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FINAL PROJECT REPORT

Forced Resonance Imaging for Buried Pipeline Detection

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PREPARED BY:

Khosrow Bakhtar, PE, Ph.D.
Bakhtar Research and Engineering LLC
Primary Authors

Yahui Yang, Ph.D.
Project Manager
California Energy Commission

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Reynaldo Gonzalez
Branch Manager
Energy Systems and Transportation Branch

Jonah Steinbuck, Ph.D.
Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

This document is the final report for the Forced Resonance Imaging for Buried Pipeline Detection project (Grant Number PIR-19-017) conducted by Bakhtar Research and Engineering. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

The goal of this agreement is to develop and demonstrate a non-invasive technology for detecting underground gas utility pipes, known as the Bakhtar Pipe Detector (BPD). The BPD enables underground gas pipeline detection, location, and material identification. The detector operates in near real time to determine underground pipeline location, dimensional details, material type, and depth independent of the characteristics of overlying geologic formations and surface cover. The technology benefits gas ratepayers by reducing potential excavation-induced damages to pipelines, enhancing operational safety in the field, and contributing to reliable and safe operations for delivering gas to ratepayers from buried pipelines. Evaluation of BPD performance in the field revealed the following measurement accuracies for buried pipeline: material (metallic/plastic) identification 100 percent, diameter 0 to 1 inch, depth 0 to 5 inches, and horizontal location 0 to 11 inches.

Keywords: natural gas, gas infrastructure, pipeline detection, Bakhtar Pipe Detector, BPD, ground penetrating radar, forced resonance imaging, FRI, technology transfer, GPS

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Background

Improperly reporting location or undetected subsurface gas utilities has resulted in injuries, fatalities, and billions of dollars in damages as evident from the San Bruno pipeline explosion that occurred in the Bay Area on September 9, 2010. Many of the underground utilities are reaching the end of their practical lives and will need upgrade or replacement. Therefore, accurate location information for these utilities is essential for utility owners, engineers, contractors, or surveyors, particularly as reference for excavation.

Most of California's gas infrastructure was built more than fifty years ago. As a result, the aging pipelines and storage facilities pose challenges to safely operating the gas infrastructure. Among the issues of concern are excavation-induced damages to buried gas pipeline. Location data on the aging buried pipelines are scarce, and in some cases, nonexistent. Lack of adequate location information compounds the difficulties associated with buried pipeline location and excavation-induced damage prevention. These challenges warrant a new technology with the ability to detect, locate, and identify buried pipeline in rapid succession. The Bakhtar Pipe Detector (BPD) developed under this California Energy Commission agreement provides a unique tool to facilitate the detection and location of buried pipeline. The BPD will allow field operators to quickly detect buried gas pipelines independent of the characteristics of the host site geology and cover material.

Project Purpose and Approach

The goal of this agreement was to develop and demonstrate an innovative device, the BPD, for buried gas pipeline detection, location, and material identification. The BPD was tested at several Pacific Gas and Electric (PG&E) gas pipeline sites. Field detections were conducted initially under known and later blind test conditions.

The research focused on developing an innovative technology for detection, discrimination, location identification, and depth estimation of buried gas pipes as well as improving pipeline asset management. The technology was based on radar and forced-resonance-imaging (an imaging technique that is similar to magnetic resonance imaging but uses a very low level of transmitted power of electromagnetic waves backscattered by buried targets) principles. The U.S. Air Force EarthRadar, a ground penetrating radar sensing technology, which was invented by the principal investigator under the Small Business Innovative Research (SBIR) program was modified to meet required applications for shallow depth detection of buried metallic and plastic gas pipelines.

An Earth Simulator, a unique apparatus simulating the impedance characteristic of the earth, was deployed for initial research. The Earth Simulator and a makeshift configuration of the BPD were deployed to determine the ranges for the test parameters and to establish the necessary digital filters. This was followed by configuring the final version of the BPD with new hardware and much improved software. The BPD main hardware components consisted of a low-power (less than 10 decibels per milliwatt, or dBm) source Vector Network Analyzer, a pair of forced resonating dipole/horn antennae, an integrated real-time kinematic (RTK) global positioning system (GPS), a small tractor hauling the antennae, transmission lines, and data acquisition and control units (laptop computer).

System verification and software fine tuning were done through several field tests at PG&E facilities following completion of the hardware configuration and implementation of new software. Testbed scanning was done by moving forced resonance (FR) antennae at constant slow speed, about 10 inches per second, over an area of interest (testbed), collecting sub-surface data followed by presenting results of the location and material of buried pipeline in the field. Procedures for field test bed interrogation, data acquisition, and result presentation were performed systematically in rapid succession. The FR antennae were designed to transmit low-power electromagnetic energy into any geologic formation including salt-saturated test beds and ocean floor. The backscattered signal was then used for detection and location of potential buried targets (pipelines). The BPD data and GPS surface footprint coordinates of buried pipelines were provided to the field crew. The feasibility of the technology was demonstrated in the field. Several detection tests performed at the PG&E sites validated the performance of the developed technology under field conditions.

Key Results

Systematic tests and measurements were conducted during the various phases of the developed technology. The results of field testing were used to confirm the uniqueness of the BPD for detection of buried pipeline independent of the characteristics of the host geology and cover material. Successes achieved under the blind test conditions in detection of buried pipelines ensured that the project goals and objectives were met. These included:

- Design and development of BPD hardware and software., including development of next generation FR antennae, integrations of new GPS system and much lighter (smaller) vector network analyzer (VNA), and updating and modification of BakhtarRadar software with new visualization algorithms.
- Development of a user-friendly manual for operation of the system hardware and software.
- Completion of pilot tests at the PG&E Training Academy in Winters, California including successfully detecting the total length, diameter, material, and depth of pipes at six sections.
- Demonstrations at four sites within PG&E gas service territory under blind conditions (the site host did not provide any information on site geology or pipeline conditions) for pipe location, diameter, material, and depth. The demonstration results were compared with PG&E's records, with pipe material type determined with 100 percent accuracy. The accuracies for pipeline diameter and depth measurement were in the range of 0 to 1 inch and 0 to 5 inches, respectively, and the accuracy of horizontal location was in the range of 0 to 11 inches.

The field demonstrations combined with previously completed field investigations conducted at the PG&E facilities provided an insight into the measurement accuracy associated with using the BPD under the field conditions. The initial tests and measurements using the Earth Simulator enabled investigations on parameters impacting BPD performance to be conducted under simulated field conditions in the laboratory. These investigations resulted in the value as well as ranges for the pertinent parameters, such as initial and final frequencies of scanning, sample bandwidth, and frequency steps, which have paramount impact on the collected field data to be determined.

Knowledge Transfer and Next Steps

Technology and knowledge transfer activities pertinent to the BPD technology began at the early stage of the research project and continued throughout the duration of the agreement. It entailed sharing and disseminating information, expertise, and technology from Bakhtar Research and Engineering to outside parties and buried gas pipeline communities. It is an important aspect of initial steps toward commercialization of the product at hand.

Technology and knowledge transfer activities for the BPD included the following:

Conferences and Publications

Bakhtar, K., "Detection and Tomographic Visualization of Buried Pipelines," Trenchless Magazine for Gas Infrastructure, Page 51, May 2022.

Xu, Tianzong (David) and Bakhtar, K., Forced Resonance Imaging for 3-D Mapping of Underground Pipeline Assets." Proceedings of the 2022 14th International Pipeline Conference, IPC2022, Calgary, Alberta Canada, September 26 – 30, 2022.

Bakhtar, K., and Xu, D., A Novel 3-D Mapping Technology for Underground Pipelines, REX2022 PRCI Research Exchange, Orlando, Florida, March 8 - 9, 2022.

Bakhtar, K., and Xu, D., "Detection of Underground Pipelines Under Challenging Conditions," Presented at the American Gas Association 2021 Operation Conference and Biennial Exhibition, Orlando, Florida October 7, 2021.

Xu, D., and Bakhtar, K., "3-D Mapping of Buried Pipeline Assets," The Northern California Pipe User's Group, 29th Annual Sharing Technologies Seminar, Virtual Event, February 18, 2021.

Technology Briefings

- Briefed and further discussed the BPD and BakhtarRadar (software) with experts from Department of Energy on March 7, 2023. The discussion focused on detection and location of buried plastic pipelines. Dr. Jack Lewnard and three of his colleagues were involved in the discussion.
- Discussed the BPD with Dr. Vittorio Ricci, Chief Technology Officer of the Naval Warfare Center Headquarter in Rhode Island for finding buried utility lines at the Naval facilities throughout United States. The subject was discussed during the visit of Dr. Ricci to the Bakhtar Research Office on December 11, 2023.

- Discussed BPD with Ms. Daphane D'Zurko from NYSEARCH Natural Gas RD&D on January 9, 2024, with arrangements being made for field a demonstration in the March-June 2024 time frame.

Future technology transfer can be facilitated through licensing agreements, joint ventures, mergers and acquisitions, and collaborative research and development projects. Further development in terms of miniaturization of hardware and software fine tuning for volumetric image reconstruction can move the technology-to-technology readiness levels 7 and 8. The system is one step away from deployment and in the process of filing for a patent in advance of commercialization.

CHAPTER 1: Introduction

Background

As evident from the Common Ground Alliance (CGA) report, the safety and integrity of underground natural gas pipelines rely on the availability and accuracy of pipeline location information. According to the CGA, improperly located or undetected subsurface utilities have resulted in death and injuries and $1.7 billion in damages during the last 20 years (CGA, 2015).

Depth detection is of paramount importance, however, ground penetrating radar, which has been widely used in extracting information of buried utilities for better utility maintenance and management cannot provide location information in three dimensions. The widely used scanning technique is limited for retrieving the precise position of buried utilities because of surrounding geologic formations with clay minerals and moisture content. Also, ground penetrating radar's ability for buried pipe detection is restricted to pipes made of conductive material (metals) and cannot detect plastic pipes, which are non-conductive and widely used in buried gas pipelines. The difficulties associated with accurately locating buried pipelines using ground penetrating radar warrants the need for more advanced non-invasive tools with ability to detect both plastic and metallic pipelines and improve location accuracy independent of the characteristics of surrounding geologic formations and cover material.

The shortcomings associated with existing detection devices warrants the need for a more advanced technology such as the developed BPD with forced resonance imaging (FRI) capability discussed in this report. This project advances the commercialization of the BPD technology through modification of a military technology (U.S. Air Force EarthRadar also called BakhtarRadar), invented by the principal investigator (Bakhktar, 2001). The BPD prototype was successfully completed, and its performance was verified in the field at PG&E facilities. Applications of BPD include capabilities to detect subsurface natural gas pipelines and collect three-dimensional location information with increased accuracy facilitate detection and discrimination of gas pipelines in rapid succession in a safe and cost-effective fashion.

Project Purpose

The purpose of this research is to develop a technology to better locate and characterize subsurface gas pipeline infrastructure with information on depth, diameter and material type, that is, plastic and/or metallic.

The BPD with FRI capability, developed and validated under the California Energy Commission (CEC) agreement, provides an innovative and cost-effective approach for accurately locating, estimating depth, and confirming the material type of underground gas pipelines. Prototype completion of the BPD enabled the feasibility of the technology to be demonstrated through several investigations at the PG&E facilities under field conditions. These tests were conducted at a predetermined operating frequency band and low-power (below 10 decibels per milliwatt, or dBm) electromagnetic (EM) signal was imparted onto test bed (geologic formations) under interrogation using FR (forced resonance) antennae. The impedance characteristic of the test bed dictated the choice for operating bandwidth selected for interrogation to required depths. The back scattered signal was used for almost real time detection of pipeline material type (metallic/plastic) identification, location, depth estimation, and anomaly (pipeline) diameter.

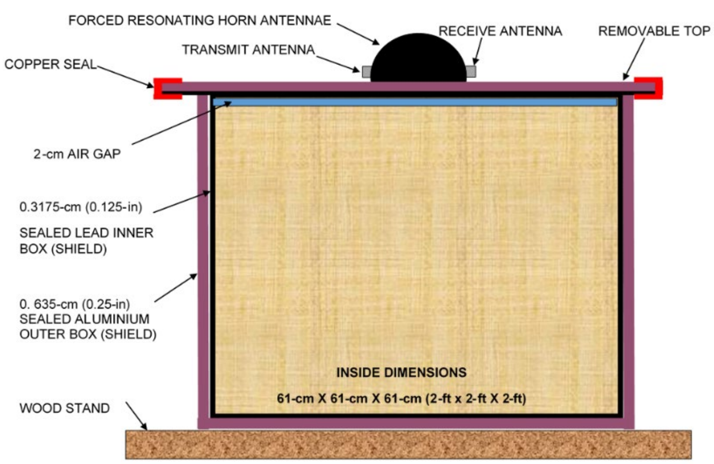
The developed non-invasive innovative technology has advantages, including but not limited to, preventing damage during excavation by accurately locating potential underground pipelines. Also, continuous data rather than discrete information from sub-surface features along the path of interrogations are obtained allowing for pipe locating and visualization with high resolution. The locating capability extends to saturated, semi-saturated and non-saturated geologic formations. They include different types of covering (soil, clay, concrete, asphalt, gravel, etc.), different pipe materials (metal and plastic), and pipelines of various diameters and burial depths. Additionally, the developed technology has potential applications in locating buried water, sewage, and electrical lines. Furthermore, it can be used for subsurface geological investigations ahead of construction and tunneling operations.

CHAPTER 2:
Project Approach

The BPD project progressed through several systematic stages as described in this chapter. The BPD was designed based on modifying the U.S. Air Force EarthRadar platform (Bakhtar, 2001). Its capability includes detection and discrimination of buried plastic and metallic pipelines, identification of dimensional details, estimation of burial depths, and horizontal location if required. Using forced resonance (FR), the BPD can detect through any geologic settings and is not impacted by the characteristics of the cover material.

A makeshift configuration of the BPD was initially used to demonstrate the feasibility of BPD detection within the first six months of the project at Pacific Gas and Electric Company (PG&E) sites in Bakersfield. Signal processing and analysis were done by post-processing of field data collected using the makeshift configuration of the BPD (Bakhtar, 2021; Bakhtar and Xu, 2021) (Figure 2). Much of the pertinent parameters for prototype development of BPD were obtained from deploying the Earth Simulator shown in Figure 1 and the makeshift configuration of BPD during the feasibility investigations. The acquired information from above studies played pivotal roles in final configuration of BPD and fine-tuning of the associated software for almost real-time buried pipe detection. Additionally, using Earth Simulator (a unique apparatus simulating the impedance characteristic of the earth) enabled much of the pertinent parameters needed for the field operation of the BPD to be determined under laboratory conditions, saving labor time.

Figure 1: Dimensional Details and Photograph of Earth Simulator



Source: Bakhtar Research and Engineering

Figure 2: Makeshift Configuration of BPD

Source: Bakhtar Research and Engineering

The early feasibility investigations enabled selection of the hardware components, assisted in software development, and established the ranges and values for the digital filters and test parameters described in the Appendix A. Numeric values and ranges for the digital filters and majority of parameters of importance for the buried metallic and plastic pipe detections were set by default in the BPD (BakhtarRadar) software. The values and ranges were established following extensive parametric investigations using the Earth Simulator. Those parameters which can be adjusted by the user include Contrast Expansion (CE) and Threshold Value (TV).

