



— BUREAU OF —
RECLAMATION

Final Report No. ST-2025-22086-01

Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

Research and Development Office

Science and Technology

Research Program



REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE 10-10-2025		2. REPORT TYPE Research		3. DATES COVERED 10-01-2022 to 09-30-2025	
4. TITLE AND SUBTITLE Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection				5a. CONTRACT NUMBER XXXXR4524KS-RR4888FARD2200701/F558A	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 1541 (S&T)	
6. AUTHOR(S) Justin B. Rittgers, PhD, PGP, Geophysicist				5d. PROJECT ID NUMBER Final Report ST-2025-22086-01	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER 86-68320	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Technical Service Center U.S. Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007				8. PERFORMING ORGANIZATION REPORT NUMBER 01	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007				10. SPONSOR/MONITOR'S ACRONYM(S) Reclamation	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) (if applicable) Report Number [01]	
12. DISTRIBUTION/AVAILABILITY STATEMENT Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Water pipeline leaks can be extremely costly in terms of non-revenue water losses, resource allocations, contracted leak detection and locating services, repair costs, water transmission service shutdowns, and even occasional legal outfall from property damage. A variety of buried pipeline monitoring and leak detection/locating techniques have been developed, but acoustic emission (AE)-based techniques were identified by the research team as the most promising for effective long-term and proactive monitoring for leak detection and locating across large pipeline systems. The primary objective of this research project was to gain knowledge and expertise for successfully developing and deploying AE sensing/monitoring systems along existing and future pipelines, so that Reclamation can self-perform early leak detection monitoring and accurate leak location services in near-real-time—at a fraction of the cost compared to single one-time or subscription-based private-sector monitoring services. Research activities included market research, literature and technology review, several laboratory and field-scale experiments, development and testing of prototype acoustic dataloggers and sensors, development and testing of custom software and scripts for performing AE detection and source localization, and pursuing acquisitions of commercial dataloggers and a distributed acoustic sensing (DAS) system for field deployments along the Mni Wiconi Rural Water Supply System.					
15. SUBJECT TERMS Acoustic emissions, pipeline leaks, leak detection, leak locating, geophysics, structural health monitoring					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			U
U	U	U			19b. TELEPHONE NUMBER (Include area code) 303-720-3010

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, Native Hawaiians, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Information in this report may not be used for advertising or promotional purchases. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research. The author would also like to acknowledge and thank Chris Haines and others in the South Dakota Area Office for their support throughout this project.

Cover Image – Photo of a steel water main leak, example acoustic emission data, and an example schematic showing acoustic emission signal cross-correlation leak-localization results.

Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

Final Report No. ST-2025-22086-01

Prepared by:

**Technical Service Center
Justin B. Rittgers, PhD, PGP, Geophysicist**

Peer Review

Bureau of Reclamation Research and Development Office Science and Technology Research Program

**Final Report No. ST-2025-22086-01
Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried
Water Pipeline Leak Detection**

Prepared by: Justin B, Rittgers, PhD, PGP
Geophysicist, Reclamation

Peer review by: Atousa Plaseied, PhD, PE
Materials, Mechanical, and Civil Engineer, Reclamation

This document has been reviewed under the Research and Development Office Discretionary peer review process, consistent with Reclamation Policy CMP P14. It does not represent and should not be construed to represent the Bureau of Reclamation's determination, concurrence, or policy.

Acronyms and Abbreviations

AE	Acoustic Emission
AI	Artificial Intelligence
ARV	Air Relief Valve
CH/Ch	Channel
DAS	Distributed Acoustic Sensing
DFOS	Distributed Fiber Optic Sensing
DOI	U.S. Department of the Interior
DSS	Distributed Strain Sensing
DTS	Distributed Temperature Sensing
GIS	Geographic Information System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GSA	General Services Administration
IU	Interrogator Unit
LiDAR	Light Detection and Ranging
ML	Machine Learning
Nb-IoT	Narrow-band Internet of Things
O&M	Operations and Maintenance
PVC	Polyvinyl Chloride
RFID	Radio Frequency Identification
R&D	Research and Development
SCADA	Supervisory Control and Data Acquisition
SDAO	South Dakota Area Office
S&T	Science and Technology
Reclamation	Bureau of Reclamation
TSC	Technical Service Center

Symbols

D	known separation distance between two sensors
ft	foot/feet
ft/s	foot/feet per second
gpm	gallons per minute
Hz	hertz
kHz	kilohertz
L	distance of a leak from the nearest sensor

psi	pounds per square inch
T	peak correlation coefficient lag-time
™	trademark
v	velocity of sound wave propagation
≈	approximately equal to
=	equal to
%	percent

Contents

	Page
Executive Summary	1
1.0 Introduction.....	1
1.1. Research Question, Objectives, and Strategy	4
1.1.1. Research Question	4
1.1.2. Research Objectives.....	4
1.1.3. Research Strategy.....	5
1.1.4. Previous Work	5
2.0 Overview of Pipeline Leak Acoustic Emissions Characteristics	6
3.0 Overview of Pipeline Leak AE Sensing Technologies.....	9
3.1. Ground Microphones and Listening Rods	10
3.2. Pushed and Tethered Hydrophones	13
3.3. Temporarily Deployed Noise Loggers and Correlator Systems.....	15
3.4. Long-term or Permanently Installed AE Monitoring Networks: Wireless Noise Logging Correlator Systems	20
3.5. In-line Free-Floating AE Sensing Systems.....	22
3.6. Distributed Fiber Optic Sensing Systems (DFOS)	26
4.0 Project Experimentation and Results.....	32
4.1. Mni Wiconi Rural Water Supply System Field Testing Site: Initial Efforts for Field-Scale Deployment and Testing along System Main Core-Line Zone 1	33
4.2. Long-Term AE Monitoring Noise Logger/Correlator System and Mobile Correlator System: BLDG 56 Hydraulics Laboratory Water Supply Line Release Test.....	35
4.3. Long-Term AE Monitoring Noise Logger/Correlator System and Prototype AE Datalogger: BLDG 810 Water Main Release Tests.....	38
4.4. Various System Tests: Denver Federal Center Decommissioned Train Tracks....	44
4.4.1. Geophone Sensors and Seismograph Deployments for Velocity Mapping 47	
4.4.2. Prototype Synthetic Leak Noise Source Development and Testing	50
4.4.3. Nb-IoT Monitoring Correlator System Tests: Synthetic Leak Noise Detection and Locating.....	53
4.4.4. Prototype AE Datalogger System Tests: Recording Synthetic Leak Noise and Hammer Tap-Tests.....	54
4.4.5. Leak Noise Localization Software Development and Geophone Sensors Deployments	59
5.0 Discussion and Next Steps.....	68
6.0 Conclusions.....	69
7.0 References.....	71

Tables

Table 1.—List of developed pipeline leak detection methodologies, including the underlying detection principles and sensor types used. Note that the terms “contact sensor” or “contactless sensor” refer to whether the sensor makes direct contact with the pipe, water column, or connected system structures. Table modified from (Ziemendorff, S., 2022).	4
Table 2.—Mni Wiconi main core-line Zone 2 access point descriptions and inter-point distances for the 16 locations identified along the segment. Access points 3 and 7 (shown in red text font) were deemed infeasible for effective and reliable sensor installations.	35
Table 3.—Results of six tap tests performed to map the velocity of sound wave propagation along the train track for use in Nb-IoT logger system correlation analysis. Note that the overall average calculated interval velocity is within approximately 50 ft/s of the commonly reported velocity of sound in steel, as found in published literature.....	49
Table 4.—Results of three tap tests performed to map the velocity of sound wave propagation along the train track segments between the geophone sensors, for use in correlation-based localization analysis. Note that the calculated interval velocities shown in red font were omitted as outliers from the final averaged value (Ch#25 arrival time picks were poorly constrained due to proximity to the shot location). Also note that the overall average calculated interval velocity is within approximately 60 ft/s of the velocity of sound in steel reported in the literature.	61
Table 5.—Results of all leak locating calculations for various data signal processing permutations, including raw data, high-pass filtered, band-pass filtered, signal envelopes with no filtering, and high-pass filtered signal envelopes. The true source was located at 217 ft.	67

Figures

Figure 1.—Schematic showing modeled elastic waves propagating outward and away from a point source (e.g., a leak) along a pipeline. As depicted, the pipe acts as a waveguide, carrying acoustic energy in both axial directions away from the leak location. Figure modified from (Paradise, A., Andalibi, Z., Prabhakar, V., et al., 2023).	8
Figure 2.—Example spectrograms showing typical differences in recorded AE power spectra as a function of time/distance along a pipeline during no-leak conditions (left), two minor leaks of less than 1 gpm (center), and a significant leak (right). In these examples, the peak energy of the spectral signatures corresponds to the leak locations. The two small leaks appear as slightly elevated amplitudes with peaks in the 2000-3000 Hertz (Hz) frequency range, located near the center of the middle plot. The spectral signature of a more significant leak is shown in the right plot as a notably elevated and broadband energy distribution, extending from approximately 1000 Hz to 8000 Hz at the leak location near the center. Figure modified from (IGNU, 2025a; Singbeil, M., and van Pol, A., 2023).....	9
Figure 3.—Schematic of a cursory listening rod survey being conducted at various surficial pipeline access points (e.g., valves or hydrants) along a pipeline alignment (left image), and a photograph of the system in use during a survey (right image). Figure taken from (Ziemendorff, S., 2022).	11
Figure 4.—Schematic of a ground microphone leak pinpointing survey being conducted along the ground surface above a pipeline alignment (left image), and a photograph of the system in use during a pinpointing survey (right image). Figure taken from (Ziemendorff, S., 2022).	12

Figure 5.—Photo of a direct-push in-line cabled hydrophone leak detection system (left), and a schematic showing the general sequence of leak locating. Figure modified from (FAST GmbH, 2025). 14

Figure 6.—Photos showing difference variations of AE noise loggers (left and center images), and a photo of a noise logger being deployed in the field with a wireless radio data harvest console (right). Figure modified from (Dalaeli, J., and Lunsford, J., 2023; Sewerin, 2025). 16

Figure 7.—Example photo of a wireless mobile correlator system with two sensors (“A” and “B”) and a system console that performs signal processing, cross-correlation, and leak locating calculations in real-time. In this example, the two sensors are mounted directly onto the pipeline or other metallic access points with built-in neodymium magnets integrated into the bottom of the sensor housing. Figure modified from (Gutermann, 2025). 16

Figure 8.—Schematic showing the principle behind correlator system leak locating. Figure modified from (Schwenen, L., 2019). 18

Figure 9.—Schematic showing the conceptual functionality of an in-line free-floating leak detection hydrophone sensor system. The system is deployed into an in-service/live pipeline from an upstream access point, and it flows along the pipe while recording various data types (example acoustic amplitude line graph depicted in the center of the figure, and two example spectrograms shown at the bottom). The sensor is then intercepted and retrieved at a downstream access point, and the data are downloaded for subsequent analyses. Figure taken from (El-Zahab, S. and Zayed, T., 2019). 23

Figure 10.—Photo showing one of three variants of the in-line IGNU Inc. Pipers™ sensor system, approximately the size of a baseball. These devices are neutrally buoyant and are offered in three different sizes (1.50, 2.3. and 2.8 inches in diameter) to adapt to several internal diameters and access points from 2 in. and greater. This specific variant of the IGNU sensor only records movement, magnetic field strength, and thermal data. Figure taken from (Whitfield, S., 2025). 24

Figure 11.—Example of magnetometer time series data (top plot) recorded by an in-line AE leak detection sensor, used to locate pipeline joints and other metallic appurtenant structures. This aids in encoding positional information to simultaneously recorded AE data. The vertical black lines (bottom plot) indicate the locations of detected pipeline joints, identified through neural network-based machine learning inference. Figure modified from (Singbeil, M., and van Pol, A., 2023). 25

Figure 12.—Example photo showing two DAS IUs deployed at Granby Dike #3 in Colorado (left), and a schematic of a DAS system showing an IU connected at one end of a fiber optic cable, carrying backscattered laser light back to the IU (right). Schematic taken from (Finfer, D., Veronique, M., Shatalin, S., et.al., 2014). 27

Figure 13.—Example of a raw DAS data “waterfall” plot showing signal intensity/amplitudes as a function of time versus distance along a fiber optic cable (color indicates signal intensity/amplitude). This data plot shows approximately 2 minutes of DAS data recorded on a 45 kilometer (≈28 mile) long fiber. Figure modified from (AP Sensing, 2025). 29

Figure 14.—Overview of the general alignment of the Mni Wiconi Rural Water Supply System, with the start and end points of two target monitoring segments near the City of Pierre labeled on the figure. 32

Figure 15.—Detailed view of the general alignment of the first AE monitoring target, “Zone 1” (bold red polyline) of the Mni Wiconi Rural Water Supply System near the City of Pierre, South Dakota. The start and end points of this target segment are indicated with red-labeled points.... 34

Figure 16.—Detailed view of the general alignment of the second AE monitoring target, “Zone 2” (bold red polyline) of the Mni Wiconi Rural Water Supply System, which starts approximately 7 miles downstream of the City of Pierre, South Dakota. The start and end points and 16 access points along this target segment are indicated with red-labeled points. 34

Figure 17.—Side-view schematic of the experimental setup for testing Nb-IoT AE correlator monitoring sensors in the Building 56 Hydraulics Laboratory..... 36

Figure 18.—Various photos taken during testing of Nb-IoT loggers in the Building 56 Hydraulics Laboratory. 37

Figure 19.—Side-view schematic of the experimental setup for testing AE correlator monitoring sensors in GSA Facilities Building 810. 40

Figure 20.—Photo of the water release outfall onto an exterior loading dock, taken during initial testing of Nb-IoT loggers at the GSA facilities Building 810 warehouse. 41

Figure 21.—Various photos taken during testing of Nb-IoT loggers in the GSA facilities Building 810 warehouse, showing the locations of the sensors and water release point..... 42

Figure 22.—Block diagrams of the prototype data logger (left) and piezoelectric sensor (right). Figure modified from (Ball, J., 2025). 43

Figure 23.—Various photos of the prototype data logger and piezoelectric sensor taken during the initial water release test at GSA Facilities Building 810. 43

Figure 24.—Photos showing the deployment of prototype piezoelectric sensors during the initial water release test at GSA Facilities Building 810. 44

Figure 25.—Photo showing one of the Nb-IoT loggers (“Logger #1”) deployed at the northern end of the train track testing segment. As designed, each logger is firmly attached to the track using the neodymium magnet integrated into its base. 46

Figure 26.—Aerial imagery of the train track testing location, showing the 800-foot segment of track utilized for various tests (red line). Deployment locations and relative distances of the three Nb-IoT loggers are indicated with labeled yellow points. The placement location of the synthetic leak noise source is marked with a labeled red star. 47

Figure 27.—Photos showing geophone sensors and seismic surveying equipment used to perform hammer tap tests for wave velocity analysis along the train track segment. 48

Figure 28.—Example shot gather showing vibration recordings from six geophone sensors during a hammer tap test, with the source located immediately adjacent to the southernmost geophone sensor (Channel #1). The source location is indicated by a red star at the top of the plot. Amplitudes recorded by each geophone are displayed as black and gray “wobble traces,” plotted as a function of channel number/distance (horizontal axis) versus time (vertical axis). The thin blue polyline represents the manually picked first arrivals of wave energy used for wave propagation velocity calculations. 49

Figure 29.—Photos showing initial testing of a prototype piezoelectric transducer synthetic leak noise source. This noise source was deemed not powerful enough, so a larger source was developed instead..... 51

Figure 30.— Photos showing initial testing of a more powerful prototype synthetic leak noise source developed for testing leak detection and localization on the train tracks. This version of

the noise source utilizes an 800-watt amplifier, a bass shaker, and a car speaker for increased acoustic energy output. 52

Figure 31.—Power spectrum of a mixed multi-track audio file developed for use as a synthetic leak noise source. 53

Figure 32.—Photo showing the prototype data logger deployed near the synthetic leak noise source. Two piezoelectric sensors are deployed along the track, 25 feet in either direction (i.e., straddling the noise source), and connected to the logger with the white audio cables visible in the photo..... 54

Figure 33.—Examples of data recorded by the prototype sensor data logger system during hammer tap tests. Note the relatively low-amplitude and repetitive system noise that is superimposed on the larger-amplitude hammer tap signals/waveforms. Also note that Channel 1 of the logger did not successfully record waveforms, likely due to a bad sensor cable connection or hardware failure. 55

Figure 34.—Power spectrum for hammer tap test #1 data recorded by the prototype sensors and logger. 56

Figure 35.—Power spectrum for hammer tap test #2 data recorded by the prototype sensors and logger. 57

Figure 36.—Example of data recorded by the prototype sensor data logger system during hammer tap tests. Note that Channel 1 of the logger did not successfully record waveforms, likely due to a bad sensor cable connection or hardware failure. 58

Figure 37.—Power spectrum for synthetic leak noise data recorded by the prototype sensors and logger. 58

Figure 38.—Aerial imagery of the train track testing location, showing the 444-foot segment of track utilized for the final leak localization tests (red line). The deployment locations of the 11 geophone sensors are indicated with yellow points (relative distances listed in inset table). The placement location of the synthetic leak noise source is indicated with the labeled red star. 59

Figure 39.—Example shot gather showing vibration recordings from 11 geophone sensor during a hammer tap test, with the source located near the center of the geophone array (Ch#25). The source location is indicated with a red star at the top of the plot, and the amplitudes recorded by each geophone sensor as a function of time are plotted as black and gray “wobble traces.” The thin blue line shows the manual picks of energy first arrivals used for wave propagation velocity calculations. Note that Ch#19 suggests a later arrival time than picked, but increasing the gain (not shown here) verified that the arrival pick time was accurate and consistent with other channels, based on average energy moveout and delays as a function of distance from the source. 60

Figure 40.—Example set of 16-second synthetic leak source waveforms (black wobble traces) recorded by the 11 geophones spanning 444 ft of track. The positive and negative 50-point mean envelopes of the waveforms are plotted as green and blue lines that bracket each waveform. The true source location is indicated with a bold red star, and the calculated/predicted source location is indicated with a labeled red asterisk at the top of the plot. Note that several relatively high-amplitude transient sound are captured by all sensors throughout the 16-second recording..... 63

Figure 41.—Power spectra for two example channels (Traces 1 and 8) of synthetic leak noise data recorded by the geophone sensors, with a 200 Hz high-pass filter applied to the waveforms. 64

Figure 42.—Three different zoom levels for plots of cross-correlation coefficients for data traces 1 and 8. The peak correlation coefficient is indicated with a labeled red asterisk. In this example, the positive time lag of the peak coefficient indicates that the source is closer to trace 8 (i.e., the source noise arrived at sensor 8 approximately 6.75 milliseconds before arriving at sensor 1)... 65

Figure 43.—Results of all source location predictions for 200 Hz high-pass filtered data, using all permutations of channel pair selections. The predicted source location is plotted as a function of permutation count in the top plot, and a histogram of the predictions is shown in the bottom plot. The corresponding mean and statistically most likely predicted source locations are indicated on each plot with dashed black and red lines, respectively..... 66

Executive Summary

Water pipeline leaks can be extremely costly in terms of non-revenue water losses, resource allocations, contracted leak detection and locating services, repair costs, water transmission service shutdowns, and even occasional legal outfall from property damage. A variety of buried pipeline monitoring and leak detection/locating techniques have been developed, but acoustic emission (AE)-based techniques were identified by the research team as the most promising for effective long-term and proactive monitoring for leak detection and locating across large pipeline systems.

The primary objective of this research project was to gain knowledge and expertise for successfully developing and deploying AE sensing/monitoring systems along existing and future pipelines so that Reclamation can self-perform early leak detection monitoring and accurate leak location services in near-real-time—at a fraction of the cost compared to single one-time or subscription-based private-sector monitoring services.

This research project primarily involved the following activities:

- Performing market research and a literature and technology review of several commercially available AE leak detection and localization technologies and services,
- Conducting several controlled laboratory and field-scale experiments that aimed at evaluating the functionality and efficacy of commercially available AE monitoring system technologies,
- Designing and developing a prototype AE datalogger, firmware, and prototype piezoelectric transducer sensors that were deployed and tested during several experiments,
- Developing custom software/scripts that were tested and used for performing leak detection and accurate leak locating with passive AE noise recordings collected during field-scale experiments,
- Collaborating with South Dakota Area Office personnel in an effort to instrument segments of the Mni Wiconi Rural Water Delivery System main core-line with an AE monitoring system,
- Pursuing a purchase request for the acquisition of wireless AE monitoring dataloggers, and subsequently pivoting to a purchase request for the acquisition of a distributed acoustic sensing (DAS) interrogator unit (IU) for field deployment along the Mni Wiconi pipeline and for use in other future project-based applications and research endeavors.

The results of the technology review and various experiments are presented in this report. The activities conducted during this research project helped Reclamation personnel gain valuable expertise in implementing AE monitoring systems and leak detection/locating techniques, and further developed capabilities for Reclamation to self-perform these activities without reliance on expensive commercial hardware and services.

CONTROLLED

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

Findings from this research highlight the need to further develop a fully functional and versatile version of the current prototype AE datalogger system—one that can be fully controlled, comprehensively evaluated/debugged, modified, and custom-configured for a variety of monitoring and leak detection/locating applications and other needs that Reclamation will undoubtedly continue to encounter in the future.

The acquisition of a DAS IU will enable a variety of exciting future research and development (R&D) activities and the development of new capabilities within the Technical Service Center (TSC), both related and unrelated to pipeline leak detection and locating.

Next steps and future work should focus on developing Reclamation's capabilities to self-perform various leak detection, locating, and long-term monitoring services—specifically through the continued pursuit and development of DAS capabilities, wireless acoustic datalogger systems, and associated data telemetry and analytics software. Reclamation's return on investment for pursuing DAS and wireless AE datalogger system development could potentially be substantial, especially when considering current practices and the monetary and resource costs incurred during leak events related to leak detection, locating, and repair activities.

1.0 Introduction

Current practices implemented by the U.S. Bureau of Reclamation (Reclamation) for buried pipeline leak detection and location determination are reactionary and not standardized, where a large lag-time between leak suspicion/detection, leak locating, and leak repair work is common. This slow and drawn-out sequence of events is typically associated with significant water losses and, occasionally, costly property damage prior to repair.

A leak is typically detected within a long segment of buried pipeline by a sudden or gradual change in water transmission rates or anomalous differences between flow meter or pressure monitoring data from two sparsely placed sensors (e.g., thousands of feet apart). The location of the leak is then unknown until a private-sector company can be contracted to perform leak locating services, or until some visual evidence of the leak manifests at the ground surface (e.g., in the form of lush green vegetation, standing water, or anomalously saturated soils along the pipeline alignment).

In many cases, surface-based leak detection surveys fail to accurately pinpoint the leak position. Furthermore, surficial expressions of a leak can be misleading, as associated wet areas have been reported to develop in locations up to 50 to 100 feet (ft) or more away from the actual leak location. This occurs because pressurized leakage water migrates within a backfilled construction trench and along the outside of the pipeline before finding a path of least resistance to the ground surface (Reclamation, 2022a). At this stage, a leak has typically progressed to a severe state, resulting in an “emergency repair” situation that evolves into a much more expensive contracting scenario and often requires large trenches to be excavated before precise leak location is determined.

The direct consequences of not implementing effective solutions to pipeline leak detection, locating, and monitoring technologies include continued significant non-revenue water losses, reliance on expensive private contractors, and the need to wait until leaks become severe enough to be visually identified—often resulting in added excavation and repair costs.

These issues are not hypothetical. Within Reclamation’s infrastructure inventory, major leaks occur relatively frequently. For example, a 1-mile segment of the Mni Wiconi Rural Water Supply System in South Dakota has experienced ongoing pipeline corrosion and significant water leaks along its 24-inch steel main line—as often as one or more leaks per month. Locating and repairing each leak typically costs between \$75,000 and \$140,000, with some cases reaching \$300,000 (Reclamation, 2021a). These figures do not include additional costs such as service disruptions, resource allocation, or legal liabilities. Reclamation and other stakeholders would benefit greatly from adopting proactive leak detection and long-term monitoring technologies to mitigate these recurring costs and risks.

As described in a recent Science and Technology (S&T) Program prize challenge competition titled “*Detecting Leaks and Flaws in Water Pipelines*,” Reclamation’s water conveyance systems include over 20,000 miles of buried pipelines made of various materials, including metal, plastic, concrete, and composite. Municipal water utility collaborators also maintain extensive transmission and distribution pipeline networks. Pipeline components—such as joints,

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

fittings, valves, and individual pipe sections—are subject to leakage due to damage, corrosion, and other types of degradation.

Detecting water loss from pipelines enables timely maintenance, conserving scarce water resources and ensuring more reliable service to clients. Typical water pipeline leak detection techniques include aerial flyover inspections, acoustic or electromagnetic evaluation of pipe integrity, visual inspection of interior surfaces, and flowrate disparity analysis (Reclamation, 2018).

This prize challenge competition sought crowd-sourced, novel solutions to address various technical and logistical challenges associated with pipeline leak detection. Several public solution submissions were selected for partial cash prize awards. These included:

- Leak-sniffing dogs,
- A “soft” robot that is deployed inside pipelines to perform leak detection via pressure anomaly mapping and light detection and ranging (LiDAR) scanning for surface roughness anomalies along interior pipeline walls,
- Radio frequency identification (RFID) deployment with exterior antenna scanning, and
- Raman LiDAR gas detection using aerial drones to detect gaseous signals along pipeline alignments (Reclamation, 2022b).

While these techniques might be suitable in certain scenarios for determining general system delivery information or for detailed evaluation of small pipeline sections, none are capable of efficiently inspecting thousands of miles of pipelines or precisely determining leak location and severity. In addition, many of these techniques are unable to inspect pipelines while they are in service (i.e., pressurized and conveying water), or they cannot overcome operational challenges such as limited pipe entry points, diameter changes, elevation variations, or lateral bends (Reclamation, 2018).

Significant R&D has been conducted, and commercially available sensors and monitoring systems have been developed across academia and industry. The main task remaining for Reclamation is to confirm the usability and limitations of these systems and techniques under various scenarios and conditions, to gain expertise in deploying existing AE leak detection and monitoring technologies/systems, and to develop standard practices for implementing these technologies in the most cost-effective and technically responsible manner. This will help transition the use of these technologies into common practice and optimize operations and maintenance (O&M) activities related to pipelines across the agency’s inventory.

Significant R&D aimed at improving methodologies and data analytics is ongoing. One specific focus area that extends various leak detection and locating techniques—as well as system-scale predictive maintenance—is the integration of artificial intelligence (AI) and machine learning (ML) to enhance and automate a variety of data analytics tasks. For example, an entire technical session at the 2023 North American Water Loss Convention, titled “*Artificial Intelligence/ML for Real Water Loss Control*,” was dedicated to this subject, with several presentations incorporating the topic in other technical sessions as well (Cha, S., Mok Ahn, B., Kim, J., et al., 2023; Hughes, D.M., 2023; Paradise, A., Andalibi, Z., Prabhakar, V., et al., 2023; Singbeil, M., and van Pol, A., 2023; Sinha, S., 2023; Sutherns, T., 2023).

