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CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

3D Visualization Software for Mapping Underground Pipelines and Improving Pipeline Asset Management

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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

3D Visualization Software for Mapping Underground Pipelines and Improving Pipeline Asset Management is the final report for Contract Number PIR-19-018 conducted by GTI Energy. 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

Under a contract awarded by the California Energy Commission and co-funded by Operations Technology Development, LLC, GTI Energy was tasked with creating a software system that integrates multiple data sources while delivering data visualizations and insights in near real time.

The software system allows the utility to locate personnel to collect attributes for underground utility infrastructure, store these collections in a geographic information system database, and visualize the results in two-dimensional and three-dimensional environments.

The goals for the project focused on evaluating existing electromagnetic and ground penetrating radar utility locate devices, data collection workflows for mapping underground pipelines with improved accuracy, and making available additional datasets that provide added value to a field operator conducting locates. These resources are visible to the operator in the field and office-side staff.

Keywords: natural gas infrastructure, underground pipelines, utility locate practices, real-time locate information, digital mapping, asset management, GIS

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Background

Inaccurate or insufficient locating practices are a leading cause of injuries and a primary contributor to excavation damage costs incurred each year. Additionally, there are potential environmental impacts to consider, as pipeline damage may result in natural gas leaks, increasing the likelihood of greenhouse gas emissions. A system that collects, stores, and displays more precise locations of buried natural gas infrastructure and assets would benefit gas utility operators and the general public.

The solution developed in this project seeks to improve the safety and integrity of underground natural gas infrastructure by increasing the accuracy and availability of horizontal and vertical pipeline location information. More accurate locate results will help prevent instances where the root cause is inaccurate locate markings or insufficient locate practices. As such, the California Energy Commission's clean energy and climate goals are supported through the potential to reduce future excavation incidents and subsequent emission releases into the environment.

Project Purpose and Approach

GTI Energy produced a field-based software technology platform to provide locate equipment operators real-time access to site condition information. The software solution integrates communications between utility locate devices, high-accuracy global navigation satellite system receivers, and a cloud-based storage solution to collect, store, and map locate points in both two-dimensional (2D) and three-dimensional (3D) visualization environments. Through the real-time acquisition, processing, and analysis of locate information integrated with the visualization software tool afforded by this solution, operators may leverage enhanced mapping capabilities to more effectively manage their underground pipeline assets.

GTI Energy leveraged a task-based approach integrated with a structured software development methodology to accomplish the goals and objectives of the project. Two primary considerations for adopting this approach were to maximize system reliability and effective operation, given the many integrated components involved. To maximize the value to locate personnel and utility operators, GTI Energy initiated project activities by performing a comprehensive review of the utility locate industry. This entailed identifying the most useful data sources to support utility locate personnel and evaluating several locate devices, assessing their capability to communicate with the software platform. To ensure the reliability and efficient operation of the system, the team leveraged industry-standard modeling techniques to define all tools, functionality, workflows, and 3D visualization application requirements. Additionally, a rigorously planned software system testing task was used to ensure that all tools and functions designed during the requirements phase were integrated and functioning properly prior to field testing. An extensive pilot demonstration effort was executed to validate the complete system functioning and ease-of-use in real-world settings, including locating devices, systems communications, software application functionality, and database storage and retrieval.

Key Results

This project successfully designed, developed, and tested a field-based application to collect, store, and visualize underground gas infrastructure location information. The application currently runs on Windows and allows utility locate personnel to gather and store field-collected utility locates (gas, water, sewer, etc.) in a digital format. Newly captured locate information is displayed alongside existing data and is available to field and office-based staff in real time. Users may toggle between 2D and 3D map views to visualize utilities from either an above- or below-ground perspective. Additionally, users may perform queries to retrieve valuable site information and enter unique site conditions. The end-to-end testing of the system highlighted the following key results.

1. Overall, the high-accuracy (defined as geolocations within a foot of those established by proven methods) data collection system performs as designed. The level of precision and accuracy of the collected data depends on a wide range of factors, including the hardware used (for example, the specifications of the Global Navigation Satellite System [GNSS] receiver), situational conditions and circumstances (for example, distance from the real-time kinematic base station, pipe tracer wire proximity to its optimal location relative to its associated pipe), and operator technique (how carefully it is confirmed that the GNSS receiver has an real-time kinematic fix when data collecting). These factors collectively impact the overall accuracy of pipe location data.
2. The system operates via a straightforward workflow that links the locate device and the field tablet via Bluetooth, streams locate information from the device to the tablet, and submits that information and additional manually entered information over a cellular network to a cloud server database.
3. System testing at GTI Energy's pipe farm in Des Plaines, Illinois, was successfully executed. For the electromagnetic device tests, average horizontal accuracy values were reported as ranging from two inches to six inches across two-inch, four-inch, and eight-inch pipes and from two inches to four inches in the vertical direction. For the ground penetrating radar device test on four-inch pipe, the horizontal direction accuracy was approximately one-and-a-half-inch with approximately a fourteen-inch differential in the vertical direction. Most importantly, the software and utility devices performed as expected and validated the application's readiness for field pilot demonstrations.
4. A six-month pilot demonstration with Pacific Gas and Electric Company and Southern California Gas Company was conducted across 14 California cities. By the pilot's completion, more than two miles of underground gas lines were located via a combination of electromagnetic and ground penetrating radar devices, encompassing various soil types and pipe materials and sizes. Evaluating the application in a real-

world setting provided invaluable insights regarding system performance, operator feedback, and improvement opportunities.

Knowledge Transfer and Next Steps

GTI Energy interfaced with industry operators through interactions with Operations Technology Development organizations. Operations Technology Development, LLC, is a research consortium of gas utilities that provided additional financial support for this project. Two member organizations, Southern California Gas Company and Pacific Gas and Electric Company, were integral pilot demonstration partners, offering subject matter expertise and feedback for all facets of the application platform. Operations Technology Development sponsor organizations were kept apprised of project activities via quarterly progress reports, while updates were provided to the CEC monthly.

The project team performed a number of outreach events aimed at sharing project information and fostering awareness and adoption of the system. Efforts occurred in the form of conference presentations, trade journal publications, and workshop execution. The infrastructure management and geographic information system communities were communicated to via a presentation at the 2022 Esri Infrastructure Management and GIS (IMGIS) Conference. Additional outreach occurred via publication of a project case study in a trade journal of the North American Society for Trenchless Technology. Furthermore, software demonstration workshops were conducted with the operator pilot demonstration partners.

Two models for turning the prototype software application into a product for regular use are identified here from the many models available. One model involves tailoring the application for use by a single entity, such as a utility company or a company that specializes in locating. A second model would be as an offering from a service provider for use by other organizations. The service provider could provide the necessary components for a one-time transaction fee for customers to take and use. An alternative to this second approach may be more representative of the software as a service model, where a provider could furnish some resources up front (for example, some or all of the hardware and perhaps the field software) while charging for ongoing services (for example, cloud services).

CHAPTER 1: Introduction

The state of utility locate practices for underground infrastructure has been centered on utilizing the proper tools to locate a pipe, followed by an operator painting the ground or inserting a flag where that utility is located. This practice is still essential for informing field crews before excavation activities occur. However, the information conveyed by the flags and paint marks may be comprehended only as long as they remain intact. As paint for marking underground utilities is water-based in nature, it is intended for the temporary identification of utility information. Through locating digitalization, information storage, retrieval, and retention, efficiency is vastly improved over manual processes and the information is available for current and future locating efforts. New enhancements associate geolocation and other information with collected data and allow it to be analyzed, processed, and contextualized for decision-making and other industry purposes.

This project's objective was to leverage the technological advancements in collecting and storing locate data to improve the safety and integrity of underground natural gas pipelines, facilitate present and future work on pipelines, and allow for other activities made possible by the digitization of this data (analytics, reporting, and so on). Key metrics for project success included:

1. Developing and demonstrating a software platform for digitally mapping underground pipelines with better accuracy.
2. Improving pipeline asset management by integrating multiple data sources from multiple proven locating technologies.
3. Aggregating pipeline asset information into a geographic information system (GIS).
4. Visualizing underground natural gas pipelines in two-dimensional (2D) and three-dimensional (3D) formats.

There are multiple user groups that may benefit from the system developed under this project. Furthermore, within natural gas operator organizations alone, there are several stakeholder entities that could make use of this system. For example, field locate staff and back-office supervisors would benefit from accessing current and previously collected locate data to verify job completion success. Operator construction planning functions would benefit from access to current and historical data to conduct preplanning on future build initiatives. Additionally, professional locating firms could benefit by leveraging the increased system functionality to deliver enhanced locating capabilities and services. Locate device manufacturers may also leverage the system to better understand how to design future devices to optimize the digital locate business function.

To ensure a high likelihood of system adoption among the end user community, it is necessary to identify key acceptance factors. Some key factors include the need for the system to: be relatively straightforward to operate, minimize complexity from the introduction of new components, and realize effort levels on a par with existing field locating processes. Additionally, sufficient training resources must be readily available for end user knowledge transfer, and the system must be sufficiently flexible to accommodate different locating devices.

There are a number of safety, environmental, and economic benefits to be realized by the application developed in this project. Regarding safety, this technology's 3D visualization component provides the ability to see where assets are in space and in relation to each other, thereby fostering cooperation among utility companies and making unsafe construction decisions and actions less likely. Having readily available and accurate information about pipeline locations has positive environmental impacts in the form of potential reductions in emission releases caused by dig-ins, as well as reduced site revisits due to the availability of digitally stored asset information. Cost reduction benefits may be realized through: the streamlined workflows that data digitalization affords, excavation damage cost avoidance through accurate asset locations, and labor hour reductions from diminished repetitive site surveys and revisits.

Under this project, GTI Energy worked to uncover the state of the art for utility locating and enhance it by digitalizing and adding 3D visualizations. Leveraging organizational knowledge, vendor outreach, and development staff, GTI Energy reviewed the current electromagnetic and ground penetrating radar (GPR) locate tools on the market and their data transmission protocols to understand how these tools collect, store, and transmit utility locate information using various methods (Bluetooth, USB, cellular, and so on). This vital information became the basis for designing and developing a primarily field-based software application with multiple functionalities to address how users see existing utilities before starting the utility locate, followed by various workflows to address the numerous states in which collected data can be mapped and stored in 2D and 3D formats within a GIS cloud database.

Upon the locate devices review completion, GTI Energy purchased two electromagnetic handheld devices and one GPR device to meet the project's needs and to form the basis of how these tools could communicate with the software application being developed. One goal was to use Bluetooth communications for passing information from the locate device to the software application in real time. Examples of transmitted information include depth of cover, frequency or current rate of change, gain or receiver sensitivity, and current or electron flow rate past a given point. An additional goal was to use that information paired with high-accuracy location information from Global Navigation Satellite System (GNSS) receivers to map and store this data as 2D and 3D points and line features in a cloud server GIS database. An effort was also made to design functionality for uploading locate data stored on locate devices (as opposed to being streamed over Bluetooth), to accommodate the need for mapping and visualizing data that may have been collected sometime in the past but never mapped.

CHAPTER 2: Project Approach

GTI Energy reviewed the current state of utility locate processes to enhance them through the development of a software application that collects and stores digital information about underground assets, displaying it in 2D and 3D. This section reviews the tasks defined in the research project's "Scope of Work," with specific details on how GTI Energy accomplished each activity, generated research results, and designed and constructed the software application used for the pilot demonstrations.

Analyze and Evaluate Participating Locate Data Sources

This section provides details on data sources that would benefit utility locate personnel performing field work and describes the ability of the evaluated locate tools to communicate with the software application built by GTI Energy.

Data sources listed in this document may be either public, private (for example, natural gas utility companies), or potentially from a locator manually entering the data into the software while in the field. Not all data sources listed in this document may be available, and not all may not be necessary to the software application's functions. For this reason, each data source was labeled as essential or nonessential (denoted in Table 1); data was classified as essential if its absence or poor quality would substantially impair the functioning or usefulness of the software, for example, causing output from the software to be incomplete or inaccurate. Should any unavailable data sources become available later, they could be integrated into the software application at that time.

Table 1: Essential and Nonessential Data Sources for Software Application

Data Source Name	Data Source Provider	Essential or Nonessential
Natural Gas Utility GIS Data	Local Distribution Company	Essential
Natural Gas As-built Drawings	Local Distribution Company	Nonessential
Utility Locator Site Reports	Local Distribution Company	Nonessential
Natural Gas Work Maintenance Reports	Local Distribution Company	Nonessential
Natural Gas Project Plans	Local Distribution Company	Nonessential
Municipal Sewer and Water Data	Local Municipalities, Utility Districts	Nonessential
Telecommunications (Fiber-optic) Lines	Telecommunication Companies or Third-party Vendors	Nonessential
Overhead Electric Lines	Local Distribution Company, California Energy Commission	Nonessential

Data Source Name	Data Source Provider	Essential or Nonessential
Underground Electric Lines	Local Distribution Company, Other Electric Utility Providers	Nonessential
TV Cable Lines	TV Cable Providers (AT&T, Xfinity, Other)	Nonessential
Soil Survey Geographic Database (Soils Data)	Natural Resource Conservation Service	Essential
Railroad Lines	United States Census Bureau, Railroad Companies	Nonessential
Building Footprint Data	Microsoft, Local County and Municipalities	Nonessential
Weather Data	National Oceanic and Atmospheric Administration, Earth Network, Aeris Weather	Nonessential

Source: GTI Energy

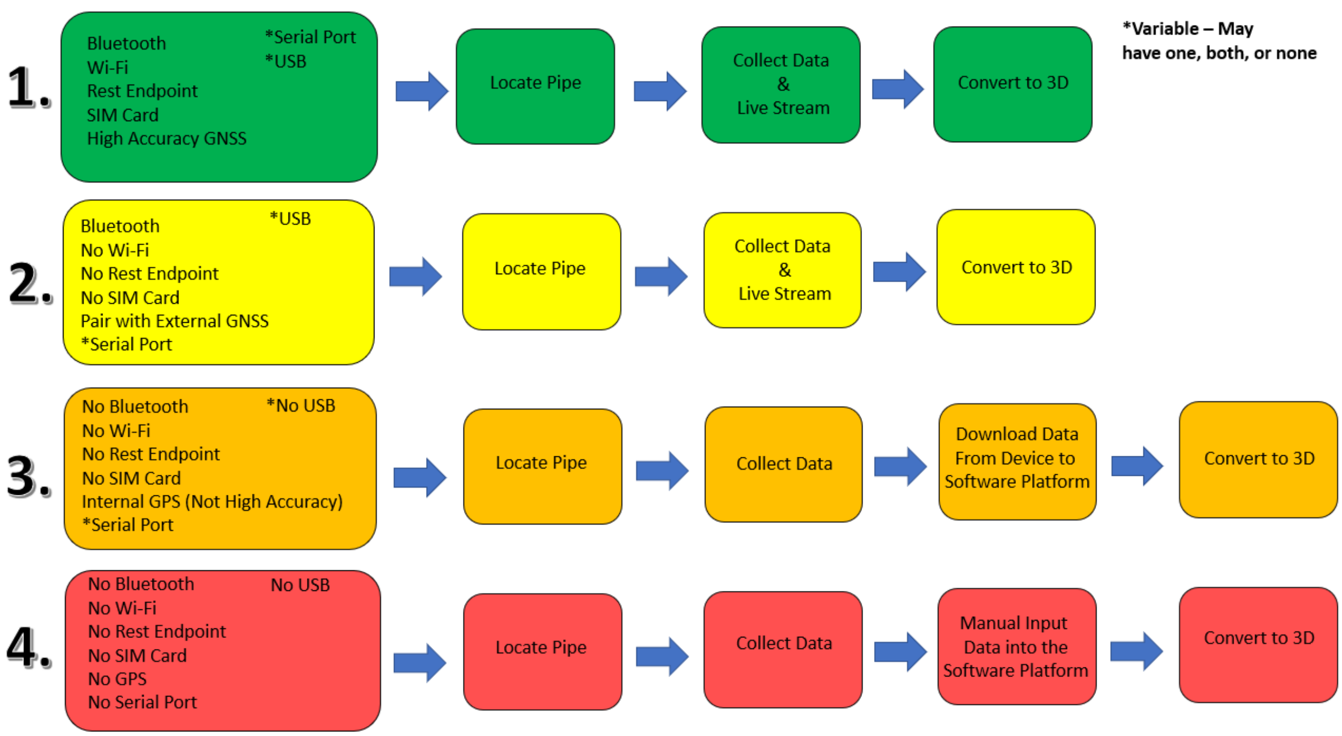
GTI Energy assessed electromagnetic (EM) and GPR locating technologies to identify devices that were amenable to the requirements of the software application. Not all assessments were conducted in person; some were handled through document review of operator's manuals, datasheets, and vendor outreach. Other device information was acquired firsthand, as part of vendor demonstrations at GTI Energy's campus, participation at utility locating conferences, and via usage of GTI Energy-owned devices.

