PSI-1474/
TR-2247

Infrasonic Frequency Seismic System for Pipeline Integrity Management

DOT/RSPA Phase II SBIR
DTRT57-05-C-10110

Final Report
Covering the Period
6 July 2005 – 5 July 2007

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1.0 Project Summary

FINAL PROJECT SUMMARY REPORT

PROJECT IDENTIFICATION INFORMATION

1. BUSINESS FIRM & ADDRESS	2. DOT SBIR PROGRAM	3. DOT CONTRACT NO.
Physical Sciences Inc. 20 New England Business Ctr. Andover, MA 01810-1077	2003 Phase II	DTRT57-05-C-10110

4. PERIOD OF PERFORMANCE
From 6 July 2005 To 5 July 2007

5. PROJECT TITLE
Infrasonic Frequency Seismic System for Pipeline Integrity Management (PSI-1474/TR-2247)

SUMMARY OF COMPLETED PROJECT

The data in this final report shall not be released outside the Government without permission of the contractor for a period of 4 years from the completion date (5 July 2007) of this project from which the data were generated.

The overall goal of this program was to advance the maturity of the PSI infrasound acoustic detection technology to a level where it could be evaluated for its performance against real-world threats in realistic implementation scenarios. The product being developed by this research will respond to the PHMSA's mission and the need identified by gas industry and government representatives at the February 2007 PHMSA R & D Forum that one of the top priorities for damage prevention was the need to monitor encroachment and prevent damage while construction equipment is digging and/or boring.

The PIGPEN sensor specifications at the start of the project are summarized in Table 1:

Table 1. PIGPEN Specifications

Parameter	**Target specification**
Detection range	1000 yards, in quiet conditions
Triangulation accuracy	10 yards at 300 yard range
Unit mass	2.5 lbs
Unit size	6.5 x 3.5 x 2.5 in3
Unit power	1 watt (max) Less with sleep mode
Unit cost	<$300 Target

The major objective of this project was to advance the PIGPEN technology from Experimental Prototype stage toward a commercially viable prototype system. We demonstrated a PIGPEN sensor and quantified its performance as a third-party damage early warning system. We demonstrated threat identification and threat location algorithms as an enabling technology for a third-party damage early warning system. We developed a PIGPEN Advanced Prototype system that forms a basis for a commercially viable product that meets both the performance and market requirements of a third-party damage early warning system. We began the transition the PIGPEN technology to a commercialization partner (working in cooperation with our potential future customer the Northeast Gas Association (NGA)).

We performed the following tasks in the performance of this program:

Technical Interchange meetings: Where working with the DoT and NGA representatives we defined interface and requirements starting at the kickoff meeting and at periodic intervals throughout the program.

Assessment of PIGPEN EP Performance and Algorithms Refinement: We acquired an extensive database of performance data with EP-2 in a long-term deployment under a variety of conditions and geometries, and developed Build-2 algorithms, based on EP-2 assessment data. We preliminarily tested the system at three locations. We performed extensive field testing in Andover, MA, the Bronx, NY, and Lawrence, KS, and analyzed the data acquired at these locations

Development of the PIGPEN Alpha Prototype (AP): We developed and fabricated, integrated sensor head and customized digital signal processor as AP; developed and implement Build-3 software algorithms; established AP performance by laboratory and field testing. We designed a network architecture, set detailed specifications for the network and communication performance. We fabricated the AP hardware, and bench tested the hardware to prove that it successfully met its design specifications.

We were successful in locating an organization interested in transitioning this technology into a commercial product. During the Phase 2 program we contacted many potential partners. We are pleased to team with one that possess an existing product line in pipeline monitoring along with a production and field service and installation capability. That company has already performed a market survey of product relevance and key acceptance criteria. They have committed their resources to help continue the development of the PIGPEN technology into a pipeline intrusion monitoring network.

APPROVAL SIGNATURES

1. PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR (Typed)	2. PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR (Signature)	3. DATE
Dr. B. David Green	Dr. B. David Green	10 Sept 2007

1.1 Technical Accomplishments

This project was performed in conjunction with a DOT-BAA with our partner, the Northeast Gas Association. The BAA was focused more on algorithm development and field testing, while the SBIR undertook the AP development. We present a summary of the entire project in this subsection. In the initial stages of the program, PSI optimized the sensor response and the analog amplifier design to improve noise performance, and developed threat identification algorithms in preparation for field tests. The Phase 1 results indicated that further improvements in the sensor were possible. We used our validated sensor model to guide the optimization of the sensor performance and system noise characteristics. We compared the responsivity and noise performance of the sensor with a goal to increase in sensitivity of 10 dB over our previous version sensor (extending detection range), and we achieved that increase. Our goal was to decrease noise by 10-20 dB over our previous amplifier design, and we also achieved that decrease as described below.

We also modified the mechanical design of the first Experimental Prototype (EP-1) sensor based on the evaluated shortcomings of the previous PIGPEN sensor design, the environment and ruggedness the final instrument will need to survive and be successful. Because sensor orientation is critical to proper functioning, we designed the chassis to ensure the correct orientation naturally during installation. We made improvements in the design to minimize 60 Hz EMC noise transmitted both electrically and magnetically. We took significant steps toward making the sensor significantly more rugged, by constraining it to eliminate forces that could damage the sensor. During this phase, we also refined our preliminary algorithms and tailored them for the future on-board digital signal processor. We exercised them against our database of threat signatures collected during previous field tests. We concentrated on refining the threat detection and threat identification algorithms. The threat detection algorithm uses the rectified time domain signal duration and was tested against the prior field-test database. This process and the methodology for the threat identification algorithm are described below.

PSI fabricated six EP-1 sensors with a weatherproof mechanical housing, and front-end electronics. During prior field tests in Phase 1 of this project, it was difficult to synchronize the data acquisition from multiple sensors because of the large distances between sensors. We chose the wireless communication between the EP-1 sensors and the central computer to permit data to be acquired from all sensors simultaneously and synchronously.

We next tested and calibrated the EP-1 sensors on the bench. Through bench testing and calibration, we validated the EP-1 design. The EP-1 sensor met the design goals of increased sensitivity and reduced noise. The front-end electronics also met the desired frequency bandwidth requirements. The resonance frequency was out-of-band as designed. We conducted calibration testing at Sypris Test and Measurement in Burlington, MA. The facility achieved excitations of 3 Hz and 1/10 G. At Sypris, we measured the sensor response and identified the natural resonances of the EP-1.

The main conclusions we draw from our initial bench testing and analyses include:

- EP-1 met all of its design criteria
- EP-1 natural frequency is 1100 Hz (goal >1000 Hz)
- EP-1 responsivity is 12 dB greater that the Phase 1 sensor (goal 10 dB increase)
- EP-1 noise is 15-25 dB lower than Phase 1 sensor (goal 10 dB decrease)
- EP-1 response is not affected by non-level mounting up to 30 deg (PDR action item)

Our preparation for field checkouts to verify system performance and validate algorithm performance is presented in Section 3 of this report. Initially we conducted three half-day field exercises at a location near PSI. At these field exercises, we acquired data using a sledgehammer as the source. We also conducted a full-day field checkout with a private contractor at a building site in the Boston area. At this field checkout, we acquired data of two types of excavators.