The most common leak detection and localization methods can be categorized based on the underlying observable phenomenon caused by a leak and associated principle of detection, as well as the type of sensor or survey approach used to measure or record the given phenomenon. A list of these various methodologies is provided in Table 1. It should be noted that some of the listed methods can only be used for leak detection, while others are capable of both detection and precise leak localization.

In most of Reclamation's major pipeline systems, various Supervisory Control and Data Acquisition (SCADA) sensors are already integrated to monitor and inform—or automate—standard system operational parameters or constraints, such as system-integrated pressure transducers and flowmeters. These SCADA systems are typically the first source of indication for leak detection along a pipeline. In such cases, the leak is only detected, but its location is generally unknown or only narrowed down to a segment of the system between two SCADA sensors (e.g., flow volume or mass-balance flowmeter disparities, where more water is flowing into a given pipe segment than is flowing out). The task of locating and repairing the detected leak then becomes the next step.

In consideration of all currently available pipeline leak detection and locating technologies, AE sensing and localization (i.e., determining the leak position) techniques were identified by the research team as one of the more promising groups of technologies for long-term monitoring of extended pipeline segments or entire systems. These techniques are particularly well-suited for early-onset leak detection, as well as for reactionary or near real-time leak localization to help guide efficient excavations and repairs.

As a result, this research project focused on evaluating various AE technologies and techniques for detecting and locating pipeline leaks, with the goal of supporting the reduction-to-practice of relevant technologies for the future benefit of Reclamation. The results of this technology review are presented in this report.

Table 1.—List of developed pipeline leak detection methodologies, including the underlying detection principles and sensor types used. Note that the terms “contact sensor” or “contactless sensor” refer to whether the sensor makes direct contact with the pipe, water column, or connected system structures. Table modified from (Ziemendorff, S., 2022).

Method	Principle	Sensor type
Listening rods	Acoustic	Contact sensor
Ground microphones	Acoustic	Contactless sensor
Leak noise correlation	Acoustic	Contact sensor
Noise logging	Acoustic	Contact sensor
Pushed hydrophones	Acoustic	Pig (in-line deployed sensor)
Tethered hydrophones	Acoustic	Pig (in-line deployed sensor)
Free-floating hydrophones	Acoustic	Pig (in-line deployed sensor)
Distributed Acoustic Sensing (DAS)	Acoustic	Sensing cable
Volume balance	Flow-rate	Contact sensor
Flow monitoring	Flow-rate	Contact sensor
Step test	Flow-rate	Contact sensor
Hydraulic leak localization pig	Flow-rate	Pig (in-line deployed sensor)
Thermal imaging cameras	Thermal	Contactless sensor
Thermal imaging drones	Thermal	Contactless sensor
Distributed temperature sensing (DTS)	Thermal	Sensing cable
Moisture measurement	Moisture	Contactless sensor
Moisture sensing smart-cables	Moisture	Sensing cable
Ground Penetrating Radar (GPR)	Electromagnetic	Contactless sensor
Conductivity/Resistivity Profiling	Electromagnetic	Contact or Contactless sensor
Satellite radar	Electromagnetic	Contactless sensor
Tracer-gas	Chemical	Contactless sensor
Sniffer dogs	Chemical	Contactless sensor
Negative Pressure Wave Method	Pressure	Contact sensor
Soil probes	Mixed	Contactless sensor

1.1. Research Question, Objectives, and Strategy

1.1.1. Research Question

What are the most appropriate application scenarios and major practical limitations of AE-based pipeline leak detection and locating systems and techniques that influence the success of leak detection efforts when implemented along Reclamation’s pipelines?

1.1.2. Research Objectives

The primary objective of this research project was to gain knowledge and expertise for successfully developing and deploying AE sensing and monitoring systems along in-service

pipelines and future newly constructed pipelines. This would enable Reclamation to self-perform early leak detection monitoring and accurate leak location services in near-real-time—at a fraction of the cost compared to single one-time or subscription-based private-sector monitoring services. Achieving this goal would also address several security concerns and administrative challenges related to granting access to sensitive information required by private-sector service providers, and would eliminate the need for cloud-based public-server data hosting and analytics platforms commonly used by these companies.

If the AE-based pipeline leak detection and locating technologies investigated by this research can be reduced to common practice and performed internally by Reclamation, the following outcomes could be achieved:

1. Decreased outage time or reduced likelihood of emergency shutdowns—allowing more time to contract repair services when needed, rather than implementing emergency repair schedules without a competitive bid process.
2. Maximized water delivery—by avoiding unnecessary water losses at pipeline leaks and reducing shutdowns during leak locating and repair efforts.
3. Reduced non-revenue water losses—directly translating to more water available each season for allocation among municipal, agricultural, environmental, wildlife, and recreational uses.
4. Reduced liabilities and costs—including direct and indirect costs of maintenance, inspections, repair work, and time required for repairs, compared to current business practices.

1.1.3. Research Strategy

A multi-year approach was taken, involving literature and technology reviews of AE equipment and analysis techniques; design and construction of prototype AE sensors and data loggers; leak simulation lab and field testing; laboratory and field testing and evaluation of commercially available AE leak detection equipment; development of software and evaluation of the standard pipeline leak localization algorithm used by various AE correlator systems; and pursuit of external partnerships and planning for field-scale deployment of monitoring systems.

Following the lab-based evaluation of the prototype AE sensor/data logger system and the commercially available systems, field-scale deployments of sensors and monitoring were pursued with the goal of comparing AE monitoring data, leak detection, and locating results to O&M performance data provided by external partners. However, this final task was not successfully carried out for a variety of reasons, which are described in more detail in subsequent sections of this report.

1.1.4. Previous Work

Beyond the recent S&T prize challenge competition (Reclamation, 2018), previous and ongoing S&T research activities relevant to this proposed research topic include:

1. **2020** – S&T scoping-level literature and technology review of DAS fiber sensing for large critical infrastructure monitoring (Justin B. Rittgers),

2. **2022** – S&T conducting-level research project on the use of distributed fiber optic sensing (DFOS) technologies for a variety of monitoring applications (John Germann),
3. **2016** – S&T conducting-level research project on measuring river and stream bed load with hydrophones and hydroacoustic data loggers (Robert C. Hilldale).

Recently, Reclamation’s Water Conveyance Group (8140), along with various area and regional offices, has experienced significant pipeline leak issues and has sought commercial leak-locating services using a “Smart Ball” pipeline “pig” technology. This service involves sending a small spherical device down the inside of a pipeline, where the system collects acoustic data and photographs along the pipeline’s length.

In many cases, this approach to sensor deployment is not feasible or comes with significant risks, such as losing the device or causing service shutdowns. It is also extremely expensive for a single, one-time survey effort. For example, a 17-mile segment of the newly constructed Navajo Gallup Reach 22b pipeline was completed, pressurized, and immediately showed a leak in the form of system pressure loss. The Farmington, New Mexico, Area Office needed to locate the leak(s) and have the contractor repair them prior to closing their contract, making this a time-sensitive survey need.

The cost of scanning the 17 miles of pipeline once with a smart ball system was more than \$250,000. Similar quotes were provided for other pipelines and issues, and these were deemed cost-prohibitive; therefore, the leaks were allowed to progress until surficial evidence revealed their locations. In at least one case, this more primitive approach has now become the standard procedure for leak locating (Reclamation, 2021b).

Furthermore, fairly expensive contracted AE sensing services do not always provide sufficient leak detection or locating accuracy, as experienced by Reclamation’s South Dakota Area Office Rural Water Division, which employed two different services unsuccessfully along the Mni Wiconi Rural Water Delivery System main line (Reclamation, 2022a; Reclamation, 2024).

2.0 Overview of Pipeline Leak Acoustic Emissions Characteristics

There are a variety of pipeline leak, including manufacturing or installation defects, progressive corrosion, impact or excavation damage, cavitation erosion, and sudden rupture failures caused by system operation errors that result in excessive pressures (e.g., water hammer transients). When a pressurized water pipe develops a leak, the escaping water generates acoustic emissions—pressure or sound waves—that propagate away from the leak location (Figure 1).

This acoustic signal is typically sudden or progressively emergent in intensity and is characterized as a sustained anomalous signal relative to normal operating conditions—mirroring the nature of the leak itself, which may also be sudden or gradually worsening and persistent until detected, located, and repaired. These AE sound waves propagate spherically outward into

the surrounding ground or medium, but a significant portion of the acoustic energy also travels in both directions along a pipeline, which acts as a waveguide.

Additionally, pressure waves propagate in both directions within the pipeline fluid (e.g., negative pressure waves). The pipe wall and the fluid-borne waves continuously interact, transmitting energy between the two media and outward into the surrounding environment along the pipe. As the distance from the leak increases, the AE signal weakens due to attenuation—caused by particle motion friction, conversion to heat, and energy loss through transmission into the surrounding medium.

Different pipe materials, geometries, and fluid types influence both the speed at which acoustic energy propagates and the rate at which it attenuates with distance. Regardless of the pipeline material or fluid, the AE signal is always strongest at the leak location and diminishes with increasing distance.

Another noteworthy characteristic of pipeline leak AE is that the energy is effectively generated by a point source (the leak location), and the waves or signals that propagate in both directions along the pipe are essentially the same. For example, the sound heard—or otherwise recorded—on the pipe 100 ft downstream of the leak should be the same, or at least very similar, to the sound heard or recorded 100 ft upstream of the leak.

Furthermore, various acoustic signals should reach these two observation locations, which are symmetric about the leak, at the same time (assuming the wave propagation velocity is consistent along both portions of pipe). If one observation point is further from the leak, the sound or signal pattern will be delayed, arriving at a later time and with lower amplitude relative to a point closer to the leak (again, assuming consistent wave propagation velocity and attenuation rates along both pipe segments).

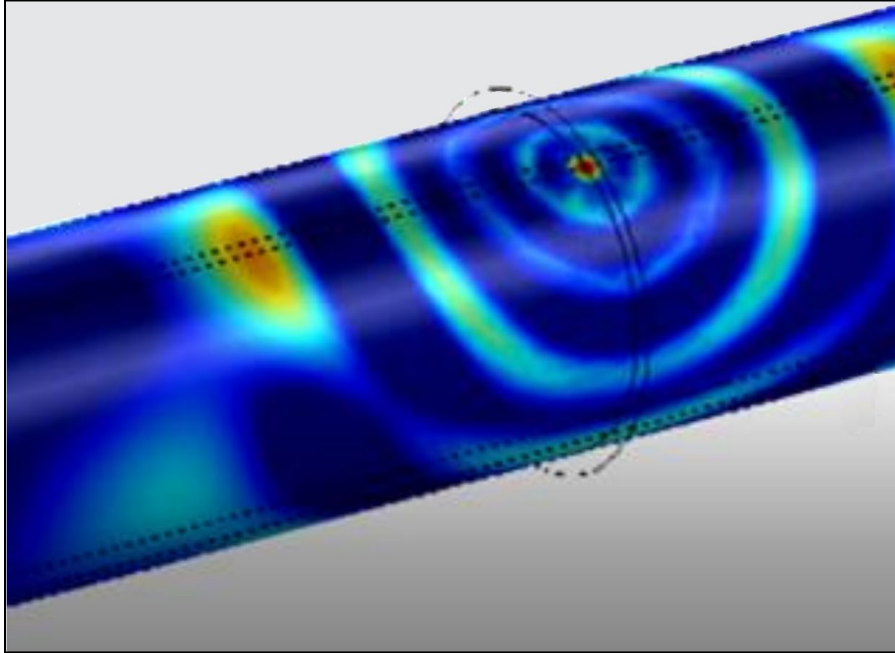


Figure 1.—Schematic showing modeled elastic waves propagating outward and away from a point source (e.g., a leak) along a pipeline. As depicted, the pipe acts as a waveguide, carrying acoustic energy in both axial directions away from the leak location. Figure modified from (Paradise, A., Andalibi, Z., Prabhakar, V., et al., 2023).

There are several factors that influence the characteristics (e.g., amplitude and frequency content) of the emitted acoustic waves. Primarily, the shape and size of the pipeline perforation, along with the operational pressure at the leak location, dictate the amplitude (loudness) and frequency content (pitch) of the associated acoustic emissions. Generally, the higher the pressure, the louder the resulting acoustic signal.

In addition to the water pressure, the size and shape of a perforation typically determine the frequency content of the emitted acoustic energy. For example, the high-frequency “hissing” sound heard when partially kinking a garden hose contrasts with the relatively quiet, low-frequency “rushing” sounds of an open-flowing hose.

Examples of the spectral content of different leak conditions are presented in Figure 2: baseline (no leak) conditions are shown in the left plot, a small leak in the center plot, and a significant leak in the right plot. In this case, AE data were recorded by an in-line, free-flowing acoustic logger as it passed by a leak. The larger leak exhibits a broader-band signature, with energy extending into higher frequency ranges. The amplitude of the larger leak (as shown by color scale) is also notably higher compared to the small leak. In both cases, the frequency and amplitude signatures are generally symmetric about the leak and show peak signals at the leak location.

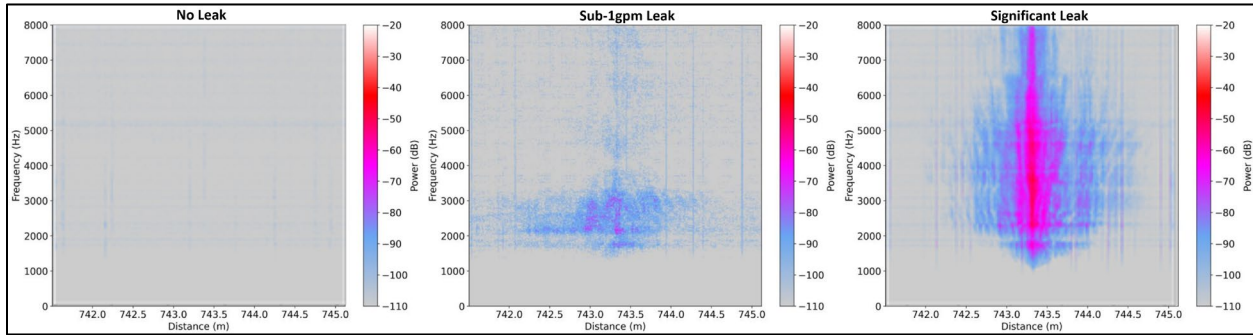


Figure 2.—Example spectrograms showing typical differences in recorded AE power spectra as a function of time/distance along a pipeline during no-leak conditions (left), two minor leaks of less than 1 gpm (center), and a significant leak (right). In these examples, the peak energy of the spectral signatures corresponds to the leak locations. The two small leaks appear as slightly elevated amplitudes with peaks in the 2000-3000 Hertz (Hz) frequency range, located near the center of the middle plot. The spectral signature of a more significant leak is shown in the right plot as a notably elevated and broadband energy distribution, extending from approximately 1000 Hz to 8000 Hz at the leak location near the center. Figure modified from (IGNU, 2025a; Singbeil, M., and van Pol, A., 2023).

These numerous characteristics of observable AE signals and wave propagation phenomena associated with pipeline leaks from the underlying data signatures that various AE leak detection and locating methods are designed to target and exploit. Specifically, these include:

1. The anomalous and sustained nature of the acoustic signal compared with baseline normal operating conditions,
2. Changes in AE signal amplitude and frequency content as a function of radial distance from the leak in any direction away from the pipe (e.g., at various points across the ground surface in the vicinity of an underlying leak).
3. Changes in amplitude and frequency content as a function of leak severity and longitudinal distance from the leak along a pipeline,
4. Symmetry of the guided wavefield signal and its propagation in both directions away from a leak along the pipe.

3.0 Overview of Pipeline Leak AE Sensing Technologies

The following subsections provide a general overview of current industry-standard AE sensing technologies for pipeline leak detection and locating. These subsections present AE sensing technologies, generally starting from the most basic to the most complex methodologies, as follows:

1. Ground Microphones and Listening Rods
2. Temporarily Deployed Noise Loggers and Correlator Systems
3. Pushed and Tethered Hydrophones
4. Long-term or Permanently Installed AE Monitoring Networks: Correlator Systems
5. In-line Free-Floating Acoustic Sensing Systems

6. Distributed Fiber Optic Sensing Systems

Each section provides a basic overview of the methodology in terms of typical application scenarios and considerations for usability, the practical order of application relative to other leak detection and locating techniques, fundamental requirements and limitations for successful use (i.e., pros and cons), generalized reliability and accuracy, implementation effort, required expertise, and the general cost of hardware and any related services. Where available or relevant, direct costs are based on market research conducted at the time of writing this report, as well as specific quotes obtained and/or purchases made for this research project in some cases. Listed costs are approximate and may vary significantly depending on a variety of factors and options not covered here.

3.1. Ground Microphones and Listening Rods

The fundamental characteristic of AE leak signals leveraged by listening rod and ground microphone locating methods is that the AE signal attenuates as a function of distance along the pipe from the noise source, as well as with radial distance from the leak in any direction away from the pipe. Ground microphones and listening rods involve manual surveys and are used to help narrow down a segment of pipe or pinpoint the exact location of a leak along a pipe segment. In many cases, the same system can be used for either a listening rod or ground microphone survey, as the two probe types are mechanically interchangeable.

Listening rod configurations utilize a handheld metallic rod connected to an audio sensor at the top of the rod (e.g., microphone or vibration transducer). The rod acts as a waveguide, carrying vibrations from the contact point up to the vibration sensor. The sensor converts these vibrations into an electronic signal, which is then sent to a console that filters, amplifies, and displays the signal amplitude on a screen. The operator can also listen to the filtered and amplified signal through connected headphones.

The tip of the rod is typically placed in contact with any accessible pipeline components at the ground surface (e.g., valves, meters, hydrants, etc.). The fundamental goal of listening rod surveys is to identify the two access points with the highest relative amplitude leak signals to determine the most likely segment of pipe where the leak is located (Figure 3). The higher of the two readings indicates the leak is likely closer to that point, or, if the signal amplitudes are equal, the leak is likely centered between the two points. These systems specifically target waveguided AE signals propagating along the pipeline away from a leak.

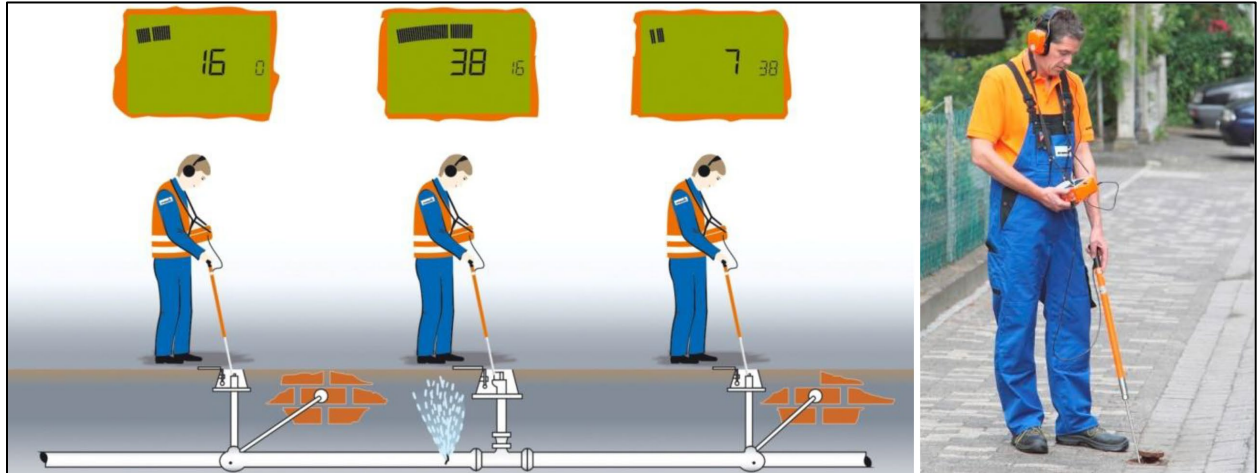


Figure 3.—Schematic of a cursory listening rod survey being conducted at various surficial pipeline access points (e.g., valves or hydrants) along a pipeline alignment (left image), and a photograph of the system in use during a survey (right image). Figure taken from (Ziemendorff, S., 2022).

Ground microphone systems operate in much the same way as listening rods, with the primary differences being the handheld probe/sensor design, the targeted component of the AE wavefield, and the sensing locations. In this case, the probe typically consists of a microphone housed inside a ground-surface coupler—a rubber cup that makes contact with the ground surface and helps isolate the microphone from surrounding noise and wind, thereby increasing sensitivity to subgrade acoustic signals.

In this configuration, a ground microphone can be moved to various points across the ground surface above a pipeline (i.e., following the known or assumed pipeline alignment) and is not constrained to pipeline system access points (Figure 4). The operator searches for the point on the ground surface where the AE signal has the highest amplitude. This location theoretically corresponds to the point directly above the leak (i.e., the point of minimum radial distance from the leak).

Here, the ground microphone survey primarily targets portions of the AE wavefield that are propagating radially outward from the leak, rather than waveguided AE energy traveling along the pipe at depth. These types of AE leak locating surveys are reactionary—they are generally used to help locate or pinpoint leaks that have already been detected.

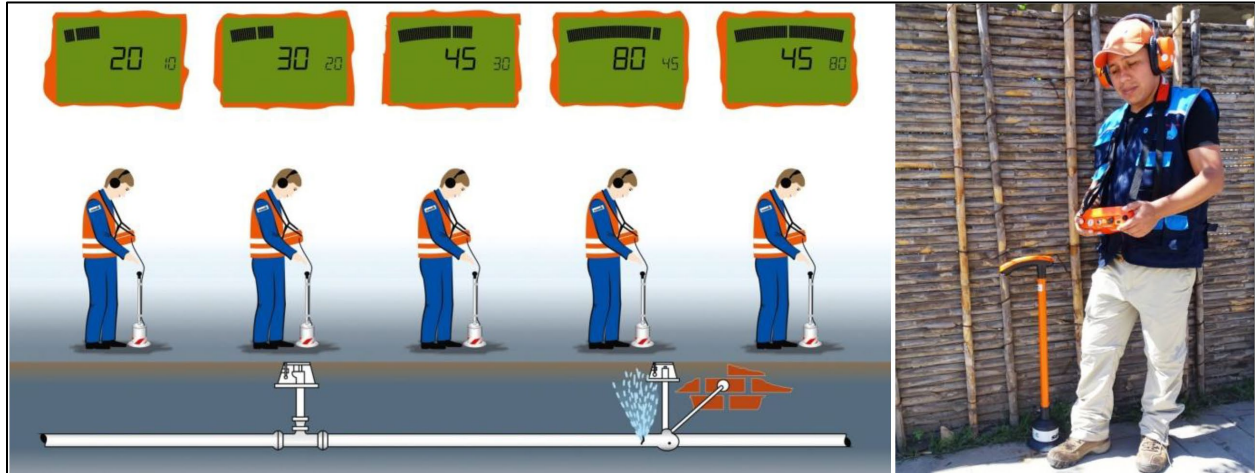


Figure 4.—Schematic of a ground microphone leak pinpointing survey being conducted along the ground surface above a pipeline alignment (left image), and a photograph of the system in use during a pinpointing survey (right image). Figure taken from (Ziemendorff, S., 2022).

Summary:

- *Typical applications and usability:* Applied along segments of pipelines where a leak has already been detected. Used to help narrow down or pinpoint the leak location prior to excavation and repair. Very simple to operate.
- *Order of application with respect to other methods:* Implemented for validation and pinpointing a leak after it has been detected and/or its location estimated by a monitoring system or other system sensors. Listening rods are usually implemented first to identify the probable pipe segment, followed by a ground microphone pinpointing survey or a mobile correlator survey.
- *Fundamental requirements and limitations for success:* Requires a known/surveyed alignment of the pipeline and a suspected search area to help “pinpoint” an already detected leak. Physical access to the alignment is required.
- *Generalized reliability and accuracy:* Success is highly variable, depending on leak noise intensity, depth of burial, pipe material, and the distance between access points. Performance is reduced in noisy environments and is somewhat subjective, depending on user experience and environmental conditions. Pipeline pressure and leak severity must be sufficient for detectability, which can vary significantly based on background noise, burial depth, backfill material, etc.
- *Efforts involved in implementation:* Manually deployed along or above a pipeline in “search-mode” to detect maximum leak sound. The process is relatively slow and labor-intensive.
- *General hardware and services costs:* Commercially available for purchase from multiple vendors. Purchase costs range from approximately \$2000 to as much as \$6,500 for more sophisticated systems with accessory packages. Service costs will vary based on project-specific scope of work and the selected company’s mobilization and billable/daily rates.

3.2. Pushed and Tethered Hydrophones

Pushed and tethered (i.e., cable-mounted) hydrophone sensors—also referred to as hydrophone or acoustic pigs—are another relatively simple option for pipeline leak locating. The method is straightforward and very similar to drain line camera inspections often conducted for households or businesses. Like drain line camera scope systems, some hydrophone pig systems incorporate illuminated borescope cameras for visual inspection of the pipeline interior during leak locating.

These systems consist of a hydrophone sensor mounted at the end of a portable reeled cable (Figure 5). The end of the cable also has a radio transponder that enables the user to locate the cable end from the ground surface using a handheld detector unit. As depicted in Figure 5, the cabled hydrophone sensor is pushed into the pipe from an open access point and advanced until the leak AE peak is identified, with the signal played audibly through a Bluetooth-connected speaker or headphones.

A distance encoder on the reel displays the amount of cable advanced into the pipe. The sensor and collocated radio transponder are left in place at the leak position, while a radio transponder detector is used to locate the exact position from the ground surface. The leak location can then be marked or immediately excavated and repaired.

Tethered hydrophones operate in essentially the same manner. The primary difference is that the cable is thinner and more flexible, with a small parachute attached at the end. The parachute pulls the hydrophone sensor downstream along an in-service pipeline until a leak AE signal peak is identified. The sensor head is then located and marked on the ground surface, as previously described.

The main advantage of these systems is that the sensors are placed inside the pipeline and moved upstream or downstream to directly locate leak signals—resulting in increased sensitivity to small leaks and highly accurate in-line distance measurements. One limitation of these sensor types is the requirement for appropriate physical access to the pipeline (i.e., open ports or valves) during normal water conveyance operations for deployment. These types of AE leak locating surveys are reactionary, meaning they are generally used to help locate or pinpoint leaks that have already been detected.

