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Infrasonic Frequency Seismic Sensor System for Pipeline Integrity Management

Phase 1 SBIR Final Report

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FINAL PROJECT SUMMARY REPORT

PROJECT IDENTIFICATION INFORMATION

1. **BUSINESS FIRM AND ADDRESS** 2. **DOT SBIR PROGRAM 2003 PHASE I** 3. **DOT CONTRACT #**

Physical Sciences Inc.
20 New England Business Center
Andover, MA 01810

DTRS57-04-C-10002

4. **Period of Performance:**

5. **Project Title:** Infrasonic Frequency Seismic Sensor System for Pipeline Integrity Management

SUMMARY OF COMPLETED PROJECT

PSI is working with the Northeast Gas Association (NGA) to develop the Proactive Infrasonic Gas Pipeline Evaluation Network (PIGPEN) system. PIGPEN uses low frequency seismic/acoustic (0.1 to 100 Hz) sensor technology to proactively detect and warn of right-of-way encroachment and unauthorized digging near underground gas pipelines before damage occurs, thereby preventing third-party damage and subsequent pipeline leaks or failure. The PIGPEN technology has the potential to detect and locate digging in the vicinity of the transmission pipe, but that does not need to be located along the entire service or main. Rather, individual point sensors are placed in the ground near the pipe. Monitoring is performed at multiple locations at ~1 km separation. Once completely implemented, this technology will result in great savings through better detection and prevention. Moreover it could be put into place at much less cost than other proactive sensors that must be co-located along the entire length of the pipeline. We have achieved nearly all of the objectives and performance goals of the Phase 1 program:

- We have demonstrated that PIGPEN has the capability to detect threats at ranges up to 1000 m
- We have demonstrated a time lag triangulation technique that can be used to locate threats.
- We have developed a preliminary design concept that is small, lightweight and inexpensive.

APPROVAL SIGNATURES

1. **PRINCIPLE INVESTIGATOR:**
Gary E. Galica [signature] **DATE:** 7 May 04

1. Overview

This final report describes the results of the Phase 1 SBIR for the development of the Proactive Infrasonic Gas Pipeline Evaluation Network (PIGPEN) system. PSI is working with the Northeast Gas Association (NGA) to develop the PIGPEN system. NGA has been funding preliminary feasibility studies since December 2002. This DoT Phase 1 SBIR continues the technology development already underway with NGA and PSI internal funding. **We have achieved nearly all of the objectives and performance goals of the Phase 1 Program:**

1. We have quantified the performance of the PIGPEN system
   a. With optional sensor and electronics, PIGPEN will detect threats at a range of 1000 m
   b. We can triangulate the position of a threat.

2. We have created a conceptual design for PIGPEN that meets the technical and market requirements
   a. PIGPEN concept is 2.2 lb and 2.4 x 3.5 x 6.3 in.^{3}
   b. Our estimates indicate that a target price of $7500.00 is achievable.

3. We have worked with our Northeast Gas Association partners to identify suitable potential commercialization partners.

We have received critical insight and assistance from our NGA partners in technical performance assessment, market requirement definition and funding support.

PIGPEN uses low frequency seismic/acoustic (0.1 to 100 Hz) sensor technology to proactively detect and warn of right-of-way encroachment and unauthorized digging near underground gas pipelines before damage occurs, thereby preventing third-party damage and subsequent pipeline leaks or failure. The PIGPEN technology has the potential to detect and locate digging in the vicinity of the transmission pipe, but that does not need to be located along the entire service or main. Rather, individual point sensors are placed in the ground near the pipe. Monitoring is performed at multiple locations at ~1 km separation (see Figure 1). If successful, this technology will result in great savings through better detection and prevention. Moreover it could be put into place at much less cost than other proactive sensors that must be co-located along the entire length of the pipeline.

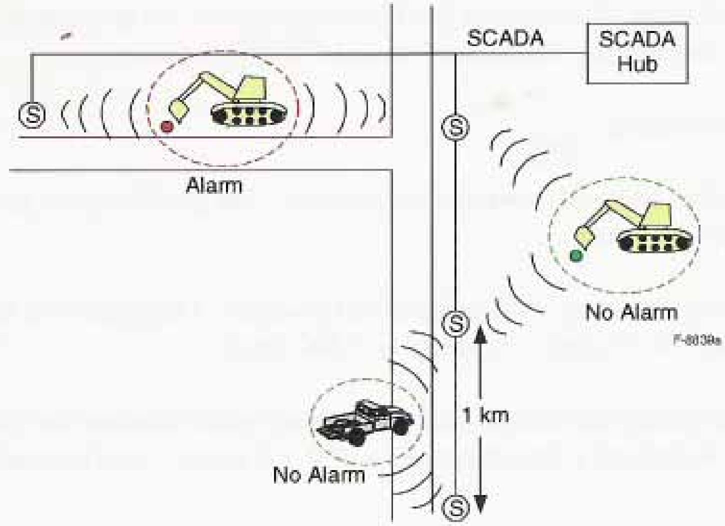


Figure 1. The PIGPEN system comprises a sparse network of point sensors, connected to a network, that detect, identify, and locate threats. Only true threats that are also in close proximity to the pipeline trigger an alarm.

The overall cost and safety benefits of *proactive* remote pipeline monitoring, i.e., detecting *impending* damage, are readily apparent. In addition, the proposed infrasonic detection technology provides several specific benefits:

1. **Low sensor cost**. The sensors themselves are simple in design and inexpensive. As described below, the PIGPEN comprises a polymeric sensor, amplifier, simple data acquisition system, and network communications system.
2. **Low network cost**. Because the infrasonic frequencies propagate for long distances, the sensor array can be quite sparse (a few sensors/km^2), thereby reducing initial cost, installation cost, and maintenance cost.
3. **Simple to install**. Existing gas pipes do not need to be disturbed (or minimally disturbed) for installation. Since the PIGPEN are point sensors, the amount of street disturbance for installation is minimized. They are also compatible with in-pipe installation.
4. **PIGPEN can be retrofit to existing systems**. PIGPEN will be compatible with existing supervisory control and data acquisition (SCADA) and monitoring systems.

2. Phase 1 Technical Objectives and Work Plan

The proposed Phase 1 program has three technical objectives:

1. Quantify the performance of the PIGPEN system for detecting and locating right-of-way (ROW) encroachment and impending third-party damage.
2. Create a conceptual design for a PIGPEN system that meets the technical and market requirements of the gas pipeline monitoring system.
3. Identify and develop a working relationship with a commercialization partner having an established manufacturing, marketing, and service capability in pipeline monitoring or related markets.

To satisfy the three technical objectives of the Phase I program, we propose to complete the following tasks using the existing breadboard model PIGPEN sensor:

- Task 1. Project kickoff.
- Task 2. Quantify sensitivity and detection range. The performance goal is 1000 yard range for a realistic threat.
- Task 3. Quantify accuracy of locating threat position. Our goal is to locate the threat with an accuracy of 10 yards at a range of >300 yards.
- Task 4. Create conceptual design and preliminary specifications for PIGPEN system. Our goals are: weight of 2 lbs, dimensions of 4 x 4 x 4 $in.^3$, and a commercial cost of <$1000.
- Task 5. Develop a threat identification algorithm.
- Task 6. Identify commercialization partner.

3. Phase 1 Activities

3.1 Task 1 - Kickoff Meeting

On 9 December 2004, we held the kickoff meeting with the participation of PSI, NGA, and the DoT. The kickoff meeting presentation is attached as Appendix A. The objectives of the kickoff meeting were:

- Summarize progress on current and past efforts
- Review DOT SBIR program objectives
- Discuss Northeast Gas Association role as a program partner
- Discuss DOT requirements and objectives
- Discuss schedule.

PSI summarized the state of the PIGPEN technology as of the start of the Phase 1 program. PSI had already demonstrated the basic feasibility of the PIGPEN concept. The focus of the Phase 1 program is to quantify the performance and modifications necessary to develop a fully functional system

3.2 Task 2. Quantify sensitivity and detection range

The performance goal is 1000 yard range for a realistic threat. **(By optimizing the sensor and electronics, we can achieve the 1000 m detection range for PIGPEN.)**

Sensor Configuration

For the Phase 1 measurements, we have used two different sensors: a vertical-axis sensor based on polyvinylidene fluoride (PVDF) piezo-polymer, and a commercially available three-axis voice-coil geophones.

Figures 2 and 3 show the configuration of the PIGPEN one-axis sensor (POS) used in Phase 1. The POS comprises a polyvinylidene fluoride (PVDF) piezo-polymer sensing element, a rigid spacer and an inertial mass. When the earth vibrates in the vertical direction, the inertial mass provides a force that compresses the PVDF polymer, creating an electrical signal. That electrical signal is input into a low-frequency laboratory amplifier. The active area of the PVDF is 1.6 cm^2, and the inertial mass is 1 lb.

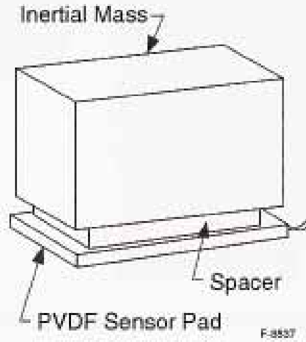


Figure 2. Schematic representation of the PIGPEN one-axis sensor.

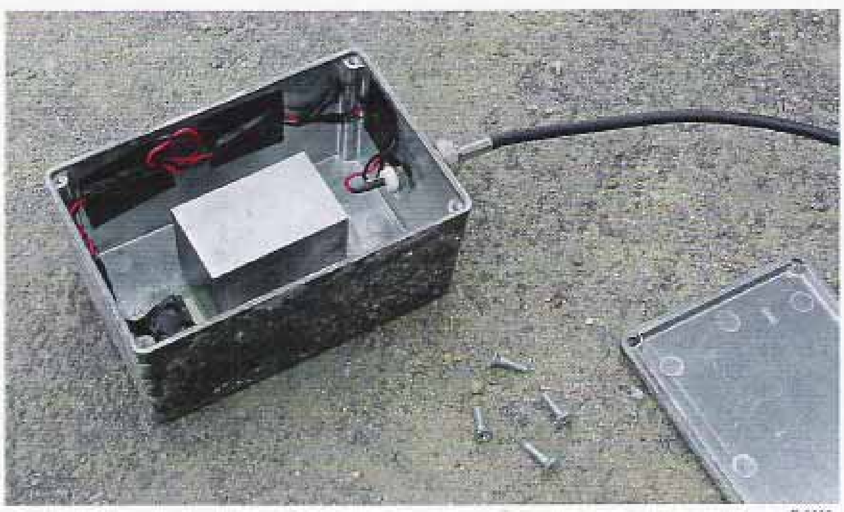


Figure 3. Photograph of the PIGPEN sensor used during Phase 1.

Figure 4 shows a block diagram of the data acquisition system. During most of the field tests, we used two sensors at each location: a single axis PIGPEN sensor and a commercially available three-axis geophone. The PIGPEN sensor amplifier output and the three geophone outputs are connected to the interface box for a National Instruments data acquisition system (DAQ). The DAQ system resides in a laptop computer. The entire system is powered by batteries.

The DAQ system simultaneously samples and digitizes the sensor outputs at a rate of 1 kHz. The DAQ system acquires data continuously and records it in 1 min, time-tagged files. For most tests, we have two sensor groups connected to independent DAQ systems. The DAQ systems computer clocks are synchronized several times during the course of a field test. The data files are time-tagged with a resolution of one second. Overall synchronization is maintained to within a few seconds over the course of an entire day.

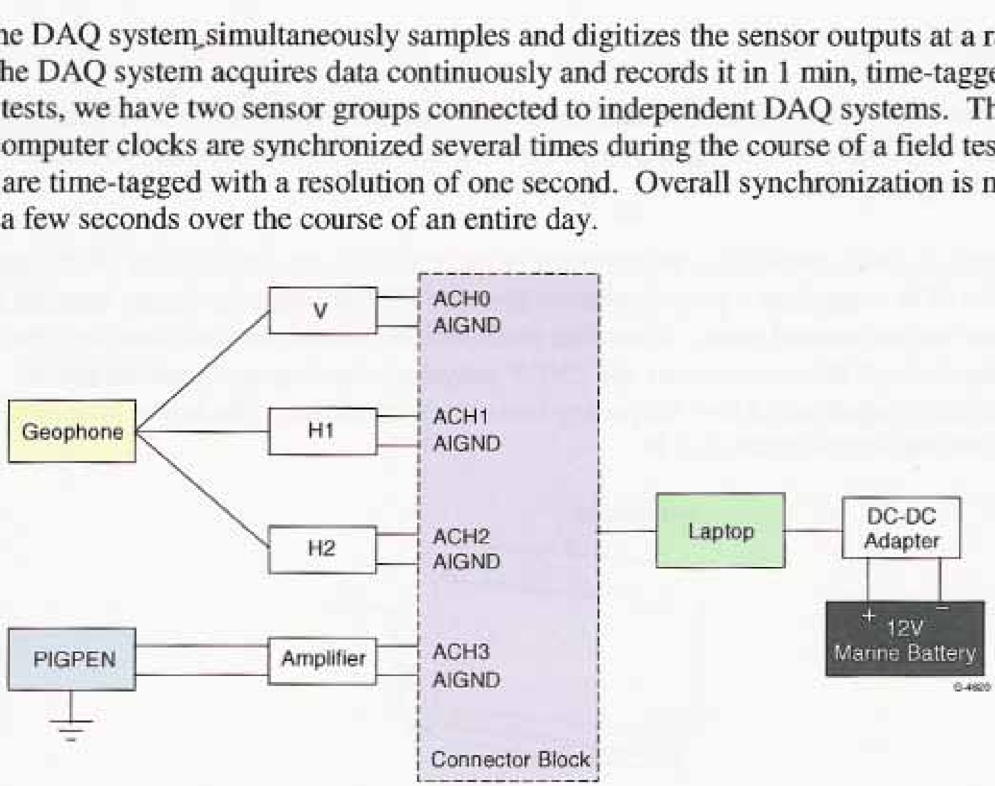


Figure 4. Block diagram of the data acquisition system.

Using the PIGPEN sensor, we have detected a backhoe at a range of 300 m (see Figure 30), albeit with a somewhat marginal SNR.

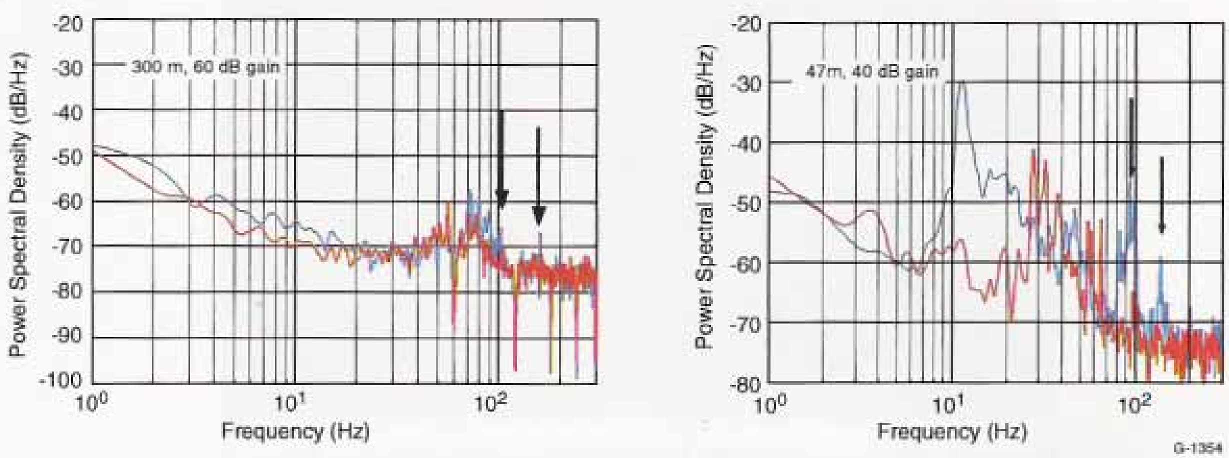


Figure 5. PSDs of backhoe at 300 yards (left) and 47 yards (right). These data were acquired under the NGA-funded program.

For a body wave propagating in non-dispersive medium, one would expect the signal magnitude to decrease with the square of the range. In a PIGPEN deployment, we would expect to be most sensitive to surface waves. In addition, in a real application, the propagating wavefront will also be subject to dispersion.

In order to better extrapolate the detection range, we conducted a very simple experiment in which we measured the signal intensity of a 5 kW generator as a function of range. Those data are shown in Figure 5. The noise floor in this configuration is approximately -80 dB re V^2/Hz

The 5 kW generator is a small source and can easily be detected at a range of 160 m (SNR=30 dB). The range dependence is roughly R^2. Therefore, with present sensor system, we would expect to be able to detect a generator at a range of 277 m (SNR=3), which is consistent with detection of the threat at 300 yards.

In order to meet the goal of detection at 1000 m, we would improve the sensitivity of the sensor and reduce the noise of the electronics.

We investigated the effects of varying the sensor physical parameters on the sensitivity. We have created a sensor model that is validated by laboratory measurements. We used that model to predict the sensitivity improvement that we can expect by varying the sensor and electronics parameters.

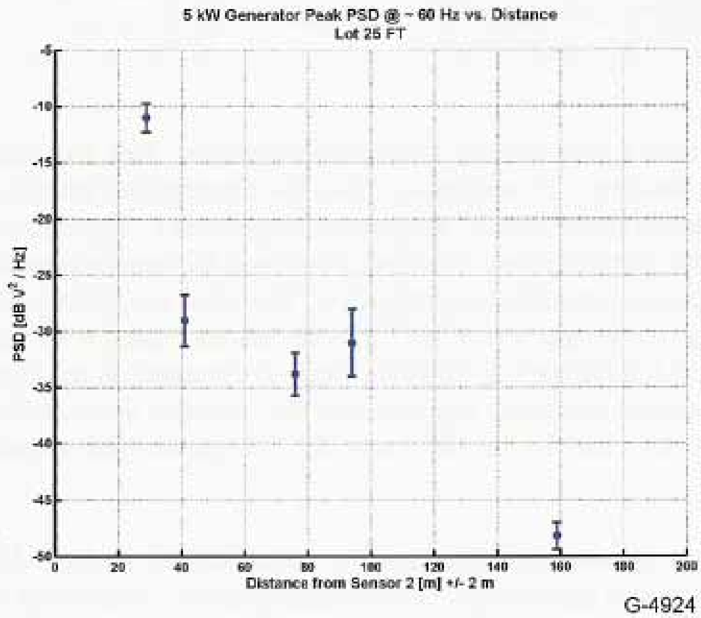


Figure 6. Signal intensity of a 5 kW generator as a function of range from the sensor. The noise floor in this configuration is approximately -80 dB re V^2/Hz.

Table 1 summarizes the sensor model predictions and values measured in the laboratory. The results validate the sensor model; therefore, we can use that model with confidence to predict the performance of various sensor configurations.

Table 1. Predicted and Measured Sensitivities for Various Sensor Configurations

Configuration	Loading Fraction	Modeled Sensitivity (dB re V/(m/s))	Measured Sensitivity (dB re V/(m/s))
28 μm × 1.6 cm^2	0.25	-5.8	-5.6
52 μm × 1.6 cm^2	0.25	+0.4	+1.4
52 μm × 1.6 cm^2	0.5	+6.4	+7.4

By varying the number of layers and electrode connections, we found that the sensitivity increased significantly. The current sensor has a sensitivity of 6.4 dB re V/(m/s). We can achieve an increase in sensitivity of >20 dB (10×) by changing the sensor configuration. Layered materials are available as off-the-shelf and custom items from the PVDF sensor vendor. Table 2 summarizes the results of our investigation.

