the Energy to Lead

FINAL REPORT

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GTI PROJECT NUMBER 21958 (21939)

Pipeline Defense with Combined Vibration, Earth Movement, and Current Sensing

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Objectives

The project objective was to demonstrate the feasibility of a pipeline right-of-way (ROW) defense system based on a suite of stationary sensors mounted on, and adjacent to, the pipeline. The sensor data from multiple locations along the pipe are wirelessly forwarded to a central location for further analysis. Analytics residing at a central location correlate the data from multiple sensors to alert operators to events of interest occurring in the ROW with minimal latency.

The purpose of this project is to design, test, and demonstrate in the field a system that automatically monitors the right-of-way (ROW) and notifies gas utility operators of various threats. The deployment of this system would allow utilities to mitigate risk to their pipelines by being better informed of where and when threats are occurring. The current practice is for utility inspectors to patrol the ROW with emphasis on areas where construction is ongoing. Automated monitoring and notification would allow personnel to be more efficiently dispatched.

This work was a collaborative effort co-funded by PHMSA and Operations Technology Development (OTD). The Southern California Gas Company provided a test site along with substantial in-kind effort for the installation of equipment. The California Energy Commission (CEC) provided financial support through the end of 2018.

Executive Summary

There are multiple threats to the integrity of utility transmission pipelines from external forces. One of the greatest threats is the operation of non-utility company excavation equipment within the pipeline's ROW, resulting in accidental damage. Damage to the pipeline from any source can have severe safety consequences, including fire, explosion, and loss of life. Pipeline damage can also lead to natural gas leaks thereby increasing greenhouse gas emissions, and disruption of natural gas delivery to customers. A system that provides advanced notice of potentially damaging activities would benefit both gas utility operators as well as the public.

The proximity of pipelines to population is a critical consideration when designing a monitoring system. Natural gas utilities' risk classification considers the probability of pipeline damage and the severity of the consequences. The more populated the area, the higher the assigned risk value. The term "high consequence areas" (HCA) applies to locations where the public is near the pipeline ROW.

Current methods to comprehensively monitor the ROW, such as distributed fiber optic sensors, require exposing the entire length of the pipe for installation. In developed areas this "open trench" installation is difficult and expensive. Open trench activities also create risks of their own for workers and the public, independent of pipeline damage. Despite challenging logistics, an HCA would most benefit from ROW monitoring due to the inherent, enhanced risk of its location. Given these conditions, finding a technological solution that is both affordable and effective is key.

This project demonstrated a monitoring system with sensor stations placed at several discrete locations in the ROW. These stations consisted of sensors on the pipe and in the soil, a data logger, and a wireless link to forward the data to a central repository. To address affordability, the project team identified how far apart the sensor stations could be spaced and remain effective. This allows the system to operate while minimizing equipment and excavation costs. The project also focused on using low-power equipment that could operate from solar power with battery storage.

The resulting hardware was designed, engineered, and tested in the field on a natural gas pipeline ROW. Various sensor types were deployed and tested, and the pipeline was hydro-tested during the installation period, allowing calibration data to be captured. Support electronics were installed, and a solar power option was successfully demonstrated. The wireless link technology is successful. A total of three sensor stations were installed over a length of roughly 4,000 feet of new pipeline. The system is currently running and providing sensor data. The web hosted user interface was successful. A user interface dashboard was demonstrated that allows visualization of the data from the three sensor stations.

To discern actual events from background noise, further development of the analytics and alert system is needed. Additional work on vibration sensors will be required to provide appropriate test data for the analytics. The vibration sensors tested during this pilot did not perform as expected. Modifications carried out (near the project's end) at one station demonstrated improved sensitivity, critical to the detection range of the system. To provide operators useful and actionable alerts, in advance of actual damage, will require jointly optimizing the analytics and the sensors.

Introduction

Background

Recent pipeline incidents have raised public awareness of the infrastructure running beneath developed areas. What were farm fields when that infrastructure was first installed, decades ago, are now subdivisions. The natural gas infrastructure is sound and well-maintained, but proximity to population raises the consequences of any failure, elevating risk. It is interesting to note the acceptable cost of monitoring has steadily risen over the past several decades. A U.S Department of Transportation research solicitation from the early 1990's indicated that the utility willingness to pay for monitoring was roughly $2,000 per mile. A 2015 California Energy Commission solicitation for work in this area set the value closer to $100,000 per mile. This metric recognizes that while the probability of a pipeline failure is low, the associated consequences can be high. Investing in a monitoring system can be effective insurance against the cost of dealing with a catastrophic incident.

The primary threat to buried infrastructure is excavation and/or construction damage. This is indicated by statistics gathered by the Pipeline Hazardous and Material Safety Administration (PHMSA) of the United States Department of Transportation (US-DOT). The threat can be from utility owned equipment, contractor equipment, or private citizens performing activities not related to the utility (**Error! Reference source not found.**).

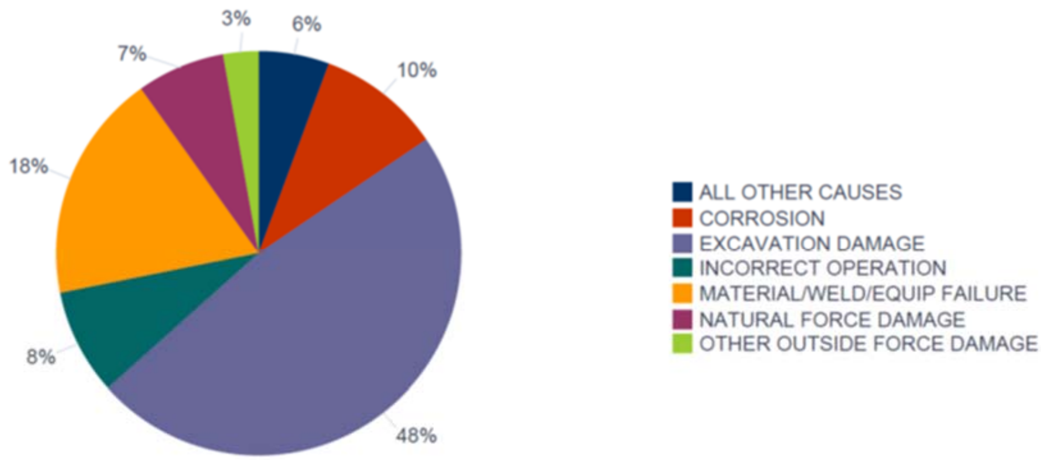


Figure 1. Sources of Damage Leading to Incidents

Source: PHMSA Pipeline Incident 20 Year Trends (1999-2018)

Detecting the presence of activity or construction equipment in the pipeline right-of-way (ROW) would allow operators to quickly dispatch personnel to investigate. Early and preemptive action would substantially mitigate the risk of a pipeline incident.

This project explored distributed sensors that could be used in combination to reduce the risk of damage from several sources, not just excavation. This was accomplished:

- Through the development of a Stationary Sensor Network (SSN) that monitors parameters at several locations on a pipeline.
- Through a Global Positioning System-based Excavation Encroachment Notification (EEN) technology that tracks the location and status of excavation equipment.
- Through the development of advanced geospatially-based analytics that can accept multiple streams of data and extract events of interest from background noise.

This approach makes use of the Global Positioning System (GPS). This technology has allowed investor owned utilities (IOU) to significantly improve the accuracy of their infrastructure maps. This has in turn, driven the adoption of Geographic Information Systems (GIS) to house utility data. GIS technology is being used with cellular-connected sensors placed on construction equipment to track their movements in real-time. Real-time tracking of construction equipment, gas system infrastructure GIS data, and activity characterization algorithms are used to alert the utility to potential damage from active excavations. Accurate location of the infrastructure, the detected threats, and the responding personnel is foundational to the analytics.

An example of location driven monitoring and response is the EEN technology developed by GTI. This technology utilizes commercial off the shelf software from Esri. A device is placed on construction equipment to stream GPS and other sensor related data via the cellular network to the utility. This allows the utility to know where construction equipment is located, if it is active, and what it is doing (digging, idling, moving locations). The EEN component of the work was funded by the California Energy Commission based on interest expressed by California utilities.

The SSN approach monitors specific locations within the ROW. A series of fixed multi-sensor stations are distributed along a pipeline to perform 24/7 monitoring. An advantage of the SSN approach is that it monitors the pipeline infrastructure itself, unlike the EEN technology. This allows the detection of different categories of threat, not related to construction.

The analytics use Esri software to access data streams from multiple field devices. A detailed and user-friendly interface provides utility operators with a clear picture of the situation and activities on the ground. Analytics will alert utility operators if individual SSN (or EEN) devices are detecting activity on the pipeline ROW. An advantage of central analytics is that they provide an overview of the monitored area. If a single SSN device indicates activity in the ROW, data from other sensors in the vicinity can be examined. These neighboring sensors may provide trends or supporting data that assist in determining if a threat is present.

Project Goals

The goals of this project are to demonstrate ROW monitoring by:

- Deploying a sensor-based system to detect threats entering the ROW
- Demonstrating the wireless collection of threat data to a hosted repository
- Demonstrating analytics that can identify actionable threats from the data
- Providing wireless notification of the identified threats to appropriate parties

The system must collect observations of multiple attributes at multiple locations within the ROW to form a detailed overall picture of pipeline status. **Error! Reference source not found.** lists attributes the demonstration system monitored. It is important to understand that more than one of these influences may be active at a given time and that circumstances other than construction activity can cause pipeline damage.

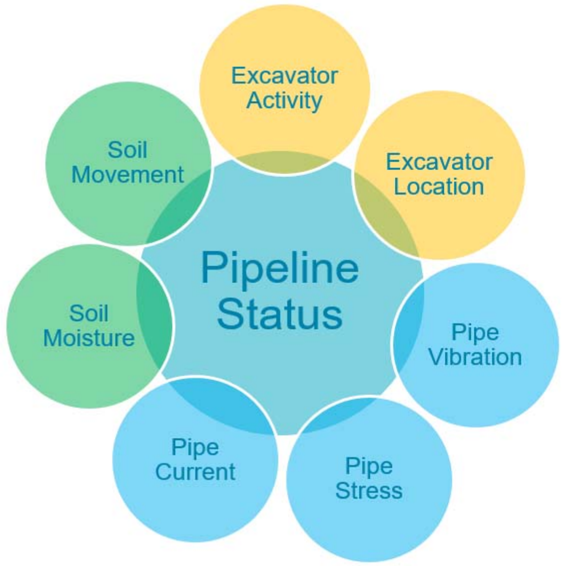


Figure 2. Overlapping Influences in the Pipeline ROW

The primary value of the monitoring system is to provide utility operators a clear view of potential developing threats to their pipeline in real-time, enabling them to proactively respond to mitigate damage or risk. In addition to improving safety, energy supply, and pipeline infrastructure, this will reduce costs related to accidents.

Proposed Project Task Structure

The tasks proposed for the execution of this project are presented below in their original form from the statement of work. There were variances from this plan that are discussed in greater detail in the body of the report.

Task 1 Technology Review and Selection

The initial activity will be to review the current state-of-the-art of ROW monitoring systems and component technologies such as sensors and communication systems. One goal of this activity will be to determine why real-time ROW monitoring systems have seen limited deployment. Also, participating OTD utilities that have evaluated such systems will be interviewed. This group of utilities will also be surveyed for other ROW monitoring practices they are currently using. Details such as cost of monitoring and frequency/latency issues will also be captured.

A conceptual design of the ROW monitor will be developed based on the findings. The design will be reviewed with the project sponsors. The minimum installation package consists of a housing, wireless link, a data logging system, vibration sensors on the pipeline, earth movement sensors, and sensors for CP monitoring. Additional sensor requirements from the project sponsors could be incorporated into the system, such as:

- Pipeline strain sensors
- Pipeline gas pressure
- Airborne methane
- Weather/meteorological

Candidate test sites offered by utilities will be considered during this task. The minimal site will have several ROW monitors installed on a single pipeline separated by a reasonable distance. The hosting utility is then required to expose the pipe for the attachment of CP test leads and vibration sensors.

Another aspect of this work is to determine if day-to-day operational data can be gathered through the same system. The possibility of co-locating the ROW monitors with existing or proposed facilities will be explored with the utilities at this time. Such facilities could be pressure monitoring stations, CP test stations, and the like. The automated capture of operational information, without personnel visits, could improve the economics of the system over one used solely for incident notification.

The end result of this task will be a report on the current state-of-the-art in ROW monitoring, analysis of weaknesses in current practices, the detailed design of the prototype ROW monitor, and the selection of a test site.

Task 2 ROW Monitor Pre-Prototype Construction

Using the information collected during Task 1, pre-prototype instrument packages will be constructed. To the fullest extent possible, these will utilize off-the-shelf components; the packages are not intended as final commercial items. A complete reference system, identical to those being deployed to the utility test site, will be constructed on GTI’s campus and connected to pipes already in place. This process will allow debugging of the sensors and instrumentation in a realistic setting prior to field deployment. The test data collected using the reference system at GTI will provide a performance baseline. The correct operation of the reference system represents a go/no-go decision point.

Several additional instrument and sensor packages will be constructed and tested after the reference system at GTI is performing satisfactorily. When the instrumentation packages are operating, the progress will be reviewed with the sponsors. The design documents for the prototype ROW monitor and guidelines for installation will be updated. This reference design will then be used for the systems deployed at the utility site.

Task 3 ROW Monitor Pre-Prototype Deployment

Appropriate housings, instrumentation, and sensor packages will be shipped to the utility test site. The scheduling and coordination for the installation will be finalized. Utility personnel will be required to assist GTI with the installation of the pre-prototypes on the test site. After installation, there will be a period of observation, prior to long-term testing, during which any adjustments to the instrumentation will be made:

- A coarse “calibration” of the monitors to their site locations will be carried out.
- The sensitivities and alarm thresholds for the various sensors will be set.
- The integrity of the wireless connections will be verified.
- The web hosting and accessibility of sensor data will be tested.

Task 4 ROW Monitor Prototype Testing

Long term testing of the monitors will be carried out during this task. For this testing, the data generated will be cloud hosted by GTI and made available to the project sponsors. Monthly reports on the operation of the ROW monitors will be issued during this task. The reference system at GTI will also continue to be operated during this time as a means to replicate any issues observed in those monitors deployed in the field.

One aspect of this task will be the establishment of a protocol for processing alert messages that are generated by the CBN analytics from the raw data. The proper utility personnel to be informed and the method of delivery (email, sms, etc.) will be established. The user interface for viewing the alerts and data will be cloud hosted and available to the testing utilities and the sponsors. This Task in conjunction with Task 5 will iteratively improve the user interface.

The data generated during this task will enable the development and improvement of CBN sensor analytics to identify events of interest within background noise. Field testing will refine the calibration of various sensor alarm thresholds and will include one or more “staged” events that involve contact with the pipeline. If possible, it will be desirable to choose a test site where construction activity is anticipated over the course of the test period. The anticipated results of these activities are a functioning ROW monitor system that has been tuned, or trained to its particular location.

At the end of Task 4, it is anticipated that the operation of the ROW monitor system will be transferred to the utilities hosting the test.

Task 5 Data Analysis and Reporting

The purpose of this Task is the development of analytics based on CBNs to identify events of interest from normal background noise on the ROW. The initial steps of this task will be to construct a cloud hosted database to capture the feeds from the various pipeline sensors and from public sources such as weather data. Wireless connections will be used to capture these feeds from the field. This database will feed the CBN analytics, which in turn, will feed a user interface, also cloud hosted.

Bayesian methods are preferred because of their robustness when dealing with sparse or less than accurate data. The output of the proposed CBN method will be an alert that an event of interest is in progress and a confidence level in the validity of the event. Dynamic CBN technology also allows for machine learning or adaptation based on new training data. The analytics will be self-improving over time.

Initial development of the CBN analytics will take place in conjunction with Task 2, wherein the first prototype ROW monitor will be set up on GTI property. The sensor systems can be tested both with recorded or simulated data as well as staged events on GTI test pipes. This initial testing will establish the basic form and priors of the CBN approach before additional prototypes are deployed during Task 3.

The coincidence of sensor events from multiple monitor stations will be the feeds for the CBN analytics. It is expected the variations in vibration, earth movement, and CP levels will be indicative of various activities in the ROW. Reporting will include the observations over the test period and recommendations for improvements to the ROW monitor.

Task 6 Project Management

The purpose of this Task is to manage the project and prepare and provide all deliverables to DOT/PHMSA including scheduling, budgeting, and reporting. Project Management also includes all meetings with DOT, peer review meetings, public presentations, other meetings, and project quality assurance activities at GTI through the laboratory’s Technical Quality Plan program and technical review activities.

Project Task Execution

A chronological narrative of the execution of the various tasks is given in this section. The schedule of the project as executed is different from that in the proposal. The reasons for this variance are discussed.

Task 1 Technology Review and Selection

During the 1st quarter of 2016, effort was expended across all the partner projects (PHMSA, OTD, and CEC) that identified off-the-shelf technologies for wireless communication links and for vibration sensors. Acellent Technologies agreed to provide piezoelectric vibration sensors for the monitoring of the test pipelines. Acellent developed these sensors under a CEC award and was subsequently funded by CEC to perform in-ground testing. Ingenu Wireless was identified as the preferred provider of wireless connectivity to the ROW Monitor hardware. Ingenu has a random phase multiple access (RPMA) radio system that has already been used by several California utilities for telemetry and metering. The prior experience with the RPMA technology helped GTI to secure two field test sites in California.

During the 2nd quarter of 2016 the overall system architecture was more fully defined. Figure 3 shows the overall block diagram of one individual sensor node to be placed on a pipeline. The vibration sensor and its associated signal processing will be provided by Acellent technologies. The other sensors and support electronics will be provided by GTI. Figure 4 (provided by Acellent) depicts their concept for the installation of vibration sensors in the ROW. The data streams from all sensors is passed to a wireless link that provides connection to a cloud hosted repository.

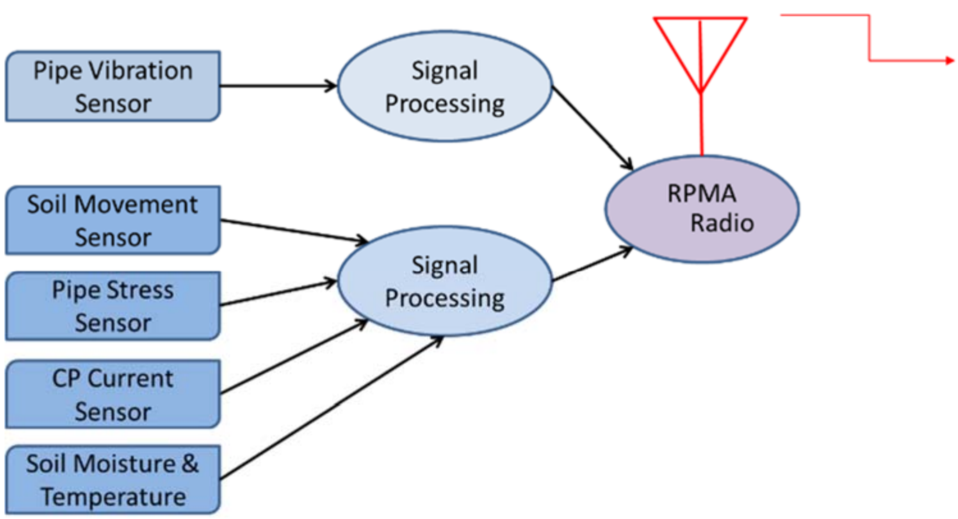


Figure 3 – Individual Sensor Node Block Diagram

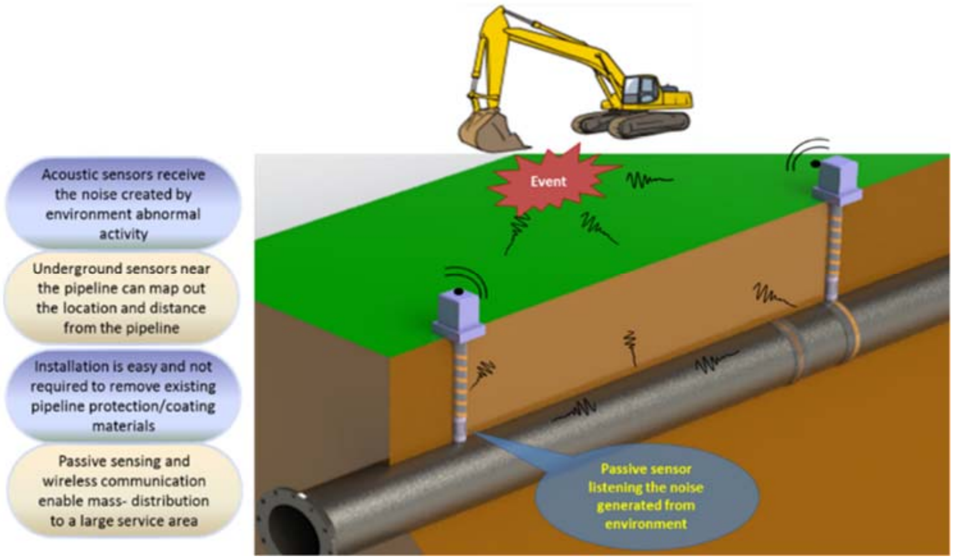


Figure 4 – Acellent's Concept for Installation of Vibration Sensors

Figure 5 shows the block diagram of the proposed network architecture. Several RPMA radios feed data to a single access point; the access point provides an internet gateway to a central data repository. Figure 6 and Figure 7, provided by Leidos, show typical end-point and access point installations in the field.