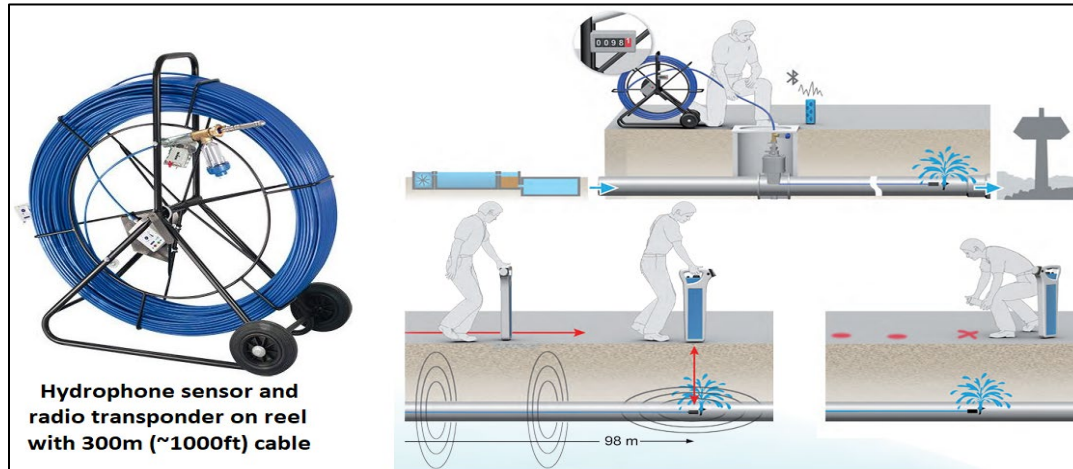


Figure 5.—Photo of a direct-push in-line cabled hydrophone leak detection system (left), and a schematic showing the general sequence of leak locating. Figure modified from (FAST GmbH, 2025).

Summary:

- *Typical applications and usability:* Both versions of cabled in-line hydrophone sensors are very simple to use and are designed for use with in-service pipelines. Cable lengths limit the distance a survey can be performed from the nearest access point.
- *Order of application with respect to other methods:* Implemented for validation and pinpointing after a leak has been detected and/or its location estimated by a monitoring system or other system sensors. Alternatively, the radio transponder and locator can be used to simply locate or map the lateral alignment of a pipeline segment, if otherwise unknown.
- *Fundamental requirements and limitations for success:* Requires a physical access point for probe insertion at a location close enough to the leak for the cable to reach it. Tethered hydrophones must be inserted upstream of the leak, and the flow rate must be sufficient to pull the hydrophone and tether cable downstream to the leak.
- *Generalized reliability and accuracy:* Success is highly variable, depending on leak noise intensity, depth of burial, pipe material, and distance between access points. Performance is reduced in noisy environments and is somewhat subjective, depending on user experience and environmental conditions. Pipeline pressure and leak severity must be sufficient for detectability, which can vary significantly based on background noise, burial depth, backfill material, etc.
- *Efforts involved in implementation:* Manually deployed from one or more access points in “search-mode” for detect maximum leak sound. The process is relatively slow and labor-intensive. Pushed sensors can likely be carefully advanced in the upstream direction if the flow rate and pipe diameter are not excessive.
- *General hardware and services costs:* Commercially available for purchase from multiple vendors. Purchase costs range from approximately \$4000 to \$7,000 for more sophisticated systems with accessory packages and an optional borescope camera. An additional cost of approximately \$1500-\$4000 is incurred to include a radio transponder and locating wand included in the package (Ziemendorff, S., 2022). Services costs will vary based on project-specific scope of work and the selected company’s mobilization and billable/daily rates.

3.3. Temporarily Deployed Noise Loggers and Correlator Systems

A more advanced and nuanced approach to detecting and/or locating buried pipeline leaks based on recording and analyzing associated AE signals involves the temporary deployment of noise loggers (Figure 6) and mobile correlator systems (Figure 7).

The fundamental characteristic of AE leak signals leveraged by temporarily deployed noise loggers is that the waveguided AE signal propagating along and within a pipeline attenuate as a function of lateral distance from the leak. Conversely, the key principle utilized by temporarily deployed or mobile correlator systems is that the waveguided AE signal propagates symmetrically in both directions away from a leak and travels along the pipe at a known or otherwise assumed/estimated propagation velocity. Both types of AE leak detection surveys are reactionary in nature and are generally used to help narrow down or locate leaks that have already been detected. Both types of systems utilize contact sensors—such as microphones, accelerometers, hydrophone sensors, or other vibration transducers—that are installed at physical access points along a buried pipeline (e.g., surface valves and hydrants) or clamped directly onto the pipe where accessible (Figure 6).

The primary difference between noise loggers and correlator systems is in how they record and process AE signals. Noise loggers independently record AE signals at each installation location for a pre-determined timeframe. In contrast, correlator systems—installed at two or more sensing locations—record AE signals and communicate wirelessly with a central console unit to perform real-time digital signal analysis of the recorded data.

Both system types can utilize externally mounted microphones or accelerometers at access points. Alternatively, they can be deployed with hydrophone sensors, which require a direct water column connection through either hot-tapped or pipe-fitting connections to the main pipeline. In such cases, all air must be bled off to ensure direct contact between the water and the hydrophone sensor diaphragm.

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection



Figure 6.—Photos showing difference variations of AE noise loggers (left and center images), and a photo of a noise logger being deployed in the field with a wireless radio data harvest console (right). Figure modified from (Dalaeli, J., and Lunsford, J., 2023; Sewerin, 2025).



Figure 7.—Example photo of a wireless mobile correlator system with two sensors (“A” and “B”) and a system console that performs signal processing, cross-correlation, and leak locating calculations in real-time. In this example, the two sensors are mounted directly onto the pipeline or other metallic access points with built-in neodymium magnets integrated into the bottom of the sensor housing. Figure modified from (Gutermann, 2025).

In the case of temporarily deployed noise loggers, the sensors are typically installed after a leak has been detected and are left in place for one or two days to allow for noise recording during quiet nighttime hours (i.e., when background noise is minimal). The recorded sound data are then retrieved from the various loggers and analyzed to detect anomalously “loud” signals that may indicate a nearby leak.

Similar to listening rods, recorded noise logger data can be used to identify the segment of pipeline where a leak is most likely located—typically between the two loudest recorded signals, with the relative location along the segment estimated by comparing the signal strengths. Alternatively, noise loggers can be deployed for longer periods or semi-permanently for early-onset, proactive leak detection. In this application, they monitor for emergent and sustained increases in noise levels that are anomalous relative to established background baselines. These longer-term systems can incorporate “edge-computing” (i.e., analytics performed on the sensor itself) and wireless data telemetry to send leak detection alerts. Wireless alerts enable stakeholders to initiate field inspections for confirmation, pinpointing, and repair of a detected leak. Additionally, longer-term noise logger sensors can be configured to support wireless “drive-by” data harvesting for periodic analysis.

In the case of mobile correlator systems, at least two sensors are temporarily deployed to help locate a leak after it has been detected. Typically, the rough position of the leak has already been determined, for example, within a segment of pipe between two flowmeters indicating anomalous flow volume or mass-balance disparities. Once the correlator sensors are installed at two physical access points, they are initialized and start recording and wirelessly transmitting AE data to a handheld logger or analyzer unit. This unit performs cross-correlation of the signals to determine the peak correlation lag time (i.e., the difference in AE signal arrival times at the two sensors) and estimates the leak location relative to the sensor locations in real-time using the standard equation shown in Figure 8.

In this method, two contact sensors are deployed along a pipeline segment with a known separation distance (D), which should account for any vertical standpipe segments between the sensors. The recorded AE signals are cross-correlated to obtain the lag time (T) between them, and the known or assumed velocity of sound propagation along the pipe (v) is used to calculate the estimated distance (L) from the nearest sensor to the leak. This technique requires that:

- The leak is located between the two sensors,
- The distance between the sensors is accurately known, and
- The sound propagation velocity along the pipeline is known or reasonably estimated.

Once the distance L is computed, the leak can be located by measuring this distance from the nearest sensor. Most correlator systems also indicate which sensor is closest to the leak and provide the relative X-coordinate of the calculated leak position, based on whether the calculated lag time is positive or negative (i.e., causal vs. anti-causal) relative to the reference sensor (typically Sensor #1).

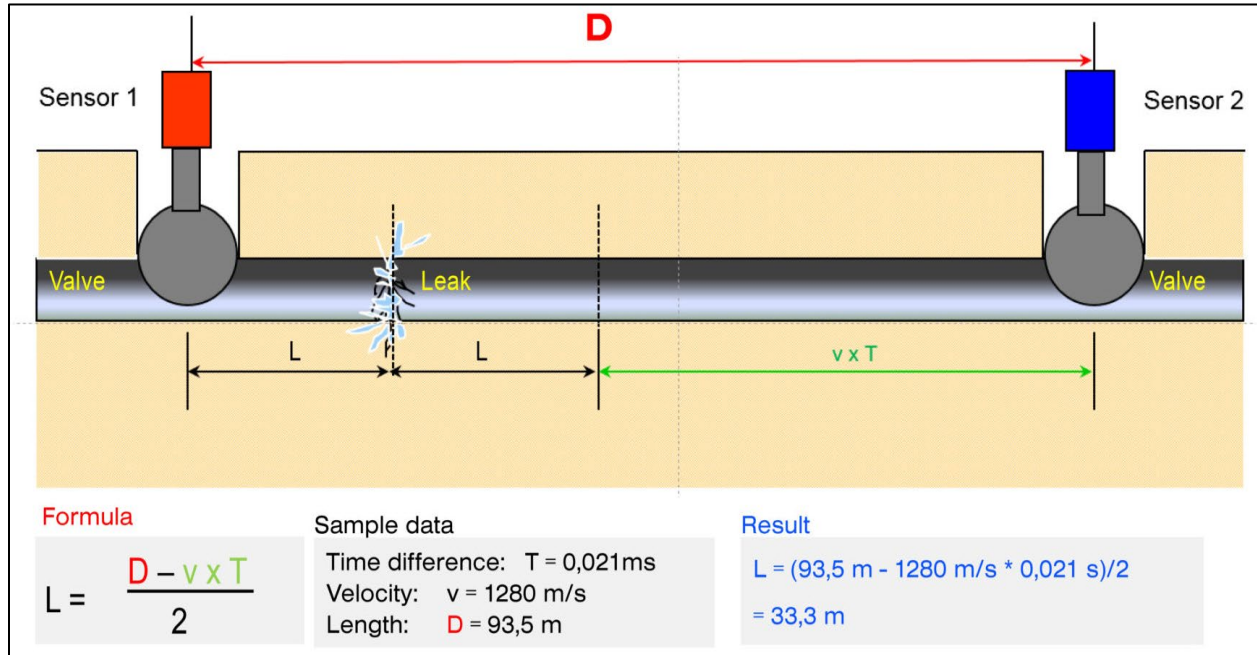


Figure 8.—Schematic showing the principle behind correlator system leak locating. Figure modified from (Schwenen, L., 2019).

This approach to leak locating is relatively straightforward and often extremely accurate. However, there are several assumptions and potential pitfalls associated with the parameters used in the calculation of L. For example, service providers or field operators typically use standard wave propagation velocities published for various pipe materials and diameters. However, actual site-specific velocities can vary significantly from these standard values due to system-specific conditions. A best practice—though rarely implemented—is to first perform a tap test to measure the actual (average) wave propagation velocity along the pipeline segment between the two intended sensing points. This is most simply done by tapping or striking the pipe or fitting at one end of the test segment and measuring the arrival time of the impact wave at the other end. Dividing the known distance by the measured propagation time yields a more accurate velocity for use in the equation shown in Figure 8.

However, the tap test is not foolproof. It only provides an average velocity between the segment endpoints and does not account for lateral variations in velocity along the segment. The longer the test segment and the more significant lateral variations, the greater the potential error in the calculated leak position if those variations are not accounted for (e.g., if the wave propagation velocity is significantly slower on one side of the leak than the other).

Additionally, other wave propagation phenomena and external noise contamination can introduce significant errors in the calculated T derived from cross-correlation of the two recorded signals. For instance, complex backscattering of energy from waves reflecting off pipe joints or fittings along the test segment can result in substantial uncertainty or error in the estimated leak location.

Summary:

- *Typical applications and usability:* Applied along segments of pipelines where a leak has already been detected. Used to help narrow down or pinpoint the leak location prior to excavation and repair. Very simple to operate, requiring minimal experience or training.
- *Order of application with respect to other methods:* Implemented for validation and pinpointing a leak after a leak has been detected and/or its location estimated by a monitoring system or other sensors. Noise loggers are typically deployed first to identify probable pipe segment, followed by mobile correlator system deployment for verification and pinpointing. Ground microphones are often used afterward to verify the correlator-indicated leak location prior to excavation and repair.
- *Fundamental requirements and limitations for success:* Requires a known/surveyed length of the pipeline test segment and a suspected search area to help narrow down and pinpoint an already detected leak. Physical access to pipeline access points is necessary. These access points must be relatively closely spaced—practical distance limitations are typically several hundred feet between a correlator sensor pair or between a leak and noise logger. Effective range is case-, site-, and system-specific, and depends on factors such as leak severity, pipe pressure, background noise levels, sensor types (range can be extended with hydrophones), and signal attenuation rate (primarily influenced by pipe material and diameter). Correlator leak locating assumes a single, constant wave propagation velocity. These systems perform best on metal pipes and less effectively on plastic or soft composite materials. Larger-diameter pipes attenuate signals more rapidly, requiring tighter sensor spacing or more sensitive sensors (e.g., hydrophones) (Ziemendorff, S., 2022).
- *Generalized reliability and accuracy:* Success is highly variable and depends on leak noise intensity, depth of burial, pipe material, and distance between access points. Performance is reduced in noisy environments and is somewhat subjective, depending on user experience and environmental conditions. Pipeline pressure and leak severity must be sufficient for detectability, which can vary significantly with background noise. Noise logger accuracy assumes a constant attenuation rate along the test segment. Correlator accuracy depends on test segment length, signal quality, and the accuracy of the assumed wave velocity. In optimal conditions, leak can be located within approximately 1% of the correlator test segment length.
- *Efforts involved in implementation:* Sensors are manually deployed at pipeline access points. “Pick-up and move” search-mode deployments may be required if the suspected leak area is large. The process is relatively slow and labor-intensive.
- *General hardware and services costs:* Commercially available from multiple vendors. Purchase costs range from approximately \$10,000 (Ziemendorff, S., 2022) to over \$30,000 for more sophisticated systems with multiple sensor types and accessory packages (based on a recent vendor quote). Service costs will vary based on the project-specific scope of work and selected company’s mobilization and billable/daily rates.

3.4. Long-term or Permanently Installed AE Monitoring Networks: Wireless Noise Logging Correlator Systems

The functionality of long-term or permanently installed AE monitoring noise logging correlator systems is effectively the same as that of temporary noise loggers and mobile correlator systems—combined into a single, integrated platform. However, several key differences extend the applications, capabilities, and hardware requirements of these modern long-term monitoring networks, including the following:

1. **Proactive monitoring:** These types of AE leak detection and locating systems are proactive—typically installed to monitor pipeline systems before leaks occur, enabling early detection and localization of otherwise unknown leaks.
2. **Hydrophone deployment:** Commonly deployed with hydrophones for larger-diameter trunk mains or where access points are sparse. Sensor identification and location information are entered into a “project” database during deployment.
3. **Edge computing:** Each sensor or data logger unit includes edge computing capabilities, allowing near-real-time leak detection and correlation-based localization directly on the device.
4. **Wireless telemetry:** Data transmission is typically handled via narrowband internet of things (Nb-IoT) or other cellular network bands. These systems send alerts for sensor/network failures, low battery warnings, leak notifications, and AE data to a cloud-hosted server.
5. **Cloud-based geographic information system (GIS) analytics:** Data are hosted in the cloud and integrated with GIS-based post-processing analytics software. GIS shapefiles of the pipeline system are uploaded, sensor/logger locations are mapped, and detected or post-processed leaks are displayed on GIS base maps, Google Maps™ or even Google Street View™.
6. **Network extension:** In areas with limited cellular coverage, repeater antennas or systems can be installed to link out-of-network sensors/loggers to the nearest cellular access point.
7. **Power requirements:** These systems require more reliable and larger power sources, such as high-capacity batteries or external solar trickle-charging hardware, to ensure long-term operation between field service intervals.
8. **Programmable settings:** Users can configure daily “wake times” and edge-computing analytics parameters, and leak detection alert thresholds.
9. **Remote configurability:** All system settings can be remotely configured or updated via the cloud platform software.
10. **Sensor expansion:** Optional integration with additional sensors, such as pressure transducers and flowmeters, is supported.
11. **Time synchronization:** Accurate (\approx millisecond scale) time synchronization across loggers is critical for reliable correlation-based leak locating. Some systems update their internal oscillator clocks each time they connect to the network—though this introduces potential timing skew due to network lag. More advanced systems incorporate GPS antennas for consistent, precise timing and more automated logger deployment.

Summary:

- *Typical applications and usability:* Applied along specific high-risk segments or critical systems for proactive leak detection. Used to help narrow down or pinpoint the leak location prior to excavation and repair. Installation and deployment of sensors and hardware are complex, requiring configuration of sensors, network setup, and project software operation. Remote or on-site support is typically needed for initial setup, field deployments, and user training.
- *Order of application with respect to other methods:* Implemented as a proactive leak detection strategy and serves as a first line of defense, complementing other system monitoring and operational sensors (e.g., SCADA systems). Leaks detected and located by the network are typically validated and pinpointed in the field using ground microphones prior to excavation and repair.
- *Fundamental requirements and limitations for success:* Requires a known and surveyed pipeline system for integration into analytics software. Physical access to pipeline access points is necessary for sensor installation. Each sensor must have cellular network connectivity, or alternatively, repeater antenna hardware must be installed in dead zones. Periodic field maintenance is also required. As with temporary or mobile systems, monitoring access points must be relatively closely spaced—practical distance limitations are typically several hundred feet between sensors to effectively monitor a given pipeline segment. Effective monitoring range is case-, site-, and system-specific and depends on factors such as leak severity, pipe pressure, background noise levels, sensor types (range can be extended with hydrophones), and signal attenuation rate (primarily influenced by pipe material and diameter). Correlator-based leak locating assumes a single, constant wave propagation velocity assigned to each network segment. These systems perform best on metal pipes and less effectively on plastic or soft composite materials. Larger-diameter pipes attenuate signals more rapidly, requiring tighter sensor spacing or the use of more sensitive sensors (e.g., hydrophones) (Ziemendorff, S., 2022).
- *Generalized reliability and accuracy:* As with their temporary or mobile counterparts, these monitoring networks exhibit highly variable success depending on factors such as leak noise intensity, pipe material and diameter, and the distance between access points. Performance is reduced in noisy environments. Pipeline pressure and leak severity must be sufficient for detectability, which can vary significantly based on background noise conditions. The accuracy of leak location using correlation depends on the test segment length, signal quality, and the accuracy of the assumed wave propagation velocity for that segment. Under optimal conditions, leaks can be located to within approximately 1% of the correlator test segment length.
- *Efforts involved in implementation:* Sensors must be manually deployed and programmed at pipeline access points. Implementation also involves occasional field maintenance, initial setup of the project software, and ongoing post-processing analytics.
- *General hardware and services costs:* Monitoring system hardware components and analytics software are commercially available from multiple vendors. Purchase costs are typically on a per-sensor/logger basis and vary significantly depending on the network size and number of loggers purchased. Per-unit costs generally range from approximately \$8,000 to over \$12,500 (based on a recent quotes from several reputable vendors). The cloud hosting and analytics software platforms are typically a subscription-based. An initial subscription period is usually included with the hardware purchase, after which the

subscription must be renewed on an annual or multi-year basis. In many cases, customers are granted full access to the cloud-hosted analytics software. However, some platforms are marketed as proprietary, where service providers do not offer customers direct access to hosted data or the ability to run their own analytics or alert workflows. Instead, these systems operate under a “black-box” model, where analytics and reporting are provided as a paid service only. This second business model often offers lower upfront hardware costs and includes comprehensive installation and maintenance services. However, it can result in significantly higher long-term costs due to ongoing service subscription fees. As a cost comparison example, three vendor quotes were obtained for monitoring a \approx 2-mile segment of the Mni Wiconi Rural Water Supply System with 14 sensors (noting that some longer segments between access points were questionable in terms of effective monitoring and leak detectability). Total hardware and subscription-based service costs over a 5-year term—including on-site installation, training, full maintenance, and data analytics/reporting support—ranged from \$123,255.41 to \$174,630.00.

3.5. In-line Free-Floating AE Sensing Systems

In-line free-floating AE sensing systems are the most recent addition to the suite of AE-based pipeline leak detection and locating technologies. This approach is similar to tethered or pushed hydrophone methods, with the key difference being that the sensor is not attached to a cable. Instead, it floats freely downstream with the water flow inside the pipeline until it is retrieved at a downstream location (Figure 9).

Sensors are typically intercepted at the extraction point using a flexible-rimmed net, which can be inserted through a relatively small access port and expands to fill the interior of the pipe, ensuring the ball sensor is captured. These AE leak detection surveys are reactionary and are generally used to help locate leaks that have already been detected.

These systems are most commonly designed as small balls (Figure 10) that use hydrophones to continuously record acoustic signals within the pipeline between the deployment and recovery points. AE data is stored in internal memory and later downloaded and analyzed for indications of leaks.

In addition to the acoustic data, these devices often include various other sensors to assist in positioning the hydrophone data along the pipeline. These sensors include cameras, magnetometers, thermal sensors, pressure sensors, accelerometers, and gyroscopes and record data that are time-synchronized with the hydrophone recordings. Without these additional data types, the speed of water flow is used for positioning the acoustic data, or simply the time difference between deployment and arrival at the extraction point is used to linearly interpolate the location of the recorded acoustic data. Additionally, some systems carry radio transponders that can be detected from the ground surface with handheld detector units to assist in data positioning and system retrieval.

As with tethered and pushed hydrophones, the main advantage of these systems is that the sensors are placed inside the pipeline and flow downstream and directly past any leaks (increased

sensitivity to small leaks due to proximity of the sensor as it passes by a leak). The example spectrograms shown in Figure 2 were recorded by one of these sensor balls, where acoustic signals from even small leaks of less than one gallons-per-minute (gpm) are discernible in some cases. Another benefit of these types of systems is that some service providers will allow the utility or pipeline owner to deploy the sensors themselves and will then provide support by post-processing and providing the locations of any detected leaks or other data signatures of concern (e.g., trapped air pockets).

The main limitation of these types of AE leak sensors is the accuracy of positioning data, which can vary widely depending on a variety of field conditions and scenarios (e.g., pipeline construction/material type, known versus unknown details of system structures and conditions, depth of burial, flow rate, consistency and complexity of pipeline geometry, etc.). As with tethered and pushed hydrophones, another limitation of this technique is the requirement of appropriate physical access to the pipeline (i.e., open ports and valves) during normal water conveyance operations for deployment and successful recovery of the unit. These types of AE leak locating surveys are reactionary (i.e., are generally used to help locate or pinpoint leaks that have already been detected).

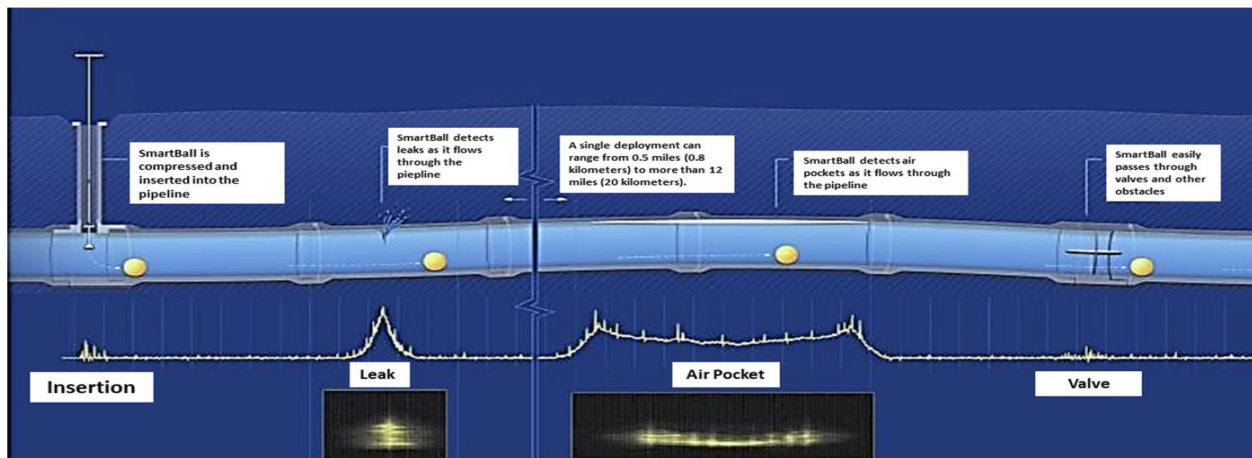


Figure 9.—Schematic showing the conceptual functionality of an in-line free-floating leak detection hydrophone sensor system. The system is deployed into an in-service/live pipeline from an upstream access point, and it flows along the pipe while recording various data types (example acoustic amplitude line graph depicted in the center of the figure, and two example spectrograms shown at the bottom). The sensor is then intercepted and retrieved at a downstream access point, and the data are downloaded for subsequent analyses. Figure taken from (El-Zahab, S. and Zayed, T., 2019).



Figure 10.—Photo showing one of three variants of the in-line IGNU Inc. Pipers™ sensor system, approximately the size of a baseball. These devices are neutrally buoyant and are offered in three different sizes (1.50, 2.3. and 2.8 inches in diameter) to adapt to several internal diameters and access points from 2 in. and greater. This specific variant of the IGNU sensor only records movement, magnetic field strength, and thermal data. Figure taken from (Whitfield, S., 2025).

The location of AE anomalies is inferred by the several sensors collecting data concurrently. The magnetometer can sense metallic pipe joints and other ferrous system components, the pressure sensor captures changes in pipe elevation, and the accelerometer and gyroscopic sensors record changes in direction. These various data types, along with accurate as-built and operational notes, allow the data scientists to understand where any anomalies of concern are located (Embry, K., 2022).

Most recent R&D efforts have involved the integration of machine learning and AI to help process magnetometer datasets for automated joint/appurtenant structure detection. Figure 11 shows an example of this post-processing step, where a neural network machine learning algorithm has been used to detect and “auto-pick” ferrous pipe joints from a magnetometer dataset. Data signatures of joints are seen as spikes or sudden offsets in the magnetic field intensity data. Once these points are identified, and the linear locations of these joints are known from construction as-built information, the time-synchronized acoustic data can be better located by means of matching the identified joint fiducials to their corresponding locations along the pipe.

