Test Station on 30” Live Main shows the breadboard being used along with the battery powered amplifier. This particular site was visited twice. As noted before, coaxial cable was used between the breadboard and the power amplifier to maintain signal integrity. On the first survey, several 100’ sections of cable with connectors were used. At that time roughly 400’ of the line was surveyed. The connectors in the coax cable were somewhat

unreliable and required careful handling. For the second survey, 1000' of continuous coax was used which allowed the survey to be accomplished more quickly.

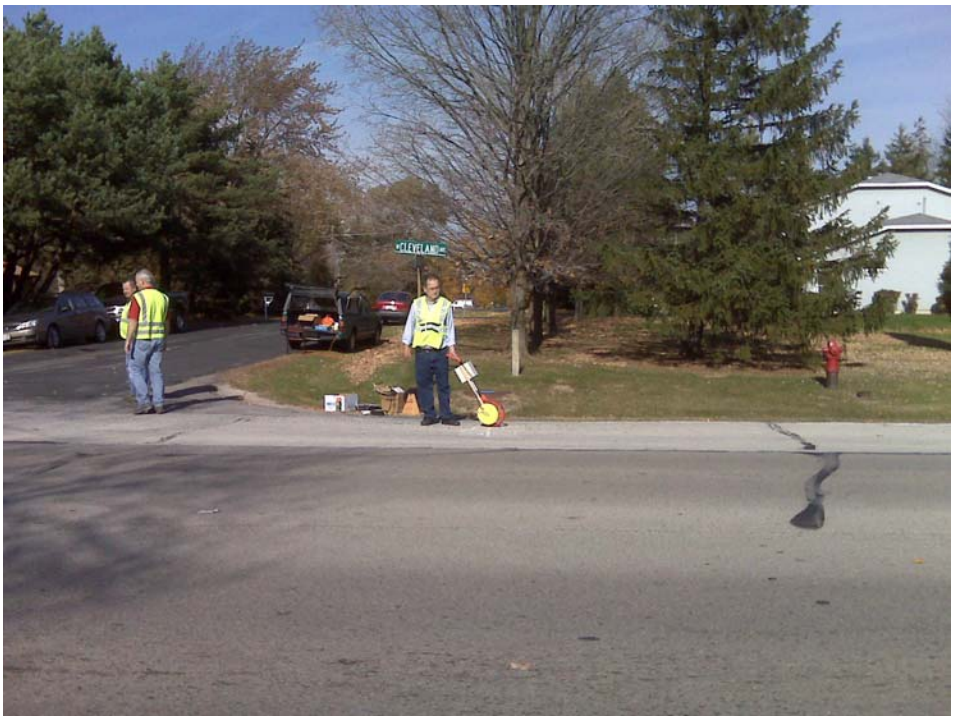

Figure 16 – Starting from Test Station on 30" Live Main

The data collected during one of these runs is shown in Figure 17 – Amplitude Data from 900 feet of 30" FBE Coated Steel. Figure 18 – Phase Data from 950 feet of 30" FBE Coated Steel shows phase data taken on the same section. An anomaly was detected by the DCVG survey at roughly 175' which can also be seen in the magnitude data. Similarly, the utility noted an anomaly at roughly 350' which shows some slope changes in the GTI data.

The utility hosting the test now plans to excavate these anomalies in the spring of 2009. This last step would allow some verification of the phase and magnitude data on real features discovered in the field. The best verification that can be performed with the data in hand is to compare it with the data taken from the fabricated disbondments. This data can be compared in a qualitative way to what was seen in the field. The pipe diameters and soil conditions are of course different between the utility site and the GTI test pipes.

The feature roughly 50' along the line was not noted by the utility as an anomaly. The utility has indicated willingness to provide a few extra excavations for features that are of interest in the magnitude and phase data. This will allow additional verification of the technique.