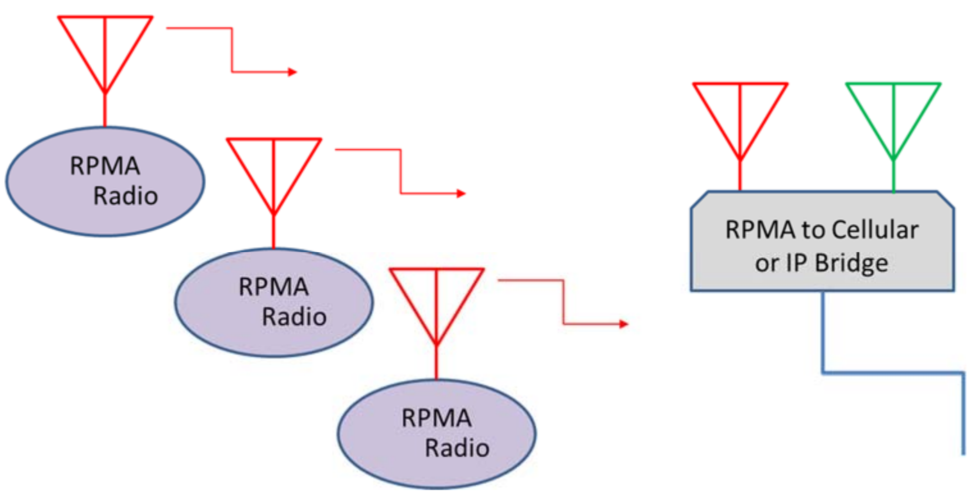


Figure 5 – Sensor Network Block Diagram

Figure 6 – Example of RPMA End Point in the Field

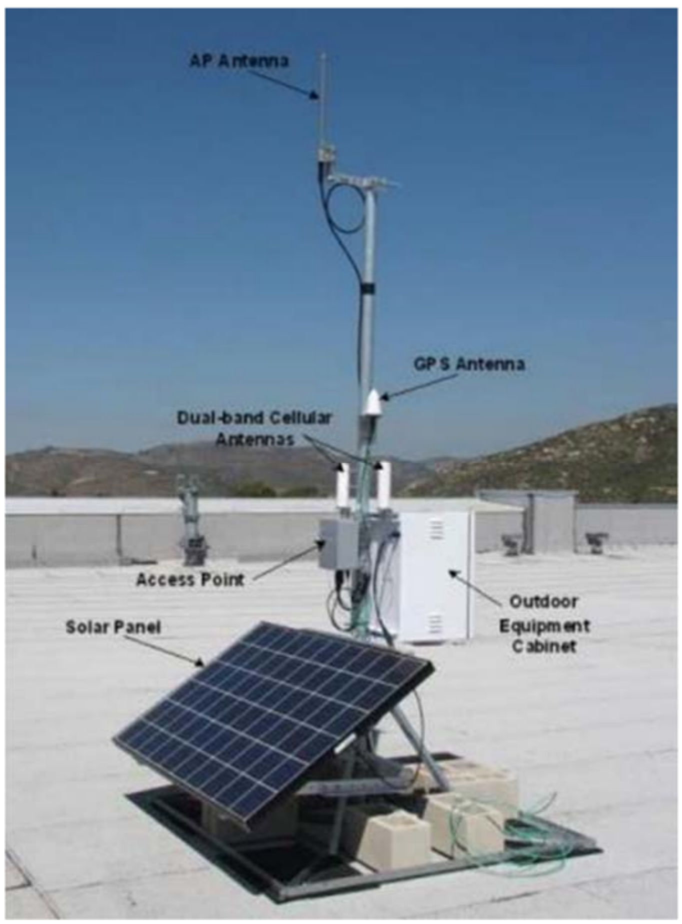


Figure 7 – Example of RPMA Access Point

The data aggregation and analysis will be carried out with a suite of Esri ArcGIS tools. The Esri GeoEvent Processor and Dashboard products will be used for feature extraction and display of the data. The decision is based on prior GTI and utility experience with these tools in other projects. The utilities hosting the test sites have some prior experience with these and should be able to adapt to them quickly.

Figure 8 shows the proposed data flow for the storage, analysis, and display portion of the system. Please note that this figure shows feeds from both stationary and mobile sensors. While this project deals specifically with stationary sensors on the pipe, the CEC partner project also includes mobile sensors on excavation equipment. Figure 9 shows an operations dashboard that can be used by an operator to visualize data from the repository. The data architecture also includes packages that can be used to analyze the data for the extraction of features of interest. This last item is crucial to project in that events that require attention must be separated from the background noise.

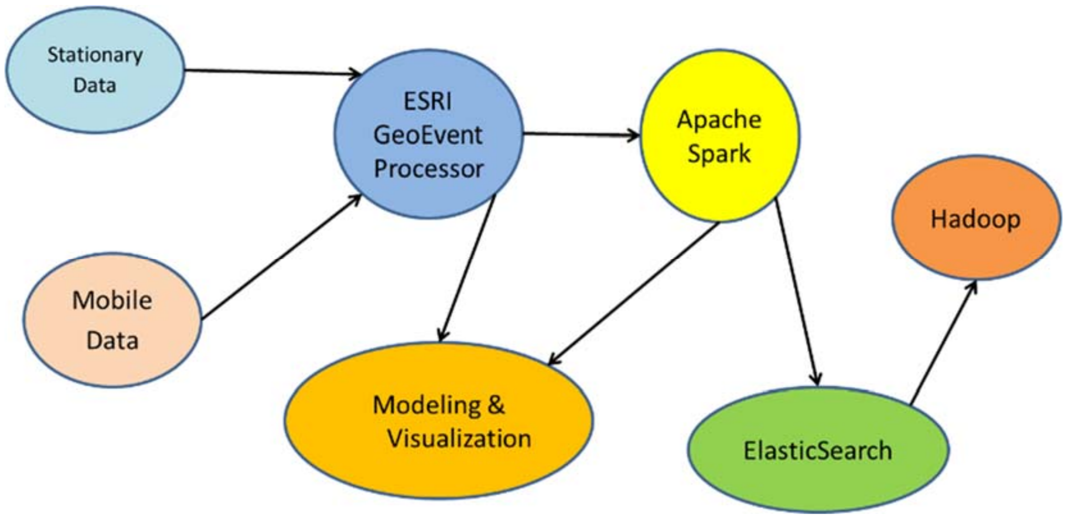


Figure 8 – Proposed Data Flow Architecture

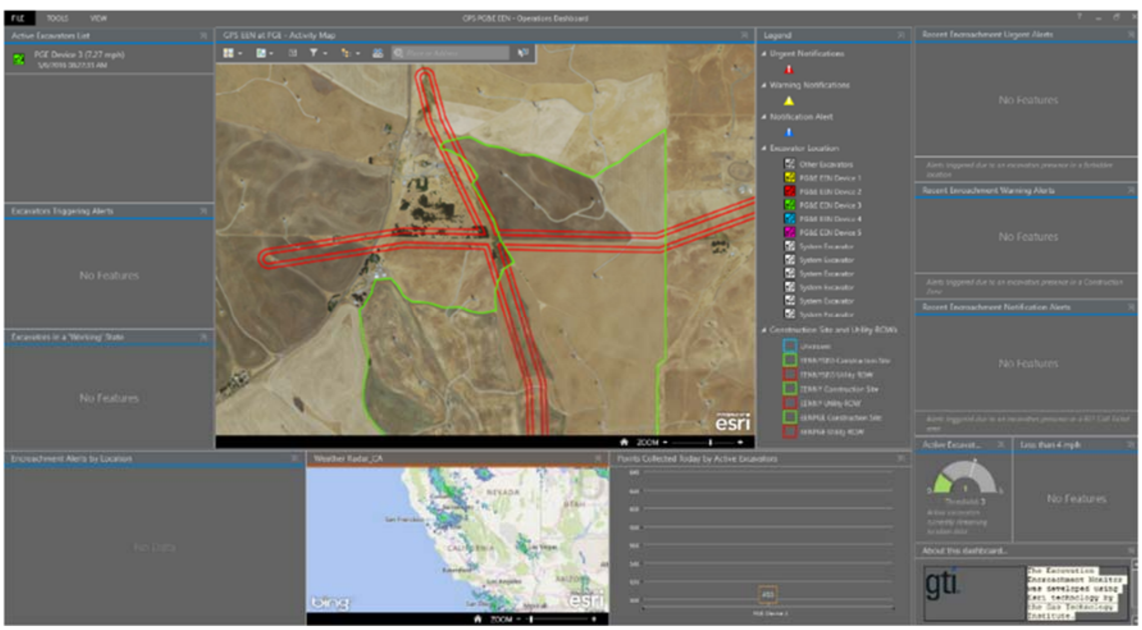


Figure 9 – Example of Data Visualization Dash Board

The general installation concept is shown in Figure 10. As noted, some categories of sensor attach directly to the metal of the pipe and others are bedded in the soil. In addition to the sensors, significant amount of electronics are required for signal conditioning and processing.

This will need to be housed in an enclosure and provided with power. Originally it was planned for the signal conditioning and the wireless data link to reside in separate enclosures.

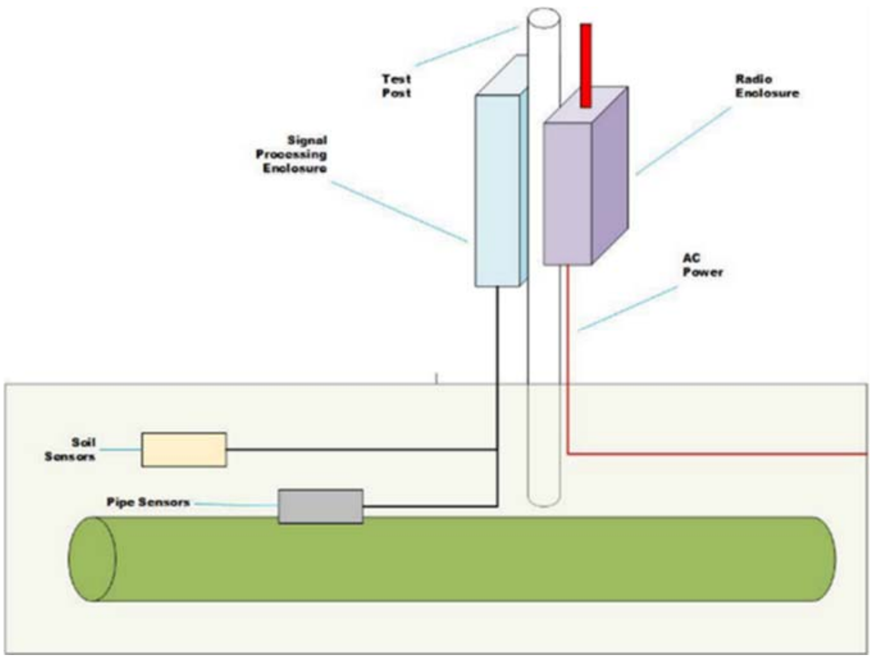


Figure 10 – Installation Concept for Stationary Sensors

During the 1st quarter of 2017, a preliminary set of sensors and associated electronics were selected for use in the monitoring equipment. The selection criterion and background information that supports the selections were the subject of a separate state of the art review. A large amount of effort was devoted to providing documentation and support materials to the utilities hosting the field tests. Their concerns were with that equipment to be installed on their systems; not with the technology overview. In the interests of securing utility test sites and keeping the project moving forward, this documentation was given priority.

Many sensor types and models have been examined. The following selections were made:

- Vibration sensors on the pipe for impact and proximity sensing
    - Acellent Technologies piezoelectric contact sensor and processor
- Strain sensors mounted on the pipe to determine tensile stress
    - Micro Measurements Strain Gauge CEA-06-125UW-350
- Pipe current sensor to determine AC and DC currents on the pipe
    - M.C Miller AC Corrosion Coupon
- Combined soil moisture and temperature sensor alongside the pipe
    - Campbell Scientific CS655
- Seismic soil motion sensors alongside the pipe to measure background noise
    - Geospace Technologies GS-30CT geophone

A presentation was prepared specific to the needs of PG&E internal stakeholders first. This was presented to several departments within PG&E to stimulate dialogue and gather support for the ROW monitoring project. These materials were shared with Southern California Gas for comment as well. A more generalized version of these materials was presented to the CEC project Technical Advisory Committee (TAC) on March 15, 2017. The TAC is made up of gas utilities, research organizations, manufacturers, and academia.

The Task 1, Item 1, Technology Review and Selection Report was submitted to PHMSA as a stand-alone document.

Task 2 ROW Monitor Pre-Prototype Construction

During the 2nd quarter of 2016 several samples of RF and sensor hardware were ordered for evaluation purposes. The procurement of the RF equipment was facilitated by a sub-contractor: Leidos Engineering. There were delays in the set up the sub-contract that put the overall project behind schedule.

During the 3rd quarter of 2016, a teleconference with the utilities that committed to test sites was held. A presentation was provided that gave a high-level review of the project and its objectives. This review provoked a good deal of discussion; the utilities expressed a need for more detail.

Based on the utility response, a detailed document that provides specific equipment types, power requirements, and dimensions is being developed. A rough draft of this was prepared and circulated to the utilities in September of 2016. The draft plans for the stationary sensor installations correspond to deliverable Item 3 in Task 2.

The report full "Task 2 Item 3 Right of Way Monitor Hardware Preliminary Design" was submitted to PHMSA during the 4th quarter of 2016. This document describes the architecture of the sensor installations that will be placed on the pipeline. The group of sensors and electronics placed at a single location along the pipeline will be referred to as a sensor node. Each node will have some sensors in direct contact with the pipe A detailed description of the individual sensors selected, the signal conditioning electronics, and the wireless connectivity hardware that make up a sensor node is given. A high-level description of the networking of multiple sensor nodes and the back-end data analytics is also provided.

One item of equipment changed after the issue of the report: based on technical discussions with Campbell Scientific a different mode of datalogger was used. The original thought was to use the CR300. It was found that the CR300 did not have sufficient analog input range to deal with the variety of sensors being used. It was necessary to step up to the CR800 (Figure 11) to accomplish what was needed. This device is roughly 40% more expensive; the equipment budget was impacted by this change.

In the 3rd quarter of 2017, Acellent, provided a signal processor (Figure 12) to accept the raw vibration signals and extract metrics indicative of impacts to the pipe. The digested vibration data is transferred to a Campbell Scientific datalogger over a serial link using the MODBUS protocol. The other pipe and soil sensors will be connected directly to the datalogger and stored there, also in a MODBUS format.

The aggregated data for a single location (Figure 13) is then transferred out through a Signal Craft Technology RPMA (random phase multiple access) radio system that is provided by Leidos Engineering (a sub-contractor under the CEC agreement). The data from multiple sensor locations is collected by a RPMA base station that is made by Ingenu Wireless. From the base station it is transferred to the Internet via a cellular or land-line connection.

Figure 11 – Campbell Scientific CR800 Datalogger

Figure 12. Acellent Technologies Vibration Signal Processor

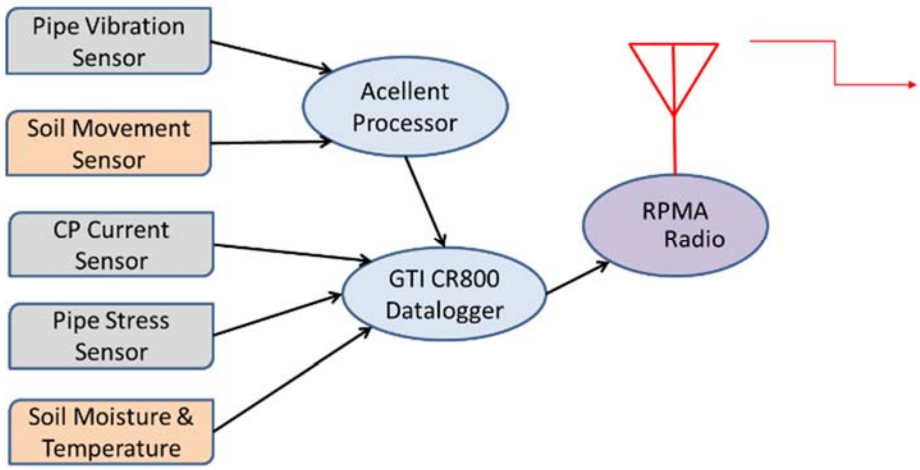


Figure 13. Data Flow Architecture for a Single Sensor Installation

During 4th quarter of 2017 it was determined that Acellent would also accept the signals from the geophone used to detect soil motion (Figure 14). This decision was based on the bandwidth of the analog inputs of the Campbell Scientific CR800 datalogger selected. The frequency content of the geophone signal is much higher than the other sensors attached to the CR800. The geophone would use most of the processing resources of the CR800 at the expense of the other sensors. The Acellent hardware will capture the data from their piezoelectric sensors and the geophone. Compressed vibration data will then be transferred to the CR800 datalogger over a serial link using the MODBUS protocol.

Figure 14. GS-30CT Geophone Soil Seismic Movement Sensor

Task 3 ROW Monitor Pre-Prototype Deployment

The procurement and installation of the sensor node wireless equipment was facilitated by a California-based sub-contractor on the CEC project: Leidos Engineering. There were initial delays in the sub-contract execution. GTI acquired some of the RPMA radio units for in house testing efforts prior to the main deployment.

A deployment-related item that caused significant delays, and ultimately a modification of the project schedule, was defining sensor installation procedures acceptable to the gas utilities. Given that several sensors are installed directly on the pipe wall, it is necessary to provide assurance that the integrity of the pipe wall or coating is not negatively affected. The installation method must also be viable under realistic field conditions.

There original attachment method did not involve the use of chemical adhesives. Adhesives can be very difficult to apply properly under field conditions. Adequate levels of surface preparation and cleanliness must be achieved. Temperature and moisture conditions have an impact on curing times and the quality of bonding. Chemicals must also be accompanied by safety data sheets and adequately vetted for safe use by utility personnel.

The proposal to the utilities hosting test sites was to use resistance welding to apply prefabricated sensors to the pipe wall. This is a method that has been used with strain gauges in structural health monitoring applications for decades. The strain gauge is adhesive bonded to a small metal shim under factory-controlled conditions. Wire leads are also attached in advance to create a prefabricated sensor. The sensor is then attached to item being monitored using a resistance welder (Figure 15) that uses a current pulse to "tack" a small area of the shim to the metal surface. The tacking process is repeated around the circumference of the sensor until it is securely in place.

Figure 15 – Field Portable Resistance Welder

The resistance welding method has been applied to pipeline monitoring by GTI and others in past work. The utilities providing the test sites for the current work requested supporting data and a demonstration of the method. There were concerns about the size of the heat affected zone (HAZ) within the pipe metal created by resistance tack welding. There were also concerns about the amount of coating that need to be removed from the pipe and the level of surface preparation required for the method.

