gti

the Energy to Lead

FINAL REPORT

GTI PROJECT NUMBER 21086

Acoustic-based Technology to Locate Buried Pipes

DOT Project # 365
Contract Number: DTPH56-10-T-000020

Reporting Period:
Final Report
September 2010 through July 31, 2011

Report Issued (Period Ending):
July 29, 2011

Prepared For:
Mr. Frank Licari
PHMSA AOTR

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

Project Technical Team:
Dr. Kiran Kothari, GTI
Ching-Chen Wu, SoniVerse Inc.
Dr. Maureen Droessler, OTD

Operations Technology Development
1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gastechnology.org

Legal Notice

This information was prepared by Gas Technology Institute (GTI)/SoniVerse Inc. (SVI) for DOT/PHMSA (Contract Number: DTPH56-10-T-000020).

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

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

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

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

Table of Contents

gti

Abstract

The objective of this project is to build a pre-commercial device, improve its performance to detect multiple buried pipes, and evaluate the pre-commercial device at utility sites. In the past, Gas Technology Institute (GTI) and SoniVerse Inc. (SVI) with support from Operations Technology Development, NFP (OTD) have developed an acoustic-technology-based technology to detect buried natural gas pipes, with emphasis on detecting buried polyethylene (PE) pipes. The concept is to send the acoustic signal into the ground and detect the reflected signal from the pipe at ground level. The device has been referred to as Emulator, and was successfully tested in the laboratory and at several utility locations under a variety of field conditions to detect both metal and PE pipes buried up to 5 feet. The Emulator consists of a laptop computer, off-the-shelf data acquisition module, high power class D amplifier, deep cycle car battery, and exchangeable sensor modules.

The work conducted under this DOT/PHMSA project improved/developed and built an integrated, hand-held device – pre-commercial unit – to detect buried pipes. The integrated device was successfully tested at several field sites. The detection of buried natural gas pipes, especially PE pipe, will assist the gas industry and pipe locator companies to locate pipes before excavations/construction. This will reduce the third party damages to the underground utilities, increase safety of the natural gas distribution system, and reduce gas industry operating costs.

Executive Summary

The driving force behind this research effort is the significant need for technology to detect and locate buried underground natural gas pipes, particularly PE pipes. Pipelines buried a few feet under the ground are subject to leaks and failures. The damage and injuries from accidental penetration of buried pipelines are very costly; therefore, it is extremely desirable to produce a method for detecting and locating plastic pipes. The industry need for the technology emphasized that the system should operate near the surface of the ground, be suitable for most soil conditions, and simple to operate. The acoustic technology has a potential to meet this need because the acoustic waves can penetrate in most soils for detecting buried pipes.

In the past, GTI and its subcontractor, SoniVerse Inc. (SVI), have developed the technology and built an operational sonic pulse-echo unit called Emulator to detect buried utility pipes under the OTD funding. This system used just two transducers – one to transmit and other to receive the sonic signal. This past system was tested under a wide variety of surface conditions in regions on the East and West Coasts of the United States. The accuracy of pipe detections in the field has been better than 80% within ± 18 inches. This accuracy is close to 90% where the pipe has to be detected within ± 24 inches. The system performance was calculated based on standard statistical methods. The pipe detection accuracy is the absolute value of the difference between predicted by the system and actual value by the verification methods. The conclusion from the past research was that the Emulator worked well under both hard and soft surface, including grassy field.

Under this jointly funded project between DOT/PHMSA and OTD, the system was improved to detect multiple buried pipes. Two highly integrated, acoustic-based, pipe inspection systems were designed, built, and field tested. A new receiver module with compact, integrated, and robust housing was designed and fabricated. An innovated, integrated suspension system was developed, built, and field tested for the receiving transducer module. This new design approach used the structural molding techniques has achieved better acoustic isolation than the previous design and its construction has been greatly simplified when compared to previous design. A high power acoustic transmission system similar to the previous design was developed and built. A new, double suspension structural design provided the transmitter module better acoustic isolation to the entire integrated system housing and to the receiving transducer. The transmitting transducer used the integrated system housing for its ground coupling weight which proved to be well balanced and meet the design requirement.

A new Nano-ITX computer form factor was selected for the integrated system's signal processing unit. The controller unit is compact and uses all off-the-shelf components. The computing performance of the processing unit is effective and adequate for the real-time data collection and signal processing tasks. New class-D power amplifier delivered sufficient driving power to the transmitting transducer. A compact, high-brightness LCD panel used for the data display and user interface was developed and implemented. The display used touch screen technology to simplify overall system operation. The elimination of keyboard and mouse inputs provided flexibility and ease of use of the inspection system during the pipe detection process.

A new multiple pipe detection algorithm and display format were designed and implemented in the system software for the integrated inspection system. The new processing technique evaluates potential underground pipe based on the detection criteria and the soil condition under test. Both vertical and horizontal signal information were processed and displayed during the detection process. This new detection technique and feature minimized the pass/fail uncertainty in many pipe detection situations.

Test procedure and test protocol for the new multiple pipe detection process was established in accordance with the new system software and user interface. In addition, several critical test criteria were incorporated into the data collection procedure, inspection protocol, and software development as the guidelines of the overall system design requirements and specifications.

The overall inspection system was field tested at various local and real-world test fields around the United States. The inspection system works as expected and met its design specification and requirement. Better than 89% accuracy was achieved based on the overall test data collected and analyzed during the field trials.

Introduction

Background and Project Objective

GTI and SVI conducted initial studies on both sonic and GPR (ground penetrating radar) approaches to detect buried natural gas pipes. Although GPR has some operational advantages to acoustic methods it was concluded that there are too many regions of the country where the soil attenuation is too high for GPR to penetrate. The signal transmission/receiving with the GPR is the fundamental issue and the technology cannot provide a solution to detect buried pipes under expected ground conditions. Hence, it was concluded that sonic technology development work would assist the gas industry to detect small diameter buried pipes, particularly PE pipes.

In the previous project (Project Number 1.h with OTD), an operational, hand-held, portable acoustic detection system, OTD-1, for detecting underground utilities was designed, built, and successfully demonstrated under the OTD funding, Ref.1. The hand-held acoustic pipe locator was developed to detect small diameter plastic pipes at relatively shallow depths (up to 5 feet). The detection worked well in various soil conditions including topsoil, concrete, and asphalt.

An Emulator unit was designed and delivered for evaluating transducer and overall system performance. The operational Emulator consists of a laptop computer, off-the-shelf data acquisition module with high-resolution analog-to-digital conversion, class-D amplifier, self-sustaining battery, and transmit-receive sensor module. The system software provides automated pipe detection program as well as easy to operate user interface. A series of system tests were performed and the overall system performance of automated pipe detection was evaluated. The Emulator was tested under a wide variety of surface conditions in regions on the East and West Coasts of the United States. The accuracy of pipe detections in the field has been better than 80% within ± 18 inches. This accuracy is close to 90% where the pipe has to be detected within ± 24 inches. The conclusion was that the operational system worked well at both hard and soft surface, including grassy field.

This Emulator provides the starting point for this DOT/PHMSA funded project with objectives to improve for detection of multiple buried pipes in the area of interest, build highly integrated, acoustic-based, pipe inspection systems, and continue the system evaluation in a series of field tests.

Theory of Operation

The wave equation is commonly used in the conventional radar and sonar techniques in detecting and locating target within specific propagation medium in space and time domains. Most developed and robust wave scattering theory adopted and derived the general wave propagation phenomena from the optical theorem and principle. In general, an acoustic pressure wave can be expresses as following linear equation form:

$$\frac{\partial^2 p}{\partial x^2} = \rho_o \kappa \frac{\partial^2 p}{\partial t^2},$$

where **p** is pressure, $\boldsymbol{\rho_o}$ is the medium density at equilibrium, and $\boldsymbol{\kappa}$ is the compressibility. This is a one-dimensional form of the wave equation in time ***t*** and position ***x***.

The general form of the basis function **p** is a continuous plane wave. As in analytic form would be:

$$p(x,t) = P_o \cos(2\pi \cdot f \cdot t + k \cdot x),$$

where $\boldsymbol{k = 2\pi \cdot f/v}$, for a plane wave of amplitude $\boldsymbol{P_o}$ and wave number $\boldsymbol{k}$ traveling along the $\boldsymbol{x}$ axis in a medium of sound speed $\boldsymbol{v}$ at time $\boldsymbol{t}$.

Using the Schrödinger equation, the plane wave function can be expressed as a complex phase factor with form as:

$$p(x,t) = P_o e^{i(k \cdot x - \omega \cdot t)},$$

where $\boldsymbol{\omega = 2\pi \cdot f}$, is the angular frequency of the plane wave of amplitude $\boldsymbol{P_o}$ and wave number $\boldsymbol{k}$ traveling along the $\boldsymbol{x}$ axis at time $\boldsymbol{t}$.

An acoustic pipe detector operates as shown in Figure 1a. A transducer transmits a short acoustic impulse into the ground. The acoustic wave reflects from any acoustic discontinuity or acoustic impedance mismatches. The interface between a solid and a gas (inside of a natural gas pipe) provides a practically 100% reflection coefficient. The reflection coefficient of earth and the outside of a utility pipe is lower, and between earth and rock is still lower. A receiving transducer detects the acoustic echo as well as a surface wave that travels directly from the transmitting to the receiving transducer, see Figure 1b.

The abilities to distinguish small diameter pipes and pipes in close lateral proximity are improved as the acoustic frequency is increased (the wavelength is shortened) but the attenuating power of the earth also increases with frequency. Earth attenuation sets the maximum usable frequency at any particular depth. The attenuation law is

$$A = A_o \cdot 10^{-\alpha \cdot f \cdot x/20}$$

where:

$\boldsymbol{A}$ = Acoustic amplitude at distance x with attenuation
$\boldsymbol{A_0}$ = Amplitude ignoring attenuation.
$\boldsymbol{f}$ = frequency (*KHz*)
$\boldsymbol{x}$ = distance into the earth (*cm*)
$\boldsymbol{\alpha}$ = soil attenuation constant (*dB/KHz·cm*).

The published values for attenuation range from 0.1 to 0.9 dB/KHz·cm depending on the type of soil, moisture level, and compaction. The nominal attenuation coefficients in the local area indicated typical values of 0.2 to 0.6 dB/KHz·cm. These coefficients can change based on the ground condition such as frozen soil.

There is a minimum frequency that can be used. This occurs (approximately) when the wavelength of the acoustic wave equals the circumference of the smallest diameter pipe to be detected. The relationship between frequency and acoustic wavelength is

$$f \cdot \lambda = v,$$

Where $\boldsymbol{\lambda}$ is wavelength (cm) and $\boldsymbol{v}$ is the propagation velocity (cm/sec).

The ability of the pipe to reflect the wave back to the receiving transducer is related to the pipe's acoustic scatter cross-section which is illustrated in Figure 1c (Mie Scattering/Theory). The vertical axis is the log of the scatter cross-section divided by the physical cross-section. The horizontal axis is the log of the ratio of the circumference of the pipe over the wavelength. As can be seen the scatter cross-section is close to the physical cross-section if the wavelength is shorter than the circumference of the pipe. If the circumference is smaller than the wavelength, the scatter cross-section drops rapidly. This means that at lower frequencies the wave diffracts around the pipe without reflection even if the reflection coefficient is 100%. Similar observations are also true for GPR reflections from non-metallic pipes.

Range resolution (the ability to distinguish pipes one behind the other) depends on acoustic bandwidth. Put it another way, the acoustic pulse must be short because

$$R = \frac{\upsilon}{2 \cdot \Delta f} \quad \text{and} \quad \Delta f = 1/\tau \quad \text{(approximately)}$$

where:

R = resolution (cm) - needed pipe separation to produce distinct echoes
Δ***f*** = bandwidth (Hz)
τ = pulse duration (sec).

What this all means is that one should use the maximum frequency permitted by the depth of the pipe and soil attenuation. This frequency determines the wavelength and hence the smallest pipe that can be detected. The maximum bandwidth (shortest pulse length) should also be used with the understanding that the higher part of the acoustic spectrum will be attenuated if the operating frequency is also high.

Work Plan

The transducer and system configurations of this PHMSA project will be similar to the OTD-1 system and to the system architecture of the emulator. In addition to the basic system controller configuration and general user interface implementation adopted from the previous system software, the signal processing routines require modification for the multiple pipes detection algorithm, advanced user interface, and other software refinements. Two stand-alone, integrated pipe detection systems will be built and tested in the field trials. No architectural or systematic change will be made as compared to the existing Emulator system which consists of a computerized system controller, data storage subsystem, data acquisition module, power amplifier, integrated sensor module, and self-sustaining battery power source.

The following tasks were identified for the acoustic-based, integrated acoustic pipe detection system:

1. All-Terrain Transducer Configuration

   As indicated, no major change of the transducer configuration will be made to the existing sensor module. However, the housing of the transducer will be optimized so that the sensor module design will be accommodated by the overall system electronic controller and other peripheral configuration and design. The modular design of the sensor module will be further improved to be truly fast exchangeable, especially in the field.

   The performance of the transmitting transducer will be optimized by using the existing coupling interface configuration, improved power penetration for the soft grassy surfaces, and padded coupling disk to reduce ringing pattern in hard surfaces such as concrete and asphalt. With optimized coupling mechanism, the sensor module performance will be further improved for both hard and soft surfaces.

The suspension system of the sensor housing will continue the use of the existing diaphragm suspension design which provides excellent acoustic isolation from both transducer housing and system packaging. No additional weight will be used as the coupling force for the receiving transducer since the overall integrated system housing has already provided necessary and adequate coupling effects.

2. Multiple Pipes Detection Algorithms

The current Emulator software is optimized for a single pipe detection based on the signal strength of the return signals. The gas industry sponsors have suggested it will be valuable to have multiple pipe detection capability, particularly in highly congested areas.