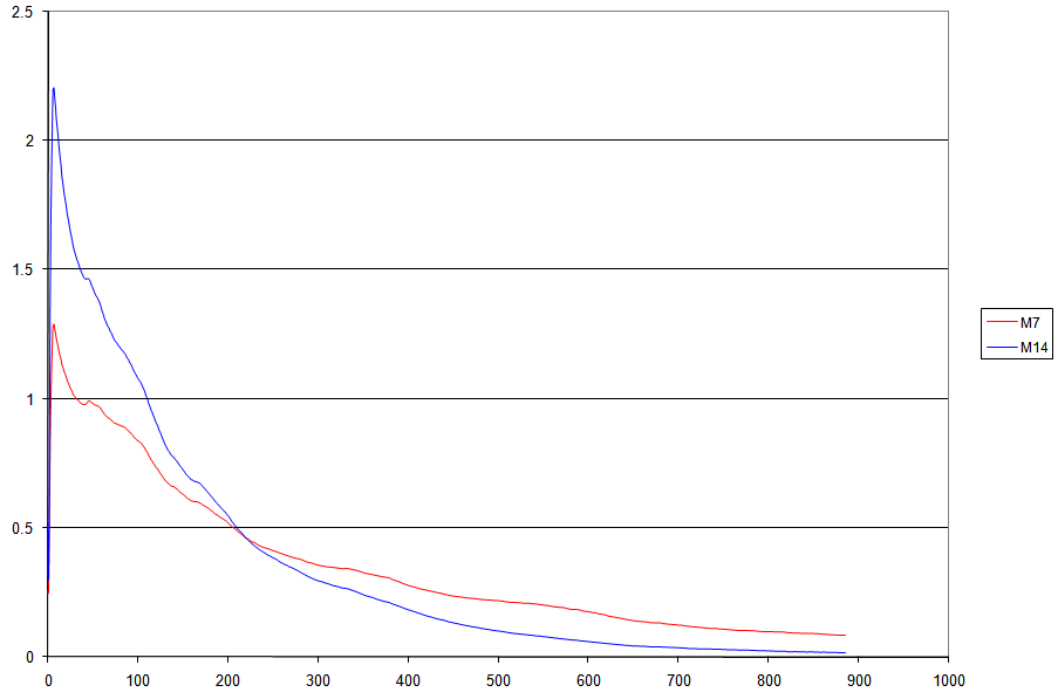

Figure 17 – Amplitude Data from 900 feet of 30" FBE Coated Steel

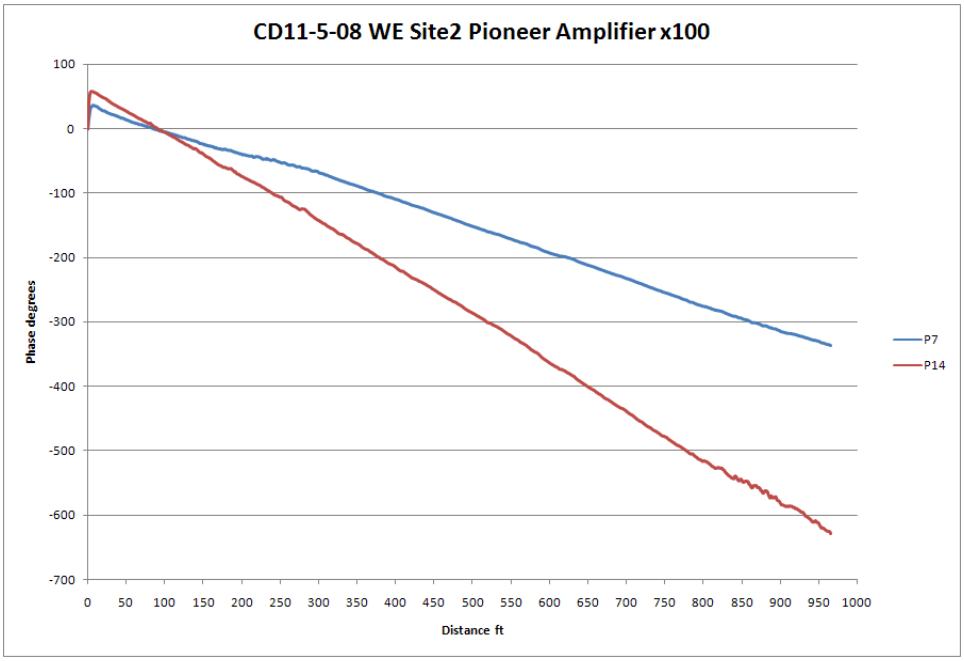

Figure 18 – Phase Data from 950 feet of 30" FBE Coated Steel

An interesting feature on the 22" is shown in Figure 19 – Magnitude Data on 22" Line Entering a Casing. At this point the 22" diameter CTE coated mains enters a casing beneath a road. The GTI apparatus was hooked to a test station near the road. With the help of utility personnel,

traffic was stopped briefly and the apparatus run from the station to the opposite side of the road. The magnitude data shows quite clearly where the casing begins: about 19' from the test station.