To address these concerns, visits were arranged to demonstrate the method at PG&E, Southern California Gas, and Acellent Technologies. GTI purchased a resistance welder and off-the-shelf samples of weldable strain gauges. The utilities wanted to witness the process and create test samples that could then be destructively tested to evaluate the HAZ and other parameters. This also allowed utility personnel that would be performing the actual sensor installations to have some familiarity with the process.

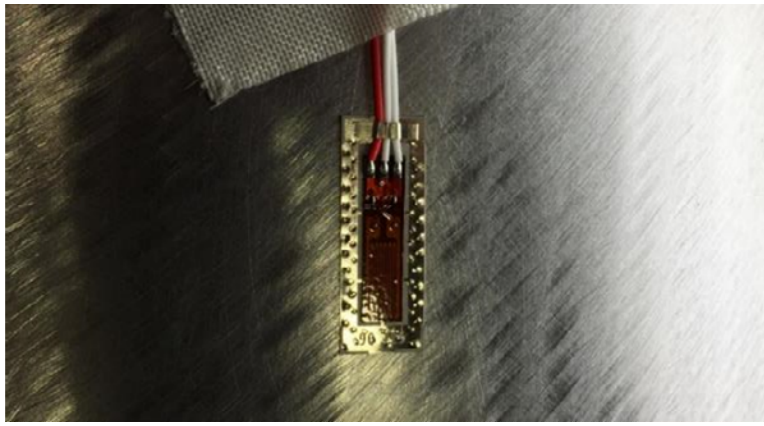


Figure 16 – Weldable Strain Gauge Demonstration

GTI provided demonstrations of applying weldable strain gauges at both utilities. Figure 16 shows one of the test specimens; in this case it was applied by utility personnel after a small amount of training from GTI. In both instances the utility provided pipe sections with the coating removed and the surface of the metal cleaned. The utilities retained the finished specimens to perform in-house metallurgical testing.

Acellent investigated a pre-fabricated vibration sensor that can be field-installed by the same method. They intend to standardize on the same stainless-steel shim material and thickness that is used for the commercial weldable strain gauges. Testing was carried out to verify that the tack welded vibration sensor has similar acoustic sensitivity to those directly epoxied to the pipe surface.

The results of results of the metallurgical testing by the utilities led to this attachment method being abandoned. While the extent of the HAZ created by any single resistance weld is small, the hardness of the steel was significantly increased by the resistance welding. The HK500 harness level rose from the range of 200 to 250 in the base material to more than 400 within the weld nugget. The utility performing the analysis pointed out that they would reject pipeline material with this hardness level. The concern expressed was that the combination of elevated hardness and cathodic protection could result in hydrogen embrittlement at the weld sites. Given that the strain gauges will be left in place indefinitely, the risk of embrittlement was unacceptable.

GTI then investigated adhesive bonded strain gauges (Figure 17) to replace the welded types. It was also necessary to specify an adhesive that satisfies the volatile organic compound (VOC) emissions criteria for the state of California. Vishay Micro Measurements, the provider of the strain gauges, also provides several varieties of adhesives. One of the utilities was familiar with the gauges and adhesives from prior work and indicated that the AE-10 type epoxy is acceptable.

Figure 17. Adhesive Bonded Strain Gauge with Cable

There are disadvantages to adhesive bonding versus resistance welding. More stringent pipe surface preparation must be achieved under field conditions. The epoxy must also be allowed to cure for several hours. GTI performed sample installation in-house to get a handle on how much time this will add. To facilitate this testing, the utilities provided GTI with several quarter-round sections of typical pipeline. This also allowed testing of the CR800 datalogger with samples of the actual gauge to be used in the field.

During the 3rd quarter of 2017, GTI with assistance from PG&E tested adhesive bonded strain gauges (Figure 18, right) to replace the welded types. It was necessary to specify an adhesive that satisfies the volatile organic compound (VOC) emissions criteria for the state of California, where the installation will take place. Vishay Micro Measurements AE-10 type epoxy is acceptable. The Safety Data Sheets (SDS) for all the other consumable chemicals used in the installation process have also been reviewed and approved by the utilities. Test installations of vibration sensors and strain gauges have been performed at utility laboratories to allow personnel to become familiar with the process. A shielding method (Figure 19) was developed to protect the pipe sensors during backfill.

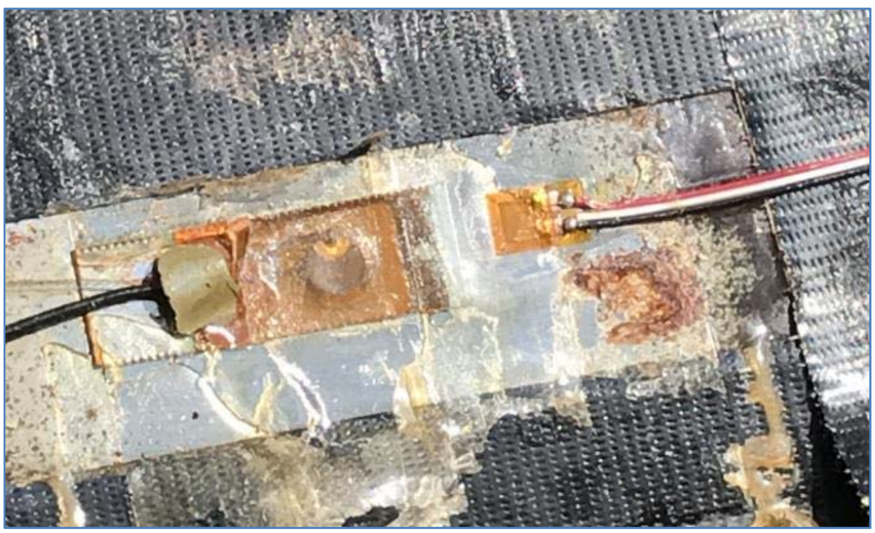


Figure 18. Vibration Sensor and Strain Gauge epoxy bonded to pipe

Figure 19. Field Shielding Developed for Pipe Sensors

Based on experience in defining procedures to attach sensors to pipelines and identifying operators qualified to perform these procedures, a definition of the appropriate test site evolved. The following attributes were required for test sites:

- The pipeline must be out-of-service at the time the sensor is attached. Examples are new lines that have not yet been commissioned or existing lines that have been cleared to carry out maintenance or repairs.
- The pipeline must be accessible through an excavation large enough for two workers. The pipe must also have 360-degree access to allow strapping or taping to mechanically protect the sensor installation.
- There must be some means to control conditions in the excavation at the time the epoxy adhesive is being applied. An awning/shelter and a portable heater should be available. The timing of construction may be such that waiting for better weather is not an option.
- The pipeline should be in an area where there is good probability of construction or other activity in or near the ROW. This will facilitate testing of the detection capabilities of the system.

An additional setback to the deployment schedule occurred this time. A PG&E test site that involved several miles of new pipe was investigated and significant effort expended in planning to deployment at this site. It became apparent however, that after the installation of the sensors there could be a delay of several months before electrical power could be brought in for the instrumentation. There was also extensive documentation and drawings that would need to be prepared before this could be executed. The added cost and schedule led to the dismissal of this site.

The alternative PG&E test sites considered were new cathodic protection rectifier installations. These sites had many desirable attributes: they require that the pipe be exposed and coating removed for the attachment of wires. Rectifiers must have a source of electrical power to function so no additional work was required for that aspect. Also, the enclosures (Figure 20) typically used for rectifiers can be used for the instrumentation. Standard rectifiers can be housed in either pole-mounted or ground-based enclosures.

Figure 20. Rectifier Instrument Box

Ultimately, no test site was secured with PG&E. The general issue was that the inclusion of the sensor system in any construction project must be planned at the earliest stages. Trying to add the ROW Monitor to an existing project required many adjustments to the schedule, permitting, and work flow.

Task 4 ROW Monitor Pre-Prototype Testing

During the 4th quarter of 2017, the field site at SoCal Gas was identified; a site visit by GTI, Leidos, and Acellent took place. The site in question (Figure 21) involved a line relocation requiring several thousand feet of new pipe. Three stationary sensor test points were planned for placement on the new line with approximate spacing of 1000' between the first two test points and 2000' to the last test point. Construction was expected to begin in February of 2018. The goal was to have the sensors in place in time so that the hydro-testing of the line can be recorded. If the RPMA wireless network was not functioning at that time, the fallback plan was for the data to be recorded on the CR800 loggers and extracted manually.

Figure 21. View of Utility Test Site

During the 2nd quarter of 2018, the vibration sensors and strain gauges were installed at on the SoCal test site (Figure 22). The soil moisture, soil movement, and current monitor sensors were installed at two of three locations. The third location will not be back-filled until after the hydro-test. The final set of soil sensors were installed at that time.

Figure 22. Sensor Installation at Utility Test Site

Software for the Campbell CR800 datalogger was developed to capture and record readings from all the major sensor types. This software was tested in laboratory conditions. This software was used to record the hydro-testing of the line at the SoCal Gas test site. The RPMA wireless system will not be set up until after the hydro-test. The RPMA system required some additional facilities to be completed at the test site that were not available at the time of the hydro-test.

This task consisted of testing the hardware and analytics on the utility provided test site (Figure 23). Representative test site data that has been captured under field conditions will be presented and discussed. Three test stations were deployed along a newly installed pipeline on the test site. The design, selection, and installation of the equipment has been detailed in other reports from this project.

Figure 23. General Site Layout from User Dashboard

The hierarchy of components, from the user perspective down, is given below. The purpose of the system is to provide remote users real-time data from their ROW.

- The ROW data is visualized on a user dashboard that is web hosted. The data for the dashboard is received from wireless feeds. The data is stored in a hosted repository.
- A wireless device is located at each sensor point along the pipeline. It collects data from local instrumentation and forwards it by radio to the hosted repository.
- Part of the local instrumentation is a datalogger that captures data from sensors and sends it to the wireless device through a wired connection. These sensors are:
  - A strain gauge mounted directly on the pipe surface
  - A current sensing wire connected directly to the pipe
  - A conductivity/moisture sensor in the adjacent soil
  - A temperature sensor also in the soil
- A vibration monitoring system captures sensor data and forwards it to the datalogger. The vibration sensors require faster processing than the logger was capable of.
  - Two piezoelectric sensors are mounted directly on the pipe.
  - A geophone is embedded in the soil alongside the pipe.
- Mobile devices mounted on excavation/construction equipment captures and transmits status data to the hosted repository by a cellular connection. This data includes:
  - The GPS location of the equipment along with its speed and bearing.

- Accelerometer and gyro data to infer what activity the equipment is performing

During the 3rd quarter of 2018, the hydro-testing of the line at the SoCal site took place. In-situ testing of the vibration sensors took place in mid-September. While the entire system was not tested during the 3rd quarter, the individual tests did provide calibration data for several components. The data from the hydro-test is provided in the Appendices section.

Task 5 Data Analysis and Reporting

Execution of Task 5 began during the 1st quarter of 2017. Much of this work is intended for the development of data analytics relating to the stationary sensors on the pipeline. The environment for visualizing the data will be based on Esri GeoEvent Processor.

Three Topical Reports were prepared and submitted to PHMSA during this project. These are stand-alone documents that provide detailed information on the technology choices, design decisions, and subsequent implementation.

- Task 1, Item 1, State of the Art Technology Review and Selection
- Task 2, Item 3, Right of Way Monitor Preliminary Design
- Task 2, Item 5, Right of Way Monitor Construction Details

The following set of technical Appendices are included with this report. These provide detailed information on activities and testing that took place on the field site. The appendices are in chronological order starting with the installation of the equipment. The initial testing covers data captured during the hydro-test of the line and the first test of the vibration sensors. The various sensors and the visualization dashboard were tested in turn.

As noted in the Executive Summary, the vibration sensors needed increased sensitivity to be effective. These were tested on three separate occasions. The final round of testing did show a means to reach the required level of sensitivity.

A. Outline of Sensor Installation Procedure at First Test Site
B. ROW Defense System Initial Testing
C. Mobile Sensor Testing
D. Second Vibration Sensor Test
E. Soil Parameter Measurements
F. Current Density Measurements
G. Demonstration of User Dashboard and Analytics
H. Third Vibration Sensor Test

Task 6 Project Management

By the 2nd quarter of 2017 it was evident that project schedule would require amendment. The project plan had originally called for 27 months; 21 months had elapsed without equipment having been installed on utility test sites. This was driven by the amount of qualification effort preliminary to any deployment and of the utility construction schedules. The following graphic (Figure 24) depicts the originally proposed project schedule in blue versus the actual execution in green at the time this decision was reached.

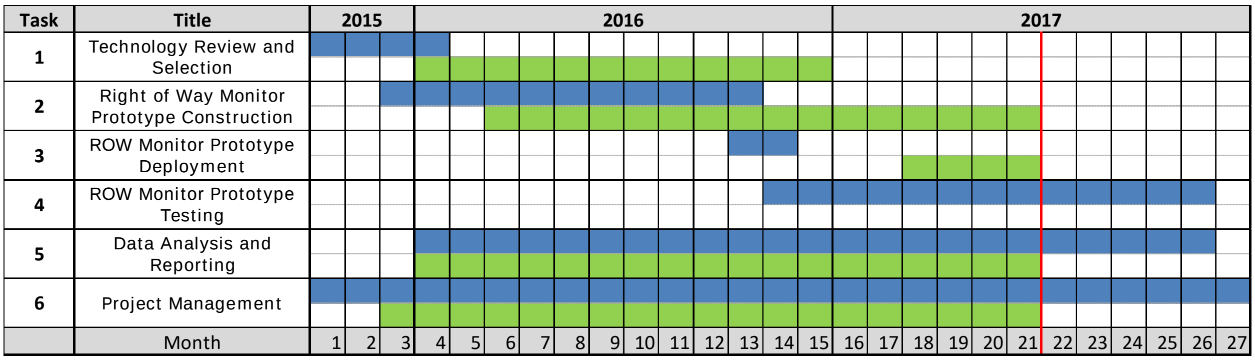


Figure 24. Original Project Schedule

A modified milestone chart and list of deliverables was submitted to PHMSA and subsequently accepted. This modification moved the end date of the project to September 30, 2018, adding 9 months to the project. No additional funding was sought. The amendments for the CEC schedule were submitted for consideration and accepted. The original schedules for both projects had called for a final report in December of 2017. Based on utility schedules, the end date would only allow enough time to install the equipment with none left for testing.

At this time, GTI instituted bi-weekly conference calls with the various project stakeholders: PG&E, SoCal Gas, Acellent Technologies, and Leidos Engineering. This provided a forum to vet the methods and procedures for equipment installation. The utilities gave the technology providers valuable feedback as to what is acceptable to them in the field.

This close communication between the utilities and the technology providers resulted in the identification of test sites that were an excellent fit for the project goals. The identified sites were pipeline replacement/installation work providing varied geography to choose from. This would allow the stakeholders to select features of interest for the field testing and monitoring phase of the work. At one site, a second pipeline with fiber optic monitoring (not funded by this work) was constructed alongside the system GTI is installing. This will allow a comparative evaluation of the discrete stationary sensor system alongside a fiber optic technology.

By the end of 2017 the amended project end date was approved. GTI reached out to the OTD companies providing co-funding to this project for additional support. The additional funding was intended to cover the extensive and unplanned effort that was required to qualify both the sensor mounting procedures and the operators that perform them. This OTD funding was secured.

GTI requested an additional project extension from PHMSA to allow the SoCal test site to continue operation into 2019. The funds obligated by the CEC for this effort could not be used beyond 2018. The construction delays that occurred during the setup of the test site, though unavoidable, did not allow a great deal of testing within 2018.

Given the amount of up-front effort that went into the setup of this site, a great deal of which was in-kind effort from SoCal, continuing to monitor the site would be advantageous to all stakeholders. In support of this, an extension through June of 2019 and a new Attachment #3 was submitted to PHMSA. This was subsequently approved and monitoring was continued.

Results and Conclusions

The equipment on the test site consists of three monitoring stations, each with a suite of sensors on the pipe and in the adjacent soil. The monitoring stations contain signal processing and recording equipment with a wireless link to transmit the collected sensor data. The site also contains a base station that provided a bridge between the monitoring stations and the internet. The base station aggregates the test station data and forwards it to a remote server via a cellular link. The three stations are at discrete locations distributed over roughly 5000' of pipeline that was newly installed in 2018.

While the hardware is functioning properly, the project was not able to run the monitoring system for the originally planned length of time nor at diverse test sites. As noted, the various delays in qualifying acceptable procedure led to only a single test site being acquired. The site that was available is not in a populous area. While it tested the basic hardware, more sites will be needed to test the ability to identify threats to the pipeline amidst background noise. The process to install equipment on utility pipelines is a rigorous one. The rigor is entirely appropriate in terms of safety both for the operators and the public.

The need for small, low impact installations remains important. Low impact means that the installed equipment is compact and can operate at low power. This has an impact on installation costs, the largest component of the overall system cost. The overall size and power will need to be reduced further for deployment in urban areas. The low impact attribute also extends to the below ground sensor components. The installation of sensors will need to be modified such that the total installation time required is reduced.

Recommendations

Work is still needed for further observations and data collection to refine the analytics. It is recommended that the ROW Monitor demonstration now in place be kept in operation. The run time of the current testing has not included any external events that are actionable. Further testing data supported by refined analytics would serve to further disseminate information about this technology opportunity to other utilities in the U.S.

There are still some issues with individual sensors that need to be addressed. The most pressing is the sensitivity of the vibration sensors to impact. This metric determines the spacing between monitoring stations. Previous testing has been disappointing. During February of 2019, some upgrades and additional testing was carried out. These results were much more encouraging and indicate that the signal to noise ratio can be improved.

The current experience points out a need for future work on non-invasive sensor technologies for pipelines. Methods of sensing strain or vibration without removing coating or direct metallic contact would be valuable. A great deal of effort was devoted to assuring that instrumentation in contact with the pipeline does not compromise the existing coating or metal integrity. This limits the amount of data that can be gathered to increase operator awareness of their system status.

Appendices

A. Outline of Sensor Installation Procedure at First Test Site

The following notes provide a general description of an installation of sensors on and near a pipeline to perform right of way (ROW) monitoring. The procedure described assumes that the pipe is not in service at the time of installation. The pipe may be new and not yet commissioned or taken out of service for maintenance. The pictures are taken from an actual installation on a new pipe prior to commissioning.

1. Prepare Excavation
   1.1. Create a properly shored excavation that provides 360-degree access to the pipe.
   1.2. Trench should be at least 4' wide and 8' long as seen in Figure 25. Safe access to the excavation must be provided.
   1.3. Conduits to bring sensor cables to the surface can be placed in advance.
   1.4. Keep excavation free of water; pump if necessary. Have heaters on hand to bring pipe surface to about 74 F. The pipe surface must be dry. The temperature effects the curing time for the epoxy used to attach sensors.

Figure 25. Excavation for Sensor Installation

2. Surface Preparation
   2.1. A utility crew will remove the outer coating over roughly 6" by 6" area of pipe surface. The crew may perform additional coarse abrasion if rust or scale is present. The sensor placement area must be free of large pits, gouges, or seams.
   2.2. The following steps in detail can be found in Micro Measurements Bulletin B-129-8 which provides the surface preparation methods for the installation of strain gauges. A high-level synopsis is given here.
   2.3. Degrease pipe surface to prevent contaminants being driven into surface. An air or electric grinder with successively finer abrasive pads is used to smooth the pipe surface. Degrease the pipe surface between changes of abrasive pads to prevent contamination.

Hand polish the pipe surface with 320 grit then 400 grit paper to further improve finish (Figure 26a).