The current test protocol of acoustic locator system used a so-called “linear-scan” method for detecting underground obstacle. In practical situation, pipe distribution spreads in the direction of detection path (laterally) and along the buried depth (vertically). Therefore, multiple pipe detection is essential in determining pipe distribution where utility junction area is presented and/or any unmapped area with old utilities.

Under this task, a multiple pipe detection routine will be implemented in the signal processing chain. The proposed implementation of the process will be focused on the development of robust signal processing techniques in quantifying signal strengths with respect to the stepping distance and the spacing between transmit-receive transducer pair. The operator will have the option to turn on or off the multiple pipe detection mode based on a priori situation.

The ability to detect multiple pipes is expected to be strongly influenced by the stepping distance used during the detection process. This modality operation differentiates the distinct pipes as long as the separation of the pipes is larger than the stepping distance during the pipe detection process and the pipes are not drastically different in the size. The stepping distance is a function of pipe size to be detected. The six inches stepping distance used in the current project was based on pipe size to be detected by gas utility operations.

3. Integrated System Housing with Electronics and Software

A new, integrated acoustic pipe locating system will replace the existing emulator system. The selection of the system electronic components (single board computer, data acquisition subsystem, and power amplifier) will be focused on the form factor that fits into the system housing design and the computation performance that meets the design requirements.

The major components of the system electronics consist of a highly configurable CPU controller board, a high accuracy (24-bit), multi-channel A/D data acquisition module, and a high capacity class-D power amplifier. All parts are off-the-shelf components that are easily replaceable and require minimum maintenance. In the early research study, Li-Ion battery stands out as the best candidate for its excellent weight-to-power ratio. The other power saving requirement can be achieved by using the state-of-the-art, low power CPU boards which are very popular in the recent development of industrial embedded controller design. Among them, the ITX (in mini-, nano-, and picoconfigurations) form factor single board computer delivers the most desirable features and well balanced design criteria between computational performance and small form factor requirement.

The integrated system housing provides the housing/packaging of the sensor module and system electronics in one unit. Functionally, the integrated housing provides strategic location and placement of coupling mechanism to the sensor module as well as locating/protecting of the system electronics and battery.

A fully automated test procedure will be implemented in the system software with the help of touch-screen user interface. Field recording and reporting routines will automatically be generated in the system software for the field tests. User interface and test result display format will be similar to the ones used in the previous field trials conducted with the Emulator. A multiple pipe detection feature is selectable by the operator during the field test.

4. Field Tests

   On completion of the integrated system, the device will be tested in the local environment. The project plan is to arrange a meeting with the project manager, utility members, and commercial partner. At each test site, depending on the available soil condition, estimated 3 to 4 days of system preparation and field testing will be performed. In between test sites, data analysis and test result assessment will be conducted. All test data and results analysis will be automatically and digitally recorded.

   The project results will be presented, the utility staff will be briefed on how to operate the device, and field tests will be conducted in the local area. Additional field trials will be performed at several sites in the utility environment. These field tests will be performed under various soil conditions (e.g. hard, soft, and grassy field surfaces) to detect buried pipes of various diameters.

5. Reporting and Project Management

   Under this task, the monthly, quarterly, draft final, and final report will be prepared and submitted.

Work Performed

At the start of project, several design review meetings were held between SVI, GTI, vendors, and subcontractors. Preliminary system configuration and design criteria of electronics, sensors, and packaging was discussed and specified. Overall, the ultimate goal was to configure a flexible test platform and instrumentation that will use mostly off-the-shelf components for easy system maintenance and operation.

All-Terrain Transducer Configuration

The sensor module configuration of the new integrated system was based on the successful designs deployed in the previous phases of the project, see Figure 2. The basic layout of the sensor module has 9″ to 12″ center-to-center spacing between the transmitter and receivers. The modular design concept of the previous sensor modules mostly relied on the self- weighting structural design to achieve the ideal and effective coupling mechanism. This coupling concept is still hold true to the new integrated design. However, the weight distribution (as well as effective coupling mechanism) of the new sensor module design comes from the housing and packaging structure surround the sensor module itself. That is to say, the effective coupling will heavily rely on the balanced weight distribution of the overall system – electronics, battery, sensor module, power amplifier, and other peripherals.

The current modular design concept of sensor module is lightweight and acoustically isolated from the main integrated system housing. Most importantly, the receiving transducer suspension employs single piece silicon molding for eliminating operational vibration from the integrated system housing and preventing acoustic resonance from the transmitting element during the system operation. As compared to the previous designs, see Figure 3, the receiver design of the new integrated system is simplified. The design focus is to provide even and adequate coupling force to most ground surfaces. Figure 4 shows the transducer design in the final sensor module configuration for the integrated system. Figure 5 shows the selected transducer components for final sensor module configuration and design. Both transducer types are high performance, industrial-grade components suitable for harsh environment and rough terrain operation.

The final configuration of the transmitting and receiving transducers for the integrated detection system are shown in Figures 5c and 5d. The finalized sensor module design is very robust and easy to fabricate. Bench performance tests for the sensor modules were conducted and evaluated. Final design validation process was completed through the local field tests.

The new transmitter housing, Figure 5c, has been equipped with double suspension and mounting system for better acoustic power transmission. A 3″ steel coupling disk, with rubber padding, was used for optimal ground coupling. The finalized dual-element receiving transducer with silicone molding design is shown in Figure 5d. Compare to the previous designs, the new suspension system is simple and more effective.

The new sensor module design is also simplified. The design focus is to provide even and adequate coupling force to all ground surfaces. The final sensor module configuration is summarized as follow:

- Transmitting transducer (acoustic actuator) –
  - ✓ 3″ steel coupling disk with rubber padding
  - ✓ Double suspension of vibration damping mounts to system housing
- Receiving transducers (accelerometers) –
  - ✓ Dual-element layout with in-line design of 1½″ spacing and
  - ✓ Light-weight silicon suspension molding and anti-vibration mounts to system housing.

The performance test showed that the modules meet the specifications and design requirements.

Multiple Pipes Detection Algorithms

Figure 6 shows a proposed (initial) display format for the new multiple pipes detection algorithm. The detection algorithm, basically, detects and processes potential pipes/targets in two major orientations – lateral and vertical. The lateral detection, on the ground surface, is a line-scan process. Its test result will be affected strongly by the stepping distance of the each linear scan/survey process. The shorter the stepping distance, the better accuracy of the target location can be achieved. However, no systematic study was performed for the stepping distance with respect to target location accuracy.

The vertical (depth) detection is more complicated due to various factors involved in the signal analyzing process. Among the influential factors, frequency range and pipe size are two dominating parameters that need to be further processed and carefully analyzed. Axial resolution, as it relates to depth information, differentiates/resolves potential target(s) in the acoustic beam propagation direction and is inversely proportional to the frequency range detected and processed. Adversely, high frequency acoustic components (signals) while resolving smaller target better than lower ones, the same signals also being attenuated quickly along the axial (depth) direction during the acoustic detection process.

The new multiple pipe detection algorithm, based on the detection criteria that separate the identifiable pipes/targets, divides the scan region into several detection zones, in vertical (depth) direction. Essentially, isolating the individual pipe/obstacle will be the major task of proper target identification during the detection process. New detection criteria was identified and developed for the final analysis.

Figure 7a shows the finalized display format for the new multiple pipes detection algorithm. The user interface uses touch screen technology as the major communication protocol between the operator and the detection system. Basically, the detection system operates in a line-scan process, as indicated in Figure 20b. At each test point (test location, normally, every 6″ apart), acoustic data were collected, processed, and analyzed. Within a given lateral distance surveyed, the final test result was depicted by a single (red) dot display indicating detected pipe (multiple dots if more than one target were detected).

The multiple pipe display format and user interface was tested through a series of data emulation. Figures 7b and 7c show the new multiple detection algorithms applied on the previous field test data. The validation process using the emulated data indicated that the new multiple pipes detection algorithms worked well and was very robust. The emulated test results were validated and met the design specification and requirement.

Integrated System Housing with Electronics and Software

As stated in previous section, the basic layout of the sensor module has 9″ center-to-center spacing between the transmitter and receivers and a 13″x6″ initial, overall projected ground footprint. The overall height of the system, including display panel, is about 30″. Figure 8 shows the initial, detailed conceptual design based on the data specification of major system components.

Apart from the previous separated design, the new portable, integrated detection system contains all system components in one operational unit. The LCD display panel, with touch screen support as shown in Figure 9, will be mounted on the top (holding rod) end of the inspection system.

One of the critical design aspects of the integrated system housing is that the acoustic coupling efficiency will heavily rely on the balanced weight distribution of the overall system – includes system electronics, sensor module, battery power source, and other peripherals. Figure 10 shows the computer board (Nano-ITX form factor) and battery (Li-Ion) power source and were acquired for the integrated system. The functional and electrical wiring diagram of the overall integrated detection system is shown in Figure 11.

The following design specification of the system electronics was identified and finalized:

- ITX (nano-) form factor single board computer –

  - ✓ Used as the main system controller and signal processing unit,
  - ✓ Fitted with LCD display with touch screen support, and
  - ✓ Matlab technical computing environment.

- USB data acquisition module –

  - ✓ High precision, multiple analogue inputs (ADCs) with simultaneous data collection, and
  - ✓ Matlab application interface (API) support.

- Class-D power amplifier –

  - ✓ Battery powered (nominal 12Vdc) and
  - ✓ > 25 watts of full audio range frequency response.

- Lithium-Ion battery –

  - ✓ ~ 20AmpHr, nominal 12-16Vdc input for DC/DC power conversion.
  - ✓ Average power consumption is less than 30 watts during normal operation and battery provides sufficient power for up to 8 hours of continuous operation.

The first iteration of the integrated system housing using sheet metal design is shown in Figure 12. This design provided insight of how system wiring arrangement and the strategic locations of major components will affect the overall performance of the detection system. Design review and update was followed after the preliminary bench test of the housing assembly populated with all essential components.

The final implementation of the transmitting and receiving sensor modules for the integrated detection system are shown in Figures 13 and 14. The finalized sensor module designs are very robust and easy to fabricate. Bench performance tests for the sensor modules were conducted and evaluated. Final design validation process was completed through the local field tests. The design met the specification and requirement.

The system software was developed using Matlab technical programming language, Ref. 2, under Windows operating system environment. Equipped with the touch screen support, the new user interface eliminated the keyboard and mouse inputs for much simplified system operation. The new display format, Figure 15, was both clear to read and easy to operate. The signal processing techniques were fine tuned and developed for the new integrated pipe detection system. The emulated test data showed the new processing is an effective and consistent pipe detection algorithm technique. Figure 16 shows the local field test results before and after applying the new multiple pipe detection algorithms. The blue dots represent the peak detection values or the return signal at each scan location. The red dot is final result of the detected pipe based on the global or localized maximum of the returned signals. The size of the dot represents the signal strength of the returned signal. The number inside red dot indicates approximate depth information. The processing routine is precise and effective in detecting multiple targets/pipes under various detection criteria and conditions.

Two integrated inspection systems were fabricated, bench tested, and demonstrated during the local field trials. Apart from the previous separated design, the new portable, integrated detection system contains all system components in one operational unit. Figure 17 shows the final build of the integrated housing design, system electronics, and sensor module. The LCD display panel, with touch screen support, mounted on the top (holding bar) end of the inspection system. The overall height of the system, excluding display panel, is around 30″. The overall footprint of the integrated inspection system measured at 16″x6″x30″ (WxDxH; including top handle height, but excluding display panel). The overall weight of the inspection system for this iteration is less than 20 pounds.

A close-up view of the finalized, integrated inspection system is shown in Figure 18. Major electronic components occupied in the first layer of the main system housing compartment, followed by the data acquisition module, battery enclosure, and sensor modules on both ends of the inspection system. Figure 19 shows the comparison between the old and new designs of the pipe inspection system. It's clear that the form factor of the new integrated design is compact, portable, and robust in overall system operation.

Several local field tests have been conducted for the overall mechanical integrity test for the system housing. Mechanical and electrical tests were also performed for the finalized sensor modules and the system electronic controller. The overall inspection system's performance was evaluated throughout a series of local and real-world field tests. The operational protocol and test procedure of the new integrated inspection system were further simplified as compared to the previous separated system configuration.

A new test procedure and test protocol has been established in accordance with the new system software and user interface using the touch screen operation. The test procedure and protocol were further improved based on the inputs from field test participating utilities.

Field Tests and Results

Overall, three field trials were conducted throughout the United States for a total of eighty-two sets of test data. At each location, the pipe detection processes were performed under various soil condition and surface covering in locating different pipe sizes. The successful rate of locating utility was greater than 89% in all soil conditions and surface coverings. Better than 9″ of overall detection accuracy within the requirement was achieved (see Appendix**).**

A series of local field trials were conducted near SVI facility, in northern California during April, 2011. Participants included project sponsor (PHMSA/DOT), GTI, commercial partner (Sensit Technologies), and SVI. Several local field test sites were chosen for various soil conditions and surface coverings. A total of twenty-seven (27) field trials were conducted. Figures 20 and 21 show several field sites tested during the local field demonstration.

The test results were compared against the ground markings by the local utility and visual inspections of utility structures (gas meters, valve box, etc.). Figures 22 and 23 show some typical test results of the local field trials. The overall system performed well and achieved good test results. In Figure 22, the final depth information ("Pipe Depth (inch): 57") was estimated from a potential, prominent (the strongest return signal) target situated at the six inches mark during the pipe detection process. The depth information was based on estimated speed of sound for reference only. The same estimated depth reference is applicable to the rest of the test results in the following paragraphs.

The next field trials were conducted with the assistance of utility in the State of New York during June 2011. Several field trials were conducted at various test sites and soil conditions. Participants included GTI, staff members from the participating utility, and SVI. Total of thirty-three (33) field tests were conducted in various soil conditions and surface coverings. Figures 24 and 25 show several field sites tested during the field demonstration in the State of New York.