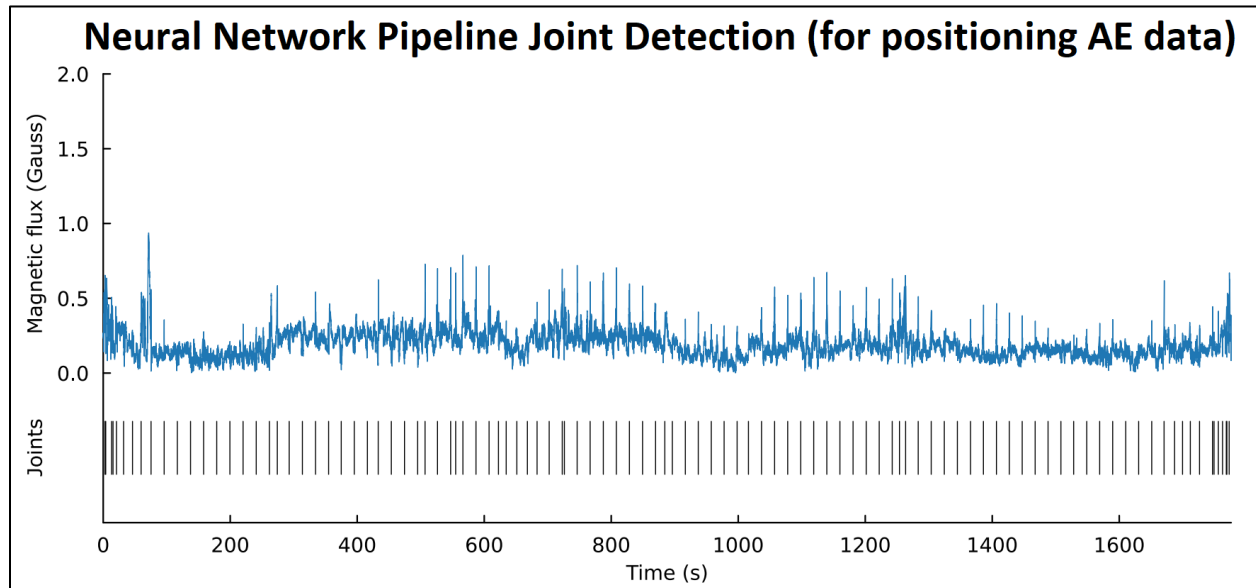


Figure 11.—Example of magnetometer time series data (top plot) recorded by an in-line AE leak detection sensor, used to locate pipeline joints and other metallic appurtenant structures. This aids in encoding positional information to simultaneously recorded AE data. The vertical black lines (bottom plot) indicate the locations of detected pipeline joints, identified through neural network-based machine learning inference. Figure modified from (Singbeil, M., and van Pol, A., 2023).

Summary:

- *Typical applications and usability:* Applied along specific segment of pipelines for reactionary leak detection and locating after a leak has already been detected. Used to help narrow down or pinpoint the leak location prior to excavation and repair. Remote or on-site support for self-deployment/recovery is an option with some vendors, while other vendors require their personnel to perform all on-site survey work. It is relatively easy to deploy and recover the sensor (with some potential pitfalls). Post processing and interpretation of the data is a vendor-service only option and requires—or otherwise significantly benefits from—accurate pipeline system specifications and as-built information for both accurate AE data (and any detect leaks) positioning and for data interpretations.
- *Order of application with respect to other methods:* Implemented for reactionary leak detection or locating after a leak has already been detected by other system monitoring/operations sensors (i.e., SCADA systems) or other system tests. These in-line, free-floating surveys are commonly followed by other pinpointing surveys, such as mobile correlator surveys or ground microphone surveys, when feasible/appropriate.
- *Fundamental requirements and limitations for success:* Requires two physical access points with adequate port size for sensor insertion or deployment upstream of the leak and for sensor recovery downstream of the leak. The flow rate must be sufficient to pull the sensor downstream and past the leak. The pipeline system can't have any bottlenecks, screens, or other obstructions that would cause the sensor to get stuck prior to recovery.
- *Generalized reliability and accuracy:* Due to the in-line deployment nature of the technique and resulting immediate proximity to a leak as the sensor passes by, these

systems are extremely sensitive to small leaks. However, leak detectability depends on system operating parameters (e.g., pressure). Detected leak position accuracy depends somewhat on pipe material and burial depth (i.e., for successful use of transponder fiducials), the accuracy of known pipeline construction details (e.g., pipe geometry, joint spacings, etc.), and sufficient flow rates to carry the sensor downstream in a consistent and steady manner.

- *Efforts involved in implementation:* Manually deployed and recovered from access points that straddle the leak position; relatively fast and not labor intensive. Post-processing for leak detection, interpretation of other data patterns, and locating any identified anomalies of concern involves the use of proprietary software and analysis services from the vendor.
- *General hardware and services costs:* Services are expensive, but commercially available from multiple vendors; sensors and software are not currently for sale (service-based business models only). Service costs vary based on the project-specific scope of work—namely, the length of the pipe segment to be surveyed, the types of features to be identified, interpreted, and reported from the data, and the selected company’s mobilization and billable/daily rates, per-mile surveyed rates, etc. One cost example from a recent Reclamation survey contract was approximately \$270k to survey a ≈17-mile-long segment of the Navajo-Gallup Pipeline. This cost was for a single (one-time) survey conducted on-site by the vendor. Prices have likely decreased in subsequent years with the addition of new vendors, increased market competition, and improved sensors, sensor designs, and data processing automation.

3.6. Distributed Fiber Optic Sensing Systems (DFOS)

DFOS is a technique that transforms fiber optic cables into dense arrays of sensors capable of measuring three types of physical phenomena within the surrounding medium (e.g., soil in the case of direct-buried cables, or engineered structures if mounted along the surface or interior of a structure). Specifically, DFOS can be used to perform the following:

1. Distributed Acoustic Sensing (DAS) to record seismic/vibrational energy impinging upon the cable,
2. Distributed Strain Sensing (DSS) to monitor and measure changes in the strain field along the cable,
3. Distributed Temperature Sensing (DTS) to monitor and measure changes in temperature along the cable.

DFOS operates by using a desktop-sized data acquisition and interferometry device known as an Interrogator Unit (IU), which emits laser pulses thousands of times per second through a connected fiber optic cable approximately ¼ inch in diameter (Figure 12). Natural or engineered structural imperfections within the cable serve as natural scattering sites that reflect portions of the light back to the IU. Transient changes in the physical environment deform the cable or alter the fiber’s optical properties and scattering characteristics, enabling the IU to detect and measure the resulting variations at specified points or segments along the cable.

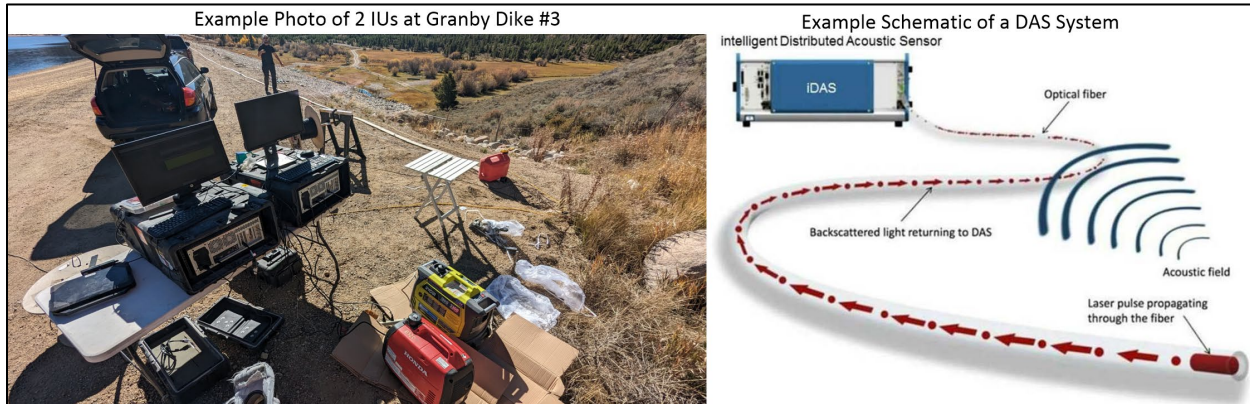


Figure 12.—Example photo showing two DAS IUs deployed at Granby Dike #3 in Colorado (left), and a schematic of a DAS system showing an IU connected at one end of a fiber optic cable, carrying backscattered laser light back to the IU (right). Schematic taken from (Finfer, D., Veronique, M., Shatalin, S., et.al., 2014).

Compared to conventional point sensors, a single kilometer-long fiber optic cable provides thousands of high-sensitivity measurements, typically spaced at ≈ 1 -meter intervals or less. AE signal locations along the fiber are known to within 1 meter (≈ 3 ft) or less, depending on how fiber is deployed (i.e., the two-way travel time of laser light directly corresponds to the signal's distance from the IU connection point). Its minimally invasive, non-mechanical design enables deployment in hard-to-access locations and ensures resilience in harsh environments, including those with extreme temperatures, pressures, or high corrosivity.

Fiber optic cables can be deployed permanently for proactive monitoring or temporarily for reactionary or occasional surveying in a variety of ways. Fiber installation techniques can include any combination of embedding within new or existing structures, deploying down water-filled pipes, or surficially affixing or weight-coupling to the ground or surface of a structure. Existing buried telecommunications fibers (e.g., "dark fiber") can also be used for DFOS, leveraging existing infrastructure.

Additionally, DFOS is highly scalable, cost-effective, and requires minimal maintenance. These advantages make it a powerful and versatile tool across a range of applications, including pipeline monitoring. DFOS can be used for both long-term passive monitoring and short-duration or intermittent interrogation surveys, such as pipeline leak locating.

Both DTS and DAS are directly relevant to pipeline leak detection and locating, but DAS is unambiguously a very powerful technique for performing AE detection and locating of pipeline leaks. The fiber optic cable can be deployed proximal to a pipeline (e.g., shallowly buried directly above and along an existing pipeline, or placed congruently in the same trench during pipeline construction), or even deployed inside an existing pipeline similar to a pushed or tethered hydrophone sensor (i.e., more rigid fiber optic cables can be pushed into a pipeline segment, or a small parachute can be attached to the end of a more flexible cable to pull it downstream from an access point).

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

Furthermore, DAS systems can be configured to target specific frequency bands or to be extremely broad-band (e.g., sensitive to vibrations ranging from less than 1Hz to several kilohertz (kHz)), and a single IU can be configured to effectively monitor more than 100 kilometers (60+ miles) of fiber from a single connection point—if the fiber has appropriate optical properties and sufficiently low attenuation rates (Cedilnik, G., Lees, G., Schmidt, P., et.al., 2019). Upper frequency band limitations are mainly dictated by the total length of the fiber being monitored and the selected gauge/sensing length interval (Wikipedia, 2025).

Similar to the AE data and spectral signature characteristics of leaks recorded by in-line free-flowing sensors (Figure 2 and Figure 9), DAS data show the exact location and intensity of a leak. The main difference between in-line free-flowing sensor surveys and an in-line deployed DAS fiber is that the fiber can be left in place and used for long-term proactive monitoring of a pipeline, or it can be left in place and reused on an as-needed basis to help locate and characterize new or otherwise suspected pipeline leaks in a reactionary sense.

These various characteristics of DAS make it a very powerful sensing and monitoring tool for large and linear structures such as pipelines. Extensive commercial use of DAS and DTS is already in practice on oil and gas pipelines for leak detection, informing system operations and performance, and for security purposes (e.g., detection of unauthorized encroachment or vandalism).

One example of raw and unprocessed DAS monitoring data collected along an oil and gas pipeline is depicted in Figure 13. Here, the real-time location of an in-line inspection “pig” system is apparent based on high-amplitude signals that track the pig location. Additionally, various negative pressure wave transients can be seen propagating in either direction along the pipe and away from the pig (source location) (AP Sensing, 2025). This exact data signature is expected in the case of pipeline leaks, which are associated with both localized high-amplitude AE signals and negative pressure wave transients that propagate away from pipeline leaks in either direction.

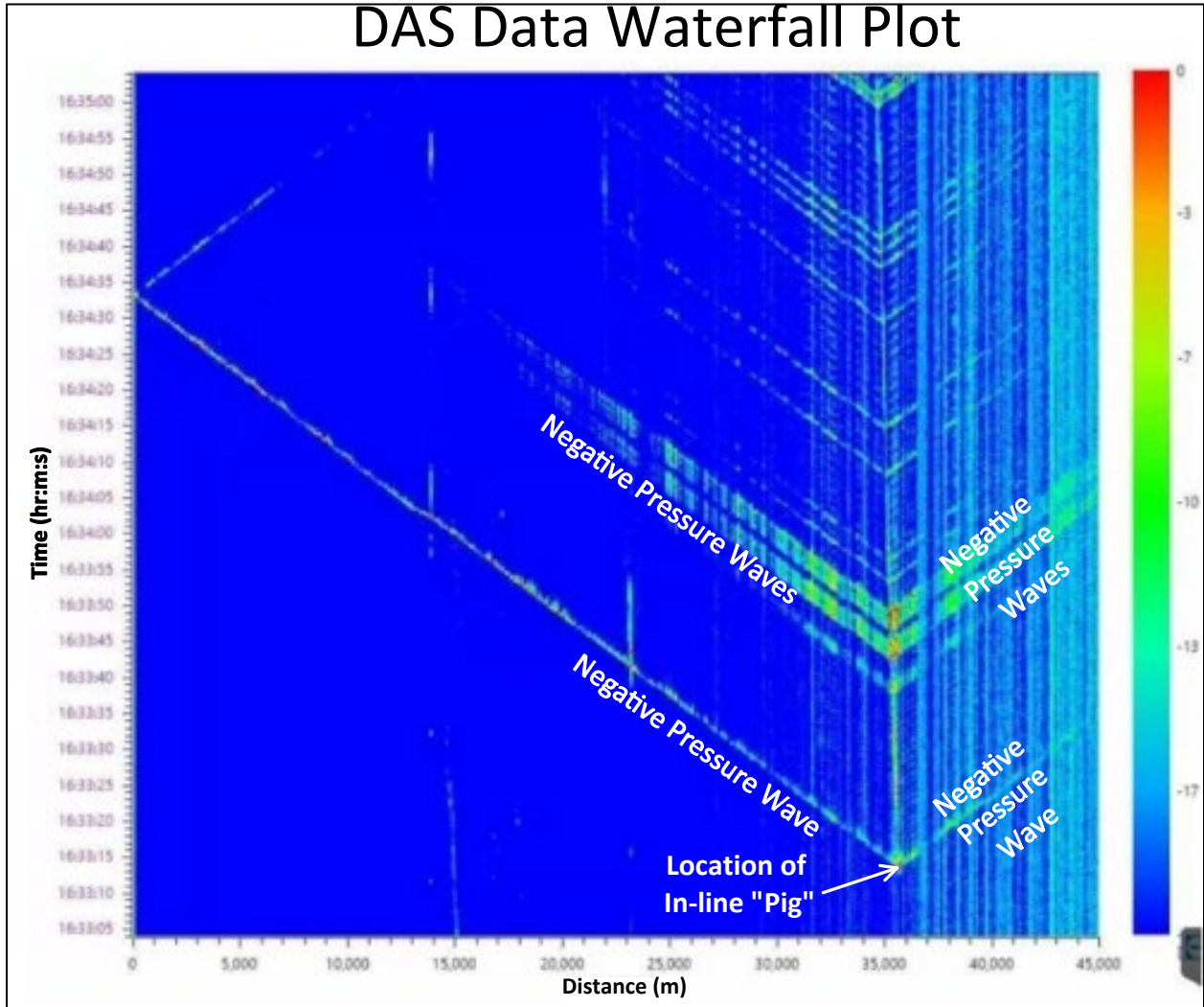


Figure 13.—Example of a raw DAS data “waterfall” plot showing signal intensity/amplitudes as a function of time versus distance along a fiber optic cable (color indicates signal intensity/amplitude). This data plot shows approximately 2 minutes of DAS data recorded on a 45 kilometer (~28 mile) long fiber. Figure modified from (AP Sensing, 2025).

Summary:

- *Typical applications and usability:* Applied along critical segments of pipelines for either proactive monitoring or reactionary leak detection or locating after a leak has already been detected. It is useful for early detection and locating a leak location prior to excavation and repair. Leak detection data processing automation is available, and post-processing and interpretation of the data is fairly technical and requires advanced signal processing skills. Several vendors offer data processing, monitoring, and reporting services. Most fiber optic cable products contain several optical fibers that can be used for collecting DAS, DTS, and DSS data types simultaneously or sequentially.
- *Order of application with respect to other methods:* Implemented either for proactive leak detection and locating monitoring, or for occasional/reactionary leak detection

and/or locating after a leak has already been detected by other system monitoring and operational sensors (i.e., SCADA). Detected and located leaks can be verified by other pinpointing surveys, such as mobile correlator surveys or ground microphone surveys when feasible/appropriate.

- *Fundamental requirements and limitations for success:* Requires fiber optic cable deployment along a target segment of pipeline, ideally with close proximity or externally mounted on the pipe for external deployments. To accurately locate a leak for excavation and repair, subsurface-deployed fiber alignments need to be surveyed (i.e., using GPS) during installation, or accurate pipeline geometry/alignments must be known if deploying the fiber inside a pipeline after construction. If utilizing parachute-tethered deployments inside a pipeline, the flow rate must be sufficient to pull the fiber downstream. Multiple segments of individually deployed fiber can be spliced together at access points to create a single continuous fiber for longer monitoring capabilities from a single IU connection point. The pipeline system cannot have any bottlenecks, screens, or other obstructions that would prevent in-line fiber deployment. Stiffer fiber optic cable products can be pushed into the pipe from an access point. It requires a secure enclosure with power service for long-term monitoring installations of IUs. Data volumes can be massive for long-term monitoring, so automation of leak detection algorithms/scripts realistically need to be installed on the IU, and data telemetry can be useful for reporting of leak detection events/alarms.
- *Generalized reliability and accuracy:* DFOS systems are extremely reliable and provide stable data outputs in terms of quality and calibrated quantitative data types. Fiber optic cables perform well over very long timeframes with minimal degradation, even in harsh environments. Severed fibers can easily be repaired by removing damaged segments and splicing in new fiber as needed. Fiber damage and breaks can be quickly and accurately detected and located by the IU or handheld fiber testing devices based on the associated backscatter signal. With regard to pipeline leak detection, DAS can detect and locate leaks in near real-time and to within a single gauge length/channel spacing (less than 1m/≈3ft, depending on the IU system utilized and the manner of fiber deployment). Sensitivity and location accuracy are optimal when the fiber is installed immediately adjacent to or inside a pipeline, where the close proximity of the fiber to a leak provides sensitivity to small leaks.
- *Efforts involved in implementation:* Fiber installation or deployment is by far the largest portion of effort for DFOS system installation. This can involve direct burial with trenching machines or a variety of other methods. The fiber must be well coupled to surrounding soils or to the target structure's surface for optimal sensitivity. IU systems most commonly require 120-volt alternating current power (standard North America power grid or gas generator power source for remote operation) but can be configured to run off of 12-volt battery power sources for added portability. Data acquisition parameters must be configured and set in the IU before data collection commences. Post-processing for leak detection, interpretation of other data patterns, and locating any identified anomalies of concern involves the use of either open-source scripts (e.g., Python-based DAScore scripting) or proprietary commercial software. Many vendors also offer data analysis and reporting services for a variety of applications.
- *General hardware and services costs:* Services are relatively expensive but commercially available from multiple vendors; sensors and software are also available for purchase

from multiple vendors. Service costs vary based on the project-specific scope of work—namely, the length of pipe segment to be surveyed, the types of features to be identified, interpreted, and reported from the data, and the selected company’s mobilization and billable/daily rates, per-mile installation or data collection/analysis rates, etc. Depending on the specific type of IU, hardware, software, technical support, warranty, and annual maintenance options selected, prices can range from approximately \$75,000 to over \$400,000. Multiple standard and specialized fiber optic cable products are available. Pricing depends on the specifications of the fiber product but can be as low as approximately \$1 per foot or less (less expensive on a per-foot basis with larger orders). Pricing and options continue to improve with the addition of new vendors, increased market competition, and improved sensors, sensor designs, data processing options, and automation of monitoring solutions.

4.0 Project Experimentation and Results

A major motivation of this research project was to help Reclamation gain in-house pipeline leak detection and locating capabilities without the need to rely on costly commercial products and services. Furthermore, based on recent involvement by TSC personnel and ongoing technical challenges faced by South Dakota Area Office (SDAO) related to repeated leaks occurring along particularly problematic segments of the Mni Wiconi Rural Water Supply System in South Dakota (Figure 14), the principal investigator of this research project was motivated to partner with the SDAO to help provide leak detection services and inform efficient repair O&M activities along that system—with the mutual benefit of informing this research project.

This pipeline system would serve as an optimal field-scale pipeline system for deployment and testing (i.e., a technology demonstration field site) of various AE sensing and leak locating technologies. As a result, the research incorporated a series of commercial sensor acquisitions and testing efforts focused on evaluation of long-term monitoring correlator networks. The research team also developed AE sensor and data logger prototypes in an effort to move toward more autonomous pipeline monitoring capabilities within Reclamation.

Finally, based on a variety of logistical challenges related to limited correlator sensor installation and monitoring access points, as well as benefit-cost considerations, the team decided to pivot towards acquisition of a DAS IU instead of correlator monitoring sensors. The various prototype development and commercial sensor testing activities, along with data analysis software development and testing results, are detailed in the following subsections.

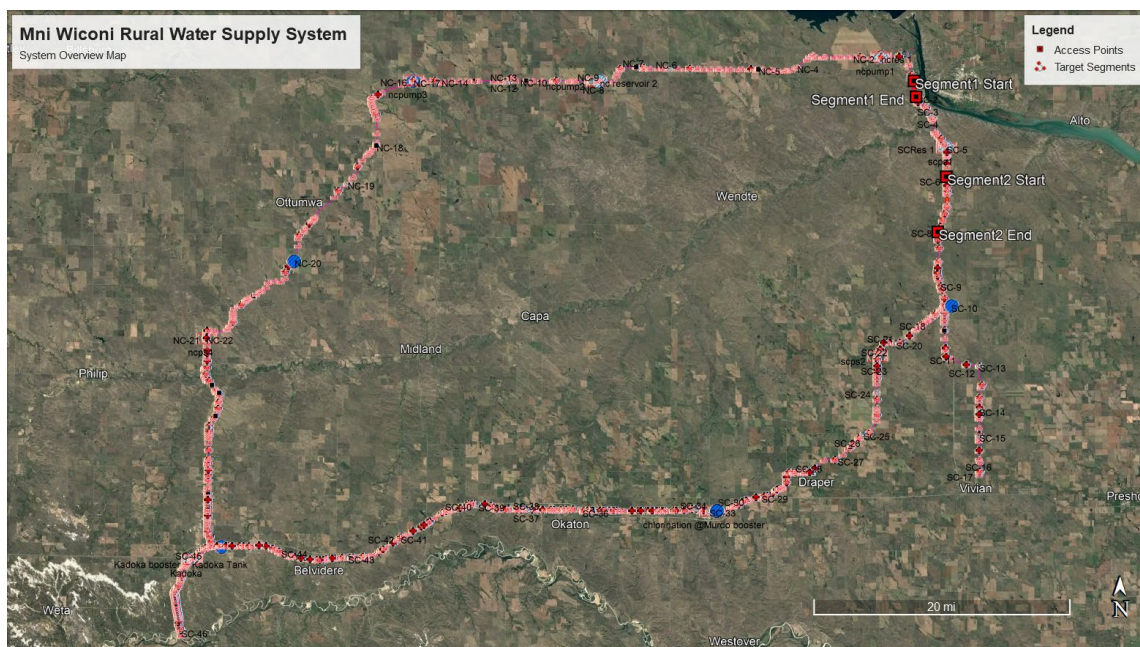


Figure 14.—Overview of the general alignment of the Mni Wiconi Rural Water Supply System, with the start and end points of two target monitoring segments near the City of Pierre labeled on the figure.

4.1. Mni Wiconi Rural Water Supply System Field Testing Site: Initial Efforts for Field-Scale Deployment and Testing along System Main Core-Line Zone 1

The Mni Wiconi Rural Water Supply System is an extensive network of water delivery pipelines that convey water primarily sourced from the Missouri River to rural areas that span 12,500 square miles across central portions of South Dakota. As a whole, the system serves a population of approximately 52,000 people and has a treated water delivery capacity of 13.4 million gallons per day.

The main core-line of the system, depicted in Figure 14, is approximately 185 miles in length and comprised of 12-inch to 24-inch coated metallic and polyvinyl chloride (PVC) high-pressure pipe materials. Various system components and facilities along the network help to treat and control successful water delivery and use, including water intake structures, pumping plants, water treatment and storage facilities, air relief valves (ARVs), fire hydrants, and various other service and testing access points (OSRWSS, 2025).

In recent years, certain segments of the main core line of the system have experienced repeated pipeline leaks. One of these especially problematic segments extends downstream from the initial pumping plant and through Fort Pierre. A subsection of this segment, referred to as “Zone 1,” was identified by SDAO engineers as a good target for trial AE monitoring system installation (Figure 15). This segment is approximately 7,000 ft long, starting at an arbitrary location that would require excavation down to the pipeline for sensor installation, and ending at an existing access point (valve/access hatch).

Unfortunately, no additional existing access points are currently available along the center portions of this segment. Based on extensive communication with various AE noise logger and correlator monitoring system vendors, the length of Zone 1 was deemed too long for effective monitoring using sensors only placed at either end. The research team held several discussions with SDAO personnel in an attempt to identify alternatives for installing additional correlator sensors along the segment (e.g., excavations or vacuum truck “potholing” down to the top of the pipe for standpipe installation and externally mounted sensor placements), but these were deemed infeasible for a variety of logistical, land-access, and cost-related reasons. As a result, the research team worked with SDAO personnel to identify an alternative “Zone 2” further downstream of Fort Pierre (Figure 16).

The Zone 2 segment of the main core line has also experienced repeated leaks in recent years and would serve as a good target for installation and testing of an AE monitoring system. This segment is approximately 23,000 ft long. A total of 16 potential access points (i.e., hydrants, air relief valves, and service hatches) were initially identified in as-built drawings at various points along this segment.

A site visit was conducted by TSC and SDAO personnel in October of 2024, and 14 of the 16 access points were eventually determined as feasible sensor installation locations (two “type 2” fire hydrants were deemed not feasible for effective and reliable sensor installations). Table 2

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

lists access point descriptions and inter-point distances along the Zone 2 segment of the main core line. Note that one 4,100-foot-long inter-point segment was deemed definitively too long for effective monitoring, and three segments were considered questionable.



Figure 15.—Detailed view of the general alignment of the first AE monitoring target, “Zone 1” (bold red polyline) of the Mni Wiconi Rural Water Supply System near the City of Pierre, South Dakota. The start and end points of this target segment are indicated with red-labeled points.