We were able to further optimize the threat algorithm using data from these tests. We also further characterized the test site measurements to support consultant activities and to develop concepts to compensate for complex geological conditions. At the Andover location, we were able to make the first measurements of triangulation performance.

We acquired three days of field data with four EP-1 units at a site near PSI (Somerset, MA) and at the NYSEARCH/NGA site (Johnson City, NY). The sensors performed well.

We measured the signatures of all the equipment available during the Johnson City Test with high SNR at ranges up to 175 m. The signatures are similar to previously acquired data but have significantly higher SNR. From the Johnson City data, we extrapolated the maximum range for the sensor to be 1750 m with SNR=16 dB under quiet conditions. During the Johnson City test, we acquired data from two types of excavators at multiple times over the two day test. The variability in these data will enable us to ensure that the algorithms are robust.

Upon detailed analysis of the data, we determined that the relative timing of the four EP-1 data streams was corrupted by the data acquisition system. As a result, the site characterization data from Johnson City is of limited use. The triangulation data can be used; however, we cannot determine absolute range. At Johnson City we were able to triangulate to obtain to acoustic source position to 3.5 m (11 ft) triangulation accuracy at a nominal range of 150 m (490 ft).

We demonstrated the ability to process the data to autonomously determine a range using a cross-correlation technique. Because the data acquisition system corrupted the timing of the data streams, we were unable to determine absolute range. We tested the cross-correlation technique near PSI. The triangulated positions are determined with a precision of ± 1 m (± 1 yard). The accuracy of the triangulated positions is on average ± 3 m (± 10 ft) at a nominal range of 150 m. In spite of this precision, the derived threat position error varies from 3 to 27 feet (1 – 8.2 meters). The triangulated jackhammer location has same accuracy as sledgehammer location. The algorithm correctly identifies jackhammer and backhoe signatures from several pieces of equipment. The Build-2 algorithm was fully implemented and tested on the EP-2 hardware.

This analysis and discussions with our development partners guided the design of the EP-2 system, culminating in a design review. EP-2 was fabricated and tested in the laboratory. We also fabricated a second data acquisition system as an alternative to the wireless data acquisition system used in the Johnson City field test. At Johnson City we chose wireless communication to enable acquisition at long distances between sensors and to acquire data from all sensors simultaneously and synchronously. However, the wireless system introduced non-reproducible artifacts in the data that made it impossible to perform triangulation analysis.

PSI provided requirements for communication and other interface to NYSEARCH's real time sensing system called GasNet. We discussed plans for extending the work for numerical modeling and field tests in complex soil conditions to address valid concerns about location accuracy raised by an independent consultant recommendation regarding location accuracy. PSI participated in discussions with NYSEARCH regarding PIGPEN specifications and triangulation accuracy requirements. We performed the rest of this program with a goal of repeatably achieving 10 foot location accuracy in all soil conditions (vs 30 foot initial goal).

After a several month hiatus, we performed a field test at a site in Kansas which was identified by the independent geophysical consultant, Don Steeples. The Kansas testing is described later in this report. The site had a sharp boundary discontinuity between loam and shale. As part of this program, we prepared and undertook a full week of testing at the site, with the support and guidance of NYSEARCH and Don Steeples. We completed the entire test matrix obtaining over 400 acoustic events in multiple sensor configurations. We were able to verify real time (via computer display) that the PIGPEN sensors detected over 99% of these events. PSI conducted an extensive analysis of the large data set collected during the November field test near Lawrence, Kansas. This analysis has resulted in the following conclusions:

1. PIGPEN detected a 30-06 down-hole rifle to a range of 400 ft in sand/loam.
2. PIGPEN detected a 30-06 down-hole rifle to a range of 200 ft in limestone/shale.
3. Threat signatures are degraded 20-30 dB (depending on initial signal strength) as they transition from limestone to sand. We were able to observe attenuated threat signatures across this discontinuity in both directions.
4. Under certain conditions when the arrival times matched geometric distance expectations, PIGPEN localized threats repeatably to ±7 ft in sand/loam. However, in many cases the accuracy was far worse, and only ± 75 ft accuracy was observed. (A 27 foot error in accuracy was observed in the more uniform soils of the Andover test site.) The decreased accuracy was not predictable, but rather (we believe) dependent on the site. The data is not statistically random (as is noise), but is tightly clustered around an incorrect answer. This indicates to PSI that a physical process is giving rise to the incorrect position determinations.
5. Under certain conditions when the arrival times matched geometric distance expectations, PIGPEN localized threats reproducably to ±9.6 ft in slate/limestone. However in many cases the accuracy was far worse, and only ± 300 ft accuracy was observed. The decreased accuracy was not predictable, but dependent on the site.

6. We were able to observe the unique signature and repeated strikes from a Backhoe across the discontinuity at all sensors.

Due to the signal degradation across the soil discontinuity, PSI has not been able to establish the positional accuracy across the soil transition for the down-hole rifle acoustic source. In addition, positional accuracy may be degraded by steep slopes within soil types. Further algorithm development in conjunction with on-site acoustic characterization will be required to improve accuracy and partially compensate for non-uniform soil conditions. The 30-06 down-hole rifle was an excellent reproducible acoustic impulse source, but its acoustic amplitude was too small to produce detectable signals in the full set of PIGPEN sensors to allow their demonstration at the desired separation range.

We successfully collected a large amount of data at the Kansas field test site. We acknowledge the great assistance of Prof. Don Steeples in site selection, initial testing and many discussions. We collected data in a grid covering loam and shale/hillside using a down-hole gun as our primary stimulant threat acoustic source. This source was very reproducible and permitted repeated testing. The signature it generated was not as strong as many real threats and as a result it did not produce signals with large SNR at all the sensors, limiting the number of data sets where we were able to attempt triangulation. After the preparation of a draft report on the Kansas data testing and results, we sent copies of this section of the report to our DOT monitor, James Merritt, Daphne D'Zurko, and the NYSEARCH Consultant for comments. The latter provided many good observations and requested clarifications and expansions in the text. We have not included those amendments here. Those revisions are included in the related final report submitted by the NYSEARCH with PSI as contributors.

Unfortunately the extensive field testing to establish the capability of this technique consumed significant SBIR program resources. As a result we were unable to extensively test the AP units developed under this program. They are available for testing and further development as further funding for this technology becomes available. We are in discussion with NYSEARCH, other consortia, and our partner American Innovations to move this technology to further development.

In parallel with the analysis, PSI assembled and bench tested the components for an advanced prototype (AP) sensor network. At the conclusion of this program we presented a status summary to Mr. Jim Merritt. American Innovations traveled to that meeting at no cost to this contract and presented company capabilities, a summary of the preliminary market analysis, and their analysis of the most important remaining issues to be addressed in follow-on activities to help ensure product acceptance. American Innovations is enthusiastic about the need for this technology and are committed to work with PSI to continue its testing, productization and market insertion.