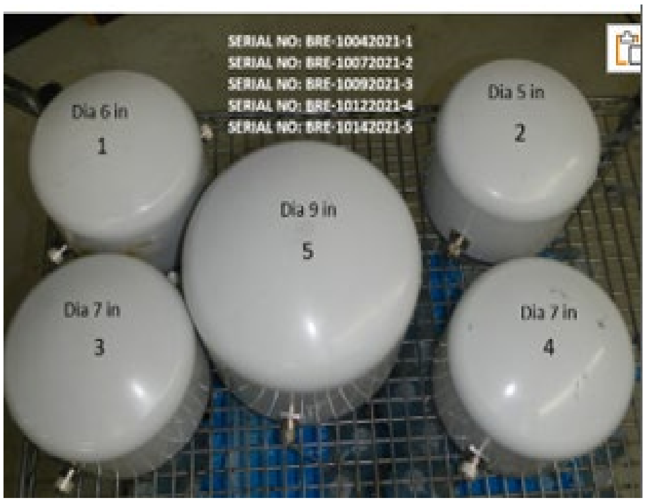
Following completion of the above investigations, the final configuration of the BPD was setup as illustrated in Figure 3. The main components consisted of a vector network analyzer (VNA) (Schwarz Model: ZNL, VNA), Carlson GPS Model BRx7, a pair of FR dipole antennae, a pair of low-noise transmission lines (TL), a pure sine wave power supply, and a small tractor to move the BPD assembly at a constant speed.

Figure 3: Final Configuration of BPD

Source: Bakhtar Research and Engineering

By far the most important components of the BPD are the FR antennae. They were designed using purely resistive elements with the overall internal impedances of almost 50 ohms. This maintained compatibility between the VNA, TL, and load (antenna). Two different configurations of FR antennae were designed and built for the BPD. Both types are center fed, adaptive, and their associated circuit boards were environmentally sealed and can operate under adverse weather conditions. Figures 4 and 5 show the next generation dipole and horn antennae designed and fabricated for BPD integration. Most importantly, results of the early parametric investigations coupled with field tests using the makeshift configuration of the BPD revealed that the most desirable operating frequency band (Δf) for detection of buried pipeline within depths to fifteen feet is 400 megahertz (MHz).[1]

Figure 4: Next Generation Horn Antennae



Source: Bakhtar Research and Engineering

Figure 5: Next Generation Dipole Antennae

Source: Bakhtar Research and Engineering

Operational Procedure

The VNA in prototype BPD transmits a small amount of energy (less than 10 dBm) at a predetermined operating frequency band onto test beds (geologic formations) and used the backscattered signal for detection of buried pipeline. The operating bandwidth for interrogation is set to accommodate the requirements for depth detection. The back scattered signal is used for near-real time depth estimation and anomaly (pipeline) diameter detection to within a fraction of an inch.

The transmitter antenna radiates low EM (electromagnetic) energy in stepwise fashion onto a test bed, which is backscattered and received by the receiver antenna. The network analyzer takes this received EM energy in forward transmission mode of VNA data collection. The energy is transmitted in several discrete frequency steps empowering realization throughout the test bed depth of interest. The operating frequency band is set by the user to suit a depth requirement and not impacted by geology and cover.

[1] The operating frequency band is calculated as $\Delta f = f_{FINAL} - f_{INITIAL} = 600 - 200 = 400$ MHz.

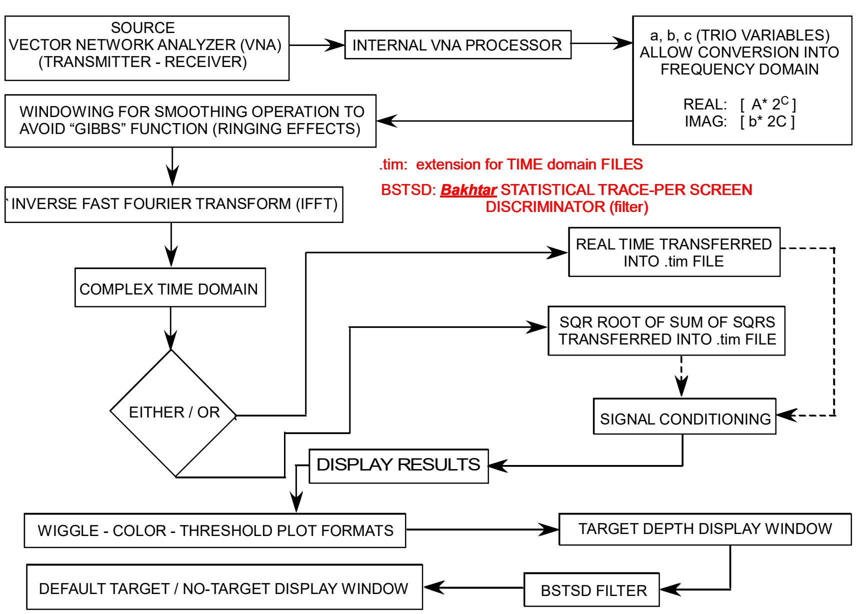
The collected frequency data is converted internally to intermediate frequency (IF) for internal processing. An anti-alias filter clips the higher unwanted frequencies. Before analog-to-digital (A-to-D) conversion the data goes through some gain ranging stages. The purpose of "gain ranging" is to ensure that the signal remains within a desired range or dynamic range without distortion or clipping. Anti-aliasing filters were designed and incorporated with the BPD software (BakhtarRadar) to attenuate unwanted high frequency components from the signal while keeping the desired frequency range.

The BPD software is the control unit. A simplified flow chart of the BPD software algorithm is shown in Figure 6. The BPD software obtains field data from the network analyzer through a USB cable interface. In the software the data is inverse fast fourier transformed (IFFT'd, the opposite operation to Fast Fourier Transform that renders the time response of a signal given its complex spectrum) to convert to time domain. After Hanning filtering (digital signal or image filtering using the Hann window) and scaling is applied the data is sequentially plotted trace by trace and can be displayed in color, threshold, or grayscale format. In the color plot the intensity of the signal determines the color map. Blue colors represent lower intensities and red colors represent higher intensities. Black color is representative of the highest intensity signals. In the threshold plot, signals having higher than cut-off intensity (Threshold Value, TV) are shown in white and signals having lower than the TV value are shown as black. Adjusting TV values in majority of cases allows discrimination between a detected buried target and associated noise or clutter. In the grayscale plot the data values are mapped to gray colors based on their intensity like X-ray images.

It is important to note that following internal processing of data, the trio variable shown in the flowchart of Figure 6 allows field data conversion into frequency domain with Real ($a*2^C$) and Imaginary ($b*2c$) components. The resulting values, that is,

$$\text{Resultant} = [\ \text{Real}\ (a*2^C) + \text{Imaginary}\ (b*2c)]^{1/2}$$

Figure 6: General Algorithm for Signal Processing and Display



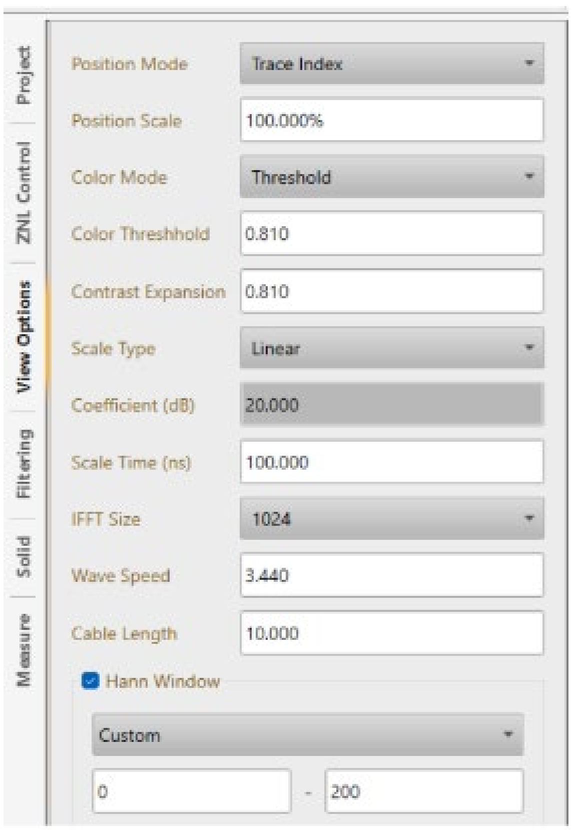
Source: Bakhtar Research and Engineering

is used for signal processing. Although either Real or Imaginary components can also be used. The result is chosen based on decades of experience by the principal investigator—that is why this version of BPD software is referred to as the "BPDResultantXFilter."

BPDResultantXFilter is a graphic user interface-based software, which performs the different functionalities using different windows. The step-by-step procedural description of the required main functionality (for buried pipeline detection and discrimination) of the software is described in the User Manual listed at the end of this report. These functions and their related parameters were the subject of the field testing and used for optimization of their values and finalized prototype configuration of the BPD for default field operation.

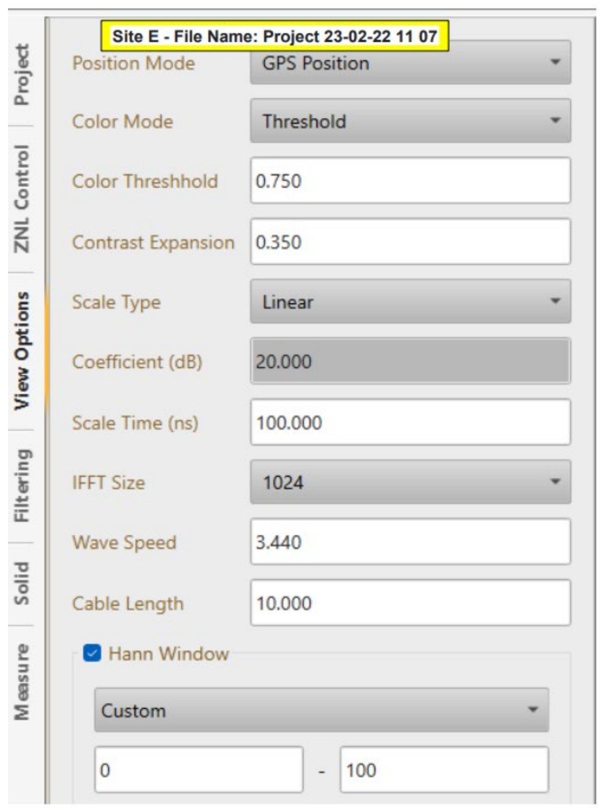
Two important parameters are the contrast expansion (CE) and threshold value (TV). These two parameters are adjusted to mask clutter and establish the threshold for discrimination between buried plastic and metallic pipelines. Buried plastic pipelines are identified by setting CE and TV value above 0.8. Buried metallic pipelines are identified by setting the CE and TV values below 0.75 as illustrated in Figures 7 and 8.

Figure 7: Plastic Pipeline with CE and TV Values Greater than 0.8of Plastic Material



Source: Bakhtar Research and Engineering

Figure 8: Metallic Pipeline with CE and TV Values Less than 0.75



Source: Bakhtar Research and Engineering

It is important to note that the mineralogy of geologic formations in California within which the buried pipelines are concealed are mostly composed of moist sandy-clay with occasional pebbles and fragmented rock pieces. Coastal areas have sedimentary deposits near the surface, influenced by processes of erosion, deposition, and sea-level changes. River valleys have alluvial deposits in the upper layer. Extensive investigations performed by the principal investigator on estimation of electromagnetic wave speed (EMWS) in various locations in California confirmed that the EMWS varies from 3.4 cm/nanoseconds to 4.8 cm/nanosecond with average of about 4.0 cm/nanoseconds. The 1-cm/nanosecond variation is the results of moisture contents within the areas near to or away from coastal regions.

BPD setup and testing processes are consistent regardless of location and can be described as follows:

- Setting up a staging area for assembling BPD components near the testbed.
- Establishing the GPS Base location or if applicable, connecting to the AT&T cellular network.
- Connecting FR antennae directly to the vector network analyzer (VNA) via TL.
- Connecting the VNA, TL, and laptop computer to the power source located in the front of the small Kabuto tractor.
- Setting up the test parameters as outlined in the BPD manual.
- Proceeding with interrogation starting from one corner of the test bed longitudinally to the end.
- Moving laterally with about 10 to 15 inches overlap with the previous line of interrogation and repeating data collection longitudinally from the start line.
- Continuing the interrogation operation longitudinally until entire test area (testbed) is covered.
- Selecting several locations along the first line of longitudinal interrogation and performing several cross-scans for exact GPS location of the buried pipeline with higher accuracy than the longitudinal interrogation.
- Providing tentative results of the buried pipeline type (plastic/metallic), diameter, depth, and GPS location in the field.

The procedure outlined above was followed initially at the PG&E test site in the Bay Area of California in 2021 using the makeshift configuration of the BPD including the old antennae, VNA, and GPS unit as shown in Figure 9. Results of interrogations are shown in Figures 10 and 11 in color and threshold formats, respectively.

Figure 9: Testing Makeshift BPD Configuration

Source: Bakhtar Research and Engineering

Figure 10: Tomographic Profiles of a Buried Steel Pipe in Color Format using Makeshift BPD

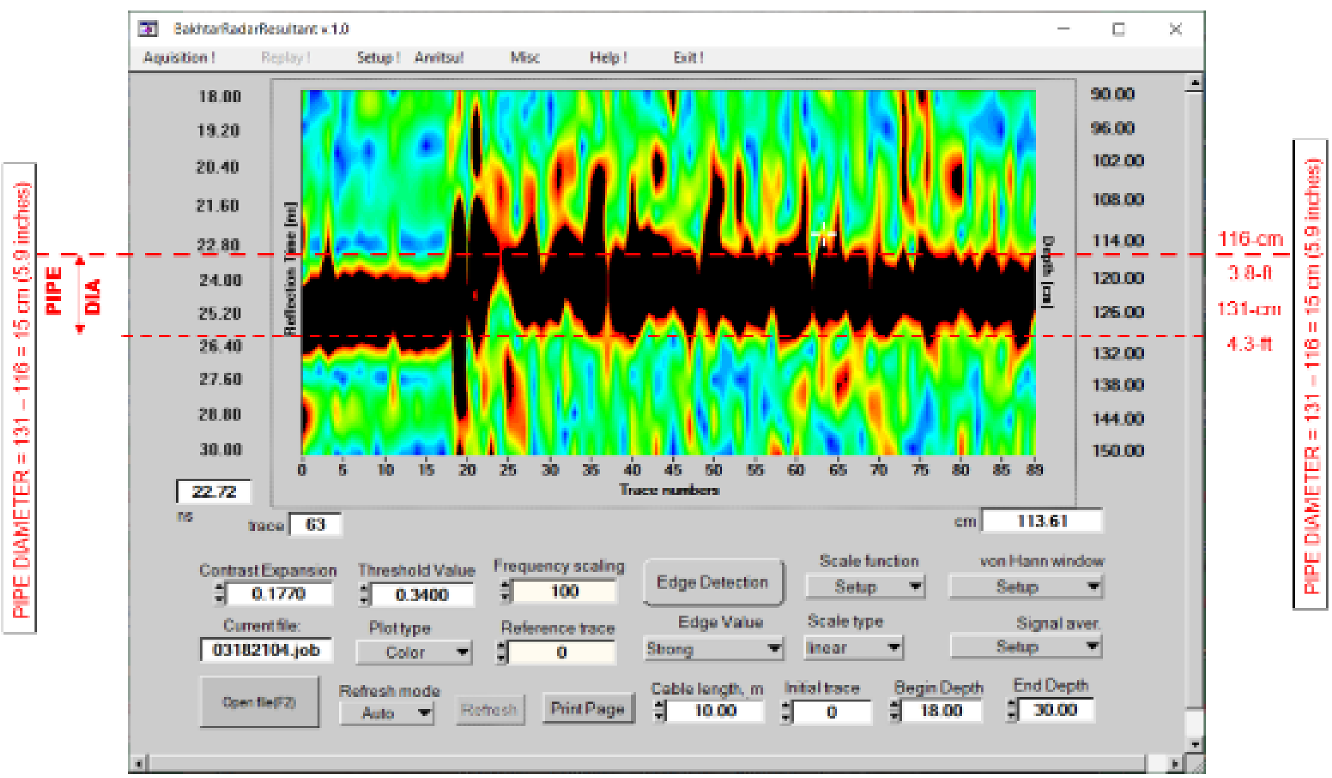
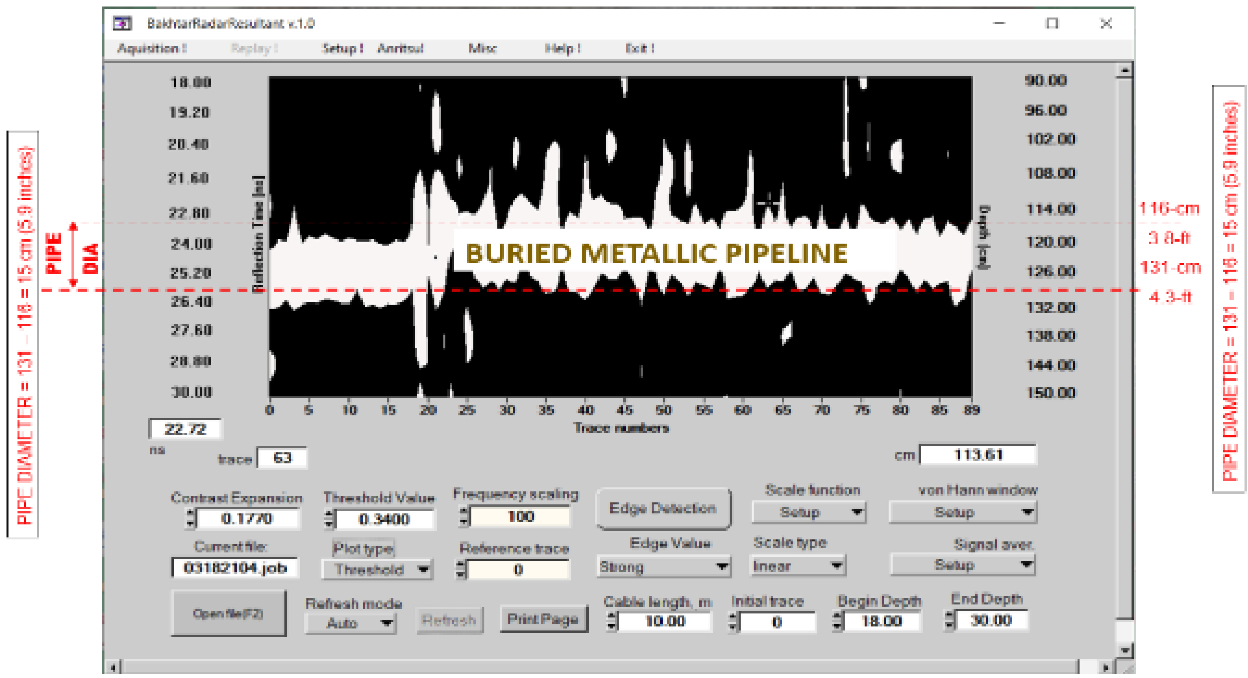