The test results were again compared with the ground markings by utility, mapping log, the EM locator when the tracer wire was available, visual inspection, and excavations. The measurement accuracies based on the above verification methods were well within the gas industry needs. The overall system performed well and met the design specification and requirement. Figures 26 and 27 show some typical test results of these field trials.

During June 2011, the last field evaluation of the system was conducted in the State of Louisiana with the assistance of the local utility. A total of twenty-two (22) field trials were conducted at various test sites, soil conditions, and surface coverings. Participants included GTI, staff members from the participating utility, staff members from two nearby utilities, Sensit Technologies, and SVI. Figures 28 and 29 show several field sites tested during the field demonstration in the State of Louisiana.

The test results were evaluated by ground markings by utility, mapping log, the EM locator where the tracer wire was installed, visual inspection, and excavations. The overall system performed well and met the design specification and requirement. Figures 30 and 31 show some typical test results of these field trials. The acoustic system detected multiple pipes and these results were confirmed by excavations at a few locations.

As mentioned above, a total of 82 field tests were conducted in various soil conditions and different ground coverings. The comments from the field test participants suggested that the overall system operation was easy and final detected result was clear and simple to interpret. The availability of results on real-time were beneficial for field operation. The accuracy of the test results were within industrial requirements. Lastly, the participants would like to have commercial product available as soon as possible. The test data accuracy with the different ground coverings is shown in Figure 32 and the test setup/condition has been provided in Appendix section.

Reporting and Project Management

The appropriate monthly and quarterly reports were submitted to the PHMSA online system. A project review meeting was held in December 2010 with the PHMSA AOTR at the GTI offices in Des Plaines, IL and the details of previous work, project status, and future plan were presented and discussed. The project was also presented and discussed during the peer review meeting arranged by PHMSA. The draft report and final reports summarizing the project work were prepared and submitted to the PHMSA online system.

Significant Results and Achievements of the Project

- Two integrated, acoustic-based, pipe inspection systems were designed, built, and field tested. The configuration of the inspection units adopted the similar system architecture from the previous phase of the project. However, the new integrated system is compact, portable, and robust.

- A new receiver module with compact, integrated, and robust housing was designed and fabricated. An innovated, integrated suspension system was developed, built, and field tested for the receiving transducer module. This new design approach used the structural molding techniques has achieved better acoustic isolation than the previous design and its construction has been greatly simplified when compared to previous design.
- A high power acoustic transmission system similar to the previous design was developed and built. A new, double suspension structural design provided the transmitter module better acoustic isolation to the entire integrated system housing and to the receiving transducer. The transmitting transducer used the integrated system housing for its ground coupling weight which proved to be well balanced and meet the design requirement.
- New Nano-ITX computer form factor was selected for the integrated system's signal processing unit. The controller unit is compact and uses all off-the-shelf components. The computing performance of the processing unit is effective and adequate for the real-time data collection and signal processing tasks. The new class-D power amplifier delivered sufficient driving power to the transmitting transducer.
- A new multiple pipe detection algorithm and display format were designed and implemented in the system software for the integrated inspection system. The new processing technique evaluates potential underground pipe/obstacle based on the detection criteria and the soil condition under test. Both vertical (depth) and horizontal (lateral) signal information were processed and displayed during the detection process.
- A compact, high-brightness LCD panel used for the data display and user interface was developed and implemented. The display used touch screen technology to simplify overall system operation. The elimination of keyboard and mouse inputs provided flexibility and ease of use of the inspection system during the pipe detection process.
- The overall inspection system was field tested at various local and real-world test fields around the United States. Better than 89% test accuracy was achieved based on the overall test data collected and analyzed during the field trials.

Conclusions

An integrated, portable, acoustic-based pipe inspection system was developed, built, and field tested. The field test results in the local and several US test fields showed very good system performance and simple operation. The detection system is compact, portable, and robust in overall system operation for all kinds of soil conditions and surface coverings. The next step is to transfer technology developed from the past OTD project and this PHMSA project to the commercial partner, Sensit Technologies. It should be noted that the OTD has agreed to fund the work associated with the Technology Transfer activities. It is believed that the commercial system based on this acoustic technology platform will be available within 12 months. Additional information may be obtained from the project's Public Page at http:// primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=365.

References

1. “Underground Pulse-Echo Inspection System” by Robert W. Cribbs, SoniPulse Inc., GRI Contract # FRI-03-1, Final Report, August 2005.
2. MATLAB, Simulink, and associated Toolbox Suite, Version R2007a. The MathWorks, www.mathworks.com, Natick, MA.

Acknowledgement

This report was prepared as a deliverable under a project with the U.S. Department of Transportation Pipeline Hazardous Materials Safety Administration (PHMSA). Mr. Frank Licari, the PHMSA technical representative for this project, participated in the initial project meeting and during the field evaluation of the system and provided suggestions that assisted in the development of the device. The assistance provided by the staff members from the New York gas distribution company and three utilities from Louisiana is highly appreciated and allowed the project team to complete the project in a timely manner.

Figures

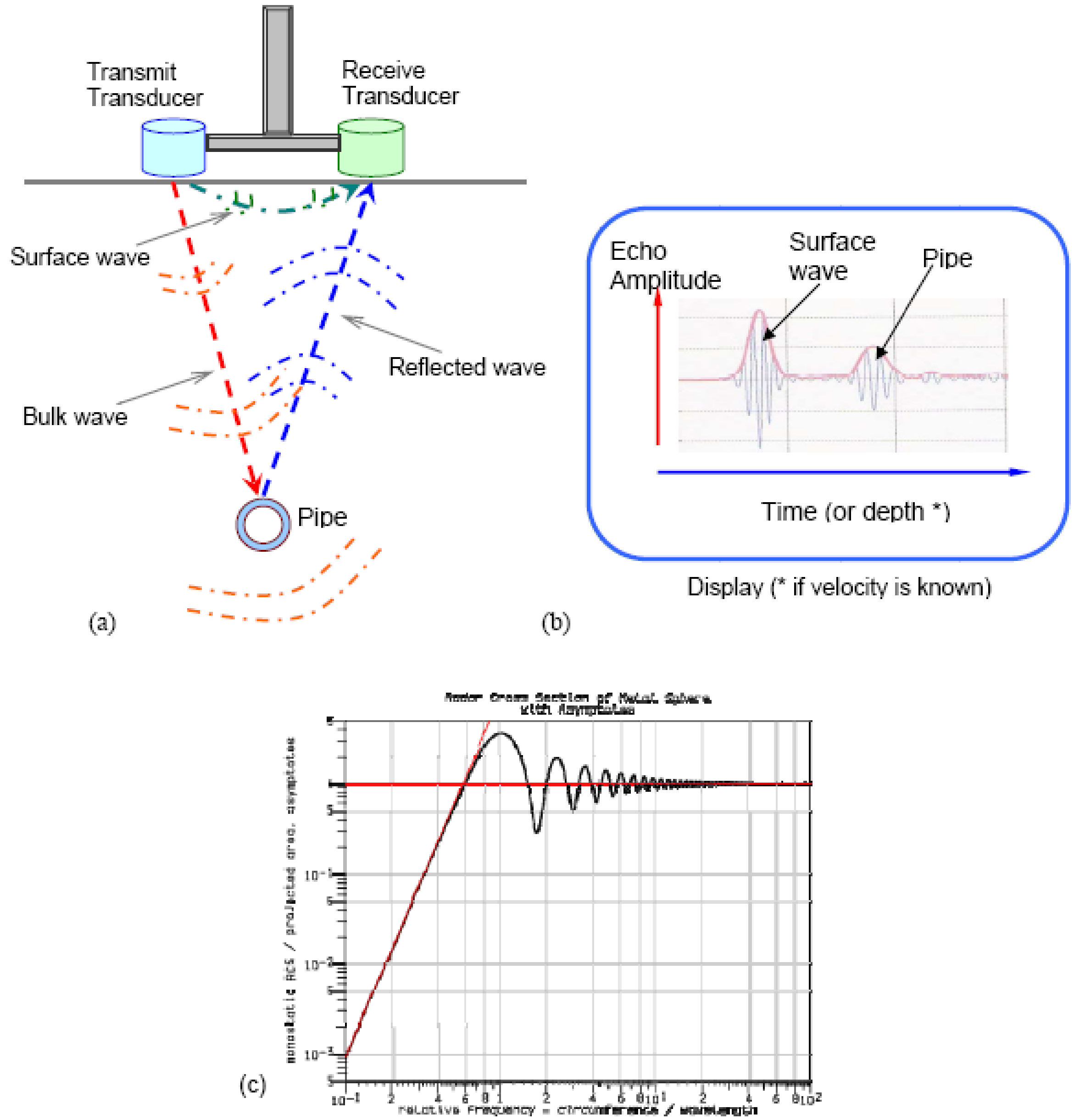
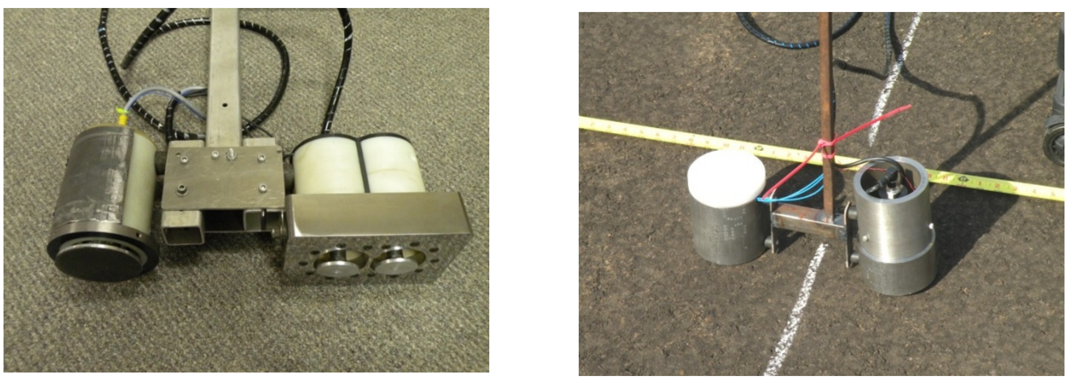
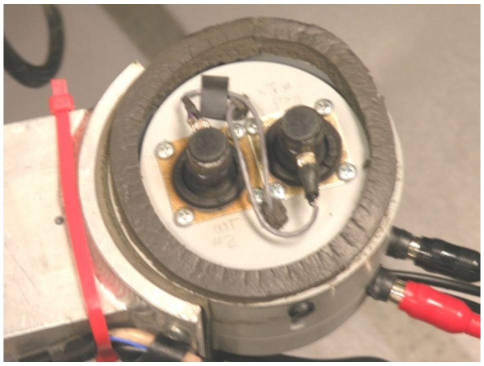


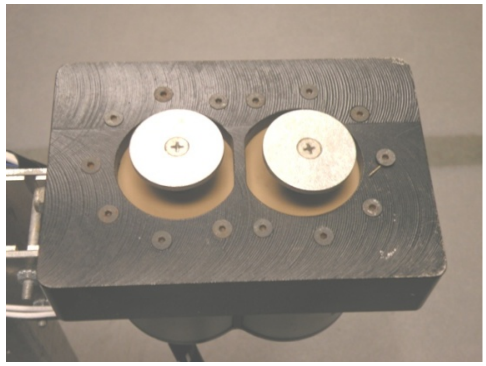
Figure 1: Basic technical concept of the acoustic based pipe locating system: (a) pulse-echo operation, (b) wave propagation, and (c) scattering effect.



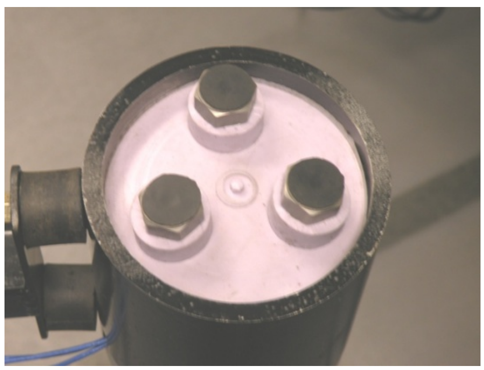
(a) (b)

Figure 2: Sensor Module configurations from the previous designs: (a) with external weights and (b) integrated steel housing.





(a) (b)



(c)

Figure 3 Receiving transducer configurations: (a) previous design with spring-loading mechanism, (b) previous design with rubber diaphragm suspension, and (c) the proposed silicon molding design for the current project, dual elements only.