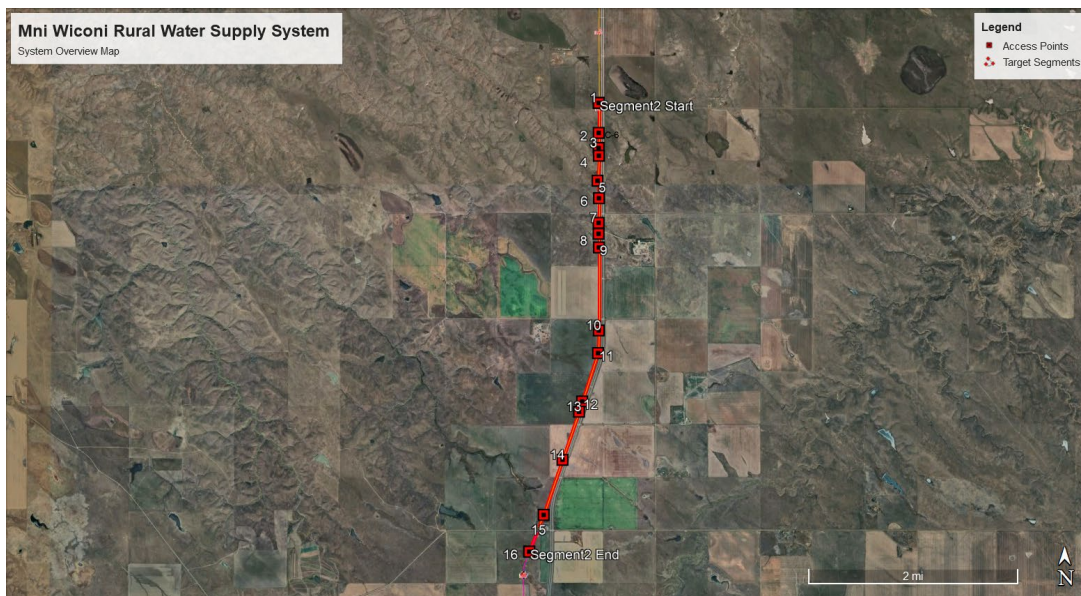


Figure 16.—Detailed view of the general alignment of the second AE monitoring target, “Zone 2” (bold red polyline) of the Mni Wiconi Rural Water Supply System, which starts approximately 7 miles downstream of the City of Pierre, South Dakota. The start and end points and 16 access points along this target segment are indicated with red-labeled points.

Table 2.—Mni Wiconi main core-line Zone 2 access point descriptions and inter-point distances for the 16 locations identified along the segment. Access points 3 and 7 (shown in red text font) were deemed infeasible for effective and reliable sensor installations.

Access Point #	Access Point Feature Type	Inter-point Distance (ft)
1	Type 1 Hydrant	0
2	ARV	1,500
3	Type 2 Hydrant	(not usable)
4	ARV	1,140
5	Type 1 Hydrant	1,250
6	ARV	890
7	Type 2 Hydrant	(not usable)
8	ARV	1,750
9	Type 1 Hydrant	760
10	ARV	4,100**
11	Type 1 Hydrant	1,131
12	ARV	2,550*
13	Type 1 Hydrant	560
14	ARV	2,525*
15	Type 1 Hydrant	2,917*
16	ARV	1,812
Total Segment Length (ft):		22,885

* Note: these three segments were identified as possibly too long for effective AE correlator sensor monitoring for leak detection and locating by two of the three vendors that were contacted for system quotes.

** Note: this segment was identified as definitively too long for effective AE correlator sensor monitoring for leak detection and locating by two of the three vendors that were contacted for system quotes.

4.2. Long-Term AE Monitoring Noise Logger/Correlator System and Mobile Correlator System: BLDG 56 Hydraulics Laboratory Water Supply Line Release Test

In an effort to evaluate, test, and learn implementation of long-term noise logger/correlator AE monitoring systems, three noise logger/correlator units were purchased and used in multiple tests carried out on the Denver Federal Center campus. The three units purchased are each comprised of a magnetically mounted sensor/logger (with a neodymium magnet built into the base of the sensor/logger device) and an external wireless communications antenna that utilizes Nb-IoT mobile networks for data telemetry. The antennas are connected to the loggers with a 3-meter-long communications cable. These units are hereby referred to as “Nb-IoT loggers” for brevity. Evaluation of the Nb-IoT loggers’ functionality, efficacy, and accuracy in leak detection and locating was primarily motivated by the intention to install monitoring sensors at the 14 access points along the Zone 2 segment of the Mni Wiconi main coreline for field-scale testing.

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

The first of these various tests conducted on the Denver Federal Center campus involved an engineered leak installed on a main water supply line inside the hydraulics laboratory. The experimental setup (Figure 17) was prepared the day prior to initiation of the test on 11/22/2022. Test day activities included on-site training for initial setup, deployment, and implementation of the Nb-IoT loggers. The on-site training and a separate mobile correlator product demonstration were provided by a vendor technical representative in the Building 56 Hydraulics Laboratory. As seen in the schematic presented in Figure 17, an engineered leak was constructed and installed on a water supply main, and Nb-IoT loggers attached to the top of the pipe on either side of the installed leak point, with variable distances from the leak. The third Nb-IoT logger (not shown on Figure 17) was installed on a separate leg of the water main pipe, further upstream from the logger #1 position shown on the figure. Figure 18 presents various photos taken of the pipe, Nb-IoT loggers, and engineered leak connected to the water main pipe. One of the mobile correlators used for the product demonstration can also be seen in top photo of Figure 18.

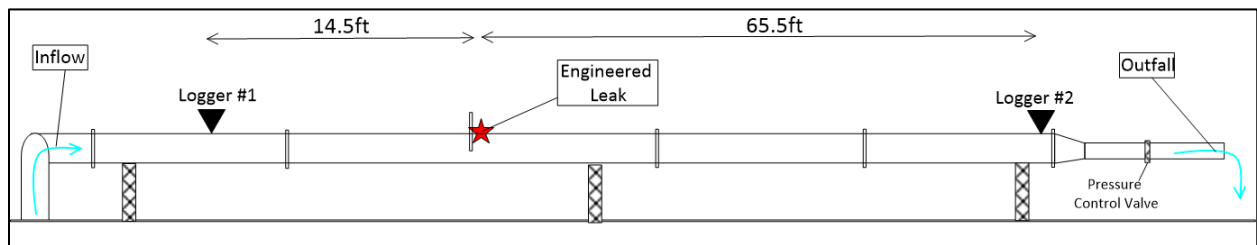


Figure 17.—Side-view schematic of the experimental setup for testing Nb-IoT AE correlator monitoring sensors in the Building 56 Hydraulics Laboratory.

The Nb-IoT loggers were set up and deployed for several days while the engineered leak was left in place to produce a continuous leak AE signal. The Nb-IoT loggers were verified to have wireless communications (i.e., despite being deployed inside a building), and the system was monitored remotely via the vendor’s online data hosting and analysis platform. Deployment of the Nb-IoT loggers involves initial programming of each unit using a communications cable connected to cell phone or tablet with a deployment app installed. Initial programming includes the following:

1. Assignment and “deployment” of each logger to a predefined “project”
2. Allocating a physical location to each logger based on GPS or manually entered latitude/longitude coordinates
3. Setting mobile network connection settings (network carrier and band allocations compatible with the unit’s embedded SIM-card)
4. Setting the pipe material, diameter, and assumed or otherwise known velocity of sound in the pipe
5. Setting any desired filters to apply to the data for edge computing analytics
6. Setting leak detection levels (relative AE decibel thresholds) for sending alarm reports
7. Defining a daily two-hour “wake-window” timeframe during which the units “wake up” from standby mode, record data, run edge-computing analytics, report summaries of logger status (tilt, temperature, battery level, and wireless network connectivity levels), and also report any identified leak events/alerts. The units also record a 16-second-long

sound file halfway through the wake window and upload that data file to the online data hosting platform for subsequent analysis.

After several days of running the test, no leaks were detected or otherwise reported by the system. Additionally, during the mobile correlator system product demonstration, that system was not able to definitively locate the leak position. Based on these two outcomes of the experiment, it was determined that the hydraulics laboratory had too much background noise (multiple loud pumps and other machinery running continuously, running and splashing water at various locations, etc.), and that the engineered leak was not loud enough for successful detection. The system was retrieved, and the experiment ended. The research team decided to pivot to a different location and experimental setup. The team also conferred with the vendor to verify whether the system had malfunctioned or if there were additional considerations for future experimental designs. The main outcome of these discussions was that the system should be deployed and allowed to first record “baseline” (no leak conditions) data for at least three days prior to initiating a leak noise/signal. This approach allows the system to develop a baseline AE signature that can then be used to compare against and help identify any anomalous leak AE signals that subsequently develop. This advice was heeded and incorporated into all subsequent experiments.



Figure 18.—Various photos taken during testing of Nb-IoT loggers in the Building 56 Hydraulics Laboratory.

4.3. Long-Term AE Monitoring Noise Logger/Correlator System and Prototype AE Datalogger: BLDG 810 Water Main Release Tests

The next set of experiments involved close coordination with the General Services Administration (GSA) for deployment of the three Nb-IoT loggers along a 4-inch-diameter high-pressure (75 pounds per square inch (psi)) water main iron pipe in Building 810, and conducting water releases through an in-line flush valve located near the center of the monitored segment of pipe. A side-view schematic of the experimental setup is depicted in Figure 19. Nb-IoT logger deployment locations included two inside Building 810, mounted along the top of the water main pipe near the ceiling, and one logger placed on a fire hydrant located outside and adjacent to the building. A surveying tape measure was used to record the various dimensions shown in Figure 19. Logger locations were programmed to account for the vertical segments of the water main system so that accurate inter-sensor spacings along the pipe were used to help maximize the accuracy of any detected and located leaks. The loggers were also programmed to have a daily wake window of 1:00 to 3:00 PM, and the assumed (standard) velocity of sound for 4-inch-diameter iron pipe was used.

Sensors were deployed on 3/13/2023, and baseline data were first recorded for seven days prior to initiating the first water release on 3/20/2023. The first test release was done by partially opening and adjusting the in-line flush valve to maximize the acoustic signal levels generated by the release, resulting in a loud hissing sound that could easily be heard from across the warehouse floor and also outside of the building. The water release was allowed to continue for the entire 2-hour wake window in order to realistically simulate a significant pipeline leak.

Based on standard published examples of sound decibel levels found through internet search results, the water release (i.e., simulated leak) noise levels were estimated at approximately 75-80 decibels—louder than a normal conversation (approximately 60 decibels), but quieter than a typical kitchen blender (approximately 90 decibels). Water release rates were measured by timing the filling of a 5-gallon bucket several times. This approach resulted in an average of approximately 5 gallons per 10 seconds, which is equivalent to 30 gallons per minute or 1,800 gallons per hour (3,600 gallons total for the 2-hour test release).

A photo of the water release outfall onto an exterior loading dock, taken during initial testing at the Building 810 GSA facilities warehouse, is depicted in Figure 20. Various photos of the experimental setup (logger deployment and water release locations) are shown in Figure 21. It should be noted that the hydrant valve at the third exterior logger location was first opened and air flushed from the hydrant standpipe to ensure optimal sound transmission up to the hydrant top/sensor.

It should be noted that these Building 810 water release tests were also used for initial testing of a data logger previously developed by a research team member for other applications (hydroacoustic river bedload monitoring) as well as a new set of prototype piezoelectric transducer sensors developed specifically for this research project. Due to a COVID-19-related Raspberry Pi™ chip shortage during the time of experiments, the existing prototype data logger

design was modified to incorporate a new Teensy™ audio board and also the new set of piezoelectric transducer sensors.

Additionally, the prototype's firmware was updated to automatically start data collection when turned on, configured to record a 1-minute audio file every 5 minutes. This prototype system was also modified to have lower power consumption compared to the previous system, enabling continuous audio recording in the field for extended periods using battery power alone, without requiring a solar array.

Block diagrams of the logger and piezoelectric sensors are presented in Figure 22. Photos of the prototype logger and sensors taken during the Building 810 water release tests are depicted in Figure 23 and Figure 24. In this setup, several piezoelectric sensors were mounted on the water main pipe directly above the water release valve, and one sensor was mounted on the exterior fire hydrant to record audio during the first release test. Additional information—including build and component specifications, block diagrams, circuit diagrams, firmware code, and bill of materials—can be found at <https://github.com/bugoutput/arroyo-teensy> (Ball, J., 2025).

Following the first test, the online Nb-IoT logger data hosting and analytics platform was inspected for any leak detections or alerts. However, no detected leaks were reported. Additionally, no recorded 16-second audio files had been uploaded to the platform. The team communicated this with the vendor, who speculated that the system might not function properly if programmed with a wake window set to afternoon hours.

While frustrated with a seemingly arbitrary response and major apparent system limitation that had not been previously described or reported in user manuals or other publications, the team worked with GSA to coordinate two additional follow-up tests. The Nb-IoT loggers were left in place to continue recording baseline (i.e., no-leak conditions) data between subsequent test releases. The loggers were reprogrammed to have a wake window of 8:00-10:00 AM, and the leak detection threshold levels were lowered to help increase the chance of leak event detection alerts and automatic correlation-based locating of the leak sound.

The second test release was performed on 03/27/2023 after recording another week of baseline data. The third and final release test was performed on 5/24/2023 after recording approximately two months of baseline data. Each release was performed identically to the first test for consistency—maximizing the sound of the release and running the release for the full two-hour wake window.

Following each subsequent release test, the online hosting and analytics platform was accessed and inspected for any identified leaks or alerts. Each time, no leaks were detected or reported by the system. The loggers were verified to have good wireless connectivity and full system functionality, including successful uploads of the 16-second audio recordings from each test. Audio recordings were downloaded and played in a computer media player, and the leak noise was verified to be audible.

Several manual correlations were run on the online analytics platform using the recorded audio files, with questionable success in most cases: multiple correlation peaks and corresponding

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

calculated leak positions were observed, some of which were located beyond the extents of the monitored pipe segment. It should be noted that predicted leaks located beyond the extents of a monitored pipe segment can occur if the assumed velocity and correlation peak time lag result in a differential distance longer than the monitored segment (see calculation equation in Figure 8). These results may be due to either inappropriate assumed velocity of sound in the water main pipe or poor data quality leading to unreliable correlation results.

The team communicated the outcomes of the two remaining tests with the vendor, who speculated that the release was either not loud enough, or the simulated leak noise was “too white” (i.e., spectrally flat, with no unique identifiable noise spikes or wave transients that would otherwise support accurate correlations). The team felt that this was unlikely—mainly due to observations made during the tests (e.g., loud noise, splashing of the water outfall on the loading dock immediately adjacent to the release valve, etc.), as well as inspection and verification that the leak was clearly audible in the recorded sound files.

Additionally, the simulated leak noise was confirmed to be audible during the tests at the exterior hydrant using a prototype piezoelectric sensor and digital audio recorder with headphones (the leak sound could be heard on the hydrant during the tests using this sensor and headset). The team believed that the experiments realistically simulated a real-world leak scenario and leak noise, making the outcome frustrating and the vendor’s response seem arbitrary. It also highlighted a major system limitation that had not been previously described or reported in user manuals or other publications.

Based on the repeated false-negative outcomes of the Nb-IoT logger system during these three water release experiments, it was determined that a more controlled and easily repeatable experimental design was required. As a result, the research team decided to pivot to a different location and experimental setup, incorporating additional sensors, a new recording system, and revised testing protocols.

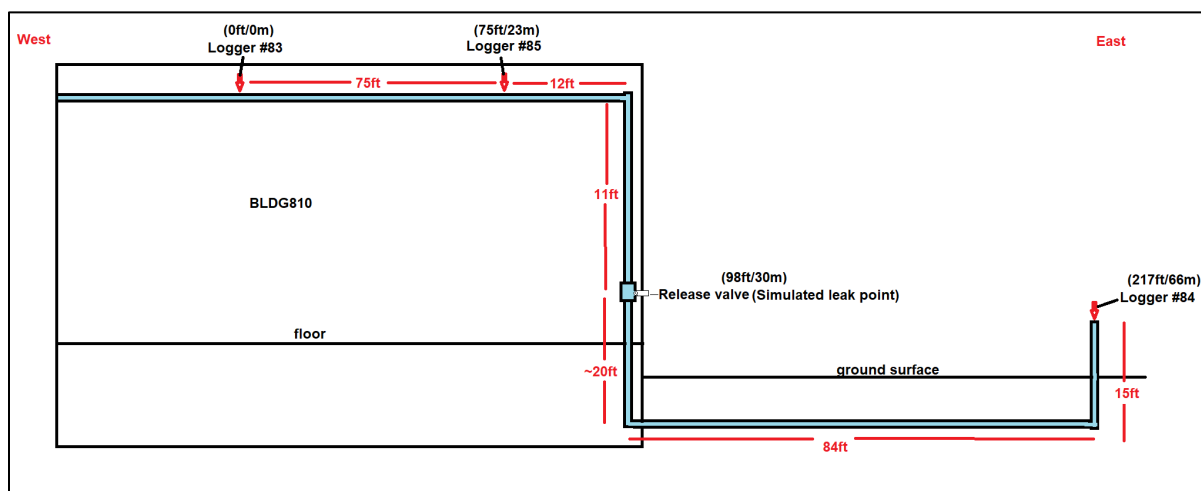


Figure 19.—Side-view schematic of the experimental setup for testing AE correlator monitoring sensors in GSA Facilities Building 810.



Figure 20.—Photo of the water release outfall onto an exterior loading dock, taken during initial testing of Nb-IoT loggers at the GSA facilities Building 810 warehouse.

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

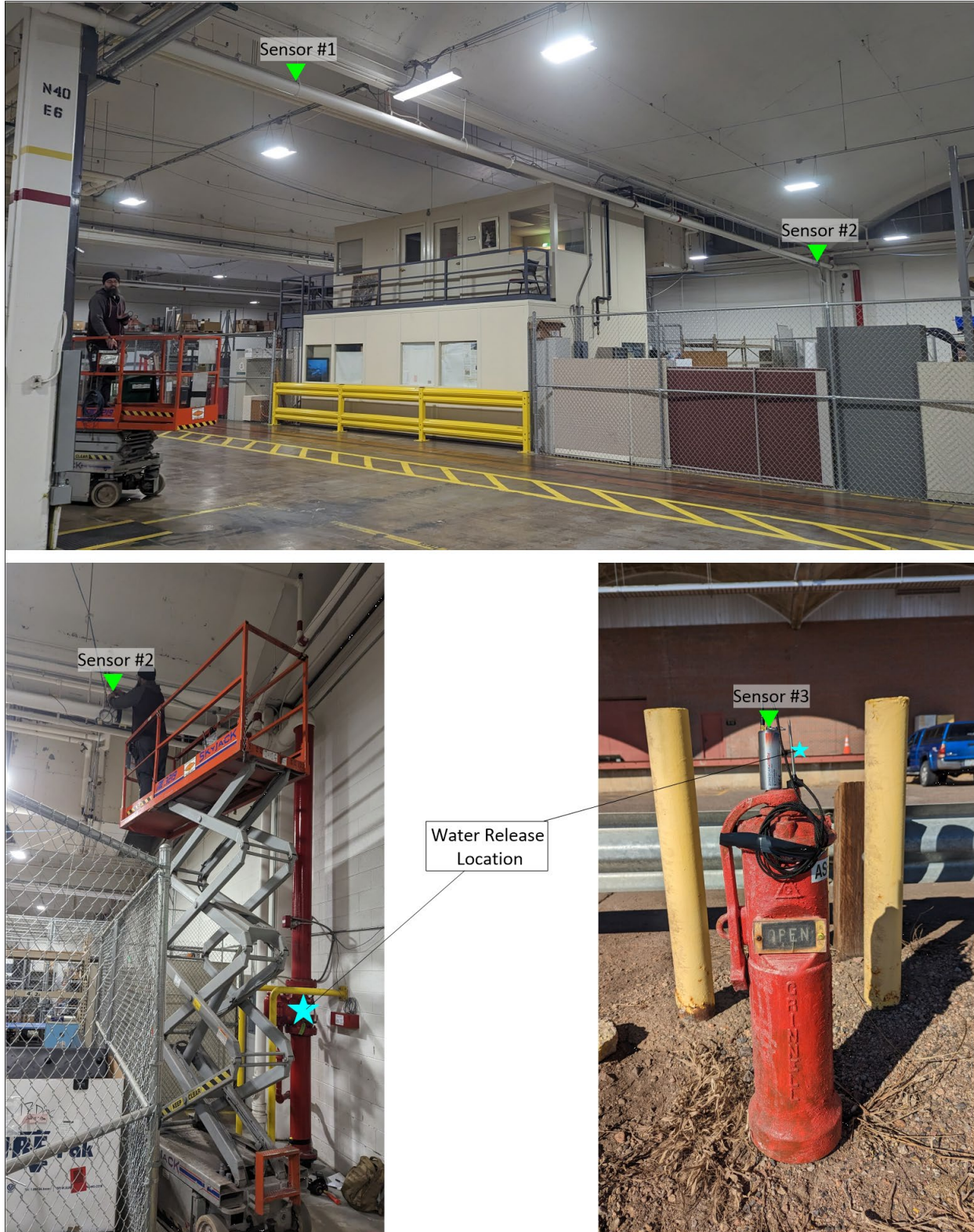


Figure 21.—Various photos taken during testing of Nb-IoT loggers in the GSA facilities Building 810 warehouse, showing the locations of the sensors and water release point.

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

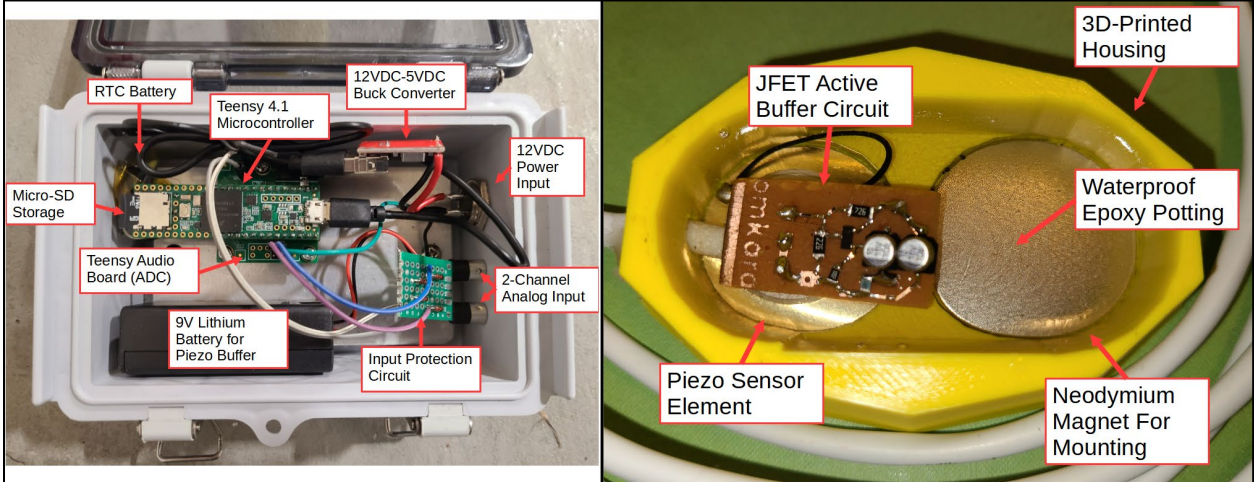


Figure 22.—Block diagrams of the prototype data logger (left) and piezoelectric sensor (right). Figure modified from (Ball, J., 2025).



Figure 23.—Various photos of the prototype data logger and piezoelectric sensor taken during the initial water release test at GSA Facilities Building 810.

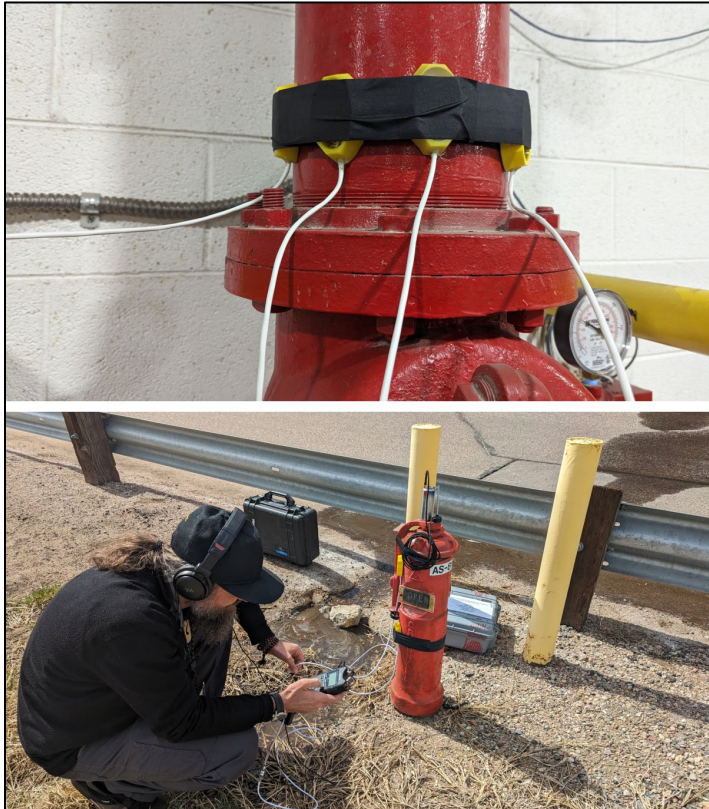


Figure 24.—Photos showing the deployment of prototype piezoelectric sensors during the initial water release test at GSA Facilities Building 810.

4.4. Various System Tests: Denver Federal Center Decommissioned Train Tracks

Based on the repeated false-negative outcomes of the Nb-IoT logger system during previous simulated water release experiments, a different location and a more easily controlled and repeatable experimental design were pursued. Some decommissioned train tracks west of Building 67 on the Denver Federal Center campus were identified as a suitable representative structure for additional testing. These steel train tracks act as an excellent acoustic waveguide and thus adequately simulate a long steel or metallic pipeline— similar to the Mni Wioni main core line pipe—for testing various sensors and the AE correlation leak localization technique.

Train track testing included the following general activities:

1. Long-term deployment of the three Nb-IoT loggers for evaluating system performance, durability, and functionality during sustained deployment in harsh environmental conditions,
2. Testing a small piezoelectric transducer for use as a synthetic leak noise source,
3. Development and testing of a larger, broadband synthetic leak noise source system,
4. Deployment of several geophone sensors and seismometers to conduct hammer tap tests for mapping wave propagation velocity along the instrumented train track,

5. Additional functionality tests of the prototype data logger and piezoelectric transducer sensors,
6. Functionality and efficacy testing of the Nb-IoT logger system for leak detection and localization using the synthetic leak noise source,
7. Code development for performing and evaluating multi-sensor correlation leak detection algorithms,
8. Final testing using geophone sensors and seismographs to record synthetic leak noise and perform multi-sensor correlation leak detection.

The initial step of testing on the train tracks involved deployment of the Nb-IoT logger system along an 800-foot segment of track on 07/26/2023. The loggers were programmed with a wake window of 8:00-10:00 AM and were successfully deployed that morning. However, a communication error notification email was received the following day for one of the loggers. That logger was subsequently checked and redeployed. A research team member then waited and confirmed that the problematic logger successfully reconnected to the mobile network and data server, and began recording data correctly within 24 hours (i.e., during the next wake window and data upload/reporting cycle).

Figure 25 shows a photo of one of the loggers deployed at the northern end of the train track testing segment. Figure 26 presents aerial imagery of the train track testing location, with the 800-foot segment used for various tests indicated with a red line. The deployment locations and relative distances of the three Nb-IoT loggers are marked with labeled yellow points.

The loggers were left in place at these locations for several months to evaluate long-term deployment functionality and robustness of the system under realistic field conditions (e.g., wide temperature and humidity variations, and various precipitation and weather events). The deployed Nb-IoT logger system was also used to perform a consecutive 5-day test for synthetic leak noise source detection and localization efficacy, as described in more detail in the following subsections.