Table 2. Sensitivity of Several PVDF Sensor Configurations

Configuration	Sensitivity (dB re V/(m/s))
1 layer - current	6.4
2 layer – series	16.5
8 layer - series/parallel	22.5
32 layer – series/parallel	28.5

In Phase 1, we used a commercial, laboratory amplifier. This amplifier is not matched to the sensor electrical parameters. To minimize noise, the preamplifier must be match to the sensor electrical parameters (capacitance, frequency, impedance). There are two dominant noise terms: voltage noise and current noise. We have examined the sensor electrical parameters and determined specification for a matched preamplifier. The ideal amplifier will have a voltage noise of 158 $nV/Hz^{1/2}$ at 10 Hz and 50 $nV/Hz^{1/2}$ at 100 Hz, combined with a current noise of 20 $fA/Hz^{1/2}$ at 10 Hz and 6.5 $fA/Hz^{1/2}$ at 100 Hz. Several commercial op-amps meet these specifications in a low power package. For example the National Semiconductor LMV751 has voltage terms of 30 $nV/Hz^{1/2}$ and 10 $fA/ Hz^{1/2}$ at 4 Hz. The power consumption of this component is <5mW.

In conclusion, we can expect to increase the sensor sensitivity by 3-10× and reduce the noise floor 10× within current technology. The resulting sensor system will have a 10-100× improvement in sensitivity. **This increase in sensitivity will result in detection capability at in excess of 1000 m.**

3.3 Task 3. Quantify accuracy of locating threat position

Our goal is to locate the threat with an accuracy of 10 yards at a range of >300 yards. **We have demonstrated the ability to triangulate the threat position using a time lag technique.**

3.3.1 Introduction and Background

The data presented in Section 3.3.1 was acquired under the NGA-sponsored program.

During early NGA-sponsored development programs, PSI demonstrated the ability to triangulate the position of a threat to within 16 feet, in uniform soil, using a time-lag technique (see Figures 7 and 8). To achieve good precision, the time-lag technique requires a uniform seismic velocity (ergo, uniform soil conditions) between the threat and all the nearby sensors. While soil types typically vary over tens of kilometers (see Figure 7), soil moisture content can vary greatly over short distances. We confirmed that the seismic velocity is highly dependent upon the soil moisture content, varying by more than a factor of 3 from dry sand to wet sand to frozen sand (see Table 1).

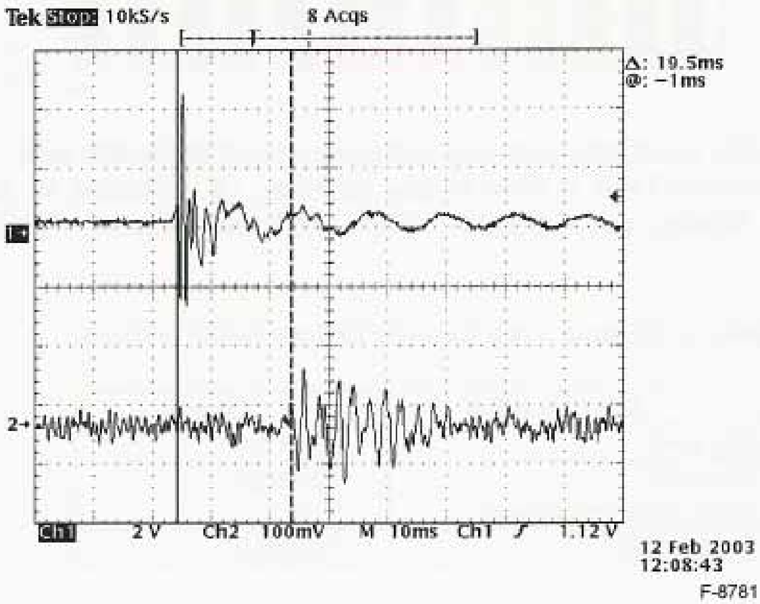


Figure 7. Time lag between signals arriving at two PIGPEN sensors. The ΔR of the two sensors is roughly 80 feet.

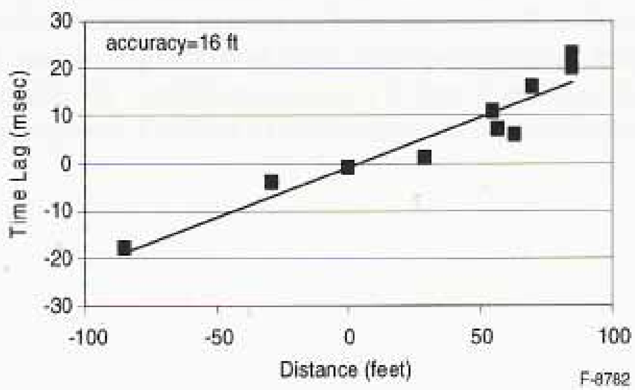


Figure 8. Plot of time versus distance between sensors. The slope of the curve is the average velocity. The standard deviation corresponds, with respect to the average line, corresponds to the triangulation accuracy and is 16 feet.

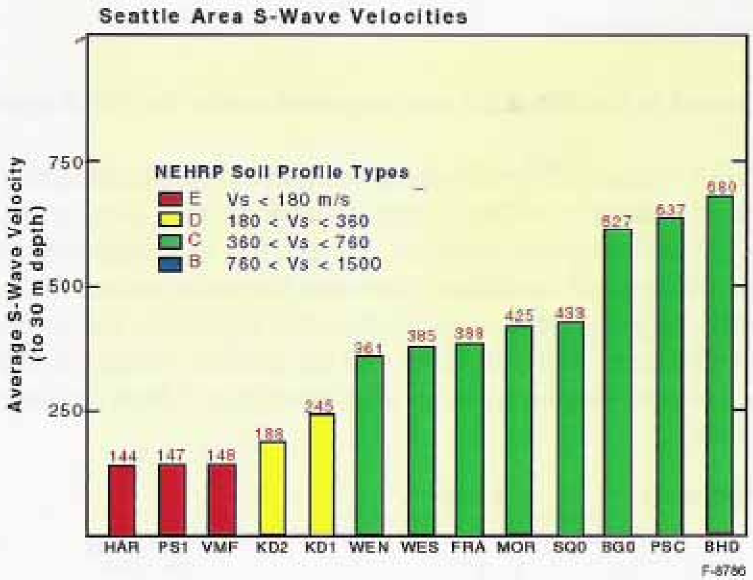


Figure 9. S-wave velocity variations in several soil types around the Seattle area. PSI measurements (see Table 3) show similar variation. [R. Williams, W. Stephenson, J. Odum, D. Worley, and A. Frankel, AGU EOS Transactions, v. 78, no. 46, p. F433]

Table 3. Seismic Velocities for Various Soil Conditions

Soil Condition	Velocity
Dry sand	140 m/s
Wet sand (10% moisture content)	240 m/s
Frozen sand	470 m/s

From these results, we concluded that although triangulation by time lag is very accurate in uniform soil conditions, the local variations in soil moisture content would confound the time-lag triangulation technique. As an alternative to the time-lag triangulation, we proposed a triangulation technique based on determination of bearing or direction to the source (see Figure 10). By using sensors having sensitivity along two orthogonal axes, one can determine the bearing by taking the ratio of the X and Y signal magnitudes. We estimated that by using this technique, we could determine the threat location to within 8 meters at a range of 300 meters.

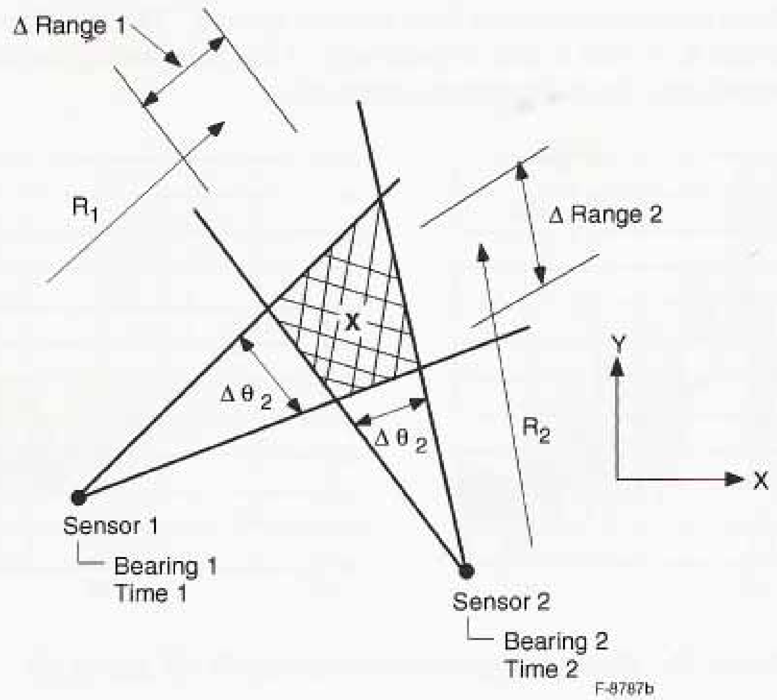


Figure 10. Schematic of triangulation using bearing. Two sensors independently determine bearing to the threat. The threat is located where the two bearing vectors intersect.

3.3.2 Initial Bearing Triangulation Measurements

The data presented in Section 3.3.2 was acquired under the NGA-sponsored program.

PSI used 3-axis geophones in an attempt to quantify our ability to triangulate using bearing. We buried two three-axis geophones at ranges of 47 and 75 meters in orthogonal directions from a site where a backhoe was digging (see Figure 11). We acquired several hours of data on all three axes of the two geophones.

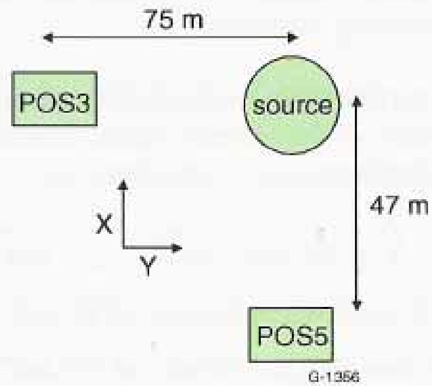


Figure 11. Schematic of experiment configuration. Sensors POS3 and POS5 were located 75 m and 47 m from the backhoe, respectively. The axes of the sensors were aligned as indicated.

Figure 12 shows representative data from the two sensors. The red, blue and green curves correspond to the X, Y, and Z axes respectively. After completing our initial analysis of the data, we could extract any clear directional information.

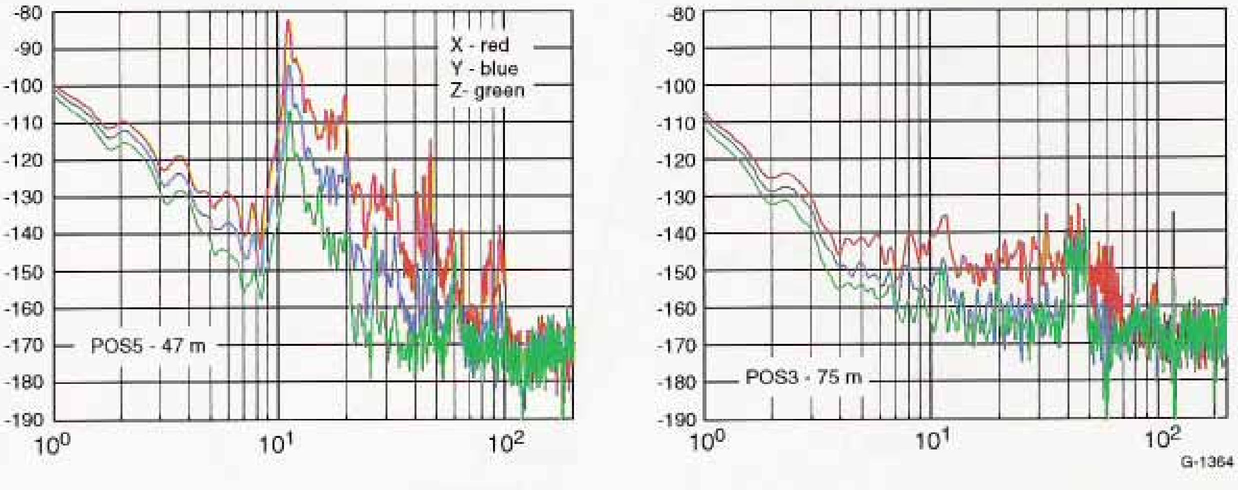


Figure 12. Three-axis geophone data from POS5 and POS3.

Because of the sensors are coaligned with respect to the source (see Figure 5), we expected to observe an obvious directional response. Our expectation was that for POS5, the X-axis signal would be much greater than the Y-axis signal. Conversely, for POS3, we expected that the Y-axis signal would be much greater that the X-axis signal. The observed signal ratios did not correspond to expectations. It appeared that the X-axis signals were larger than the Y-axis signals for both POS5 and POS3, but that the ratio was frequency dependent. We concluded that a more complex analysis was required.

A complex analysis hodograph analysis revealed that particular frequencies did show good directional specificity. Other frequencies, however, appear more isotropic. We hypothesize that frequency signatures characteristic of the machinery show the directional specificity. The broader spectral feature between 10 and 100 Hz, however, is a resonance of the earth, and as expected, appears essentially isotropic.

The hodograph analysis is performed by analyzing the relationship between the phase of the vertical and horizontal components of the seismic signal. Mathematically, the hodograph, $y(\varphi, f)$, is a function of phase and frequency and is calculated by:

$$\begin{aligned} y(\varphi, f) &\approx \sqrt{C^2_{H1,V}(f)\cos^2(\varphi) + C^2_{H2,V}(f)\sin^2(\varphi)} \\ C^2_{H1,V}(f) &= \text{Cross Spectral Density of H1 and V axis} \\ C^2_{H1,V}(f) &= \text{Cross Spectral Density of H2 and V axis} \end{aligned} \qquad (1)$$

Figure 13 shows the hodographs for POS2 and POS5 at a frequency of 27.5 Hz. As expected, the lobes of the POS3 hodograph are aligned along the Y-axis , while the lobes of the

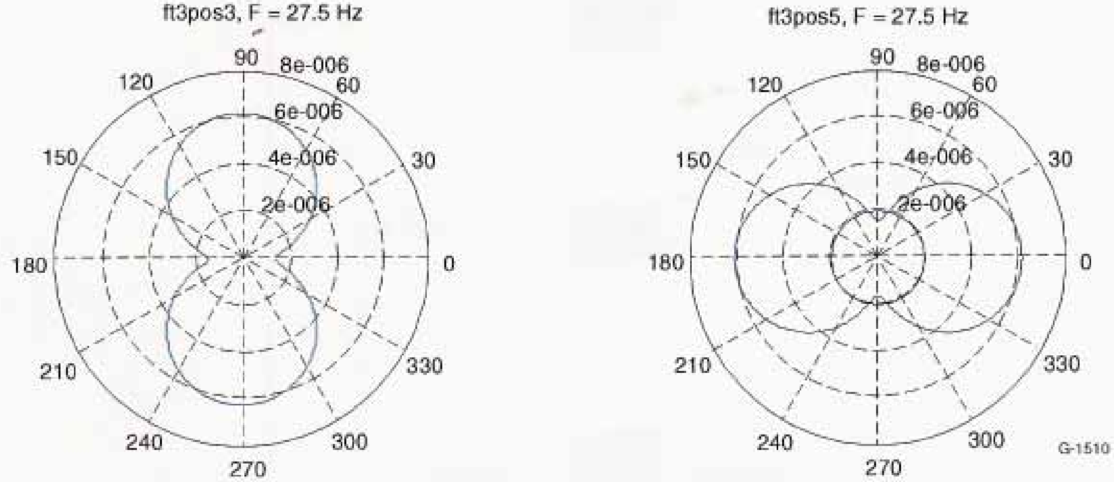


Figure 13. Hodographs for POS2 and POS5 at a frequency of 27.5 Hz. As expected, the lobes of the POS3 hodograph are aligned along the Y-axis , while the lobes of the POS5 hodograph are aligned along the X-axis.

POS5 hodograph are aligned along the X-axis. We conclude that by isolating specific frequencies, we do achieve the directional specificity necessary for triangulation.

3.3.3 Bearing Triangulation Experiments

Overview

While our previous triangulation data acquired using the multi-axis geophones appeared promising, it was not conclusive. Because of the limitations and shortcomings of the previous field measurements, we recommended an additional, well-defined experiment to quantify the triangulation technique.

One of the difficulties in our previous field tests was the lack of control over the experimental configuration and conditions, particularly the measurement geometry and various interferences. We propose to define and conduct an experiment that will isolate effects and provide the data to quantify the directional capabilities of the PIGPEN system. We proposed an experiment in which we could define and vary the measurement geometry, control the source signature, control the source operation, and limit external interferences.

Figure 14 shows the nominal measurement geometry for the proposed experiment. Sensor S1 will remain fixed at a range of approximately 50 m from the source. Its position with respect to the source defines the X-axis for the measurements.

Sensor S2 will be moved to various locations. In position P1, it is located approximately 50 m from the source, and lies along an orthogonal direction to sensor S1, thereby defining the Y-axis for the measurements.

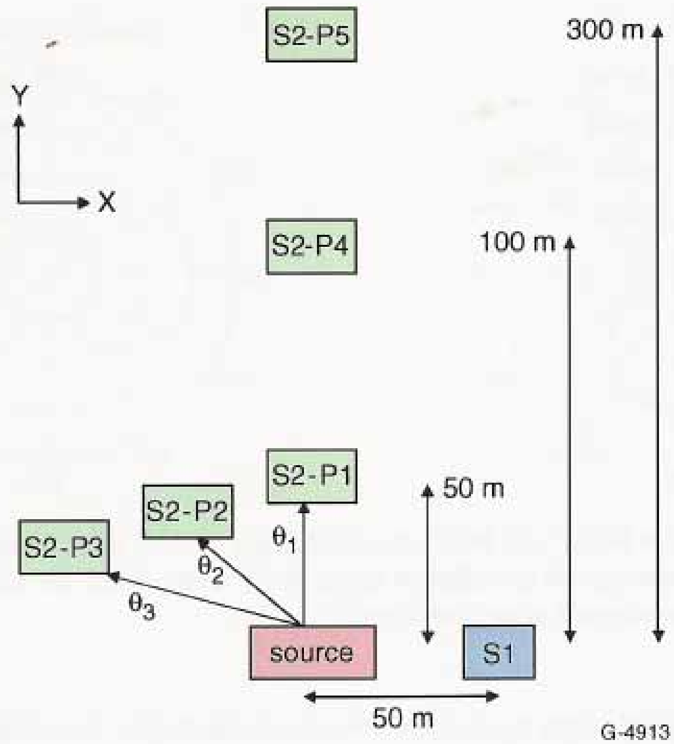


Figure 14. The schematic sensor configuration. Sensor S1 remains fixed at a distance of approximately 50 m from the source. Sensor S2 is moved to several positions to acquire the necessary data.

Sensor S2 will be moved to several positions roughly 50 m from the source, but with different bearings to the source (P2 and P3). Sensor S2 will also be positioned along the Y-axis, but at longer ranges (100 m and 300 m) to the source.

We will measure the range and bearing to the source using a laser rangefinder and a theodolite. We will compare the bearing determined from the geophone data, to the actual, physically-measured bearing. From these data, we will be able to determine the precision to which we can measure the bearing to a source. From those data, we can infer the accuracy of locating the source.

The measurements at longer range (100 m and 300 m) will allow us to determine the how the angular accuracy degrades as the signal strength decreases.

Source Signatures

During the previous field tests, we acquired geophone data with a backhoe digging as the only source signature. While the backhoe has a few discrete spectral features, overall the signature is quite broad. Since the directional specificity is highly frequency dependent, we must isolate specific frequency bands that are associated with the threat source, and differentiate those frequency bands from the earth resonance. If the source signature has more discrete frequency components, for example, a jackhammer (see Figure15), it is easier to isolate specific frequency bands.