The time difference of arrival approach while offering the POTENTIAL for high time resolution and spatial location accuracy, was not capable of delivering that accuracy in complex real world conditions. Discussions with Mr. Merritt in March 2007 identified an alternate analysis approach based on relative signal amplitude. During the last months of this program PSI performed a re-analysis of Kansa data and the Andover triangulation data using PSI internal funds to evaluate the effectiveness of the relative signal amplitude approach. We notified our technical monitor and also presented this new approach to our partner/ customer – the NYSEARCH committee in early June 2007. The new approach performed robustly and reproducibly in several soil conditions, and provided 20 to 50 foot localization accuracy for the cases examined. PSI (and our commercial partner AI) are actively seeking support from our partners to couple the PIGPEN sensor technology – matured in this SBIR program – with the new algorithms into a robust affordable pipeline intrusion monitoring network.

2.0 Initial Development and Testing Activities

2.1 Kickoff Meeting

The kickoff meeting was held on 14 July 2005 at the offices of the Northeast Gas Association in New York, NY. The Northeast Gas Association (NGA) has been funding the PIGPEN technology development in its early stages along with DOT/OPS and is PSI's SBIR Phase III partner. The kickoff meeting briefing is included as Appendix A.

At the kickoff meeting, we reviewed the technology status, the Phase II program plan, and schedule. We also presented a brief review of data acquired on complementary development programs, including the DOT/OPS and NGA co-funded BAA.

2.2 Improving Data Acquisition System Performance

PSI had conducted a field test of the PIGPEN system in conjunction with NGA in April 2005. That field test was conducted at a site in Johnson City, NY. PSI met several objectives of the field test including acquiring equipment signatures and quantifying the range and sensitivity capabilities. However, we did not meet the objective of quantifying the triangulation performance of the system.

While we acquired data with multiple sensors at different locations, the data acquisition system introduced artifacts into the data that prevented us from quantifying the triangulation performance. At Johnson City, the relative timing of the data streams from the 4 sensors was corrupted by the data acquisition system

At the Johnson City test, we used wireless serial DAQ system – wireless facilitates acquisition of remote sensor data at long range (see Figure 1). Internal buffering in the computer introduced non-reproducible time lags in the data

For the Johnson City test, we chose a wireless RS-232 data acquisition system That DAQ system was chosen because 1) it minimized system noise by enabling transmission of digital data directly from the sensor, and 2) it enabled transmission of data easily over long distances (up to 500 m). However, internal buffering in the computer introduced non-reproducible time lags in the data (Figure 2). The misalignment of the four sensor data streams was not apparent until the Apr 05 field test data were analyzed.

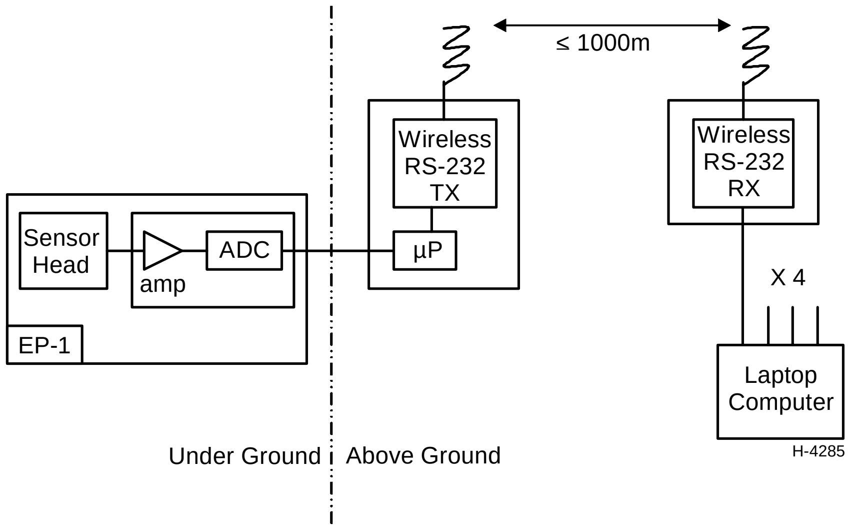


Figure 1. Block diagram of EP-1 and wireless data acquisition system.

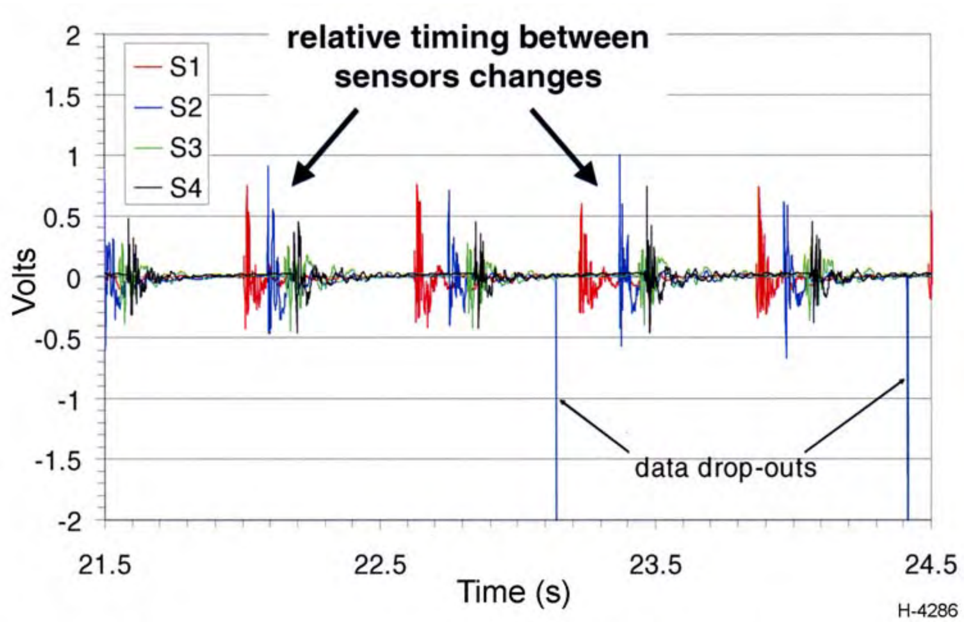


Figure 2. Due to internal buffering of the data acquisition system, non-reproducible time lags were introduced into the data stream.

In order to acquire the data needed to assess the triangulation accuracy, the time base of the four data streams (from the four sensors) must be aligned to within 1 msec. In order to accommodate this requirement, we devised an alternative data acquisition system (see Figure 3).