Electromagnetic locational tools came from various resources, including approved device lists from Pacific Gas and Electric Company (PG&E), Southern California Gas Company (SoCalGas), Ameren, GTI Energy, and online research. Each device was evaluated based on its functionalities and capabilities, with significant importance placed on its ability to communicate with other devices (specifically, field tablets) via its communication protocol (specifically, Bluetooth, Wi-Fi, USB, and Serial Port).

In addition to communication protocols, emphasis was placed on the locator's high-accuracy GNSS devices capabilities. Many locate tools either do not have an internal global positioning system (GPS) chip or incorporate a chip that does not produce high-accuracy (specifically, measurement accuracies in the range of feet rather than inches and centimeters). On the other hand, some newer locating devices do incorporate an internal high-accuracy GNSS chip or can pair it with a high-accuracy GNSS receiver to collect more accurate X, Y, and Z values.

Based on the variety of communication protocols within the devices evaluated, GTI Energy ranked each device into four categories, as shown in Figure 1. Category 1 includes the most capable devices, with built-in high-accuracy GNSS, Bluetooth, and cellular SIM cards. In contrast, a device with a category 4 ranking may not have any data transfer option at all (specifically, no Bluetooth, no pairing with a high-accuracy GNSS device, and no USB or serial port connection). GTI Energy documented a workflow for low-level devices in category 4 for users to collect a high-accuracy X, Y, and Z value after the locator detects and marks the pipe. Additional steps in this workflow require the user to manually input the values displayed on the locator's screen into the software application, while collecting the high-accuracy location with a separate GNSS device. Category 2 describes devices that can transmit data in real time, making it possible to combine their data with data transmitted from a GNSS receiver. Category 3 devices cannot be used in tandem with a high-accuracy GNSS receiver but may have an internal GPS chip and some data transfer option via a wired connection. A category not listed in Figure 1 can be labeled as Category 5, which includes devices that did not report depth, a vital attribute for 3D visualization. These devices were not considered for this project.

Figure 1: Data Transmission Protocol Ranking of Select Market Devices (as of 2021)



Source: GTI Energy

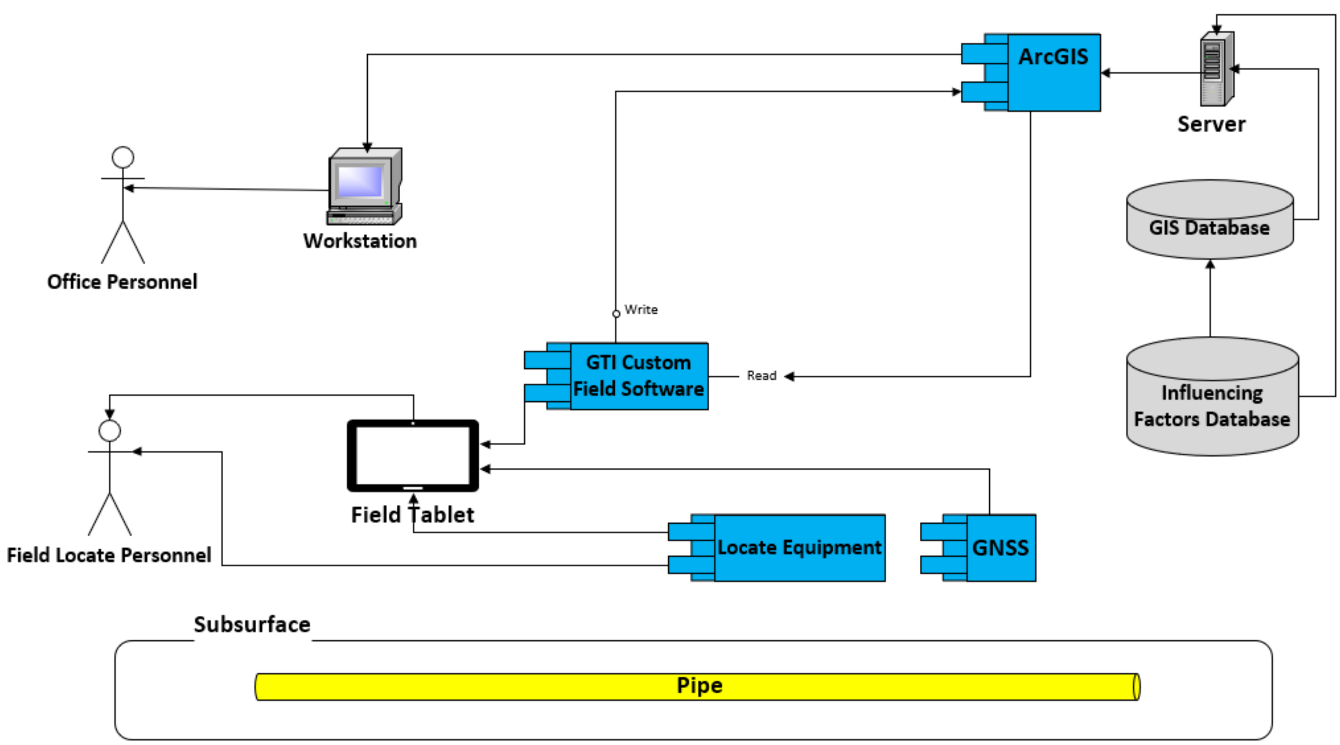
During this evaluation, GTI Energy discussed with PG&E and SoCalGas their experience with specific devices on the list and what devices might be in their future research plans. Two devices showed promise in transferring data in real time and collecting high-accuracy X, Y, and Z data from the electromagnetic locational tools discussed: the vLoc3 RTK-Pro from Vivax-Metrotech and the RD8200G from Radiodetection. For lower-level device testing (categories 3 and 4), the approach was to disable some functionality on the devices listed above to emulate a workflow needed to capture high-accuracy X, Y, and Z values in near real-time for 3D visualization. GPR locational tools were also evaluated through a document review of operators' manuals, datasheets, and vendor outreach.

Software System Requirements and Design

The Software System Requirements and Design task produced six project deliverables (listed in the Project Deliverables section at the end of this report), resulting from activities the project team performed related to system requirements and design. Industry-standard modeling techniques defined by the Business Process Model and Notation standards were employed to capture internal and industry subject matter expert knowledge. The work conducted under system requirements and design outlines current business workflows used in the utility locating process and identifies changes to these standard processes brought on by utilizing the software application developed under this project.

Workflow modeling also aids in the development process by allowing the team to understand what requirements are needed to create an application that will successfully meet the needs of a utility locate end user. The material found in the project deliverables is the culmination of desktop research, a review of locating device operator manuals, and input from GTI Energy and industry subject matter experts. Figure 2 provides an overview of the software application design.

Figure 2: Software Application Design Overview



Source: GTI Energy

All system requirements documents contained in the various project deliverables outline the tools and functionality that the 3D visualization application is required to support. Additionally, these documents were used internally by the development team to guide the creation of tools and functionality required to support existing and modified utility locate workflows. A list of all deliverables for system and design requirements is located in the Project Deliverables section at the end of this report, under Task 3.

Develop Cloud-based and Field-based Software System

The software application developed under this project is a field-based and office-based software system to integrate multiple data sources in one tool and deliver data visualizations of underground utility locates in real time. Most data visualizations are accessible in both a 2D and a 3D format, depending on the source and attributes of the dataset being used. GTI Energy utilized the methodology contained in the *Department of Justice Systems Development Life Cycle Guidance Document* (U.S. Department of Justice, 2003) to gather the requirements for the software development process. To develop this application, the project team leveraged an existing product generated from a previous project designed to aid in field data collection. The application was constructed utilizing Esri's JavaScript API and a Microsoft Azure cloud server set up with ArcGIS Server. The development code was written using Electron, a tool for creating desktop operating system applications using web-development languages and tools, and it was designed for the first release to be deployed on a Windows-based tablet.

During development, the project team employed a task planning approach to identify: specific items to be integrated into the application, bugs encountered during development, and product enhancements for future phases of work. Planned tasks were aligned with the original requirements outlined under the Software System Requirements and Design phase of this project and were scaled for optimal performance.

As tasks were completed, GTI Energy developed an Integration Testing Plan to ensure that all design and functionality requirements were included in the end product for proper software system testing. This integration and testing plan was used for initial testing and to construct a Development Phase Bug Resolution Document, to identify the type of bug found, its severity, the estimated fix date, and the documented eradication path. Additional work performed under the development phase of this project entailed the creation of a Demonstration Site Key Performance Indicators (KPI) Evaluation Plan to track the metrics and performance of the application during pilot demonstrations, as well as a Field-based Testing Workflow and Data Collection Form to help users learn how to use the application and score performance. As designated testers were used to test the field-based workflows, any additional bugs uncovered were documented and tagged for fixing before the re-deployment of the application to the field tablets. This process continued until the application was approved for full software system testing.

Perform Software System Testing

For software system testing, GTI Energy created an Integration Testing Plan to ensure that all tools and functions designed under the requirements phase of this project were integrated into the software and were working properly before extensive on-site field testing. The project team detailed many components and functionalities that the software application needed for optimal performance and to meet the scope of work. Many of these components and functionalities were outlined as individual software and hardware requirements or were included in a workflow diagram detailing how the software application should act in a field or an office setting. The following sections detail the approach, environment, and use cases defined to ensure the application performed as intended.

Approach

New software functionality was developed almost weekly, depending on the complexity, and lightly tested. More rigorous field testing was done once all functions were implemented. The Integration Testing Plan was intended to ensure that the documented requirements and application functionality were aligned and that the testing process would yield successes and potential bugs. It was necessary to periodically revisit the test plan to ensure that all bugs were corrected and the application was ready for pilot project testing.

Test Environment

After application development was completed, the tools and software were tested against a controlled underground piping network at GTI Energy's campus, followed by defect identifying, fixing, and retesting. The pipe farm consists of three sections of 100-foot pipe of various sizes, including 2-inch, 4-inch, and 8-inch sizes. The software application was deployed to a Windows Mesa tablet, where it was used in conjunction with two electromagnetic handheld utility locators, one GPR utility locating device, and a high-accuracy GNSS receiver.

Test Cases

The test cases described in the following sections align with the requirements that were developed under the Software System Requirements and Design task, with a specific focus on the integration of software and system application development under the Software and System Requirements document. Utility locate workflows found in other design documents from the requirements phase were satisfied by ensuring that the software application encompassed the necessary functionality, as laid out in the Software and System Requirements document. It should also be noted that some requirements were added or adjusted throughout this project, based on industry suggestions or constraints on the ability to develop the functionality as initially designed.

Demonstration Equipment

The following subsections detail all hardware, software, and additional field equipment utilized throughout the software system testing and what equipment was selected for use under the pilot demonstration plan. Electromagnetic and ground penetrating radar devices were paired with global navigation satellite systems receivers, and communications between these components and a cloud-based storage solution were successfully established. Most of the hardware and software listed in the following section are categorized into groups called Field Demo Units. Some items from the separate groups may be interchangeable, depending on availability or user preference.

Field Demo Unit 1:

Hardware for this demo unit is shown in Figure 3 and includes:

- Radiodetection RD8200G locator and transmitter.
- EOS Arrow Gold high-accuracy GNSS receiver.
- Survey pole with attachments for holding the GNSS Receiver and Windows tablet.
- Windows Mesa 3 tablet.

Software for this demo unit includes:

- GTI Energy's 3D visualization software installed on the Windows tablet.
- EOS Tools Pro third-party software for connection from the GNSS receiver to a real-time kinematic (RTK) base station.

Figure 3: Field Demo Unit 1

Source: Radiodetection, EOS, Juniper Systems

Field Demo Unit 2:

Hardware for this demo unit is shown in Figure 4 and includes:

- Vivax-Metrotech vLoc3 RTK-Pro locator and transmitter.
- Windows Mesa 3 tablet.

Software for this demo unit includes:

- GTI Energy's 3D visualization software application installed on the Windows tablet.

Figure 4: Field Demo Unit 2

Source: Vivax-Metrotech, Microsoft

Field Demo Unit 3:

Hardware for this demo unit is shown in Figure 5 and includes:

- Leica DSX GPR (ground penetrating radar) device.
- Leica GS18i high-accuracy GNSS receiver.
- Leica Getac Windows tablet.

Software for this demo unit includes:

- GTI Energy's 3D visualization software application installed on the Getac Windows tablet.
- Leica DXplore software application installed on the Getac Windows tablet.

Figure 5: Field Demo Unit 3

Source: Leica

Test Case 1: The Vivax-Metrotech vLoc3 RTK-Pro device was connected to the software application via Bluetooth, the transmitter for the locator was connected to a steel pipe, and a signal was transmitted onto the pipe. The locator was also connected to an RTK base station to receive high-accuracy GNSS data. Various locating points were performed along the pipe(s) in the pipe farm to confirm collection, transmission, and conversion to 2D and 3D features within the application. The appropriate attributes from the locate device or manually entered in the data form were stored with the collected data points.