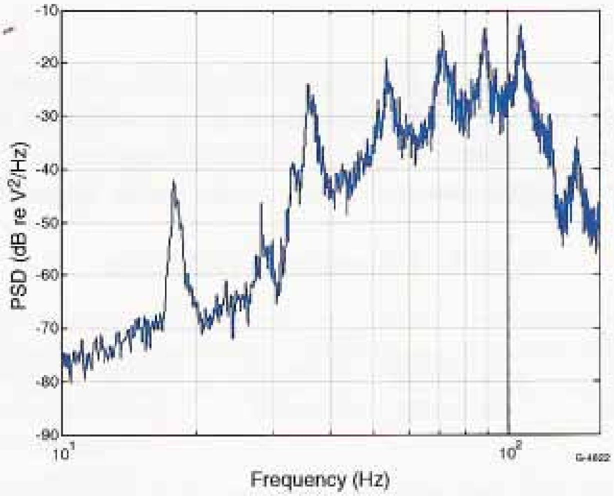


Figure 15. Spectral signature of the jackhammer.

We propose to use a jackhammer in addition to the backhoe to perform the proposed measurements. We will use the jackhammer to compare on-frequency and off-frequency directional dependence. The backhoe data provides a more generalized threat signature.

Source Operation

In order to ensure the best data, we recommend that other seismic sources in vicinity (within 300 m) be inactive. Obviously, normal road traffic and similar activities cannot be eliminated. However, to as great extent as possible, we recommend that only one source be operating at a time.

Measurement Matrix

Table 4 summarizes the measurement matrix. The times are exclusive of set-up time, and are only approximate. We will of course work with the field crew and management to coordinate the measurements, and to ensure that the measurements cause minimal disruption at the worksite.

Table 4. Proposed Measurement Matrix

Measurement	S1 Location	S2 Location	Source	Duration
1	S1 fixed	S2-P1	Jackhammer	30 min
2		S2-P1	Backhoe	30 min
3		S2-P2	Jackhammer	30 min
4		S2-P2	Backhoe	30 min
5		S2-P3	Jackhammer	30 min
6		S2-P3	Backhoe	30 min
7		S2-P4	Jackhammer	30 min
8		S2-P4	Backhoe	30 min
9		S2-P5	Jackhammer	30 min
10		S2-P5	Backhoe	30 min

Results

PSI conducted three field tests to investigate triangulation by bearing (see Table 5). **Taken together, the results are conclusive that there is not sufficient bearing information contained within the geophone data to enable reliable triangulation. We therefore recommend the time-lag triangulation technique as the better approach.**

Table 5. Triangulation Field Tests

Test	Location	Date	Equipment
FT4	Pelham, NH	22 Dec 03 – 23 Dec 03	Electric pavement breaker
FT5	Westtown, NY	14 Jan 04 – 16 Jan 04	Jackhammer Compressor Backhoe
FT6	PSI	1 Mar 04 – 3 Mar 04	Sledgehammer Electric pavement breaker Generator

Please note that the Field Test in Westtown, NY was arranged and partially funded by NGA.

Sensors were buried approximately 18 to 24 in. below the surface. The holes are backfilled and compacted by hand. Relative position of the sensors and threats were determined using a laser rangefinder (accuracy = ±1 m) and a sighting compass (accuracy ±3 deg). Geophone axes are aligned along magnetic cardinal directions using the compass. Range and magnetic bearing between all sensor and threat locations are measured and recorded.

FT4 Results

FT4 showed positive initial results for determining bearing from the geophone data. Figure 16 shows the experimental configuration for FT4. The distance from the sensor to the threat is 27 m (11 m along the H2 axis and 24.5 m along the H1 axis). The angle with respect to H1 is 24 deg.

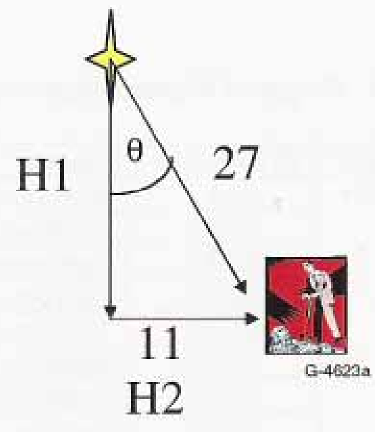


Figure 16. Experimental configuration for FT4.

Figure 17 shows data acquired during FT3. The black curve (top) is vertical. The red curve is H1. The blue curve is H2, and the green curve (bottom) is the PIGPEN sensor. The jackhammer signature is clearly visible at 28 Hz and 42 Hz. A simple analysis of these data using the 28 Hz and 42 Hz magnitudes yield angles of 21 deg and 22 deg. These are in good agreement with the measured angle of 24 deg.

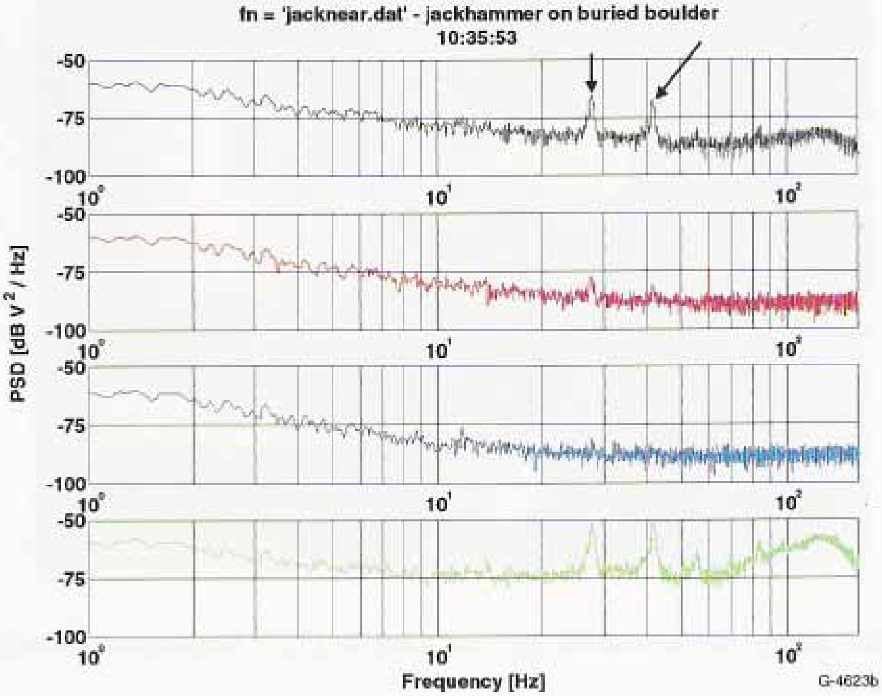


Figure 17. Measured PSDs from FT4. The black curve (top) is vertical. The red curve is H1. The blue curve is H2, and the green curve (bottom) is the PIGPEN sensor.

FT5 Results

Northeast Gas and one of its member organizations (ConEdison) was able to arrange a quiet site in Westtown, NY and to supply a contractor with backhoe, compressor and jackhammer to help with the field testing. NGA also partially funded PSI's costs to participate in this field test.

The site was located in a rural area along a pipeline right of way. The site was approximately 300 yards from a rural county road with minimal traffic. No industry or significant activity was occurring near this site.

Figure 18 shows an aerial photograph of the site with the source and sensor positions overlaid. Table 6 lists the sensor positions. Figure 19 shows the equipment and site during the testing. Since the air temperature hovered around 0 F for the entire test with wind chills nearing -30 F, we deployed the test electronics in portable shelters equipped with catalytic heaters. The interior temperatures in the shelters were maintained around 40-50 F. The ground was frozen to about 8 in. The sensors were buried below the frost line at about 18 in. depth. The holes were backfilled and insulated with hay to prevent freezing. The soil below the frost line was damp and clay-like. The source was located on the shore of a small pond.

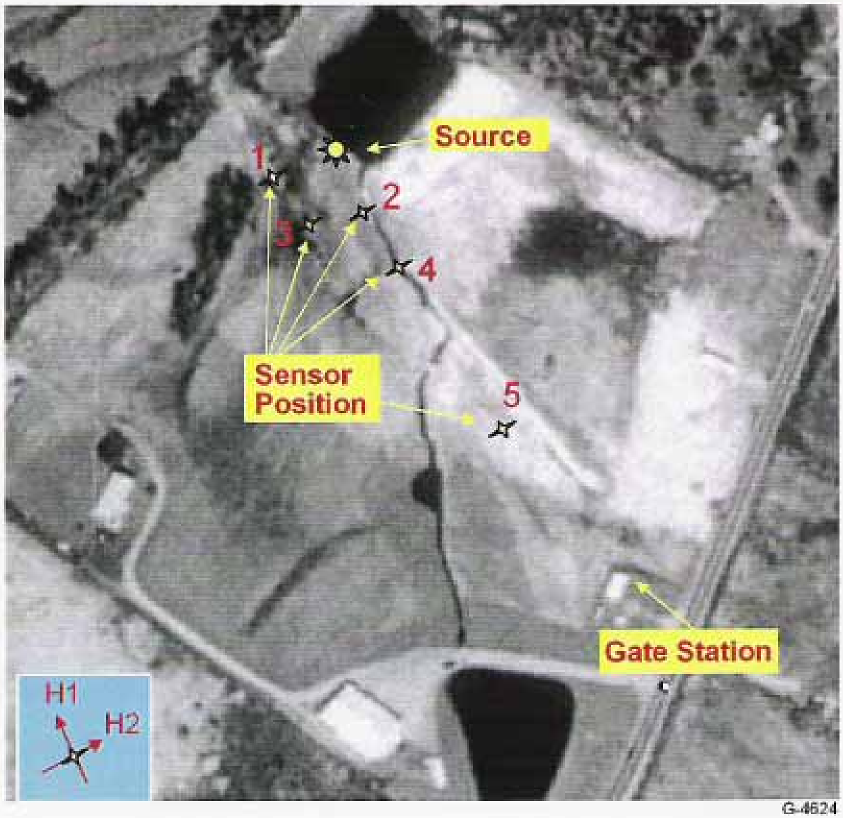


Figure 18. Aerial view of the Westtown, NY site used for FT5. Sensor and source positions are overlaid.

Table 6. Sensor Locations for FT5

Sensor	Range	Bearing to Threat (Relative To H2)
Position 1	30 yd	0 deg
Position 2	30 yd	90 deg
Position 3	30 yd	45 deg
Position 4	60 yd	90 deg
Position 5	150 yd	90 deg

Figure 19. Photographs of test site and equipment for FT5.

The results from FT5 seemed to indicate that the geophone data did not contain any directional information. Figure 20 shows the geophone PSDs from position 3 (45 deg wrt H1 and H2). As before, the black curve (top) is vertical, the red curve (middle) is H1 and the blue curve (bottom) is H2. The jackhammer signature is clearly evident at 22 Hz. The grey curves represent the background. We would expect the magnitudes of H2 and H2 to be approximately equal. In this case the magnitude of H1 is -85 dB re V^2/Hz and magnitude of H2 is -90 dB, differing by a factor of 1.8 x.

As a comparison, Figure 21 shows the geophone data from position 2 (90 deg wrt H2, 0 deg wrt H1). Again, the jackhammer signature is clearly visible, somewhat shifted in frequency. (The jackhammer frequency likely changes with load.) We would expect that the H1 magnitude would be large and the H2 magnitude would be nearly zero. However, we find that the H1 and H2 magnitudes are nearly identical. After analyzing these data, we decided to conduct an even simpler and more controlled field test.

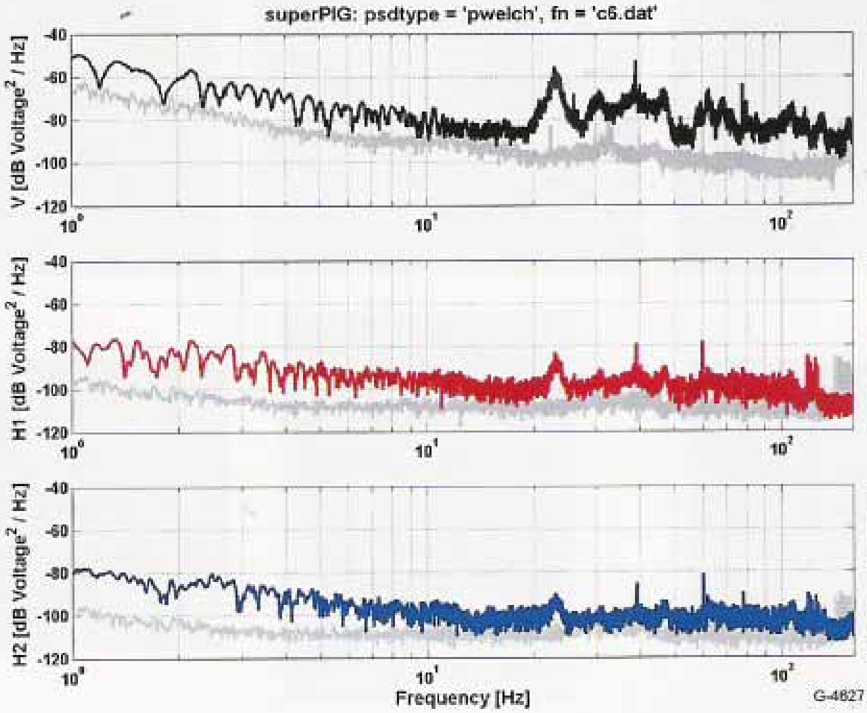


Figure 20. FT5 geophone data from position 3. The black curve (top) is vertical, the red curve (middle) is H1 and the blue curve (bottom) is H2.

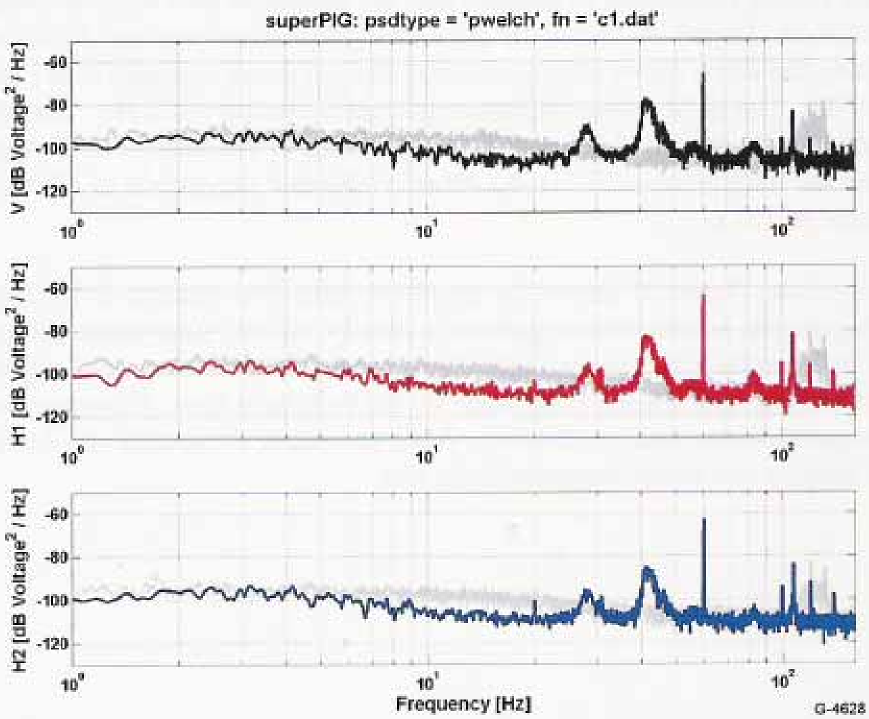


Figure 21. FT5 geophone data from position 2. The black curve (top) is vertical, the red curve (middle) is H1 and the blue curve (bottom) is H2.

FT6 Results

After achieving the unexpected results from the analysis of FT5 data, PSI conducted another field test to investigate triangulation by bearing. FT6 was conducted in an empty building lot across the street from PSI's Andover location (see Figure 22). The test site is located in a relatively quiet office park situated near the Merrimack River. The nearest source of backgrounds is an interstate highway located 400 m away.

Figure 22. Photographs of FT6 test site.

We conducted a series of very simple experiments using a sledgehammer and an electric pavement breaker as sources. In the first experiment (FT6-1) , we used the sledgehammer as a source located 20 m from the sensor along the four cardinal directions (N, S, E, W magnetic bearing). H1 is aligned along magnetic north. H2 is aligned along magnetic east (see Figure 23).

Figure 24 shows the time series data from experiment FT6-1. The hammer strikes are the clearly visible fours sets of six spikes. The first group is east, then south, west, and north. These data show a clear directional trend. For the east and west strikes, H2>H1. For the north and south strikes, H1>H2. However, there appears to be significant coupling between H1 and H2.

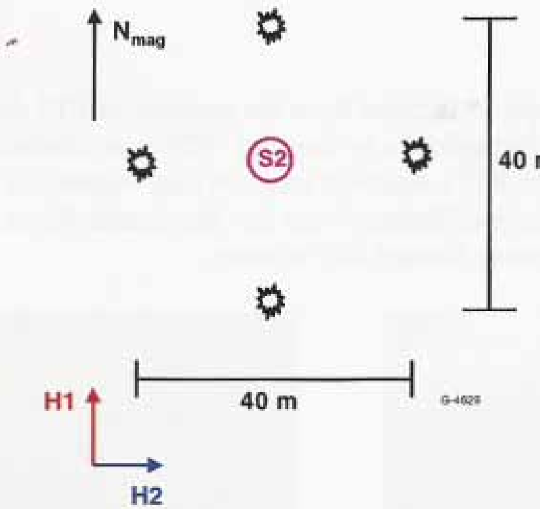


Figure 23. Configuration of experiment FT6-1.

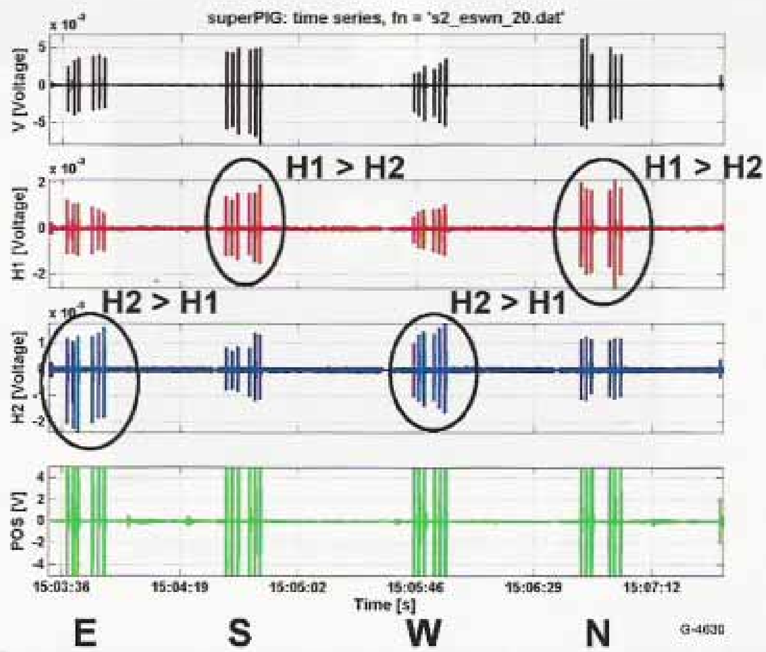


Figure 24. Results of experiment FT6-1.

Figure 25 shows a blow up of the signals from one of the hammer strikes. The signal-to-noise ratio is high in all channels. The data is not being undersampled. The S- and P-wave arrivals are clearly visible in the data. Overall the data itself appears to be of high quality.