Figure 11: Tomographic Profiles of a Buried Steel Pipe in Threshold Format using Makeshift BPD



Source: Bakhtar and Xu[5]

The makeshift configuration of BPD for the Bay Area (2021 investigations) measured the buried pipeline diameter and depth using Figures 10 and 11 to be 5.9 inches and 3.8 feet, respectively. The boundaries of the tomographic profiles (cross section profiles of pipe along the length or axis) of the buried metallic pipe appeared to have many spikes due to induced noise as results of vibrations overcoming of friction at the interface of polyethylene skid and asphalt as deduced from Figures 10 and 11.

Best Practices for BPD Operation

The experience gained through calibration and preliminary blind tests enabled the final configuration of BPD hardware and software to be implemented for the prototype unit development, testing, and demonstration. It is highly recommended that the procedures outlined in the Operational Procedure Section of this chapter be implemented during the data acquisition phase of the field investigations. Furthermore, to facilitate real-time detection, the depth of detection should be set to less than 10 feet as the maximum depth of most buried pipeline is anticipated to be less than 5 feet (Folga, 2007).

The CE and TV for detection and discrimination of plastic and metallic buried pipelines can be set during the field data acquisition to the following values:

1. Buried plastic pipes thresholds of detection:

    a. CE > 0.85
    b. TV > 0.92

2. Buried metallic pipes thresholds of detection:
   a. CE < 0.80
   b. TV < 0.90

Also, to maintain the signal quality during data acquisition in the field the following precautionary measures should be implemented:

- Avoid using cell phones within a 20-foot radius of the BPD.
- Avoid overlapping the TL of antennae.
- Avoid any kinks or curvatures within the TL to omit formation of standing waves, which causes additional losses during transmission and reception.
- Use phase stable and low-noise TL.
- Check structural integrity of TL prior to any field investigation.
- Check all connectors are tight at each port and free from particles around inner parts of female and outer parts of the male components.

Lastly, the BPD assembly should be grounded by dragging the TL on the ground next to the FR antennae.

CHAPTER 3: Project Results

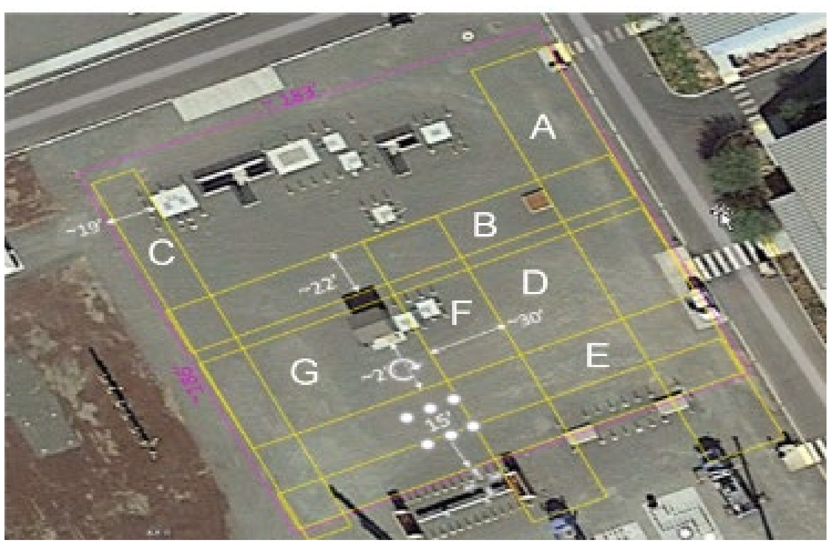
This chapter provides the results of blind tests conducted at the PG&E test sites using the final configuration (prototype) of the BPD. A Field Demonstration Plan was developed, outlining step-by-step procedures for field data collection and reporting. It also summarized the accuracy of measurements using the BPD with its integrated high resolution GPS system.

Following completion of parametric investigation and initial testing using the makeshift configuration of the BPD, field testing commenced at the PG&E buried pipeline facilities in Winters, California followed by additional testing in the Bay Area. Performance assessment investigations performed at several sites including the sites in Southern California revealed that the Electromagnetic Wave Speed (EMWS) through the ground varied from 3.44 centimeters (cm) per nanosecond to 4.48 cm per nanosecond depending on proximity of the test bed to water table and moisture content of the soil. Furthermore, visual observations of test bed topography and minerology revealed that the topsoil within all tested areas was mostly sandy clay with varying moisture content and occasional fragments of rock and gravel.

Blind Test at PG&E Training Academy in Winters, California

The blind field testing, that is, those tests where information on buried pipeline presence/absence was not disclosed, occurred over several months. Google map (Figure 12) illustrates the six sections within the PG&E test site in Winters, California. At each section longitudinal and cross scans were made to detect buried pipeline. Surface topography at the Winters testing location is shown in Figure 13. The EMWS based on the on-site testing was calculated to be 3.44 cm/ns. Examples of buried plastic and metallic pipes detected at the PG&E Training Academy in Winters are provided in the following pages.

Figure 12: Google Map Showing PG&E Test Locations



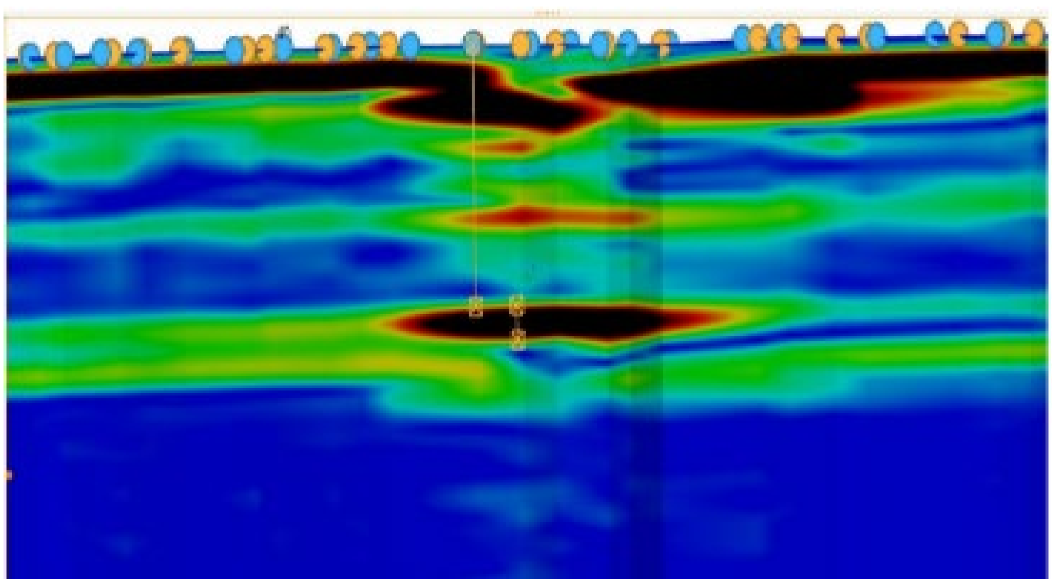
Source: Bakhtar Research and Engineering

Figure 13: Topography at Winters Test Site

Source: Bakhtar Research and Engineering

Section A: a plastic pipe with diameter of 4 inches at depth of 29 inches was detected based on CE and TV greater than 0.80. Tomographic profiles (cross-section) and dimensional details of the detected plastic pipe in color format are shown in Figure 14.

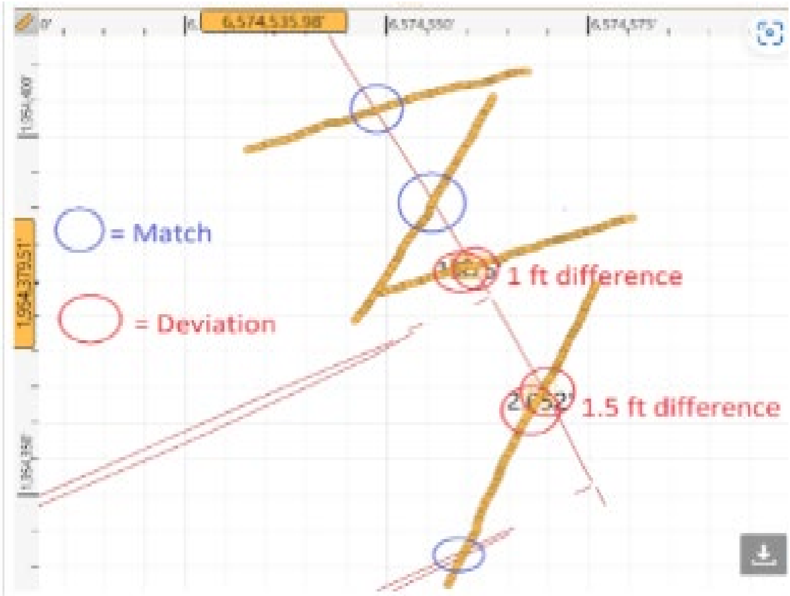
Figure 14: Tomographic Profile of Plastic Pipe in Color Format Pipe in A



Source: Bakhtar Research and Engineering

Figure 15 shows comparison of buried plastic pipe detected by BPD and PG&E records. An exact match was seen at two locations and differences of 1 ft to 1.5 ft at the other two locations. It may be an error in the PG&E records or an offset at this location due to unforeseen effects.

Figure 15: Comparison of BPD and PG&E Data Record in A



Source: Bakhtar Research and Engineering

Section B: another plastic pipe with diameter of 4 inches at depth of 29 inches was detected based on CE and TV greater than 0.80. Tomographic profile and dimensional details of the detected plastic pipe in color format are shown in Figure 16.

Figure 16: Tomographic Profile of Plastic Pipe in B

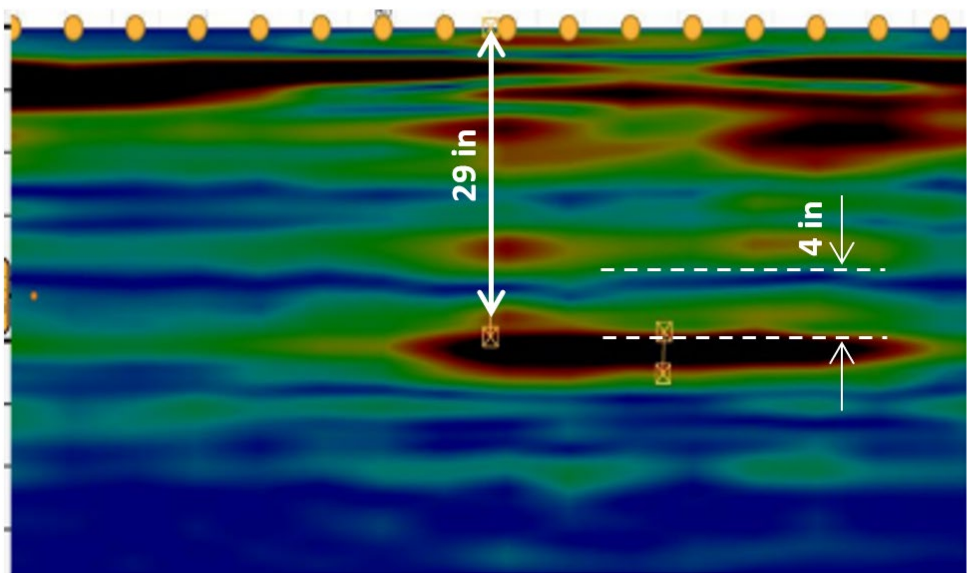
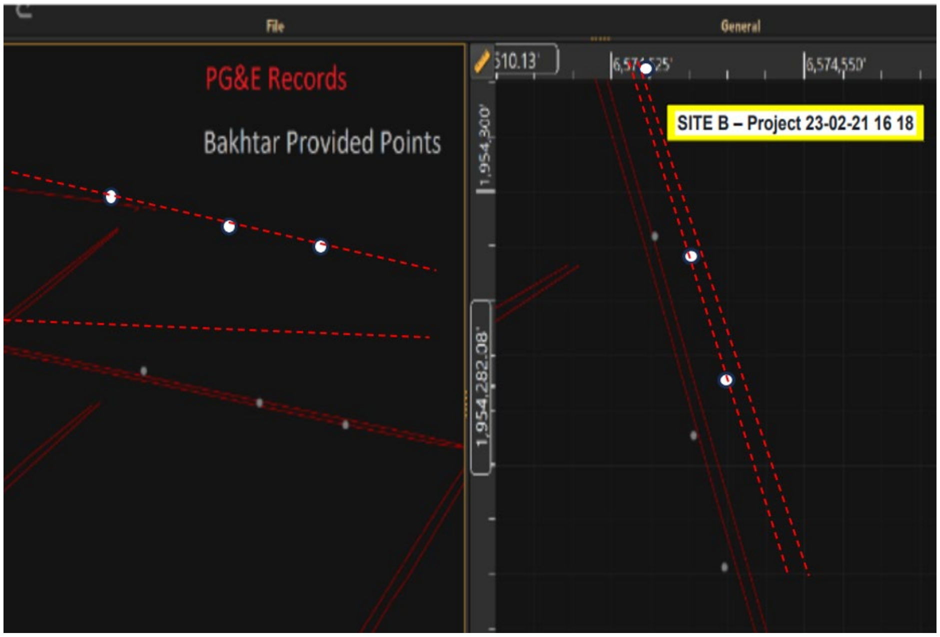


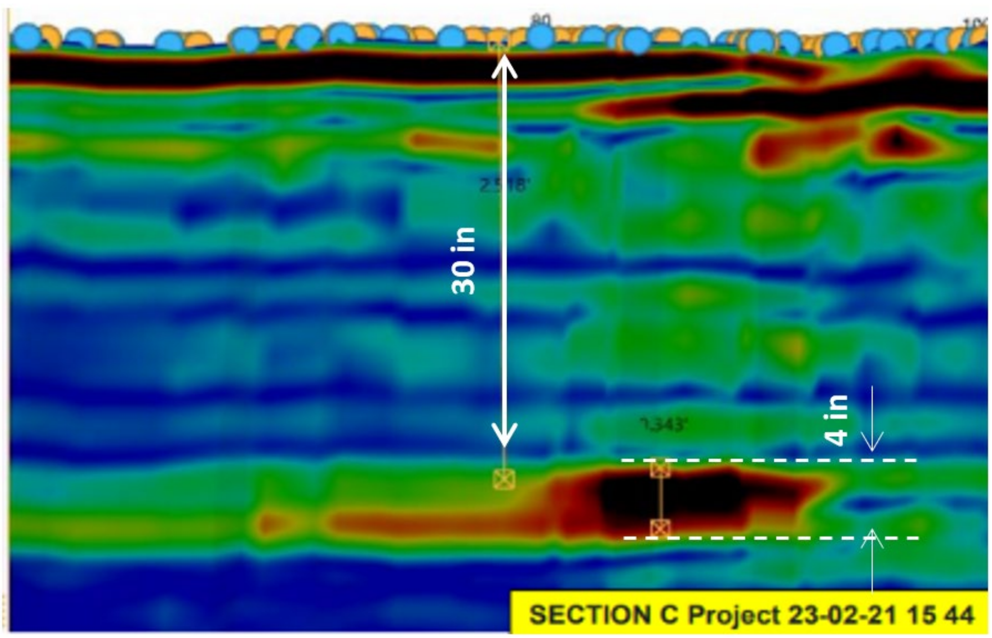
Figure 17 shows comparison of buried plastic pipe detected by BPD and PG&E records. For Site B PG&E records and BPD data match.