A simple way to maintain the relative data timing and acquire data at the required 1000 samples/sec/sensor rate using a conventional laptop computer, is to transmit the raw analog

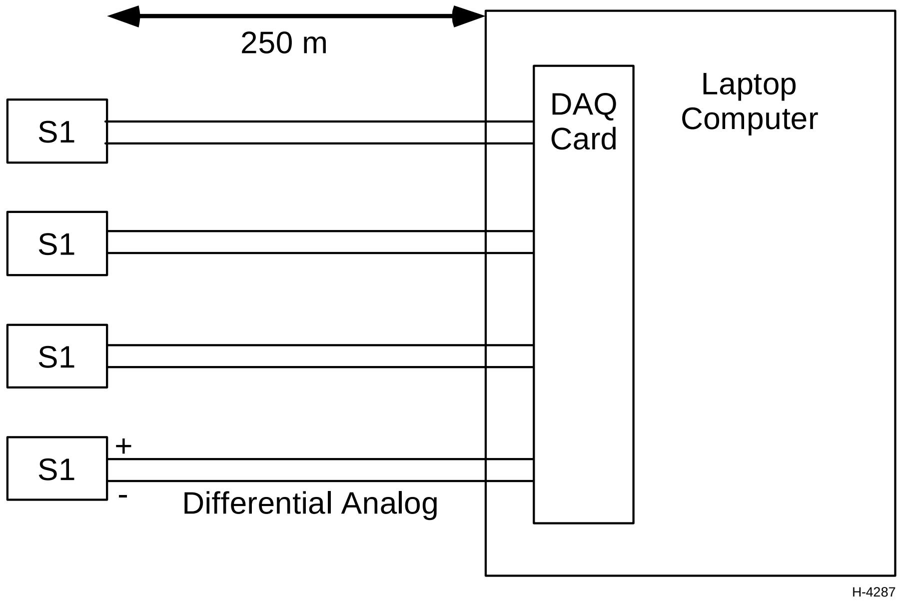


Figure 3. Analog DAQ system that will ensure relative synchronization of the four sensor data streams.

signals from each sensor to a National Instruments Data Acquisition card. That card resides in the PCMCIA port of the laptop computer, and digitizes the analog inputs with 16-bit precision. The PIGPEN ADC also digitizes at 16-bit precision. This is an interim solution to allow field testing.

With short cable lengths (<10 m), this approach works quite well and is often the least expensive approach to data acquisition. The challenges arise when long cable lengths are required. Long cables are quite efficient at picking up excess noise from the electromagnetic environment. In addition, the PIGPEN analog electronics are not designed to drive long lengths of cable. Usually buffer amplifiers are necessary to drive analog signals down long cable lengths without signal attenuation or distortion. The PIGPEN analog circuit is designed to transmit the signals to the ADC input, only a few millimeters distant.

In order to maintain low noise operation, we transmitted the data differentially up to the required 250 m distance. In addition, we used shielded, twisted-pair cable. In order to transmit the analog signals that distance without distortion, we used special low-capacitance cable (<20 pF per foot). By using these special accommodations, we were able to implement an analog data acquisition system that will meet the timing requirements and offer acceptable noise, attenuation and distortion performance.

Figures 4 and 5 show oscilloscope traces of the PIGPEN analog signals directly from the sensor (Figure 4) and after having traversed 300 m of cable (Figure 5). These signals were generated by sharply hitting the bench top about 1 m from the sensor. The “AC-coupled bounce” observed in Figure 4 is due to the oscilloscope probes. The high frequency content is comparable with the short cable and long cable. While the source was not calibrated, the response appears to be 2X less with the longer cable. There is also some 60 Hz noise pickup visible in the long cable case.

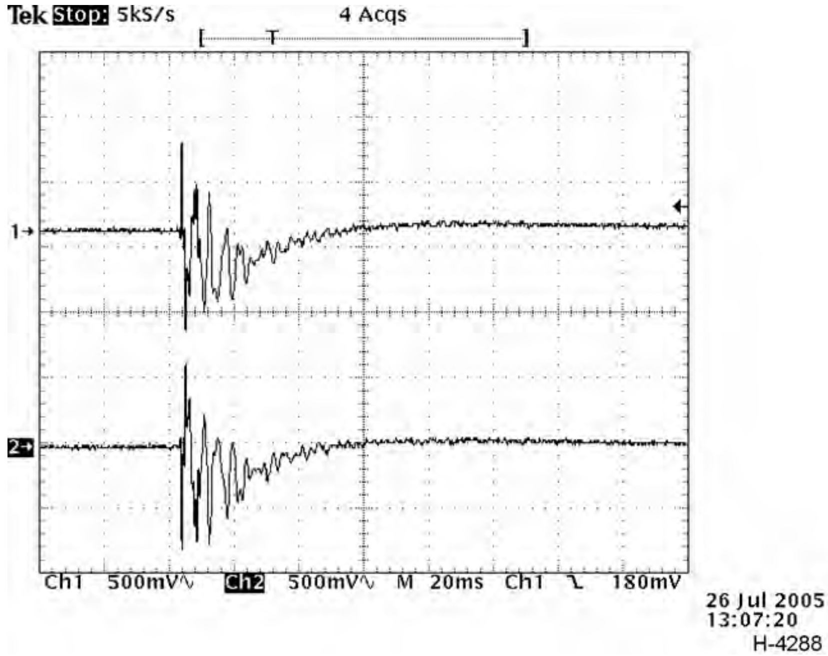


Figure 4. Oscilloscope trace of + (CH1) and – (CH2) differential analog signals from the PIGPEN sensor at 20 msec/div.

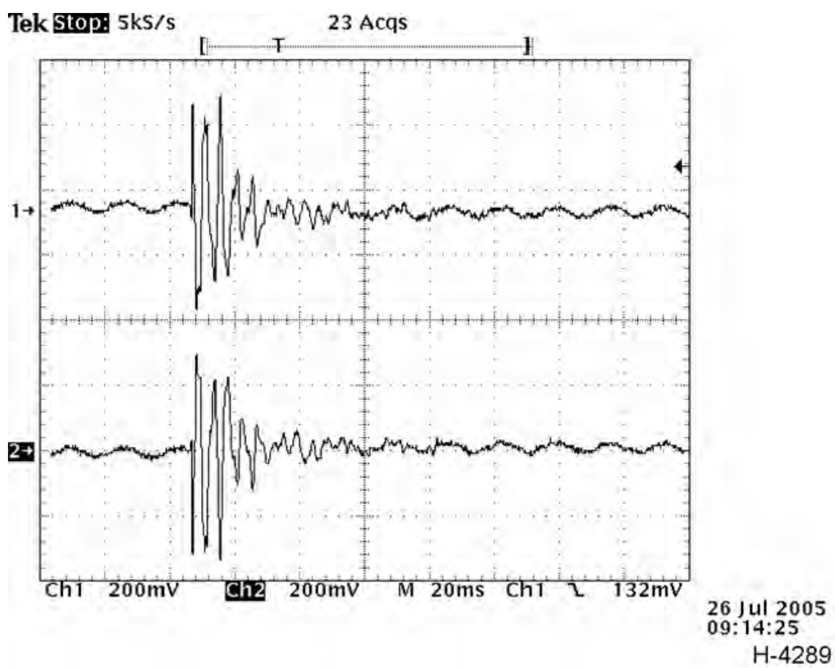


Figure 5. Oscilloscope trace of + and – differential analog signals from the PIGPEN sensor through 300 m of cable at 20 msec/div.

Figures 6 and 7 compare the short cable and long cable responses at higher temporal resolution. The slight differences in high frequency response are more readily apparent; however, since the acquisition system is sampling at 1 kHz, these differences will not be apparent in the digitized data.