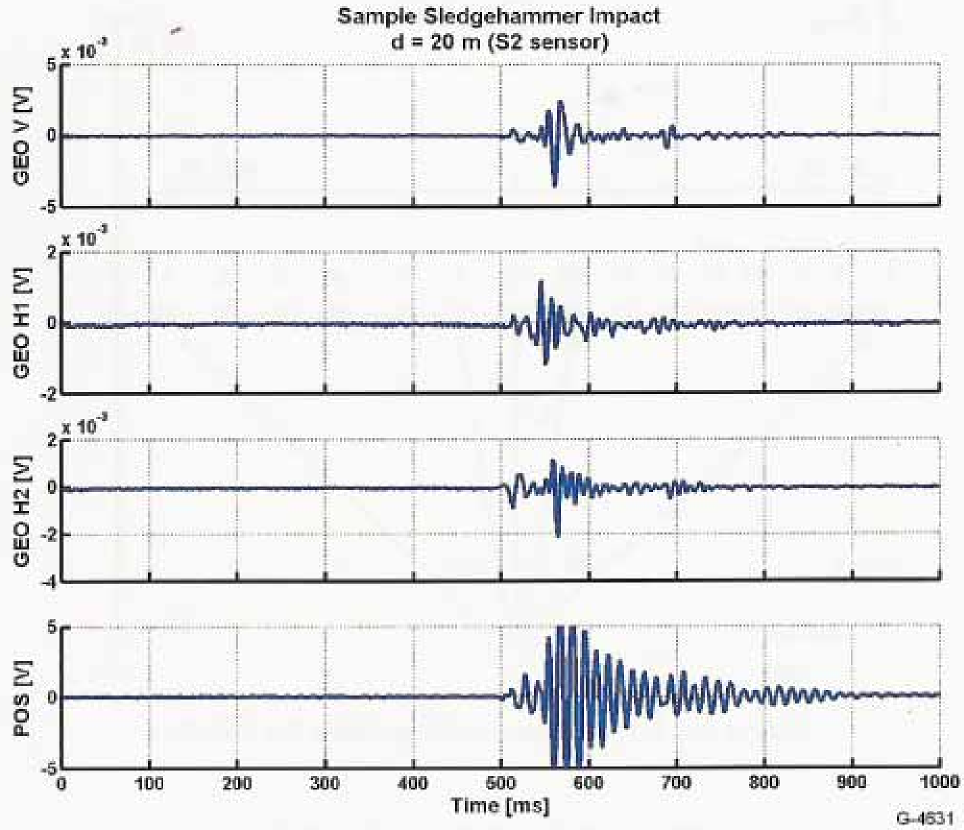


Figure 25. Geophone and PIGPEN sensor response from a single sledgehammer strike.

To acquire additional angles, we conducted a second experiment (FT6-2). In this experiment (see Figure 26 we used the sledgehammer at several points along a line between two sensors. The range between the sensors is 58 m.

Figure 27 shows the results from FT6-2. We have plotted the ratio of H1/H2. We would expect that H1/H2 would be zero at 90 deg and blow up at 0 deg. We would also expect that H1/H2 would vary smoothly from 0 to 90 deg. It is true that H1/H2 at 0 is greater than at 90 deg, but the ratio is 0.6 and 1.6 at those limits. In addition, the H1/H2 ratio does not change monotonically with angle, as expected.

We also conducted a more thorough study of angular dependence using the electric pavement breaker (experiment FT6-3). We moved the source location in a 120 deg arc at a fixed distance of 50 m from the sensor (see Figure 28). This experiment was intended to map out the angular dependence of the H1 and H2 components of the geophone.

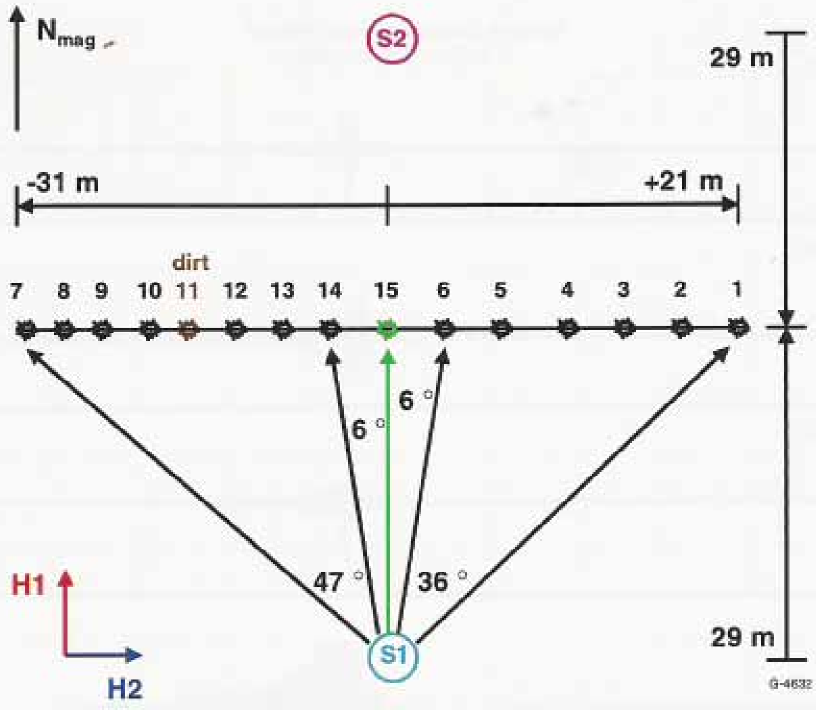


Figure 26. Experimental configuration for FT6-2.

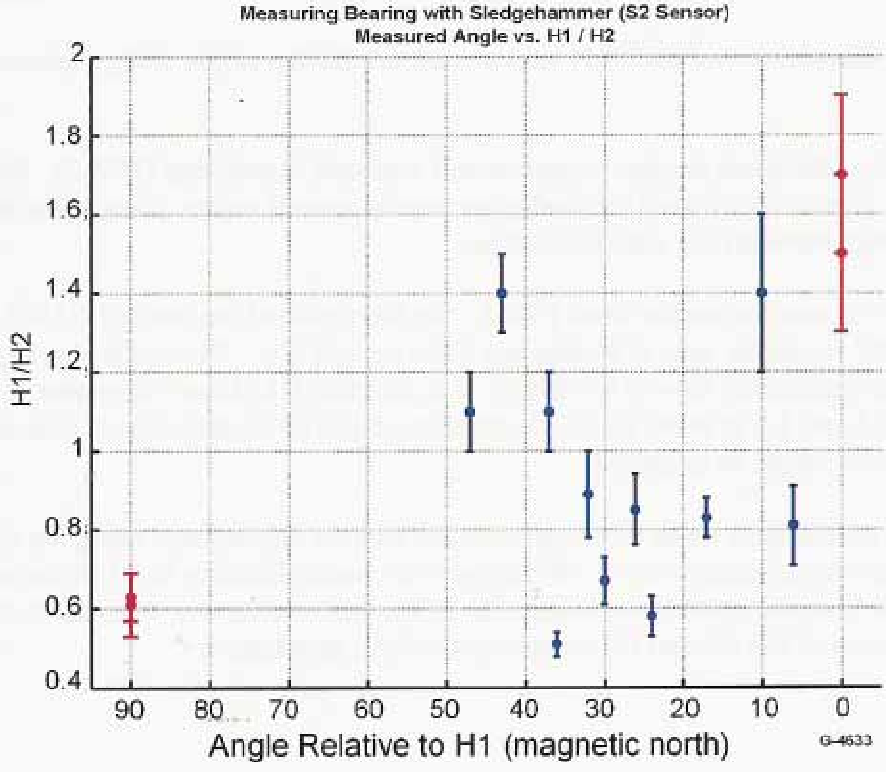


Figure 27. Ratio of H1/H2 signal magnitude for the FT6-2 field test measurements.

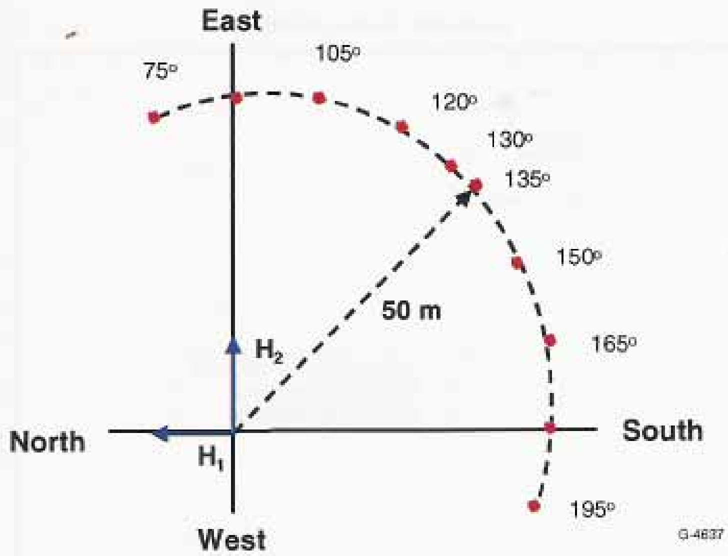


Figure 28. Experimental configuration of FT6-3. The source was moved in a 120 deg arc at a fixed distance of 50 m.

Figure 29 shows the PSDs from geophone channels and PIGPEN sensor. The signatures of the pavement breaker are at a high signal-to-noise ratio and are distinct. We examined the in-band power for the 24-25.5 Hz, 33-39 Hz, and 46-52 Hz bands. Figures 30 through 32 show those results. **The results show no clear angular dependence.**

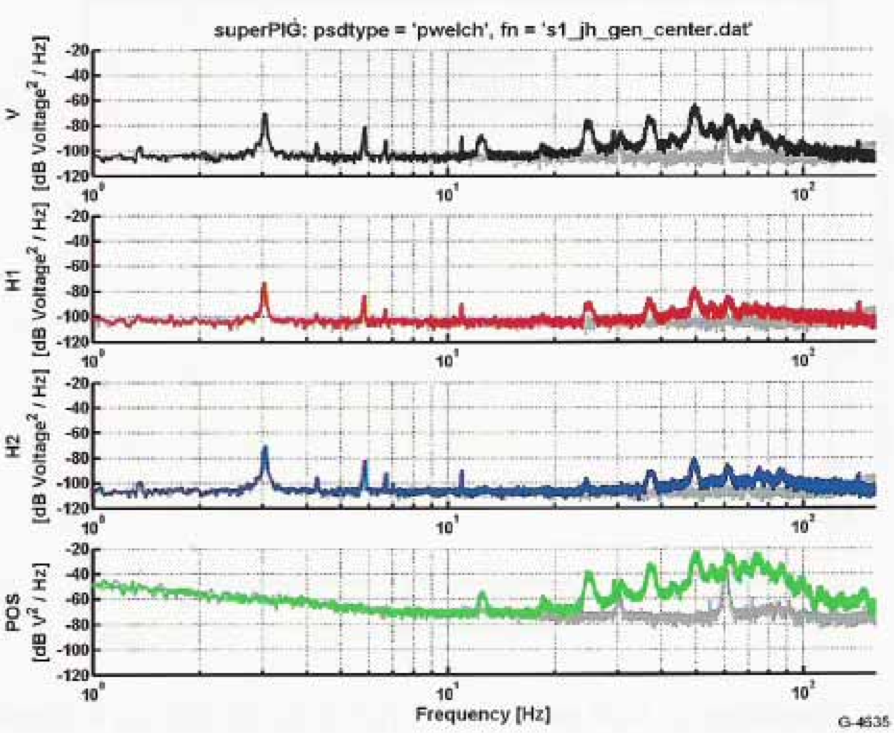


Figure 29. PSDs of geophone and PIGPEN sensor data from FT6-3.

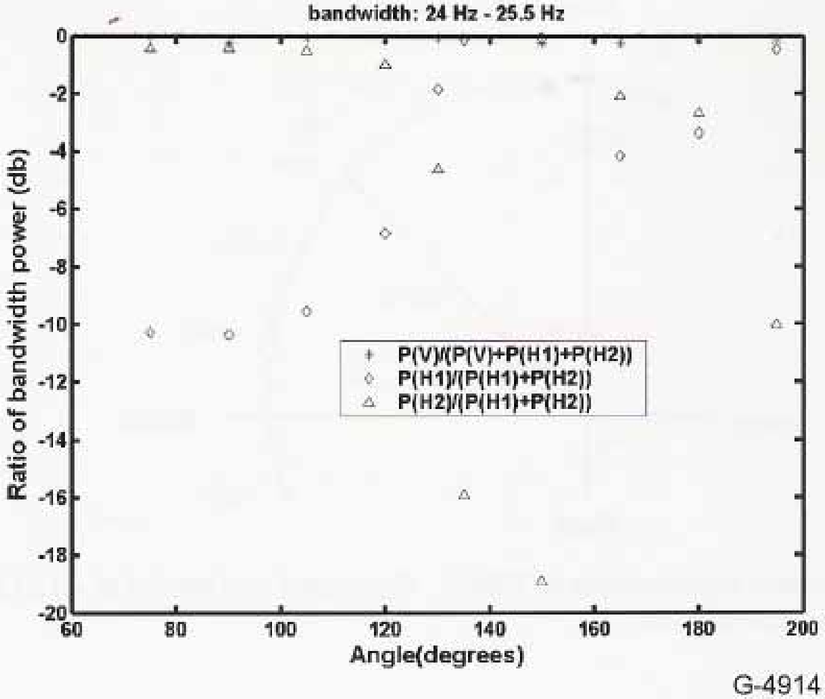


Figure 30. Normalized in-band power (24-25.5 Hz) of the H1, H2 and V channels.

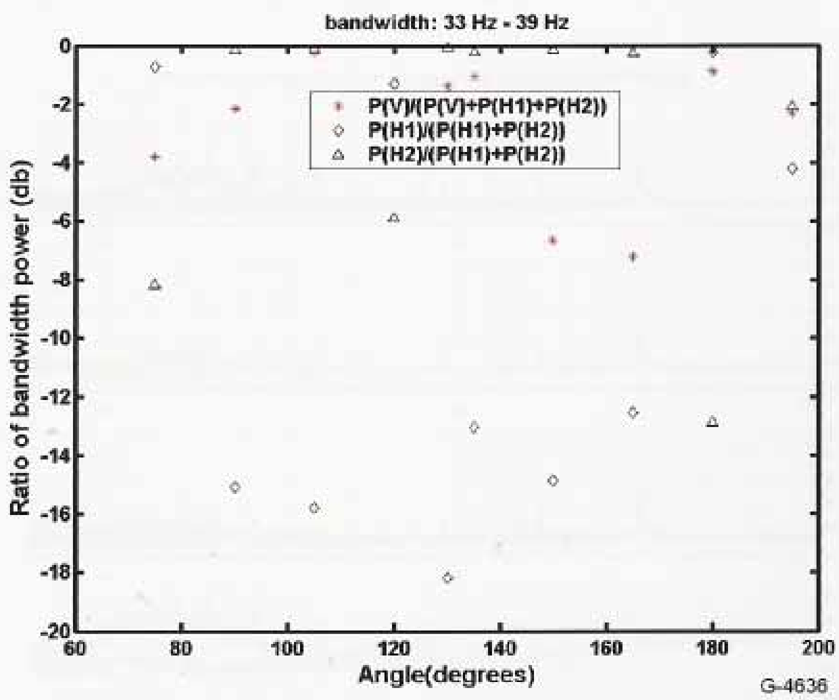


Figure 31. Normalized in-band power (33-39 Hz) of the H1, H2 and V channels.

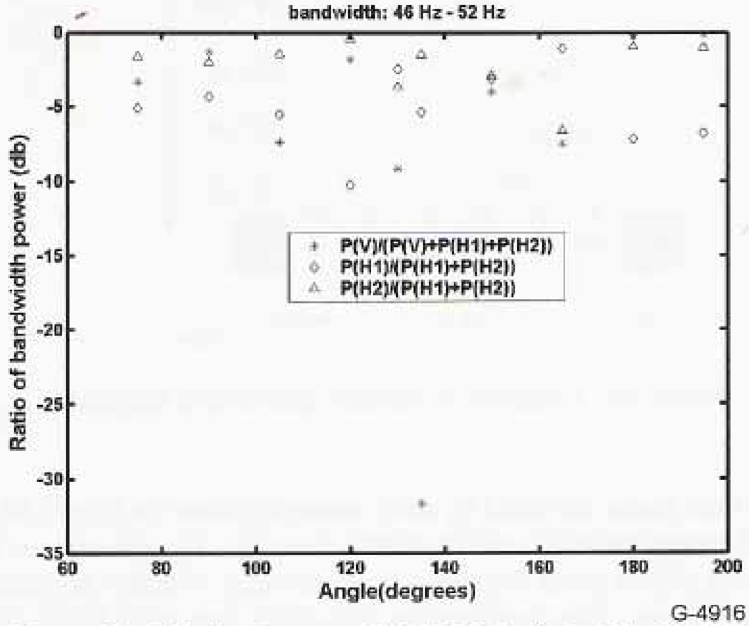


Figure 32. Normalized in-band power (46-52 Hz) of the H1, H2 and V channels

We surmise that the non-intuitive results in the directional data are caused by reflections from large and small objects in the soil. Boulders and large rocks have a different seismic impedance than the bulk fill. As a result, seismic energy can be reflected off of these surfaces. Reflection centers near the sensor will tend to reorient the seismic energy to the point that directional information is difficult to extract from the data.

3.3.4 Time Lag Field Test at PSI

We investigated the time lag triangulation method using PSI's Proactive Infrasonic Gas Pipeline Evaluation Network (PIGPEN). Two sensors were placed in the ground at a depth of approximately 1 ft and each sensor was connected to an EPAC amplifier with a gain of 60 dB. The output of the amplifier was connected to a data acquisition system. A fast relay (Teledyne Relays # 722) was used to generate a trigger signal for each data file such that the data files from each computer could be synchronized to within 0.001s in post processing.

The computer clocks were synchronized to with a second and the acquisition programs for each sensor were started simultaneously. However, during the writing process time is lost between files. In order to synchronize the times between computers a trigger switch was used. Each time a file updated, the relay was switched on and off. Directly after the trigger signal was sent, the source was initiated. The source consisted of a sledgehammer impacting asphalt 3 to 6 times. This was repeated twice for each source position. The sensors were located 60 meters from each other. A sign convention was chosen such that the difference in distances from the source to each sensor is positive when the source was closer to S1. The difference in distances is simply $\Delta D = D(S2,source) - D(S1,Source)$. The time lag is given by the difference in arrival times: $\delta t = T_{S1} - T_{S2}$. Figure 33 shows the position of the sensors as well as the various source locations.

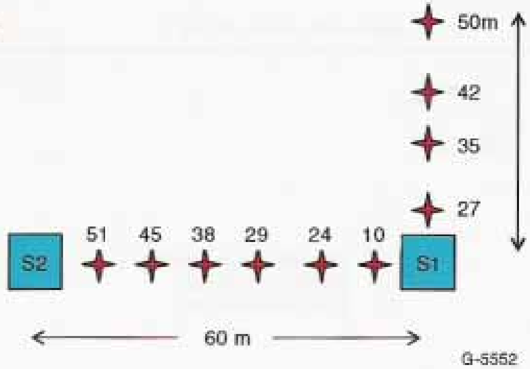


Figure 33. Location of Sensors and Source impacts.

An example of the traces recorded by each sensor is shown in Figure 34. In this case the source was located 42 meters from S2 and 18 meters from S1. The time traces have been corrected for any timing offsets using the signal from the relay which is not shown. The time lag is clearly evident in the figure. The signal arrives first at S1 then at S2 0.017 s later.

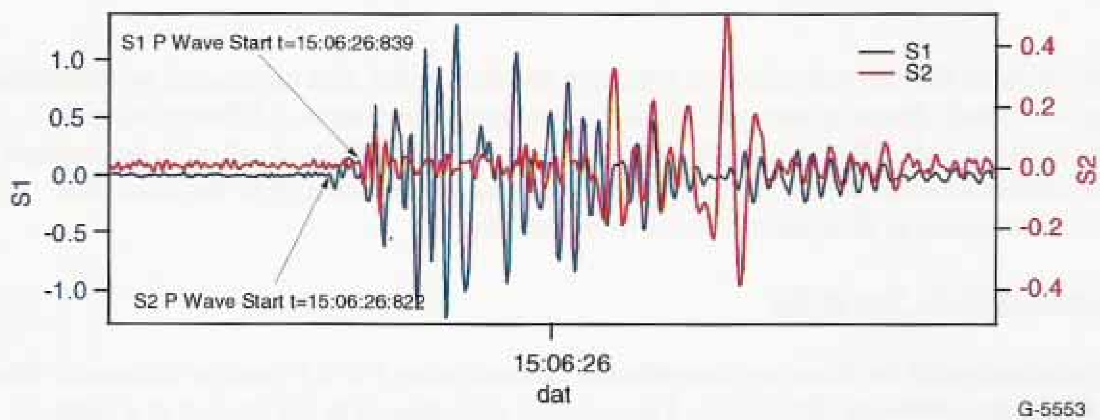


Figure 34. Distance S1-Source =18 m, Distance S2-Source = 42 m; ΔD= 24 m; Time Lag = 0.017 s.