Figure 17: BPD Data and PG&E Record Comparison in B



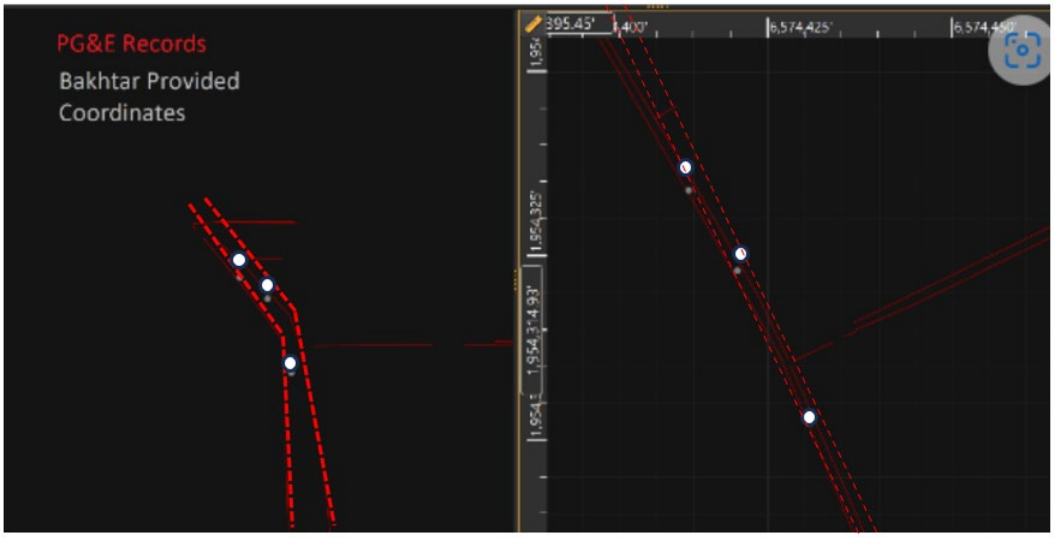
Section C: one more plastic pipe with diameter of 4 inches at depth of 30 inches was detected based on CE and TV values greater than 0.80. Tomographic profiles and dimensional details of the detected plastic pipe in color format are shown in Figure 18. The BPD provided GPS footprints of the detected buried plastic pipeline in Section C closely matched the PG&E records as shown in Figure 19.

Figure 18: Tomographic Profile of Plastic Pipe in C



Source: Bakhtar Research and Engineering

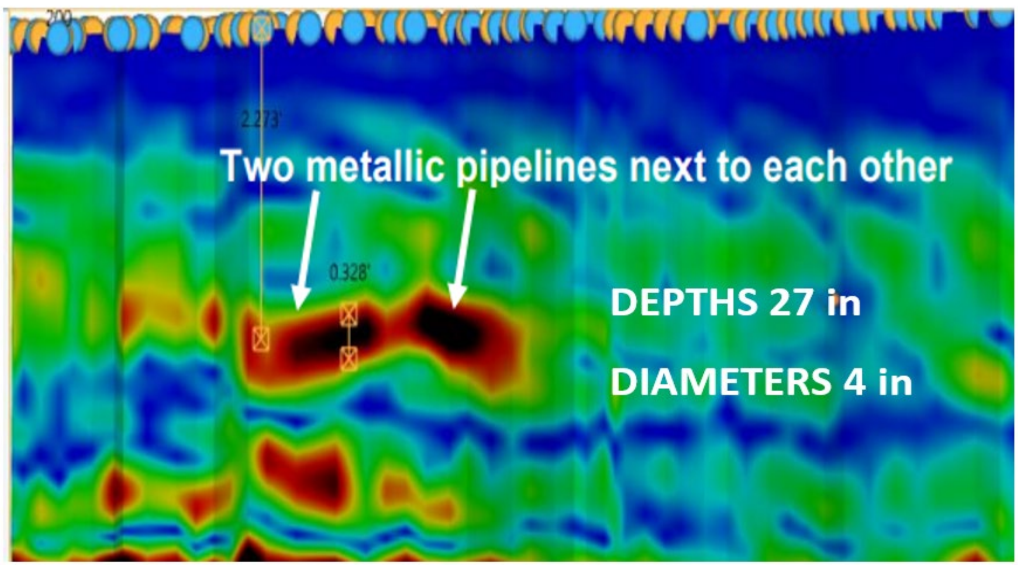
Figure 19: BPD Data and PG&E Record Comparison in C



Source: Bakhtar Research and Engineering

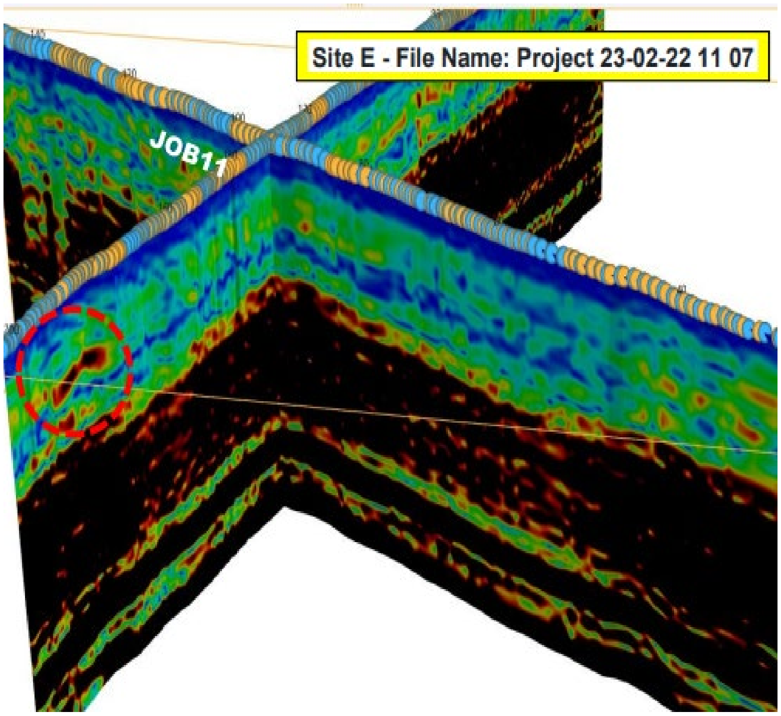
Section E: two metallic pipes with diameters of 4 inches at depth of 27 inches were detected based on CE and TV values less than 0.80. Tomographic profiles and dimensional pipes in color format are shown in Figure 20. The two metallic pipes were detected at the intersections of longitudinal and cross scans as illustrated in Figure 21.

Figure 20: Tomographic Profile of Metallic Pipes in E



Source: Bakhtar Research and Engineering

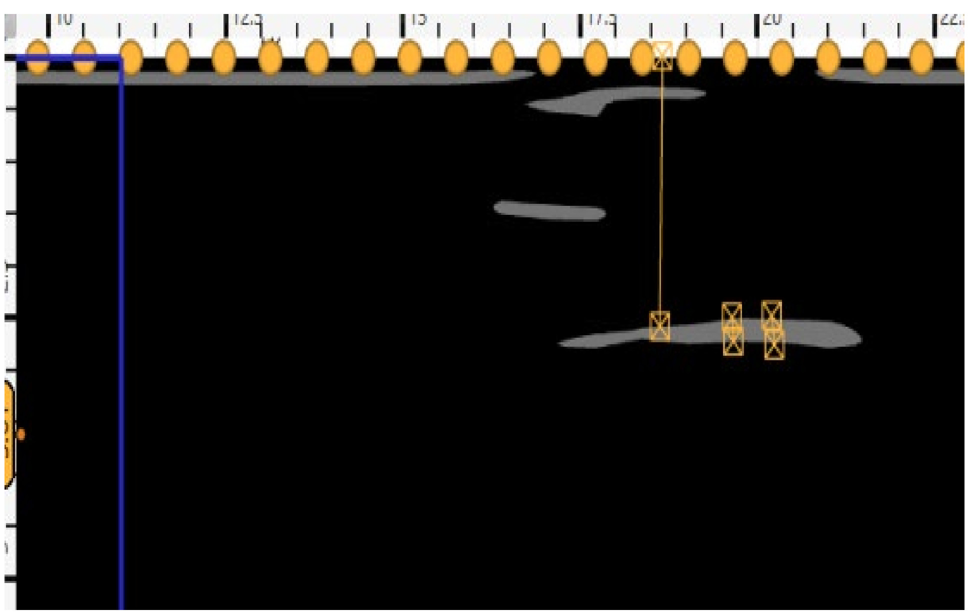
Figure 21: Longitudinal and Cross Scans used to Detect Buried Metallic Pipes in E



Section F: a plastic pipe with diameter of 2 inches at depth of 28 inches was detected based on CE and TV greater than 0.80. Tomographic profile and dimensional details of the detected plastic pipe in threshold format are shown in Figure 22.

For all results shown from tests conducted at the PG&E Training Academy close agreements with the PG&E records were observed. The PG&E personnel and the CEC agreement manager closely observed data collection and reporting in the field.

Figure 22: Tomographic Profile of Plastic Pipes in F



Source: Bakhtar Research and Engineering

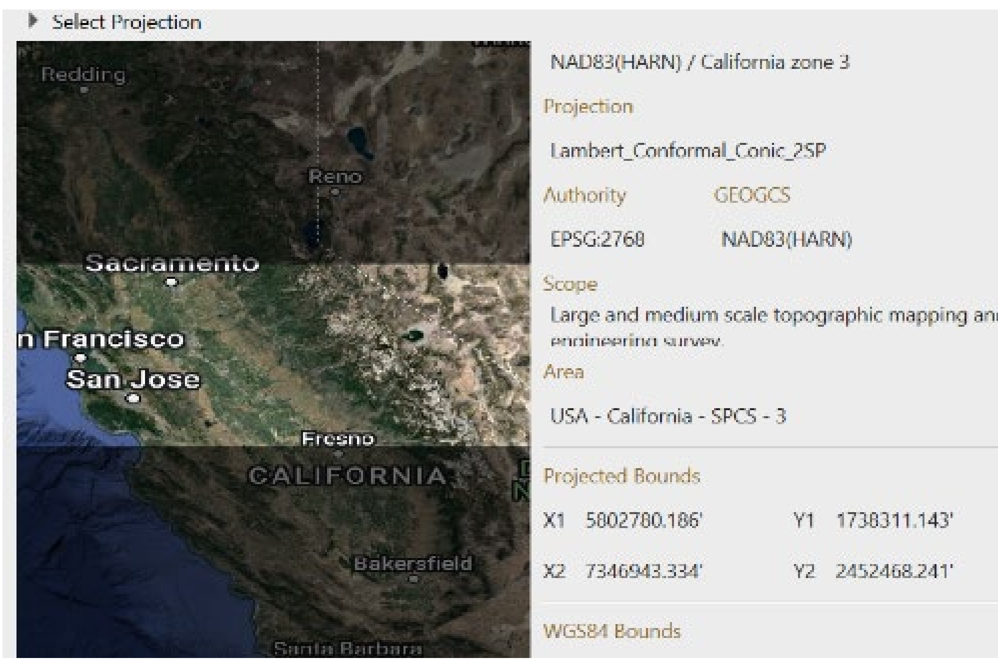
Blind Tests Results at PG&E Sites in Alameda and Union City, California

To complete field testing of the BPD, in May 2023 additional investigations were performed under blind test conditions in compliance with the Agreement PIR-19-017. The field testing was performed under PG&E directions and on-site supervision at four different locations:

- East Shore Drive, City of Alameda
- Ravens Cove Lane, City of Alameda
- Rocklin Drive, Union City
- Tamarack Drive, Union City

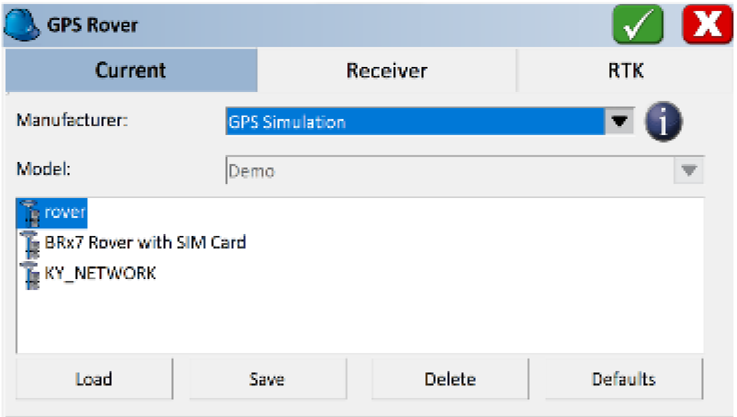
NAD83 (HARN) / California Zone 3 was selected for the GPS projections with details shown in Figure 23. In Carlson software, Bakhtar Job Manager, which is a component of Bakhtar software, was used to connect to the GPS cellular network authorized by PG&E. Figure 24 shows the software user interface operation to connect GPS to PG&E network. This eliminated the use of the base and facilitated the ease of communications and GPS setup in the field.

Figure 23: Projection selected for Setting GPS at Test Sites



Source: UC San Diego, Scripps Orbit and Permanent Array Center

Figure 24: Selecting ROVER in Carlson Software to Connect to PG&E Network



Source: Bakhtar Research and Engineering

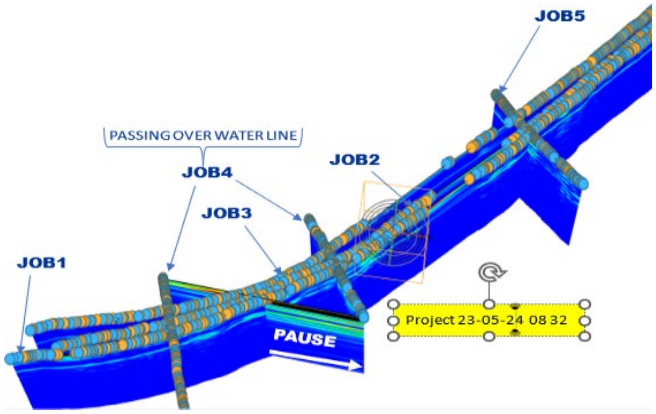
Efforts were taken to expedite the field data acquisition while ensuring proper data for both the BPD (BakhtarRadar traces) and GPS coordinates were collected and stored in the field computer. Procedures described in the Field Demonstration Plan were followed for field data collection, analysis, and results presentation. Results from field data collected at each site are discussed in the following pages.