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection



Figure 25.—Photo showing one of the Nb-IoT loggers (“Logger #1”) deployed at the northern end of the train track testing segment. As designed, each logger is firmly attached to the track using the neodymium magnet integrated into its base.

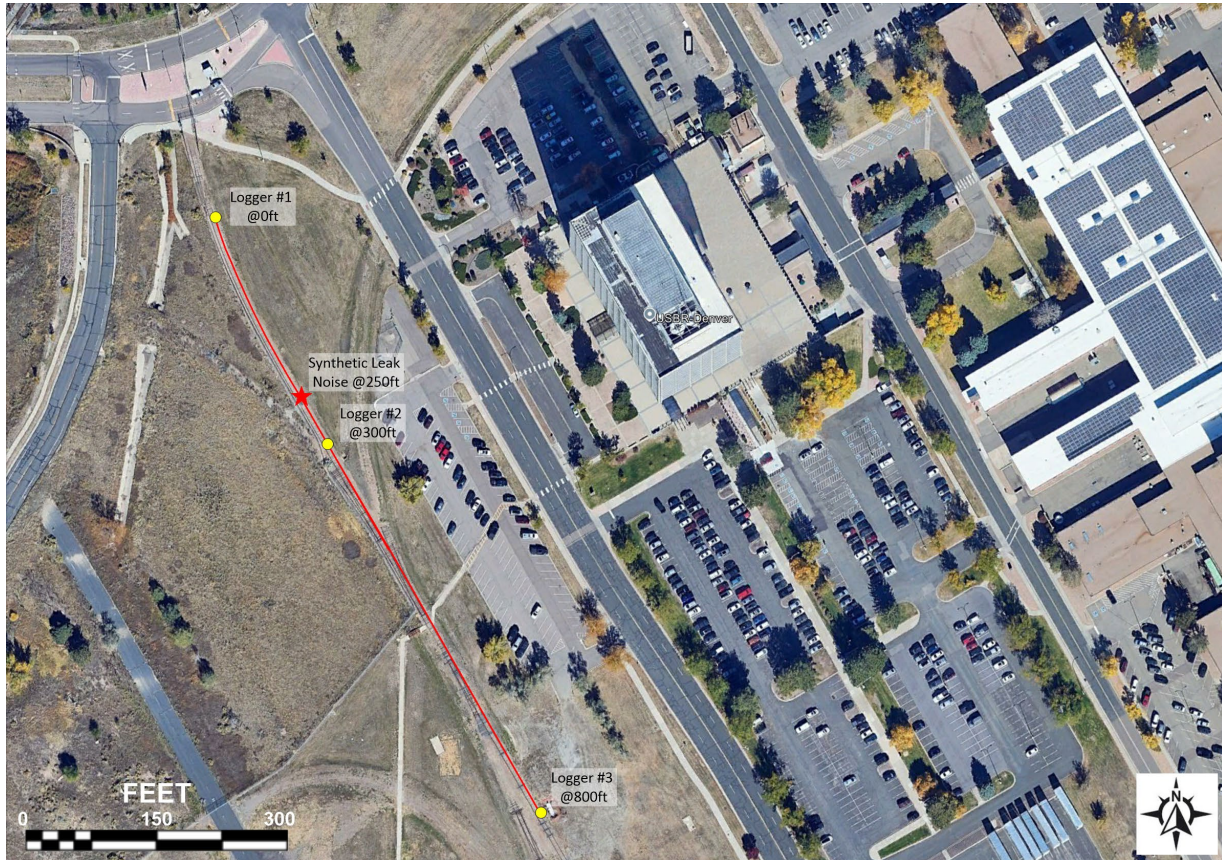


Figure 26.—Aerial imagery of the train track testing location, showing the 800-foot segment of track utilized for various tests (red line). Deployment locations and relative distances of the three Nb-IoT loggers are indicated with labeled yellow points. The placement location of the synthetic leak noise source is marked with a labeled red star.

4.4.1. Geophone Sensors and Seismograph Deployments for Velocity Mapping

Prior to conducting a consecutive 5-day experiment to test the Nb-IoT system’s efficacy in detecting and localizing a synthetic leak noise source, hammer tap testing was performed to accurately map the sound wave propagation velocity along the 800-foot segment of track. This was carried out on 01/24/2024 by installing six high-frequency (effective sensitivity bandwidth of 40 Hz to 2000 Hz) vertical-axis geophones (vibration sensors) at various points along the test segment and recording several sledgehammer impacts at varying distances from the sensor array.

Vibrational data from the hammer impacts were recorded using two interconnected 24-channel (Ch) seismographs. A surveyor’s measuring tape was used to verify the relative locations and spacings of the geophone sensors for subsequent velocity analysis (Figure 27). Several hammer impacts were performed at 0, 10, 20, 30, 50, and 80-foot offsets from the southernmost geophone sensor. The recorded waveforms were saved to a field laptop, and the data were then plotted. First arrival times of compression wave energy at each sensor (i.e., sound waves propagating along the train track) were manually picked using custom MATLAB™ scripts (Figure 28).

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

Once the arrival times at each geophone were established for a given hammer tap, the measured distances were used in conjunction with the picked times to calculate wave propagation velocities for various segments of the track (i.e., $\text{velocity} = \text{distance} \div \text{time}$). Specifically, the distance between each pair of geophones was used along with the associated difference in arrival times (i.e., the time it took for energy to propagate between the two sensors). After completing this process for all hammer tap tests, the calculated velocities for each sensor pair were averaged to determine an overall average sound propagation velocity in the train track (Table 3).

It is worth noting that the established average velocity of sound in the steel train track segment was within approximately 50 feet per second (ft/s) of the commonly reported average velocity of sound in steel (as found via a simple internet search). This measured average velocity was then used to program and configure the Nb-IoT logger for the subsequent AE leak source detection and locating tests.



Figure 27.—Photos showing geophone sensors and seismic surveying equipment used to perform hammer tap tests for wave velocity analysis along the train track segment.

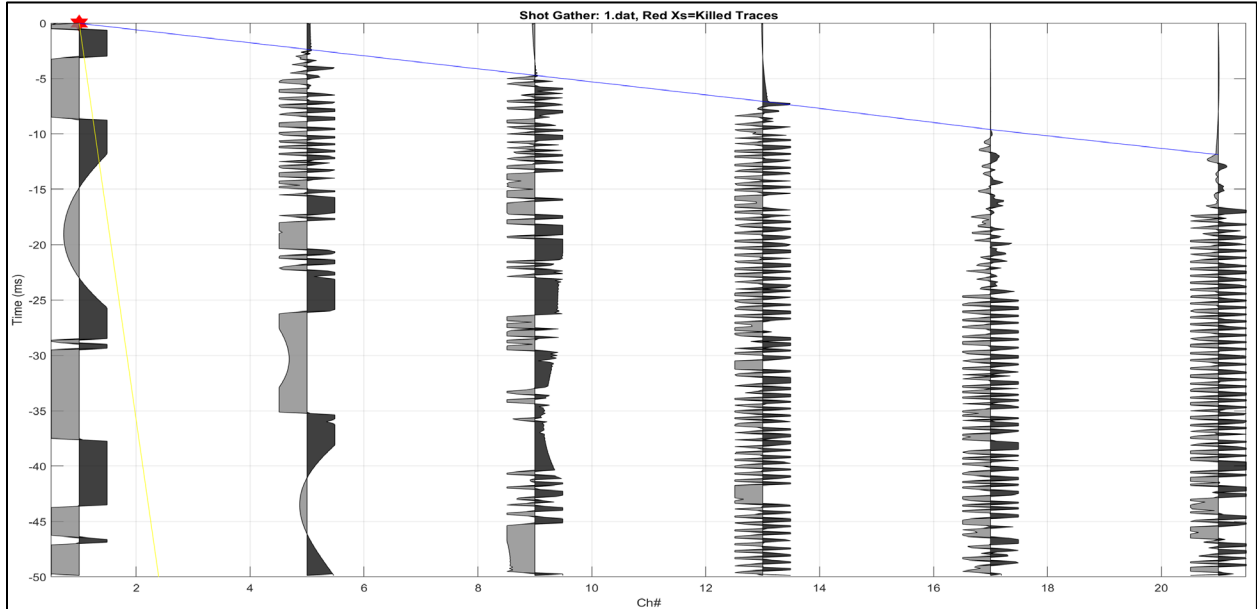


Figure 28.—Example shot gather showing vibration recordings from six geophone sensors during a hammer tap test, with the source located immediately adjacent to the southernmost geophone sensor (Channel #1). The source location is indicated by a red star at the top of the plot. Amplitudes recorded by each geophone are displayed as black and gray “wiggles traces,” plotted as a function of channel number/distance (horizontal axis) versus time (vertical axis). The thin blue polyline represents the manually picked first arrivals of wave energy used for wave propagation velocity calculations.

Table 3.—Results of six tap tests performed to map the velocity of sound wave propagation along the train track for use in Nb-IoT logger system correlation analysis. Note that the overall average calculated interval velocity is within approximately 50 ft/s of the commonly reported velocity of sound in steel, as found in published literature.

Tests 1-6: Ave. Vel. (ft/s)	Velocity (ft/s)
Average Ch1-5 Interval Velocity	13,525.27
Average Ch5-9 Interval Velocity	20,502.48
Average Ch9-13 Interval Velocity	16,653.73
Average Ch13-17 Interval Velocity	15,325.44
Average Ch17-21 Interval Velocity	17,900.15
Overall Average Interval Velocity:	16,781.42
Reported Velocity of Steel:	16,732.28

4.4.2. Prototype Synthetic Leak Noise Source Development and Testing

Prior to conducting a consecutive 5-day experiment to test the Nb-IoT system for synthetic leak noise source detection and localization efficacy, prototype synthetic leak noise sources were first developed and tested for useability. A small piezoelectric transducer was initially developed and tested as a noise source on 08/03/2023. This source consisted of a wireless Bluetooth audio player with an integrated amplifier circuit used to drive the transducer. Audio was played from a Bluetooth-connected cellphone, and the system output was maximized.

Signals were monitored at various distances from the transducer along the track using the prototype piezoelectric sensors and digital recorder with headset (Figure 29). The source signal was audible at distances up to approximately 50 ft but was ultimately deemed not powerful enough for reliable use in subsequent tests.

The next version of a synthetic leak noise source was designed and built for testing (Figure 30). This second source was comprised of an 800 W Class D Kicker™ KMA800.1 weather-resistant mono car amplifier, an 800-watt DaytonAudio™ Pro Tactile Bass Shaker, and an 800-watt 6.5-inch Kicker™ mid-range speaker. These components were impedance-matched and configured with a 100-amp-hour, 12-volt deep-cycle marine battery for powering the system over long periods of time and with high-power output. The system's audio input is simply a 1/8-inch jack-connection to any audio player with compatible output port.

A synthetic pipeline leak noise was created in the form of a multi-track layered audio file generated using Audacity™ software. Several different audio tracks from various online sources were selected, including rushing river sounds, babbling brook sounds, waterfall sounds, white static noise, and “brown” static noise. These audio tracks were merged and then repeated/stitched to produce a single 5-minute audio track of synthetic leak noise. The result is a broadband signal ranging from approximately 2 Hz to 13,000 Hz before high-end spectral roll-off (Figure 31). Subjectively, the audio track sounds like a realistic pipeline leak noise, with superimposed loud high-frequency “hissing,” lower-frequency static and rumbling, and various incidental/transient noises. The synthetic leak noise source was implemented by playing the sound file through the amplifier and bass shaker/speaker using a field laptop set to continuously repeat the audio track as long as needed for testing. Finally, as seen in the bottom photo of Figure 30, the speaker and bass-shaker were each screwed onto to 1x3-inch boards that were used to mount the units onto the train track with tape. Initial testing of the new and larger synthetic leak noise source was conducted on 04/08/2024.

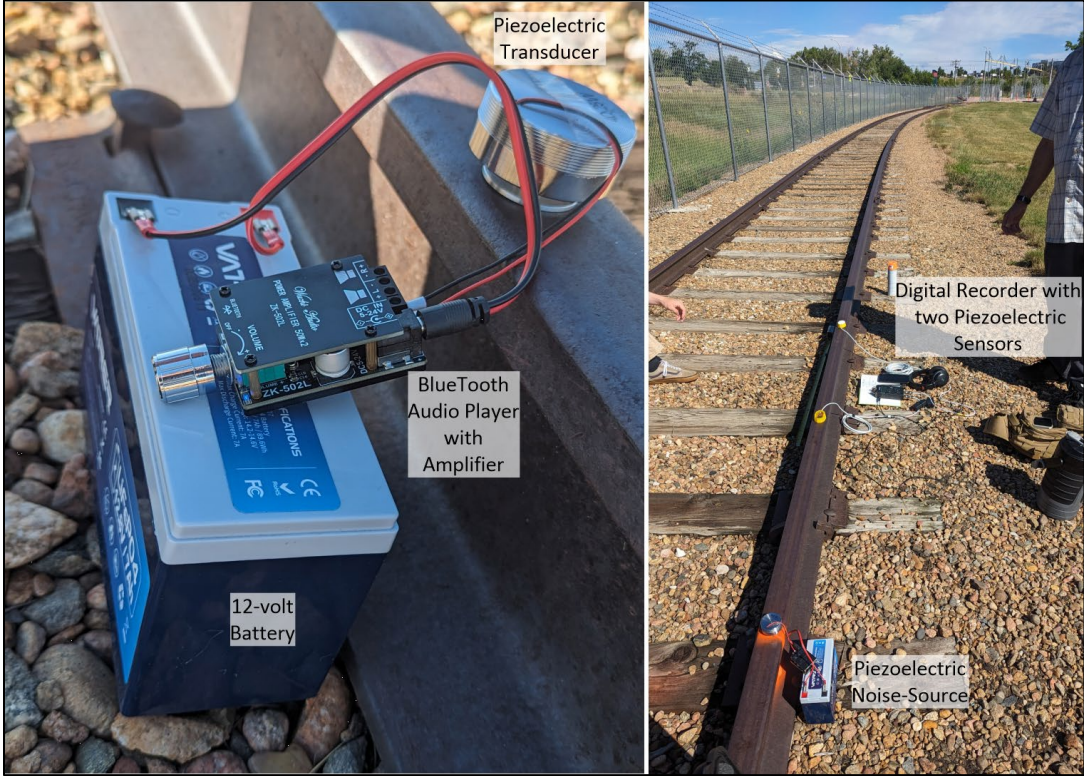


Figure 29.—Photos showing initial testing of a prototype piezoelectric transducer synthetic leak noise source. This noise source was deemed not powerful enough, so a larger source was developed instead.

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

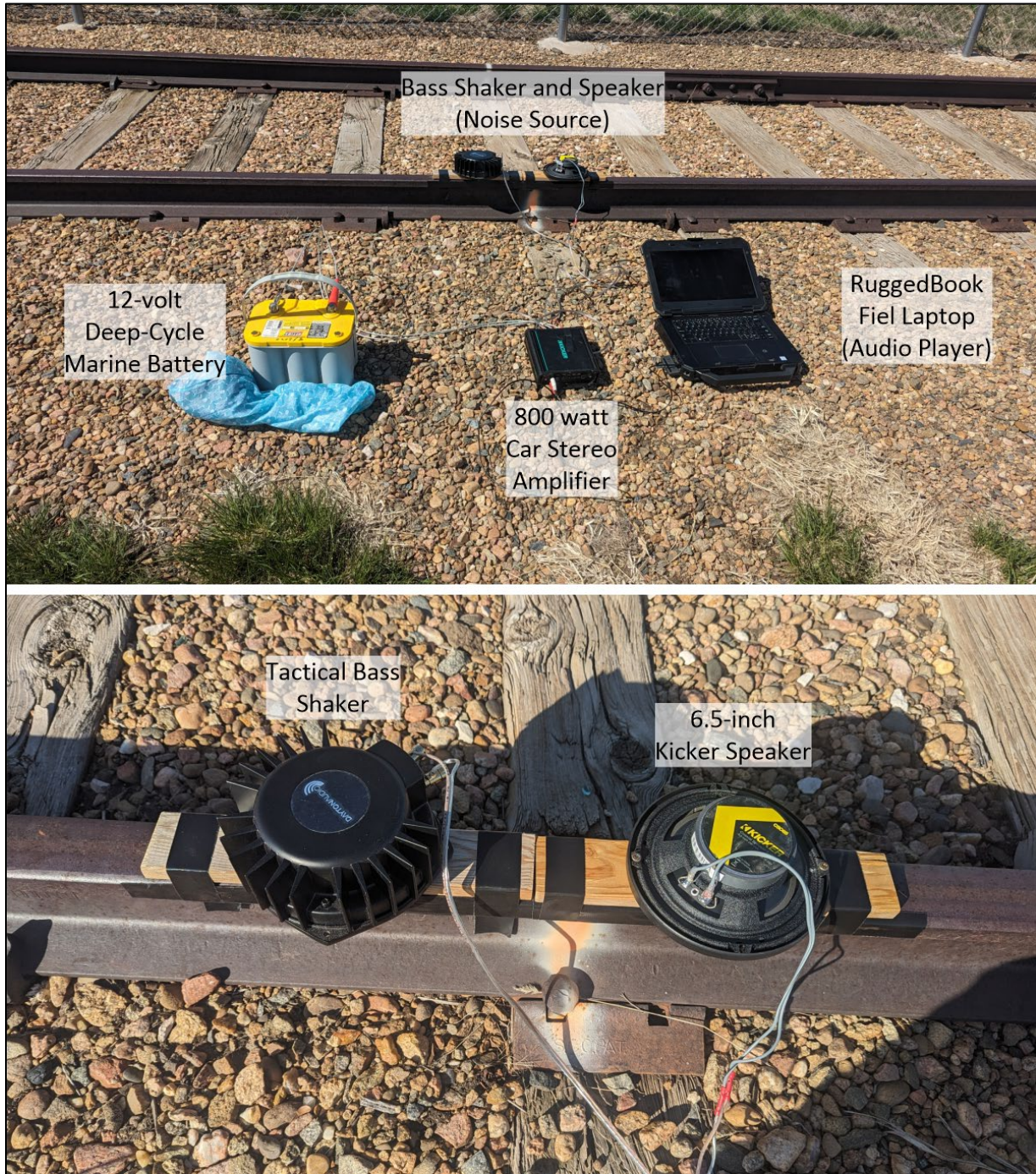


Figure 30.—Photos showing initial testing of a more powerful prototype synthetic leak noise source developed for testing leak detection and localization on the train tracks. This version of the noise source utilizes an 800-watt amplifier, a bass shaker, and a car speaker for increased acoustic energy output.

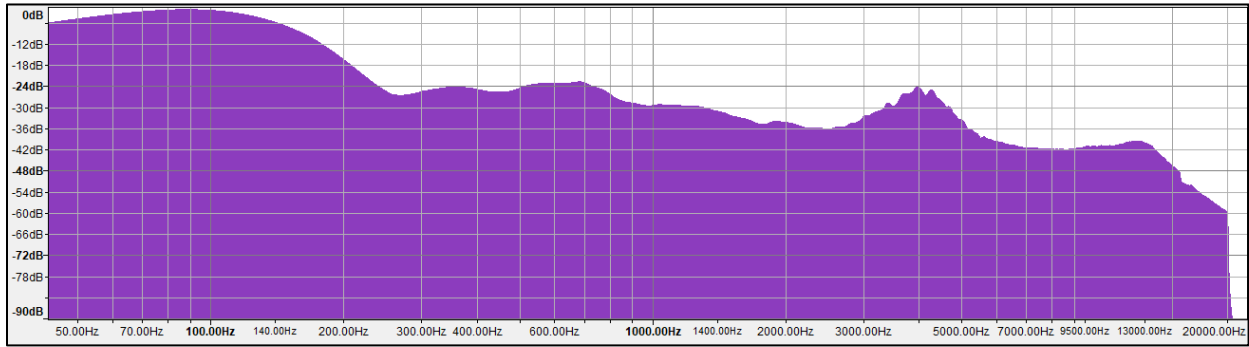


Figure 31.—Power spectrum of a mixed multi-track audio file developed for use as a synthetic leak noise source.

4.4.3. Nb-IoT Monitoring Correlator System Tests: Synthetic Leak Noise Detection and Locating

Following wave propagation velocity tests and the development and testing of the synthetic leak noise source, a consecutive 5-day test was performed to determine whether the Nb-IoT loggers could detect and locate the leak noise source applied to the train track. As previously mentioned, the Nb-IoT loggers were initially deployed on 7/26/2023. The consecutive 5-day test was carried out from 04/11/2024 to 4/16/2024, so the three Nb-IoT loggers had recorded baseline data (i.e., no-leak conditions) for approximately nine months prior to commencement of the 5-day test.

The 5-day test involved applying the synthetic leak noise source to the train track at a selected location within the three-sensor array (station 250 ft; see red star in Figure 26) during the wake window timeframe each day (8:00-10:00 AM) to determine whether the Nb-IoT loggers could detect and locate the noise source. Unfortunately, the leak noise was not detected or located, and no leak alerts or notifications were received. As with the previous Building 810 water release tests, the loggers were verified to have good wireless connectivity and full system functionality, along with successfully uploading 16-second audio recordings during each wake window throughout the 5-day test. Audio recordings were downloaded and played in a computer media player, and the synthetic leak noise was verified to be audible. Several manual correlations were run on the online analytics platform using the recorded audio files, with questionable success in most cases; multiple correlation peaks and corresponding calculated leak positions, some of which were located beyond the extents of the monitored train track segment. Based on the false negative outcomes of the prior four experiments and this final experiment—which realistically represented a real-world logger system deployment and leak monitoring scenario—the research team decided to end testing for determination of the Nb-IoT logger system’s efficacy for leak detection and locating.

Following the 5-day synthetic leak noise test, the Nb-IoT loggers were left in place for an additional five months, resulting in a total deployment timeframe of approximately one year and two months without any servicing of the units (deployed on 7/26/2023 and retrieved on 9/24/2024). During this period, the Nb-IoT loggers’ batteries maintained sufficient voltage for normal operation. However, a total of 20 occasional communication failure event reports were received; these were temporary and self-corrected within 24 hours of each notification. All of

these errors were associated with one specific logger out of the three (the furthest-south sensor), which also reported the lowest average battery voltage. These errors may have been caused by occasional voltage drops during data telemetry on colder days, which could be prevented successful data transmission and communication.

4.4.4. Prototype AE Datalogger System Tests: Recording Synthetic Leak Noise and Hammer Tap-Tests

On the last day of the 5-day synthetic leak noise source testing (04/16/2024), two of the prototype piezoelectric sensors and a data logger were deployed on the train track to record both the synthetic leak noise and several additional hammer tap tests. Figure 32 shows the prototype sensors and logger deployed along the track, with the sensors straddling the noise source. For the hammer tap tests, example recorded waveforms with various amplifications and corresponding power spectra are presented in Figure 33 through Figure 35. In Figure 33, relatively low-amplitude and repetitive system noise—likely electrical noise generated by the analog-to-digital converter on the prototype unit—is observed to superimpose the larger-amplitude hammer tap signals/waveforms. This prototype system noise likely contributes to the high-frequency content seen in the recorded data’s power spectra (Figure 34 and Figure 35). Note that Channel 1 of the logger did not successfully record hammer tap test or synthetic noise test waveforms, likely due to a bad sensor cable connection or hardware failure. Due to this channel failure, the prototype system data could not be used for attempting correlator analysis for leak localization calculations.

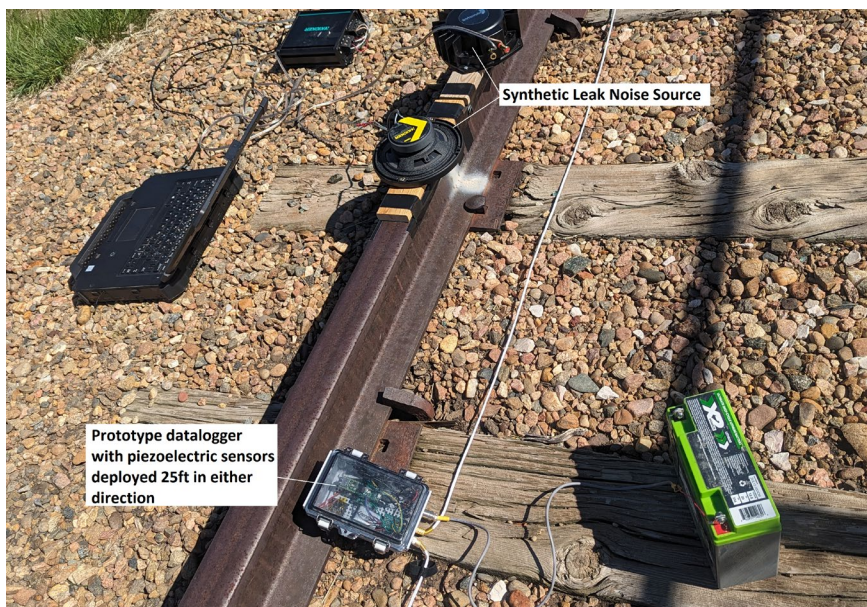


Figure 32.—Photo showing the prototype data logger deployed near the synthetic leak noise source. Two piezoelectric sensors are deployed along the track, 25 feet in either direction (i.e., straddling the noise source), and connected to the logger with the white audio cables visible in the photo.