The arrival times of the p- waves were determined for the locations specified in Figure 1. Unfortunately a few of the arrival times could not be determined. In some cases the signal to noise was too low. Additionally, over the course of the test the computers became asynchronous and some of the data from the relay was not usable. Figure 35 shows the time lag recorded at each position plotted versus the difference in distances between the source and each sensor. The velocity is determined from a linear fit to the data. The velocity of the p-wave is 1.5 ± 1 km/s. This is comparable with seismic velocities in other materials. For example, sandstone exhibits velocities on the order of 1.4-4.3 km/s and concrete 3.6 km/s whereas seismic velocities in sand range from 0.2-2.2 km/s depending on saturation.* We obtained a position accuracy of 7 m.

* http://www.mines.edu/fs_home/tboyd/GP311/MODULES/SEIS/NOTES/rvel.html.

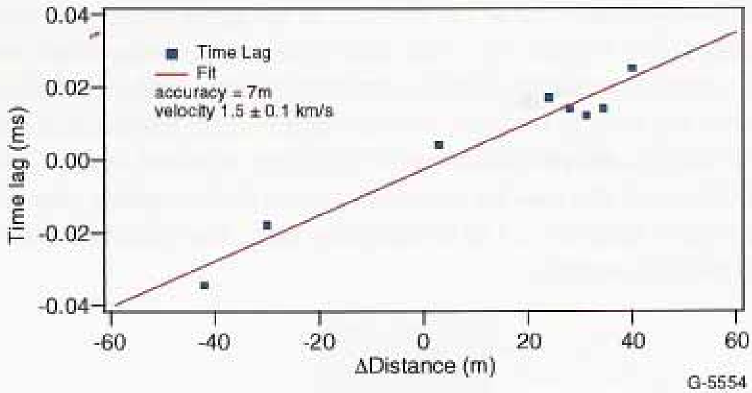


Figure 35. Change in Distance versus Time lag. Velocity 1.5 ± 0.1 km/s. Position Accuracy = 7 m.

3.4 Task 4. Create conceptual design and preliminary specifications for PIGPEN system

Our goals are: weight of 2 lbs, dimensions of 4 x 4 x 4 in.[3], and a commercial cost of <$1000.3.5

Overview

Figure 36 shows a preliminary block diagram for the PIGPEN system. An individual PIGPEN unit head comprises the sensor itself, an amplifier, an imbedded controller, some data-logging capability (memory), a warning circuit and an interface to a SCADA system (supervisory control and data acquisition).

The embedded controller is a simple processor commonly used in the automotive industry. It includes data acquisition capability and a signal processor. The signal processor would identify a received signal as a threat (or non-threat) and react appropriately. If the signal was identified as a threat, the PIGPEN unit would alert the system, via the SCADA network, to the presence of the threat and its identity. The processor would then provide relevant triangulation information to the system. In the case of a time-lag triangulation system, the PIGPEN unit would provide the time of the threat. In the case of the directional-based triangulation system, the PIGPEN unit would provide the bearing to the threat. The preliminary parameters are weight <2 lb, dimensions < 4×4×4 in.[3] and price < $300.

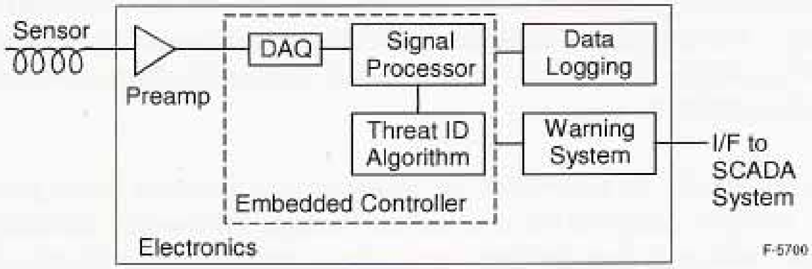


Figure 36. Preliminary block diagram for a PIGPEN unit.

The data acquisition system used in the Phase 1 is set up to mimic the data acquisition of the ultimate sensor concept (See Figure 37). The sensor outputs are amplified and buffered before being input into a data acquisition (DAQ) card that resides in the backplane of a laptop computer. A GUI enables the user to controls the data acquisition parameters and displays raw and processed data. The DAQ card precision can be changes adjusted from 12-bit to 16-bit. The dynamic range of the DAQ card can also be adjusted, as can the sampling rate. After some limited optimization, we have selected a 1 kHz sampling rate. Our nominal data set is a 1 min acquisition, resulting in 60,000 samples.

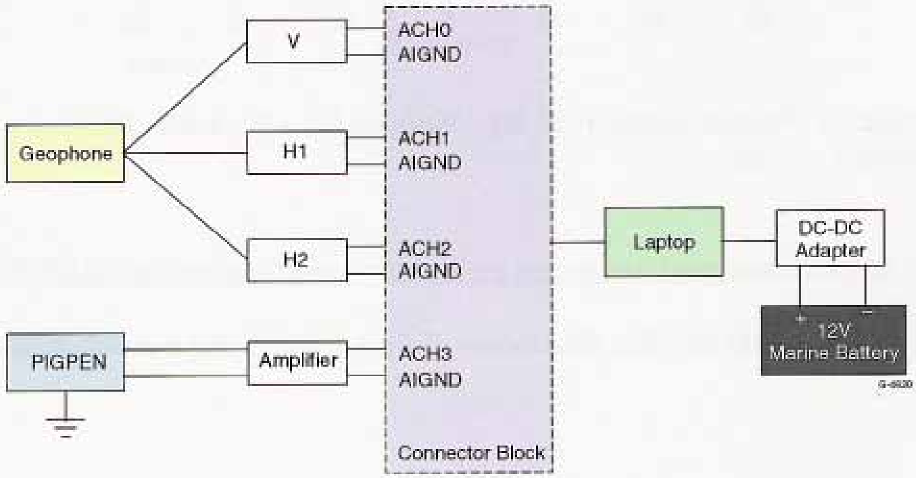


Figure 37. Data acquisition system used for Phase 1 measurements.

Based on input from NGA, a 1 min acquisition time is acceptable from a systems point of view. Five to fifteen minutes is a reasonable amount of time for the system to react to a potential threat. Even allowing for a sensor to declare an observation a potential threat only after observing it three times, the system response time would be well under 5 min. In a real system, the sampling time would be adjusted to acquire a 2^N number of samples in a minute (e.g. 65,536 samples acquired in 1 min at a rate of 1.092 kHz, or 65,536 samples acquired at a rate of 1 kHz in a period of 65.636 seconds). These details will be decided when the specifications for the imbedded processor are developed.

Mechanical Configuration

In designing the next generation of the PIGPEN instrument, we evaluated the Phase 1 design shortcomings. We also considered the environment and handling circumstances the final instrument will need to survive in order to be successful. Figure 38 shows the concept drawing for the next-generation PIGPEN sensor.

Orientation is critical. To assure that the instrument in installed in the ground in the correct orientation, we have designed the box that encourages the correct orientation naturally. By having the output cable exit from the top center, the instrument will naturally be installed with this cable pointed up. This also limits the side loading on the cable by dirt and gravel as the instrument is buried. The cable will be strain relieved, so that it can withstand the inevitable, although discouraged, case of being lowered into the ground by the cord.

The Phase 1 sensor proved to be susceptible to 60 Hz noise from AC power. In order to minimize this disturbance, we have located the sensor pre-amplifier as close to the sensor as possible. Minimizing the cable length between the sensor and the preamp with reduce its effectiveness as an antenna to pick up radiated EMI from overhead lines and nearby buildings. In addition, the cabling will be constructed to further reduce this susceptibility by twisting the wires. e enclosure will be a water tight box with integrated environmental seals.

Mechanically the sensor is most susceptible to side loading during handling, such a being dropped or banged. The sensor is bonded to the enclosure and to the mass. This adhesive selection is critical in that it needs to provide enough strength to hold the components during a shear load, but not damped out the vibrations we are trying to measure. For the next-generation sensor design, we have added a central pin with precision bearing that minimizes the side loading on the adhesive and the sensor, but still allows minimally restricted vertical motion. (see Figure 39) The shear strength of the sensor was compared to the reduced load induced by the restricted motion. This load is well under the shear strength of the sensor. The adhesive recommended by the sensor manufacturer has different mix ratios to achieve different properties. During future phases we will evaluate a range of formulas to optimize the strength of the adhesive verses sensor response.

The estimated mass of the PIGPEN sensor, including electronics, is 2.2 lbs.

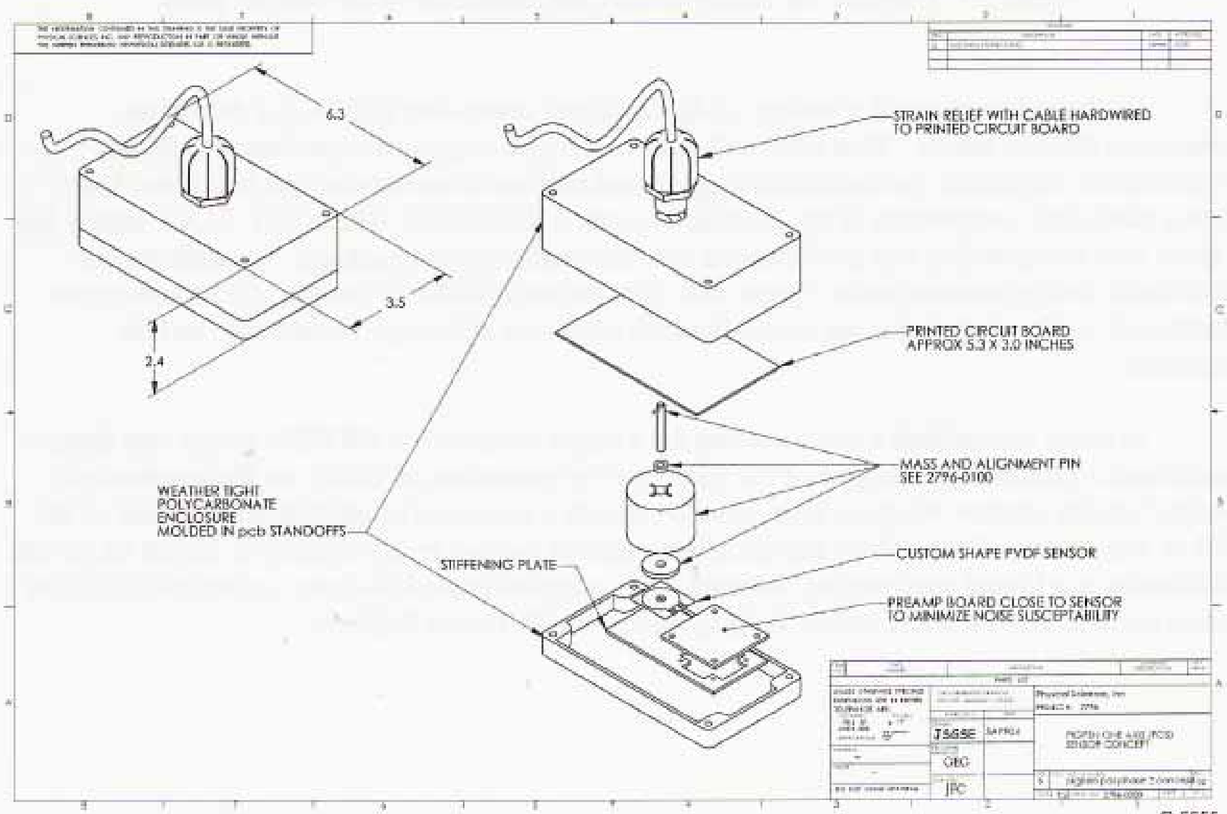


Figure 38. Concept drawing for the next-generation PIGPEN sensor.

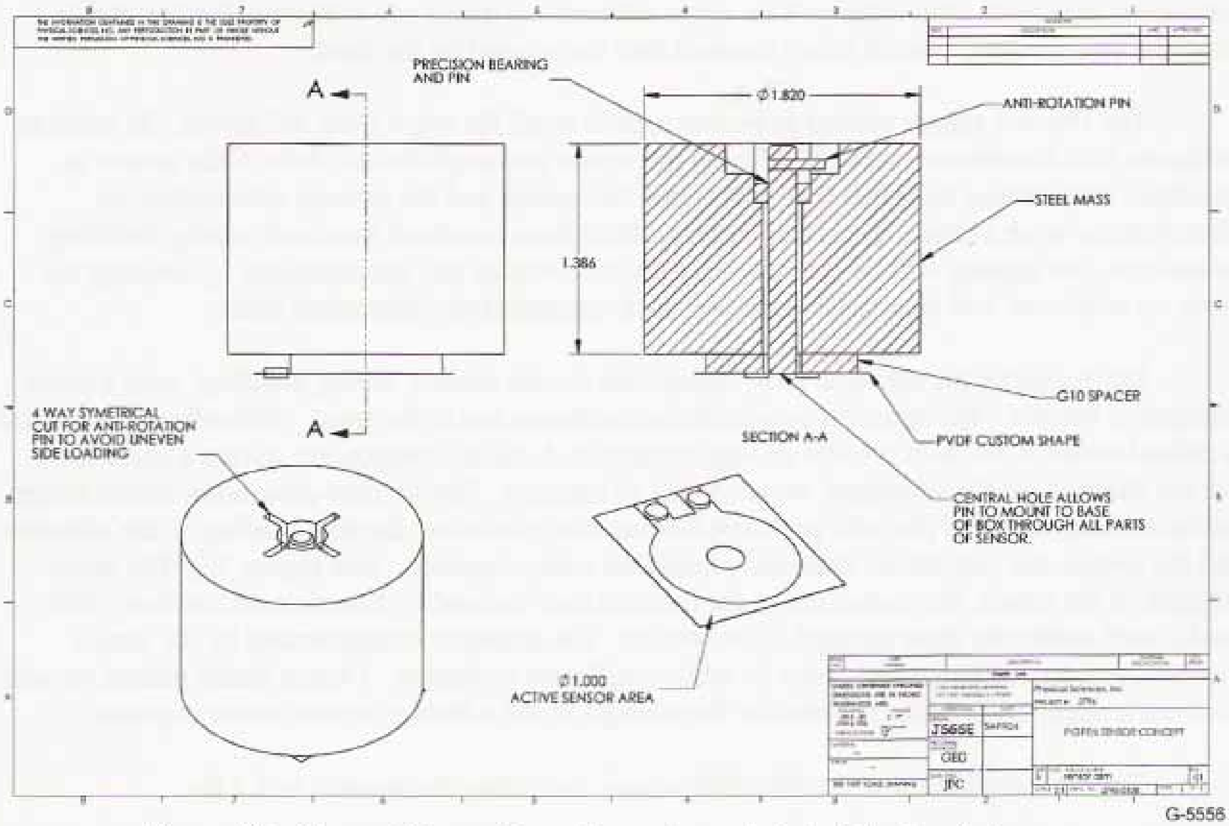


Figure 39. Concept for configuration and constraint of the inertial mass.

We have investigated a variety of digital signal processors (DSPs) for the future-generation PIGEN sensor. That DSP will control the data acquisition, perform the threat identification algorithm, perform data-logging and perform communications functions. One strong candidate components is the Analog Devices ADSP-218X. The ADSP-21XX family has a great deal of capability and performance in a reasonably-priced package. In addition, our electronics design partners have a great deal of experience with this device. It can accept one channel of buffered analog input and will acquire the data at the appropriate rate and bit resolution.

In order to establish a cost baseline for a future commercial PIGPEN sensor, we have performed a preliminary analysis of the parts cost for quantities of 1000. As the mechanical design is fairly mature, we have been able to provide a reasonably high fidelity estimate of the Bill of Materials (BOM). Since the electronics design has not really begun yet, the BOM for the electronics is a liberal engineering estimate. The estimated materials costs (quantity=1000) for a future commercial PIGPEN unit is slightly more than $100 (see Table 7).

Table 7. Estimated BOM for Commercial PIGPEN Sensor in Quantities of 1000

Part	Material Cost (Qty=1000 units)
Mass	$5.00
Bushing	4.50
Pin, Ultra Precision	2.50
Machining of Above	1.00
Spacer	1.00
Mounting Base	2.00
Custom Ring Sensor	5.50
Box	9.55
Strain Relief	3.85
Nut	0.27
Electronics	75.00
TOTAL BOM	**$110.17**

Obviously, the BOM cost does not include assembly, testing, marketing, etc. However, given a BOM of $100, one could probably expect to sell commercial PIGPEN sensors for <$500. As product acceptance increases, production volumes would also increase, and costs would decrease accordingly.

3.5 Task 5. Develop a threat identification algorithm

Data Processing Investigation

The first step in the data processing is the calculation of the power spectral density (PSD). We have systematically investigated the different methods of estimating PSDs and different windowing functions to achieve the best balance of speed and SNR for the PIGPEN application.

Figures 40 through 42 show the effect of varying the FFT window length when calculating the PSD. These calculations were performed on a 184 second data segment using MATLAB on a desktop computer. Table 8 summarizes the results.

Table 8. Summary of Results from PSD Window Length Investigation

Figure	Npoints	Window Length	Resolution	Computing Time (Relative)	SNR
Fig.40	184,000	184 sec	0.005 Hz	10 s	High freq. 'noise' masks signatures
Fig. 41	10240	10.24 sec	0.098 Hz	1 s	Acceptable
Fig. 42	3072	3.072 sec	0.326 Hz	<1 s	Features washed out

The smallest window length obviously has the fastest computing time; however, the spectral signature features are "washed out" because of the degraded resolution. The largest window length has the slowed computing time; however the spectral features are considerably wider than the resolution function. The largest window length also enables the user to discern lower frequency features; however, as practical matter, frequencies less than 0.1 Hz are not as useful for this application because of the long acquisition times. **The best compromise is the intermediate window length of 10.24 sec. This window length provides some averaging of the high frequency fluctuations in the PSD without degrading the SNR of the spectral features. The minimum resolution also allows detection of low frequency features down to 0.1 Hz.**

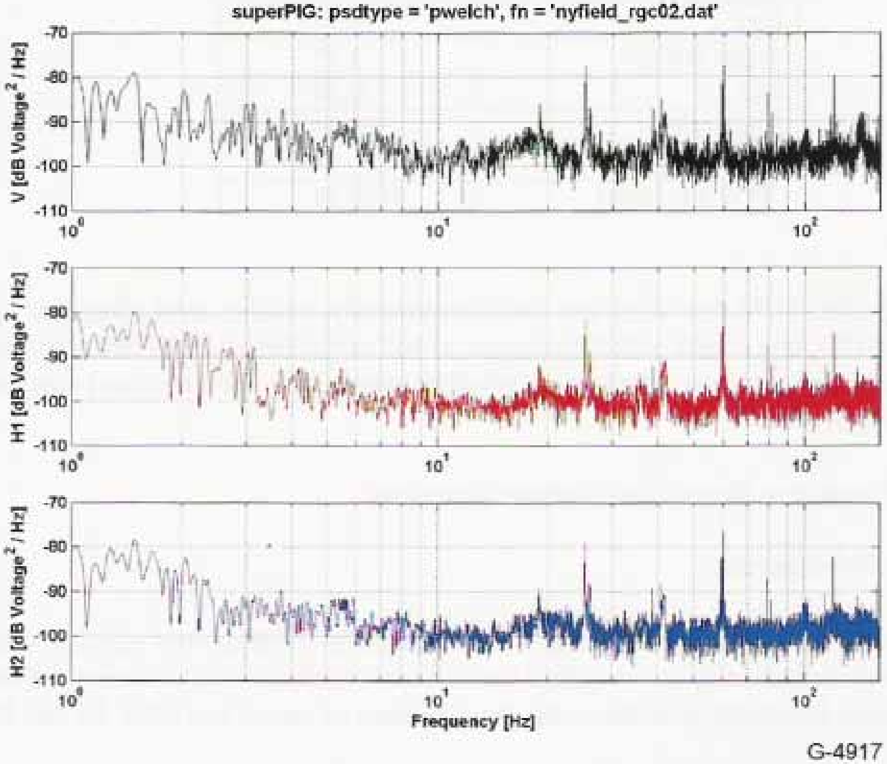


Figure 40. PSD of 184 second data segment using a 184 second wide window function.