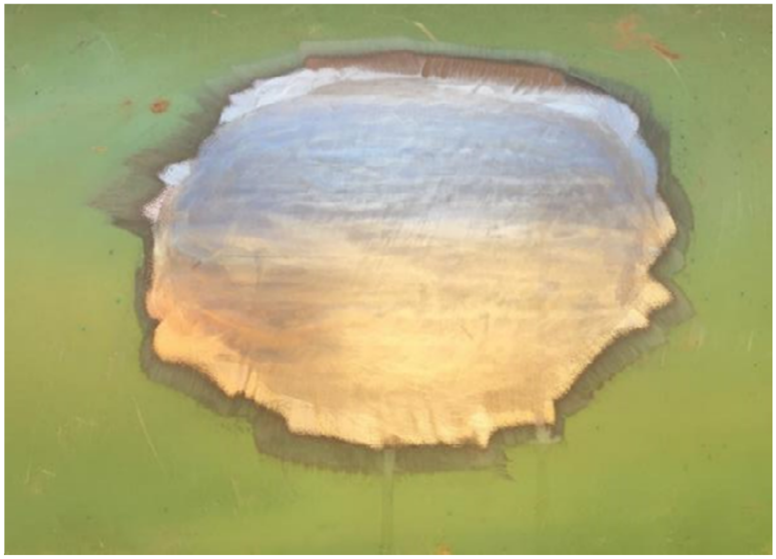


Figure 26. Cleaned Pipe Surface

2.4. Use a straight edge and burnishing tool or ballpoint to mark layout lines on the pipe surface. For this project, the layout lines are parallel to the longitudinal direction, or flow direction of the pipe.

2.5. Wet clean the surface with M-Prep Conditioner being careful not to remove the layout lines. Clean the surface again with gauze sponges and M-Prep Neutralizer. Wipe from the interior of the cleaned area outward in one stroke. Do not re-use gauze.

3. Sensor Application

3.1. Sensor application must be done immediately after completing the surface prep and cleaning. For vibration sensors, clean the back surface with degreaser. For strain gauges, leave in plastic covers until just before application.

3.2. When performing this work under field conditions, it is good practice to install an extra strain gauge. Once the area is prepared, the additional labor for an extra gauge is minimal. This helps ensure that a good gauge installation is available.

3.3. Pre-positions sensors and tape down leads outside of cleaned area. Use the layout lines to orient strain gauges with the sensitive axis in the longitudinal direction.

3.4. Mix the appropriate amount of the AE-10 epoxy for the sensors. Generally, one 10 gram package of the epoxy is sufficient for four sensors. The pot life of the epoxy is roughly 20 minute but can be reduced by high temperatures.

3.5. Use stirring rod to apply epoxy to pipe surface. Position sensors with tweezers and/or dental pick. Cover sensor with Teflon tape, then apply magnet or other clamping mechanism to surface of Teflon (Figure 27).

3.6. Wait for epoxy to cure based on ambient temperature: roughly four hours at 74 degrees F. Supplemental heat may be needed during cold weather. Care must be taken to exclude water from the sensor area during the cure time.

Figure 27. Sensors During Epoxy Cure

4. Test and cover
   4.1. Remove magnets and Teflon tape from sensors. Test strain gauges with Vishay instrument (Figure 28) or ohm meter. Test vibration sensors with Acellent instrument or oscilloscope.
   4.2. If a sensor installation is found to be questionable it should be removed and/or replaced. If a "spare" sensor was installed, the best practice is to cut the cable from the suspect sensor to prevent later confusion.

Figure 28. Vishay Micro Measurements Strain Indicator

   4.3. Wipe down area adjacent to sensors with acetone for full 360 degrees. Bracket the immediate sensor area with two strips of Viscotaq. Press cables into first layer of

Viscotaq and sandwich with additional strip (Figure 29). Cover over sensor area with additional strips perpendicular to the border strips to form a patch.

Figure 29. Form Protective Patch over Sensor Area

4.4. Over the sensor protection patch, perform a spiral wrap of the pipe with Viscotaq as per manufacturer instructions. Start wrap at least 6” before sensor area; continue wrap to 6” beyond sensor area. Counter wrap the pipe with protective PVC tape over the top of the Viscotaq (Figure 30).

4.5. Test all sensors again prior to backfill.

Figure 30. PVC Tape Wrap being applied over Viscotaq Wrap

5. Initial Backfill and Soil Sensor Installation

5.1. Position excess sensor cable near the edge of excavation and on the bank. If the data logging equipment is available, it can be hooked up to record the back-fill process (Figure 31 and Figure 32). The change in pipe strain level during fill indicates the gauges is working correctly.

5.2. Begin filling trench with zero sack or other flowable fill, taking care not to strike the cables.

Figure 31. Monitoring Back Fill

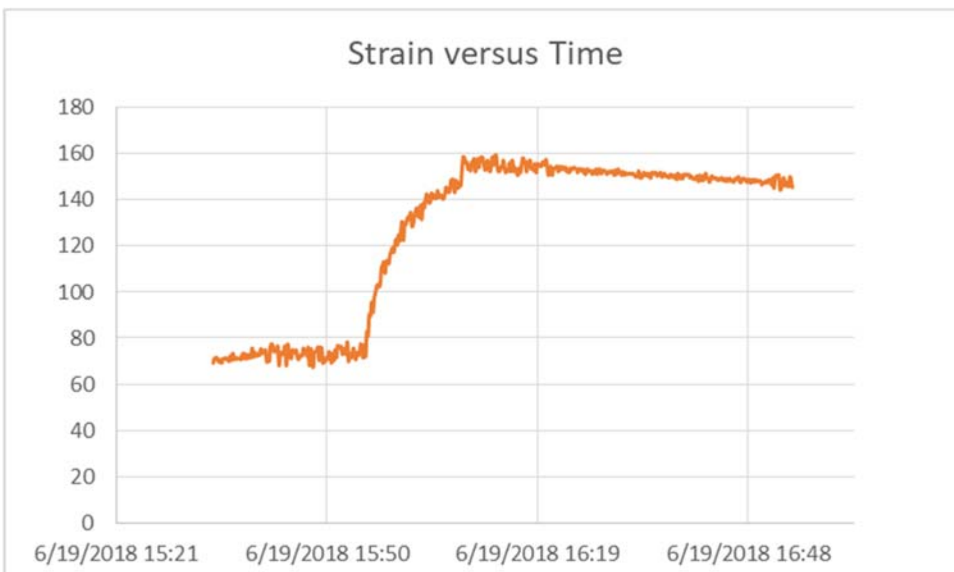


Figure 32. Micro-Strain Recorded During Flowable Fill

5.3. Flow fill from alternate sides of the sensor area to achieve a fill level to roughly 18" above the pipe crown line (Figure 33). When the fill level has been achieved, allow the fill to set for 1-2 hours until the surface becomes firm enough to walk on.

Figure 33. Excavation Partially Filled over Sensor Area

5.4. After the fill has set sufficiently, make a roughly 12" by 18" excavation by hand to the side of the pipeline near the bank. Insert the soil sensors into this excavation with the geophone in the center. Place the soil moisture and current coupon sensors at opposite ends of the hand excavation. Taking care to place the soil sensor cables on the bank, fill the excavation by hand (Figure 34).

5.5. After all sensors are installed under flowable fill, repeat tests using datalogging equipment and/or testers to verify that all sensors are working.

Figure 34. Sensors Installed

5.6. The sensor cables are then run through conduit from the top of the flowable fill to the surface of the ground. This is in preparation for the installation of the instrument cabinets. When the cables are within conduit, standard backfill procedures can be used for the remainder of the excavation.

B. ROW Defense System Initial Testing

As noted previously, installation of the sensors on the site began in June of 2018. This is the first step in the deployment process and must be accomplished while pipe is exposed in open trenches. The trenches were constructed to provide adequate and safe access for the installations to take place. Those sensors attached directly to the pipe surface (strain, vibration, and current) required removal of the coating and surface preparation (Figure 35). Once the surface was prepared, strain and vibration sensors were immediately applied (Figure 36) using a two-part epoxy. The current sensor wire was installed by thermite welding. These steps were repeated at all three locations.

Figure 35: Surface Preparation

Figure 36: Adhesive Bonding of Sensors

Adequate time was allowed for the epoxy to cure. Given the hot, dry conditions at the test site, four hours was needed. The sensors were tested for continuity and functionality prior to sealing them up. A tape wrap product (Figure 37) was applied over the sensors and both over and under their wiring to provide a long-term seal against moisture. The sensor cables were temporarily secured to the cross braces.

Surry fill was poured into the trench up to a level roughly 18" above the top of the pipe (Figure 38). The slurry was allowed to set for about two hours until it was firm enough to walk on. Personnel hand dug a small pit in the slurry next to the pipe and installed the soil sensors: the current coupon, the geophone, and the soil moisture/temperature sensor. The soils sensors were then covered by hand. Because of construction schedules, the slurry process was performed at two locations in June and the third in August. The excavations were all topped up with normal backfill to bring them up to grade.

Figure 37: Black PVC Tape applied over Viscotaq Tape Wrap

Figure 38: Slurry and Soil Sensors in Place

The pipeline was hydro-tested in early July. The permanent instrument enclosures were not complete at the time of the hydro-test. The instrumentation temporarily deployed (Figure 39) for a three-day period to capture this data. This provided test data for some of the major systems. There was no cathodic protection in place during the hydro-test preventing

testing of the current coupon. The instrumentation was run from a combination of batteries and/or generators. The RPMA radios were not available making it necessary to recover the test data by directly connecting (
Figure 40) to a laptop.

Figure 39: Instrumentation Running on Battery Power

Figure 40: Recovering Data

The following plots show longitudinal pipe strain data that was capture over the course of the hydro-test. The pressure profile (
Figure 41) ramps up to a spike value for roughly 15 minutes. The pressure is then held at 80% of the MAOP value for 8 hours. After that time the pressure was released, and the water was pigged out. The strain data recorded at another location on the pipe (

Figure 42) showed a noise artifact for part of the test. This noise is attributable to the use of a generator to recharge the instrumentation batteries. The battery voltage plot (Figure 43) for the same location clearly shows when the generator was being run. The first plot (
Figure 41) shows a station that was run purely on battery power for the entire duration of the test. The lesson from this is that truck-mounted or other temporary generators lack adequate grounding and can be a source of noise.

Figure 41: Strain Data at Location 1

Figure 42: Strain at Location 3

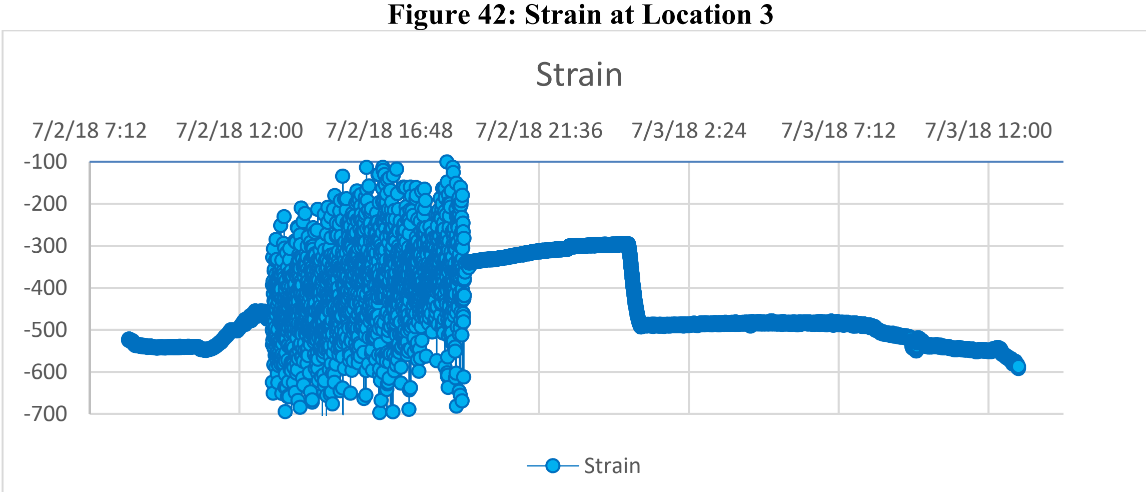
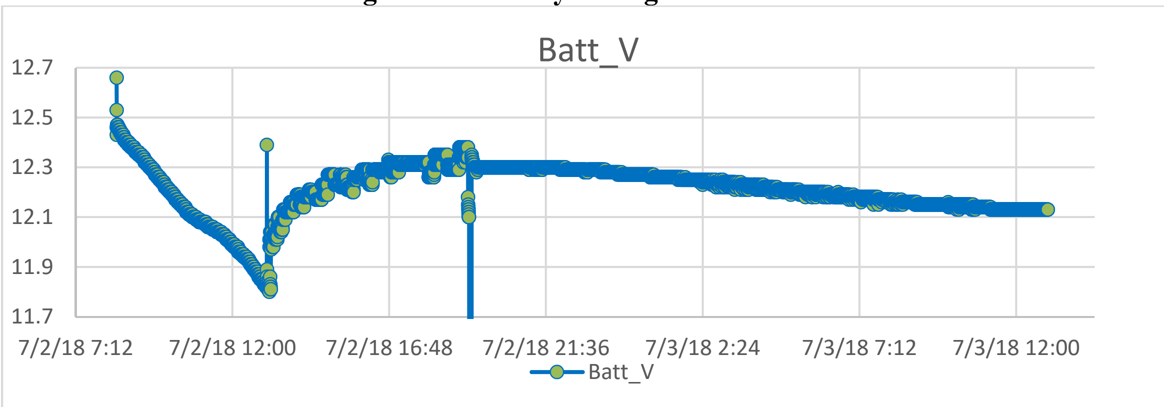


Figure 43: Battery Voltage at Location 3



After the hydro-test was complete, the instrumentation was removed to a safe storage area in the construction yard until the permanent enclosures could be completed. The sensor cables were pulled through conduits and brought above ground. Footings (Figure 44) were poured at two locations to support the pole for the instrumentation cabinet during July. The remainder of the soil backfill was put in place on top of the slurry fill covering the pipe.

Figure 44: Footing and Conduit in Place

The poles were put in place and the permanent enclosures with their solar power system (Figure 45) installed in early September. The CR800 dataloggers and associated sensors were installed and wired by SoCal personnel and contractors using the installation drawings developed by GTI. The Acellent vibration processors and RPMA radios will be installed in the future. Space has been left at the top of the 15’ pole for the radio enclosure. This installation is typical for 2 of the 3 locations on this site.

Figure 45: Solar Powered Enclosure in Place

The third location on this site to house instrumentation will be inside the fence of a permanent station being constructed by SoCal. The array of sensors is the same as the other locations, but the instrumentation will reside in an equipment shed (Figure 46) that is supplied with AC mains power. A 15' mast will be provided for the RPMA radio equipment. This location was completed near the end of September and has not been tested yet.

Figure 46: Equipment Sheds at Location 3 under Construction

A series of tests were carried out on September 12th to verify the response of the system to vibrations and impacts. This testing involved locations 1 and 2 only; the equipment shed at location 3 was under construction at the time. For this series of tests, the Acellent signal processing equipment was installed in the enclosure (Figure 47) and connected to the sensors. SoCal provided a soil compactor and an excavator to support this testing.

The purpose of the compactor testing was to put repeatable vibrations into the ground at known locations between station 1 and station 2. This would provide data on the sensitivity of the vibration sensors mounted on the pipe and on the attenuation of the soil-pipe system. The compactor testing (Figure 48) began 50' south of location 1 and proceeded continuously over the pipeline to a point 50' to the north. The testing continued proceeding north toward location 2 (Figure 49) with the compactor being moved to discrete points rather than run continuously. These points were 100', 200', 400', 600', 800', and 1000' north of location 1. The compactor was run for roughly 2 minutes at each point. The last point in this series was roughly 43' south of location 2. To complete the series the compactor was run continuously from this point to on 50' to the north of location 2.

Figure 47: Equipment Enclosure Interior View

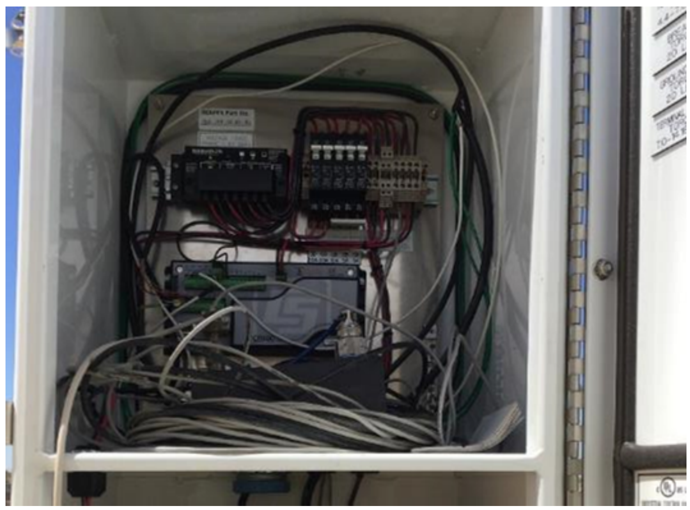


Figure 48: Compactor Testing

Figure 49: Test Site Overview

The excavator testing was carried out at the same set of discrete points as the compactor but in reverse order. The excavator started at a point 50' to the north of location 2 and proceeded to a point 50' to the south of location 1. At each point the excavator removed a small amount of soil, impacted the arm onto the ground several times, and then replaced the soil. At no time was more than 12" of soil removed or was there any hazard to the pipeline.

Figure 50: Excavator Testing

At the end of this testing sequence the excavating equipment withdrew from the site and the data was recovered from the recording equipment. This was accomplished by attaching laptops to the various dataloggers as the radio system is not yet in place. It was found at this time that the Acellent equipment had failed to record any vibration events. Also, the Acellent equipment appeared to be overheating.

Based on these results Acellent removed the signal processors from the enclosures and took them back to their facility in Sunnyvale for testing. The equipment was found to be in working order. Acellent set up a pipe with sensors at their facility and performed several impact tests to test the noise floor and sensitivity. The determination was that several gain and trigger threshold values had not been set appropriately for the actual field conditions.

On September 26th Acellent returned the equipment to the test site to run several diagnostic tests and measure the equipment noise floor on the actual site. These activities allowed the appropriate settings to be established. Acellent reported that they were able to record some background events during this round of testing. The Acellent signal processors were left in the enclosures running at the end of this test.

Consideration is being given to how and when to repeat the compactor testing. SoCal Gas has nearly completed all their site construction activities and will be de-mobilizing their equipment and contractors. It is unlikely that they can provide the equipment again. Acellent is not a sub-contractor to GTI but rather a collaborator. Acellent is developing the vibration sensor technology under their own separate Grant Agreement with the CEC. It has been suggested to Acellent that they should bear the expense of hiring equipment to repeat the testing.

At this time the RPMA radio equipment is being prepared by Leidos Engineering, a sub-contractor to GTI. The expected installation time is during the second week of October. This would be the point at which all hardware is in place. Testing of the full system could begin at that time.

C. Mobile Sensor Testing

The purpose of the mobile sensors is to provide the location and status of excavation or construction equipment. The mobile sensors (Figure 1 incorporate GPS technology to capture the location, heading, and speed of the equipment. They also incorporate motion sensors such as gyros and accelerometers to determine the equipment status: excavating or idling. A cellular link is incorporated to stream the sensor data to a central repository. This concept is termed Excavation Encroachment Notification (EEN). A fundamental premise of EEN is that the utility has their critical infrastructure mapped with GPS data. This allows the establishment of a "geo-fence" area around the infrastructure. If the mobile sensor moves within this geo-fence, an alert is forwarded to the utility. Additional alerts are generated if sensor data indicates that the equipment is also engaging in digging activity.

Figure 51. EEN Device Prototype

A first-generation prototype of the EEN device was constructed and tested early in this project. An additional project was funded by the Commission (PIR-15-015) that produced pre-commercial prototypes. These devices were more advanced than the original prototypes and were readily available at the time of field testing. The original test plan had included simultaneously testing the stationary vibration sensors and EEN sensors on excavators on the same ROW.

During the actual field testing, the access to excavation equipment was limited to less than one day. There were issues with the stationary vibration sensing equipment, discussed in the next section, such that the utility hosting the test site did not provide a second round of excavator testing. In place of the excavator testing, the EEN device was placed in several vehicles that were used on the test site. This allowed several key attributes of the EEN devices to be tested.

- The cellular coverage on the site was such that the EEN devices could be tracked.
- The geo-fence around the pipeline on the test site could be established.
- Notifications were generated when the EEN device entered the geo-fenced area.
- The notifications could be displayed on the same operations dashboard as the stationary sensor data.

Error! Reference source not found. shows representative test data visualized in the user interface dashboard. The database and analytics that underlie this visualization will be discussed in more detail in later section. The symbology is as follows: the EEN device is the red circle with the inscribed triangle. The pipeline is shown in yellow and its geo-fence as the two blue lines that bracket the pipeline. In this case the geo-fence area is set for 25’ on either side of the pipe location. The stationary sensor locations are designated with light blue squares. Clicking on the EEN device symbol in the dashboard will produce a drop-down display with the most recent data received.