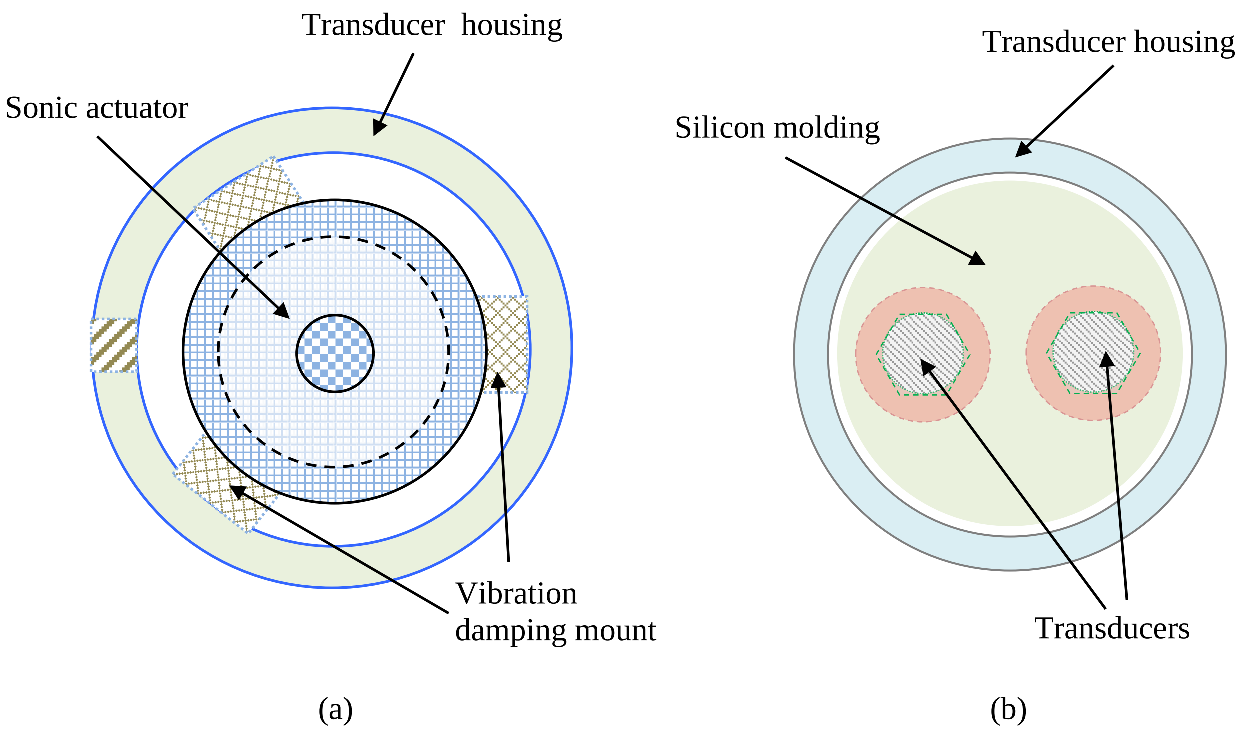
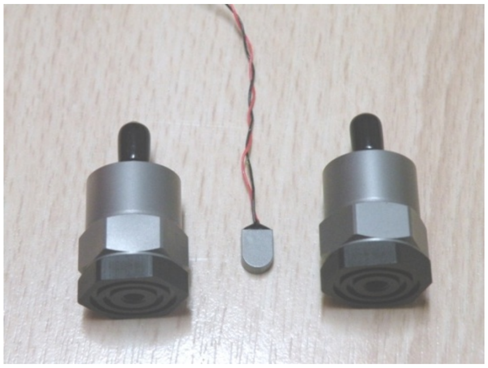
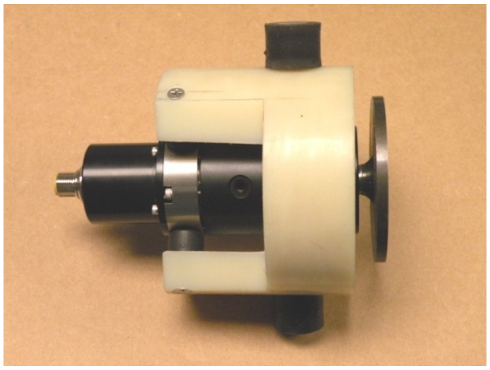
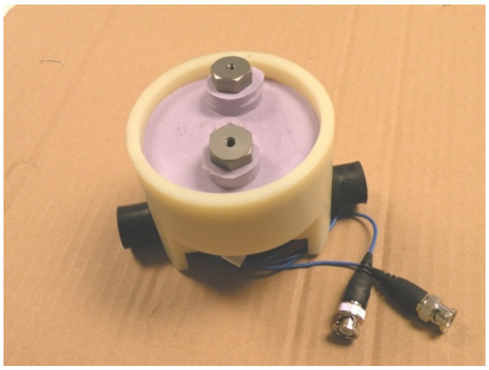


Figure 4 Transducer configuration of the sensor module: (a) transmitter module and (b) receiver module.



(a) (b)





(c) (d)

Figure 5 Acoustic transducers and the Sensor Module design: (a) high power transmitting acoustic actuator, (b) dual, high sensitivity receiving accelerometers and high-G sensor (centered) used for monitoring transmitting transducer, (c) final build of the transmitter module, and (d) final build of the receiver module.

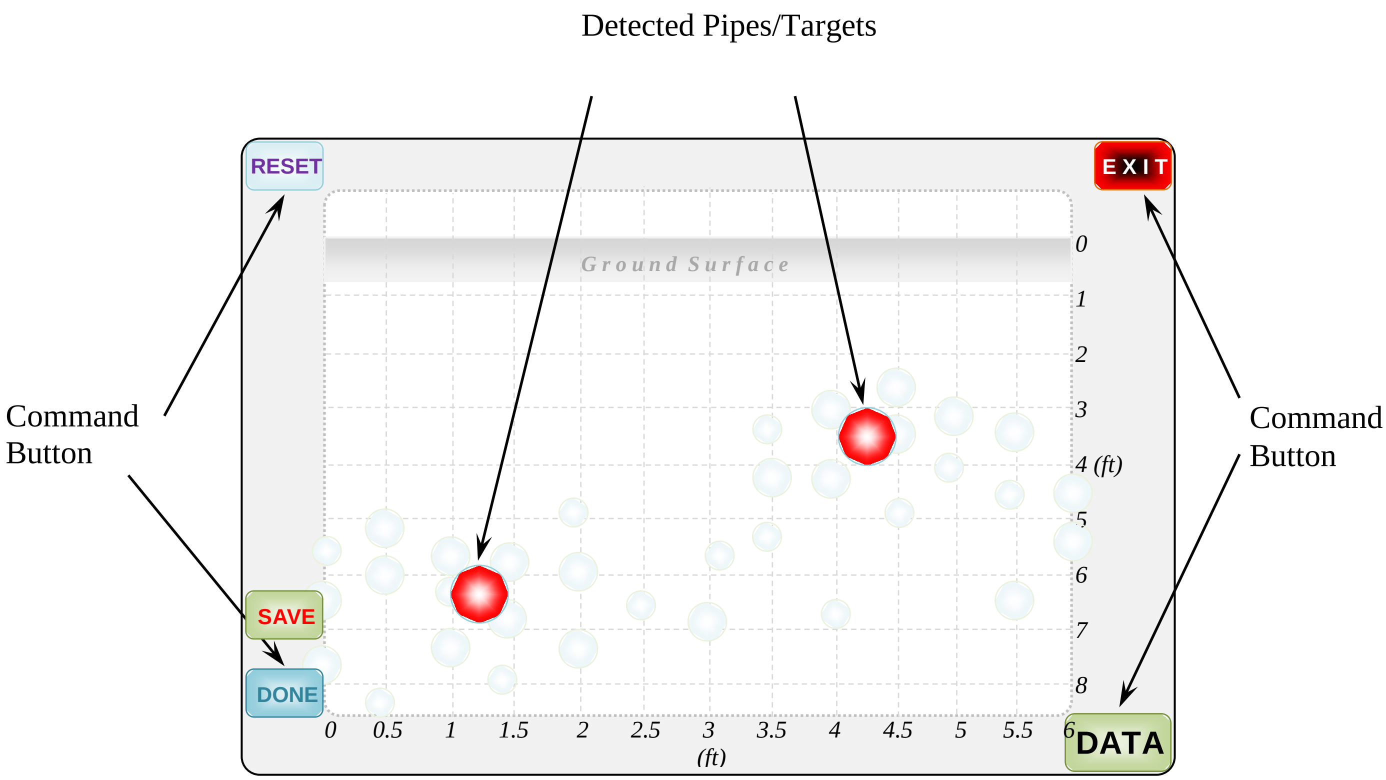


Figure 6 Proposed display format of the user interface for the multiple-pipe detection system.

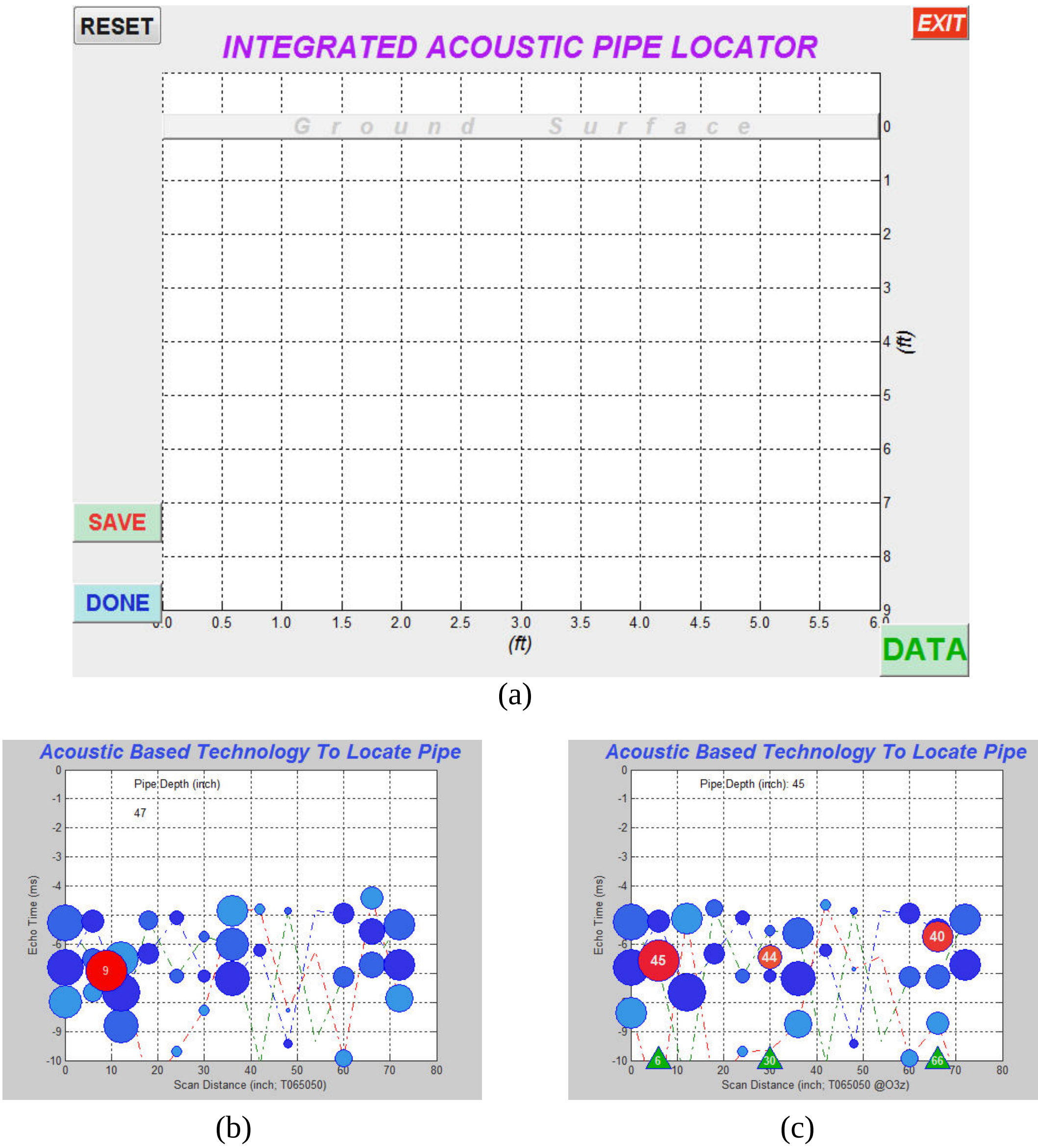


Figure 7 The screen capture (a) of the preliminary user interface implementation for the multiple pipe detection system with touch screen support and the test results of the emulated data before (b) and after (c) the application of multiple pipe detection algorithm.