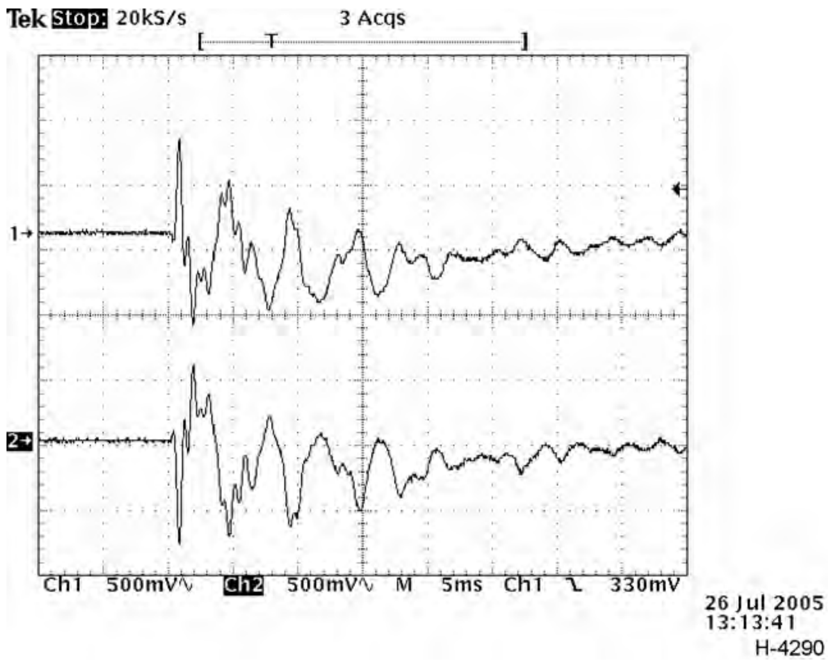


Figure 6. Oscilloscope trace of + and – differential analog signals from the PIGPEN sensor at 5 msec/div.

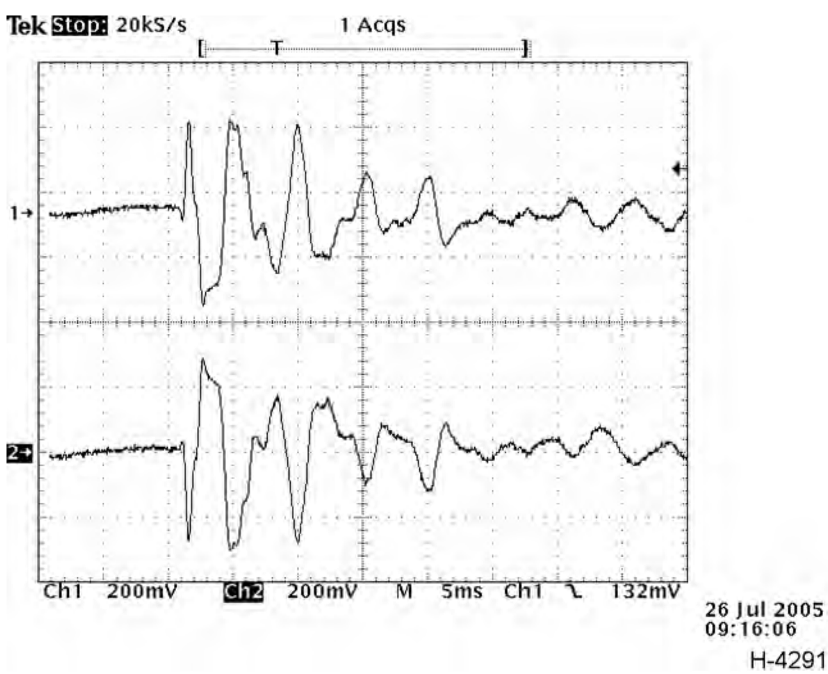


Figure 7. Oscilloscope trace of + and – differential analog signals from the PIGPEN sensor through 300 m of cable at 5 msec/div.

Figures 8 through 11 show the data acquired with the analog DAQ system through short (1 m) and long (300 m) cables. In the DAQ data, the frequency content is identical for the long and short cable cases. This result is expected since the sampling rate is 1 kHz. As in the oscilloscope traces the long cable signals are attenuated by approximately two- to three-fold.

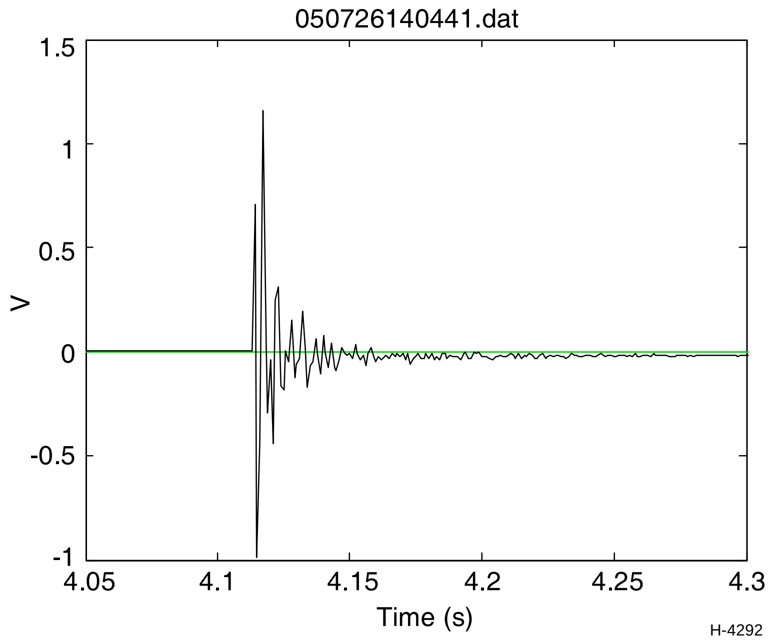


Figure 8. PIGPEN sensor data acquired with analog DAQ system with 1 m cable.

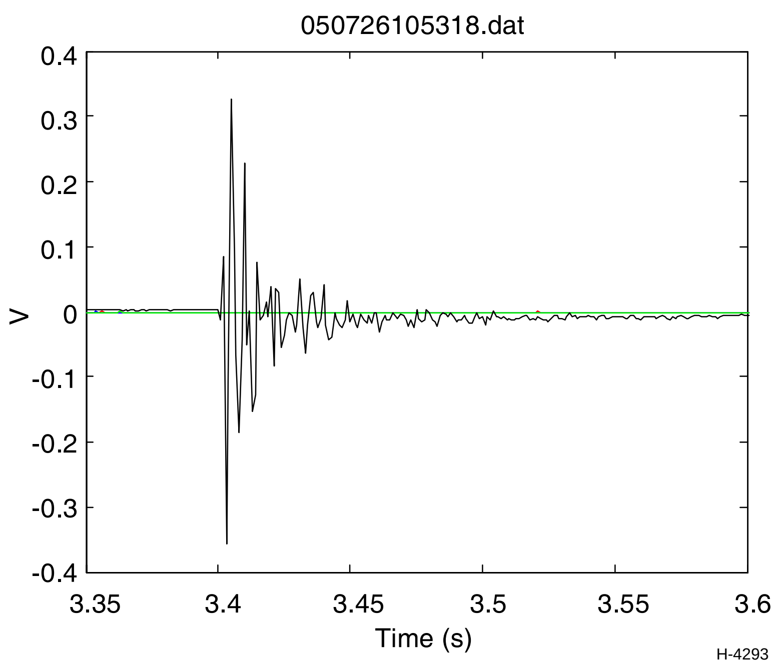


Figure 9. PIGPEN sensor data acquired with analog DAQ system with 300 m cable.