Included in Test Case 1 were checks for proper Bluetooth connection and data transmission between the locator and the Windows Mesa tablet, establishment of a connection to an RTK base station, and proper storage and rendering of the collected data in 2D and 3D formats.

Test Case 2: The Radiodetection RD8200G device and a separate GNSS receiver were connected to the software application via Bluetooth. A direct connection from the external GNSS receiver to an RTK base station was also established to receive high-accuracy GNSS. The transmitter of the locate device was connected to a steel pipe to begin the transmission of a signal onto the pipe. Various points of locating along the pipe(s) in the pipe farm were performed to confirm collection, transmission, and conversion to 2D and 3D features within the application. The appropriate attributes from the locate device or manually entered in the data form were stored with the collected data points.

Included in Test Case 2 were checks for proper Bluetooth connection and data transmission between the locator and GNSS receiver to the Windows Mesa tablet, establishment of a connection to an RTK base station, and proper storage and rendering of the collected data in 2D and 3D formats.

Test Case 3: The Leica DSX GPR device was connected to an existing RTK base station to receive high-accuracy GNSS. A grid was marked out on the ground to perform the data collection on some sections of pipe in the pipe farm. After data were collected and downloaded from the test run, a file upload button (not listed as an original requirement) on the software application deployed on the tablet was used to load data from a file to create GIS data in 2D and 3D formats. The proper attributes from the GPR device or manually entered in the data form were stored with the collected data points from the scanned grid.

Test Case 3 included establishing a connection to an RTK base station, performing a gridded scan of a pipe segment, saving a file to the tablet, uploading that file for data conversion to the cloud storage location in a 2D and a 3D format, and visualizing this data in 2D and 3D formats with its proper attributes.

Test Case 4: The proper completion of a Site Conditions Form from within the software application was tested. This test included opening the Site Conditions Form, recording information about the area of the locate and the locate itself, and then submitting the form for storage in the cloud. The ability to click on an existing point of interest originally collected with the Site Conditions Form and retrieve its attributes was also tested.

Test Case 5: The functionality of transferring data from a file containing previously collected and recorded utility locates was tested. Validation that the uploaded data were properly converted and mapped in 2D and 3D formats, along with any attributes that coincide with the existing utility locate schema, was also tested. Since existing locate data from multiple locators was not available, the data downloaded from either the Vivax-Metrotech vLoc3 RTK-Pro or the Radiodetection RD8200G device was used.

Test Case 6: Manually entering the attributes about a locate from the screen of a locate device that is not able to pair with the software application was tested. This test addressed the application's ability to work with devices that don't have Bluetooth technology or may not have a method for downloading and storing utility locate data.

Requirements that were integrated into the software application but were not tested via the use cases listed above were reviewed individually using Table 2. Any functionality integrations that did not operate properly were flagged and documented in the Development Phase Bug Resolution Document for correction and eventual retesting.

Table 2: Software Application Integration Testing Additional Requirements List

Title	Type
Site Conditions Form	Functional
Geospatial Data — Locate Device Connection	Functional
Geospatial Data — GNSS Device Connection	Functional
Geospatial Data — Elevation	Functional
Geospatial Data – Record Retention	Functional
Geospatial Data — GIS Mapping	Functional
Stake Out Locates	Functional
Operator Support — Best Practices	Functional
Operator Support — Operating Manuals	Functional
Operator Support — Existing Data	Functional
Operator Support — Base Maps	Functional
Operator Support — 3D Visualization	Functional
Locate Quality — KPIs	Functional
Operator Support — 3D Visualization	Functional
Operator Support — Real-Time Visualizations	Functional
In-Office Visualizations	Functional

Title	Type
Create Point Features	Functional
Receive NMEA Messages from a GNSS	Functional
Display GIS Data Layers	Functional
Ease of Use	Usability
Large Buttons	Usability
Sunlight Readability	Usability
Always Have Access to Table of Contents	Usability
Synchronize Data to the Server Frequently	Reliability
Configuration Support	Supportability
User Management	Supportability
Updateable Configurable Behaviors	Supportability
System Architecture — Client/Server	Design
Cloud Services	Design
Legacy Locate Tools	Interface
Device Integration	Interface
Data Integration	Interface

Title	Type
User Log In	Functional
Create, Read, Update and Delete Records	Functional
Display Summary View of Current Work	Functional
Free Form Field to Record Additional Information	Functional

Title	Type
Cloud Services — Data Integration	Interface
Operate with Gloves on	Physical
Ergonomic Support	Physical
Survive Adverse Conditions	Physical

Source: GTI Energy

Findings From Software System Testing

Software system testing successfully paired the selected utility locate devices and high-accuracy GNSS receivers with the software application. Listed are the pros and cons developed from feedback on the digital utility process that are specific to the software application designed for this project.

- Training to use high-accuracy GNSS receivers and connecting to an RTK base station can take a little bit to get used to and add some time to the initial training process.
- Digital data collection time was slightly longer than traditional utility locating, but the benefits of having this information collected and stored properly far exceed the additional time.
- There were not enough prompts to help the user use the application more effectively (for example, a warning message to users regarding the status of their connection to an RTK base station). If users lose the highest quality RTK fix during collection, they must be notified before submitting a point to the cloud GIS database. A warning message function was developed within the data collection form to mitigate this issue.
- Utility locate devices that required an external GNSS receiver and a survey pole created a poor ergonomic situation for the utility locate personnel.
- Users need a sufficient cell phone signal to send collected utility locate point data to the cloud database. Future development could address this need by adding offline editing capabilities, with data uploads occurring when cellular service is re-established. Additionally, locate devices with built-in high-accuracy GNSS receivers that support RTK corrections need reliable cell service for geolocating to be accurate.
- Utilizing a utility locate device without a high-accuracy GNSS receiver and an RTK connection will result in poor digital mapping accuracy. The horizontal (X,Y) values can be feet off from the intended target, and the vertical (Z) values can be off in feet and be represented as both above and below ground.
- The battery life of the utility locate devices, field tablet, and the high-accuracy GNSS receivers were good and would last a full day of work.

- The time to collect one locate point after initial equipment set up was minimal (15 to 30 seconds).
- To provide a good profile of the underground pipe using the depth value measured from the locate device, users should collect a new point every 10 to 15 feet.
- The attributes collected from the utility locate devices, and the user input, would provide an accurate record for future field use or existing GIS data comparisons.
- To construct a line from the utility locate points, users have to click on the collected first and last points. With the re-development of the data collection form, this extra step could be eliminated to create a more efficient process.
- Switching from a 2D map to a 3D scene worked well on the software application but, once in 3D mode, navigation on the Windows tablet was not easy to perform. It is recommended that a web application be used at this stage. Perhaps migration to an iOS- or Android-based operating system would enhance the navigation performance, which was not tested under this project.
- Bluetooth connections between locate devices and the software application on the tablet require opening a communications port specific to the device being connected. This function worked well with the development of a device management tool, but it was suggested that users keep the locate devices and a specific tablet together to avoid having to unpair and re-pair a different locate tool. Although it was possible to perform this unpairing and re-pairing of Bluetooth connections and devices, keeping existing connections was deemed more efficient.
- Users could access the tracking tool to revisit an existing locate, but using a high-accuracy GNSS receiver was also recommended. The GPS in the tablet would work with this tool, but the accuracy would not be good enough to navigate to the exact location of the original locate.
- The 3D scene did have labels for each utility locate point, based on the depth of cover of the pipe recorded. After initial use, it was decided that the base map in the scene should have a slight transparency so the labels could be more visible.
- The GPR selected for this project can generate good results, but users must establish a 10-meter x 10-meter grid before performing a lawn-mower-like scan to detect the underground pipe. This process is time-consuming, so users should plan their time accordingly when visiting a site.
- Assuming GIS data is available for use in the application as a base layer, it is beneficial if the pipe data has an attribute indicating if it shares a trench with a neighboring utility (for example, electric, telecommunications). Having this information before performing a utility locate can help users understand if they need to monitor the locate frequency for potential bleed-off of their electromagnetic signal to other utilities in the area.
- The current tool for uploading existing data sources is handy for mapping and visualizing prerecorded utility locates. To incorporate more data sources than the current two, an example dataset is needed to match the attribute schema between the

upload file and the cloud database schema. This process holds for incorporating other utility locate devices not present in the project.

Summary of Project Approach

The following summarizes the project approach and provides a reference for topics discussed in the remainder of the report.

- Familiarization with current utility locate processes, especially with an eye towards improvements that could be made via digitalization
- Identification, evaluation, and selection of popular locate hardware that could transmit data via Bluetooth
- Coordination with utility companies to acquire relevant data for use in and with the software application and conducting initial pilot testing planning
- Setup of the GIS environment in which data created by the new software would reside and be analyzed
- Development of the new software on the client and server sides
- Testing of the newly developed system (comprising the newly developed software, locate hardware, and GNSS hardware) at GTI Energy's pipe farm, for bug fixing and system and process refinement
- Planning and execution of the pilot tests in utility companies' territories

CHAPTER 3:
Project Results

GTI Energy utilized a near real-world setting at its Des Plaines, Illinois, pipe farm for additional testing prior to application field deployment. The pipe farm is considered a controlled environment, consisting of three relatively straight segments of steel pipe, each varying in diameter (2 inches, 4 inches, and 8 inches) and spanning a linear distance of approximately 100 feet in length. Users could connect a locate transmitter directly to the steel pipe, induce a signal, and begin to locate. These pipes were free from other interference and provided a good test bed for evaluating the software application and utility locate tools. The site can be seen in Figure 6.

Figure 6: Snapshot of GTI Energy's Pipe Farm Before Backfill

Source: GTI Energy

The controlled environment was established by collecting the underground pipes' locations with high-accuracy GNSS receivers and a field tablet before backfilling, to create a baseline for comparison against the above-ground utility locates. If data collection issues existed in the software application, they would quickly be flagged during these system tests, using desktop review of the horizontal and the vertical accuracy measurements. Each locate tool selected for this project was combined with a high-accuracy GNSS device (unless already integrated, as in the case of the Vivax-Metrotech vLoc3 RTK-Pro) and used to locate each pipe at a span of approximately every 10 feet. Not only were the locate tools tested but the workflows of every tool developed inside the application were again tested. The GPR device utilized a different approach, where the user was required to upload the file exported from the Leica DSX GPR device. This same file upload feature could also handle files from the Radiodetection RD8200G electromagnetic handheld device and was designed to facilitate the handling of data from other locate devices in the future.

The tables following detail how the software application, paired with the utility locate tools and high-accuracy GNSS receivers, performed at GTI Energy’s pipe farm in the horizontal (X, Y) and vertical (Z) dimensions.

Table 3: Vivax-Metrotech vLoc3 RTK-Pro Device Horizontal and Vertical Accuracy Levels

Pipe Size (Inches)	Average Horizontal Accuracy (Inches)	Average Vertical Accuracy (Inches)
2	4.8	1.99
4	2.99	3.35
8	5.46	3.37

Source: GTI Energy

Table 4: Radiodetection RD8200G Device Horizontal and Vertical Accuracy Levels

Pipe Size (Inches)	Average Horizontal Accuracy (Inches)	Average Vertical Accuracy (Inches)
2	3.42	3.37
4	3.07	3.42
8	2.61	3.58

Source: GTI Energy

Table 5: Leica DSX GPR Device Horizontal and Vertical Accuracy Levels

Pipe Size (Inches)	Average Horizontal Accuracy (Inches)	Average Vertical Accuracy (Inches)
4	1.41	13.53

Source: GTI Energy

It is important to note when collecting points while using a high-accuracy GNSS receiver that, the further the user is from an RTK base station, the greater the potential for a degradation in accuracy. GTI Energy’s campus has its own RTK base station, which removes the potential for accuracy degradation based on its proximity. In addition, electromagnetic and GPR utility locate tools have their constraints to consider when working in the field (specifically, surrounding soils, nearby utilities). GTI Energy’s pipe farm has fewer of these complicating factors, thus adding to a clean control site for testing. The accuracy values in the tables above are average distances across a sampling of approximately 10 points to 15 points collected by each electromagnetic utility locate tool over 100 feet per segment of 2-inch, 4-inch, and 8-inch diameter pipe. The Leica DSX GPR device was tested on only a small sampling of the 4-inch pipe due to the long setup, data acquisition time, and tool limitations of acquiring only 30 feet of pipe at a time. The locations collected by each utility locate tool were compared to the high-accuracy open-trench survey data.

The two handheld utility locate tools (the vLoc3 RTK-Pro and the Radiodetection RD8200G) produced somewhat similar results. However, it is believed that recent rains contributed to a more significant deviation in this comparison with the Leica DSX GPR device, as soil moisture can contribute to GPR detection issues. All three utility locate tools were used with a high-accuracy GNSS receiver. However, whereas the Radiodetection RD8200G and the Leica DSX GPR leveraged an external receiver, the Vivax-Metrotech vLoc3 RTK-Pro had its own internal receiver. All three devices also utilized GTI Energy's local RTK base station, located within 1000 feet of the testing location. Variances in the horizontal and vertical accuracies between the two handheld electromagnetic devices are most likely attributable to the number of satellites being received and the actual position of where the locator picked up the strength of the electromagnetic field. Users of the vLoc3 RTK-Pro needed only to find the pipe via the signal and collect the point with one click on the device, while the Radiodetection RD8200G requires the user to locate the pipe with the utility locate tool and then collect that point again with the high-accuracy GNNS receiver. Points collected between the two electromagnetic devices were never collected at the same location. Hence, the averages were respective to the pipe itself, but it may not be easy when comparing the two devices against each other.

Many factors can impact accuracy, especially when utilizing and combining two separate tools: a utility locate device and a high-accuracy GNSS receiver. Utility locate devices operate on the frequency set by the locate personnel on the transmitter. If too strong, these signals can bleed off to nearby pipes. Bleed-off was not an issue with GTI Energy's pipe farm testing, but it could be a factor in congested areas in real world settings. When using GNSS high-accuracy receivers, the users must be aware of the status of their connections to RTK base stations. It is not uncommon for a user to lose connection to a base station because of a weakened cellular signal. When this occurs, they are not receiving the highest accuracy possible, known as an RTK Fix. Locators risk a reduction in accuracy, from the centimeter level or inch level to upwards of a few feet, based on the receiver's connection type when collecting with anything less than an RTK fix.

Additionally, the tested Vivax-Metrotech prompts the user to level it before capturing a point using RTK corrections. However, many locating devices that rely on a third-party GNSS receiver mounted on a survey pole or other configuration require the operator to keep the GNSS antenna level by using a bubble level. If the antenna is not level, the accuracy of the collection point can degrade in the range of centimeters to feet, depending on how far off level the receiver is.