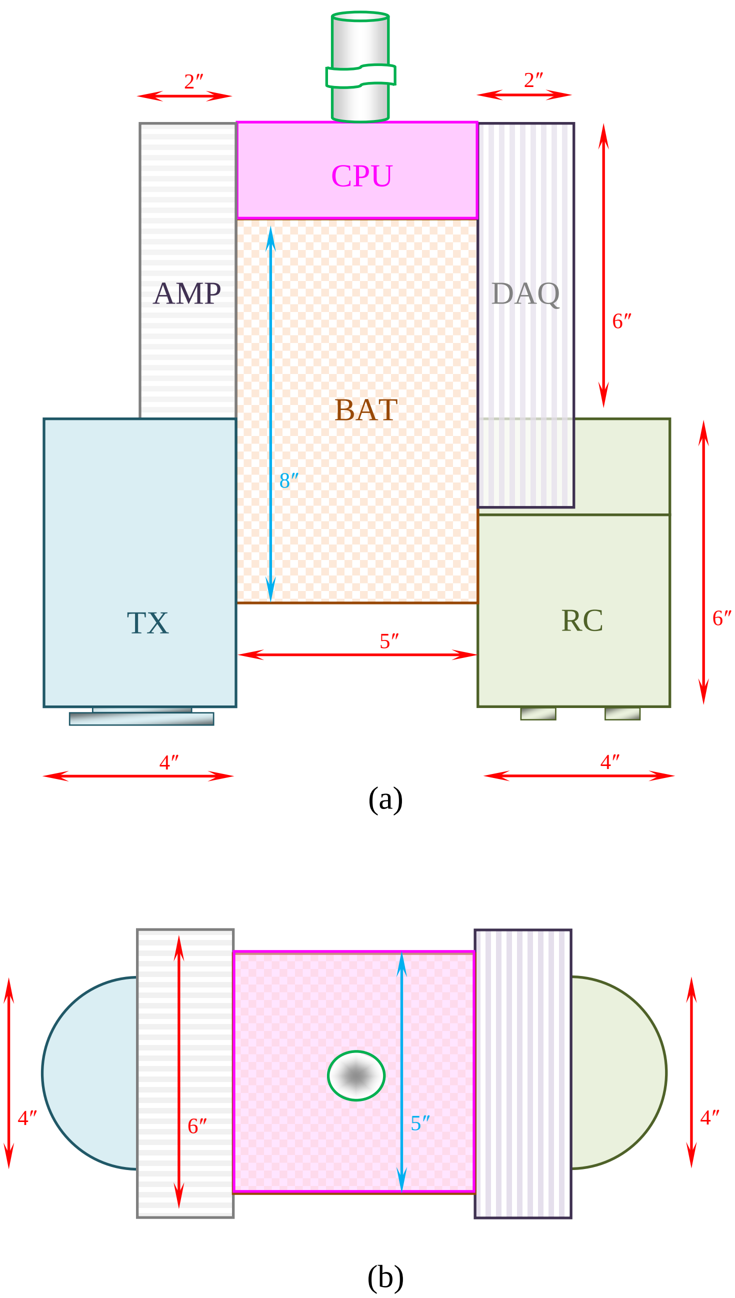
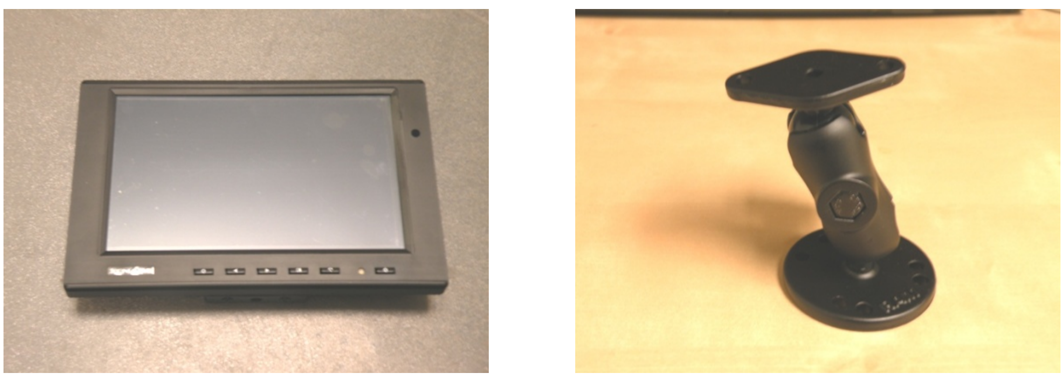
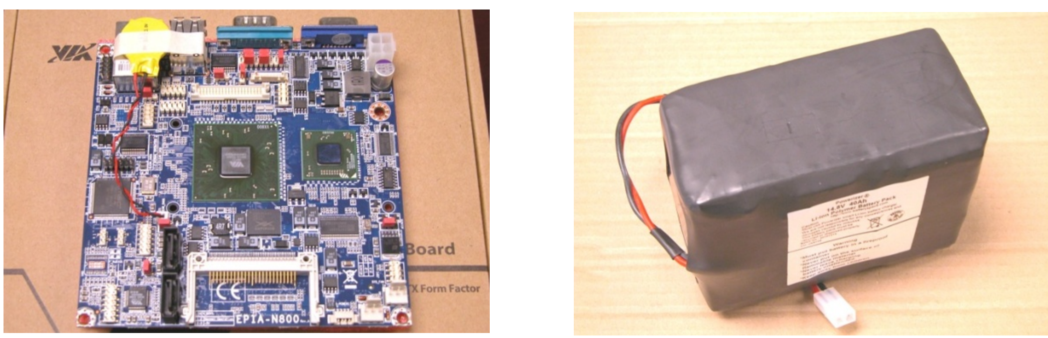


Figure 8 Detailed, conceptual system design showing the respective system components (AMP – class-D amplifier, CPU – system controller, DAQ – data acquisition module, BAT – rechargeable Li-Ion battery, TX/RC – transmitting and receiving transducers) and their layout arrangement of the integrated inspection system: (a) side view and (b) top view.



(a) (b)

Figure 9 The LCD display panel (a), with touch screen support, and (b) the mounting mechanism used for the project.



(a) (b)

Figure 10 The system electronics: (a) single board computer (Nano-ITX form factor) used in the detection system and (b) Li-Ion battery capable of running the detection system for more than eight hours per charge.

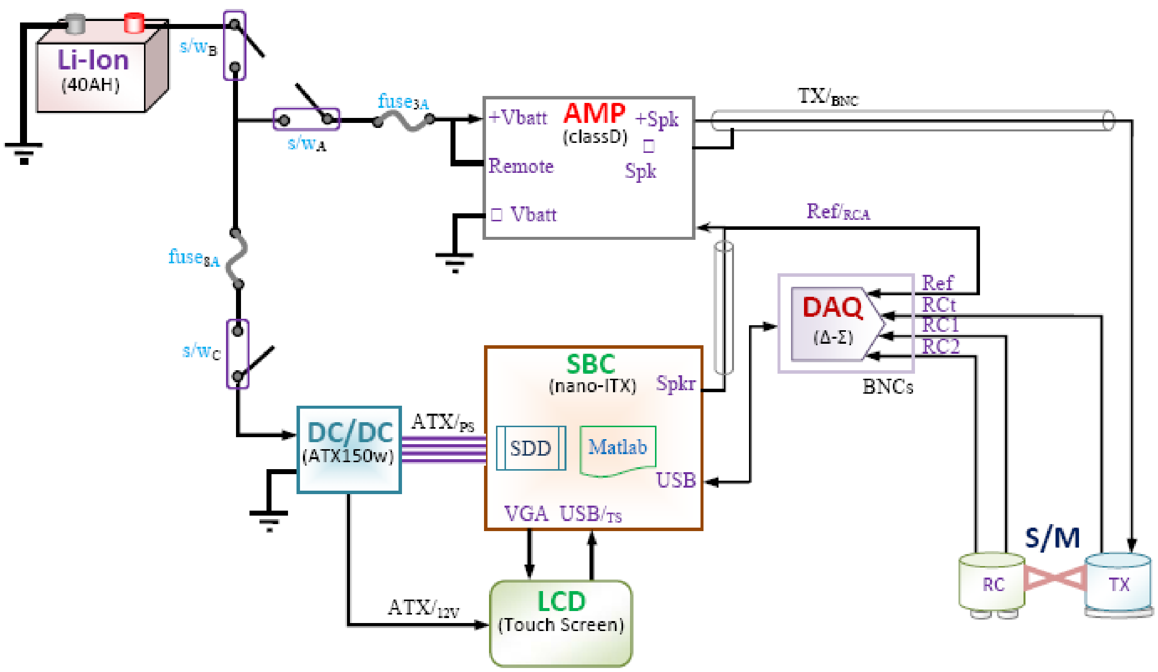
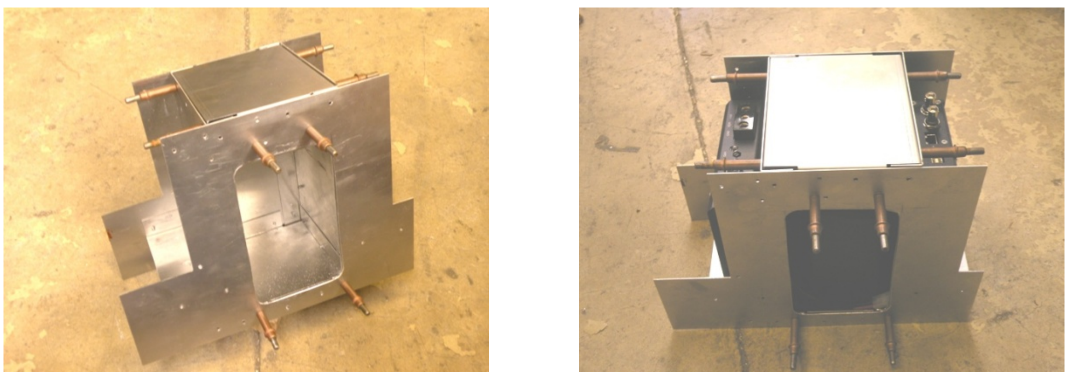


Figure 11 The electrical wiring diagram of the overall integrated pipe detection system.

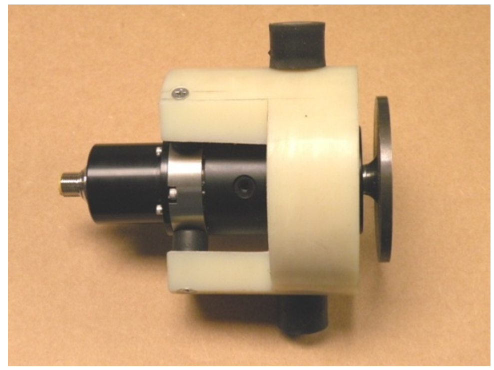
Li-Ion – Lithium battery
AMP – class-D power amplifier
SBC – single board computer
DC/DC – dc to dc converter
DAQ – data acquisition system
LCD – LCD display panel
S/M – sensor module



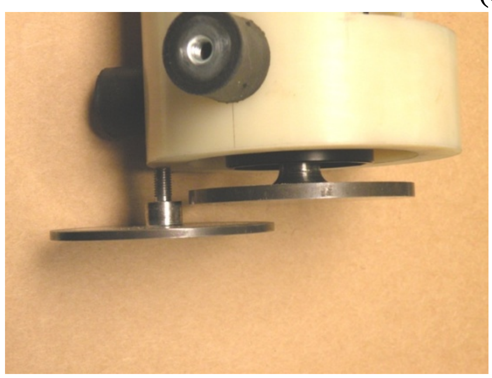
(a) (b)

Figure 12 The sheet metal design used in the integrated system housing: (a) compartment fabrication of the system electronics housing and (b) the system housing fitted with various system components during the assembly process.

(a)



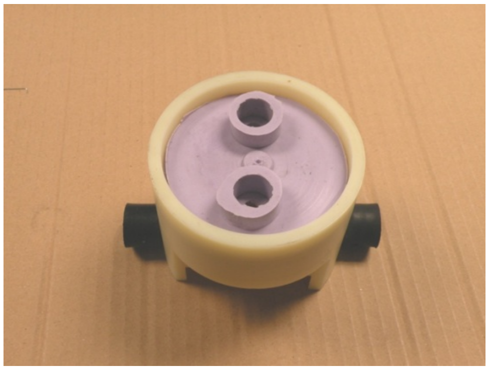
(b)



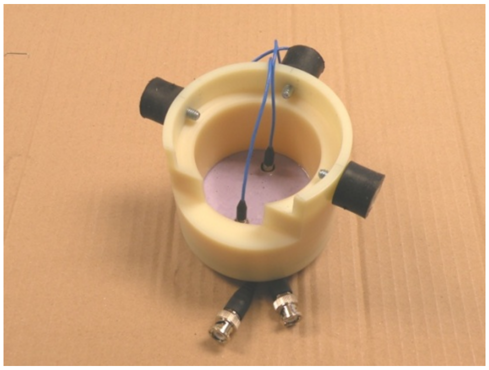
(c)

Figure 13 Finalized transmitting transducer configuration: (a) double suspension and mounting system, (b) side view of the transmitter and its steel coupling disk, and (c) comparison of various size of coupling disks.

(a)



(b)



(c)

(d)

Figure 14 Finalized receiving transducer: (a) interior view of the silicone molding, (b) dual-element molding design, (c) interior view of the molding with transducers mounted, and (d) final dual receiving transducers configuration.

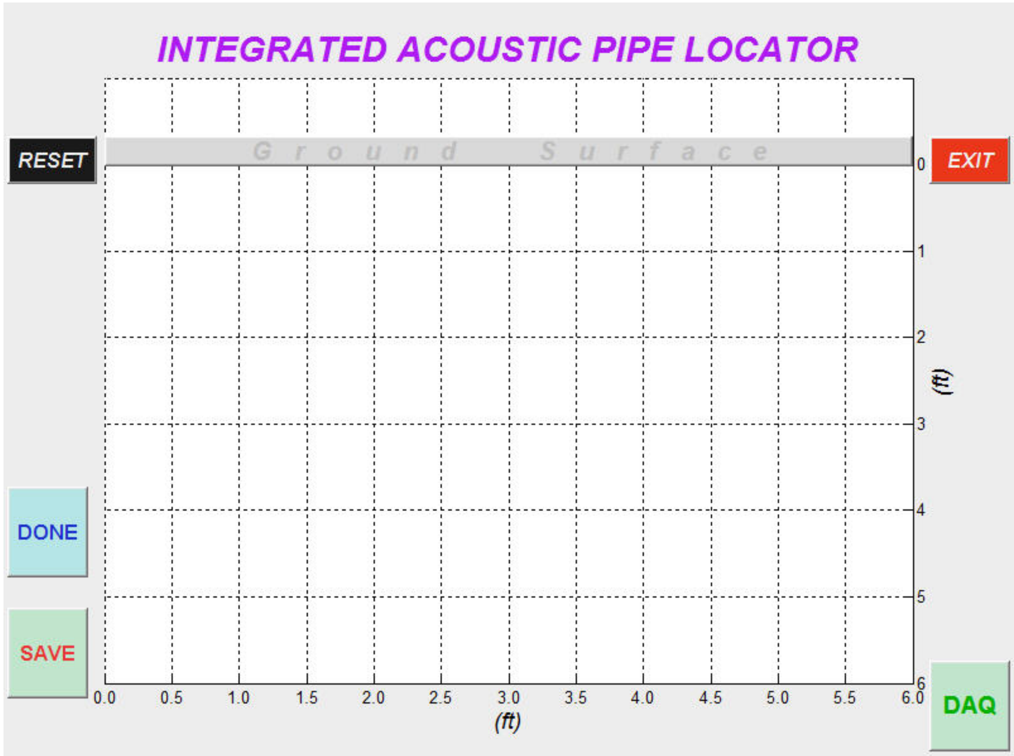


Figure 15 New, modified user interface for better system operation: larger command buttons for improved and precise touch screen operation.