East Shore Drive, City of Alameda: The test bed is shown in the photograph presented in Figure 25. As can be deduced from the composite tomographic profiles shown in Figure 26 three longitudinal and two cross-scans were made at this site. Figure 27 presents superposition of the field data on the Google map.

Figure 25: Test Bed in East Shore Drive, Alameda

Source: Bakhtar Research and Engineering

Figure 26: Tomographic Profiles of Scan Paths



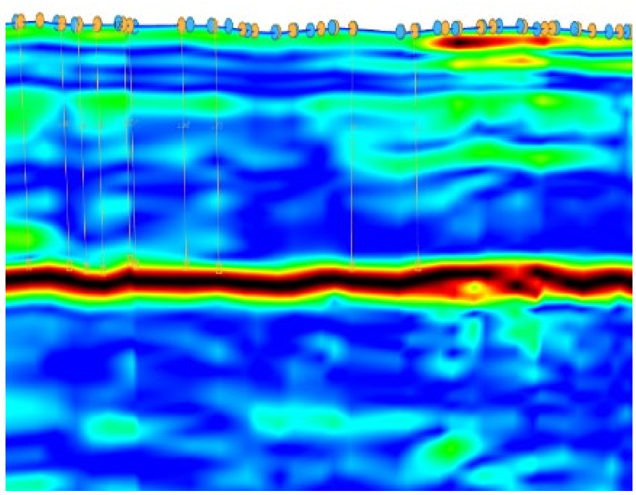
Source: Bakhtar Research and Engineering

Figure 27: Projections of Surface Footprints of *BakhtarRadar* Traces and GPS Coordinates on Google Map

Source: Bakhtar Research and Engineering

Buried pipeline was detected in data stored in the file named JOB3. Adjusting CE and TV associated with incipient of detection (the time when the traces of target boundaries initially appear on the monitor) revealed that the buried pipeline is made up of metallic material, that is, CE and TV values less than 8.00. Depth and diameter of the buried metallic pipe was measured from its tomographic profiles (Figure 28) at incipient of detection to be 36 inches and 2 inches, respectively. Ten GPS coordinates along the detected buried metallic pipe were projected on the Google map as can be seen in Figure 29. This figure was used to measure the horizontal distance from the surface footprint of the buried metallic pipe to the curb as illustrated in Figure 29, which was found to be 6.24 feet. The inset next to Figure 30 provides a list of GPS coordinates used to make the surface footprint of the detected pipeline on East Shore Drive.

Figure 28: Tomographic Cross-Sections (Profiles) of Buried Metallic Pipeline in Color Format



Source: Bakhtar Research and Engineering

Figure 29: Projection of GPS Data Google Map

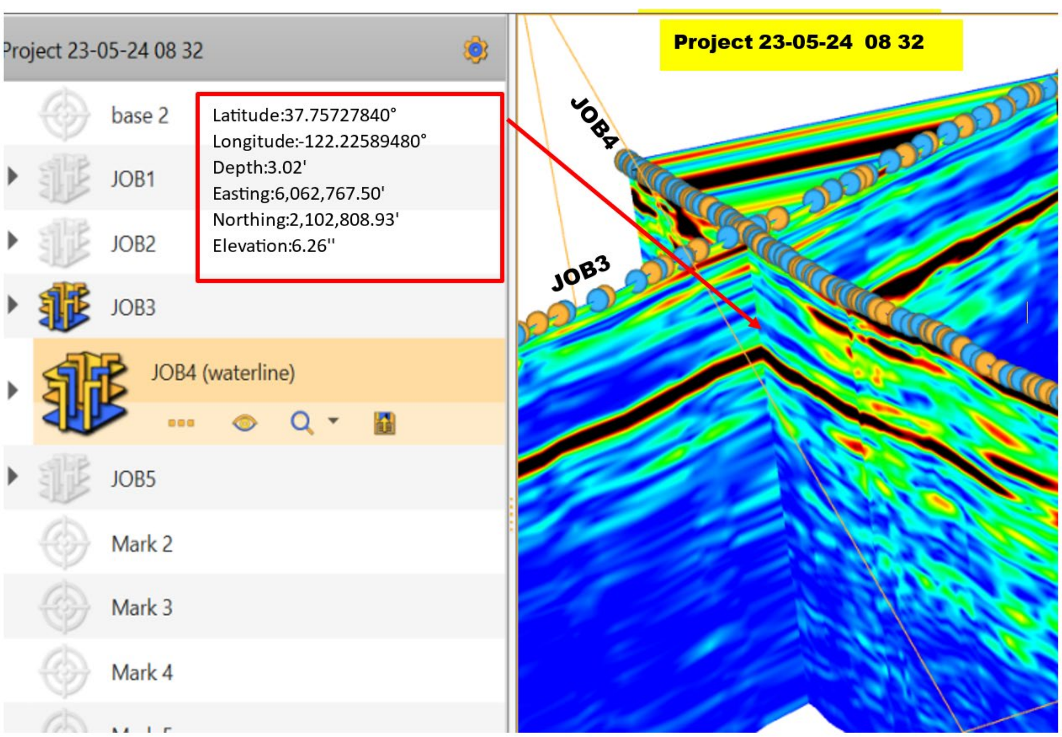
Source: Bakhtar Research and Engineering

Data Point #	Dia (in)	Depth (in)	Latitude	Longitude
3	2.28	36	37.61046517	-122.020227
16	1.92	36.02	37.61046002	-122.020207
33	1.92	36.02	37.61045528	-122.020188
55	2.16	36.04	37.6104479	-122.020161
95	1.92	37.08	37.61043497	-122.02011
110	2.28	36.01	37.61043151	-122.020093
128	2.16	36.01	37.61042791	-122.020077
140	1.92	36.02	37.61042532	-122.020067
160	1.92	36.02	37.61042037	-122.020046
184	2.04	36.03	37.61041468	-122.020023
AVERAGE VALUES	2.05	36.13		

Source: Bakhtar Research and Engineering

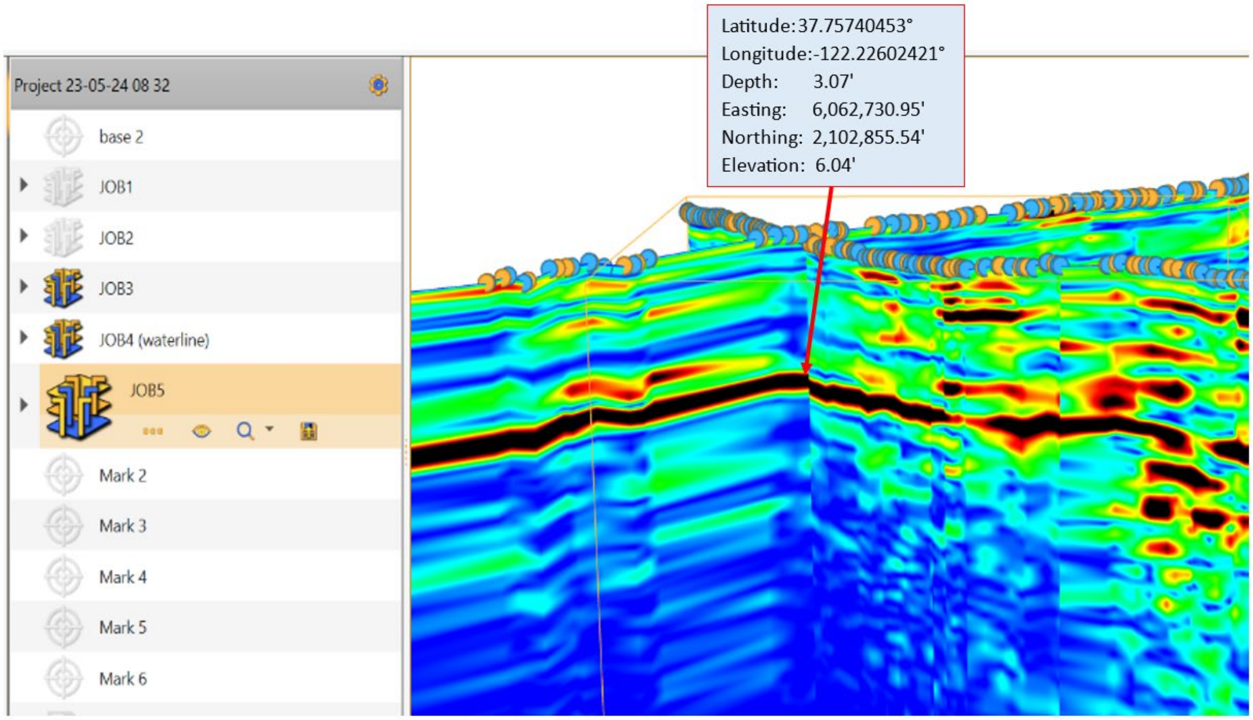
Figures 30 and 31 illustrate the intersections of the longitudinal and cross scans. These intersections can be used to establish the GPS surface coordinates of buried metallic pipeline, depths, and elevations above sea level as shown in the insets of Figures 30 and 31.

Figure 30: Coordinates of Buried Pipeline at Intersection of Longitudinal Scan (JOB3) and Cross Scan (JOB4)



Source: Bakhtar Research and Engineering

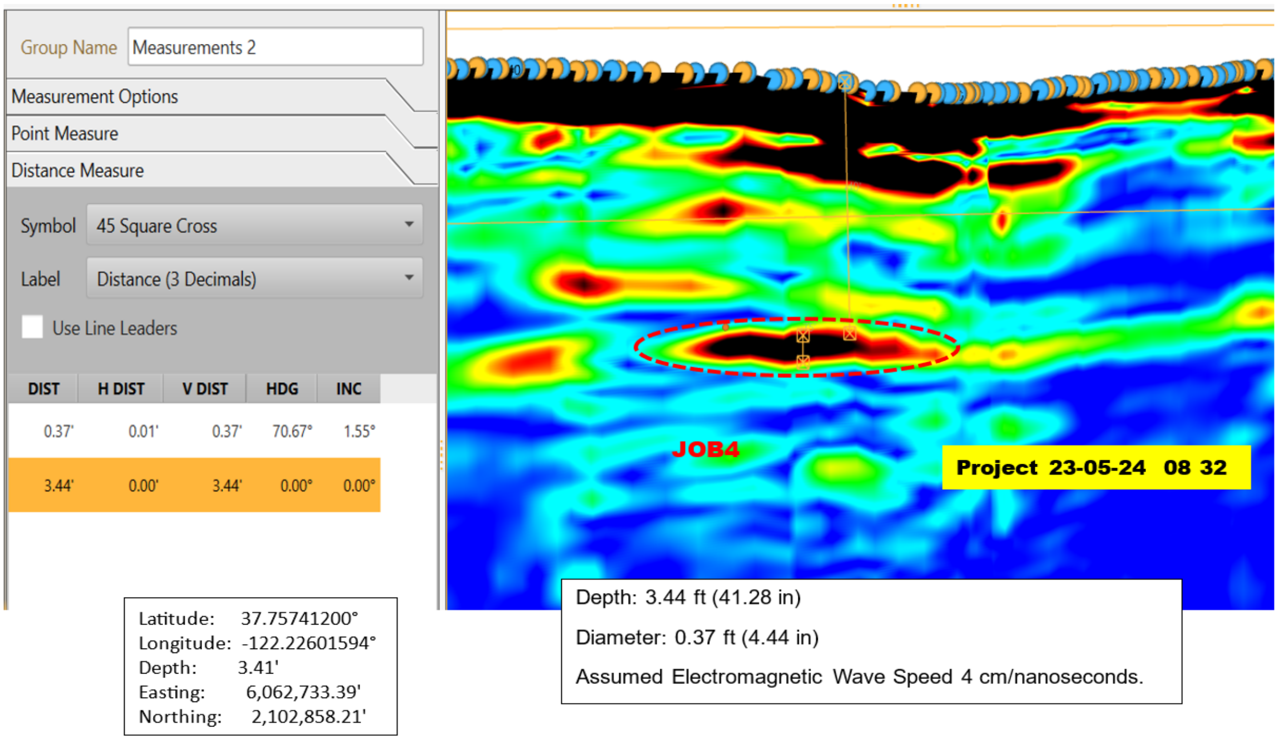
Figure 31: Coordinates of Buried Pipeline at Intersection of Longitudinal Scan (JOB3) and Cross Scan (JOB4)



Source: Bakhtar Research and Engineering

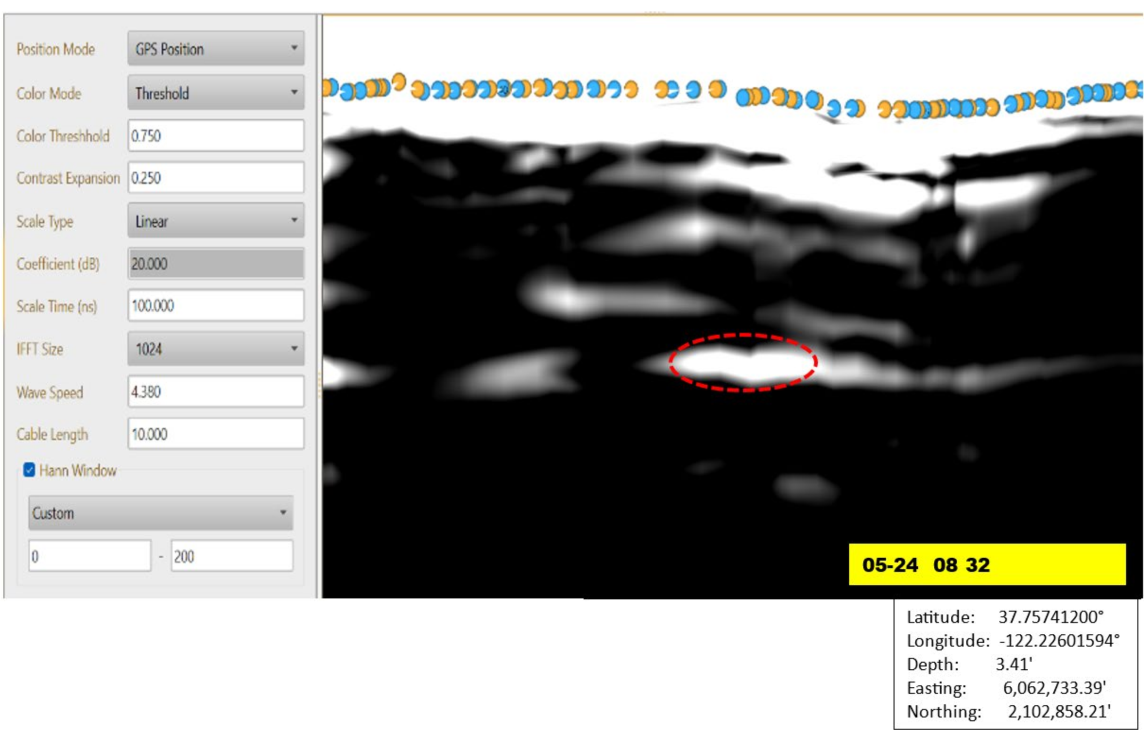
Data collected and stored in JOB 4 also encompassed passage over a water pipeline with a man-hole cover marked water. Figures 32 and 33 show tomographic profiles (cross-section) of the buried water line, which is made of metallic material. At the incipient of detection, the CE and TV values were much less than 0.80. GPS coordinates at the intersection with the longitudinal passes shown in JOB 4 and JOB5 are included in the insets of the figures. The depth and diameter of the buried metallic pipeline were measured to be 41.88 inches and 4.68 inches, respectively. The GPS coordinates, depth of burial, and elevations above sea level for the center of surface footprint of water pipeline are shown in the insets on Figures 32 and 33.