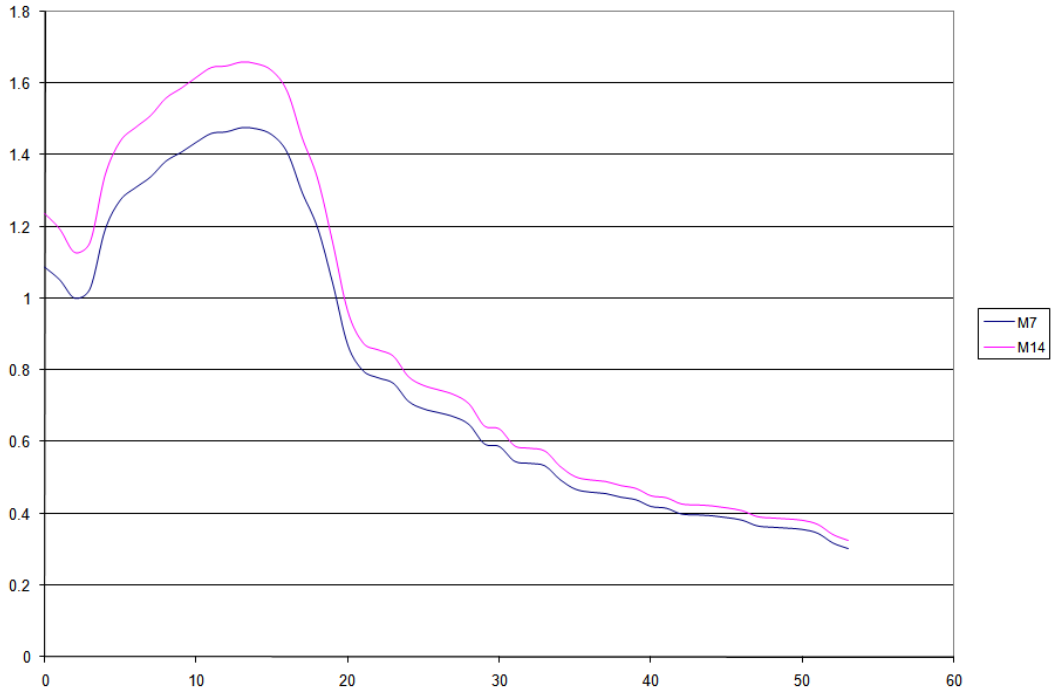

Figure 19 – Magnitude Data on 22" Line Entering a Casing

Business Status Section

Resource Status

Table 2 – Planned versus Actual Expenditures by Task shows the project expenditures as of December 1st, 2008. There is sufficient funding to prepare the final report for PHSA. There is also some co-funding remaining in the SMP portion of the project.

Table 2 – Planned versus Actual Expenditures by Task

	PHMSA Plan	SMP Plan	Total Plan	PHMSA Actual	SMP Actual	Total Actual	Variance
Task 1	$36,161	$47,955	$84,116	$39,994	$39,387	$79,381	$4,735
Task 2	$41,482	$49,745	$91,227	$13,621	$26,715	$40,336	$50,891
Task 3	$73,701	$104,521	$178,222	$116,942	$129,708	$246,650	-$68,428
Task 4	$34,066	$39,663	$73,729	$5,891	$24,245	$30,136	$43,593
Task 5	$62,765	$18,116	$80,881	$55,119	$32,937	$88,056	-$7,175
Total	$248,175	$260,000	$508,175	$231,567	$252,992	$484,559	$23,616

Discussions with Operators or Potential Users

GTI has been collaborating with a local gas distribution company. Several trips were carried out during September and October to survey lines at this company. The lines were chosen on the basis of having been recently surveyed by traditional methods. For budgetary and schedule reasons, none of the lines surveyed will be excavated during 2008. One of the test sites is scheduled to be excavated during the spring of 2009. GTI will work with the utility and the SMP to allocate the resources to allow GTI personnel to be present when the excavation takes place.

Quarterly Accounting

The quarterly accounting was not finalized at the time this report was written. DOT can expect the accounting to be completed and invoicing submitted within 1 month from the end of quarter.

Payable Milestones (completed this reporting period)

This report serves as the final report submission. GTI requests that any comments on this final be submitted within a reasonable period. The full submission will be complete when GTI has submitted the quarterly accounting numbers, submits to PHMSA, and the invoice summary entered into the online system.

Results and Conclusions

Accomplishments

A portable breadboard that could measure the magnitude and phase of a signal injected into the pipe was fabricated and tested. It was demonstrated to have sensitivity to anomalies detected by the DCVG survey technique currently used.

Engineering Analyses and Conclusions

At this time, the best data in hand on an actual disbondment is that taken on the test pipes described in the section on Task 2. These are the intentionally fabricated disbondments at the GTI test facility. Figure 6 – Magnitude Data on Fabricated Disbondments and Figure 7 – Phase Data on Fabricated Disbondments both show indications at the position where the disbondment is known to be. There is also some indication of the welds visible in the phase data.

There are similar indications in the data obtained on the 30" live main. To verify that these correspond with disbondments or holidays will require excavation. This cannot be accomplished within the time frame of the current project.

It was noted during the field test that the GTI apparatus was able to determine the point where a main enters a casing. This capability may warrant further study in itself.

Issues, Problems or Challenges

The utility providing the test site will not be able to excavate the sites surveyed within 2008. This is due to budgetary and schedule constraints at the utility. Some of the sites are now scheduled for spring of 2009.

Plans for Future Activity

GTI will endeavor to provide an addendum to this report as such time as it is possible to excavate the utility sites. We will work with the SMP to allocate the resources to accomplish this.