Training for high-accuracy digital locates is as much for the user to understand the functionality of the locator as it is for the user to understand the underpinnings of quality high-accuracy data collection. Proper training on all hardware and software is recommended, as the time spent to create a digital locate will only be worth it if it is trustworthy and useable by parties other than the ones who originally collected the data.

Environmental factors such as soil type and moisture levels can pose issues for utility devices. Ground penetrating radar devices can struggle in soils (especially clay and silt) with high moisture content, as the penetration signals tend to bounce right back. In comparison, electromagnetic tools perform better in compacted soils like clay and not as well in loose soils like sand. GTI Energy’s pipe farm consists of mostly clay soils, with some sand and silt. Based on the accuracy of the results, as listed in the following, it is not likely that the soils greatly impacted the electromagnetic utility locate tools. In contrast, post-rain moisture seemed to have affected the GPR device, as data collection occurred after a local rain event.

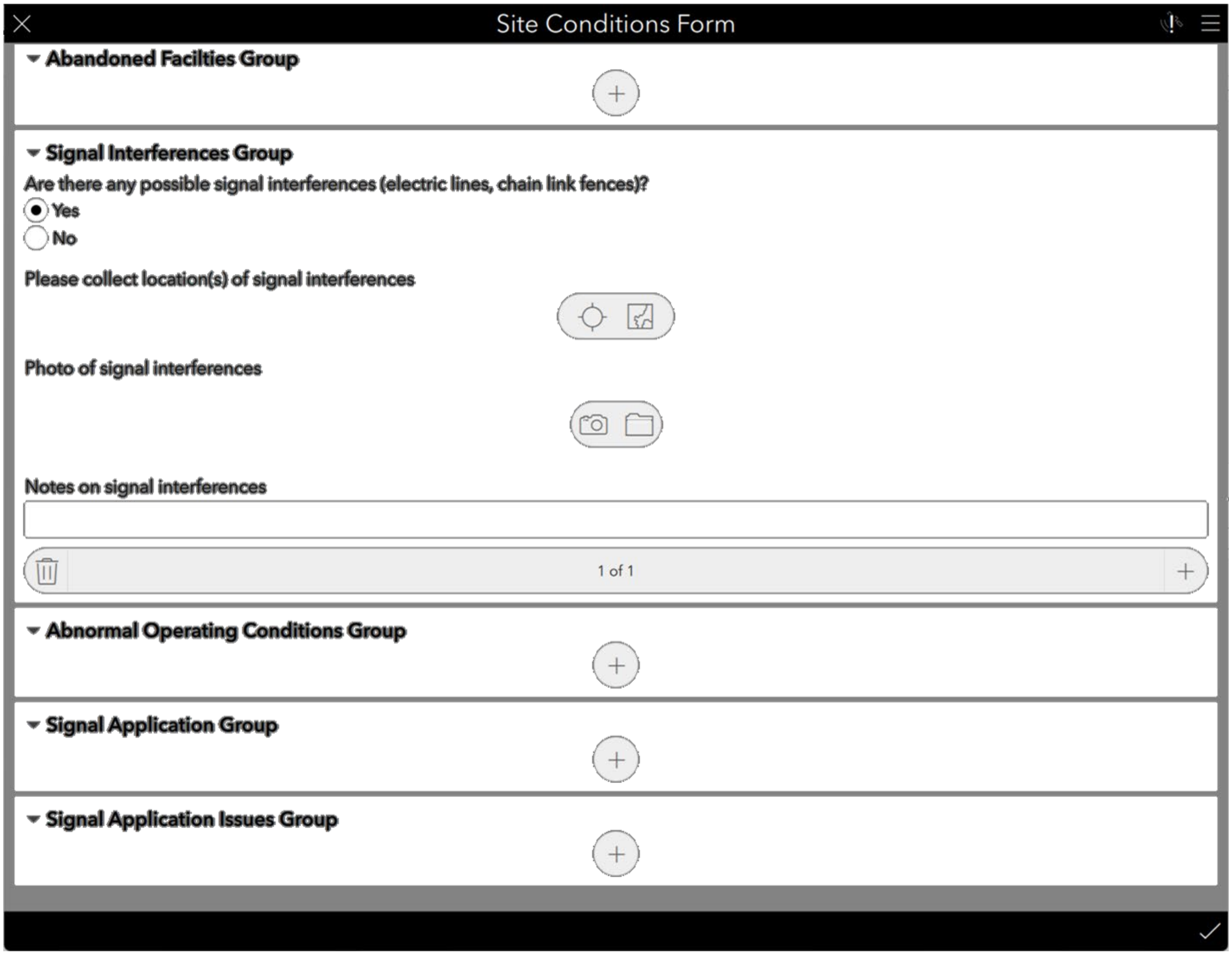
As the software application and utility locate tools navigated from a controlled setting at GTI Energy’s pipe farm to the pilot demonstration sites in California, the horizontal (X, Y) accuracy values varied slightly. Multiple factors can lead to variances in data quality when moving from a controlled setting to the real world. Table 6 summarizes some factors that can contribute to locating issues in the field and, thus, reduced accuracy. Additionally, Figure 7 displays a smart form survey that the users can access in the field to digitally record the site conditions at the job site. This form is aimed at recording conditions that may pose an issue to a more accurate utility locate.

Table 6: Categories and Descriptions That May Affect a Utility Locate

Locate Tools/GNSS Receiver Collection/GIS Pipe Location Data	Environmental/Utility Conditions
Distance of high-accuracy GNSS receiver from RTK base station	Tracer wire not sufficiently attached to pipe or broken
Proper leveling of high-accuracy GNSS receiver antenna	Nearby underground utilities causing interference
Not establishing an RTK fixed position with the high-accuracy GNSS receiver	Insulators on pipe disrupting signal on pipe
Inaccurate maps provided to locate staff	Too high of a frequency set on transmitter, causing bleed-off onto nearby pipes

Source: GTI Energy

Figure 7: Smart Form Survey to Record Job Site Conditions

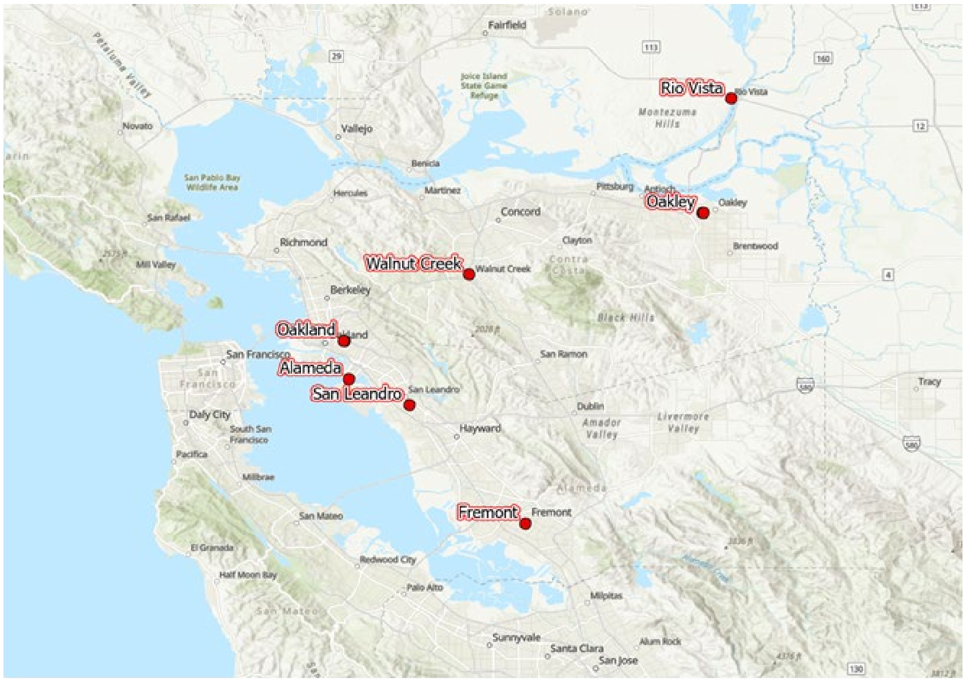


Source: GTI Energy

Pilot Demonstrations With PG&E

The pilot demonstration with PG&E took place for three months, starting in June 2022 and ending in August 2022. GTI Energy, Trident Engineering, and PG&E met in Dublin, California, and San Ramon, California, at the beginning of June to conduct training sessions on using the software application with all three utility locate tools. The training lasted two days and focused on the end-to-end process of collecting high-accuracy digital locates with two handheld electromagnetic tools and one ground penetrating radar device. The pilot team collected approximately 700 feet of the underground pipeline during this training session using various tools. Additionally, the team was instructed to use the smart form surveys to collect information on the site conditions as well as predefined KPI metrics for each stretch of pipe. Figure 8 displays the cities where the pilot demonstration team collected digital utility locate data in the first three months of the pilot. Table 7 details the attributes of each site visited and whether a site was in a low-income area. Low-income areas are based on the "percent of population living below two times the federal poverty level" (California Office of Environmental Health Hazard Assessment, 2023).

Figure 8: Map of Pilot Demonstration Sites Within PG&E Service Territory



Source: GTI Energy

Table 7: PG&E Service Territory Pilot Demonstration Attributes

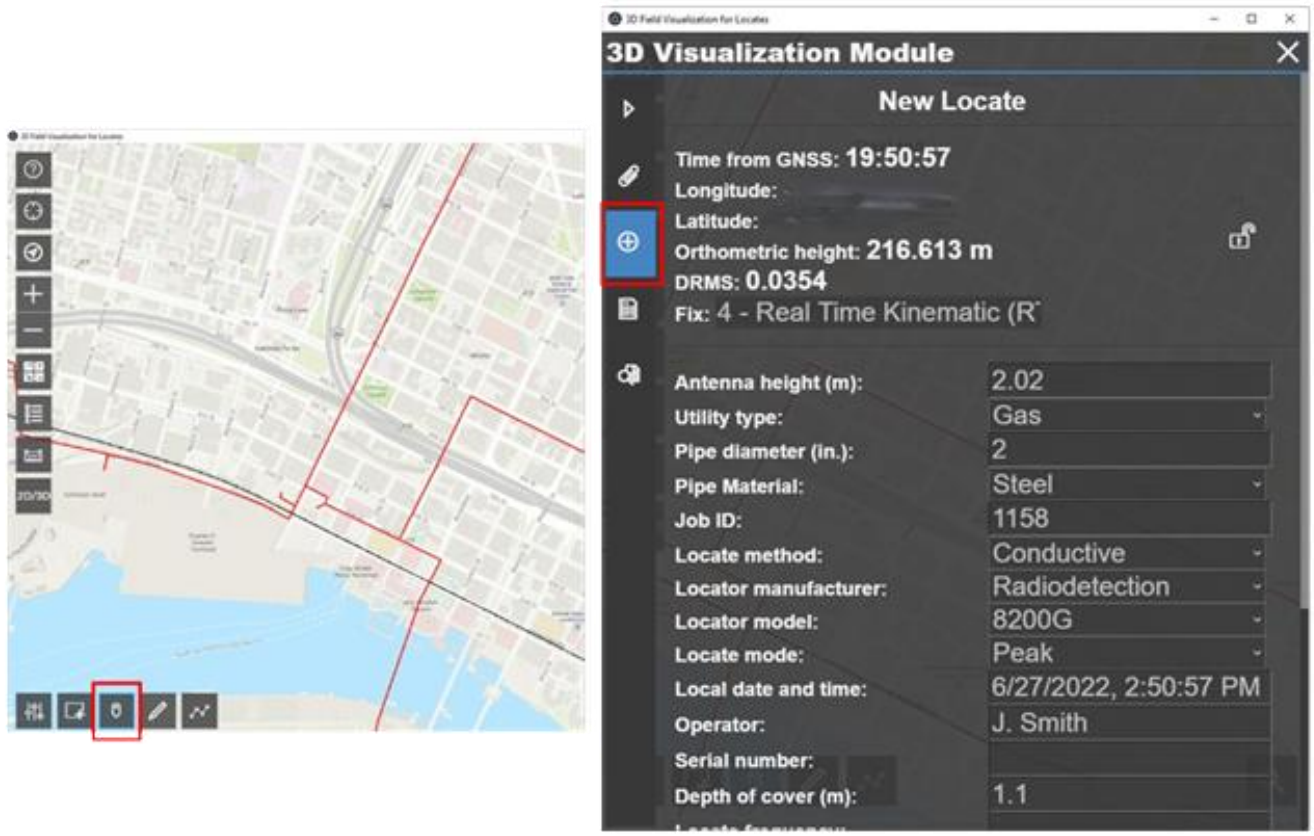
City	Pipe Size (inches)	Pipe Material	Joint Trench	Soil Type	Date of Collection	Linear Feet Collected	Low-Income Area
Oakley, CA	2	PE	No	Sandy	6/28/2022	865	Yes
	2	PE	No	Sandy		616	Yes
Rio Vista, CA	2	PE	No	Sandy	6/29/2022	169	Yes
	4	Steel	No	Sandy		352	Yes
	2	PE	No	Sandy		20	Yes
	4	Steel	No	Sandy		276	Yes
Oakland, CA	3	Steel	No	Relatively Clay	7/14/2022	559	No
	3	Steel	No	Relatively Clay		727	No
Walnut Creek, CA	1.25	PE	No	Relatively Clay	7/14/2022	352	No

City	Pipe Size (inches)	Pipe Material	Joint Trench	Soil Type	Date of Collection	Linear Feet Collected	Low-Income Area
Fremont, CA	2	PE	No	Mostly Silt/Some Clay	7/28/2022	2,095	No
	2	PE	No	Mostly Silt/ Some Clay		721	No
Alameda/San Leandro, CA	6	PE	No	Mix Sand/ Silt/Clay	8/9/2022	674	No
	4	PE	No	Sandy		871	No
					Total	8,297	

Source: GTI Energy

Data collection methods at the California pilot demonstration sites mirrored the data collection efforts at GTI Energy's pipe farm by utilizing the same locate tools and software application. As seen in Figure 9, the data collection form auto-populated with values directly from the utility locate device when the user submitted a data collection point. These values, paired with the manual input data already in the form, made up the attributes that were stored as a geospatial point in the cloud server GIS database. If the user paired a high-accuracy GNSS receiver with the tablet, those values automatically streamed into the data collection form, and the user could lock the spatial location when standing over the locate point. If the utility locate device had its own internal high-accuracy GNSS receiver, those spatial location attributes transmitted via Bluetooth. Once the form was completed, the Submit button was selected to send the collection point to the cloud.

Figure 9: Software Application Data Collection Form With Attributes From Utility Locate Device and Manual Entry



Source: GTI Energy

The point is stored in the GIS database and shown on the software application's map in real time. When a user selects a point in the map, a list of attributes about that specific utility locate point is displayed. These attributes can be seen in the following figure.