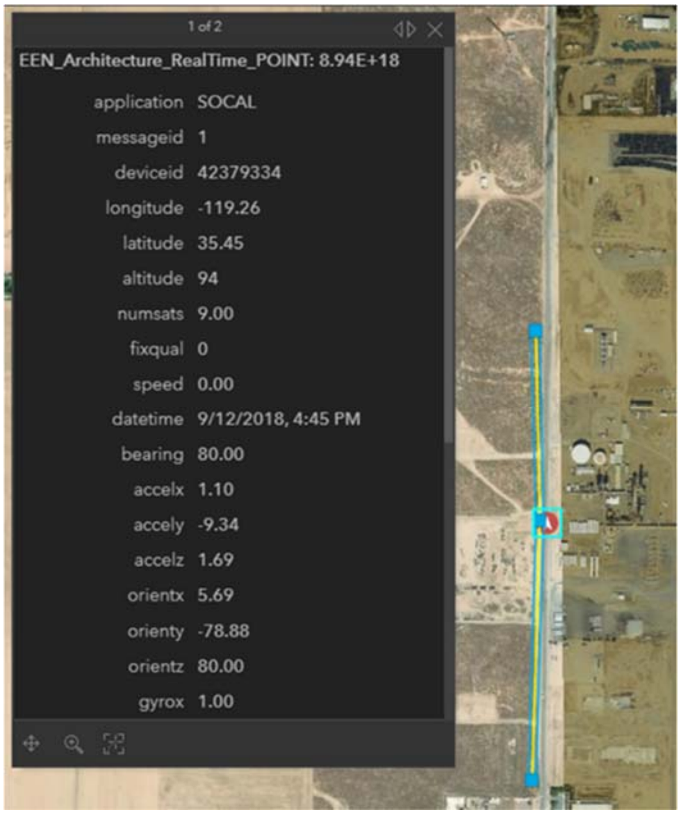


Figure 52. EEN Device Data on Dashboard

D. Second Vibration Sensor Test

The purpose of the vibration sensors is to provide early indication of activity on/near the pipeline ROW. There are two sensors directly attached to the pipe to measure vibrations travelling directly in the pipe material. These are piezoelectric sensors made from a lead-zirconium titanite (PZT) ceramic. There is also a moving-magnet geophone in the soil adjacent to the pipe to capture seismic events.

The first series of vibration tests were carried out on September $12^{th,}$ 2018 to verify the response of the system to the presence of compactors and construction equipment. This testing was carried out with both a soil compactor and a backhoe. There were significant problems with vibration monitoring equipment at that time. The equipment was removed and taken back to Acellent Technologies' (the manufacturer) laboratory for investigation and adjustment. It was found that signal levels were not adequate to trigger the threshold for data acquisition (like the trigger function of an oscilloscope). The algorithm embedded in the equipment was modified to acquire data continuously and pass those results to the datalogger for archiving and radio transmission.

The vibration monitoring equipment was returned to the test site and the continuous data acquisition verified. The vibration testing of the equipment was repeated on November 13^{th} and 14^{th} using a soil compactor as the signal source. Data from this testing was captured both as processed data in the Campbell CR800 datalogger and as raw data within the Acellent vibration processing equipment. This section will provide a detailed look at the testing at Station 1, located at the south end of the test site. With minor variations, this data is typical of all three stations.

For the second round of vibration testing a soil compactor was operated near the buried sensors at Station 1. The first test occurred on top of the sensor location. For the second test, the compactor (Figure 53) was moved to a location 75' from the sensors. The compactor was operated for 2 minutes continuously in both locations.

Figure 53. Vibration Test with Compactor

The raw data was recorded internally by the Acellent Technologies vibration monitor (ATVM) and a processed version of the data was passed to the Campbell datalogger (CR800) for storage. The radio system was not active the day of the vibration test; storage in the web hosted system was not available.

The processed version of the data passed to the CR800 is based on the Fast Fourier Transform (FFT) of the raw data and some statistics. For each of the three vibration channels the following five parameters are provided.

- An alarm value that is set to 1 if activity is detected, 0 otherwise
- The mean value of the raw signal
- The standard deviation of the raw signal
- The frequency of the highest peak in FFT of the raw signal: F1
- The frequency of the second highest peak in the FFT: F2

Table 1 shows example processed data for two such sensors as captured by the CR800. While the details of the processing algorithm are proprietary to Acellent, the following high-level description was provided. The FFT will exhibit a stable frequency spectrum when no activity is producing vibration in the ROW. When activity takes place and excites the vibration sensors, the spectrum will change. The change in the FFT features are used by the Acellent algorithm to determine the state of the alarm flag.

Table 1: Processed Vibration Sensor Data

	Piezoelectric Sensor					Geophone Sensor				
Time	Alarm	Mean	Std Dev	F1	F2	Alarm	Mean	Std Dev	F1	F2
2018-11-14 15:26:27	1	-24	3	302	298	1	3	0	60	8
2018-11-14 15:26:29	1	-24	3	299	299	1	3	0	9	8
2018-11-14 15:26:31	1	-24	3	302	302	1	3	0	9	60
2018-11-14 15:26:33	1	-24	3	300	300	1	3	1	8	22
2018-11-14 15:26:35	1	-24	3	302	301	1	3	1	25	12
2018-11-14 15:26:37	1	-24	3	299	300	1	3	1	27	26
2018-11-14 15:26:39	1	-24	3	304	303	1	3	0	13	57
2018-11-14 15:26:41	1	-24	3	300	299	1	3	24	54	56
2018-11-14 15:26:43	1	-24	3	302	302	1	3	27	55	66
2018-11-14 15:26:45	1	-24	3	299	300	1	3	30	54	53
2018-11-14 15:26:47	1	-24	3	302	302	1	3	35	54	65
2018-11-14 15:26:49	1	-24	3	299	299	1	3	40	53	64
2018-11-14 15:26:51	1	-24	3	303	304	1	3	49	54	64
2018-11-14 15:26:53	1	-24	4	299	298	1	2	82	54	54
2018-11-14 15:26:55	1	-24	5	301	55	1	3	93	55	44
2018-11-14 15:26:57	1	-24	4	301	300	1	2	105	44	33
2018-11-14 15:26:59	1	-24	4	302	301	1	3	103	43	32
2018-11-14 15:27:01	1	-24	5	299	53	1	3	81	43	32
2018-11-14 15:27:03	1	-24	4	55	44	1	3	74	44	33
2018-11-14 15:27:05	1	-24	5	299	298	1	2	111	43	32
2018-11-14 15:27:07	1	-24	4	302	303	1	3	117	44	43
2018-11-14 15:27:09	1	-24	4	295	296	1	3	104	43	32
2018-11-14 15:27:11	1	-24	5	280	281	1	3	85	50	50
2018-11-14 15:27:14	1	-24	4	300	300	1	3	72	54	43
2018-11-14 15:27:15	1	-24	3	301	302	1	3	39	53	54

The following graphs use the processed data passed to the CR800 during the November vibration test. As noted earlier, the test was carried out at two locations. At time 15:26, the soil compactor was run in the immediate vicinity of the buried sensors for roughly 3 minutes. The compactor was then moved 75' north of the sensor location, but still directly above the pipe, and started at 15:31. Again, it was run for roughly 3 minutes. Based on the description of the algorithm, one would expect the event flags to transition from 0 to 1 when the compactor started and back to 0 when it stopped. This is not observed in the data; the event flags stayed in the "alarm=1" state for most of the observed time (Figure 54), providing no clear indication of when the compactor was operating.

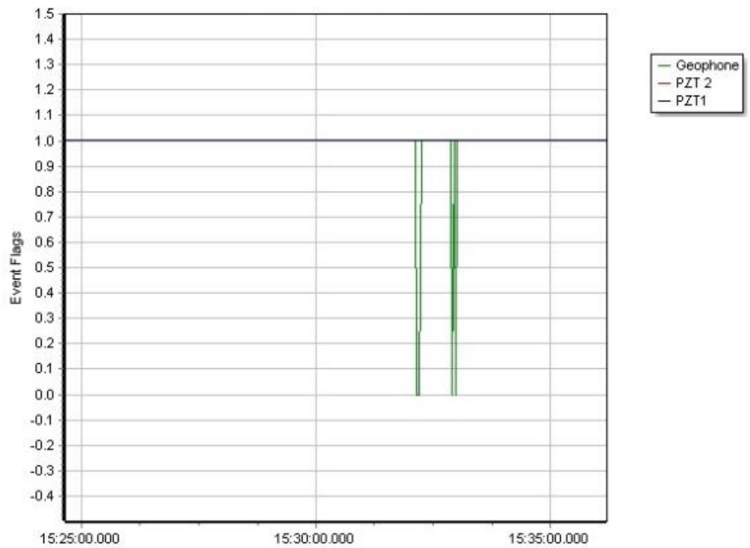


Figure 54. Event Flags During Vibration Tests

The other indicator proposed by Acellent was that the dominant frequencies in the FFT would shift when the installed sensors were exposed to an external vibration source. There is an observable shift (Figure 55) in the frequencies seen during this test. The highest, and the second highest (Figure 56) components the signal FFT in Hertz are provided. The geophone and PZT sensors both clearly show frequency shifts during the close testing interval. The response is there during the far testing interval but to a lesser degree.

The physics of the two sensors are very different, causing them to operate at different frequencies. The geophone is a magnetic mass on a spring that moves through a coil; it operates at low frequencies that propagate through soil. The piezoelectric sensors are discs of vibration sensitive material bonded directly to the pipe, behaving somewhat like microphones. The piezoelectric sensors can accommodate higher frequency signals travelling in the metal of the pipe.

The data shows that when the soil compactor was in the immediate vicinity (time 15:26), there was observable changes in the frequency (in Hz) across all sensors. In some instances, the dominant frequencies of the piezoelectric sensors and geophone came close to coinciding. When the compactor was moved 75' north (time 15:31) along the pipe, the effect is diminished. It is more reliably observed in the geophone than the piezoelectric sensors. The frequency shift data is somewhat more reliable than the event flags.

Figure 55: Primary Frequency during Vibration Testing

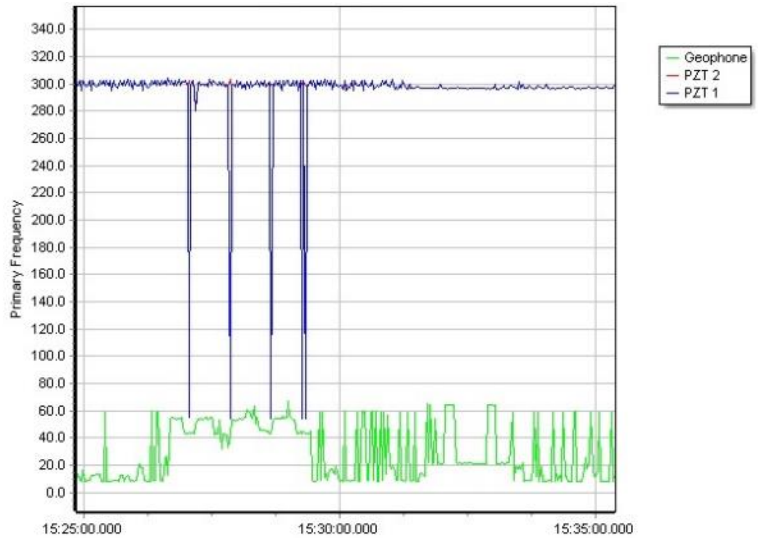
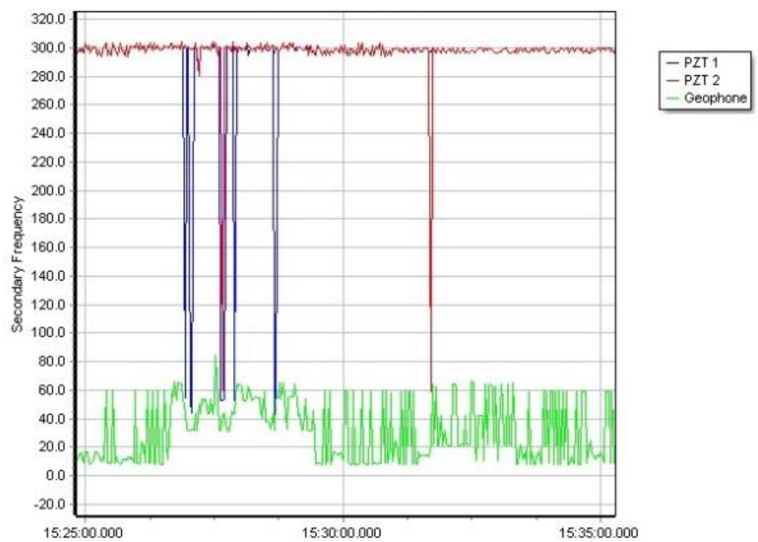


Figure 56: Secondary Frequency during Vibration Testing



A more reliable indicator than the error flag or frequency shift provided by the ATVM of activity in the ROW is needed. The standard deviation of the signal (Figure 57) is a good estimate of signal energy. In cases where standard deviation departs substantially from the signal mean it approaches the RMS value of the signal. The signal energy provides a clearer indication of when the compactor starts and stops. It also became clear that the geophone buried in the soil provided a much stronger response to the compactor than the piezoelectric sensors, PZT 1 and PZT 2.

When looking at only the response (Figure 58) of the piezoelectric sensors, there is indication that they were able to detect the closer of the two vibration tests. It is unclear why the response of the PZT sensors is so low. In other condition monitoring applications, the manufacturer claims that the PZT sensors produce several volts of signal with no additional amplification. It is possible that attachment to a massive pipeline and layers of coating over the sensors are the cause. In this application a preamplifier might improve the results.

When looking specifically at the far test (

Figure 59), with the compactor 75' from the sensors, the geophone still shows a small response to the excitation. The two piezoelectric sensors do not show any deviation from their baseline values whatsoever. This observation reinforces the argument that the PZT sensors require some form of amplification to be effective in this application.

Figure 57: Signal Standard Deviations for Near Test

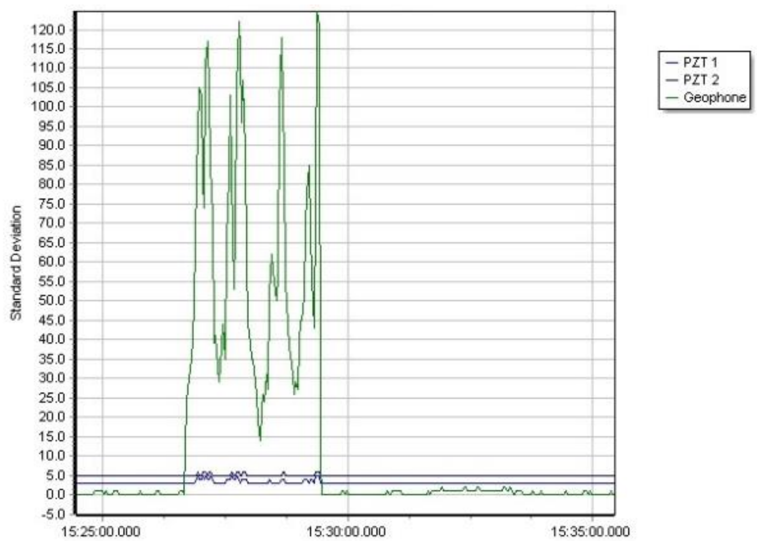


Figure 58: Standard Deviation for PZT Sensors Only

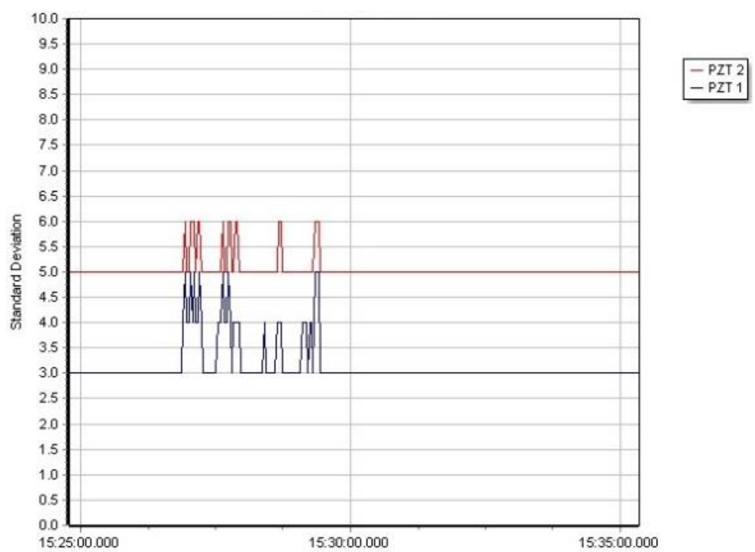
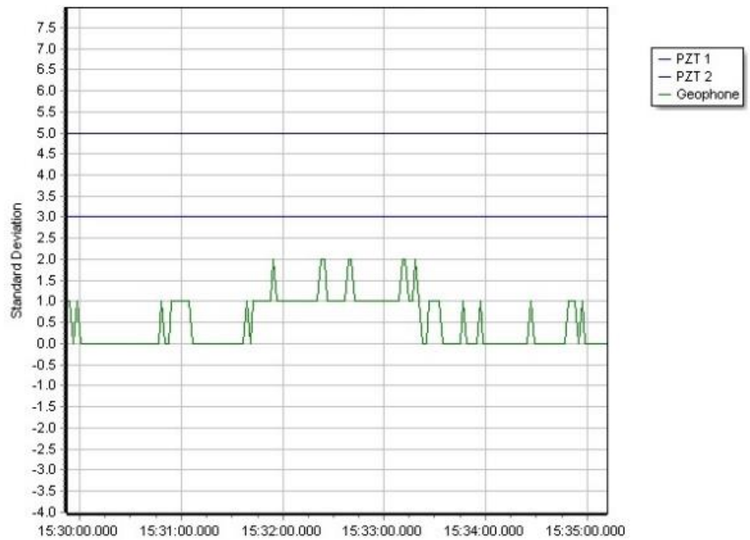


Figure 59: Signal Standard Deviations for Far Test



Raw data from the ATVM was provided to GTI by Acellent. This data consists of 1-second bursts of the mean signal values. These can be plotted to provide the time waveform of the signals. Acellent indicated that the y-axis values correspond to raw analog to digital converter counts. Calibration data provided by Acellent indicates that one count equals 0.365 millivolts. When looking at the time axis note that the internal time clock of the ATVM is a close, but not exact match for that of the CR800.

Figure 60 shows one second of raw data that captures the start of the compactor running near the sensors. The geophone is clearly responding to the compactor input; the PZT sensors are not clear. Figure 61 shows a closeup of the PZT 1 sensor signal over the same one second interval. There is some correspondence visible between the peaks of the geophone signal and the PZT.

The soil compactor was moved across the area that contains the sensors. Figure 62 shows a point in time when the compactor was closer to the sensor location and the signals correspondingly greater. Figure 63 shows the signal for PZT 1 over the same time interval. The response of the two sensor types more clearly corresponds in this instance.

There are several conclusions that we can draw from this data. The ATVM is capturing data from two PZT sensors and one geophone; the basic functionality is fulfilled. The response of the PZT sensors is very low; it is only evident that they capture the same data as the geophone is during periods of very high signal intensity.

The fact that the dominant frequencies of the two sensor types (Figure 55) are similar during high intensity signals indicate that the "normal" frequency of the PZT sensors is not driven by the environment. The 300 Hz median value that the PZT sensors generally exhibit appears to be channel noise in the ATVM instrument itself.