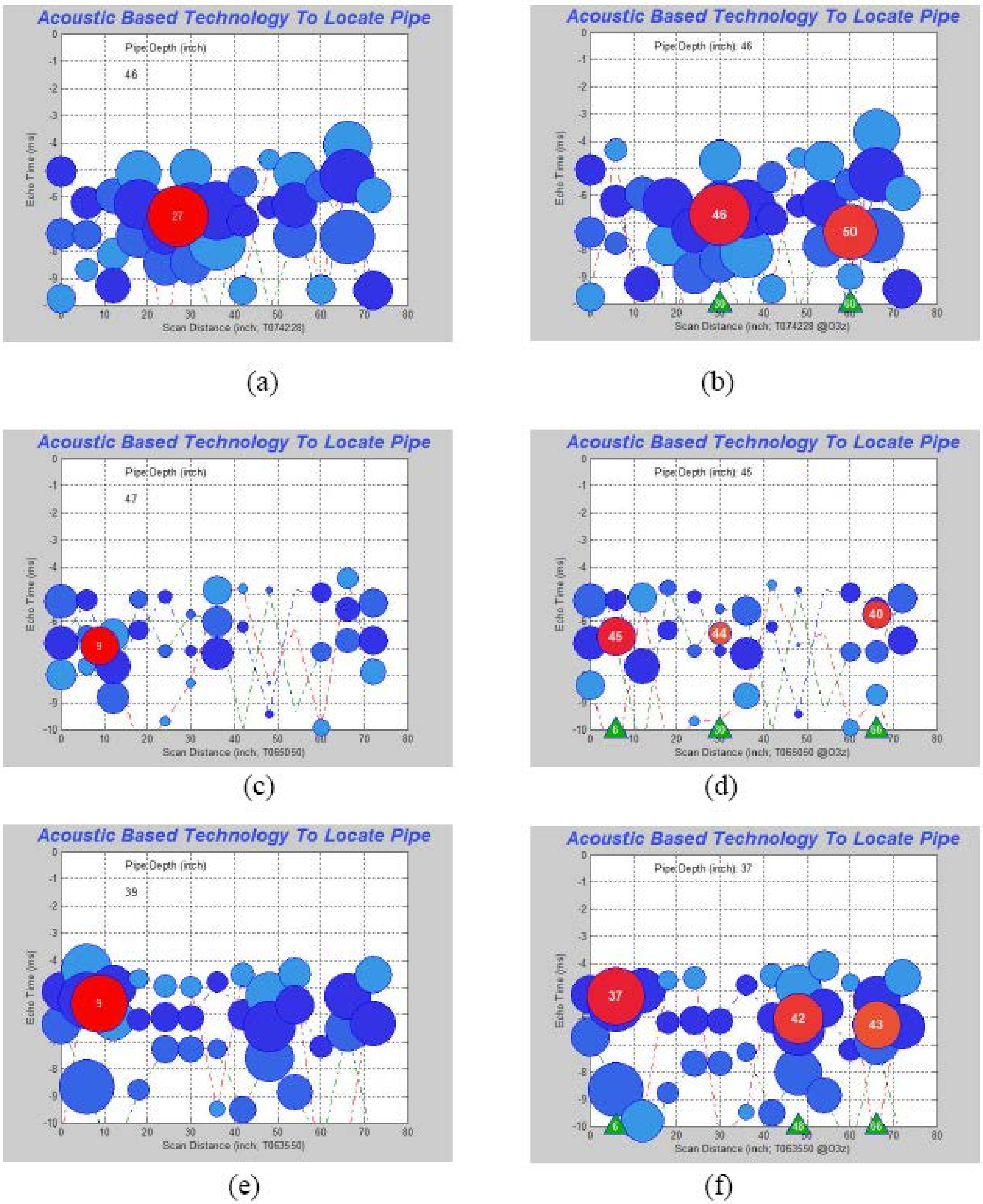


Figure 16 Multiple pipe detection algorithm and displayed results (emulated data from the previous field tests): (a, c, e) single pipe detection and (b, d, f) new multiple detection process and display.

gti

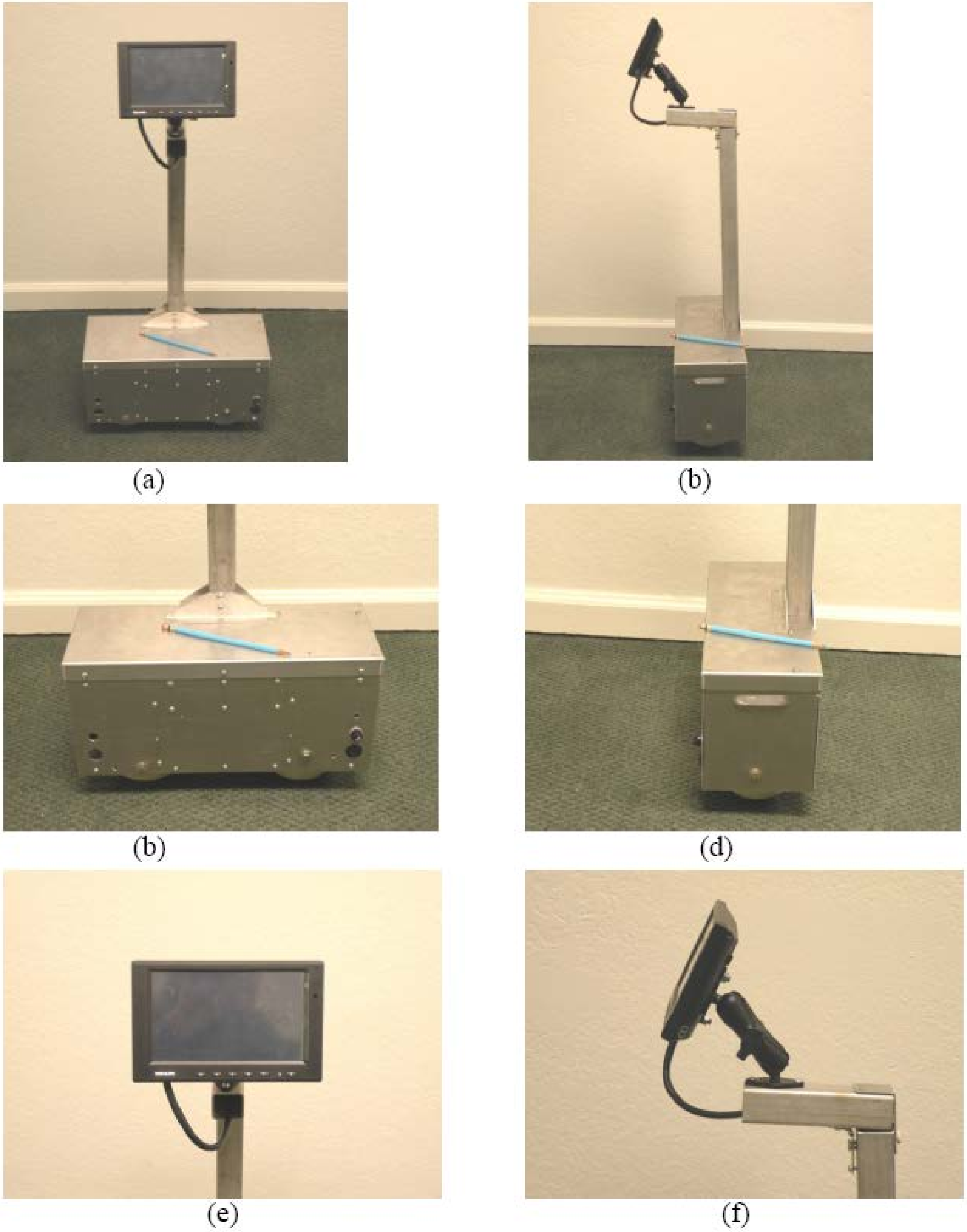
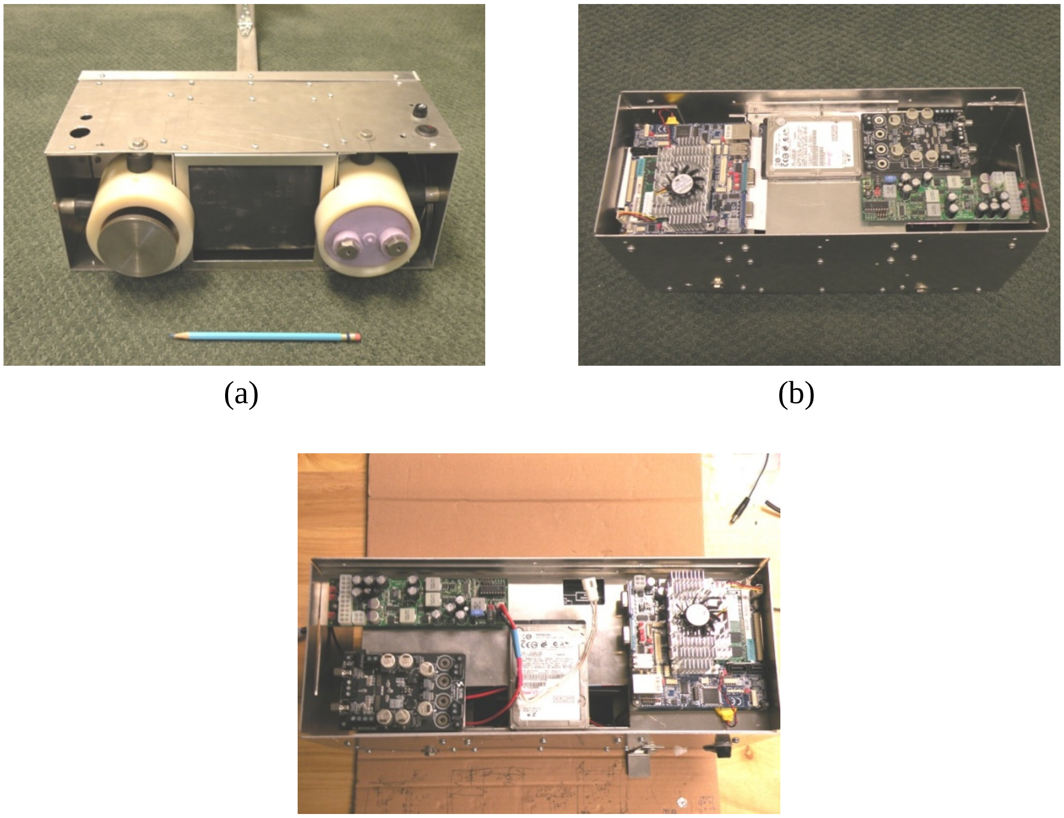


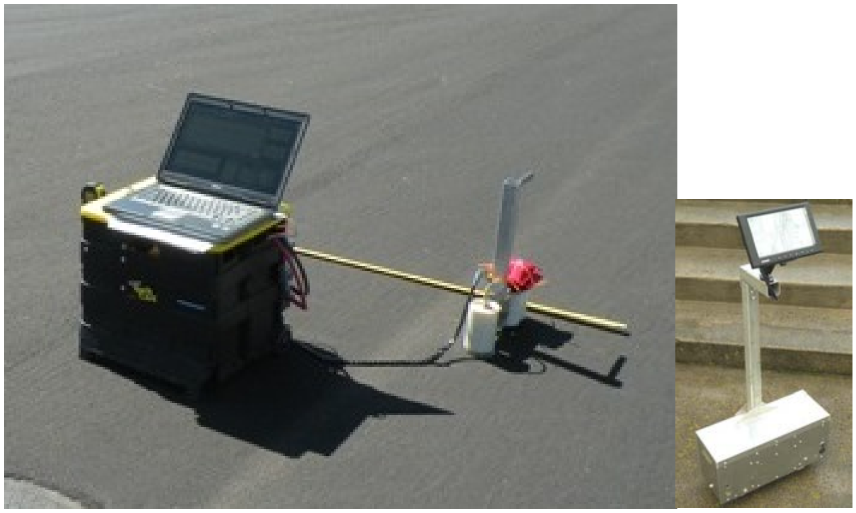
Figure 17 Final build of the modified, third iteration, integrated housing design: (a – b) overall view of integrated pipe detection system, (c - d) electronic controller box, and (e - f) LCD display panel.



(a) (b)

(c)

Figure 18 Final build of the modified, third iteration, integrated housing design: (a) close-up view of the sensor module, (b) exposed view of the electronic components under integrated housing (before electrical wiring), and (c) a modified and wired electronic controller.



(a)

(b)

Figure 19 Comparison between early design of the pipe inspection prototype system and the new integrated pipe detection system: (a) old inspection design with separated electronic controller and sensor module and (b) the new integrated pipe detection system. Note: picture insert in (a) has been scaled for dimensional comparison between new and old system designs.

(a)

(b)

(c)

(d)

Figure 20 Field demonstration at local test fields: (a-b) local pipe farm with various surface coverings: asphalt, concrete, grass, and top-soil and (c-d) residential area with concrete and grass soil conditions.

(a) (b)

(c) (d)

(e) (f)

Figure 21 Field demonstration at local test fields: (a - b) commercial property with asphalt field, (c - d) grass field at industrial park, and (e - f) public street with asphalt ground coverings.