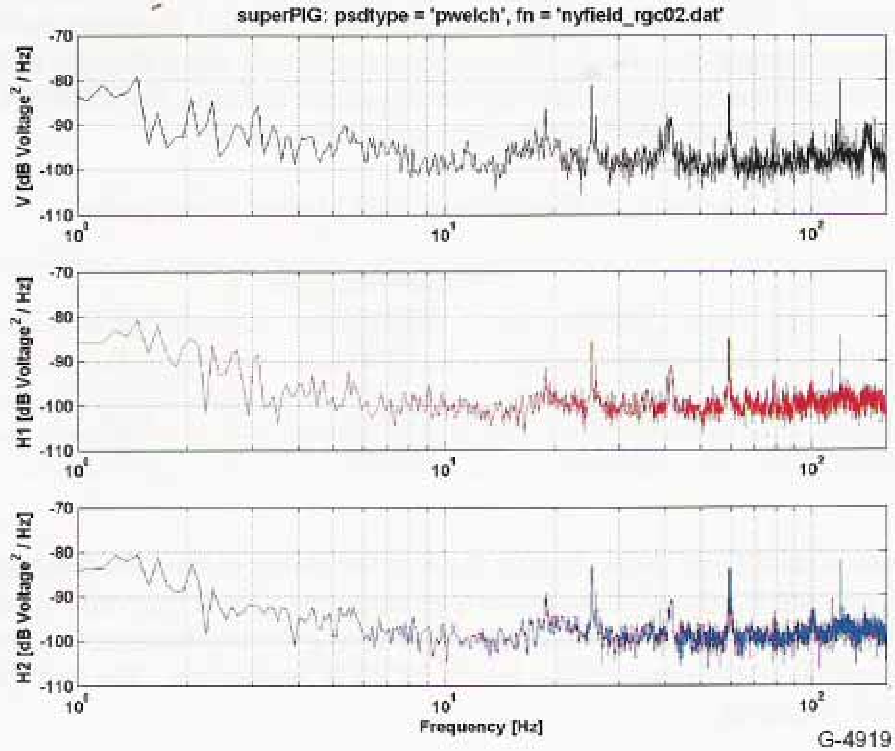


Figure 41. PSD of 184 second data segment using a 10.24 second wide window function.

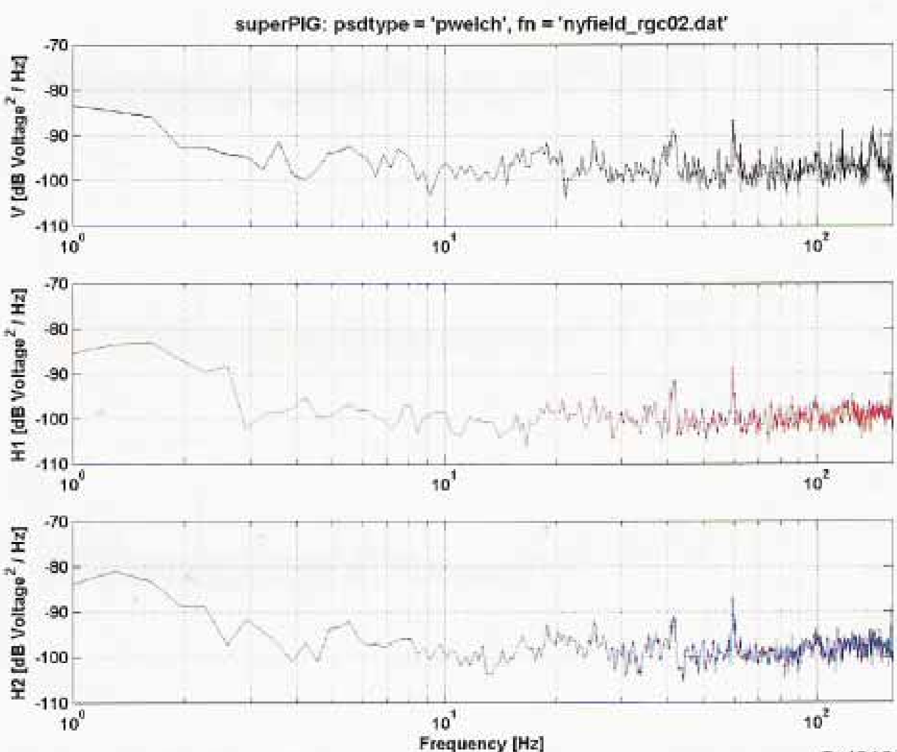


Figure 42. PSD of 184 second data segment using a 3.072 second wide window function.

We also investigated different methods for calculating the PSD. Our standard method is called Welch's method. We also investigated used periodograms, and Thomson multitaper method with different parameter settings. These different methods allow the user to tune the PSD and provide the optimum balance between resolution and leakage. For PIGPEN, there are also computing time considerations. Table 9 summarizes the results.

Table 9. Summary of Results from PSD Method Investigation

	Figure	**Computing Time (Relative)**	**Resolution**	**SNR**
Welch's method	Fig. 43	10 sec	OK	OK
Periodogram	Fig. 44	2 sec	Maximum	Poor
Thomson multitaper nw=1.5	Fig. 45	112 sec	High	Fair
Thomson multitaper nw=4.0	Fig. 46	222 sec	OK	OK

The Thomson multitaper methods offer the user the ability to tune the resolution and leakage using an adjustable parameter; however the computing time is unacceptably long. The periodogram is faster than Welch's method. While providing the maximum resolution, the periodogram also yields a very noisy PSD – for the PIGPEN application. The best results are provided by Welch's method.

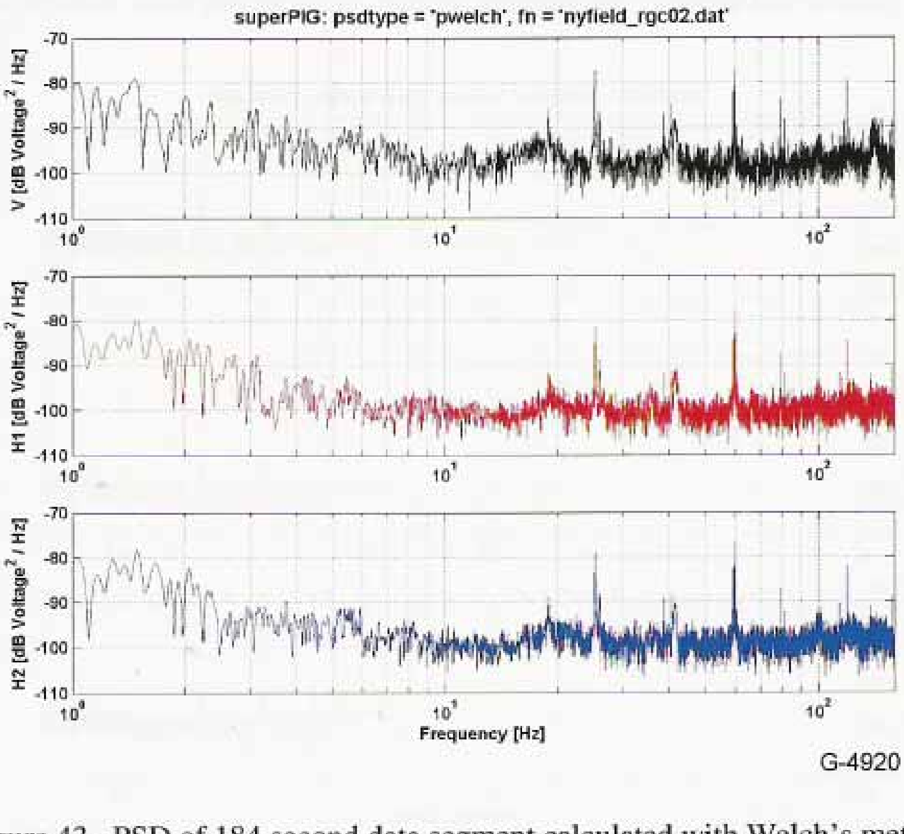
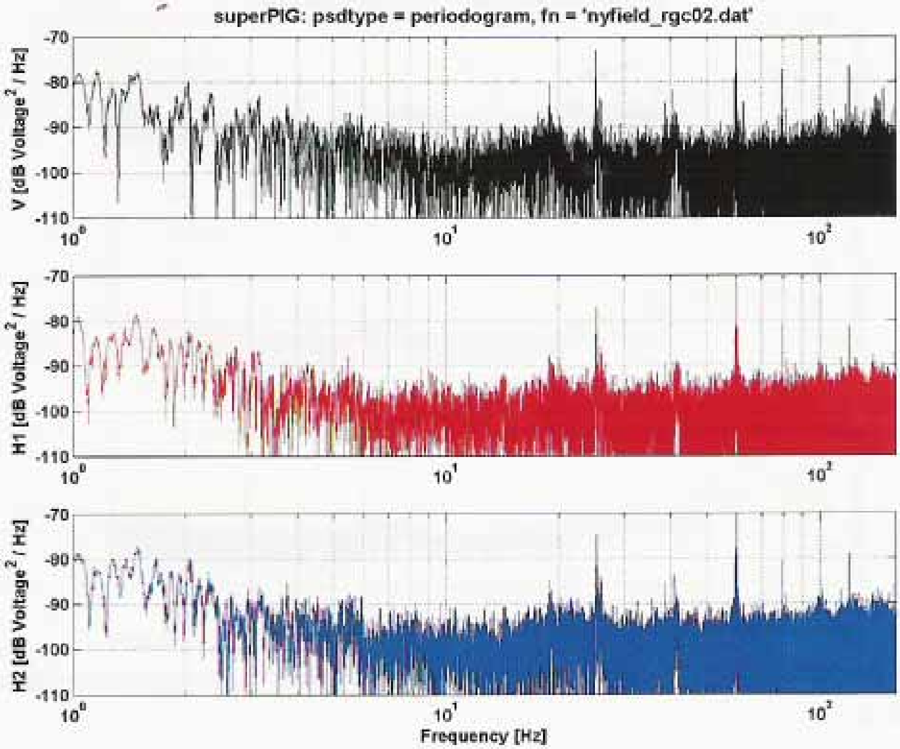


Figure 43. PSD of 184 second data segment calculated with Welch's method.



G-4921

Figure 44. PSD of 184 second data segment calculated using a periodogram method.

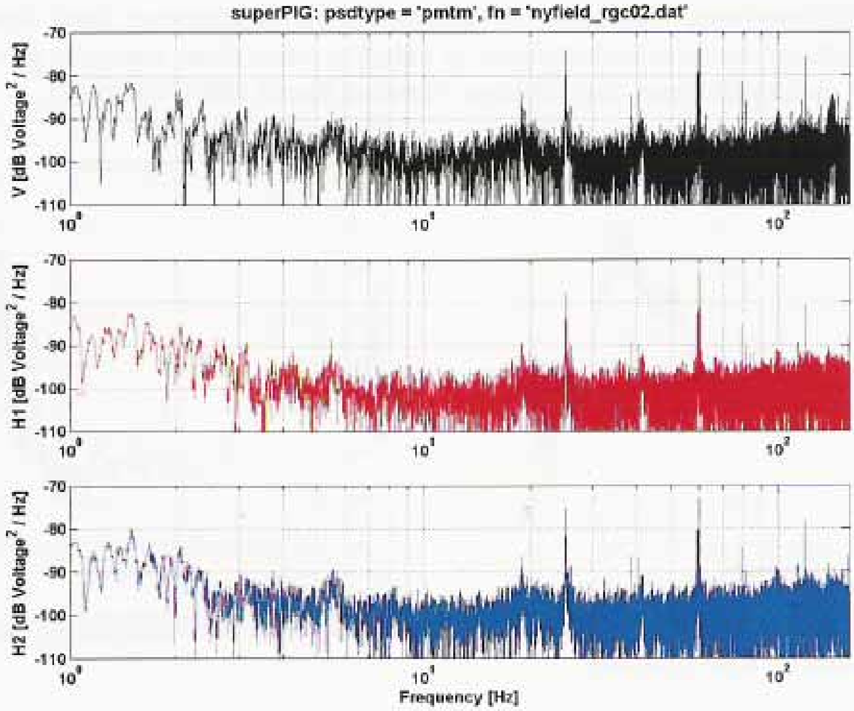


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Figure 45. PSD of 184 second data segment calculated with the Thomson multitaper method, nw=1.5.

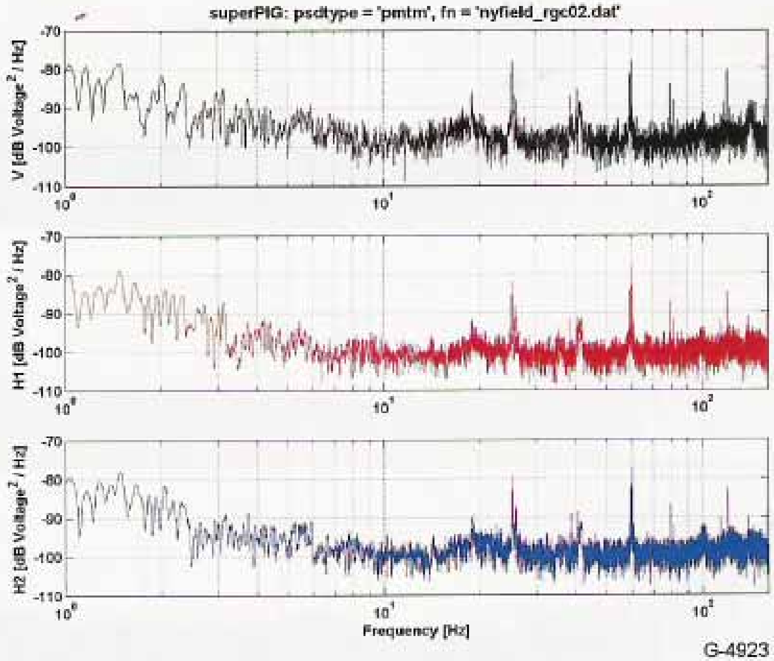

Figure 46. PSD of 184 second data segment calculated with the Thomson multitaper method, nw=4.0.

Summary of Threat Identification by Spectral Analysis

The spectral responses (signatures) of various threats (jackhammer, mini-dozer sledgehammer, backhoe, etc.) on various types of material (steel plate, concrete, gravel, dirt, etc.) are different from one another and they all have a limited bandwidth (Figure 47).

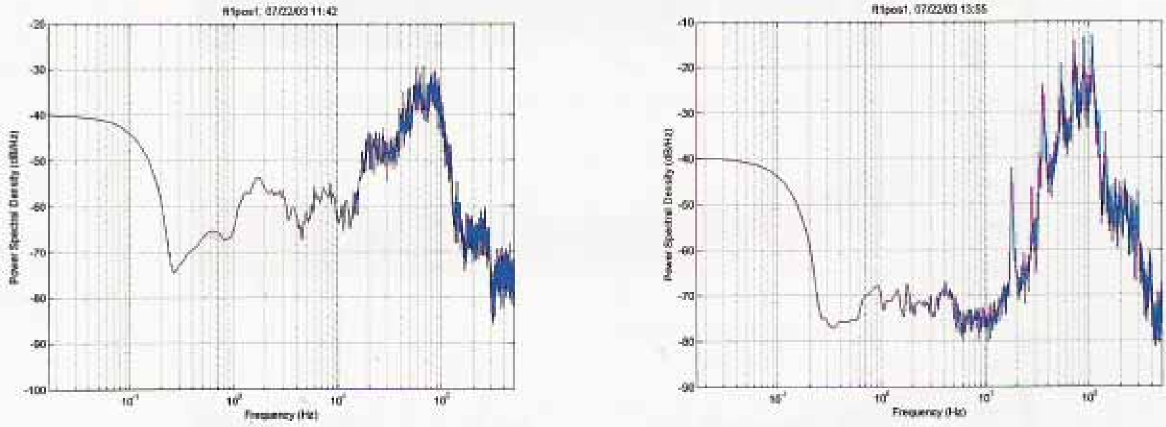

Figure 47. Power spectrum density (a) Signal generated by a backhoe digging (b) Signal generated by a jackhammer.

We propose to use a digital filter bank for automatic threat identification. A filter bank is a collection of M digital filters, with a common input (here, the recording of the PIGPEN sensor). The filter bank is a spectral analyzer; it splits the input signal into M signals typically called *subband signals*. Each filter is a band-pass filter whose subband signal represents the portion of the PSD of the sensory data in the pass-band of the filter. Thus, each subband signal is a 'spectrum' of the sensory data computed based on the most recent M samples of the sensor recording.

In Figure 48, each $H_k(z)$ is a digital band-pass filter and each T_k is a threshold-based comparator. We detail the implementation of the filter bank in the sections below.

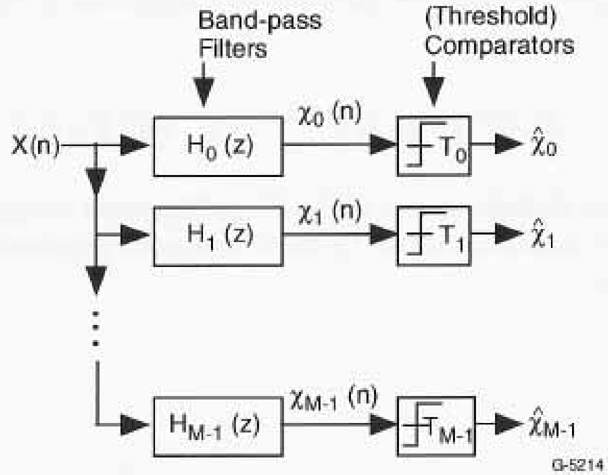

Figure 48. Architecture of proposed filter bank system.

Threat identification method

The filter bank divides the whole frequency spectrum into different small frequency bands that are analyzed by different digital filters. When the output of a filter crosses its corresponding threshold*, this indicates that the signal recorded from the PIGPEN sensor has a relevant spectral component in the bandwidth of the filter. Thus, by analyzing sections of the total frequency spectrum we can differentiate between various threats.

The output of the comparator is binary (i.e., 0/1) such that the output sequence of the proposed filter bank looks like this: $[\hat{x}_0 \quad \hat{x}_1 \quad \dots \quad \hat{x}_{M-1}] = [0 \quad 1 \quad 1 \quad \dots \quad 0 \quad 1]$. This sequence will be compared to the signature sequences of all known threats. The Cartesian distance (d_s) between the known signatures and the sequence is calculated as follows

$$d_s = \sum_{k=0}^{M-1} (s_k - \hat{x}_k)^2 \qquad (2)$$

* The threshold value will be set using the repertoire of PSD of known threats.

where $[s_0\ s_1\ \ldots\ s_{M-1}]$ represents the signature sequence of a known threat. Finally, the threat whose signature has the smallest distance to the identification sequence will be chosen as the most likely source of the signal.

Implementation of proposed digital filter bank

The simplest example of a uniform filter bank is obtained for:

$$H_0 = 1 + z^{-1} + \ldots + z^{-(M-1)} \tag{3}$$

Which implies that $|H_0(e^{jw})| = |\sin(Mw/2)/\sin(w/2)|$ as plotted in Figure 49. It follows that $H_k(z)$ has response

$$H_k(e^{jw}) = H_0(e^{j(w-(2\pi k/M))}), \quad \text{for} \quad k = 1, 2, \ldots, M\text{-}1.$$

Clearly, each $H_k(e^{jw})$ is a shifted version of $H_0(e^{jw})$ as illustrated in Figure 49. Each analysis filter in this case has order M, and offers about 13 dB of minimum stopband attenuation (with respect to zero-frequency gain).