Figure 60: Raw Vibration Data 15:26:06

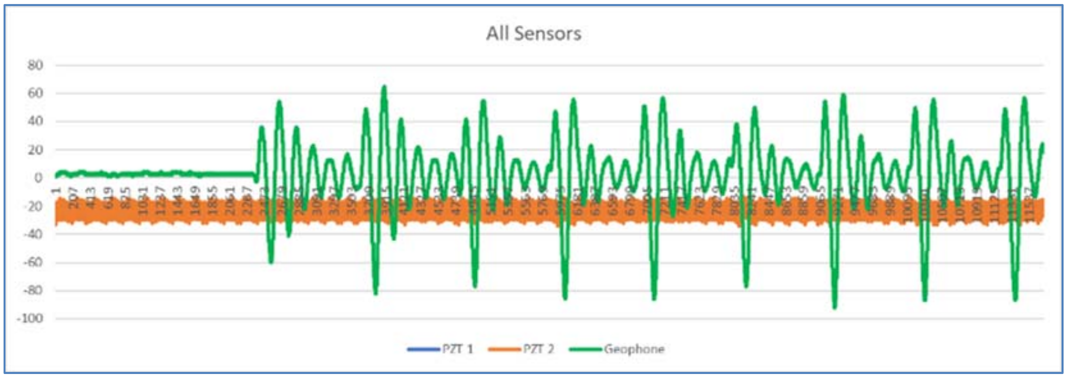


Figure 61: Raw PZT 1 Signal 15:26:06

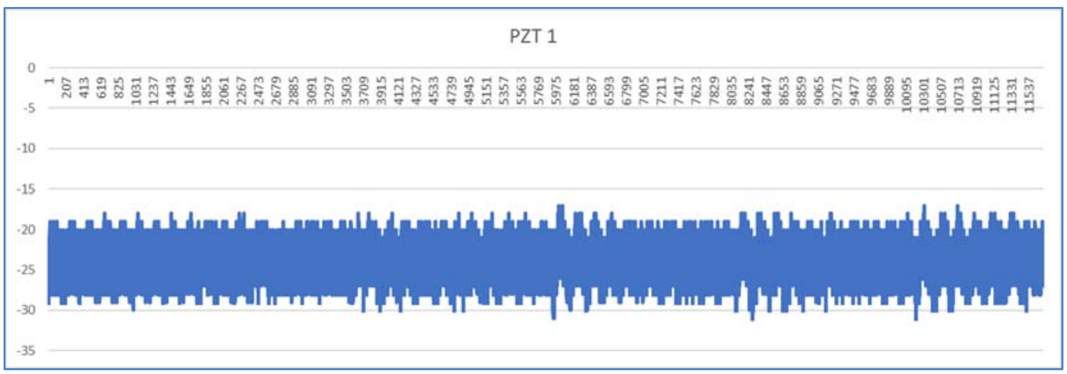


Figure 62: Raw Vibration Data 15:27:00

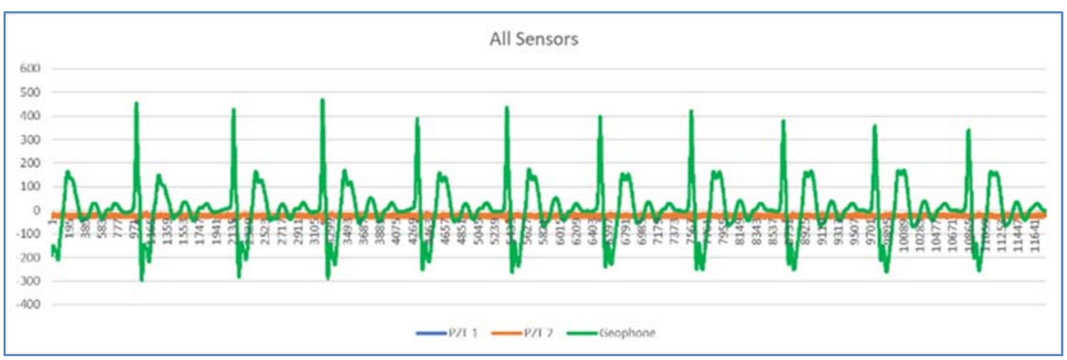
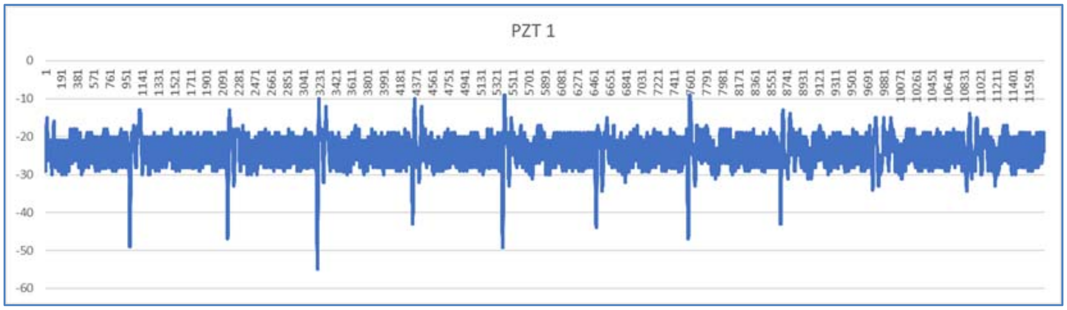


Figure 63: Raw PZT 1 Signal 15:27:00



Raw data was also captured during the quiet interval when the compactor was turned off and being moved to the second location and while the compactor was running over the pipe 75’ from the sensor location. In the case (Figure 64) where there is no signal present, the channels with PZT sensors still exhibit a significant noise floor. The geophone noise floor is much lower. When the compactor is activated 75’ from the sensors (Figure 65), the geophone does show some response while the PZT responses appears unchanged.

Figure 64: Raw Vibration Noise Floor 15:31:05

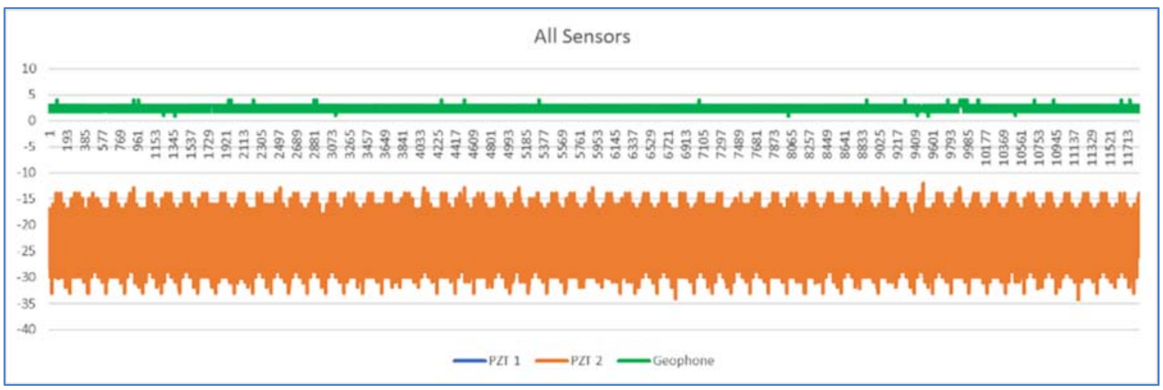


Figure 65: Raw Vibration Data Far 15:31:25

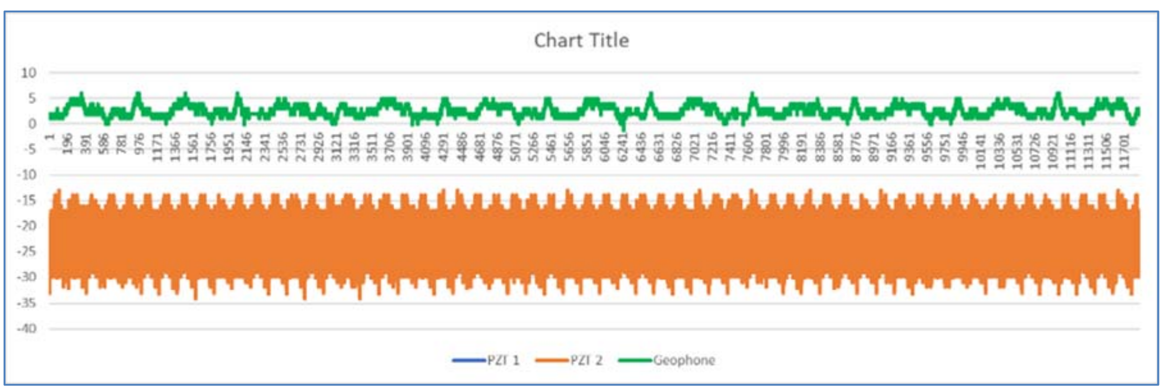


Table 2 shows standard deviation values derived from the raw data and then scaled to millivolts. As noted earlier, this is a reasonable estimate of signal strength. The “Off” column provides the background noise when the compactor in not operating. The “Far” and “Near” columns show signal strength when the compactor is operated 75’ down the pipeline from the sensor locations and directly over. The signal to noise ratio (SNR) between background (Off state) and the cases when the compactor is operated provides a measure of sensor performance. Clearly, the SNR for the PZT sensors is not adequate in their current form.

Table 2: Signal Strengths in Millivolts

Sensor Type	Compactor State		
	Off	Far	Near
PZT 1	1.106	1.110	1.461
PZT 2	1.877	1.877	1.952
Geophone	0.182	0.404	37.649

What measures can be taken to improve the SNR of these sensors? The introduction of a preamplifier between the PZT sensors and the ATVM would both boost the signal level and present a lower impedance to the ATVM. This would, in the author’s opinion, lower the channel noise that is probably caused by the high impedance of the PZT sensor interacting with the ATVM analog to digital convertor input. Without some such modification, the PZT vibration sensors will not be effective for detecting events in the ROW.

E. Soil Parameter Measurements

The sensors placed in the soil immediately adjacent to the pipe provide information on the immediate pipeline environment which may impact the integrity of the pipeline. Extremes of soil moisture or temperature may represent threats to the pipeline. The soil parameters interact with other measurements such as pipe strain and current density. No single measurement is considered in isolation to the others.

Soil Conductivity

The soil conductivity in dS/m is measured directly by the Campbell CS655 sensor. The soil volumetric moisture content is then calculated from the conductivity. The graphs below (Figure 66 and Figure 67) show the conductivity and moisture over a two-week period. The conductivity decreases steadily over this time as the soil becomes drier. The "staircase" seen in the soil moisture is due to the calculation precision of the CS655 sensor. The trend of decreasing conductivity/moisture is common to all three sensor locations.

Figure 66: Soil Conductivity Station 1

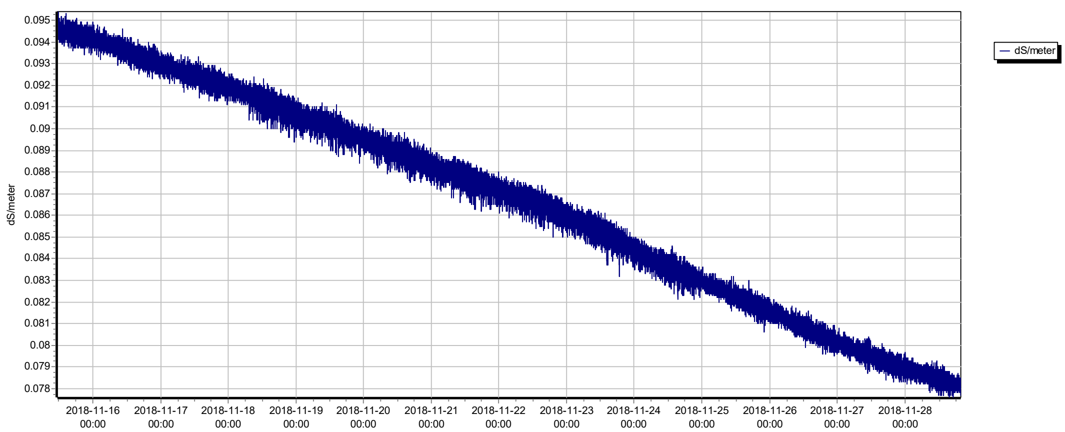
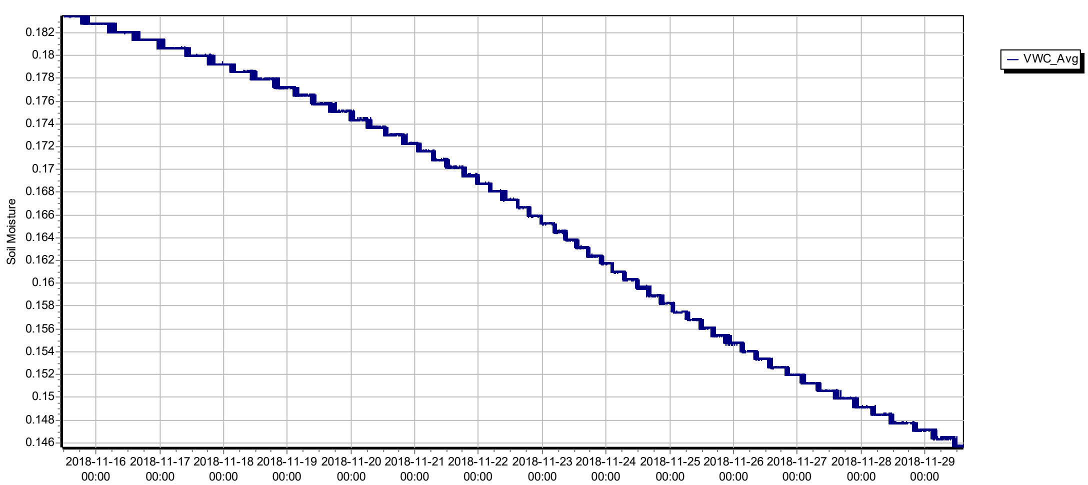


Figure 67: Soil Moisture Station 1



There are some variations in the magnitude of soil conductivity across the three sensor station locations. Figure 68 and Figure 69 show the soil conductivity at the Station 1 and Station 2 locations plotted to the same scale. While the trend of decreasing conductivity/moisture is the same the magnitudes are significantly different. This difference can be attributed to the size of the excavation and the amount of time it stood open during construction. Station 1 was the smallest of the three excavations; it was partially backfilled in June and completed in July. Station 3 was part of a large excavation that involved a pig launcher and multiple valves. This excavation was open for roughly two months longer than the others, giving the soil additional exposure to hot and dry conditions.

Figure 68: Soil Conductivity Station 1

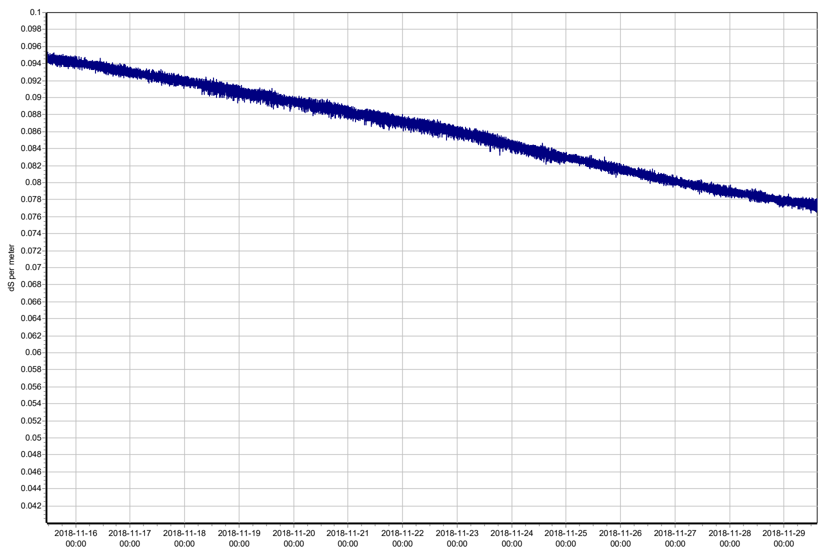
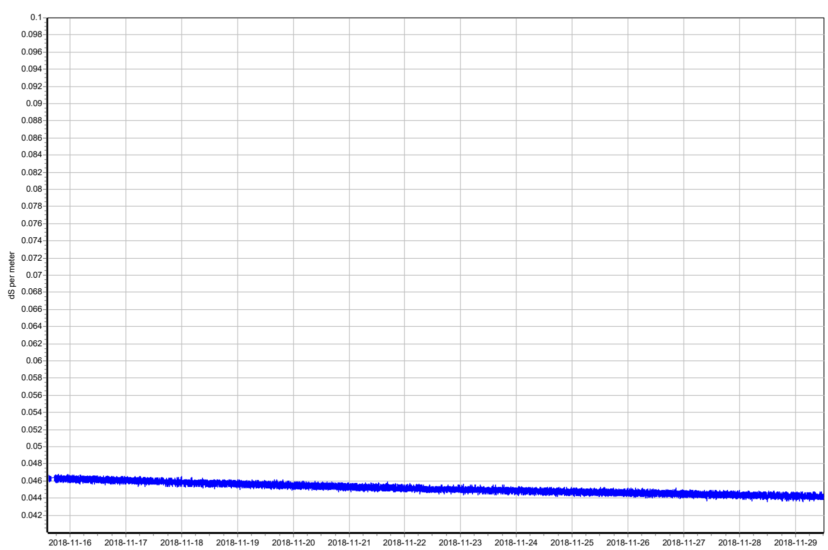


Figure 69: Soil Conductivity Station 3

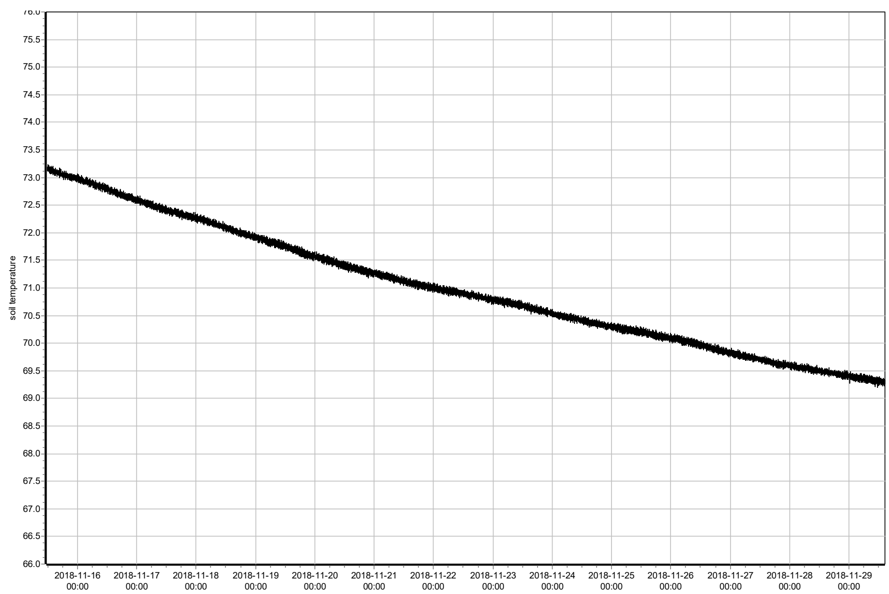


Soil Temperature

The soil temperature is also measured by the Campbell CS655 sensor. The purpose of tracking the soil temperature is that is has a direct influence on the pipe strain level. Expansion and contraction of the metal will drive the longitudinal strain level. In the case of extreme low temperatures, an effect known as "frost heave" can occur. If the soil freezes to below the pipe level and then thaws the pipe is subjected to stresses in both directions. A downward force is created as the soil freezes from the top down. The soil will then thaw from the top down exerting an upward force on the pipe from the frozen soil still beneath. The force is created by the expansion of water in the soil and can heave the pipe out of the soil with repeated cycles

Figure 70 shows the seasonal decline in soil temperature at sensor Station 1. The data for Station 2 is nearly identical. In the case of Station 3 the trend is the same, but the values are roughly 3 degrees F higher for the same period. As noted in the previous section, the Station 3 excavation was open and exposed to direct sun for two months longer than the other two.