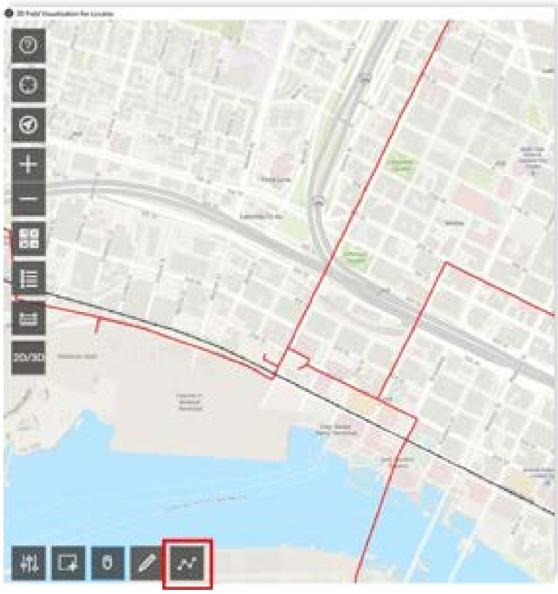
Figure 10: Data Attributes Collected and Stored Utilizing the Software Application and Utility Locate Tools

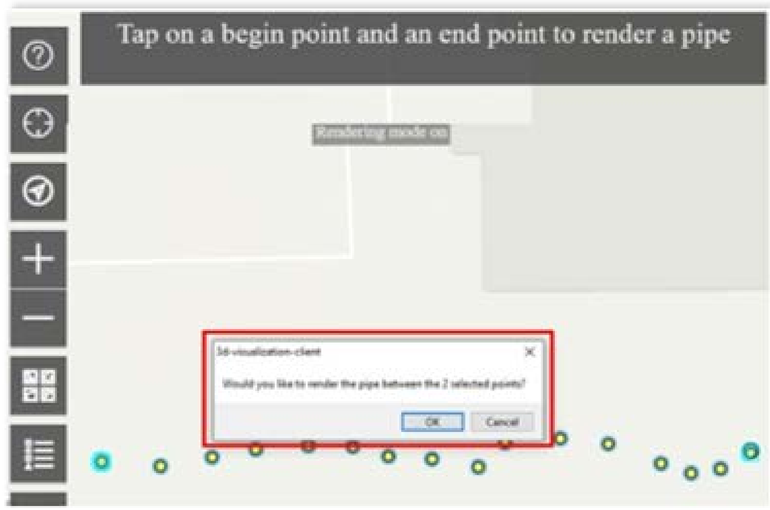
Utility Type	Gas	Locate Current	0.02	HDOP	0.50
Pipe Diameter	4.00	Operating Mode	Peak +	Fix Type	RTK Fixed
Pipe Material	PE	Locate Antenna Mode		Number of Satellites	23
Job ID	590	CD Phase			
Locate Method	conductive	Signal Strength	0.80		
Date_Time	7/14/2022, 12:59 PM	Gain	63.00		
Operator	MH	Absolute Height	11.33		
Manufacturer	Radiodetection	GPS_Antenna_Height	2.02		
Model	8200G	Notes			
Serial Number		Receiver Name			
Depth of Cover	0.91	Latitude			
Locate Frequency	9820.00	Longitude			

Source: GTI Energy

To promote efficiencies during data collection, the form retains the attributes that the user manually entered while the spatial location coordinates are updated with the new positional values. Once the entire line is located, a tool within the software application is used to connect all the points for that specific utility locate into a line. Additionally, some of the common attributes from the collected point data, such as pipe size, pipe material, operator, and collection date are attached to the line. An example of this tool can be seen in Figure 11.

Figure 11: Software Application Tool to Create Lines From Utility Locate Points

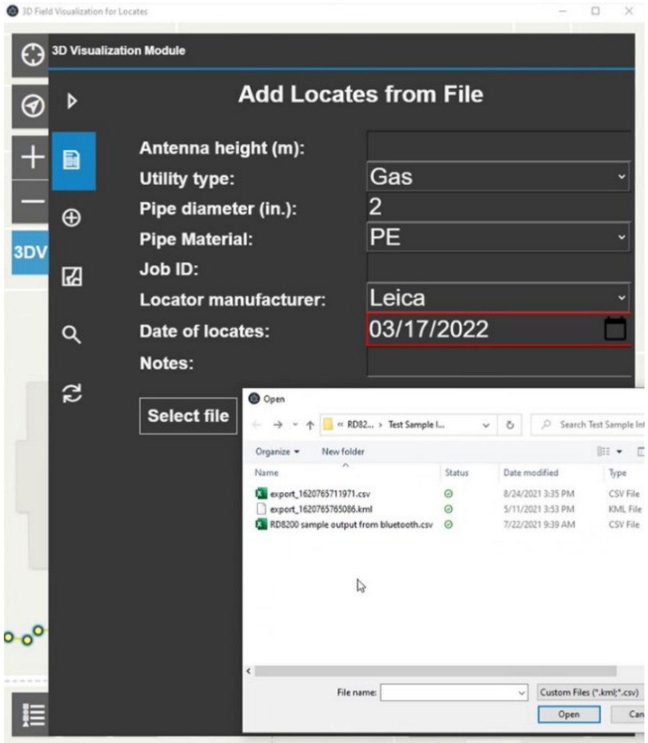




Source: GTI Energy

In addition to the users collecting utility locate points in real time, the software application includes a tool that allows for uploading existing utility locate data from a file (for example, CSV file format). For this project, the project team only incorporated this functionality for two utility locate tools, but the tool can accommodate other utility locate devices with minor development time. Figure 12 shows an example of the file upload tool.

Figure 12: File Upload Tool Within the Software Application



Source: GTI Energy

Having reviewed the software application utility locate procedures, it is possible to discuss data collection statistics and horizontal accuracy levels. Table 8 summarizes the overall horizontal mean, minimum, maximum, and median accuracy levels across seven PG&E pilot sites for all three locate devices. All data points collected over the seven pilot demonstration sites were compared to PG&E internal high-accuracy pipe locations collected from an open trench. This was accomplished by constructing a lateral line between the utility locate line and the PG&E line. Each lateral line created contained a distance measurement between the two lines and was used to create statistics for horizontal mean, minimum, maximum, and median accuracies, as shown in Table 8.

Table 8: PG&E Pilot Locate Tools Horizontal Accuracy Levels (Compared to PG&E Open-trench High-accuracy Data)

Manufacturer	Point Collection Count	Linear Feet Collected	Horizontal Mean Differential (Inches)	Horizontal Minimum Differential (Inches)	Horizontal Maximum Differential (Inches)	Horizontal Median Differential (Inches)
Leica DSX GPR	80	126.9	20.36	0.26	92.58	16
Radiodetection RD8200G	339	5,166.2	7.76	0.17	24.86	7.4
Vivax-Metrotech vLoc3 RTK-Pro	289	4,475.5	9.28	0.10	53.70	4.16

Source: GTI Energy

Table 9 provides a more detailed look at each site's horizontal accuracy mean, minimum, maximum, and median values. The differentials are the distances from the measured locate points to the lines formed by (virtually) connecting the open-trench survey points to each other.[1]

Some data collection points may have a larger horizontal maximum differential distance if the point was collected without connection to an RTK base station or if personnel was a substantial distance from the base station at collection. Factors such as base station integrity and the actual GNSS receiver being utilized can contribute to inaccuracies. Still, a standard estimate is 10-centimeter accuracy loss per 100 kilometers of baseline distance. Only one percent of points collected during the PG&E pilot demonstration were not collected with an RTK fixed position (where a fixed position indicates the best level of accuracy possible).

Table 9: PG&E Pilot Locate Tools Horizontal Accuracy Levels, by Device Name

City	Date of Collection	Manufacturer	Horizontal Mean Differential (Inches)	Horizontal Minimum Differential (Inches)	Horizontal Maximum Differential (Inches)	Horizontal Median Differential (Inches)
Oakley, CA	6/28/2022	Radiodetection RD8200G	2.74	0.23	16.44	1.96
Oakley, CA	6/28/2022	Vivax-Metrotech vLoc3 RTK-Pro	3.35	0.11	14.46	2.48
Oakland, CA	6/28/2022	Radiodetection RD8200G	9.21	0.17	21.57	8.9
Oakland, CA	6/28/2022	Vivax-Metrotech vLoc3 RTK-Pro	12.85	0.36	24.86	13.29
Rio Vista, CA	6/29/2022	Radiodetection RD8200G	9.98	1.31	19.7	8.75
Rio Vista, CA	6/29/2022	Vivax-Metrotech vLoc3 RTK-Pro	6.62	0.43	15.07	7.62
Rio Vista, CA	6/29/2022	Vivax-Metrotech vLoc3 RTK-Pro	5.76	1.25	8.24	6.31
Walnut Creek, CA	7/14/2022	Vivax-Metrotech vLoc 3 Pro RTK	2.82	0.1	10.31	1.46
Oakley, CA	7/15/2022	Leica DSX GPR	2.31	0.26	3.38	2.51
Oakley, CA	7/15/2022	Leica DSX GPR	88.51	82.58	92.58	89.4
Fremont, CA	7/28/2022	Radiodetection RD8200G	10.2	3.03	21.18	9.9
Fremont, CA	7/28/2022	Radiodetection RD8200G	5.8	0.21	14.44	5.56
Fremont, CA	7/28/2022	Leica DSX GPR	16.8	15.98	17.67	16.83

[1] For information on the distance and proximity information calculated by the ArcGIS Pro tool, see https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/near.htm

City	Date of Collection	Manufacturer	Horizontal Mean Differential (Inches)	Horizontal Minimum Differential (Inches)	Horizontal Maximum Differential (Inches)	Horizontal Median Differential (Inches)
Fremont, CA	7/28/2022	Leica DSX GPR	23.35	11.29	32.3	24
Alameda, CA	8/9/2022	Vivax-Metrotech vLoc3 RTK-Pro	13.33	8.58	16.56	13.18
Alameda, CA	8/9/2022	Vivax-Metrotech vLoc3 RTK-Pro	2.86	0.13	8.99	2.4
San Leandro, CA	8/9/2022	Vivax-Metrotech vLoc3 RTK-Pro	27.18	2.09	53.7	24.27

Source: GTI Energy

Note that it is presumed that the second row of Oakley, California, data was collected without a connection to an RTK network or that the network was dropped shortly after setup.

Table 10 reflects the data collected with the various RTK connections. Points that have "Unknown" in the Percent Collected column are related to the type of metadata this device stores and saves in the file output. RTK connections were made while using the Leica DSX GPR, but it is possible that the accuracy may have unknowingly deviated during the data collection process.

Table 10: PG&E Pilot Total Points Collected by Device Name and RTK Fix Percentage

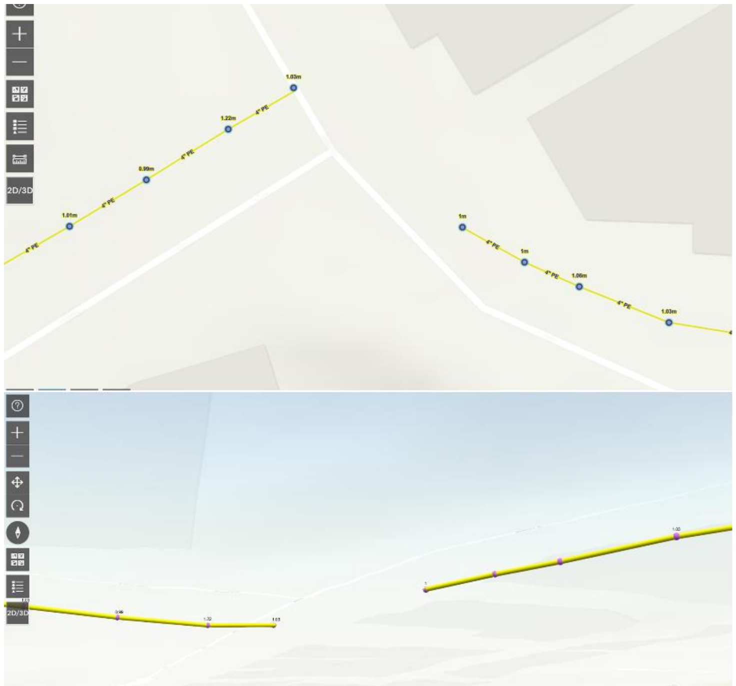
Manufacturer	Point Collection Count	Percent Collected With RTK Fix (Best Accuracy Potential)
Leica DSX GPR	80	Unknown
Radiodetection RD8200G	339	98.82%
Vivax-Metrotech vLoc3 RTK-Pro	289	99.65%

Source: GTI Energy

Field users were asked to collect multiple points at various locations along the pipe and to construct a line of all the points. These lines were constructed by selecting the first and the last point, resulting in a 2D and a 3D representation of that line. The following figures are examples of the 2D and 3D representations created for two separate pilot demonstration sites within PG&E territory.

Figures 13(a) and 13(b): 2D and 3D Representations of PG&E Pilot Demonstration Site

(a)



(b)

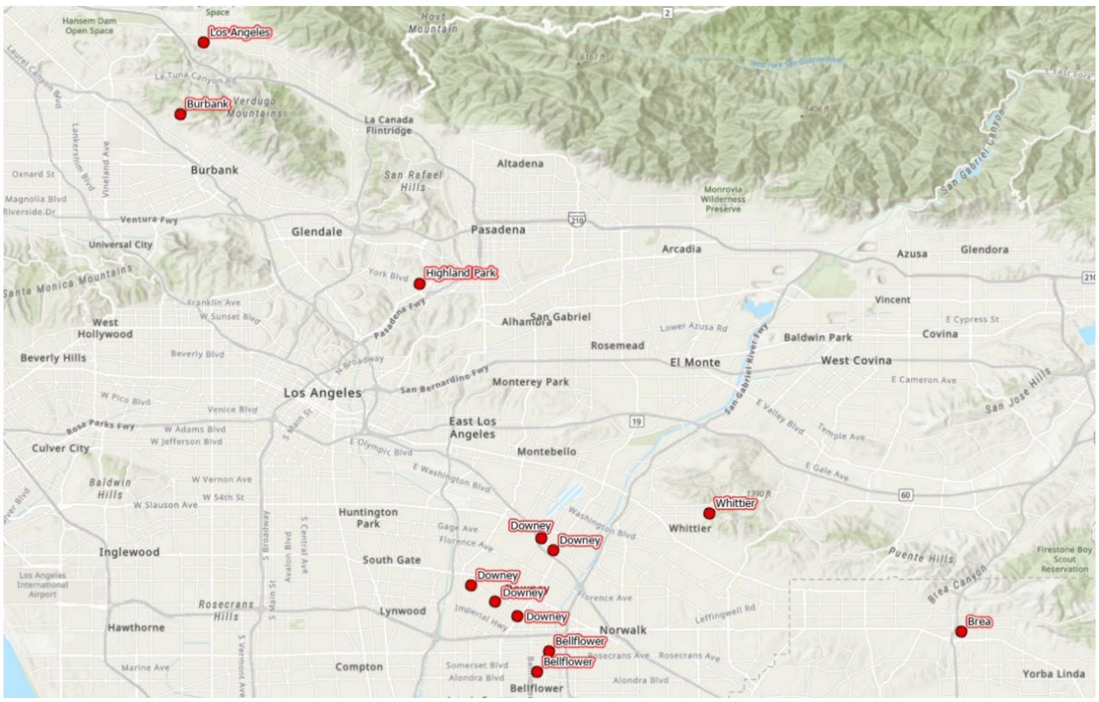
Source: GTI Energy

Pilot Demonstration With SoCalGas

The SoCalGas pilot demonstration took place over three months in multiple locations in the greater Los Angeles, California, area between September 2022 and November 2022. These sites included urban and suburban locations, with various pipe sizes, pipe materials, and soil types. An overview map of the pilot site demonstration locations is shown in Figure 14.