Figure 32: Tomographic Cross-Sections (Profiles) of Buried Metallic Water Pipeline in Color Format



Source: Bakhtar Research and Engineering

Figure 33: Tomographic Cross-Sections (Profiles) of Buried Metallic Water Pipeline in Threshold Format

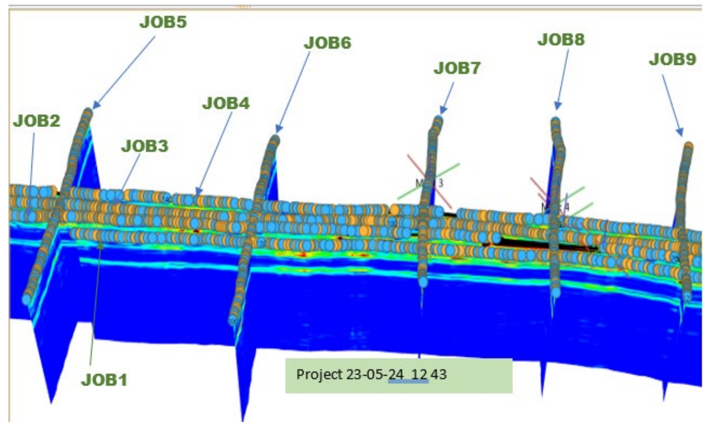


Source: Bakhtar Research and Engineering

Ravens Cove Lane, Alameda: The test bed is shown in the photograph presented in Figure 34. As can be deduced from the composite color format tomographic profiles shown in Figure 35, *BakhtarRadar* collected four longitudinal and five cross scans of the area.

Figure 34: Ravens Cove Lane Testbed

Figure 35: Composite Tomographic Profiles with Four Longitudinal and Five Cross Scans



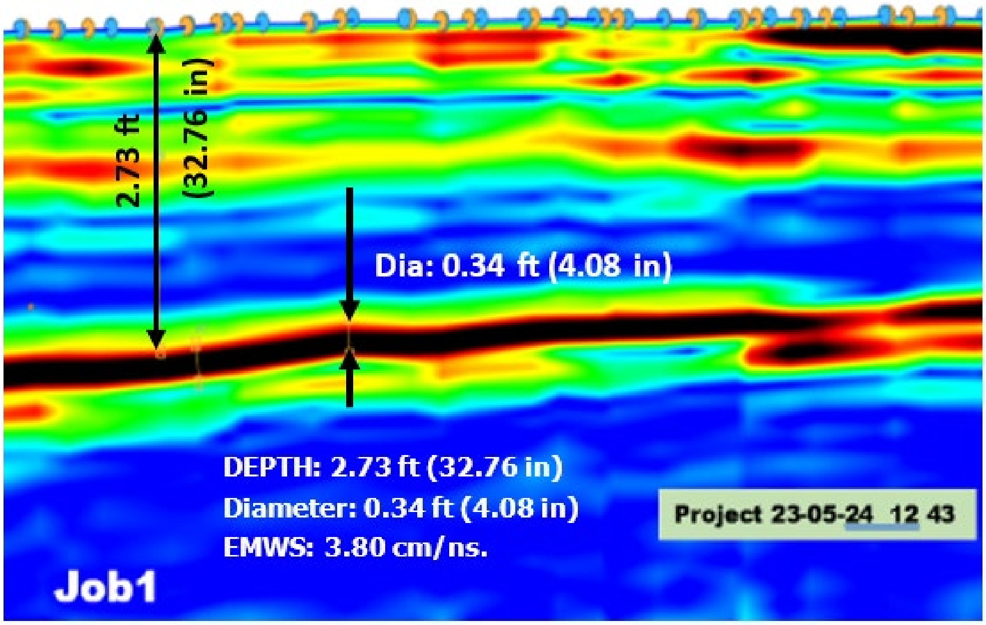
Source: Bakhtar Research and Engineering

Figure 36 shows the same data set superimposed on a Google map. A buried pipeline was detected in data stored in the file named JOB1. Adjusting values of CE and TV enabled discerning of the tomographic profiles of the buried pipeline greater than 0.80 indicative of the pipe made of plastic material. Tomographic profiles of the buried pipe further enabled depth and diameter of the buried pipeline to be measured as 32.76 inches and 4.08 inches, respectively, shown in Figure 37 in color format.

Figure 36: Projection of Scan Paths on Google Map

Source: Bakhtar Research and Engineering

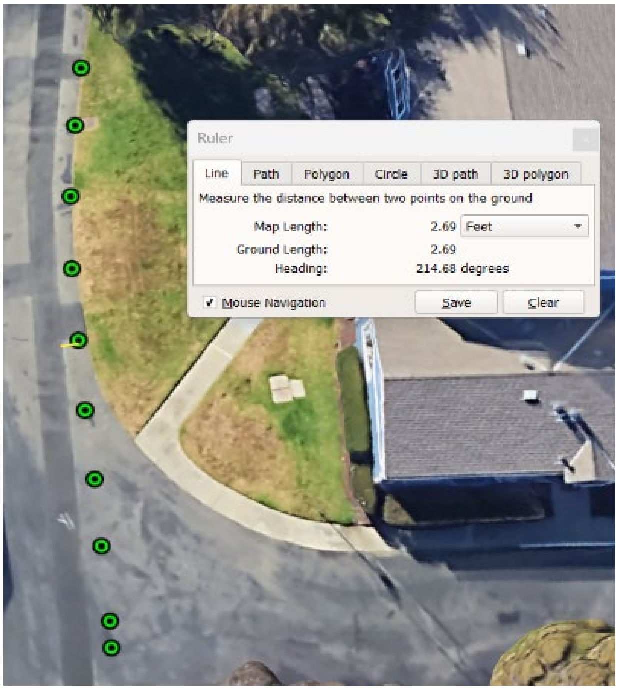
Figure 37: Tomographic Cross-Sections of Buried Plastic Pipeline in Color Format



Source: Bakhtar Research and Engineering

Ten GPS coordinates along the detected buried plastic pipe were projected on the Google map as can be seen in Figure 38. This figure was used to measure distance from the surface footprint of the buried plastic pipeline to the curb, which was measured to be 2.69 feet, as illustrated in Figure 38.

Figure 38: Measured Surface Footprint of Buried Pipeline from the Curb at Ravens Cove City of Alameda



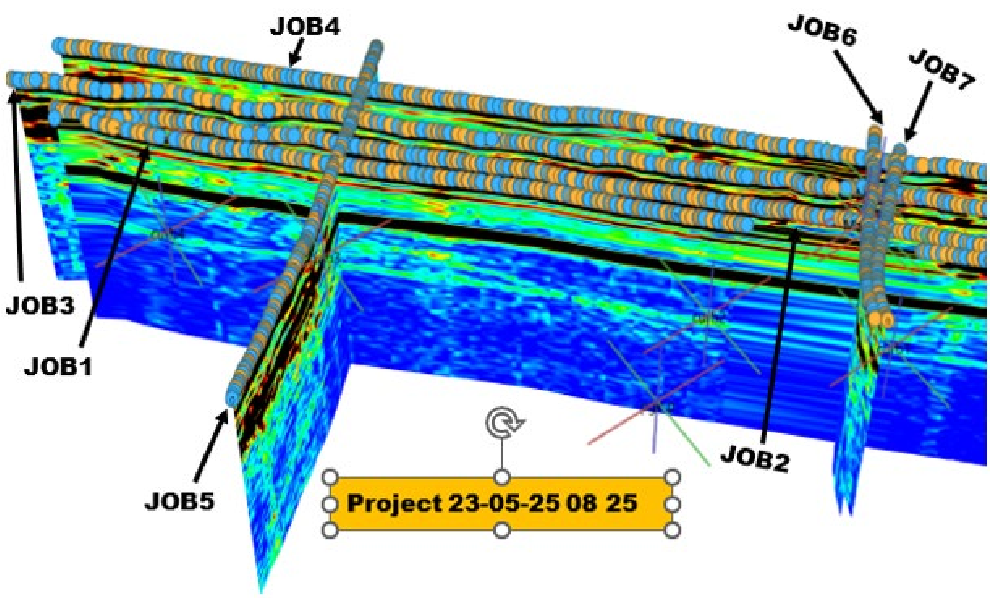
Source: Bakhtar Research and Engineering

Rocklin Drive, Union City: The test bed is shown in Figure 39. As can be deduced from the composite color format, tomographic profiles shown in Figure 40 subsurface *BakhtarRadar* traces and surface GPS coordinates were collected along four longitudinal and three cross-scans. The collected data was stored in the field computer for on-site results presentations and further analysis and report preparation in the office. Figure 41 presents superposition of the field data collected along longitudinal and cross-scan directions on the Google map.

Figure 39: Rocklin Drive Union City Testbed

Source: Bakhtar Research and Engineering

Figure 40: Paths of Interrogations for Longitudinal and Cross-Scan



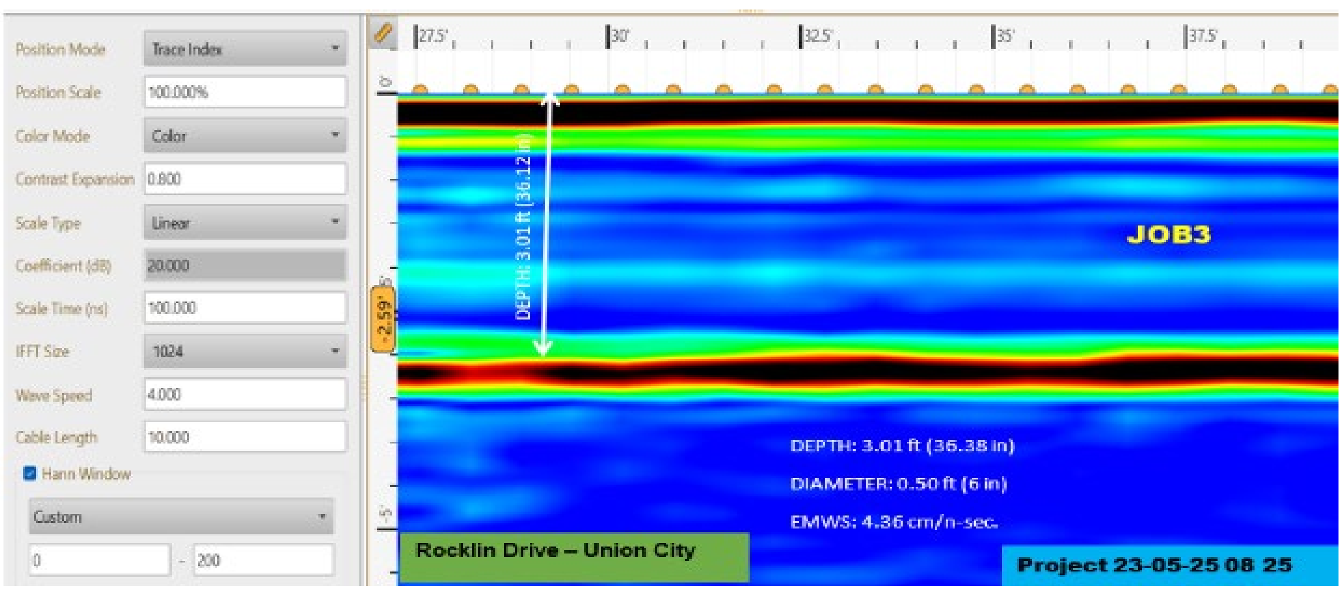
Source: Bakhtar Research and Engineering

Figure 41: Projection of Scan Paths on Google Map

Source: Bakhtar Research and Engineering

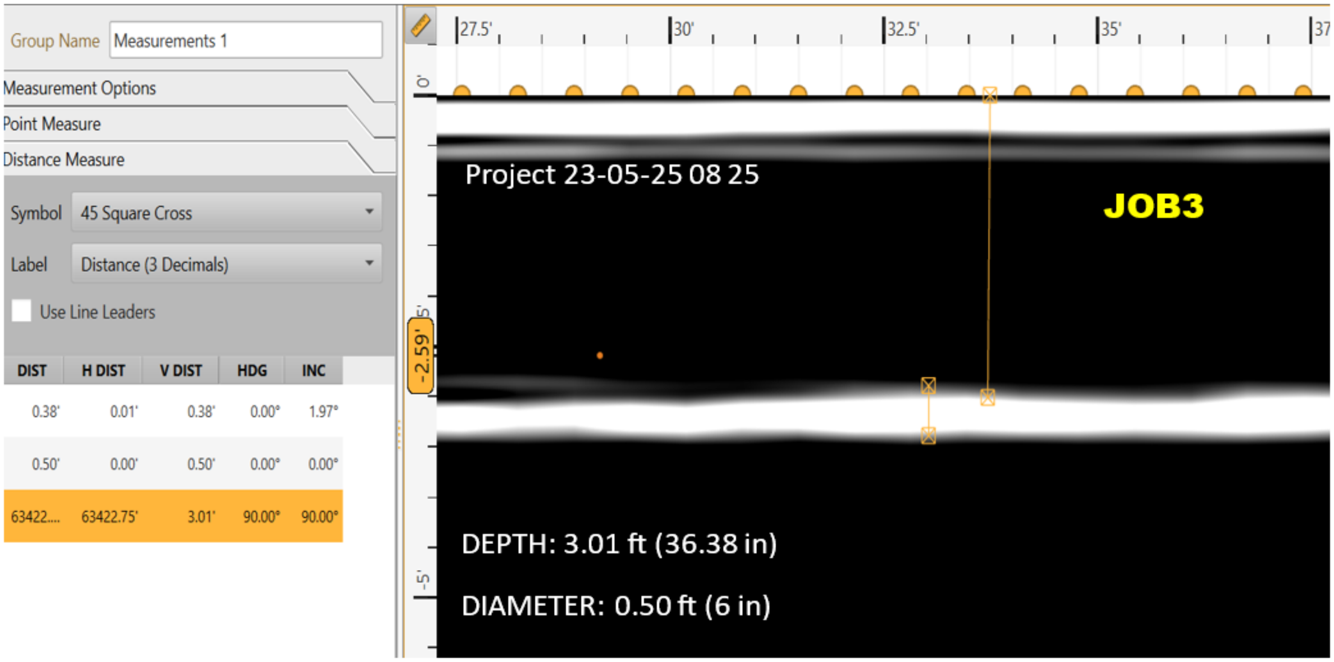
A buried pipeline was detected from data collected and stored in file JOB3. The CE and TV parameters at the incipient of detection revealed values much more than 0.80 indicative of the detected pipe being made up of plastic material. Tomographic cross-sections of detected buried plastic pipeline in color and threshold formats are shown in Figures 42 and 43. From these profiles, the diameter and depth of buried plastic pipeline were measured to be 6.00 and 36.38 inches, respectively.