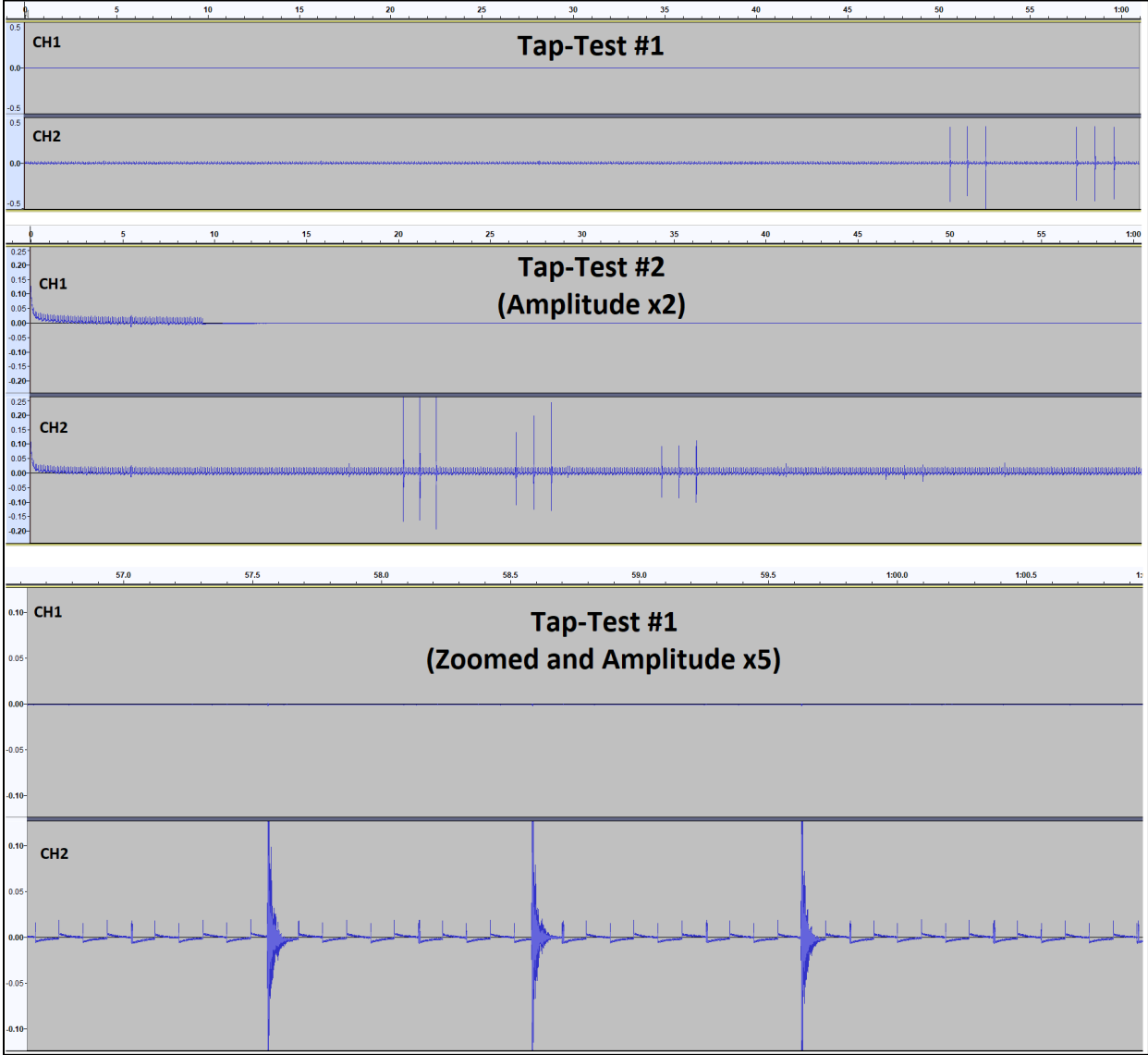


Figure 33.—Examples of data recorded by the prototype sensor data logger system during hammer tap tests. Note the relatively low-amplitude and repetitive system noise that is superimposed on the larger-amplitude hammer tap signals/waveforms. Also note that Channel 1 of the logger did not successfully record waveforms, likely due to a bad sensor cable connection or hardware failure.

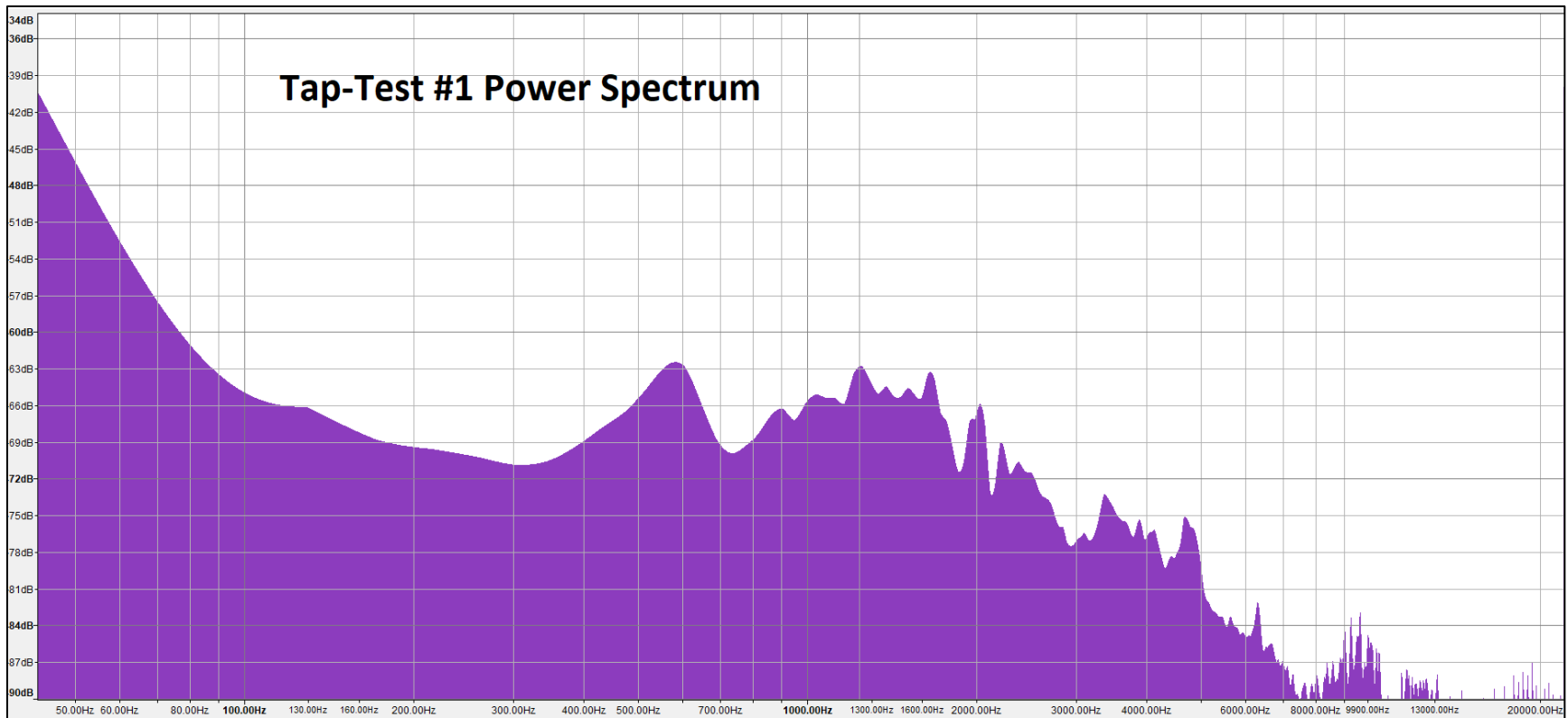


Figure 34.—Power spectrum for hammer tap test #1 data recorded by the prototype sensors and logger.

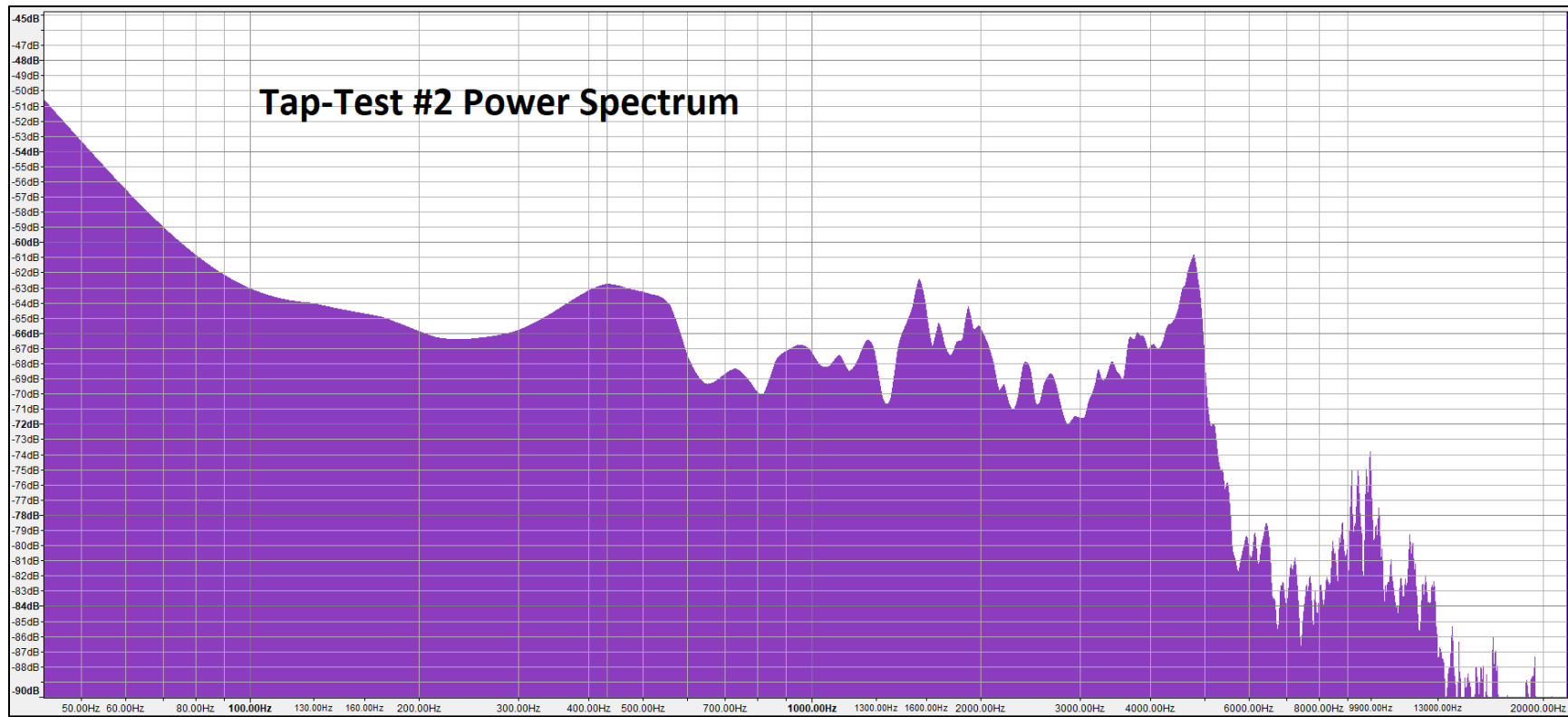


Figure 35.—Power spectrum for hammer tap test #2 data recorded by the prototype sensors and logger.

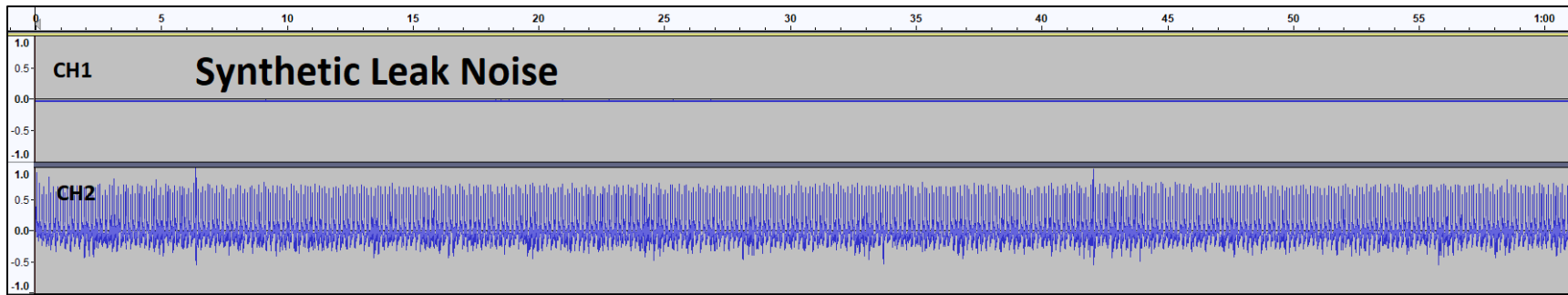


Figure 36.—Example of data recorded by the prototype sensor data logger system during hammer tap tests. Note that Channel 1 of the logger did not successfully record waveforms, likely due to a bad sensor cable connection or hardware failure.

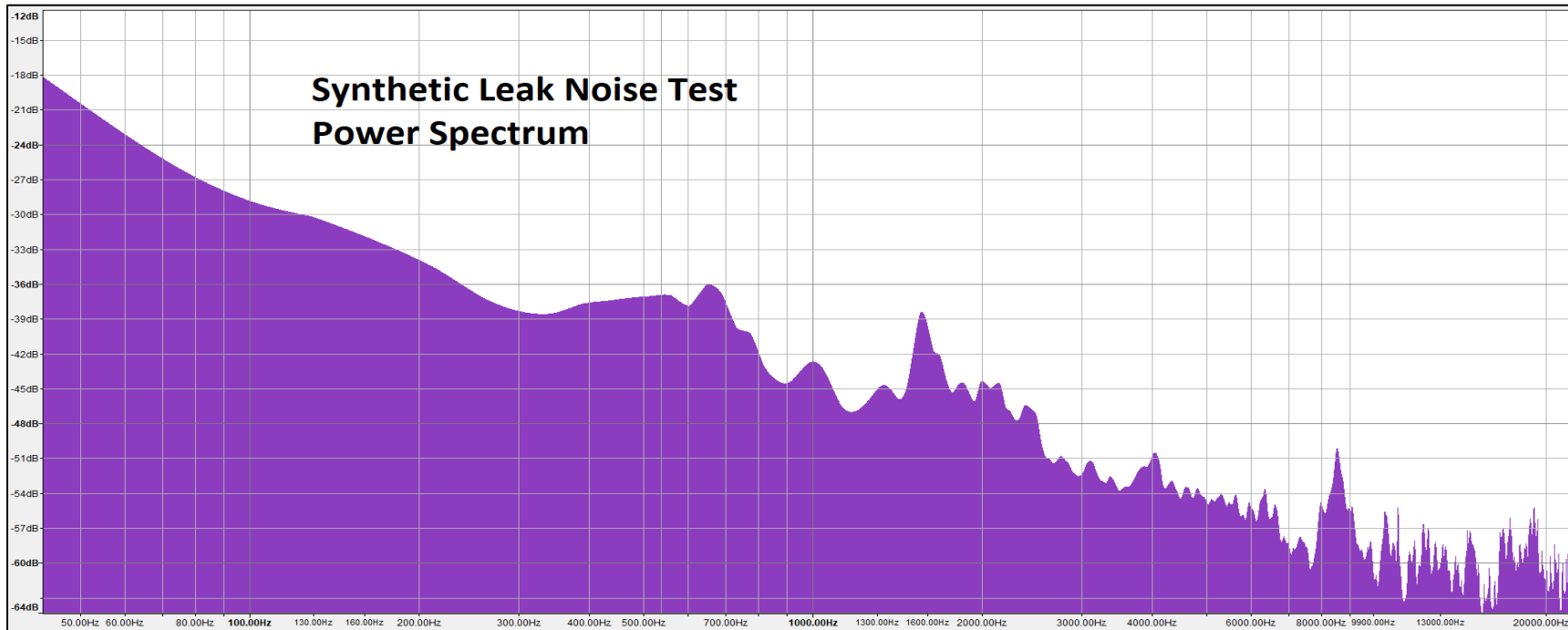


Figure 37.—Power spectrum for synthetic leak noise data recorded by the prototype sensors and logger.

4.4.5. Leak Noise Localization Software Development and Geophone Sensors Deployments

The last R&D efforts for this project focused on evaluating the AE correlator-based leak localization technique using reliable seismic equipment (geophones and seismograms) for synthetic leak noise data collection, along with the development of custom MATLAB™ scripts for processing that data to perform leak locating calculations. This last test was conducted on 08/24/2025. As shown in Figure 38, 11 geophone sensors were deployed at various locations along the same train track used in previous tests, and the synthetic leak noise source was placed near the center of the geophone array (labeled red star in Figure 38). First, a series of three velocity tap tests were performed to verify the sound propagation velocity of the instrumented track segment (example waveforms with first arrival picks are shown in Figure 39, and the various resulting calculated velocities are listed in Table 4). The overall average of these velocities—again, within approximately 50 ft/s of the standard published velocity of sound in steel—was used in the final synthetic leak source location calculations and estimations.

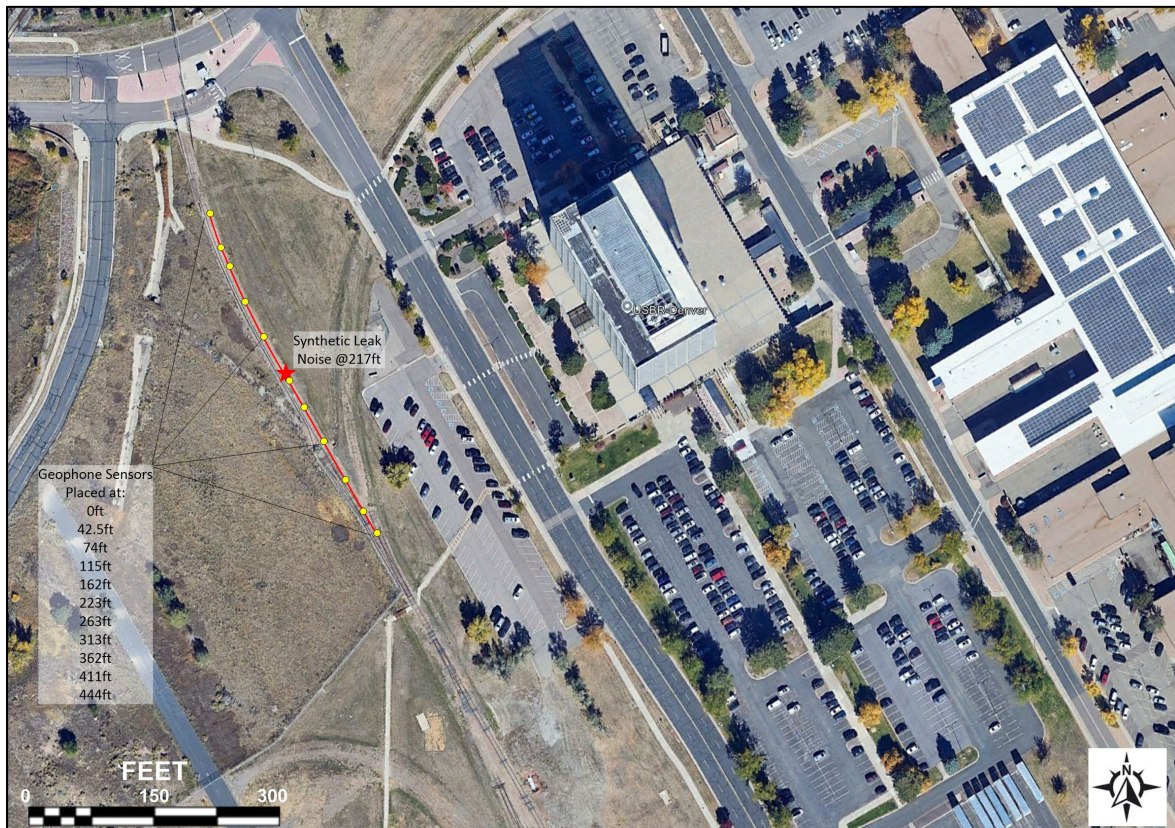


Figure 38.—Aerial imagery of the train track testing location, showing the 444-foot segment of track utilized for the final leak localization tests (red line). The deployment locations of the 11 geophone sensors are indicated with yellow points (relative distances listed in inset table). The placement location of the synthetic leak noise source is indicated with the labeled red star.

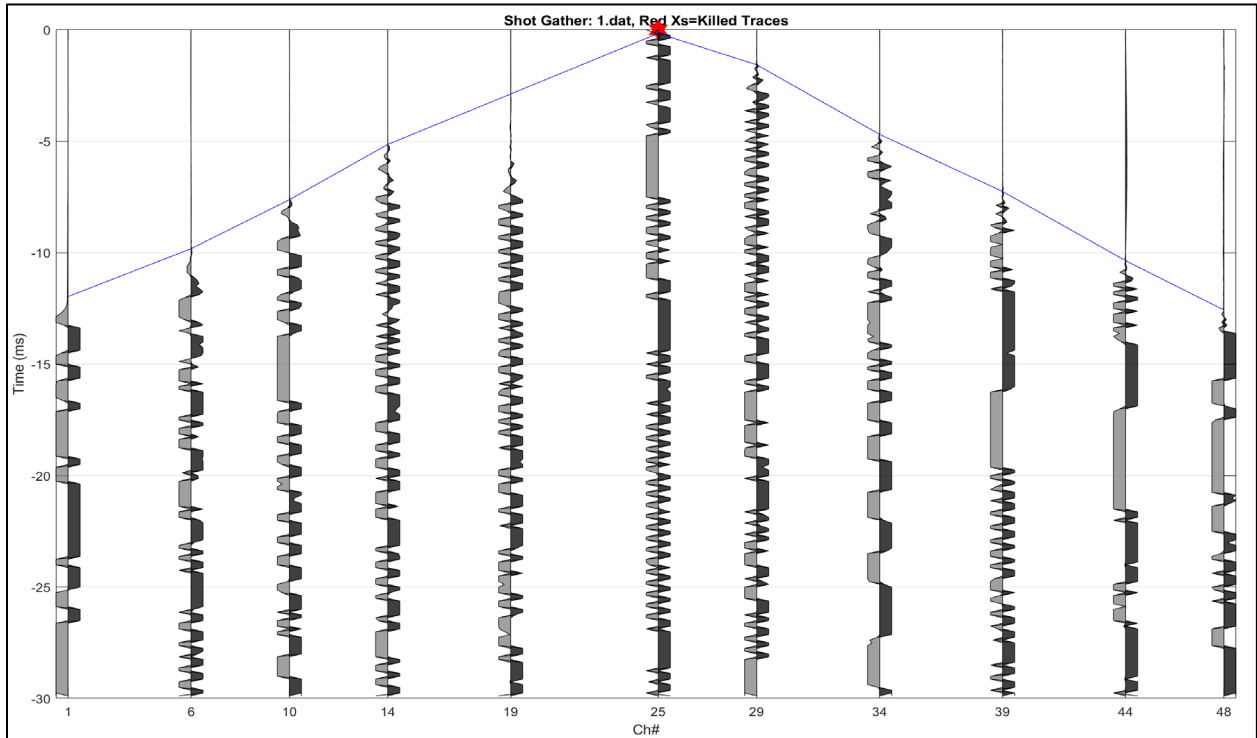


Figure 39.—Example shot gather showing vibration recordings from 11 geophone sensor during a hammer tap test, with the source located near the center of the geophone array (Ch#25). The source location is indicated with a red star at the top of the plot, and the amplitudes recorded by each geophone sensor as a function of time are plotted as black and gray “wiggle traces.” The thin blue line shows the manual picks of energy first arrivals used for wave propagation velocity calculations. Note that Ch#19 suggests a later arrival time than picked, but increasing the gain (not shown here) verified that the arrival pick time was accurate and consistent with other channels, based on average energy moveout and delays as a function of distance from the source.

Table 4.—Results of three tap tests performed to map the velocity of sound wave propagation along the train track segments between the geophone sensors, for use in correlation-based localization analysis. Note that the calculated interval velocities shown in red font were omitted as outliers from the final averaged value (Ch#25 arrival time picks were poorly constrained due to proximity to the shot location). Also note that the overall average calculated interval velocity is within approximately 60 ft/s of the velocity of sound in steel reported in the literature.

Tests 1-3: Ave .Vel. (ft/s)	Test #1 (ft/s)	Test #2 (ft/s)	Test #3 (ft/s)
Average Ch1-6 Interval Velocity	19,800.13021	17,124.43694	18,499.39173
Average Ch6-10 Interval Velocity	14,339.31298	14,675.39063	13,417.5
Average Ch10-14 Interval Velocity	16,520.04505	16,299.77778	17,340.18913
Average Ch14-19 Interval Velocity	20,761.23457	17,142.30377	20,019.7619
Average Ch19-25 Interval Velocity	22,454.52675	22,248.52192	22,180.69106
Average Ch25-29 Interval Velocity	28,396.8254	21,109.14454	25,927.53623
Average Ch29-34 Interval Velocity	16,030.46595	15,369.41581	15,776.01411
Average Ch34-39 Interval Velocity	19,098.25708	16,697.33333	18,611.67728
Average Ch39-44 Interval Velocity	15,794.77477	16,415.9176	16,233.51852
Average Ch44-48 Interval Velocity	14,908.33333	16,399.16667	15,870.16129
Overall Average Interval Velocity:	16,797.69 ft/s		
Reported Velocity of Steel:	16,732.28 ft/s		

Following hammer tap tests, synthetic leak noise was applied to the train track, and several 16-second data files were recorded using the seismic system. These files were then used in conjunction with custom MATLAB™ scripts to perform correlation-based leak localization using the following steps:

1. Read in each 16-scond SEG2 raw data file,
2. Calculate the positive and negative 50-point mean envelope of each waveform,
3. Perform cross-correlation of waveforms for all permutations of channels that straddle the known synthetic leak noise source, iteratively using the following versions of the input waveform data:
 - a. Raw waveforms,
 - b. 200 Hz high-pass filtered waveforms,
 - c. 200-500 Hz band-pass filtered waveforms,
 - d. 200-1000 Hz band-pass filtered waveforms,
 - e. 500-1000 Hz band-pass filtered waveforms,
 - f. 1000-1900 Hz band-pass filtered waveforms,
 - g. Raw waveform envelopes,
 - h. 200 Hz high-pass filtered waveform envelopes.
4. Apply corrections to the selected correlation coefficient peak (i.e., if $v \cdot T$ is longer than the inter-geophone sensor pair distance; see inset equation in Figure 8),
5. Calculate the predicted source location for each permutation (approximately 355 permutations in total for this experiment),
6. Calculate the mean of all predicted source locations across all permutations,
7. Calculate the statistically most likely predicted source location from all permutations.

An example set of 16-second synthetic leak source waveforms (black wiggle traces) recorded by the 11 geophones spanning 444 ft of track is shown in Figure 40. The positive and negative 50-point mean envelopes of the waveforms are plotted as green and blue lines that bracket each waveform. The true source location is indicated with a bold red star, and the calculated/predicted source location is indicated with a labeled red asterisk at the top of the plot. Note that several relatively high-amplitude transient sound events are captured by all sensors throughout the 16-second recording. These transient signal events can assist with stable and accurate correlation of the various waveforms. Figure 41 shows power spectra for two example channels (Channels 1 and 8) of synthetic leak noise data recorded by the geophone sensors, with a 200 Hz high-pass filter applied to the waveforms.

Figure 42 presents three different zoom levels for plots of cross-correlation coefficients for data traces 1 and 8. The peak correlation coefficient is indicated with a labeled red asterisk. In this example, the positive time lag of the peak coefficient indicates that the source is closer to trace 8 (i.e., the source noise arrived at sensor 8 approximately 6.75 milliseconds before arriving at sensor 1). The resulting predicted source location for this particular permutation of channel pair and filtering is depicted in Figure 40, as previously described. The results of all source location predictions for this example—using 200 Hz high-pass filtered data and all permutations of channel pair selections—are shown in Figure 43. In the top plot, the predicted source location is plotted as a function of the permutation count, while the bottom plot shows a histogram of the predictions. The corresponding mean and statistically most likely predicted source locations are indicated on each plot with dashed black and red lines, respectively.

Finally, the average results for each data processing/filtering option are presented in Table 5. The predicted source locations are fairly accurate, with absolute errors ranging from 22.7 ft to 1.1 ft, and an overall average predicted source location error of only 1.1 ft. These results generally indicate that the multi-channel correlator leak locating technique performs quite well. However, the specific error spreads observed in these results are likely experiment- and data-processing-specific and should not be considered universally representative of expected outcomes in all leak locating scenarios. These absolute error spreads could likely be improved significantly through more nuanced selection of channel pair permutations or signal windowing based on data quality metrics—such as signal coherence—prior to cross-correlation of signal pairs. Nonetheless, the results of this final experiment demonstrate promise for this leak locating technique, and further improvements to sensors and processing software would likely benefit Reclamation in the future.