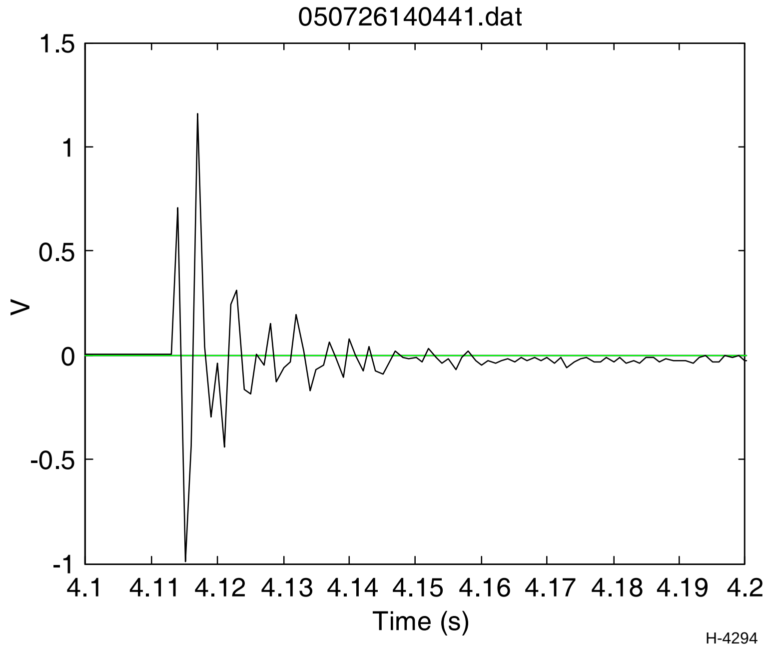


Figure 10. PIGPEN sensor data acquired with analog DAQ system with 1 m cable.

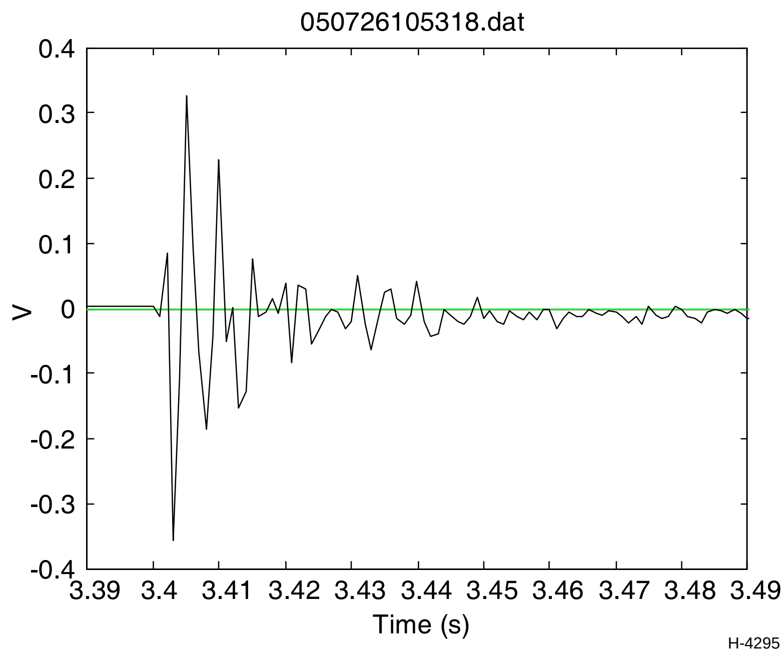


Figure 11. PIGPEN sensor data acquired with analog DAQ system with 300 m cable.

These data collections identified the important improvements necessary to undertake the next field tests that would evaluate PIGPEN performance for signal arrival times and triangulation accuracy, and the necessity to establish long time noise performance baselines. [Cables will not be required in the commercial product.]

2.3 Initial Long Term Deployment Testing

One of the first tasks in the SBIR Phase II program was to acquire long term performance data on the PIGPEN sensors. We identified a suitable site near PSI's Andover facility. The site is an empty building lot roughly 250 m x 200 m in size. We deployed 4 PIGPEN sensors at a site near PSI's facility (see Figures 12 and 13). The sensors were buried on 2 August 2005 and remained in the ground for nearly 2 months.