Figure 42: Tomographic Profiles (Cross-Sections) of Detected Buried Plastic Pipeline in Color Format at Rocklin Drive Union City



Source: Bakhtar Research and Engineering

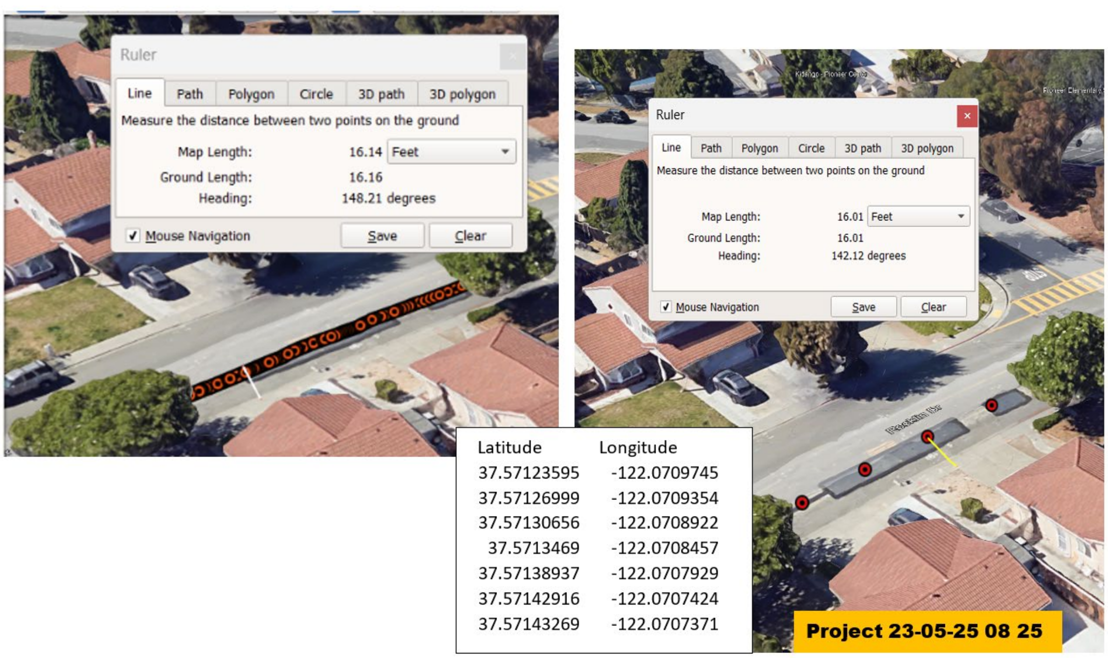
Figure 43: Tomographic Profiles (Cross-Sections) of Detected Buried Plastic Pipeline in Threshold Format at Rocklin Drive Union City



Source: Bakhtar Research and Engineering

The surface footprint of the detected plastic pipeline on Rocklin Drive in Union City was used to measure its distance from the sidewalk curb on a Google map. This was measured to be 16.10 feet to 16.16 feet as illustrated in Figure 44.

Figure 44: Measured Surface Footprint of Buried Pipeline from the Curb at Rocklin Drive Union City



Tamarack Drive, Union City: the test bed, for first and last scans, are shown in Figures 45 and 46. Data was collected 12 runs using the BPD. This included seven longitudinal and five cross-scans (runs). Tamarack Drive test bed constituted of a very steep slope and, based on the quick survey performed at the site, the slope was measured to be 8 degrees over the interrogation distance of 162.69 feet. The BPD data was collected along the positive slope (going up the steep hill at the subject site). This was done to have better control over the constant movement of the BPD assembly.

Figure 45: Tamarack Drive Union City Testbed

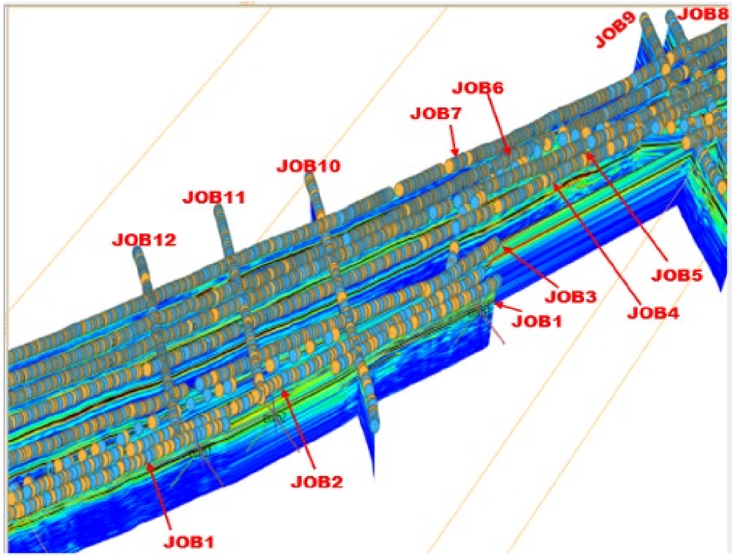
Figure 46: Last Longitudinal Scan (JOB7)

Source: Bakhtar Research and Engineering

The longitudinal scans started from the curb side and moved laterally with overlaps to the center of the street on Tamarack Drive. Below the grade, street asphalt cover, many discrete and continuous anomalies comprising of metallic and non-metallic objects as well as potential power line with high intensity signatures were observed at various depths and orientations. From data collected and stored in JOB1 file (closest to the curb side) to JOB3 a metallic pipeline was detected in JOB2.

Paths of interrogations for the twelve scans (runs) completed at the subject site are depicted in Figure 47. Blue and yellow circles in Figure 47 refer to the surface footprints of the *BakhtarRadar* traces and GPS coordinates, respectively. A Google map with projections of paths of interrogation followed for detection of buried pipeline at Tamarack Drive Union City is shown in Figure 48.

Figure 47: Paths of Interrogations in Union City Union City



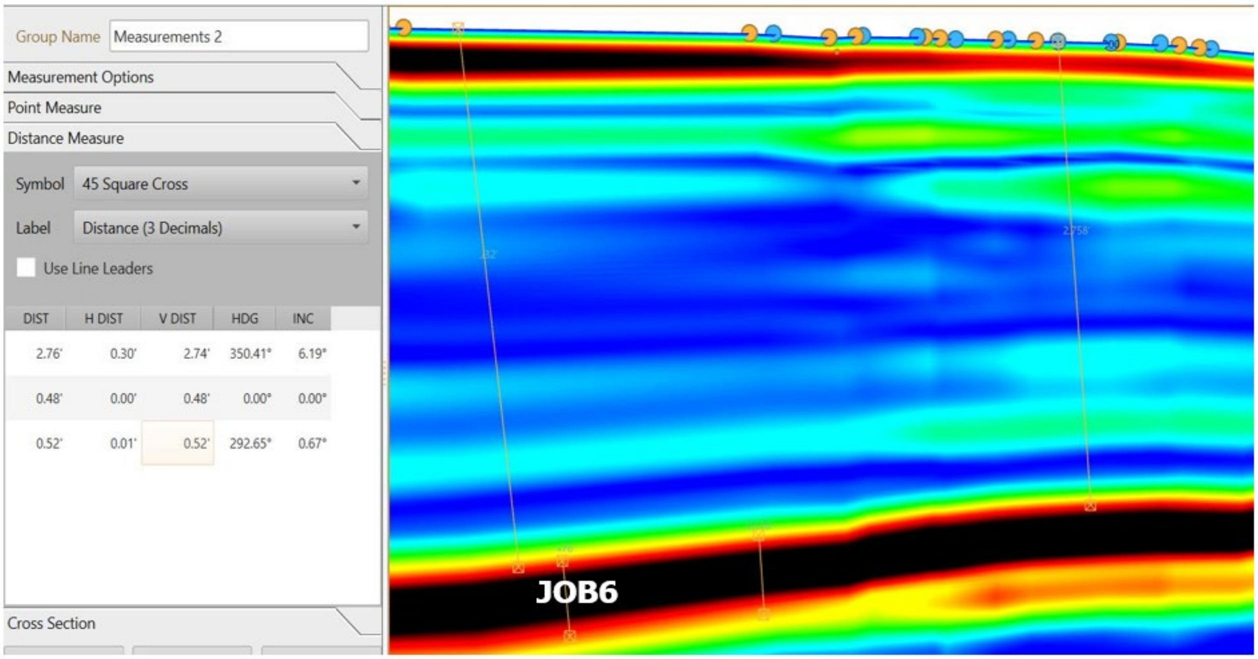
Source: Bakhtar Research and Engineering

Figure 48: Projections of Field Data on Google Map

Source: Bakhtar Research and Engineering

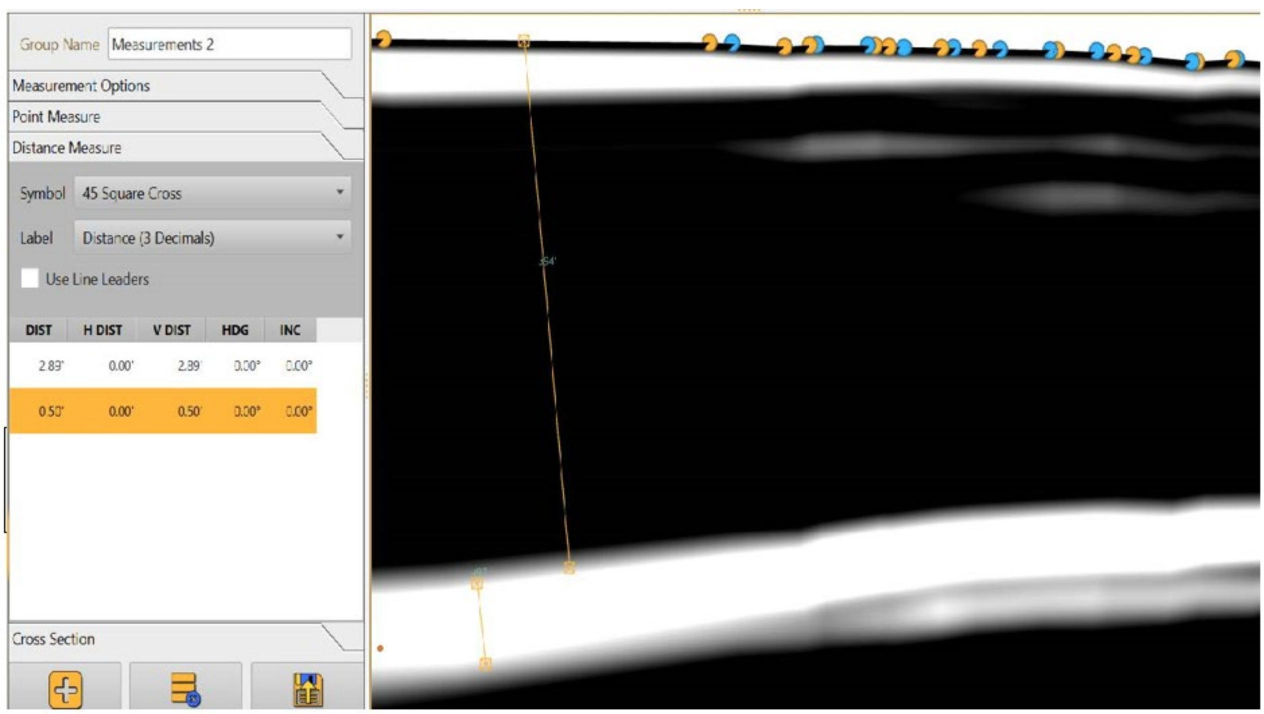
Data collected in the seven longitudinal scans (JOB1 to JOB7) were examined for detection of buried plastic pipelines by selecting CE and TV above 0.999 and adjusted down until the buried plastic pipe tomographic profiles were fully discerned at values around 0.856. Figures 49 and 50 show the tomographic profiles of detected plastic pipeline in color and threshold formats (JOB6). From these profiles the diameter and depth of detected buried pipeline were measured to be 6.00 and 33.33 inches, respectively. Eight locations along the sixth longitudinal scan were selected with their GPS coordinates projected on a Google Map as shown in Figure 51. From the Google map in Figure 51, the distance from the surface footprints of the buried plastic pipeline to the curb was measured to be 8.93 feet to 9.20 feet.

Figure 49: Tomographic Profiles of Plastic Pipeline Detected from Data Extracted from File JOB6 at Tamarack Drive Union City in Color Format



Source: Bakhtar Research and Engineering

Figure 50: Tomographic Profiles of Plastic Pipeline Detected from Data Extracted from File JOB6 at Tamarack Drive Union City in Threshold Format



Source: Bakhtar Research and Engineering

Figure 51: Distance from Curbs to Surface Footprints of Buried Plastic Pipeline Averaging 9.0 Feet Tamarack Drive Union City

Latitude	Longitude
37.61047586	-122.02022
37.61045586	-122.0201381
37.61043822	-122.0200701
37.61041574	-122.0199859
37.61039141	-122.019891
37.61036837	-122.0198094
37.61034032	-122.019722
37.61032316	-122.019672

Source: Bakhtar Research and Engineering

Summary of Blind Test Results

The results of the blind field tests at the PG&E Training Academy in Winters proved close matches between data collected using BPD and those maintained at the PG&E records. This is evident from Figures 15, 18, and 20 for the GPS coordinates and tomographic profiles plots for the type, depths, and diameters of detected buried pipelines reported in Figures 14, 17, 19, 21, and 22. Deviation of 1.5 ft shown in Figure 15 is attributed to the error of measurement performed by PG&E as indicated by the PG&E personnel or offset at these locations due to unforeseen effects.

Table 1 describes the measurement accuracy based on blind tests reported. Overall results of the Bay Area blind tests are presented in Table 2. Table 3 presents the data extracted from PG&E records for the same test sites. Table 4 presents comparison of the field data with PG&E records. The differences between the results of field tests using BPD and those from PG&E records appeared to be negligible.

Table 1: Measurements Accuracy of BPD

Measurements	Accuracy
Pipeline material (Metallic/plastic)	100 percent
Pipeline diameter	0 – 1 inch
Pipeline depth	0 – 5 inches
Pipeline horizontal location	0 – 11 inches

Source: Bakhtar Research and Engineering

Table 2: Results of Blind Field Tests Using the BPD

Demonstration Site	Total Length of Pipe Located	Total Number of Traces Collected	Pipe Material	Pipe Diameter (in)	Pipe Depth (in)	Distance from Curb (ft)
East Shore Drive Alameda (Project 23-05-24 08 22)	100 ft.	172	Metallic	2.01	36.36	6.23
Ravens Cove Lane Alameda (Project 123-05-24 12 43)	100 ft.	166	Plastic	4	33	2.69
Rocklin Drive Union City (Project 23-05-25 08025)	100 ft.	180	Plastic	6	36	16.12
Tamarack Drive Union City (Project 23-05-25 10 04)	100 ft.	405	Plastic	6	33	8.93

Source: Bakhtar Research and Engineering

Table 3: Buried Pipeline Data Extracted from PG&E Records

Demonstration Site	Total Length of Pipe Located	Total Number of Traces Collected	Pipe Material	Pipe Diameter (in)	Pipe Depth (in)	Distance from Curb (ft)
East Shore Drive Alameda	N/A	N/A	Metallic	2	36	6.5
Ravens Cove Lane Alameda	N/A	N/A	Plastic	4	33	----
Rocklin Drive Union City	N/A	N/A	Plastic	6	36	16
Tamarack Drive Union City	N/A	N/A	Plastic	6	33	9

Source: Bakhtar Research and Engineering

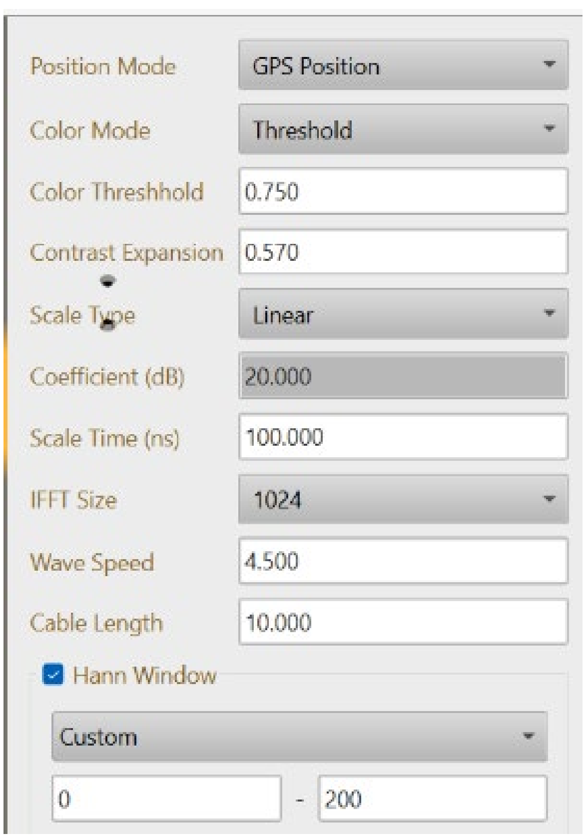
Table 4: Comparison of Field Results With PG&E Records