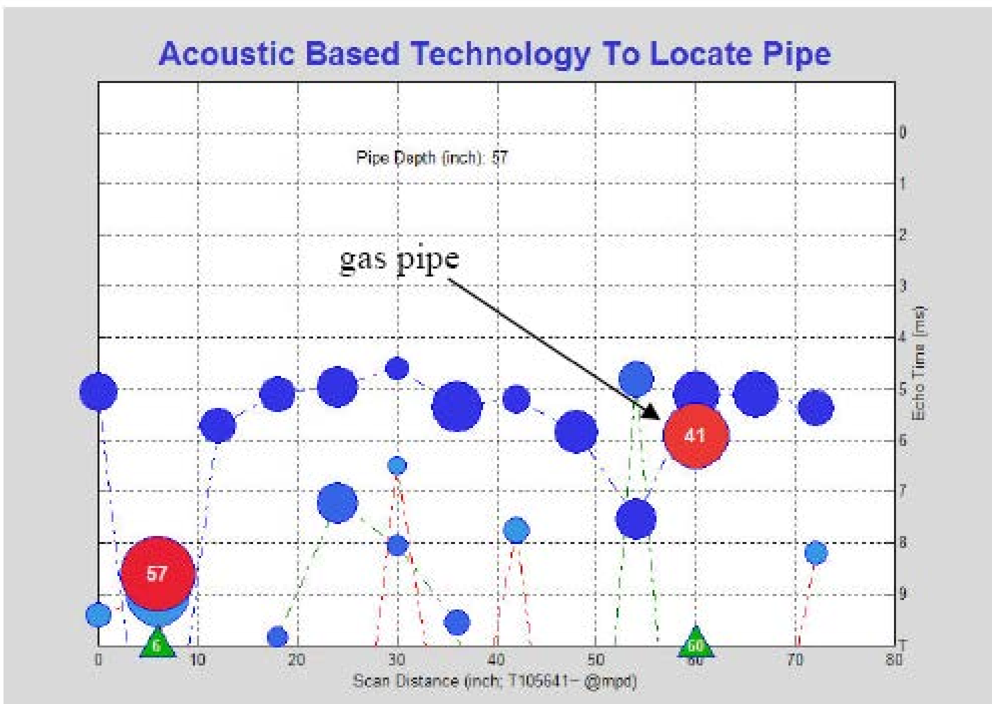


Figure 22 Local field test results: multiple pipes under grass; depth information is for reference only. (Test ID # 27, See Appendix)

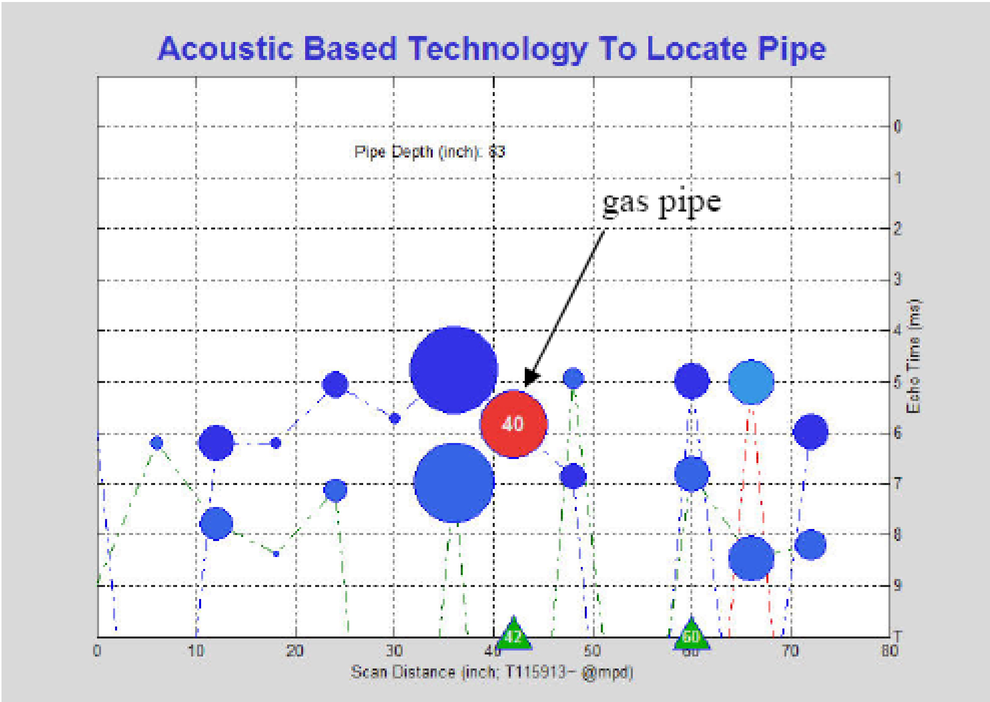


Figure 23 Local field test results: gas pipe under asphalt pavement (Test ID # 10).

(a)

(b)

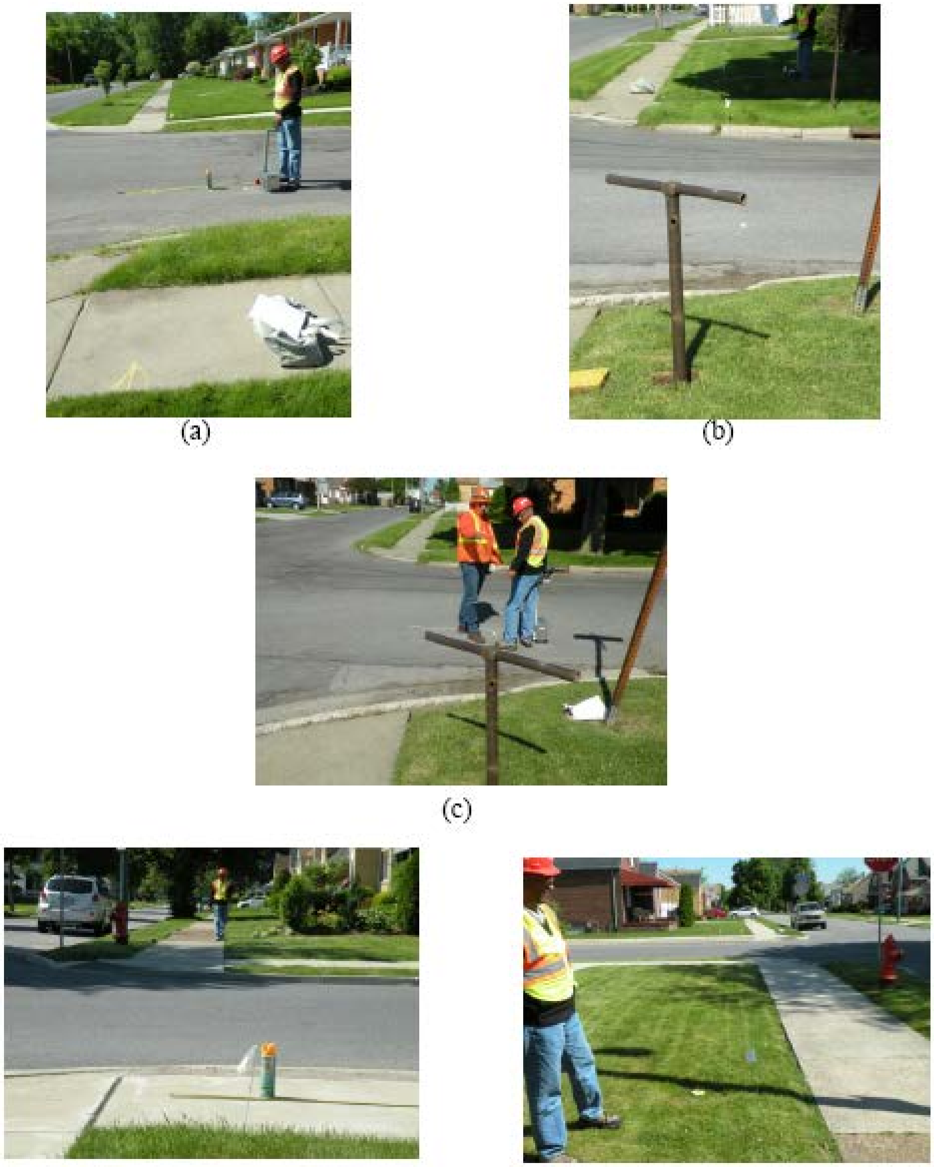
(c)

(d)

(e)

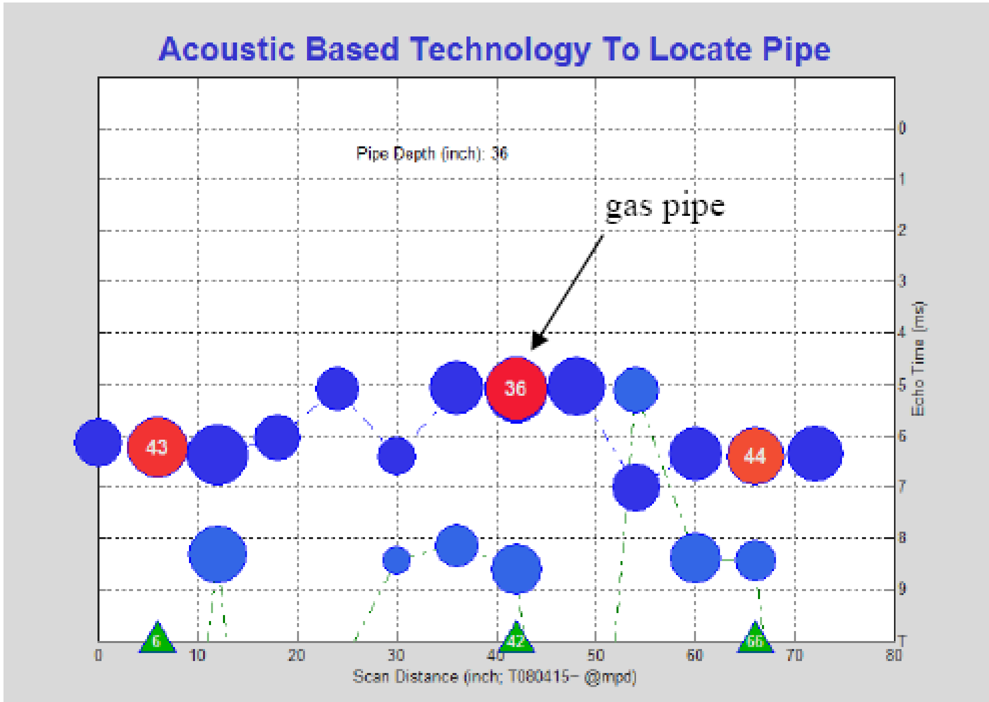
(f)

Figure 24 Field demonstration in the State of New York area: (a - b) gas service lines under grass, (c) gas service line on asphalt pavement, (d) gas service line under concrete walkway, (e) gas main under grass, and (f) gas main under concrete; all in residential area.

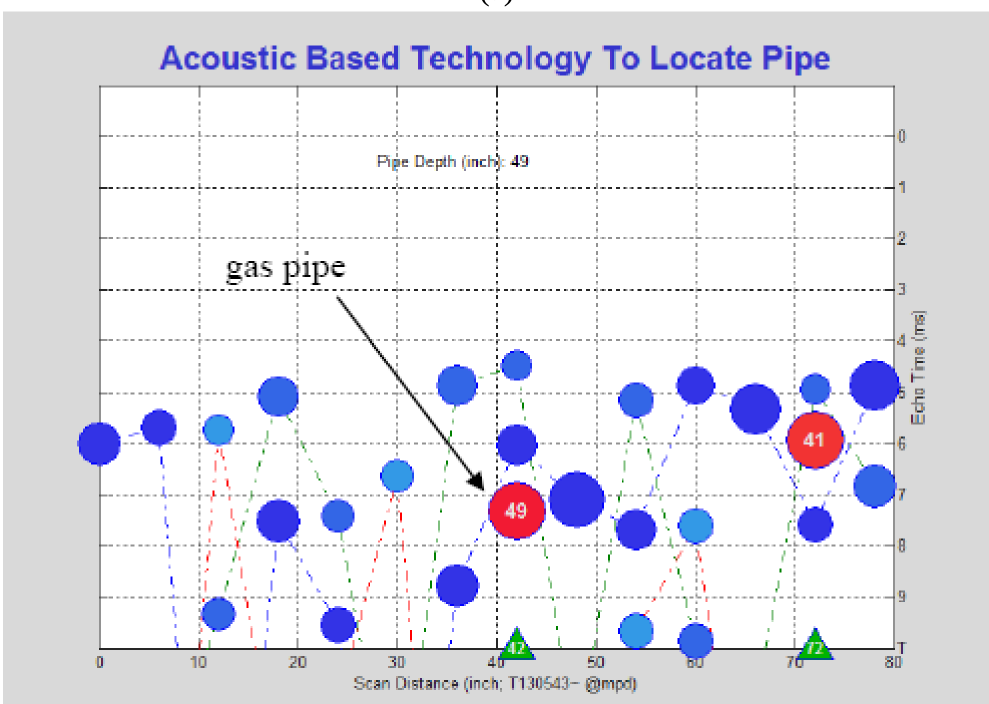


(a) (b) (c) (d) (e)

Figure 25 Field demonstration in the State of New York area: gas main under (a - c) asphalt and grass fields, (d) gas main under concrete, and (e) gas main under grass; all in residential area.