Figure 70: Soil Temperature at Station 1

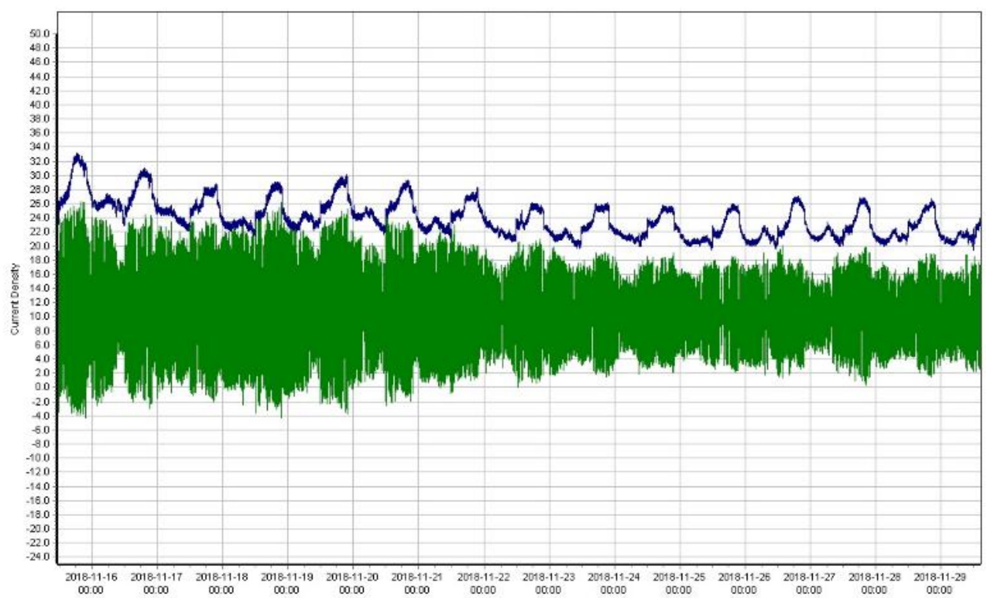


F. Current Density Measurements

The pipeline current density measurement provides insight as to the effectiveness of the corrosion protection system. This measurement is made using a steel coupon that is buried in the soil. The coupon has an exposed surface area of 1 square centimeter in contact with the soil and is connected to the CR800 by a wire. Another wire is connected directly to the pipe and brought up to the CR800. The pipe and coupon wires are connected through a shunt resistor that allows the current flowing from the soil to the pipeline to be measured. The coupon area serves as a simulated break in the coating and measures the amount of current required to protect that area relative to the local soil.

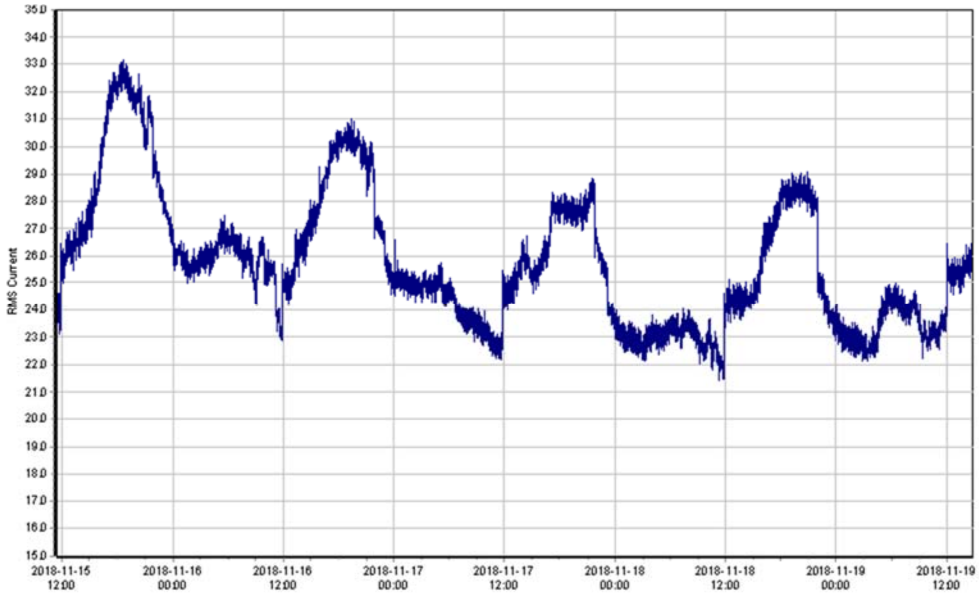
The current density (Figure 71) can be resolved into average (or DC) and RMS components. The average, or DC component is an indicator of how well the pipe is protected from corrosion. The RMS value indicates how much AC current may be on the pipe. AC pipeline currents can be caused by induction from nearby power lines or from direct contact with other buried facilities. In the plot below, the DC component (green trace) does show a reasonable median value but also some noise. The RMS component (blue trace) shows an interesting periodic structure. Both features show a slight downward trend over time. This trend corresponds with the gradual decrease in soil conductivity that was noted in an earlier section. It is relevant to correlate these factors; when conductivity is low the rate at which corrosion may occur is also low.

Figure 71: Average and RMS Current Density at Station 1



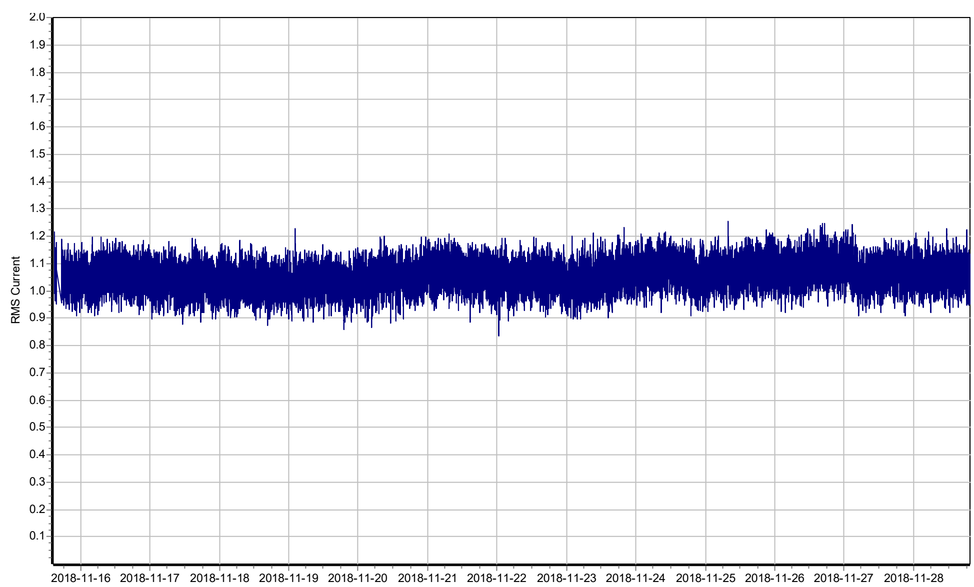
What causes the periodic structure in the RMS current? When one expands the RMS feature for closer examination (Figure 72), clearly the period is 24 hours. There is a set of nearby AC power lines that run parallel with the pipeline. The effect being observed is an AC current induced in the pipeline proportional to the power line current. Looking at the time stamps, the highest values mirror the highest demand for electricity between noon and midnight. There is a corresponding drop in demand after midnight; the cycle repeats daily. This is a reasonable result that has been observed in many other cathodic protection studies.

Figure 72: Detail of RMS Pipe Current



The current density data at Station 1 and 2 was consistent. Station 3, however has current densities (Figure 73) an order of magnitude lower. The reasons for this are still being investigated. As noted earlier, the soil conductivity at Station 3 is lower than the other two locations given that the excavation was open for a much longer time. This extra drying time for the soil may cause the lower current. The other possibility, again based excavation time, is that the cables were damaged during construction of the other facilities.

Figure 73: RMS Current Density at Station 3



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G. Demonstration of User Dashboard and Analytics

A web-hosted user interface will be used to present data from the ROW Monitoring and Notification System to the operators. A mockup version of this interface was demonstrated by GTI for several stakeholders. The audience for the demonstration were representative of SoCal Gas (the operator) and Leidos Engineering (provider of wireless technology).

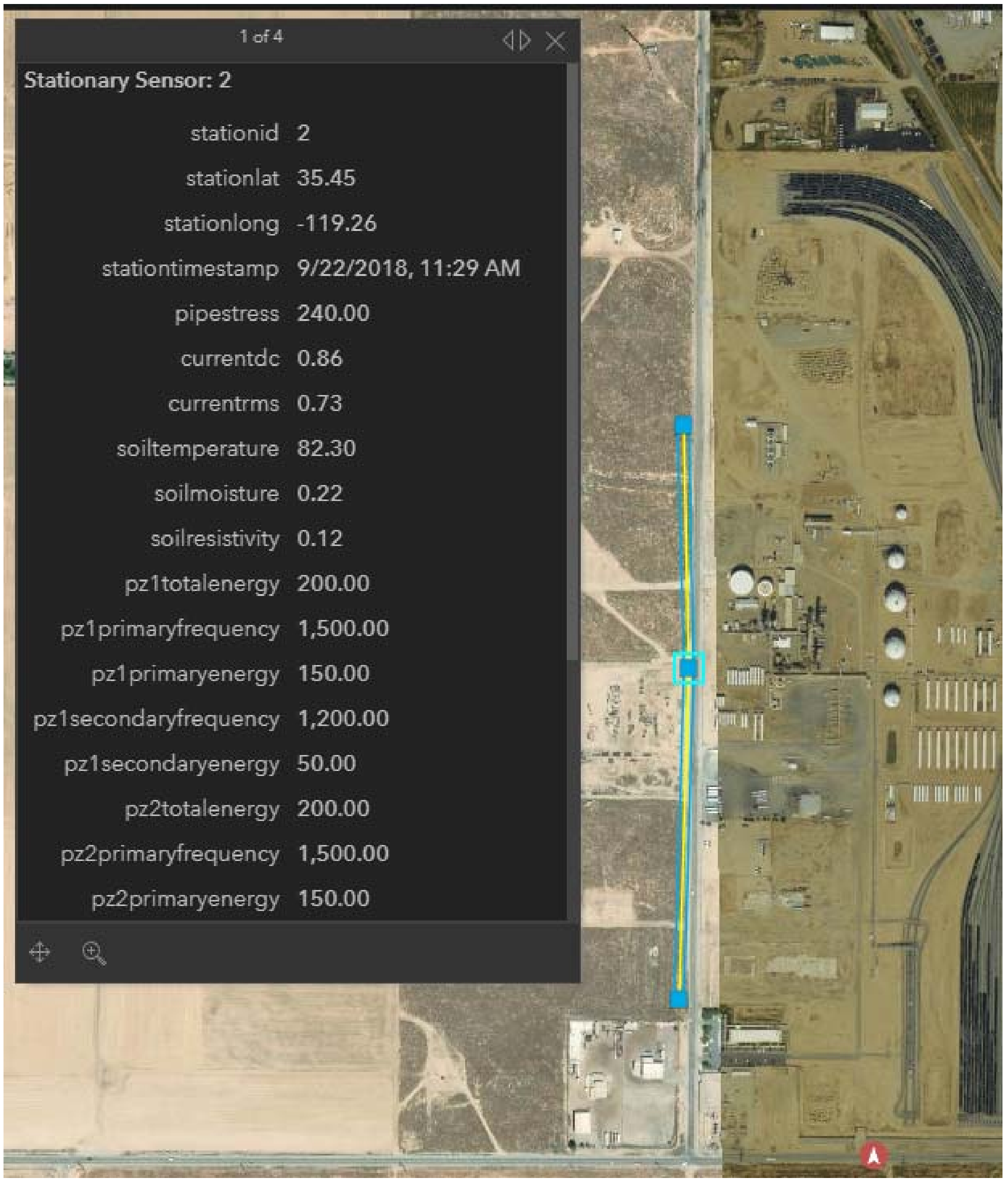
The purpose of the web-hosted user interface is to provide a single portal to view data from both Stationary Sensor Nodes (SSN) and Excavation Encroachment Notification (EEN) devices. The user interface is based on Esri Operations Dashboard (Figure 74) for the presentation layer and on Esri GeoEvent Processor for the underlying logic.

The demonstration was a simulation based on data recorded on the actual site. At the time of this demonstration wireless connectivity is not in place. Data captured during the hydro-test and during vibration testing was used to populate the model. The simulation can be run faster than "real time" for testing and demonstration. At this writing, real-time wireless data is available for the sensor stations and analytic development is proceeding with live data.

Figure 74: Mockup of Operator Data Dashboard

For the demonstration, an instance of the operator dashboard was run on an ArcGIS server licensed by GTI. The first feature demonstrated was the drop-down list (Figure 75) associated with the SSN locations. Each SSN is displayed in the map view as a square; selecting and clicking on that point produces a display of the current sensor readings.

Figure 75: View of Data from Stationary Sensor Node



The next feature demonstrated was alarm notification when one of the SSN sensors is out of bounds. The alarm is created by modifying one entry in the table of typical data used to drive the simulation. The test case was increasing the "total vibration energy" (V^2/Hz) above a threshold that is defined in GeoEvent Processor. Every time the simulation would loop through the modified entry the alarm would display on the dashboard (Figure 76).

The alarm is exhibited by the map point turning yellow and a text box being populated with the corresponding data. The plan going forward is to implement 2-level alarms for key SSN sensor readings. The first alarm threshold will trigger a yellow alert warning.

The warning condition can also generate and email (Figure 77) or SMS/text messages. The email of one of the SoCal personnel was used during the mockup demonstration. Both dashboard events and email/SMS transmissions are configured in GeoEvent Processor which provides underlying support logic (Figure 78) for Operations Dashboard.

Figure 76: Demonstration of SSN Warning Capability

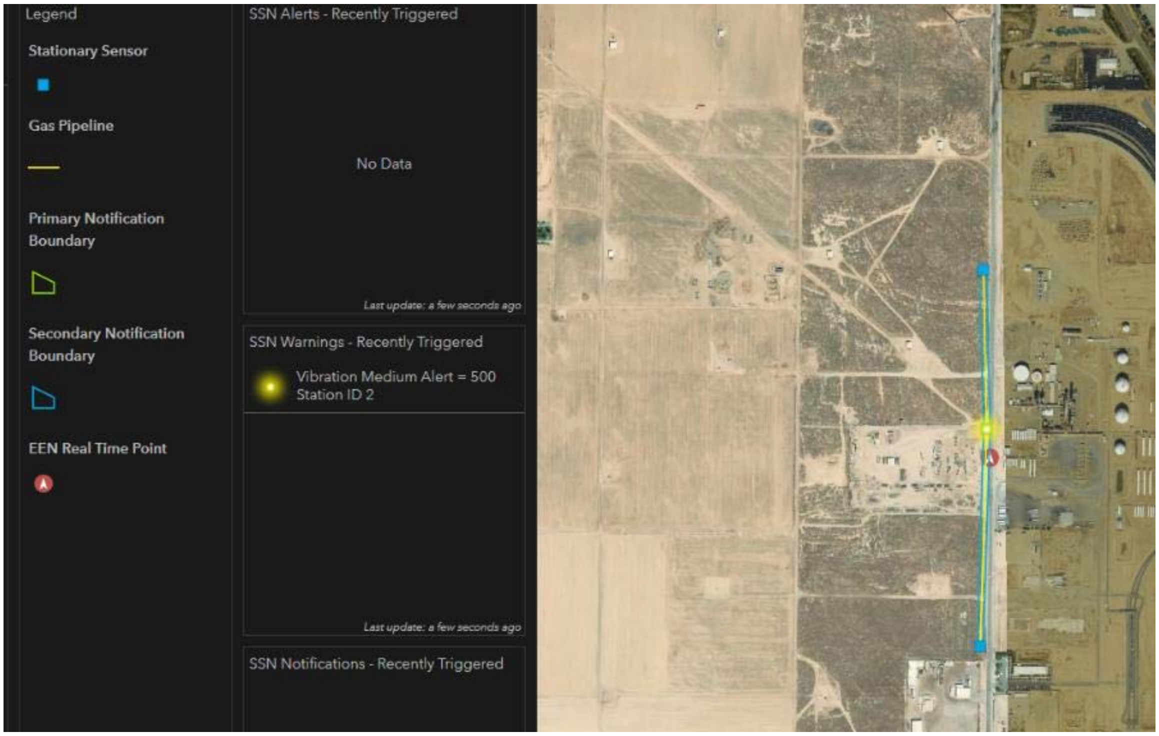
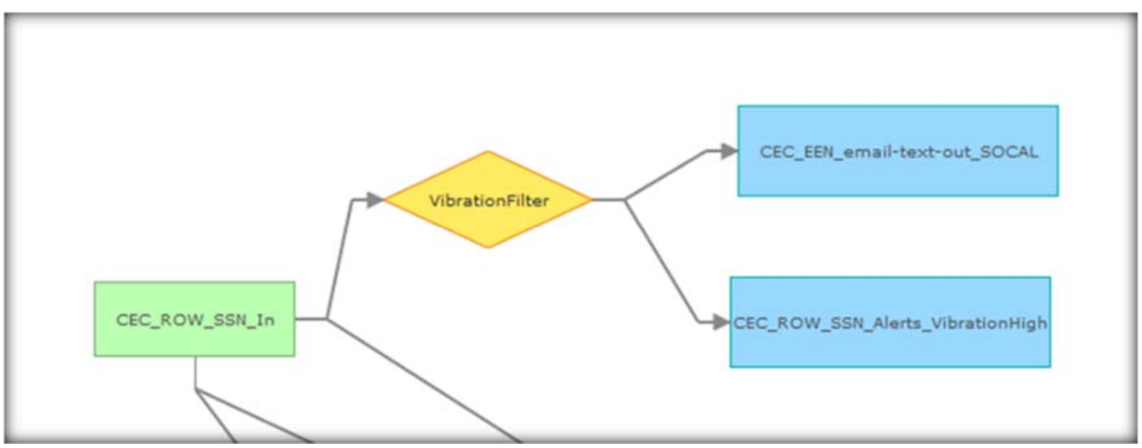


Figure 77: Email Content Generated by SSN Warning

From: gti.demo99@gmail.com <gti.demo99@gmail.com>
Sent: Wednesday, September 26, 2018 9:37 AM
To: gti.demo99@gmail.com <gti.demo99@gmail.com>
Subject: Station ID 2 has Vibration Notification

Station ID 2 has Medium Vibration of **500.0**
This activity happened at Latitude: 35.44702, Longitude: -119.26123 occurring @ Sat Sep 22 16:28:35 UTC 2018.

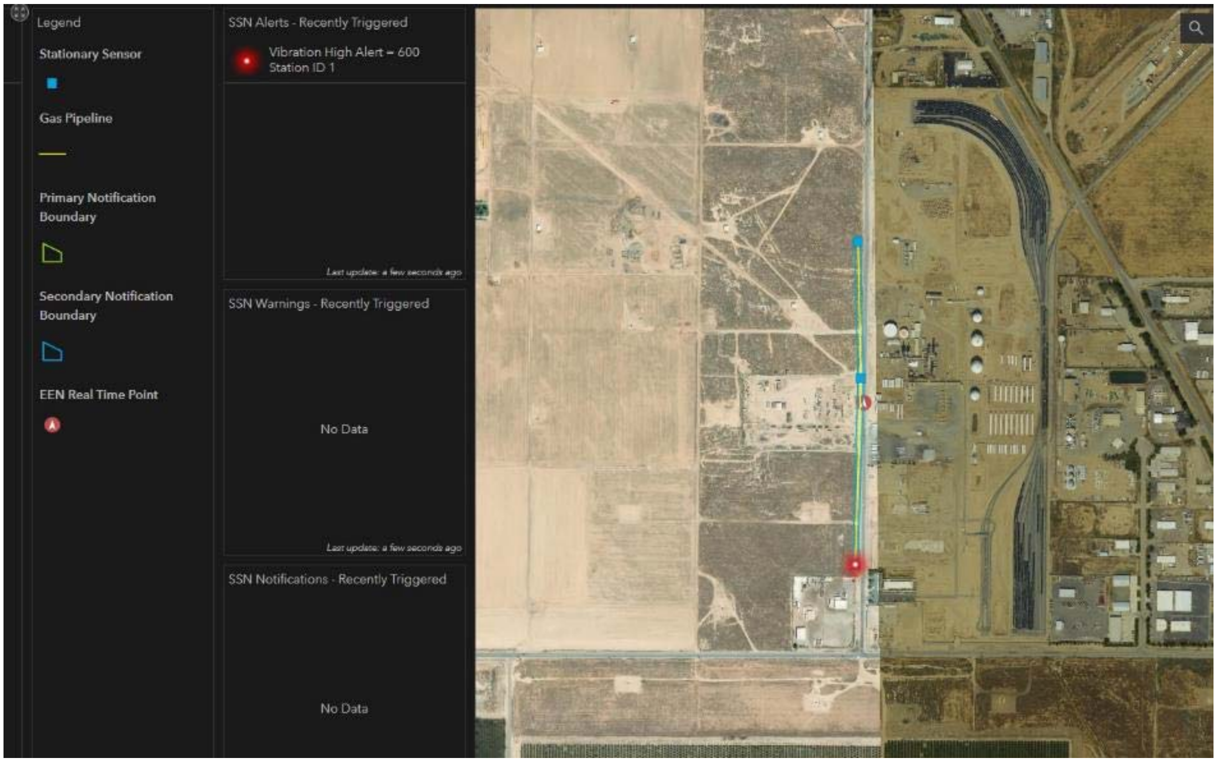
Figure 78: GeoEvent Processor Visual Programming Interface



gti

If a higher threshold is crossed, a red alert is generated (Figure 79). As with the lower threshold, the map location changes color and the descriptive text appears in the appropriate location in the dashboard. An email or SMS can be triggered by the alert threshold. It is possible to have multiple email destinations attached to the alert which may be desirable in the case of red alerts.