Demonstra-tion Site	Pipe Material	Pipe Diameter (in)	Depth Located (in)	PG&E Records		Diameter Differential (in)	Depth Differential (in)	Horizontal Distance Differential (in)
				Pipe Diameter (in)	Pipe Depth (in)			
East Shore Drive Alameda	Metallic	2.01	36.36	2	36	0.02 -0.16	0.02 – 5.28	3.6
Ravens Cove Lane Alameda	Plastic	4.00	33.00	4	33	0.18 – 0.20	0.16 – 0.56	10
Rocklin Drive Union City	Plastic	6.00	36.00	6	36	0.12 – 0.20	0.12 – 0.76	2
Tamarack Drive Union City	Plastic	6.00	33.00	6	33	0.01 – 0.36	0.10 – 0.12	3.12

Source: Bakhtar Research and Engineering

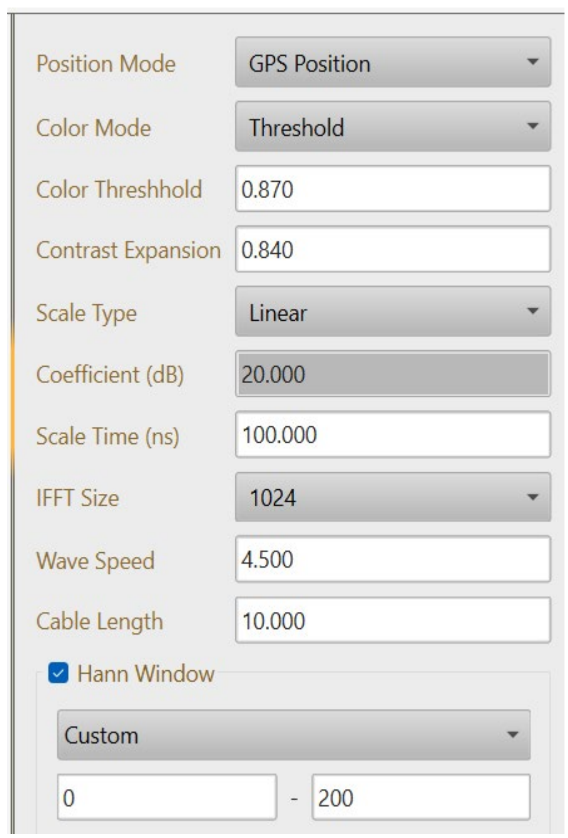
It should be emphasized that the buried metallic pipes were detected at the CE and TV values set to below 0.800 as shown in Figure 52. The buried plastic pipes were detected at the CE and TV values above 0.800 as illustrated in Figure 53. The test parameters are explained in greater detail in the User Manual listed under Project Deliverables section of this report.

Figure 52: CE and TV for Metallic Pipe Detection



Source: Bakhtar Research and Engineering

Figure 53: CE and TV for Plastic Pipe Detection



Source: Bakhtar Research and Engineering

CHAPTER 4: Conclusions and Recommendations

Conclusions

Based on the results of field investigations, it is evident that the detection and discrimination capability of the BPD device is dependent on the forced resonating (FR) antennae performance defined by their operating frequency band (Δf). Experience gained by testing at different sites indicated that most of the shallow buried gas pipes at depths from few inches to down to 5 feet can best be detected and identified within operating frequency band (Δf) of 400 megahertz (MHz) ($\Delta f = f_{FINAL} - f_{INITIAL}$ = 600 MHz - 200 MHz = 400 MHz). Outside this range ground characterization should be conducted to determine the most appropriate frequency band of operation. Two types of FR antennae were developed, namely dipole and horn antennae, and their performances were verified in the field. The former is best to be used for detection and discrimination of the main buried gas pipelines and the latter for service lines.

Results of laboratory investigations using the Earth Simulator shown in Figure 1 coupled with field testing in southern and northern California provided general information on the geologic settings hosting buried pipelines. The test beds are typically made up of clay and sand with occasional rock fragments and small gravels within depths of interest for buried gas pipeline investigations. The round rock pieces combined with gravel are cemented with clay typical of alluvial soil that has been formed from material transported by action (stream) of water. Level of accuracy on measuring the depth of buried gas pipes is very much dependent on Electro-magnetic Wave Speed (EMWS) through the volume of earth being investigated (testbed). Experience gained during the research period revealed that the electromagnetic wave speed (EMWS) varied from 3.34 cm/nanosecond to 4.45 cm/nanosecond depending on the moisture content of the soil and proximity to the water table. Still, by setting the EMWS to 4.35 cm/ nanoseconds with operating frequency band of 400 MHz, that is, $\Delta f = f_{FINAL} - f_{INITIAL} = 600 - 200 = 400$ MHz, depth measurement can be made with high accuracy (below 5 inches). It should be mentioned that much enhancement in estimating the depth of burial for the gas pipelines at a given site can be made if the BPD FR antennae are calibrated with a buried target of known depth (elevation) at a test site. Lastly, although the impact of EMWS can be severe in-depth detection, it does not significantly affect the ability for the pipe diameter measurements. Furthermore, on-site EMWS can also be performed for test beds that may appear to have a complex geologic feature.

The BPD device with its integrated high resolution RTK GPS is capable of detecting buried gas pipelines. Results of field testing proved that the BPD is capable of determining the buried pipeline material type with 100 percent accuracy, diameter with 0.01- to 0.36-inch accuracy, pipe horizontal location with 2 to 10 inch accuracy, and depth with 0.02 to 5.28 inch accuracy as indicated in Table 4. With connection to the AT&T cellular network the GPS position was improved to be within 1 inch of accuracy. Overall evaluation of field investigations revealed that the subsurface pipelines (main lines, metallic and plastic) detected were from 2 inches to 6 inches in diameter buried within depths of 27 inches to 38 inches. Furthermore, at the incipient of detection buried metallic pipes can be detected at CE and TV values less than 0.800 and those made up with plastic material at CE and TV values above 0.800 (Figures 52 and 53).

The spacing of antennae dictates the swath of interrogation. The GPS antennae measure the local coordinates at the center of the swath. The larger the spacing the more real estate is covered during the interrogation. To compensate for increased spacings cross-scans are made as illustrated in Figures 30 and 31 The intersections of the longitudinal tomographic profiles (cross-sections) and that of cross-scans provide accurate GPS coordinates for the buried pipeline location identification.

The BPD benefits gas ratepayers in several ways, which include but are not limited to:

- Detect and locate buried plastic and metallic pipelines with the ability to differentiate between plastic and metallic pipe materials.
- Detect buried pipelines in adverse geologic settings, that is, clay rich soil with high moisture content, without being affected by characteristics of the cover material, including soil, concrete, asphalt, steel plates, etc.
- Generate employment opportunities for low-income and disadvantaged communities in California. This is facilitated by hiring operators for deployment of multiple units of the BPD to assist in location identification and discrimination of buried pipelines for repairs and replacements.
- Assist the construction companies to locate buried gas pipelines in advance of excavation to prevent catastrophic incidents from taking place in cases of excavation-induced damages to buried gas pipelines.
- Reduce costs from buried pipeline damage by at least 50 percent or more.

Recommendations

Based on the above conclusions the following recommendations are made for effective application and further improvement of the BPD:

- Deploy FR dipole antenna for detection of buried main (delivery) pipeline.
- Deploy horn antennae for detection of buried service lines.
- Select operating bandwidth at 400 MHz.
- Set GPS base by selecting:
    - Cellular network if accessible.
    - U.S. Geological Survey monument if no cellular network.
    - Any known coordinates within the area of investigation.
    - Arbitrary coordinates (Easting, Northing, Elevation).
- Adjust CE and TV values in the View Option menu to below 0.800 to detect buried metallic pipeline.

- Adjust CE and TV values in the View Option menu to above 0.800 to detect buried plastic pipeline.
- Use a wider spacing for mounting FR antennae to the polyethylene skid to cover more area to reduce operating cost and labor time.
- Use more cross-scan intersections with the longitudinal scan to accurately measure the surface footprints of GPS coordinates of the buried pipelines as illustrated in Figures 27 and 28.
- Reduce the physical size of the BPD by investing in new VNA and power supplies as faster processors become available in the market.
- Consider developing a hand-operated BPD with integrated horn and GPS antennae for service line detections.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
A-to-D	Analog-To-Digital
BPD	Bakhtar Pipe Detector
CAM	Commission Agreement Manager
CE	Contrast Expansion
CEC	California Energy Commission
CGA	Common Ground Alliance
CPR	Critical Project Review
CPUC	California Public Utilities Commission
dB	Decibel
dBm	Decibel Milli-Watt
EM	Electromagnetic
EMWS	Electromagnetic Wave Speed
FR	Forced Resonance
FRI	Forced Resonance-Imaging
GPR	Ground Penetrating Radar
GPS	Global Positioning System
IF	Intermediate Frequency
IFFT	Inverse Fast Fourier Transform
LAT/LONG	Latitude/Longitude
MHz	Megahertz
Ns	Nanoseconds
PG&E	Pacific Gas and Electric Company
RTK	Real-time Kinematic
SBIR	Small Business Innovative Research
SBW	Sample Bandwidth
TL	Transmission Lines
TV	Threshold Value
VNA	Vector Network Analyzer

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Project Deliverables

The following technical reports were prepared and submitted to the CAM during the course of the agreement under Tasks 2 to 7.

TASK-2

- Field Test Plan
- Preliminary Field Test Results Report

TASK-3

- Reports on Support and Motorized Platforms
- Diagnostic Software Report

TASK-4

- Antennae Design, Construction and Performance Assessment Report

TASK-5

- User Manual

TASK-6

- Software Report

TASK-7

- Configuration and Validation Report
- Field Demonstration Plan
- Field Demonstration Report

CALIFORNIA ENERGY COMMISSION

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Ranges and Values for Digital Filters and Test Parameters for the BPD

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APPENDIX A:
Ranges and Values for Digital Filters and Test Parameters for the BPD

Sweep Setup Parameters: These parameters are designed for determining how the signal is generated by the Vector Network Analyzer (VNA).

Initial freq.: This is the initial sweep frequency of transmission. The unit is MHz. The Vector Network Analyzer (VNA) starts transmitting at this frequency at each sweep.

Final freq.: Refers to frequency to complete one sweep of transmission. The unit is MHz. The Vector Network Analyzer (VNA) completes the sweep cycle at this frequency. The difference between the Final freq. and Initial freq. is the operating frequency bandwidth (∆f), where ∆f = [(Final freq.) – (Initial freq.)]. Example if the Initial freq. is 1500 MHz and Final freq. is 1900 MHz then the operating frequency bandwidth is 400 MHz (∆f = 400 MHz).

Frequency steps: This is the number of frequency steps / data points in the transmitted signal. The choices are 51, 101, and 201, although other numbers can be chosen depending on the SETUP parameters and VNA power. For a given operating frequency bandwidth (∆f), the larger the steps are the finer the resolution and the higher the memory usage.

Sample bandwidth: This is the acronym for sample bandwidth. It refers to the intermediate frequency (IF) of the vector network analyzer (VNA). The unit is Hz. The reflected/received signal gets converted to this frequency for internal processing. The choices are 30, 300, and 1000.

Power: Refers to the power of the signal generated by the VNA. The unit is dBm. The power must be less than 10 dBm.

Analyzer: ROHDE & SCHWARZ, Model ZNL Vector Network Analyzer are to be deployed for the subject project prototype unit(s).

Display Setup Parameters: These parameters determine how the acquired signal are plotted in acquisition window for near real-time detection and discrimination.

Plot type: This control specifies the type (format) of plotting to be performed. There are four options to choose from: Color, Grayscale, and Threshold. The color map consists of 40 different colors. In the Grayscale option data points are mapped to gray colors. The color map fort this scheme consists of 15 different shades of gray. In the threshold option data values are mapped to either "white" or "black" colors based on signal magnitude.

IFFT array size: This refers to the length of array holding the Inverse Fast Fourier Transforms of the signal. The value can be set to either 512 or 1024.

Display time: The portion of the total signal, in nanoseconds, that is displayed on the ACQUISITION plot window. The value is used with the "electromagnetic wave speed" (EMWS) to determine the maximum distance / depth for the received signal.

Trace/screen: This parameter determines how many individual traces are plotted in the ACQUISITION plot window per screen.

Cable Length: The signal must pass through the cable, also called transmission line or TL, connecting the antennae (loads) and the Vector Network Analyzer (VNA). Specifying the cable length allows BPD to compute the contribution of the radiation effects associated with a given length of TL from the input data and make the necessary adjustments to account for associated energy losses. Specification of length in VIEW Window overrides value specified in REPLAY Window.

Initial trace: The user can enter any value here to start plotting from later trace than trace zero. Specification in View Option Window overrides value specified in REPLAY Window.

Wave speed: The wave speed (electromagnetic wave speed) is used to calculate the depth / distance, in centimeters, for REPLAY Window. The wave speed should be entered in centimeter per nanoseconds [(cm)/(nanoseconds)].

Von haan window These parameters determine how the von Haan window (a window function for signal or image filtering using a fast Fourier transform) is applied. The von haan window is used for reducing the Gibbs effect (the phenomenon that the discontinuous nature of the ideal low pass filter causes ringing to occur in the filtered output). It is a type of window function used in signal processing and digital signal analysis. Window functions are applied to data sequences to reduce the effects of spectral leakage when performing IFFT (Gibbs effect).

Initial freq. Refers to the initial frequency of the **von haan filter**.

Final freq. Refers to the final frequency of the **von haan filter**.

HannWin Clicking on this button displays a plot on the panel showing the shape and range of the von hann window determined by the start and stop frequencies. The plot shows frequency in MHz along the abscissa, and ratio of signal passing among the ordinate.

Scaling function Parameters These parameters determine how Scaling function is to be applied.

Scale Coeff.	Amount of downscaling applied to the transmitted signal to affect an amplification of the reflected signal of interest, in decibel (dB). Reference should be made to the REPLAY window for more detailed description.
Scale time	Amount of time over which scaling is applied in nanoseconds (ns). Reference should be made to the REPLAY window for more detailed description.
Scale	Clicking on this button displays the scaling function determined by **Scale coefficient** and **Scale time**.
Signal averaging	First item under Averaging function is the selection of the type of averaging function to be applied to the signal: **subtract**, **smooth**, and **subtract and smooth**. Specification in SETUP overrides value specified in the Hotkey Setup window item associated with REPLAY.
Average coeff.	The descriptor is the intensity of the averaging coefficient specified in trace operations of the REPLAY window. Specification in SETUP overrides value specified in the Hotkey Setup window item associated with REPLAY.
Average	Clicking on this button displays the shape of the weighting function applied to the first ten traces of the signal.
Save parameters as default	After setting all the parameters the user should click on this button to save the parameter values specified in the SETUP window.
Contrast Expansion:	This coefficient determines how the color plot is for different signal strength. Increasing the contrast value makes the color lighter, that is, it shifts it toward blue color, and decreasing the contrast makes the color stronger, that is, it shifts it toward the red color.
Threshold Value:	This parameter determines how much of the target (buried pipe) is to be shown and how much the noise is to be suppressed. Increasing the threshold value makes weak signal disappear, while decreasing the threshold value makes weak signal appear in the screen.
Begin Depth & End Depth:	These controls are used to display a user-determined range of signal depth. The part of the target (buried pipe) that lies within this range is shown in the acquisition window. These controls are of paramount importance for near real-time display of pipeline location in the field.