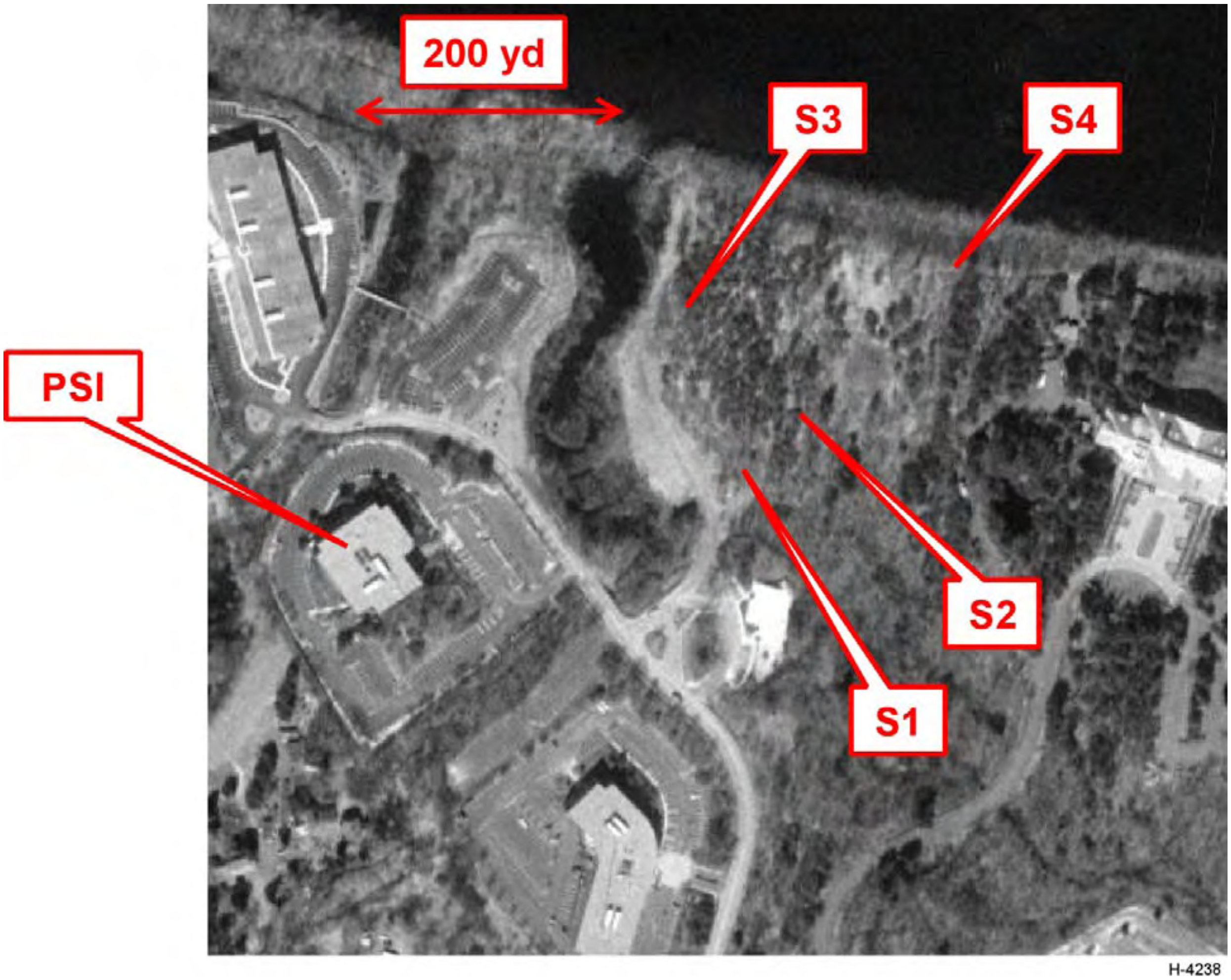


Figure 12. Aerial view of the test site and approximate sensor deployment geometry.

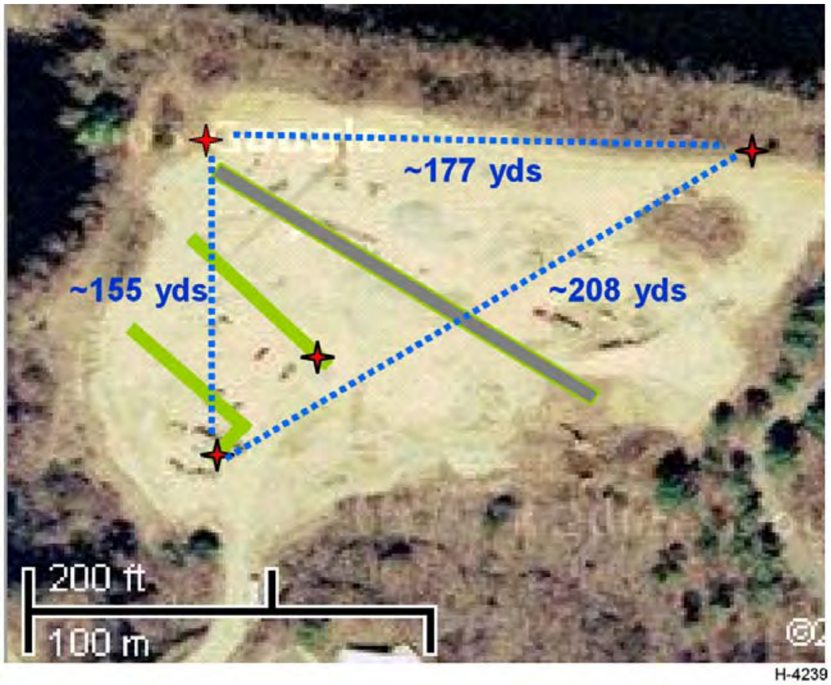


Figure 13. Sensor deployment geometry.

The sensors were buried 2 feet below grade. The holes were backfilled and the soil compacted by hand. The sensors remained in the ground, in their hermetic chasses between acquisitions. Data from a variety of sources was acquired at intervals over a two month period.

2.4 Initial Assessment of Triangulation Performance

One objective of the long term deployment was to quantify the triangulation performance of the PIGPEN. Triangulation accuracy depends on a variety of factors, including the local soil conditions. The site comprises alluvial fill (see Figure 14) and appears uniform in composition. The results of this test represent our attempt to determine the fundamental accuracy achievable in a real system. Varying geological conditions could degrade performance. Other factors such as site calibrations and modeling may then reduce uncertainties caused by adverse geological conditions.

We excited the ground in various locations with a sledgehammer, and then measured the time lags between the appearance of signal in each sensor. Those time lags are then used to determine the excitation position.

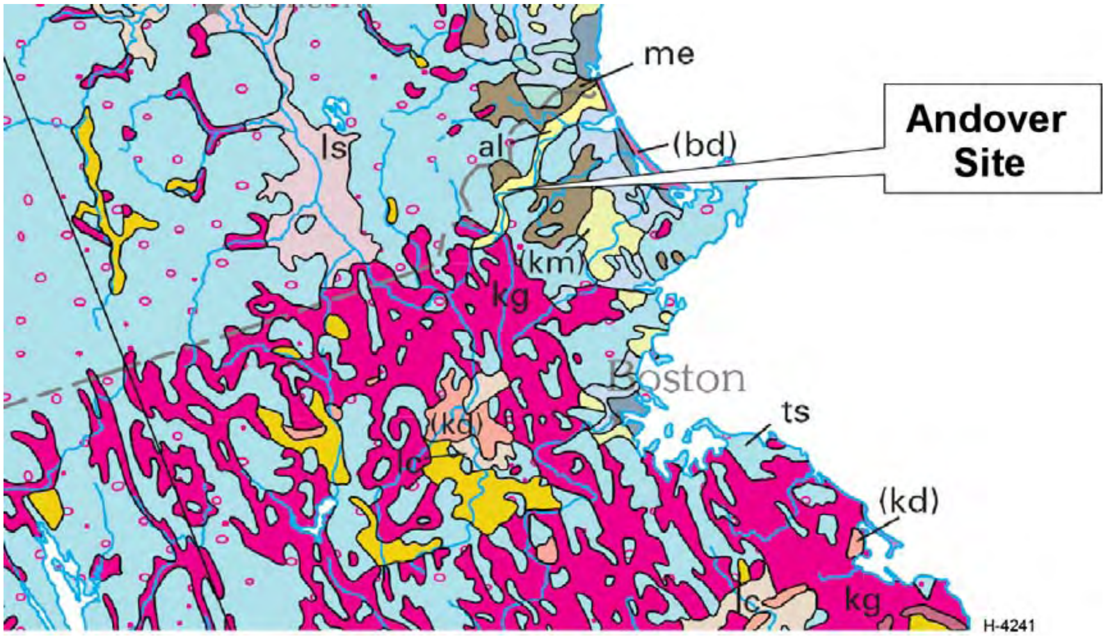


Figure 14. Geological map showing soils in the Boston area. The Andover site lies within the yellow band (surrounding the Merrimack River) that represents alluvium.

The first measurable parameter obtained is the soil velocity. Figure 15 shows the velocity calculated from data on two different days using sledgehammer impacts at varying locations at Andover site. The results show excellent agreement day-to-day with a velocity of 282 ± 4 yards/sec (256 m/sec). This velocity is consistent with NEHRP class D soil (National Earthquake Hazard Reduction Program). The measured velocity is also consistent with that of alluvial fill.