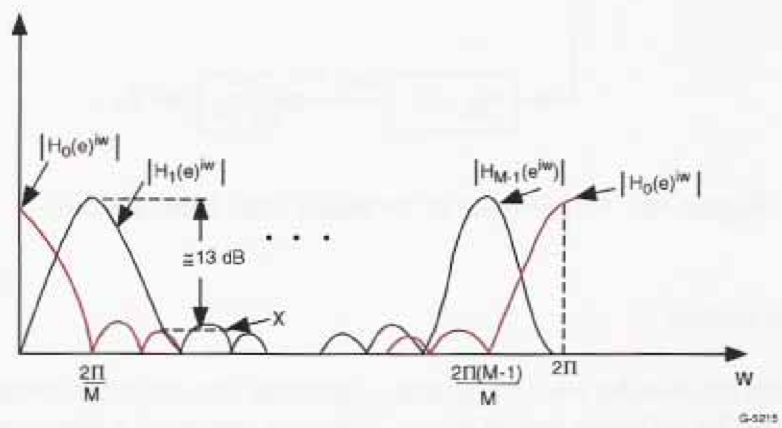

Figure 49. Frequency response of proposed filter bank.*

Instead off designing M distinct filters we propose a simpler implementation as illustrated in Figure 50. This figure shows that the sensory data is first fed into a delay chain where M delayed versions of the signal are created. The delay chain is usually a simple memory storage (a shift register) of size M. The second block shown in Figure 50 is an M x M matrix, which has elements $[W]_{km} = e^{j2\pi km/M}$.

* The digital frequency (w) is related to the continuous domain frequency (f) by $w = 2\pi fT$, where T is the sampling rate of the sensory data.

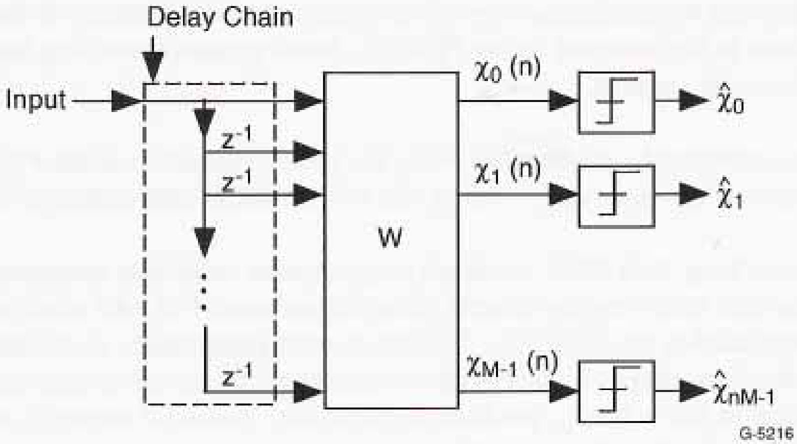

Figure 50. Digital filter bank implementation.

$$W = \begin{bmatrix} 1 & 1 & . & . & . & 1 \\ 1 & e^{j2\pi\frac{1}{M}} & . & . & . & e^{j2\pi\frac{M-1}{M}} \\ . & . & . & & & . \\ . & . & & . & & . \\ . & . & & . & & . \\ 1 & e^{j2\pi\frac{M-1}{M}} & . & . & . & e^{j2\pi\frac{(M-1)(M-1)}{M}} \end{bmatrix} \tag{4}$$

This matrix generates M sequences $x_k(n)$ (where n represents discrete time) which each represents the spectrum of the sensory data, i.e., some kind of averaged version of the exact spectrum of the sensory data, around the region $w = 2\pi k/M$.

Note that the filters used in this design have wide transition bands and stopband attenuation of only 13 dB. The system can be improved, for example, by using a higher order prototype $H_0(z)$ with a sharper response. Then the shifted versions will have reduced amount of overlap. Furthermore, the resolution of this spectrum analyzer can be improved by simply increasing M. Finally, the implementation of the filter bank into an embedded system can easily be done with a cheap processor.

3.6 Task 6. Identify commercialization partner

The PSI process for sensor development typically leverages government and industrial funding to develop and demonstrate several phases of prototypes. We begin with a novel concept, i.e., an invention, and demonstrate feasibility via laboratory experimentation and engineering two or three generations of prototypes, including low volume production. To penetrate high-volume markets, we work with partners having established manufacturing, marketing, and service capabilities.

We have already been working very closely with the Northeast Gas Association as a partner, cofounder and future customer for the PIGPEN technology. NGA funded the intial feasibility studies and the preliminary proof-of-principal measurements of the PIGPEN system. They will continue to be involved in the PIGPEN development, providing both technical guidance and financial support.

We have submitted a proposal to NGA for the continuation of the PIGPEN development effort. That proposal has been approved by the NYSEARCH committee of NGA.

PSI are working with NGA to identify appropriate candidate commercialization partners. After identifying and interviewing several potential partners, PSI will select one organization to assist in commercializing the PIGPEN. Current market penetration, ownership of complementary technology, readiness to accept new technology, technical competence, sales and service, reputation in the industry, production capability, financial strength, and market knowledge will be important factors in the selection process.

Depending on the capabilities of the commercialization partner, PSI could either license the technology to the partner for manufacturing or provide the completed PIGPEN units as OEM devices to the partner. The commercialization partner will assist in defining the system technical and market requirements (unit cost, user interface, etc.) and in developing the commercialization plan. They may also participate in the field testing.

In this task, we will select a commercialization partner, with the help of NYSEARCH. Through discussions with our commercialization partner and with NEGA, we will assess the current technology and needs of the gas industry.

We will also discuss market-driven specifications for the PIGPEN, such as cost, size, ease of use, etc. PSI has demonstrated the ability to create teams that lead to new tools for the gas industry. PSI is currently working with Heath Consultants on the NYSEARCH- and EPA-funded Remote Methane Leak Detector (RMLD) program.

4. Conclusions

We have achieved nearly all of the objectives and performance of the Phase I program.

- With an optimized sensor and electronics, the PIGPEN system will detect threats at a range of 1000 m.
- After investigating two triangulation techniques, we have concluded that triangulation by time lag will provide the best performance.
- The uncertainties caused by changing soil conditions should be overcome by a combination of periodic in-situ calibration.
- We have developed a preliminary design concept for the commercial PIGPEN sensor. We have addressed several critical mechanical and electrical issues.
- The PIGPEN concept meets our goals with a 2.2 lb mass and 2.4 x 3.5 x 6.3 in^3 size, and a <$500.00 target price.
- We have received critical insight and assistance from our NGA partners.
- We are working with NGA to identify potential commercialization customers.

APPENDIX A

Physical Sciences Inc. Viewgraph Presentation VG03-390

Kickoff Meeting

Infrasonic Frequency Seismic Sensor System for Pipeline Integrity Management

Phase 1 SBIR Kickoff Meeting

9 December 2003

G.E. Galica, R.G. Chaves, M.L. Silva, B.D. Green, and J.M. Glynn
Physical Sciences Inc.
20 New England Business Center, Andover, MA 01810

R. O'Neil, G. Vradis, D. Dzurko
Northeast Gas Association
1515 Broadway, 43rd Floor, New York, NY 10036-5701

Kickoff Meeting Objectives

VG03-390-1

- Summarize progress on current and past efforts
- Review DOT SBIR program objectives
- Discuss Northeast Gas Association role as a program partner
- Discuss DOT requirements and objectives
- Discuss schedule

Contact Information

VG03-390-2

Organization	Individual	Contact information
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	George Vradis	gvradis@aol.com 212-354-4790
	Daphne Dzurko – R&D Director	ddzurko@optonline.net 212-354-4790

PIGPEN

Proactive Infrasonic Gas Pipeline Evaluation Network

VG03-390-3

- **PSI proposed to develop a sensor system to proactively detect and warn of right-of-way encroachment and threats to pipelines before third-party damage occurs**
- **The proposed DOT program builds on, and complements, current PSI research funded by NGA, DTRA, and PSI IR&D**
- **Low frequency seismic/acoustic sensor technology (0.1 to 100 Hz)**
  - technology already under development at PSI
- **Sensors do not need to be installed along the entire length of a service main or ROW**
  - a single PIGPEN unit can monitor a large area from a single point
  - lower cost than other proactive sensors
- **A successful PIGPEN sensor will result in great savings through better detection and prevention**

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Benefits

- **PIGPEN is a *proactive* system: it detects *impending* damage**
  - passive, "listening" technology

1) Low Sensor Cost

- sensors are simple and inexpensive
- PIGPEN comprises a polymeric sensor, some electronics, and a network connection

2) Low Network Cost

- infrasonic seismic energy propagates for long distances – sparse sensor array
- few sensors/km^2 – reduced cost initially and for installation and maintenance

3) Simple to install

- "point" installation, does not require installation along entire length of service

4) PIGPEN can be retrofit to existing systems

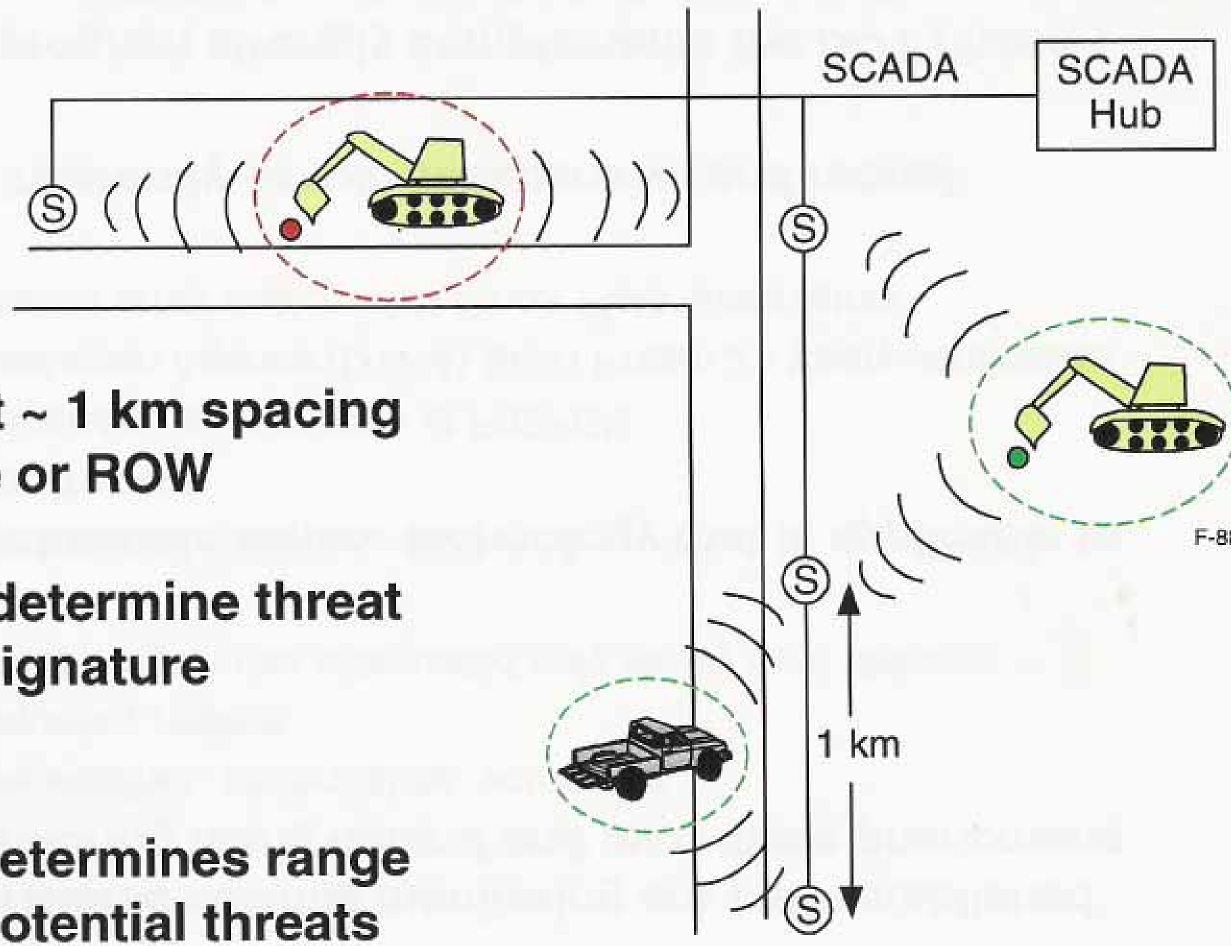
Infrasonic Sensor Technology

VG03-390-5

- **Infrasound and infrasonic seismic monitoring are well-established techniques for monitoring many natural and man-made phenomena**
  - avalanches, severe weather, earthquakes, volcanoes
  - 0.01 to 100 Hz frequency regime
  - low frequency acoustic signatures attenuated only slowly over distance
- **PSI is developing infrasonic sensor technology that is applicable to remote pipeline monitoring**
  - Northeast Gas Association sponsorship of PIGPEN
  - Defense Threat Reduction Agency (DTRA) SBIR Phase 2 - treaty verification
    - Infrasound detector array deployed at Pinon Flats observatory
- **The technology is inherently simple, inexpensive and robust**
- **The ongoing NGA program strongly complements the DOT Phase 1**
  - Program partners committed to transitioning the technology into the commercial marketplace
  - NGA has already funded PIGPEN development since Sep 02

Concept of Operations

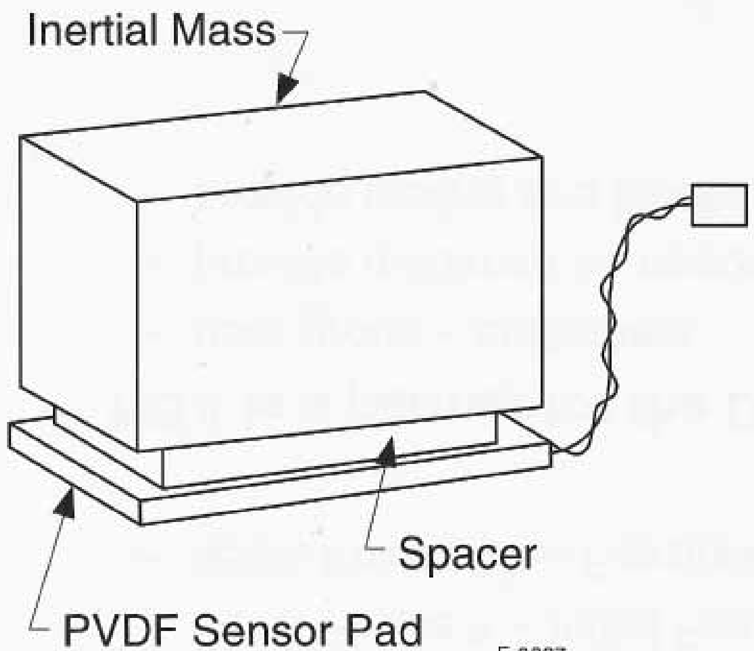
VG03-390-6



- Sensors placed at ~ 1 km spacing along the pipeline or ROW
- PIGPEN sensors determine threat status based on signature (backhoe or bus)
- PIGPEN system determines range and direction of potential threats
- Only true threats that are close to the pipe trigger a warning

PIGPEN Sensor Configuration

VG03-390-7



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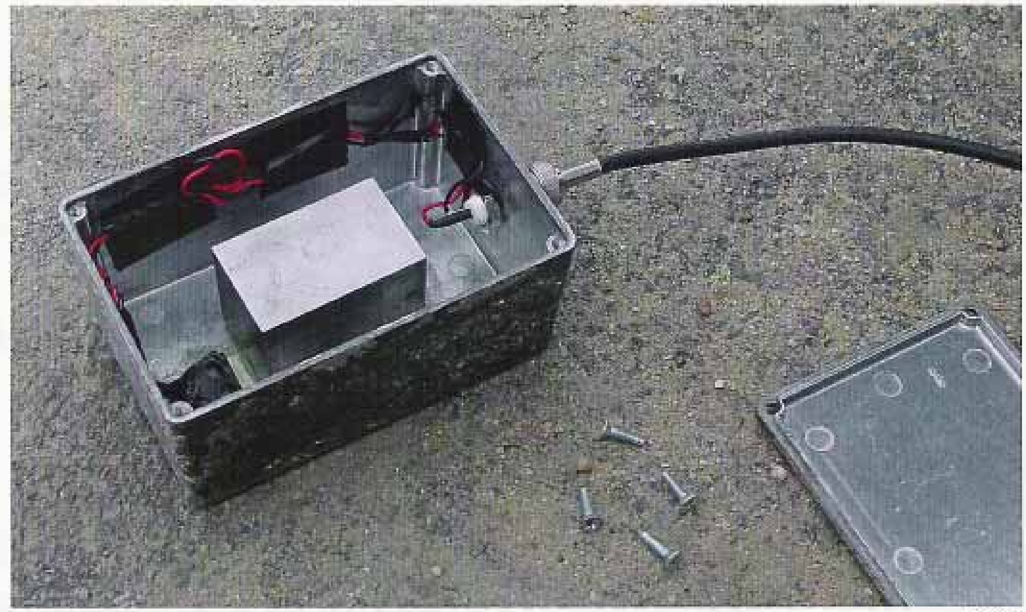

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- **Sensor comprises:**
  - PVDF sensor pad
  - rigid spacer
  - inertial mass
  - preamp (not pictured)

Northeast Gas Association

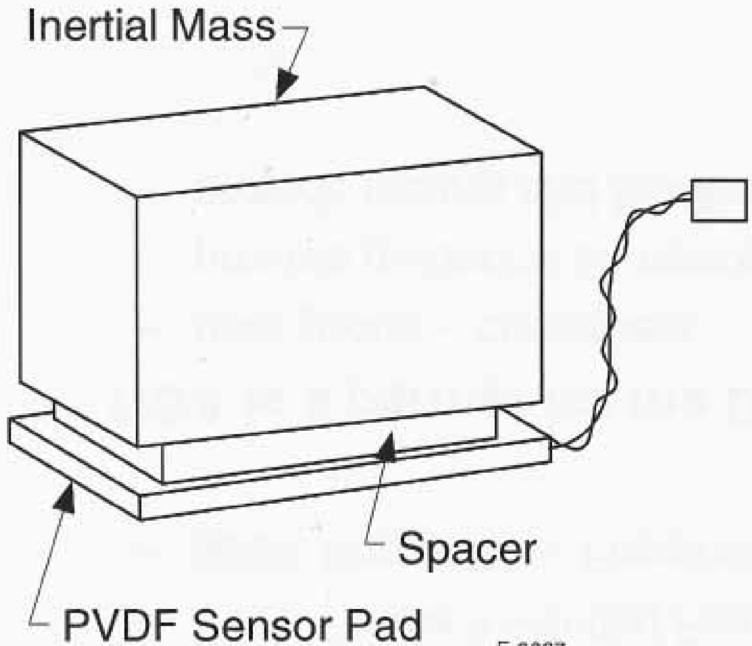
VG03-390-8

- **NGA has funded PSI to develop PIGPEN for proactive detection of impending third-party damage to transmission pipelines**
  - $21K Phase 1 – Initial Feasibility Study
  - $59K Phase 2A – Feasibility Demonstration

- **NGA is a partner for the DOT SBIR program**
  - user group – customers
  - provide guidance on needs and requirements
  - provide testing and feedback

PIGPEN Sensor Configuration

VG03-390-7



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- **Sensor comprises:**
  - PVDF sensor pad
  - rigid spacer
  - inertial mass
  - preamp (not pictured)

Northeast
GAS ASSOCIATION

Introduction to NGA & NYSEARCH

NYSEARCH Interest in the PIGPEN Project

What is the Northeast Gas Association?

- The Northeast Gas Association is a non-profit regional trade association representing the gas utilities of the New York and New England States
  - formed on January 1, 2003 with the merger of the New York Gas Group (1973) and the New England Gas Association (1926)
  - 6.8 million customers served
  - 32 Gas Distribution companies
  - 6 Gas Transmission companies
  - 1 LNG company and 260 Associate members

The NGA

- The NGA has several functions:
  - Provide education and training for the member companies
    - Gas Operations
    - Gas Supply
    - Gas Planning
  - Conduct a Gas Technology Research, Development and Demonstration Program through its RD&D Committee (NYSEARCH)
  - Public outreach and marketing

What is NYSEARCH?