Table 11 details asset attributes for each site visited. For SoCalGas data collection, no internal GIS data were provided for comparison between the utility locates and the actual GIS records. Ground truth of the utility locate data collected during these pilot demonstration sites would require internal GIS data or potholing for the pipe location. None of these techniques were conducted during the demonstration site data collection efforts.

Figure 14: Overview Map of SoCalGas Pilot Demonstration Sites



Source: GTI Energy

Table 11: SoCalGas Pilot Demonstration Sites Visited, September 2022 to November 2022

City	Pipe Size (Inches)	Pipe Material	Joint Trench	Soil Type	Date of Collection	Linear Feet Collected	Low-Income Area
Downey, CA	2	Plastic	Yes	Sandy	9/28/2022	647	No
	2	Plastic	Yes	Sandy		329	No
	2	Steel	Unknown	Sandy	10/11/2022	469	Yes
	2	Plastic	Unknown	Sandy		268	No
	2	Steel	Unknown	Sandy		298	No

City	Pipe Size (Inches)	Pipe Material	Joint Trench	Soil Type	Date of Collection	Linear Feet Collected	Low-Income Area
Whittier, CA	4	Steel	Yes	Mix Sand/ Silt/Clay	9/22/2022	215	No
Bellflower, CA	2	Steel	Unknown	Sandy	10/11/2022	542	No
	2	Steel	Unknown	Sandy		665	No
Highland Park, CA	2	Steel	Unknown	Sandy	10/18/2022	904	No
Brea, CA	2	Plastic	Unknown	Mix Sand/ Silt/Clay	10/18/2022	1,455	No
Los Angeles, CA	2	Plastic	Unknown	Sandy	10/19/2022	508	No
Burbank, CA	2	Steel	Unknown	Sandy	10/19/2022	719	No
					Total	7,019	

Source: GTI Energy

Table 12 details the total points collected per device, the percentage of these points that were collected with high-accuracy RTK connection, and the linear feet collected per device. Note that the Leica DSX GPR device was not selected for use in the SoCalGas pilot demonstration.

Table 12: SoCalGas Pilot Point Summary

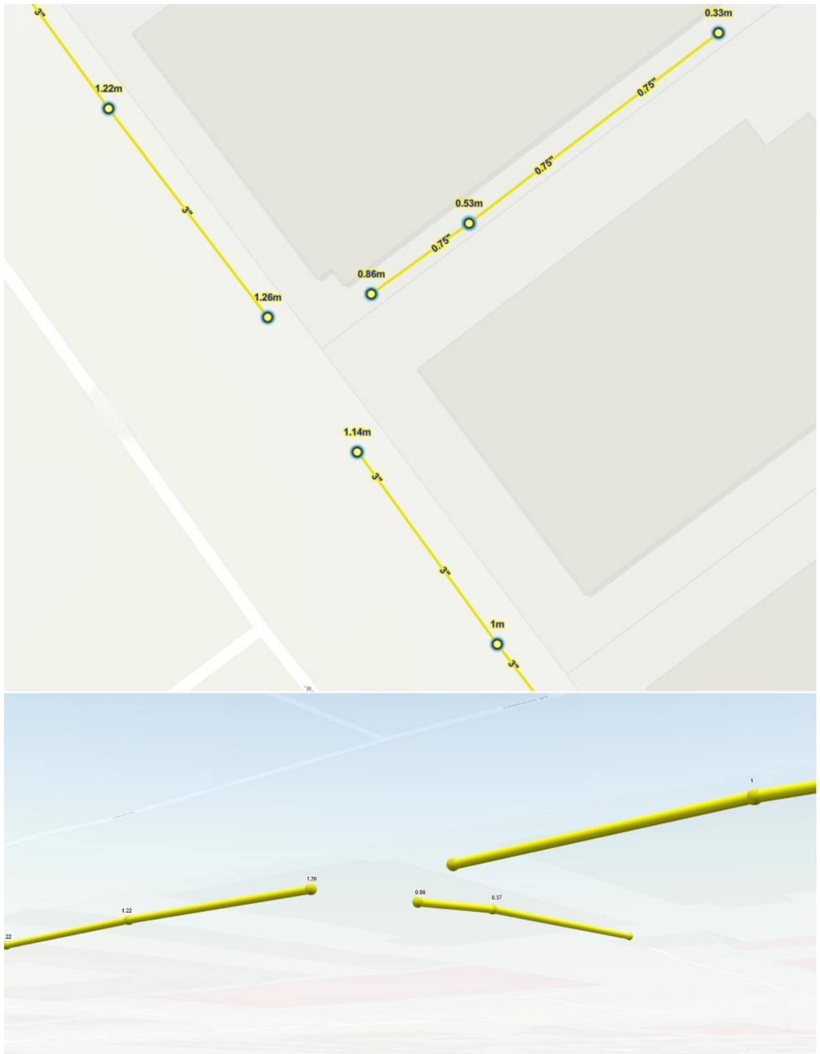
Manufacturer	Point Collection Count	Percent Collected with RTK Fix (Best Accuracy Potential)	Linear Distance Collected (Feet)
Radiodetection RD8200G	49	79.60%	2,389.7
Vivax-Metrotech vLoc3 RTK-Pro	155	80.65%	4,632.1

Source: GTI Energy

Figure 15(a) and Figure 15(b) below detail examples of 2D and 3D representations created for two separate pilot demonstration sites within SoCalGas territory.

Figures 15(a) and 15(b): 2D and 3D Representations of SoCalGas Pilot Demonstration Site

(a)



(b)

Source: GTI Energy

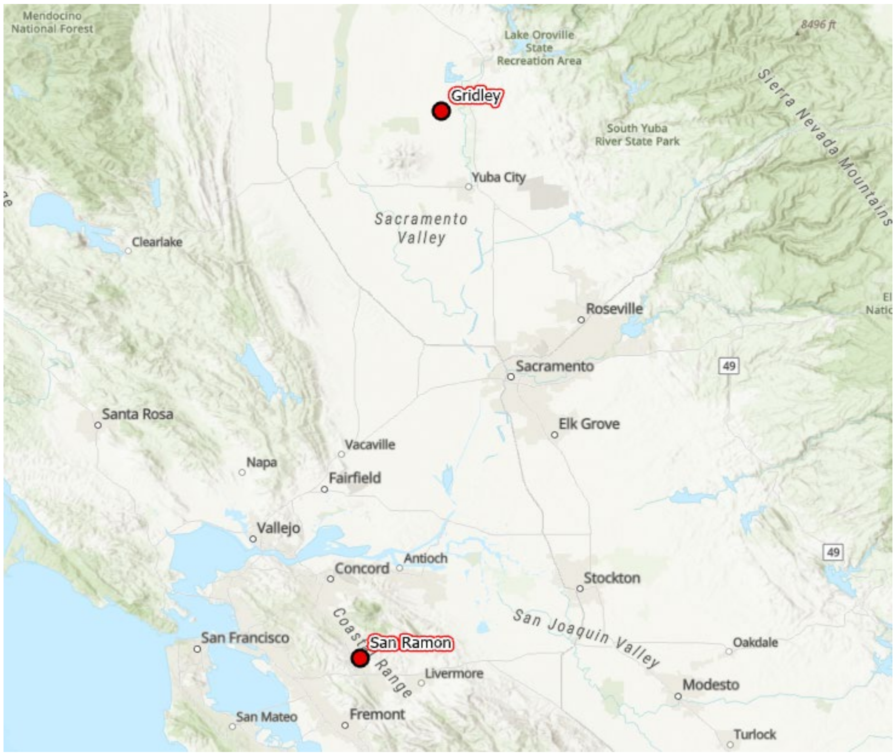
Pilot Demonstration With 2M Utility Locating

2M Utility Locating (2M) is a private utility locate company based in Sacramento, California. 2M serves California and Western Nevada and specializes in GPR, EM, and GPS/GNSS technologies. A company whose sole or primary business function is utility locating likely has the expertise and knowledge to be able to provide valuable feedback on new technology, including its usefulness and viability. Additionally, 2M currently performs digital utility locates with a separate software vendor, making the company a good fit to review the software application developed under this project.

The pilot demonstration took place over one week in two separate locations, San Ramon, California, and Gridley, California, in June 2023. The two sites totaled approximately one mile in length and were compared to in-house high-accuracy GIS records supplied by PG&E. The methods of high-accuracy data collection found in the supplied PG&E data consisted of open-trench data collection and paint markings collected from above ground during a horizontal directional drilling process, both with high-accuracy GNSS receivers. 2M met with members of the GTI Energy and Trident Engineering teams to receive training on the software application, locate devices, and high-accuracy GNSS receivers. After the training, members of all teams worked together to collect a variety of underground pipelines using the Vivax-Metrotech vLoc3 RTK-Pro, the Radiodetection RD8200G, and the GSSI SIR 4000 GPR device. The GSSI SIR 4000 GPR device was supplied by 2M and was used in areas of the San Ramon pilot demonstration site where transmitting a signal to the buried pipe was not possible. Despite all connection points nearby being tested, none produced a signal in the direction of the specific pipe to be located. The GSSI SIR 4000 GPR device can operate in a more linear fashion and did not require a grid to be set up for scanning in a lawn-mower-like pattern. For the use of this GPR device, 2M scanned the street to locate the pipe and, when it was discovered, the project team collected a high-accuracy data point at that location with the software application and a high-accuracy GNSS receiver. To generate a 3D point, the 2M staff member would read out the depth of cover at that location and another team member would enter that number into the data form before submitting the data to the cloud-based GIS database. This method was fast and demonstrated a different collection method that the software application can perform.

Figure 16 below shows the location of the pilot demonstration sites during work conducted with 2M. Table 13 details some of the characteristics of each site location.

Figure 16: Overview Map of 2M Pilot Demonstration Sites



Source: GTI Energy

Table 13: 2M Pilot Demonstration Sites Visited in June 2023

City	Pipe Size (Inches)	Pipe Material	Joint Trench	Soil Type	Date of Collection	Linear Feet Collected	Low Income Area
San Ramon, CA	2	Plastic	No	Relatively Clay	6/26/2023	2,462	No
	2	Plastic	No	Relatively Clay	6/27/2023	1,847	No
Gridley, CA	4	Plastic	No	Mix Sand/Silt/ Clay	6/28/2023	672	Yes
	2	Plastic	No	Mix Sand/Silt/ Clay	6/28/2023	135	Yes
	6	Plastic	No	Sandy	6/28/2023	1,064	Yes
					Total	6,180	

Source: GTI Energy

Like the data analysis performed for the PG&E pilot demonstration sites, data collected by 2M was also compared to PG&E internal high-accuracy open-trench collected pipe locations by constructing a lateral line between the utility locate line and the PG&E line. Each lateral line created contained a distance measurement between the two lines and was used to create statistics for horizontal mean, minimum, maximum, and median accuracies between, as shown in Table 14.

Table 14: 2M Pilot Locate Tools Horizontal Accuracy Levels (Compared to PG&E Open-trench High-accuracy Data)

Manufacturer	Point Collection Count	Linear Feet Collected	Horizontal Mean Differential (Inches)	Horizontal Minimum Differential (Inches)	Horizontal Maximum Differential (Inches)	Horizontal Median Differential (Inches)
GSSI SIR 4000 GPR	53	1462.8	9.93	0.33	23.07	9.44
Radiodetection RD8200G	129	2396.6	10.49	0.07	47.88	6.47
Vivax-Metrotech vLoc3 RTK-Pro	120	2562.5	21.22	0.075	67.36	16.63

Source: GTI Energy

Table 15 provides a more detailed look at each site's horizontal accuracy mean, minimum, maximum, and median values. As stated in the PG&E pilot demonstration section above, some data collection points may have a larger horizontal maximum differential distance if the point was collected without a connection to an RTK base station or if there was a substantial distance from the base station itself.

Table 15: 2M Pilot Locate Tools Horizontal Accuracy Levels by Device Name and Site

City	Date of Collection	Manufacturer	Horizontal Mean Differential (Inches)	Horizontal Minimum Differential (Inches)	Horizontal Maximum Differential (Inches)	Horizontal Median Differential (Inches)
San Ramon, CA	6/26/2023	Radiodetection RD8200G	5.83	.07	20.87	5.65
San Ramon, CA	6/26/2023	Vivax-Metrotech vLoc3 RTK-Pro	6.84	0.008	32.4	4.51
San Ramon, CA	6/27/2023	GSSI SIR 4000 GPR	9.93	0.33	23.06	9.44
Gridley, CA	6/28/2023	Radiodetection RD8200G	22.25	4.31	37.76	25.96
Gridley, CA	6/28/2023	Vivax-Metrotech vLoc3 RTK-Pro	35.6	2.46	67.36	28.75

Source: GTI Energy

From the tables above, there are slightly larger distance differentials when comparing the data collected with the software application and locate tools utilized on this project versus the high-accuracy lines supplied to GTI Energy by PG&E, specifically to some of the lines collected in Gridley, California. Metadata from PG&E regarding the pipes installed in Gridley, California, states that they were captured digitally using high-accuracy GNSS receivers atop paint markings on the ground surface. These paint markings were sprayed at locations where a sonde was detected with an above-ground utility locate device. The sonde is attached to the drilling equipment and can be accurately tracked from above ground using a utility locator in the sonde mode. As the sonde is pushed through the ground with the drilling equipment, field personnel can walk along the surface and spray paint markings where that sonde is detected. After markings are made, field personnel can return to those paint markings to collect data points with a high degree of accuracy. This process can be efficient and accurate, but it is different than collecting high-accuracy data points of the pipe while there is an open trench. When comparing the data collected from the sonde method versus the points collected with the software application by the pilot demonstration team, the distance differentials are slightly larger than typically seen in the rest of the pilot demonstration sites. The pilot demonstration team noted no issues with connecting and sending a signal to the pipe. Moreover, the team collected the lines with an established connection to an RTK base station for the points with a large deviation. Some of the areas where the collection occurred did have nearby utilities, but they were not thought to have generated any interference in locating the gas line. There may be reason to believe that something may have caused such a high deviation between the two datasets, but no single explanation can be determined.