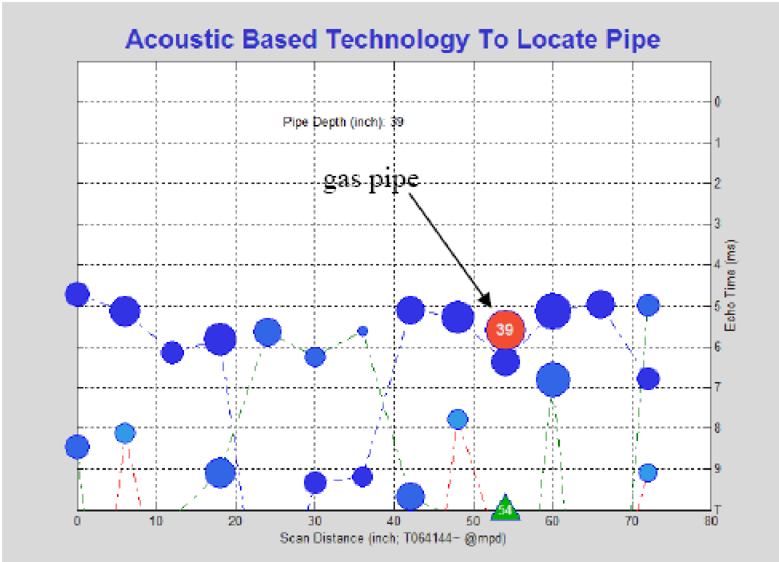


(a)

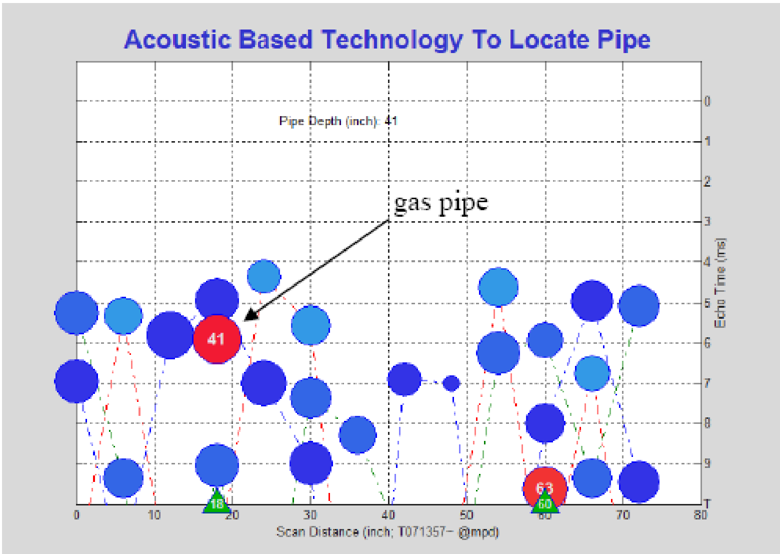


(b)

Figure 26 Test results at sites in the State of New York area: (a) multiple service pipes under grass lawn (Test ID #43) and (b) multiple service pipes under asphalt (Test ID # 53); all in residential area.



(a)



(b)

Figure 27 Test results at sites in the State of New York: (a) gas main under asphalt (Test ID # 57) and (b) gas main under concrete walkway (Test ID # 60); all in residential area.

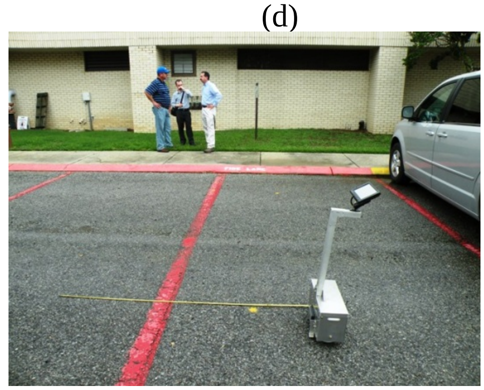
(a)

(b)

(c)

(d)

(e)



(f)

Figure 28 Field trials in Louisiana area: (a – d) gas main/service line and water line under grassy field and (e - f) gas service line under asphalt covering; all in industrial setting.

Figure 29   Field test results at Louisiana sites: (a - c) gas service line under grass field in residential area; testing in commercial area for (d) gas main under grass, (e) gas service line under concrete, and (f) gas service line and sewer under grassy field.

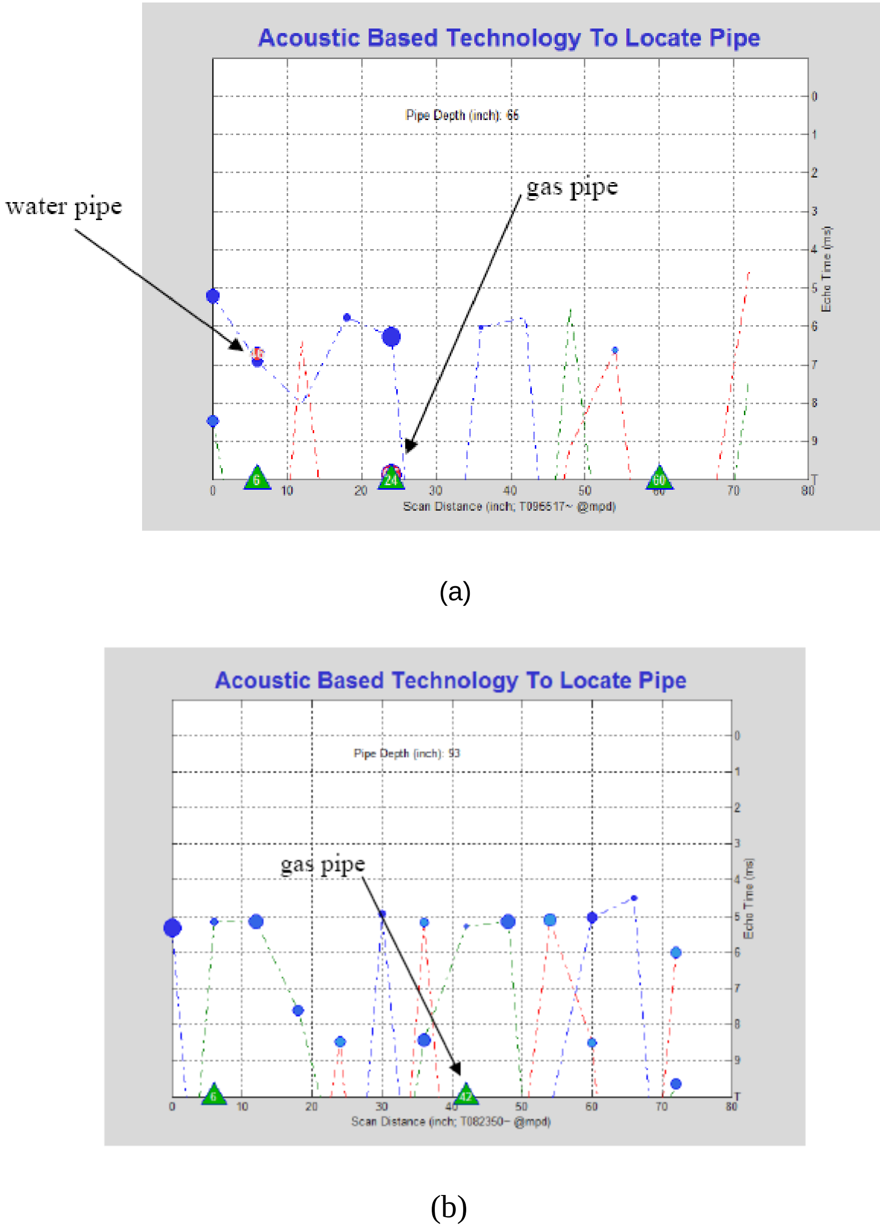


Figure 30 Field test results in Louisiana test sites: (a) gas main and water line under grass lawn (Test ID # 72) and (b) gas service line under asphalt (Test ID # 75); all in industrial setting.

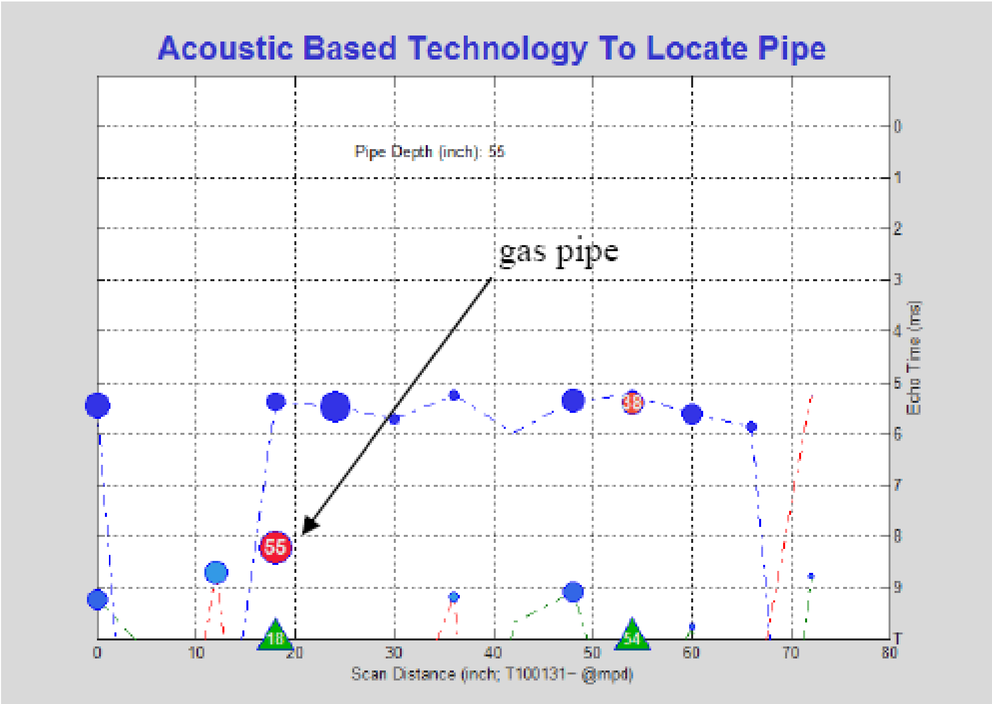


Figure 31 Field test results at Louisiana site: gas service line under grass in residential area (Test ID # 77).

Overall System Performance: Total 82 Tests

Test Accuracy (%) / Ground Coverings	**< ±18" (%)**	**< ±24" (%)**
Asphalt	92%	100%
Concrete	91%	100%
Grass	87%	96%
All Conditions	**89%**	**98%**

Figure 32 Performance of the acoustic based locator during the field tests.

Appendix

List of Field Test Setup

Test ID	Soil Type	Utility	Verification	Accuracy	Location
1	asphalt	1", gas service	Marker	6	CA
2	asphalt	1", gas service	Marker	18	CA
3	asphalt	1", gas service	Marker	6	CA
4	asphalt	1", gas service	Marker	0	CA
5	asphalt	1", gas service	Marker	6	CA
6	grass	1", gas service	Marker	6	CA
7	concrete	4", gas main	Marker	6	CA
8	asphalt	1", gas service	Marker	24	CA
9	asphalt	1", gas service	Marker	18	CA
10	asphalt	1", gas service	Marker	6	CA
11	asphalt	1", gas service	Marker	12	CA
12	asphalt	1", gas service	Marker	6	CA
13	asphalt	1", gas service	Marker	12	CA
14	asphalt	4", gas main	Marker	0	CA
15	grass	1", gas service	Marker	9	CA
16	grass	1", gas service	Marker	6	CA
17	grass	1", gas service	Marker	0	CA
18	concrete	2", PE, gas main	Marker	12	CA
19	concrete	2", PE, gas main	Marker	6	CA
20	grass	1", gas service	Marker	0	CA
21	asphalt	1", gas service	Marker	0	CA
22	concrete	4", PE, gas main	Map	12	CA
23	concrete	4", PE, gas main	Map	12	CA
24	grass	4", PE, gas main	Map	30	CA
25	grass	4", PE, gas main	Map	24	CA
26	grass	1", PE, gas service	Marker	12	CA
27	grass	1", PE, gas service	Marker	24	CA
28	grass	2", gas main	Excavated	0	NY
29	grass	2", gas main	Excavated	0	NY
30	grass	5/8", gas service	Map	10	NY
31	grass	5/8", gas service	Map	10	NY

Test ID	Soil Type	Utility	Verification	Accuracy	Location
32	grass	2", gas main	Map	12	NY
33	asphalt	2", gas main	Map	24	NY
34	asphalt	2", gas main	map	0	NY
35	asphalt	2", gas main	map	0	NY
36	asphalt	2", gas main	map	12	NY
37	grass	5/8", gas service	marker	12	NY
38	grass	5/8", gas service	marker	18	NY
39	grass	5/8", gas service	marker	6	NY
40	grass	5/8", gas service	marker	6	NY
41	asphalt	5/8", gas service	marker	12	NY
42	grass	3", gas main	locator	6	NY
43	grass	3", gas main	locator	6	NY
44	grass	5/8", gas service	locator	18	NY
45	grass	5/8", gas service	locator	0	NY
46	grass	5/8", gas service	locator	6	NY
47	grass	2", gas main	locator	6	NY
48	grass	2", gas main	locator	12	NY
49	grass	5/8", gas service	locator	18	NY
50	concrete	5/8", gas service	locator	12	NY
51	grass	2", gas main	excavated	0	NY
52	grass	2", gas main	excavated	0	NY
53	grass	2", gas main	excavated	0	NY
54	asphalt	5/8", gas service	locator	3	NY
55	asphalt	8", gas main	marker	0	NY
56	grass	8", gas main	marker	0	NY
57	asphalt	4", gas main	marker	0	NY
58	grass	4", gas main	locator	6	NY
59	grass	4", gas main	locator	6	NY
60	concrete	4", gas main	locator	8	NY
61	concrete	4", gas main	marker	15	LA
62	concrete	4", gas main	marker	15	LA
63	asphalt	4", gas main	marker	9	LA
64	asphalt	4", gas main	marker	3	LA
65	asphalt	4", gas main	marker	5	LA
66	grass	1½", gas service	marker	3	LA
67	grass	1½", gas service	marker	3	LA
68	grass	1½", gas service	marker	15	LA

Test ID	Soil Type	Utility	Verification	Accuracy	Location
69	grass	4", gas main	marker	0	LA
70	concrete	4", gas main	marker	18	LA
71	grass	2", gas main	excavated	0	LA
72	grass	2", gas main	excavated	0	LA
73	grass	2", gas main	excavated	3	LA
74	asphalt	1¼", gas service	map	6	LA
75	asphalt	1¼", gas service	map	6	LA
76	grass	1¼", gas service	excavated	9	LA
77	grass	1¼", gas service	excavated	0	LA
78	grass	1¼", gas service	marker	27	LA
79	grass	1¼", gas service	excavated	9	LA
80	grass	1¼", gas service	excavated	21	LA
81	concrete	1¼", gas service	map	21	LA
82	grass	4", gas main	map	18	LA

Accuracy in inches.