- NYSEARCH is a voluntary Research, Development and Demonstration organization residing within NGA
  - 10 member companies
  - 5 Associate members (from various parts of the country)
  - Approximately 35 projects
  - 3 full time staff members, 1 consultant
  - NYSEARCH staff manages contract R & D projects on a day-day basis
  - NYSEARCH has been in existence since the early 80s; voluntary program has been in place since 1996
- Approves ~$3 million/per year in new R&D programs
- With multi-year projects and outside cofunding, NYSEARCH oversees a $30 million program

How Does PIGPEN fit?

- Two very important RD&D areas for NYSEARCH are
  - Pipeline integrity
  - Third party damage prevention.
- Third party damage
  - Distribution: 2800 incidents reported in NYS in '01; 41% from carelessness/disregard
  - Transmission: 80 incidents reported in US in '01; 50% third party damage

How Does PIGPEN Fit? (continued)

- Industry would like a detection system with the following features:
  - Approaching threats recognition
  - High accuracy with low false alarm rate
  - Low cost
  - Durable
  - Monitors 24/7
  - Notifies a central control in timely manner so that investigator arrives before damage occurs

How Does PIGPEN Fit? (continued)

- NYSEARCH has currently three programs in this area
  - FFT: fiberoptic cable
  - PSI: PIGPEN distributed network of sensors
  - GTI: Acoustic monitoring system
- PIGPEN, if proven, promises to provide all the desired features for such a system

NGA Phase 1 & 2A Program Accomplishments

VG03-390-16

- **Conducted several field tests under ideal and realistic conditions in cooperation with LDCs and private contractors**
- **Demonstrated detection of a credible threat at a range of 300 m**
- **Evaluated optimization of the sensor and electronics**
  - up to 3-10x increased sensitivity
  - up to 3-10x reduced noise
- **Measured unique seismic spectral signatures for several typical threats**
  - these signatures form the basis for discriminating between threats
- **Made progress on demonstrating triangulation**
  - remaining physics issues
  - we are developing a strategy for new triangulation methods
- **These technical accomplishments form the core of PSI/NGA IP**

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DOT Phase 1 Program Objectives

VG03-390-17

1) Quantify performance of the PIGPEN sensor for detecting and locating ROW encroachment and impending third party damage

2) Create a conceptual design for a PIGPEN system that meets technical and market requirements

3) Identify and develop a working relationship with a commercialization partner

Phase 1 Work Plan

VG03-390-18

- **1) Program Kickoff**
  - review objectives and tasks
  - summarize progress on NGA-funded efforts
- **2) Quantify sensitivity and detection range**
  - GOAL: detect realistic threat at 1000 yds
- **3) Quantify accuracy of locating a threat**
  - GOAL: accuracy of 10 yards at a range of 300 yards
- **4) Create conceptual design and preliminary specs for PIGPEN system**
  - GOAL: <2 lbs, <4 x 4 x 4 in3, <$1000/unit
- **5) Develop a threat identification algorithm**
  - use background and signature databases
  - develop preliminary algorithms:
    - identify threat
    - reject backgrounds
    - localize threat
- **6) Identify commercialization partner**

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Task 1 – Program Kickoff

VG03-390-19

- **9 Dec 03**
- **Summarize progress on NGA-funded efforts**
- **Review program objectives**
- **Discuss DOT requirements and objectives**
  - PSI welcomes input from DOT on sensor requirements and specifications
- **Discuss schedule**

Task 2 – Quantify Sensitivity and Detection Range

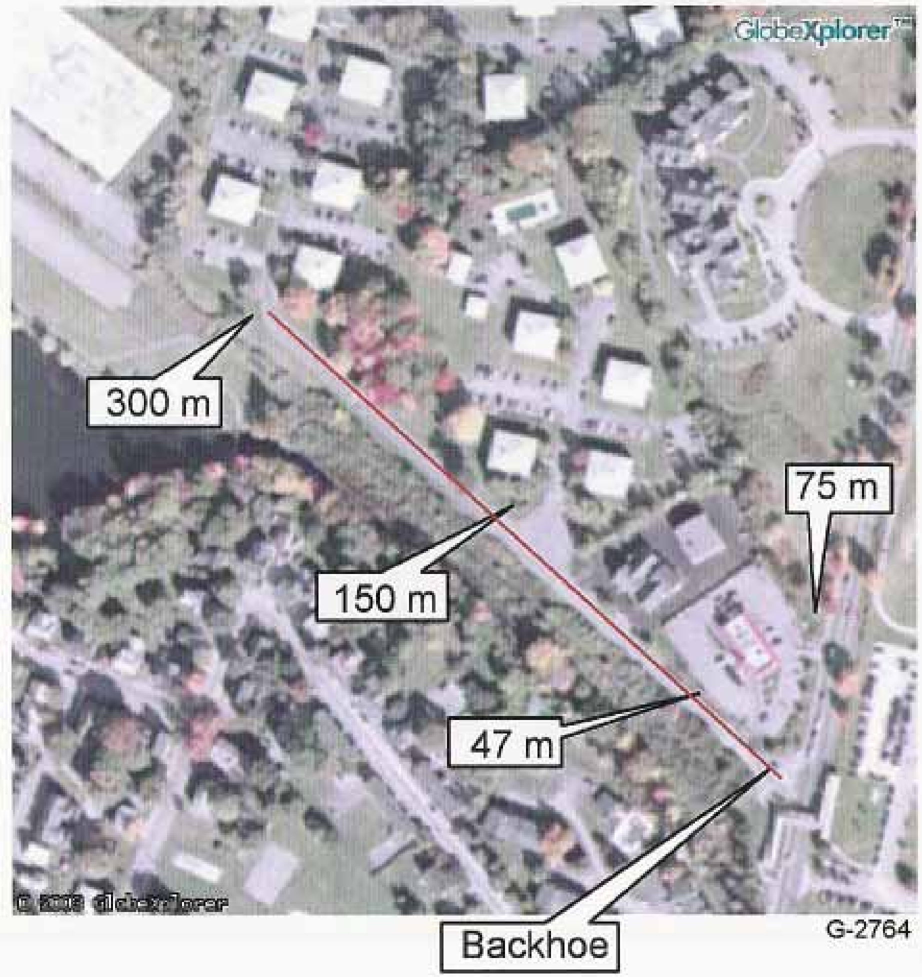
VG03-390-20

- **GOAL: Detect realistic threat at 1000 yds**
- **Demonstrated detection of a credible threat at a range of 300 m**
  - several field tests under ideal and realistic conditions in cooperation with LDCs and private contractors
- **Optimization of the sensor and electronics will enable detection at longer ranges**
- **We are presently making arrangements for the next field tests**
  - sites with 1000 yd ranges are difficult to find
  - more data collection at shorter ranges combined with laboratory sensitivity measurements – extrapolate detection range
- **NGA role:**
  - advising PSI on typical threat scenarios
  - arranging and enabling field test opportunities

Field Test 1 & 3 Configurations

VG03-390-21

- Field Tests 1 & 3 were conducted with the cooperation of a private contractor (Gioioso Construction)
- PVC sewer main being laid along a residential street in North Andover, MA
- Residential street intersects a busy main artery (Rte 114)



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Equipment

VG03-390-22

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Field Test Photos

VG03-390-23

Pipe in trench

PIGPEN sensor in ground

Backhoe digging at intersection

Taking data at 300 m

14 2:29PM

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Task 3 – Quantify Accuracy of Locating Threat

VG03-390-24

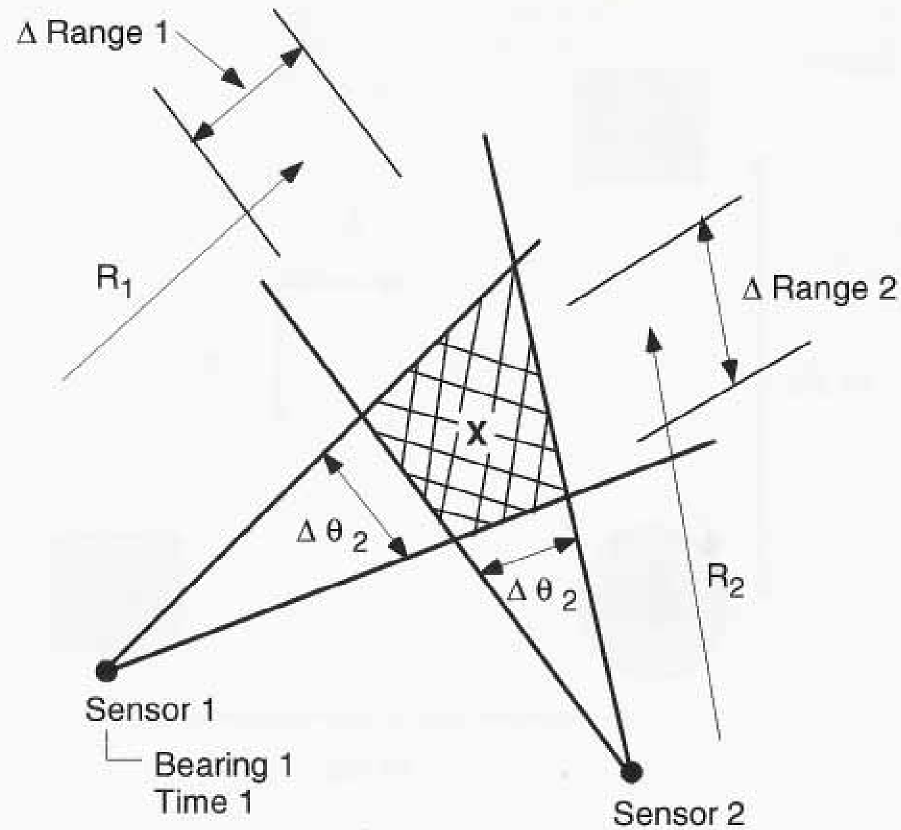
- **GOAL: accuracy of 10 yds at a range of 300 yds**

- **Triangulation is the most challenging aspect of the project**
- **Time-lag triangulation**
  - demonstrated triangulation accuracy is 16 ft rms in uniform soil conditions
  - sound velocities vary by 3.5X from dry sand to frozen sand
    - dry sand 140 m/s
    - wet sand (10%) 240 m/s
    - frozen wet sand 470 m/s
  - moisture content will confound determinations of threat location by time-lag alone
- **Triangulation by bearing**
  - directional sensor determines threat direction is not affected by velocity uncertainties
  - bearing, combined with time-lag, will provide a more accurate position determination
  - standard technique used in seismology and sonar
- **NGA role:**
  - advising PSI on gas industry requirements and applications
  - arranging and enabling field test opportunities

Directional Sensor Operation

VG03-390-25

- **Directional sensor response does not depend on velocity or uniformity of velocity over path**
  - removes soil-type effects
- **Directional sensor determines bearing from the ratio of signals of two orthogonal, colocated detectors**
- **Bearing accuracy determination**
  - 5% amplitude precision correlates to 8 m position accuracy at 300 m range
- **Bearing and range from two or more sensors put the disturbance within an uncertainty box**



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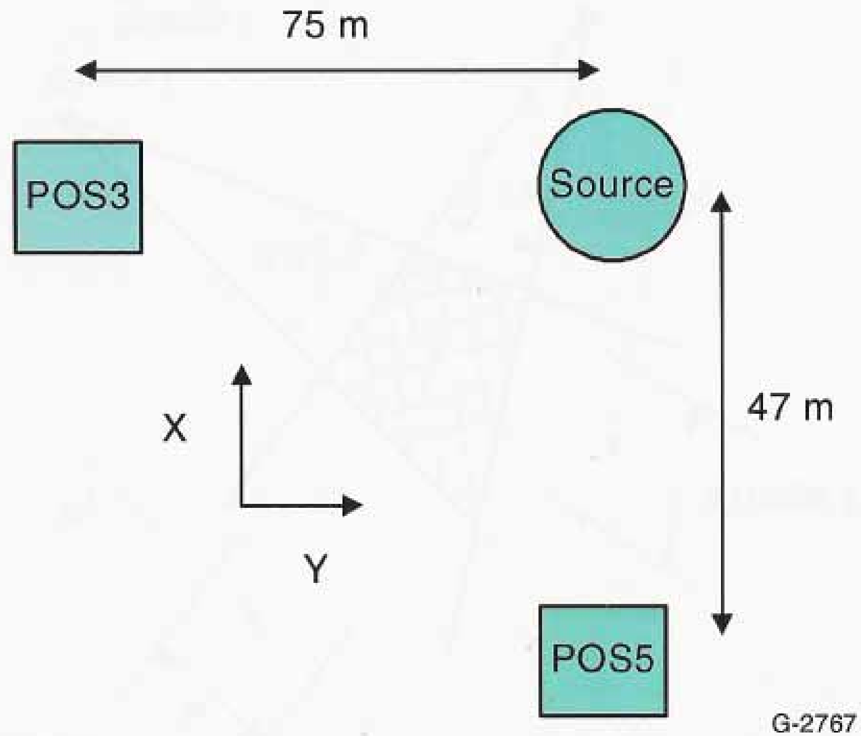
Preliminary Directional Sensor Results

VG03-390-26

- **We deployed conventional 3-axis geophones during our Aug03 field test**
- **Good correlation between PIGPEN sensor and vertical geophone channels**
- **Triangulation results were mixed**
  - hodograph analysis showed some directional sensitivity
  - background noise & poor sensor location complicated analyses
- **Triangulation is the top priority for the next field tests**



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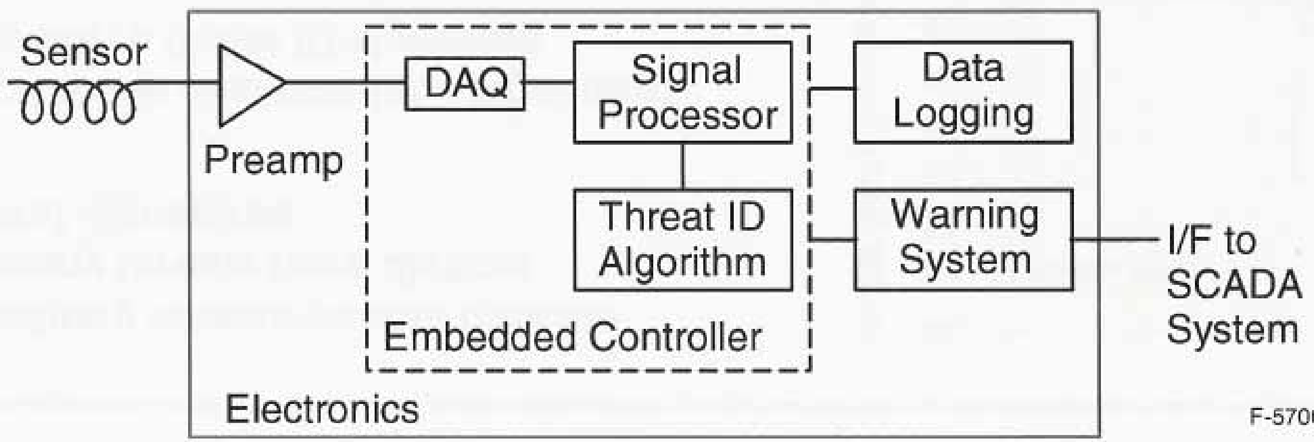
Task 4 – Create Conceptual Design

VG03-390-29

- **GOAL: Scale <2 lb, <4 in. cube, <$1000/unit**
- **PIGPEN comprises: sensor head, low noise preamplifier, DAQ electronics, threat ID, data logging, SCADA interface**
- **DAQ, processor and threat ID accommodated in an inexpensive imbedded controller (auto industry)**
- **Preliminary results still support this basic concept**
- **NGA role:**
  - advising PSI on customer interface and infrastructure issues



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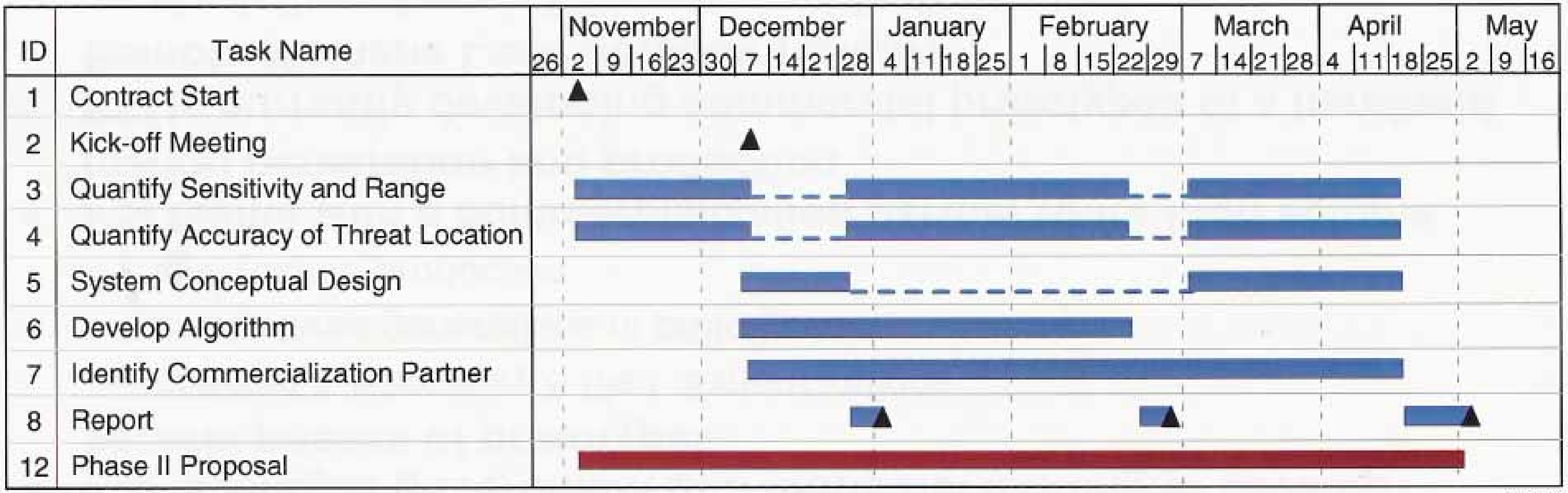
Task 6 – Identify Commercialization Partner

VG03-390-31

- **PSI will work with NGA and DOT to identify a commercialization partner**
- **NGA role:**
  - identifying potential commercialization partners
  - providing customer input and feedback to prototype development
- **PSI leverages government and industrial funding to develop several phases of prototypes**
  - concept & laboratory & filed demonstrations
  - two to three generations of prototypes
  - low-volume production
- **PSI teams with a commercialization partner to for high volume market penetration and production**
- **PSI is currently developing commercial prototypes of a handheld Remote Methane Leak Detector (RMLD)**
  - Heath Consultants is PSI's commercialization partner
  - NGA has been involved in RMLD development with PSI for several years

Phase 1 Schedule & Milestones

VG03-390-32



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- **NGA PIGPEN Phase 2A final report – 15 Sep 03**
- **DOT Phase 1**
  - Interim progress report #1 – 4 Jan 04
  - DOT Interim progress report #2 – 4 Mar 04
  - Final Report – 4 May 04
- **Phase 2 proposal due date – ???**
- **NYSEARCH committee meetings – Mar 04, Jun 04**

PHYSICAL SCIENCES INC

Phase 2 & Beyond

VG03-390-33

- **PSI's focus is on bringing the PIGPEN technology to the commercial marketplace**
  - NGA is program partner
  - identifying commercialization partner

- **Future Phases would entail:**
  - developing pre-prototype PIGPEN units
  - developing network architecture
  - conducting extensive field testing (PSI and NGA)
  - developing alpha prototype & test regimen
  - developing beta prototype & test regimen
  - handing off production to commercialization partner
  - supporting product roll-out