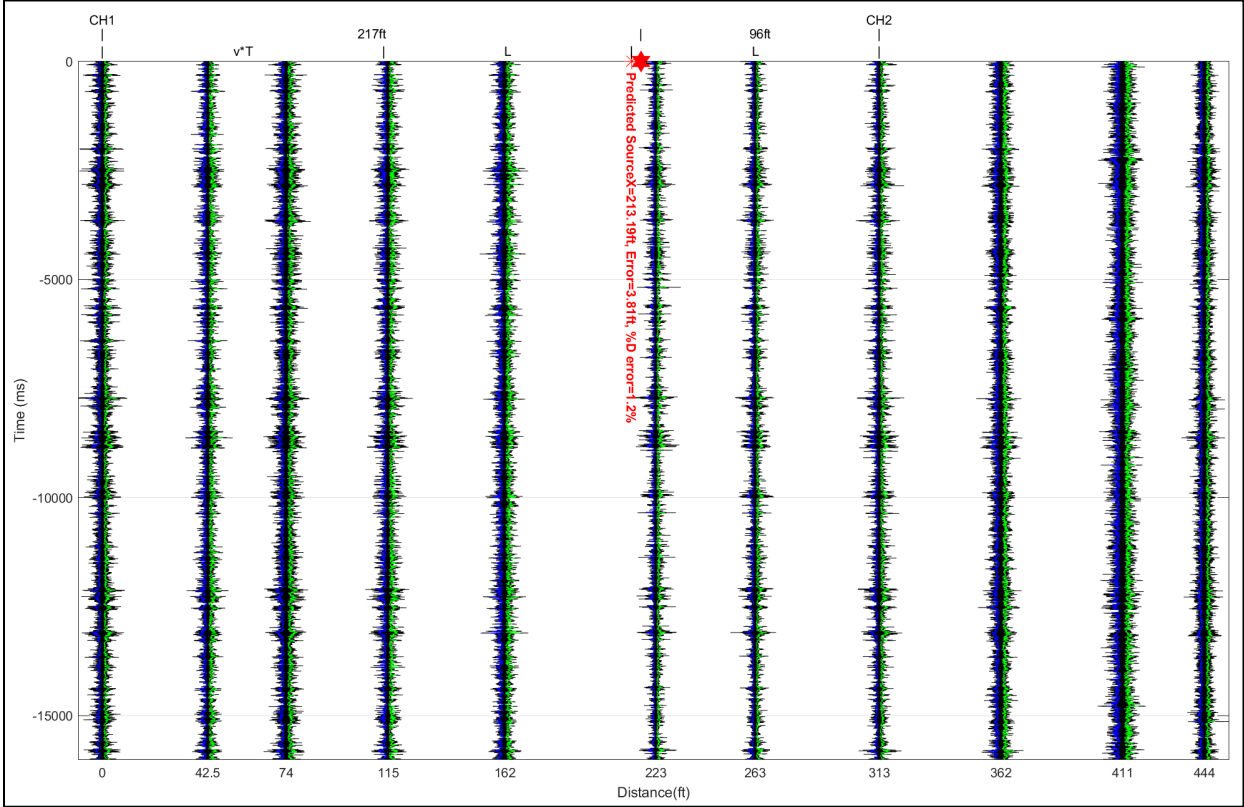


Figure 40.—Example set of 16-second synthetic leak source waveforms (black wiggly traces) recorded by the 11 geophones spanning 444 ft of track. The positive and negative 50-point mean envelopes of the waveforms are plotted as green and blue lines that bracket each waveform. The true source location is indicated with a bold red star, and the calculated/predicted source location is indicated with a labeled red asterisk at the top of the plot. Note that several relatively high-amplitude transient sound are captured by all sensors throughout the 16-second recording.

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

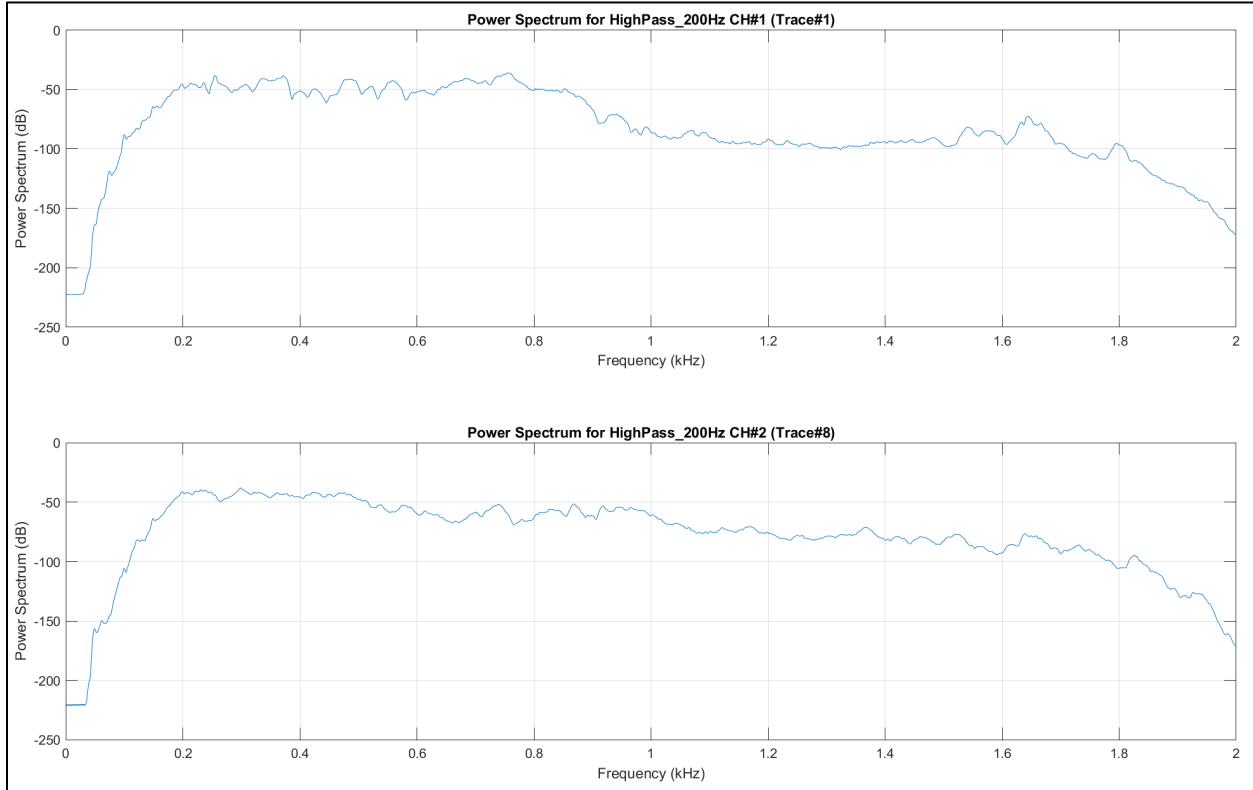


Figure 41.—Power spectra for two example channels (Traces 1 and 8) of synthetic leak noise data recorded by the geophone sensors, with a 200 Hz high-pass filter applied to the waveforms.

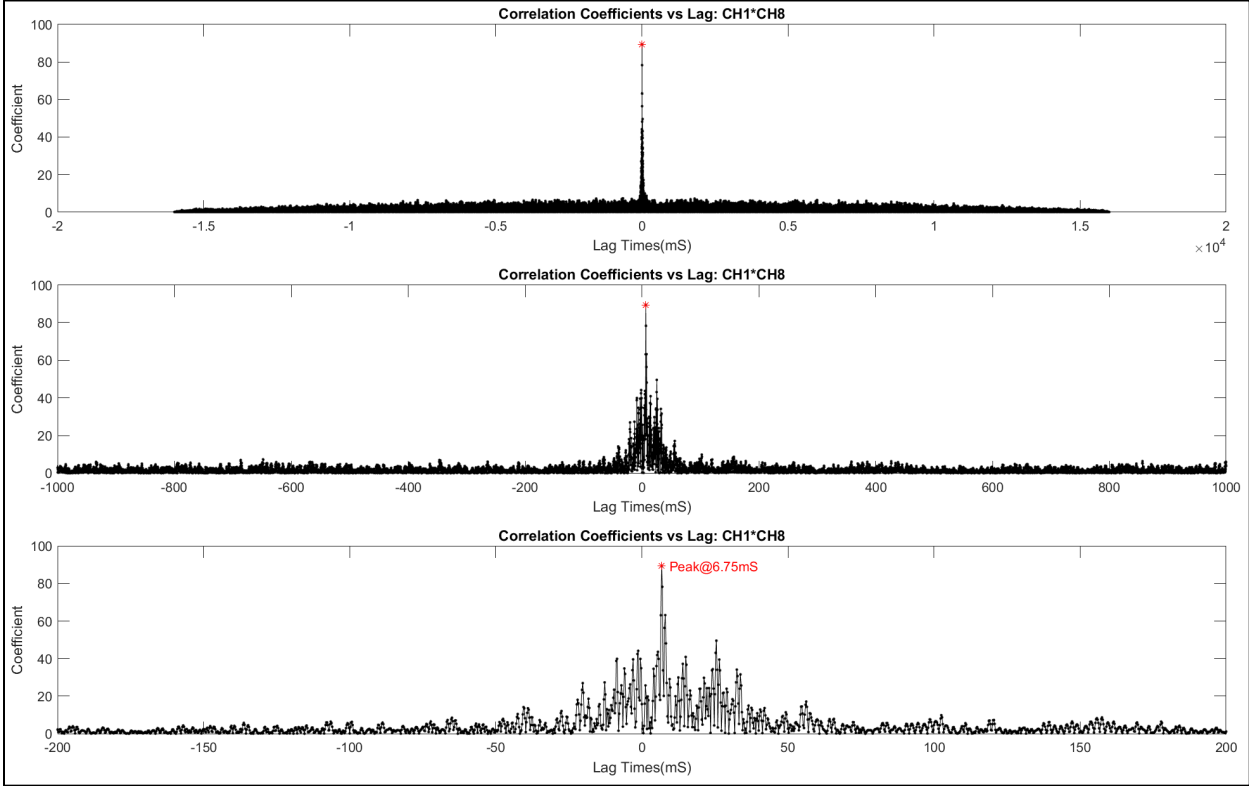


Figure 42.—Three different zoom levels for plots of cross-correlation coefficients for data traces 1 and 8. The peak correlation coefficient is indicated with a labeled red asterisk. In this example, the positive time lag of the peak coefficient indicates that the source is closer to trace 8 (i.e., the source noise arrived at sensor 8 approximately 6.75 milliseconds before arriving at sensor 1).

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

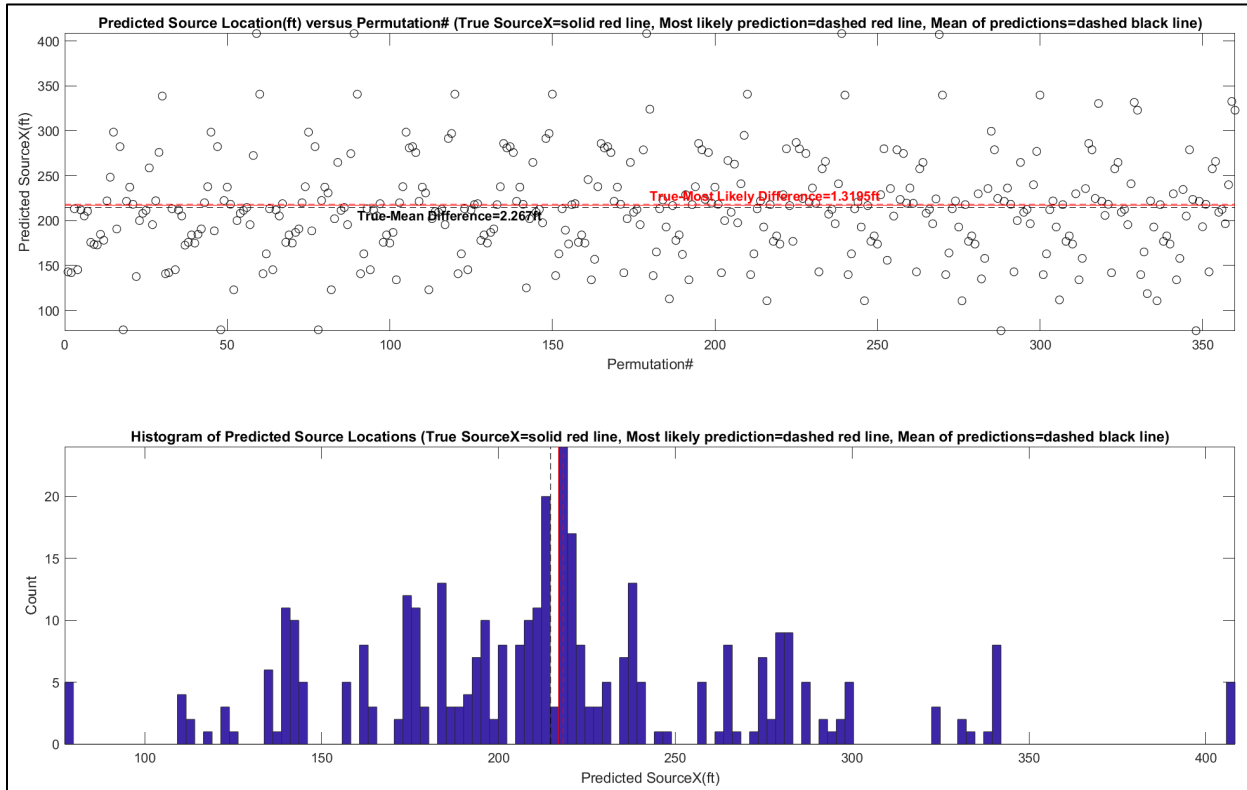


Figure 43.—Results of all source location predictions for 200 Hz high-pass filtered data, using all permutations of channel pair selections. The predicted source location is plotted as a function of permutation count in the top plot, and a histogram of the predictions is shown in the bottom plot. The corresponding mean and statistically most likely predicted source locations are indicated on each plot with dashed black and red lines, respectively.

Table 5.—Results of all leak locating calculations for various data signal processing permutations, including raw data, high-pass filtered, band-pass filtered, signal envelopes with no filtering, and high-pass filtered signal envelopes. The true source was located at 217 ft.

Signal Processing Option	Most Likely Predicted Location (ft)	Predicted Source Error (ft)
Signals, no filtering	226.0	9.0
Signals, 200 Hz high-pass filtered	218.3	1.3
Signals, 200-500 Hz band-pass filtered	194.3	22.7
Signals, 200-1000 Hz band-pass filtered	218.1	1.1
Signals, 500-1000 Hz band-pass filtered	219.6	2.6
Signals, 1000-1900 Hz band-pass filtered	222.0	5.0
Signal Envelopes, no filtering	223.2	6.2
Signal Envelopes, 200 Hz high-pass filtered	223.3	6.3
Overall Averages	218.1	1.1

5.0 Discussion and Next Steps

Several AE leak detection and localization technologies have been identified and reviewed in detail in this report. The various AE technology review sections presented here can be used by Reclamation and stakeholders to help guide selection of the most appropriate technologies for use during future pipeline leak events. Any of these technologies could prove extremely useful to Reclamation in specific scenarios involving pipeline leak locating and monitoring applications.

While the specific Nb-IoT logger system acquired and used for testing throughout this research project unfortunately did not effectively detect or locate simulated or synthetic leak noises, the technique itself was demonstrated to work well during the final train track tests. Numerous case studies across the industry also show that this technique can be effective in certain scenarios. However, the various false positive outcomes observed in the experiments described in this report highlight how the “black-box” nature of these commercial systems can be limiting in terms of system evaluation and successful implementations for leak detection and event reporting. This underscores the need to further develop a fully functional and versatile version of the current prototype AE data logger system—one that can be fully controlled, comprehensively evaluated and debugged, and custom-configured for a variety of monitoring and leak detection/locating applications that Reclamation will undoubtedly continue to encounter in the future. A fully developed AE logger prototype could even, theoretically, be deployed as a neutrally buoyant in-line free-floating sensor, helping Reclamation avoid the need for emergency contracting of expensive one-time commercial leak locating services.

As previously mentioned, the efforts for instrumenting portions of the Mni Wiconi main core line culminated in a site visit and the acquisition of several system quotes from various vendors of long-term monitoring noise logger and correlator systems. These quoted systems incorporated hydrophone sensors to help maximize the chances of effectively monitoring relatively long segments of the pipeline.

However, several challenges were encountered in the effort to successfully carry out a purchase request for the required hardware (14 hydrophone sensors/Nb-IoT loggers and necessary accessories) and associated services. These quoted systems and services were also deemed cost-prohibitive from a benefit-cost perspective (i.e., costs ranged from \$123,255.41 to \$174,630.00 to monitor only 4 miles of pipeline for 5 years). As a result, the research team decided to pivot to acquiring a DAS IU instead of the Nb-IoT loggers for future research and project use.

A purchase request has been submitted for acquiring a DAS IU and is currently pending final department-level funding allocation approvals. Researchers are hopeful that this acquisition will be approved and successfully completed by winter/spring of 2026. The acquisition of a DAS IU will enable a variety of exciting future R&D activities and new technical services capabilities within TSC (both related and unrelated to pipeline leak detection and locating).

Coincidentally, the Mni Wiconi core line was determined to have a telecommunications fiber optic cable buried within the same trench as the pipeline, which will enable future DAS leak detection and locating tests at this target field site. One caveat is that this buried fiber has

intermittent optical repeater stations along its alignment that limit the length of fiber that can be monitored from a single IU connection point (i.e., DAS cannot “see” through these repeaters, and so monitoring could only be performed along a segment of fiber extending between a given pair of adjacent repeater stations/access points). However, most of these monitorable segments of fiber are on the order of miles long, which still provides an opportunity for extremely valuable leak detection and locating services during future leak occurrences on this particular pipeline system. Other pipelines with no existing fiber could benefit from temporary fiber deployments for leak locating (e.g., via surficial deployments or tethered in-line deployments of fiber).

Next steps and future work should focus on development of Reclamation’s capabilities to self-perform various leak detection, locating, and long-term monitoring services—specifically through the continued pursuit and advancement of DAS capabilities, wireless acoustic data logger systems, and associated data telemetry and analytics software.

6.0 Conclusions

This research project successfully reviewed the current state of science and standard industry technologies currently available and in use for AE leak detection and localization. Several experiments helped advance Reclamation’s knowledge and capabilities for self-performing AE leak detection and locating services. Continued pursuit and further development of these capabilities will provide significant benefits to Reclamation. Specifically, developing the ability to self-perform effective and efficient monitoring, leak detection, and leak locating services will help inform and guide large pipeline system O&M activities in an economical fashion. Reclamation’s return on investment for pursuing DAS and wireless AE data logger system development could potentially be substantial, considering current practices and the associated monetary and resource costs incurred (both tangible and intangible) during leak events related to detection, locating, and repair activities.

7.0 References

- AP Sensing, 2025. Detecting Leaks with Fiber Optic Sensing. Process Automation and Pipeline Monitoring Case Studies webpage. Accessed 9/02/2025, available at: <https://www.apsensing.com/en/news/detail/detecting-leaks-with-fiber-optic-sensing>
- Ball, J., 2025. Arroyo-teensy: Low-cost hydroacoustic datalogger GitHub project page. Accessed 9/02/2025, available at: <https://github.com/bugoutput/arroyo-teensy>
- Cedilnik, G., Lees, G., Schmidt, P., Herstrøm, S., Geisler, T., 2019. Pushing the Reach of Fiber Distributed Acoustic Sensing to 125 km Without the Use of Amplification. IEEE Sensors Letters, vol. 3, no. 3, pp. 1-4, March 2019, Art no. 5000204, doi: 10.1109/LSENS.2019.2895249. Accessed 9/02/2025, available at: <https://ieeexplore.ieee.org/document/8625530>
- Cha, S., Mok Ahn, B., Kim, J., et al., 2023. Enabling Non-Experts to Detect Water Leaks through Industrial Internet of Things and Machine Learning Technologies. North American Water Loss 2023, Conference proceedings. Accessed 9/02/25, available at: https://events.tpni.com/gcmaintenance/awwa/html_files/30000231/onlineagenda/index.htm?switch=files&dl=1
- Dalaeli, J., and Lunsford, J., 2023. Installing Continuous Monitoring Sensors in the Distribution System to improve water loss control, operations, and asset management. North American Water Loss 2023, Conference proceedings. Accessed 9/02/25, available at: https://events.tpni.com/GcmMaintenance/AWWA/Uploads/30000231/30233461_010324102112_THU05-03_Dalaeli.pdf
- El-Zahab, Samer & Zayed, Tarek. (2019). Leak detection in water distribution networks: an introductory overview. Smart Water. 4. 10.1186/s40713-019-0017-x.
- Embry, K., 2022. Product Profile – New Kids on the Block for In-Line Leak Detection. Trenchless Technology digital magazine article. Accessed 9/02/2025, available at: <https://trenchlesstechnology.com/new-kids-on-the-block-for-in-line-leak-detection/>
- FAST GmbH, 2025. PipeMic XL/XXL Precise leakage detection, product information brocher. Accessed 9/02/25, available at: https://www.fastgmbh.de/images/FAST/Produktbeschreibungen/EN/PipeMicXL/PipeMicXL_V3.pdf
- Finfer, D., Veronique, M., Shatalin, S., Parker, T., and Mahmoud, F., 2014. Borehole Flow Monitoring Using a Non-intrusive Passive Distributed Acoustic Sensing (DAS). Proceedings - SPE Annual Technical Conference and Exhibition. 5. 3597-3605. 10.2118/170844-MS. Accessed 9/02/2025, available at: https://www.researchgate.net/publication/287773719_Borehole_Flow_Monitoring_Using

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

a Non-
intrusive_Passive_Distributed_Acoustic_Sensing_DAS?_tp=eyJjb250ZXh0Ijp7ImZpcnN
0UGFnZSI6Il9kaXJlY3QiLCJwYWdlIjoieX2RpcmVjdCJ9fQ

Gutermann, 2025. Gutermann AQUASCAN 610 – Leak Noise Correlator product information webpage. Accessed 9/02/25, available at: <https://en.gutermann-water.com/product/aquascan-610-leak-noise-correlator/>

Hughes, D.M., 2023. Are Your Large Meters Leaking Revenue? North American Water Loss 2023, Conference proceedings. Accessed 9/02/25, available at: https://events.tpni.com/GcmMaintenance/AWWA/Uploads/30000231/30233346_010324110005_WED09-01_Hughes.pdf

IGNU, 2025a. Thailand: The Underwater Leak Case study, accessed 9/02/2025, available at: <https://ingu.com/thailand-the-underwater-leak/>

IGNU, 2025b. Thailand: The Underwater Leak Case study, accessed 9/02/2025, available at: <https://ingu.com/water-wastewater-solution/>

OSRWSS, 2025. Oglala Sioux Rural Water Supply System, Mni Wiconi Water Treatment Plant / Coreline. System Statistics webpage. Accessed 9/02/2025, available at: <https://www.mni-wiconi.org/system-stats>

Paradise, A., Andalibi, Z., Prabhakar, V., et al., 2023. How AI-assisted Acoustic Leak Detection Can Help Utilities Reduce Operational Costs. North American Water Loss 2023, Conference proceedings. Accessed 9/02/25, available at: https://events.tpni.com/GcmMaintenance/AWWA/Uploads/30000231/30233389_010324180719_THU09-01_Paradise.pdf

Reclamation, 2018. Research and Development Office Prize Challenge Competition Launch Announcement: Detecting Leaks and Flaws in Water Pipelines – Stage 1. Accessed 9/2/2025, available at: https://www.usbr.gov/research/challenges/docs/leakypipes_preview.pdf

Reclamation, 2021a. Technical Service Center Water Treatment Group Civil Engineer: Verbal communication, April 28th, 2022.

Reclamation, 2021b. Technical Service Center Water Treatment Group Manager: Verbal communication, April 28th, 2022.

Reclamation, 2022a. South Dakota Area Office Rural Water Division Supervisory Civil Engineer: Verbal communication, April 11th, 2022.

Reclamation, 2022b. Technical Service Center Materials and Corrosion Laboratory Group Materials Engineer: Verbal communication, April 28th, 2022.

ST-2025-22086-01: Evaluation of Acoustic Emission Sensing Technologies for Pressurized Buried Water Pipeline Leak Detection

Reclamation, 2024. South Dakota Area Office Rural Water Division Supervisory Civil Engineer: Verbal communication, October 18th, 2024.

Schwenen, L., 2019. The Principle of Correlation, Esders GmbH overview webpage. Accessed on 9/02/2025, available at: <https://www.esders.com/2019/08/the-principle-of-correlation/>

Sewerin, 2025. SePem Water Leak Noise Loggers for the Early Recognition and Detection of Leaks in Water Supply Networks. Product overview webpage, Accessed 9/02/25, available at: <https://www.sewerin.co.uk/products/water-leak-location/sepem/>

Singbeil, M., and van Pol, A., 2023. Acoustic Leak Detection Using an Inline Free-floating Sensor Device, North American Water Loss 2023, Conference proceedings. Accessed 9/02/25, available at: https://events.tpni.com/GcmMaintenance/AWWA/Uploads/30000231/30250669_010324103834_THU09-03_Van_Pol.pdf

Sinha, S., 2023. Development of the National Water Loss Models: From Source to Tap. North American Water Loss 2023, Conference proceedings. Accessed 9/02/25, available at: https://events.tpni.com/gcmaintenance/awwa/html_files/30000231/onlineagenda/index.htm?switch=files&dl=1

Sutherns, T., 2023. Putting it to Practice: Studies on How Utilities from California to Wisconsin have Leveraged AI to Reduce their NRW. North American Water Loss 2023, Conference proceedings. Accessed 9/02/25, available at: https://events.tpni.com/gcmaintenance/awwa/html_files/30000231/onlineagenda/index.htm?switch=files&dl=1

Whitfield, S., 2025. New Chevron Venture Program Selects Pipeline Inspection Technologies, Journal of Petroleum Technology online article, published August 29, 2017. Accessed 9/02/2025, available at: <https://jpt.spe.org/new-chevron-venture-program-selects-pipeline-inspection-technologies>

Wikipedia, 2025. "Distributed acoustic sensing." Wikipedia, The Free Encyclopedia. Accessed 9/02/2025, available at: https://en.wikipedia.org/wiki/Distributed_acoustic_sensing#cite_note-3

Ziemendorff, S., 2022. COMPARISON OF SUITABLE LEAK DETECTION METHODS Guideline with special consideration of the conditions in countries with emerging markets and developing economies. 10.5281/zenodo.6625858. Accessed 9/02/2025, available at: https://www.researchgate.net/publication/361176512_COMPARISON_OF_SUITABLE_LEAK_DETECTION_METHODS_Guideline_with_special_consideration_of_the_conditions_in_countries_with_emerging_markets_and_developing_economies