Table 16 below details the total points collected per device and the percentage of these points that were collected with a high-accuracy RTK connection. Note that the GSSI SIR 4000 GPR utilized the software application paired with a high-accuracy GNSS receiver to collect utility locations and did not use a GNSS receiver on the actual GPR device. Depths from the GPR device were manually input into the data entry form on the software application via verbal communication between the pilot demonstration team members from what was reported by the GPR device.

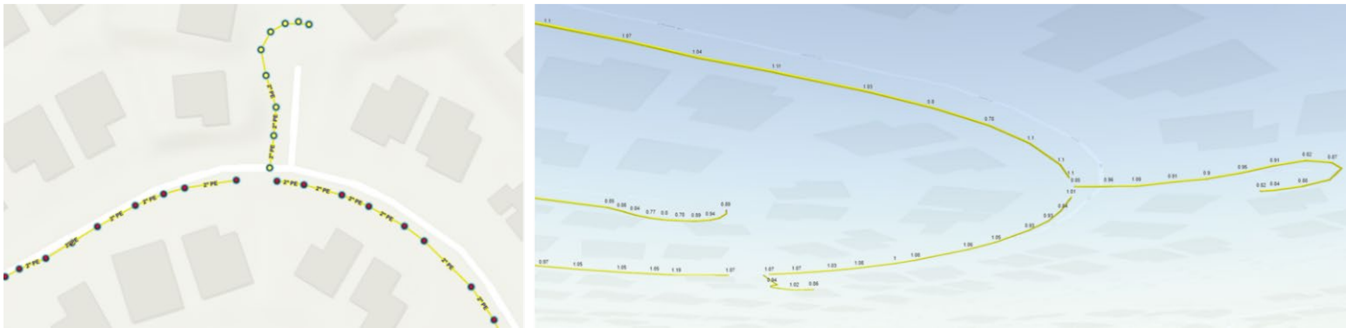
Table 16: 2M Pilot Total Points Collected by Device Name and RTK Fix Percentage

Manufacturer	Point Collection Count	Percent Collected With RTK Fix (Best Accuracy Potential)
GSSI SIR 4000 GPR	53	100%
Radiodetection RD8200G	129	91.40%
Vivax-Metrotech vLoc3 RTK-Pro	120	100.00%

Source: GTI Energy

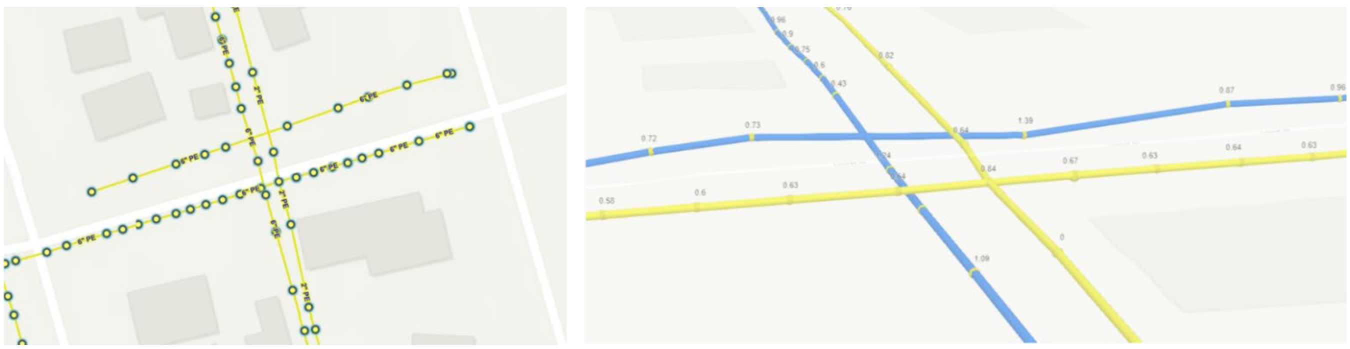
Figure 17 and Figure 18 detail examples of 2D and 3D representations created for two separate 2M pilot demonstration sites within PG&E territory. Additionally, Figure 18 displays the collection of gas and water lines as an example that data on multiple utilities can be collected with the software application and can provide help for future pre-construction exercises.

Figure 17: 2M Utility Locating Pilot 2D and 3D Data Representations — Site 1



Source: GTI Energy

Figure 18: 2M Utility Locating Pilot 2D and 3D Data Representations — Site 2



Source: GTI Energy

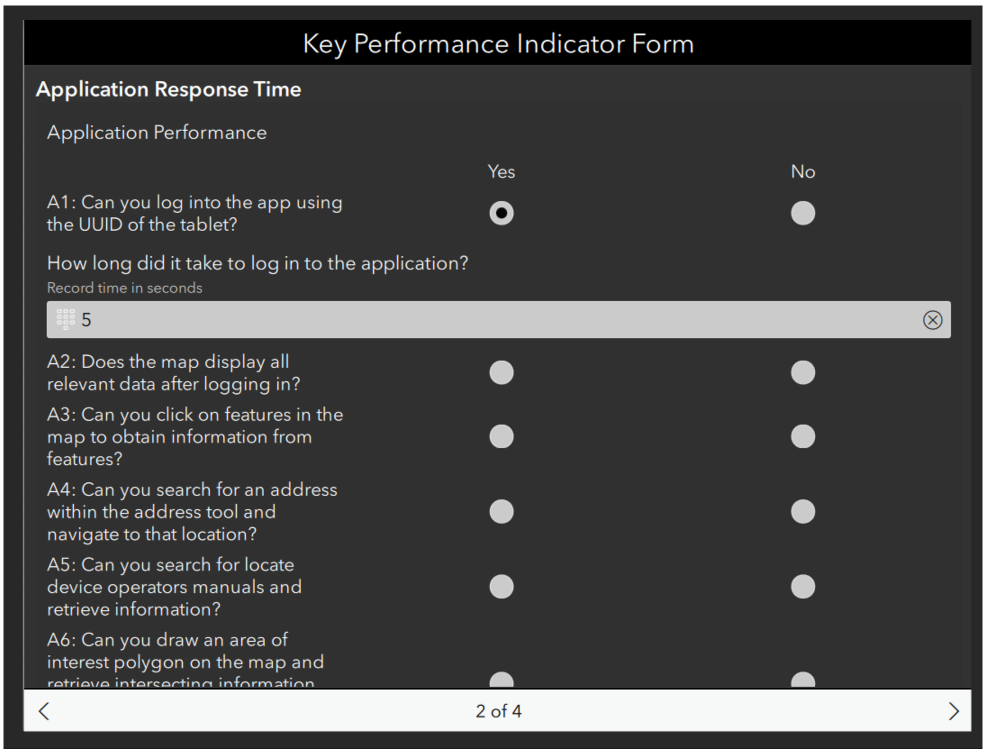
Key Performance Indicator Metrics

In addition to the utility locate data collection portion of this project, GTI Energy was interested in collecting KPI metrics to gauge the performance of the software application while being utilized in the field. These KPIs were collected via a smart form survey accessible on the tablets. These metrics were broken into four separate categories with a range of 8 to 13 questions and addressed the following categories:

- Application Response Time — *how well the application responds when loading data, clicking features to retrieve attributes within the map, toggling from 2D to 3D, etc.*
- Software and Hardware Functionality
    - Device Connections — *how well the software application establishes connections between hardware and software components.*
    - Data Collection — *the user's ability to collect digital utility locates with the tools and software application.*
    - Mapping Interaction — *how well the map within the software application performs when viewing, editing, and querying data.*
- Data Mapping and Data Quality — *how well the software application records, stores, and makes data available about the utility locates collected in the field.*

The following sections discuss each KPI category, based on a collective summary of the performance documented at each site during the pilot demonstration plan. The metrics include PG&E and SoCalGas combined. To collect these metrics while in the field, GTI Energy created a smart form survey that the users could fill out after they completed one full utility line locate. If some of the questions did not apply, they were skipped. The survey users varied within the pilot team, depending on the site and crews that were in the field that day. Eleven KPI surveys were completed by three field crews. If problems occurred, they were addressed by the GTI Energy team. The response time was then measured after the troubleshooting process. The survey asked if certain operations within the software application worked and, if so, how long it took for a given operation to complete. Figure 19 displays an example of the smart form survey used to collect these metrics.

Figure 19: KPI Metric Smart Form Survey



Source: GTI Energy

Poor cellular connection or access to open skies for satellite acquisition can affect the reported values and did, at times, contribute to the pilot team needing to move to a new site to alleviate these issues. However, most values in each category reflect sites where data collection was carried out with adequate cellular connections. It is important to note that digital data collection efforts will most certainly add a little more time to the utility locate experience. Nonetheless, with proper training, collection efficiencies will be realized.

Application Response Time

From software development to testing in the field, applications must perform correctly or they can risk not being adopted. User acceptance can be affected quickly, especially with new technology, new workflows, and necessary training. Application response time metrics provided an excellent way to evaluate the performance of the software and inform the development team of any modifications needed. Table 17 details the metrics defined to understand the application's responsiveness at various points in the software application.

Table 17: Application Response Time Questions and Metrics Measured in Seconds

Application Response Time Questions	Minimum Time in Seconds	Median Time in Seconds	Maximum Time in Seconds
A1: Can you log into the app using the UUID of the tablet?			
How long did it take to log in to the application?	5	5	8
A2: Does the map display all relevant data after logging in?			
How long did it take for the application to load all data?	5	5	7
A3: Can you click on features in the map to obtain information from features?			
How long did it take to retrieve information from features on the map?	3	5	7
A4: Can you search for an address within the address tool and navigate to that location?			
How long did it take to find a location using the search address tool?	5	5	8
A5: Can you search for locate device operator's manuals and retrieve information?			
How long did it take to retrieve results from the operator manuals search?	7	10	10
A6: Can you draw an area of interest polygon on the map and retrieve intersecting information from GIS and influencing factors database?			
How long did it take to draw a polygon and retrieve information?	5	6	30
A7: Can you click on the submitted utility locate point in 2D and 3D on the map to retrieve attributes about that locate?			
How long did it take to retrieve attributes from the locate point (average of 2D and 3D features)?	5	5	9
A8: Can you toggle from a 2D map to a 3D map and visualize their most recent locates?			
How long did it take to toggle between 2D and 3D?	5	7.5	10

Source: GTI Energy

Software and Hardware Functionality

This project included multiple pieces of hardware that connected and transferred data to the software application over Bluetooth. A utility locate device may connect to the tablet and send locate data in real time while a separate high-accuracy GNSS receiver is also connected and transferring data. Some of the characteristics of these hardware devices can generate communication problems that are out of the user's control but are worth monitoring. Table 18 below details the metrics used to track the functionality of these components concerning device connection, data collection, and mapping interaction.

Table 18: Software and Functionality Questions and Metrics Measured in Seconds

Software and Hardware Functionality Questions	Minimum Time in Seconds	Median Time in Seconds	Maximum Time in Seconds
Device Connections			
B1: Establish a connection from the field tablet to an RTK (Real-Time kinematic) base station?			
How long did it take to make a connection?	5	9	300
B2: Did you establish a connection between the field tablet and the high-accuracy GNSS receiver?			
How long did it take to make a connection?	5	8	300
B3: Did you establish an RTK fix between the GNSS receiver and the RTK base station?			
How long did it take to make a connection?	5	5	300
B4: Did you establish a connection between the field tablet and locate device via Bluetooth?			
How long did it take to make a connection?	5	5	10
Data Collection			
B5: Were you able to collect a geo-point of the underground utility gas line and accompanying attributes with the locate device streaming data to the software application (Vivax-Metrotech vLoc3 RTK-Pro)?			
How long did it take to collect a geo-point with this device?	5	5	10
B6: Were you able to collect a geo-point of the underground utility gas line and accompanying attributes with the locate device streaming data to the software application (Radiodetection RD8200G)?			
How long did it take to collect a geo-point with this device?	5	5	8
B7: Were you able to collect a geo-point of the underground utility gas line and accompanying attributes with the locate device streaming data to Leica's software application (Leica DSX GPR)?			
How long did it take to collect geo-points with this device?	5	302.5	600

Software and Hardware Functionality Questions	Minimum Time in Seconds	Median Time in Seconds	Maximum Time in Seconds
Mapping Interaction			
B8: Can you view the locate geo-point in 2D and 3D on the application?			
How long did it take to view the geo-point in both 2D and 3D modes?	5	5	12
B9: Can you edit or delete a located geo-point?			
How long did it take to edit a located geo-point?	5	5	10
B10: Can you query the surrounding area near the pipe to be located and retrieve information to help in the utility locate process?			
How long did it take for the query to run and retrieve results?	5	6	120
B11: Can you map and store existing locate data by uploading a file to the software application?			
How long did it take to upload a file and map the data?	5	12	15
B12: Can you use the tracking tool to navigate to an existing pipe or an existing utility locate point?			
How fast did the tracking tool find you on the map and follow you as you walked?	5	9	30

Source: GTI Energy

Data Mapping and Data Quality

Currently, utility locating processes typically involve using small flags or spray paint to mark an underground pipe. The paint and flags are temporary; once the work is complete, the marks eventually disappear. This process works and allows for safer construction activities, but the lack of a digital record for further analysis or future use (specifically, preplanning activities) is a missed opportunity. Moreover, digital locate data can help utility companies in their data integrity efforts by comparing high-accuracy utility locates to their existing GIS databases. The data mapping and data quality metrics intend to capture the benefit of a real-time data collection and storage platform for a digital utility locate data and metadata attribution. Table 19 below details the metrics used to track the mapping quality of the digital utility locate data collected under the pilot (quality as measured by the additional data captured in a digital locate versus traditional mark and locate procedures).