Figure 79: Demonstration of SSN Alert Capability

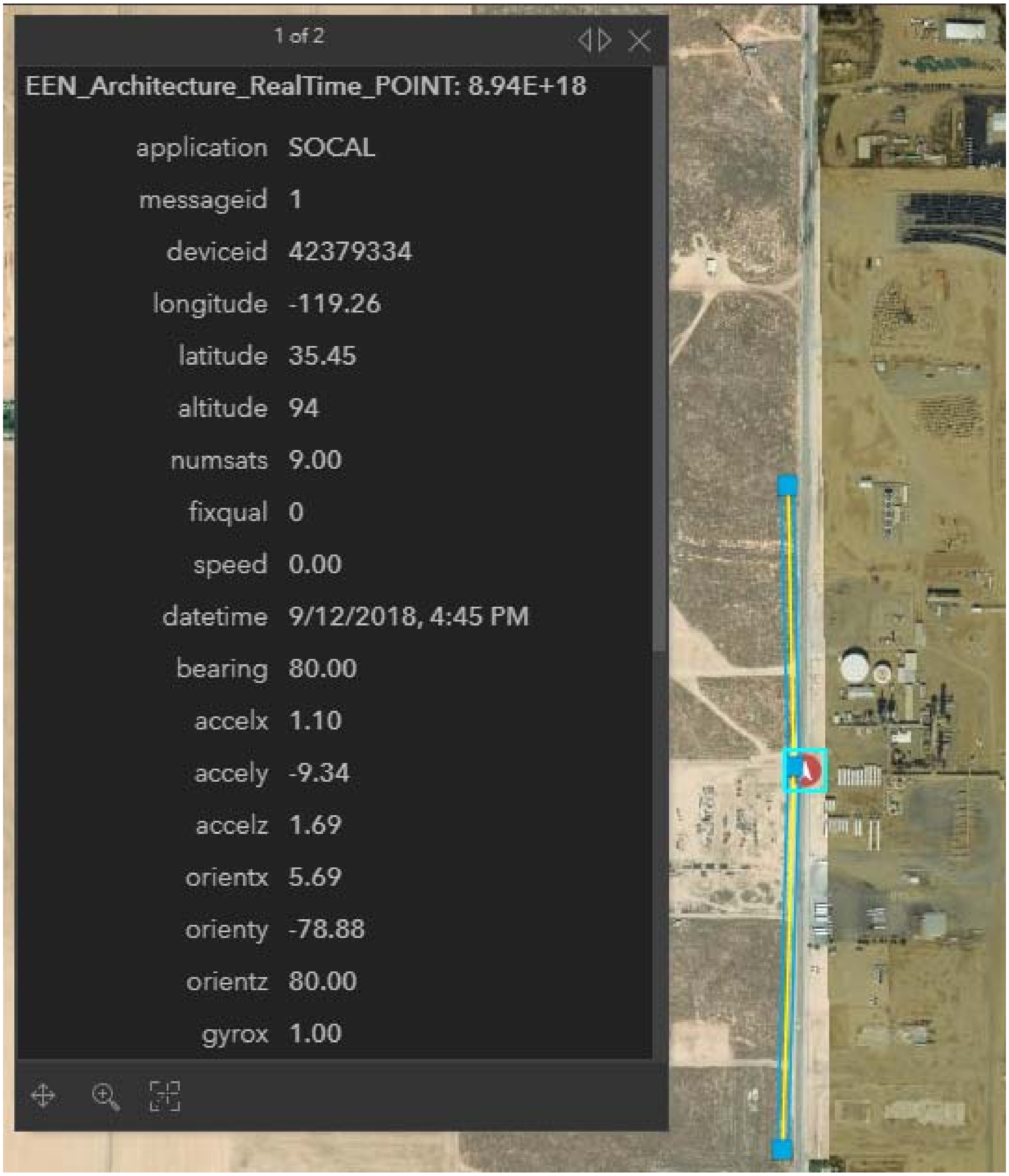


Functionality of the EEN mobile sensors was also demonstrated during this session. The data used for this part of the simulation was captured by placing one of the EEN devices in a vehicle that was on the site during the September 12 vibration testing. The map location of the vehicle at any point in time is marked by a red circle with an inscribed white triangle.

The mobile sensors have GPS capabilities and built in sensors for acceleration, heading, and orientation. These items can be accessed through a drop-down list (Figure 80). The sensors allow estimates of the speed of the equipment and its direction of travel. In the case of excavators, the sensors can determine if digging is taking place.

The alert generation mechanism for the EEN devices is based on location rather than specific sensor values. If the location of the EEN device is within the "geo-fence" of a utility asset an alert is generated. The geo-fence is a predefined boundary around a pipeline or other utility installation. In these figures the pipe is represented as a yellow line and the geo-fence boundaries are represented as blue lines on either side. In this instance, the boundaries were set at plus or minus 25 feet of the recorded pipeline positions. It is possible to provide two levels of boundary that allow for warnings and then alerts as the pipeline is approached.

Figure 80: Demonstration of EEN Functions



H. Third Vibration Sensor Test

The purpose of the vibration sensors is to provide early indication of activity on/near the pipeline ROW. AT each sensor station, there are two sensors directly attached to the pipe to measure vibrations travelling directly in the pipe material. These are piezoelectric sensors made from a lead-zirconium titanite (PZT) ceramic. There is also a moving-magnet geophone in the soil adjacent to the pipe to capture seismic events.

The first series of vibration tests were carried out on September 12^{th,} 2018 to verify the response of the system to the presence of compactors and construction equipment. This testing was carried out with both a soil compactor and a backhoe. There were significant problems with vibration monitoring equipment at that time. It was removed from the site for adjustments.

The vibration equipment was returned to the site and testing repeated on November 13th and 14th using a soil compactor as the signal source. Data from this testing was captured both as processed data in the Campbell CR800 datalogger and as raw data within the Acellent vibration processing equipment. The data from this round was analyzed and presented in the last report. While there was improvement, the sensitivity still was not sufficient. It was also found that the vibration analyzers would stop working after several days. A hardware reset would fix this, but the problem was recurring.

Additional vibration sensor tests were carried out on February 12th, 2019 by GTI and Acellent Technologies. Two upgrades were made to the vibration monitor prior to tests. Acellent applied a software upgrade to the signal processor at all three locations. This fixed the need for recurring resets noted above. GTI procured and installed a pre-amplifier (Figure 81) at one of the sensor stations. This preamplifier provided a gain of 100 to both piezoelectric sensors attached to the pipe. No gain was applied to the geophone embedded in the soil alongside the pipe.

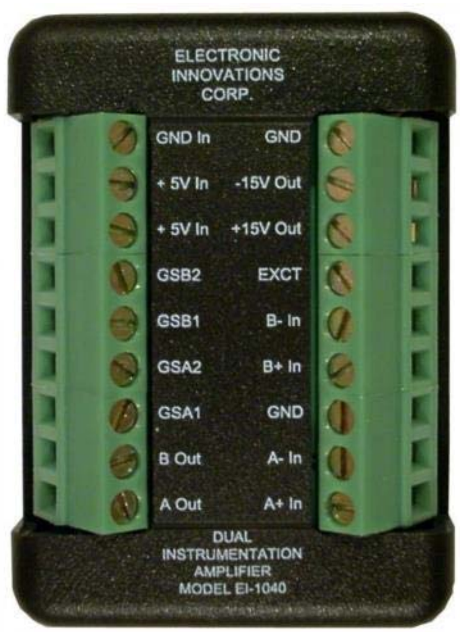


Figure 81. Two-Channel Instrumentation Amplifier

For this round of vibration testing a dynamic cone penetrometer (DCP) was used to generate the signal in the soil. This is a hand-held, manual device that consists of a drop weight on a rod that is raised a fixed distance above the ground and then released (Figure 82). The DCP is normally used as a means of testing soil compaction density repeatedly driving a pointed tip into the ground and recording the number of hits required to advance a certain distance.

Figure 82. DCP to Generate Impact Signal

For this test, the pointed tip was removed, and the blunt face of the DCP put in contact with the soil. The drop was raised and released 5 times at each location. The test was carried out a series of locations along the pipe with a spacing of 10' between locations. One of the locations was directly over the sensors on the pipe. For this given drop weight and travel distance the impact energy was just over 12 Joules per impact. This is a much smaller signal than that generated by a backhoe or compactor. It is GTI's judgement that sensitivity must be sufficient for small impact (at least close to the sensors) must be detectable for this technology to be successful.

The raw data from the piezoelectric sensors and the geophone was recorded by the Acellent device during these tests. These files were provided to GTI for post-processing. The processing was carried out using the Anaconda 3.4 Python environment. This provided a programmatic means to open the files, plot data, and perform various filtering functions. The raw data (Figure 83 & Figure 84) shows the impact of the DCP clearly but also shows a good deal of 60 Hz noise is present in the piezoelectric (PZT) transducers. There power lines in the immediate vicinity and the noise is seen in other sensor, though at a lower level.

Several types of filter were tested to remove the noise while preserving the impact signal. A decimation filter (Figure 85) performs some smoothing and lowers the number of samples by a factor of 4. After some testing, it was established that an elliptical filter (Figure 86) provided good suppression of 60 Hz while preserving the impact signal.

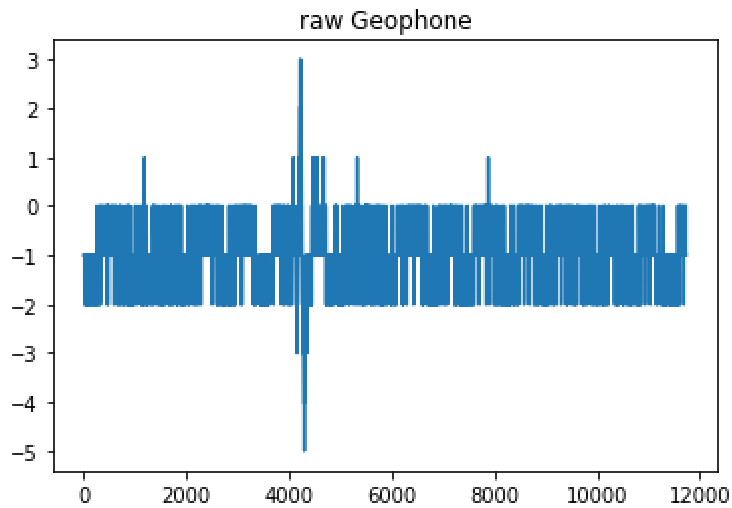


Figure 83. Geophone Signal about 10' from Sensors

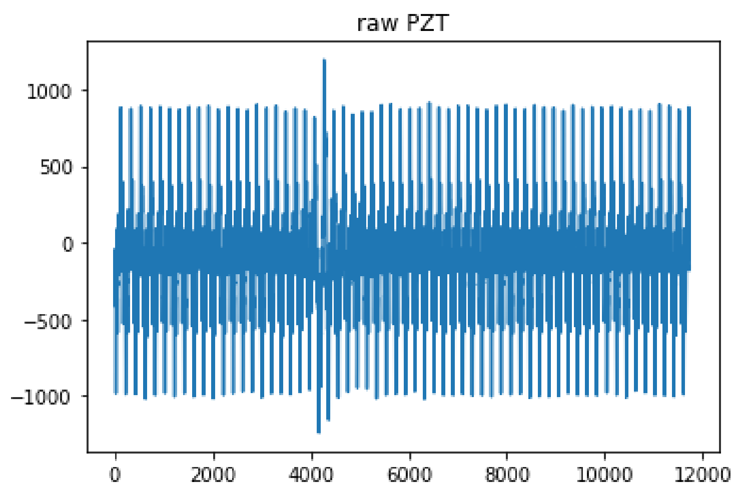


Figure 84. Piezoelectric Signal about 10' from Sensors

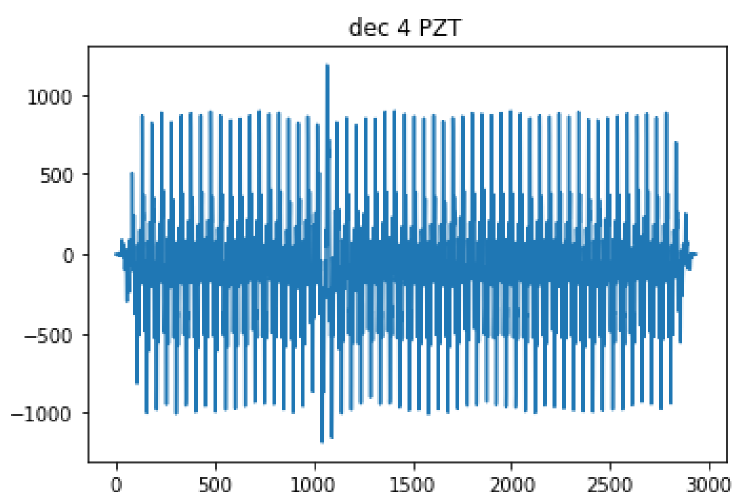


Figure 85. PZT signal after Decimation Filter

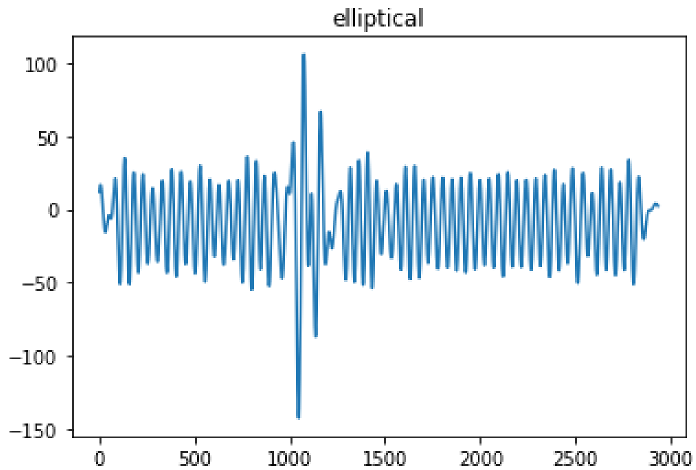


Figure 86. PZT with Elliptical Filter - Impact at 10'

The following series of graphs are with the DCP hit directly over the sensor location. The raw data (Figure 87 & Figure 88) is like that in the previous example but with greater amplitude. The elliptical filter removes much of the 60 Hz noise. For comparison, the output of a Finite Impulse Response (FIR Figure 90) is shown as well. The FIR filter also does a good job of removing the 60 Hz artifacts but may be too computationally intense for field deployment. The elliptical filter requires 10 coefficients to execute while the FIR require 50.

The conclusion from this data is that the PZT sensors have the intrinsic sensitivity to detect much smaller impacts than previous tests disclosed. The sensors were first installed with no preamplifier; a decision by Acellent that GTI questioned on multiple occasions. Given reasonable gain and filtering, the mild impact from a DCP can be seen, even at some distance. The 60 Hz artifacts may also be resolved by improving grounding at the station in question.

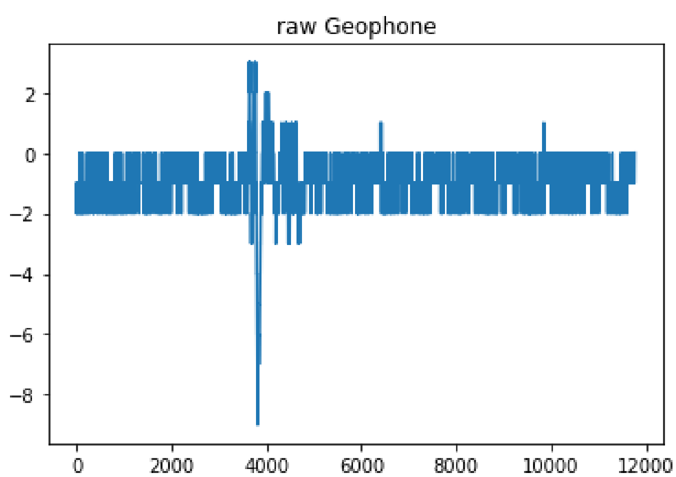


Figure 87. Raw Geophone Signal with hit Directly over Sensors

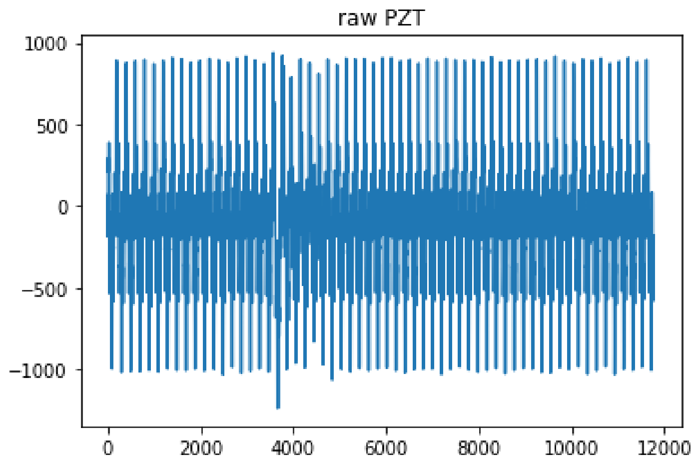


Figure 88. Raw PZT Signal with hit Directly over Sensors

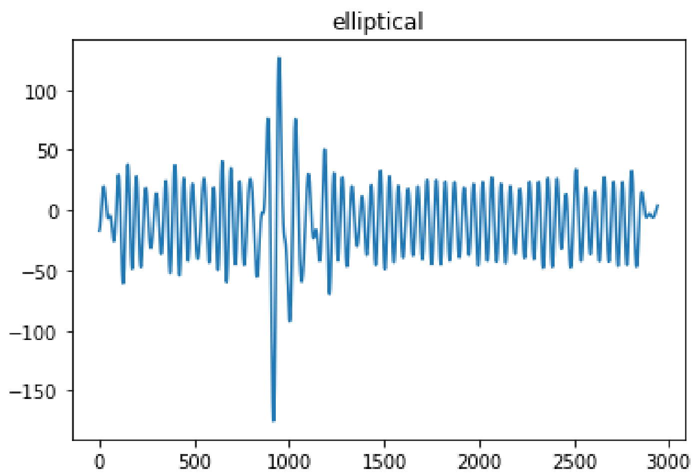


Figure 89. PZT direct hit Elliptical Filter

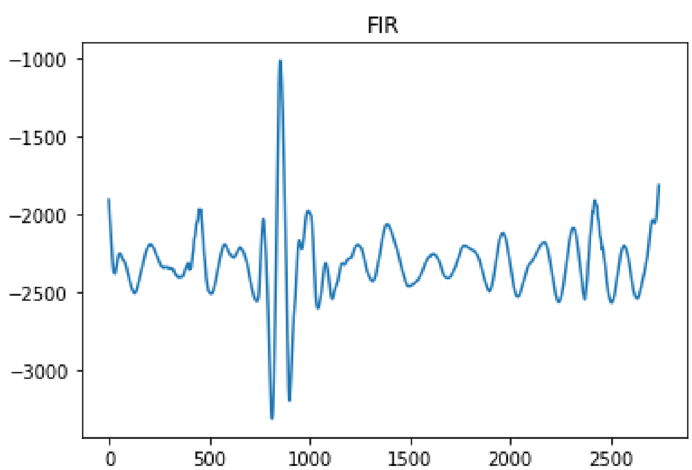


Figure 90. PZT direct hit FIR filter

End of Report