Table 19: Data Mapping and Data Quality Questions and Metrics Measured in Seconds

Data Mapping and Data Quality	Minimum Time in Seconds	Median Time in Seconds	Maximum Time in Seconds
C1: Can you see that Latitude, Longitude, Altitude, and Depth have been recorded and submitted to the backend cloud database and display on the map as a geo-point?			
How long did it take to record these attributes?	5	5	8
C2: Can you see additional fields from the locate device are recorded and stored as attributes on the mapped geo-point (i.e., frequency, antenna type)?			
How long did it take to record these attributes?	5	5	74
C3: Has a Job ID been recorded and submitted with the locate geo-point?			
How long did it take to record these attributes?	4	5	35
C4: Can you see that the locate geo-point was submitted with an RTK status defining the general quality of the locate point collected?			
How long did it take to record these attributes?	5	5	35
C5: Can you see the number of satellites is recorded from the GNSS receiver (either from an external device or from the locator itself) and is stored on the geo-point?			
How long did it take to record these attributes?	5	5	10
C6: The depth of utility locate is recorded and stored on the locate geo-point from the locate device or entered manually by locator personnel?			
How long did it take to record these attributes?	5	5	8
C7: Can you see that the Absolute Height is automatically calculated and recorded on the locate geo-point submitted?			
How long did it take to record these attributes?	5	5	8
C8: Can the located geo-point collected be compared to legacy GIS records displayed on the map?			
How long did it take to make this comparison?	5	6	20
C9: Can you see which locator device and antenna type that was used to perform the locate equipment are recorded and stored with the geo-point?			
How long did it take to record these attributes?	5	5	55
C10: Was the utility being located recorded based on its type (i.e., Gas, Water, etc.)?			
How long did it take to record these attributes?	3	5	5
C11: Can you see that the Site Conditions Form has been submitted, and results are visible on the map?			
How long did it take to see the results on the map?	5	5	5

Data Mapping and Data Quality	Minimum Time in Seconds	Median Time in Seconds	Maximum Time in Seconds
C12: Can you see the utility locate points collected and stored in 2D and 3D formats?			
How long did it take to see the results on the map?	5	5	10
C13: Can you see the utility locate lines constructed from the collected points are stored in 2D and 3D formats?			
How long did it take to see the results on the map?	5	5	10

Source: GTI Energy

These metrics show good performance results for the software application during the pilot demonstrations with PG&E and SoCalGas. Most of the answers to the questions suggest the application responded appropriately while out in the field. The exceptions are perhaps some slight issues with connecting to an RTK base station or configuring the locate devices to communicate with the tablet promptly. Unfortunately, these issues are common when using a workflow encompassing multiple pieces of hardware and software set up to collect high-accuracy utility locate points. Table 20 below shows a breakdown of pilot demonstration sites, the total time of the entire utility locate, the average time spent at each data collection point, and the median distance between data collection points measured in feet.

Table 20: Digital Utility Locate Points Summary Statistics for PG&E and SoCalGas Pilots

Location	Data Collection Start Time	Data Collection End Time	Total Data Collection Time (Hour, Min, Sec)	Average Time Spent Per Collection Point (Min, Sec)	Linear Distance of Job (Feet)	Median Distance Between Points (Feet)
Oakley, CA	6/28/2022 17:04	6/28/2022 17:32	0:27:33	0:41	616	15.82
Oakley, CA	6/28/2022 18:28	6/28/2022 18:43	0:14:54	0:18	865	16.79
Rio Vista, CA	6/29/2022 18:42	6/29/2022 18:50	0:08:47	0:29	276	13.29
Rio Vista, CA	6/29/2022 21:05	6/29/2022 21:31	0:26:25	0:55	483	17.09
Rio Vista, CA	6/29/2022 22:16	6/29/2022 22:23	0:07:04	1:01	169	13.30
Oakland, CA	7/14/2022 17:50	7/14/2022 18:14	0:24:12	0:36	727	5.86
Oakland, CA	7/14/2022 18:28	7/14/2022 18:43	0:15:12	0:29	559	17.70
Walnut Creek, CA	7/14/2022 21:12	7/14/2022 21:22	0:10:23	0:28	352	17.63
Fremont, CA	7/28/2022 16:59	7/28/2022 17:05	0:06:23	0:07	702	19.10
Fremont, CA	7/28/2022 20:08	7/28/2022 21:18	1:10:36	0:34	2069	12.71
Alameda, CA	8/9/2022 16:58	8/9/2022 18:08	1:09:24	1:01	840	32.19

Location	Data Collection Start Time	Data Collection End Time	Total Data Collection Time (Hour, Min, Sec)	Average Time Spent Per Collection Point (Min, Sec)	Linear Distance of Job (Feet)	Median Distance Between Points (Feet)
San Leandro, CA	8/9/2022 21:38	8/9/2022 21:50	0:12:28	0:14	674	26.03
Whittier, CA	9/8/2022 15:13	9/8/2022 15:27	0:14:21	1:12	215	30.44
Downey, CA	9/8/2022 16:36	9/8/2022 16:41	0:05:29	0:47	158	40.98
Downey, CA	9/8/2022 16:49	9/8/2022 17:02	0:13:49	0:33	489	30.53
Downey, CA	9/8/2022 17:35	9/8/2022 17:49	0:14:00	1:16	329	31.06
Downey, CA	10/11/2022 16:23	10/11/2022 16:46	0:22:46	2:04	469	34.73
Downey, CA	10/11/2022 17:27	10/11/2022 17:35	0:08:26	0:46	268	42.21
Downey, CA	10/11/2022 18:15	10/11/2022 18:22	0:07:04	0:42	298	20.26
Bellflower, CA	10/11/2022 20:38	10/11/2022 20:49	0:11:05	0:33	667	29.89
Highland Park (LA), CA	10/18/2022 17:59	10/18/2022 18:08	0:09:00	0:26	904	12.71
Los Angeles, CA	10/18/2022 20:53	10/18/2022 21:00	0:06:45	0:20	508	79.50
Burbank, CA	10/19/2022 16:37	10/19/2022 16:55	0:18:34	1:14	719	21.51
Brea, CA	10/19/2022 18:02	10/19/2022 18:26	0:24:27	1:07	1455	23.45

Source: GTI Energy

The pilot demonstration sites and the data collection efforts provided unique insight into conducting a digital utility locate versus a typical ground spraying/flag placing locate. Field locators were encouraged to collect data more frequently than a spacing of 25 feet to 50 feet, as more frequent data collection generates a more accurate 3D underground representation of the buried pipe. As the depth of cover was collected from the locate device, it was then used to create the pipe below-ground, giving the users a great depiction of how the pipe was installed and its current position. Knowing these below-ground elevations can then be used for pre-digging evaluations or pre-construction design to ensure no damages occur. Additionally, users can access this data immediately after it is collected via their tablets in the field and on remote computers that have access to the GIS into which the locate data were saved; this is done by navigating to the precise location of the previously collected locate to see labels of the depth of cover of the pipe at that exact location. These tools and the data collected with their use indicate that collecting utility locates in a digital format has a large value-added for preventing future pipe damages, as long as the data is collected properly with high accuracy and stored with the proper attributes.

CHAPTER 4: Conclusions and Recommendations

This project aimed to improve the utility locate process through development of a software application to permanently record locate information as digital data that is integrated and visualized in existing geographic information systems in both 2D and 3D formats. Field-usable software was created to capture, store, and visualize locate measurements and geolocations, with the data being available for planning, analysis, and reporting purposes. Real-world setting pilots conducted with utility personnel and professional locators demonstrated the technology's ability to generate accurate data without making the locate process unduly cumbersome. Pilot participants' feedback on the technology's usefulness was positive. The following conclusions were drawn from project execution.

Conclusions

This project moved away from solely utilizing locate ground markings towards leveraging data stored and displayed in a centralized GIS cloud database to facilitate the locating process. The custom-built software application allowed field users and office personnel to visualize these digital locates in real time in both 2D and 3D formats via a tablet or desktop computer.

The project's application development intent was not only to perform and validate the digital locate business process but also to simultaneously provide useful information to locators to inform decision-making prior to or during field activities. The software application made existing GIS data available, guiding users with current pipe location information. Newly collected data were mapped alongside existing data in real time, offering an option for utility companies to review the two datasets and realign their existing data. Vital information available included joint trench installations, tracer wire existence, ground penetrating radar device suitability, and surrounding soil properties.

Throughout the software platform evolution from design to build to pilot demonstrations, emphasis was placed on enabling end users' quick success with minimal training. To effectively utilize the system, locators need only understand how to connect to the locate device, to connect a high-accuracy GNSS receiver to a tablet, and to access the application's data access form. Users typically found the process simple after one day to two days of training and field practice, as they were able to collect hundreds of linear feet of pipe in approximately 15 minutes to 30 minutes.

Though a rare cell phone service issue was experienced that prevented RTK base station connectivity, generally the application performed as expected during the pilot demonstrations. Data were still able to be collected, but high-accuracy capabilities were preferred for providing transparency on the pipe's true location. Regardless of methodology, digital locate data must be properly attributed to ensure locate validation. If this database continues to grow with utility locate data in similar areas, it will need some form of data governance to ensure that the most accurate data is being represented, so as not to confuse the viewer on the actual location and depth of the underground pipeline.

The software application holds significant potential to help the industry move towards reduced dig-in damages. The combination of 2D and 3D visualization formats and accurately attributed data facilitates locate efficiency through improved site transparency and informed decision-making. Digital utility locates improve legacy GIS data by providing an extra dataset for quality analysis and control. As the industry moves toward better record retention and data sharing, many are starting to require the collection of vertical (Z) values in unison with traditional horizontal (X, Y) values. This project, and the application developed as part of the scope of work, has proven that collecting digital utility locates in all three dimensions (X, Y, and Z) is not only feasible but also helps to better understand the subsurface environment.

Project Benefits

The benefits of the wide adoption of the technology developed in this project span several categories.

Cost Reduction

Cost reductions would likely result from several aspects of the technology:

- Feedback from utility personnel indicate that savings would result from a reduced need for surveying services (up to $2,500 per day).
- There would be a reduced need for revisiting sites, because locate information would be available digitally in perpetuity rather than just as paint marks on-site. This means a reduction in labor hours, saving both time and money and freeing workers for other productive tasks.
- A streamlined workflow that is facilitated by digitalization (as opposed to storing and retrieving locate data on paper or not at all) represents cost-saving efficiencies.
- Costs related to excavation damage would be reduced. The Pipeline and Hazardous Materials Safety Administration has documented that, in 2021, excavation damages in the state of California cost $2,911,112. In 2022, that number was $713,139 (Pipeline and Hazardous Materials Safety Administration, 2023). Though it is difficult to say what percentage of incidents this technology could prevent, a very conservative estimate of 20 percent, based on the easy availability of high-accuracy pipeline location information, would mean savings of over $700,000 in the state of California alone.

Safety Enhancement

Having readily available and accurate information about pipeline locations also results in safety enhancement:

- This technology’s expected reduction in pipeline encroachment would not only save money but also protect the health and life of industry workers and people living nearby.

- Being able to remotely view underground data would mean less need for visits to sites, including some that are inherently unsafe.
- The 3D visualization component of this technology means being better able to see where assets are in space and their relation to each other; this fosters cooperation among utility companies and makes unsafe construction decisions and actions less likely.

Operational Efficiency Opportunities

This data digitization technology supports improved operational efficiency:

- Locate information in digital format is more conducive to performing advanced trend analyses to support increases in business function efficiency via continuous process improvement efforts.
- This technology promotes advanced planning initiatives by enabling users to view and conceptualize the location of assets as they realistically are underground. Successful detailed planning, in turn, provides the opportunity for improved field work execution efficiencies and outcome success.
- The ability to back up, archive, and restore data in digital format during business continuity activities makes them much less prone to permanent loss than locate data retained in paper format.
- Other data digitization advantages, such as integration with other systems, sharing with cross-functional organization groups, and status reporting, also apply to the digitization of locate data.

Industry Engagement and Information Sharing

GTI Energy worked with industry operators through Operations Technology Development organizations. Operations Technology Development, LLC, is a research consortium of gas utilities that provided additional financial support for this project. Two member organizations, SoCalGas and PG&E, were integral pilot demonstration partners, offering subject matter expertise and feedback for all facets of the application platform. Operations Technology Development sponsor organizations were kept apprised of project activities via quarterly progress reports, while updates were provided monthly to the CEC.

The project team performed a number of outreach events aimed at sharing project information and fostering awareness and adoption of the system. Efforts occurred in the form of conference presentations, trade journal publications, and workshop execution. The project team communicated to infrastructure management and GIS communities via a presentation at the 2022 Esri IMGIS Conference. Additional outreach occurred via publication of a project case study in a North American Society for Trenchless Technology trade journal. Furthermore, software demonstration workshops were conducted with the operator pilot demonstration partners.

Recommendations and Next Steps

Two models for turning the prototype system into a product for regular use are identified here from the many models available for system advancement. One model involves tailoring the system for use by a single entity, such as a utility company or a company that specializes in locating. A second model would be the creation of systems by a service provider for use by other organizations. The service provider could provide the necessary components for customers to take and use, for a one-time transaction fee. Alternatively, given the present popularity of the software as a service business model, the provider could provide some resources up front (for example, some or all of the hardware and perhaps the field software) while charging for ongoing services (for example, cloud services).

Future development of the technology could include improvements, refinements, and additional software features, such as the ability to run on iOS and Android, support for more locate devices, integration with non-Esri GIS, and more robust user authentication and security. Commercialization of the technology could involve partnering with locate device manufacturers, companies that provide locating as a service, or possibly utility companies. Another possibility is partnering with an existing locate software company to incorporate one or more of the features, for example, 3D visualization. Though no specific activities were undertaken at the time of the writing of this report, GTI Energy sees value in such endeavors for continued development and eventual commercialization of the developed technology.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
2D	two-dimensional
2M	2M Utility Locating
3D	three-dimensional
CEC	California Energy Commission
EM	electromagnetic
GIS	geographic information system
GNSS	Global Navigation Satellite System
GPR	ground penetrating radar
GPS	global positioning system
IMGIS	Infrastructure Management and GIS (Esri conference)
KPI	key performance indicator
PG&E	Pacific Gas and Electric Company
RTK	real-time kinematic
SoCalGas	Southern California Gas Company

References

California Office of Environmental Health Hazard Assessment. 2023. "CalEnviroScreen 4.0." Available at https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40.

Pipeline and Hazardous Materials Safety Administration. 2023. "Incident and Accident Pipeline Social Equity Tools." U.S. Department of Transportation. Available at https://dac-phmsa-usdot.hub.arcgis.com/pages/incidents-accidents-data-for-download.

U.S. Department of Justice. 2003. "Systems Development Life Cycle Guidance Document." Available at https://www.justice.gov/archive/jmd/irm/lifecycle/table.htm.

Project Deliverables

TASK 2: ANALYZE AND EVALUATE PARTICIPATING LOCATE DATA SOURCES

Products:

- Data Source Evaluation Document

TASK 3: SOFTWARE SYSTEM REQUIREMENTS AND DESIGN

Products:

- General System Business Requirements Document
- GIS Re-Mapping Pipe Locating Business Requirements Document
- GIS Stake-Out Locating Business Requirements Document
- Hardware/Software Interface Requirements Document
- Software and System Requirements Document
- Field/Office Side Interface Design Document

TASK 4: DEVELOP CLOUD-BASED AND FIELD-BASED SOFTWARE SYSTEM

Products:

- Integration Testing Plan
- Development Phase Bug Resolution Document
- Demonstration Site Key Performance Indicators (KPI) Evaluation Plan
- Field-based Testing Workflow and Data Collection Form

TASK 5: PERFORM SOFTWARE SYSTEM TESTING

Products:

- System Testing Scripts Document
- System Testing Phase Bug Resolution Document

TASK 6: PILOT DEMONSTRATION AND ANALYSIS

Products:

- Demonstration Plan
- Pilot Demonstration and Analysis Document

TASK 9: PRODUCTION READINESS PLAN

Products:

- Production Readiness Plan

These deliverables are available upon request by submitting an email to pubs@energy.ca.gov.