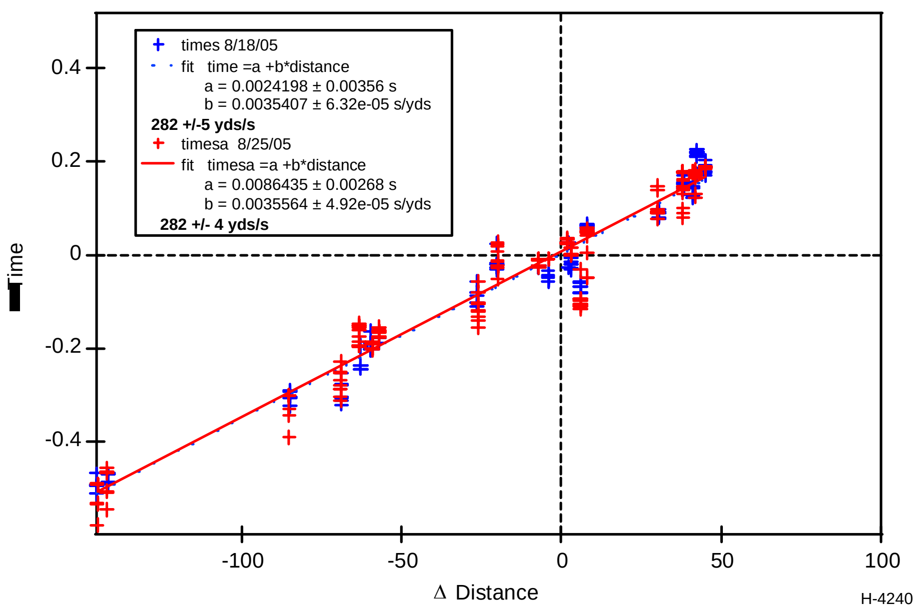


Figure 15. Velocity determination on two different days.

Typical surface wave velocities for alluvium in New York State range from 140m/sec to 430 m/sec [Nottis, "Predictive Equations for Soil Shear-Wave Velocities," Lamont Doherty Earth Observatory]. The empirical predictive model of Nottis yields a typical velocity of 324 m/sec for depth of 30 m.

Seismic waves spread reflect and refract as they pass through the soil. Even an impact signature that is essentially a delta function in time (at t=0) will appear as a complex wavepacket when observed by a sensor some distance away - it was not always easy to accurately and objectively determine time lags visually.

To address this we developed a cross-correlation algorithm for automatically extracting time lags from seismic data (see Figure 16). The time series data are filtered and input into the cross-correlation algorithm. The output is rectified and filtered to extract the time lag.

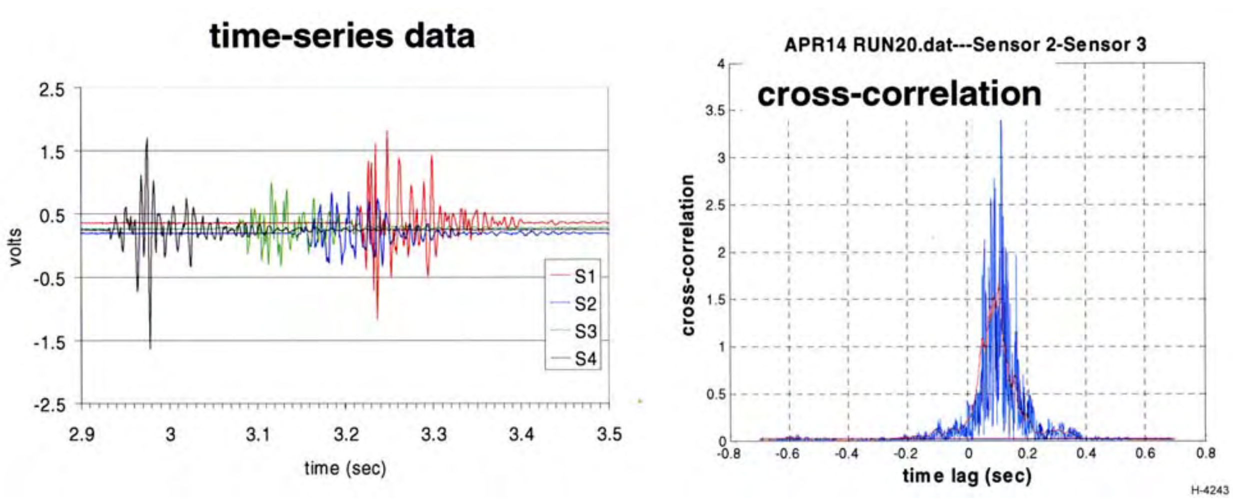


Figure 16. Cross correlation algorithm result (right) after processing PIGPEN time series data (left).

While determining velocity is an important first step, it is not sufficient only toward determining an actual threat position. That is determined using a triangulation algorithm. The algorithm is generalized and straightforward.

Two sensors locate a threat on a hyperbola (Figure 17). Additional sensors (up to 4) localize the threat to a point (Figure 18), or region when uncertainties are included.. We have also made the simplifying assumptions that the threat is on the surface and that the velocity field is uniform. Neither of these assumptions is required; however, they simplify the determination greatly.

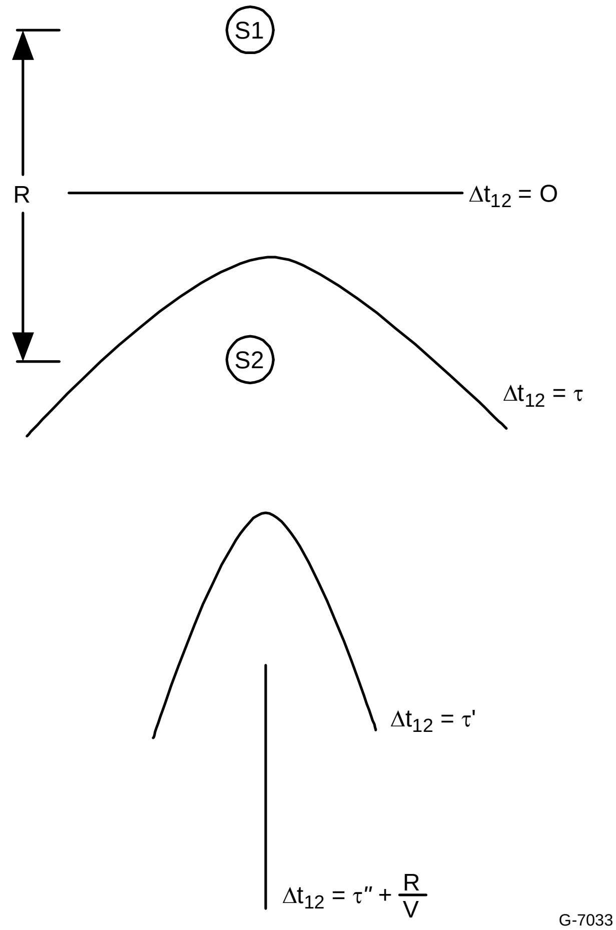


Figure 17. Two sensors localize a threat on a hyperbola when the threat is restricted to the same plane as the sensors.

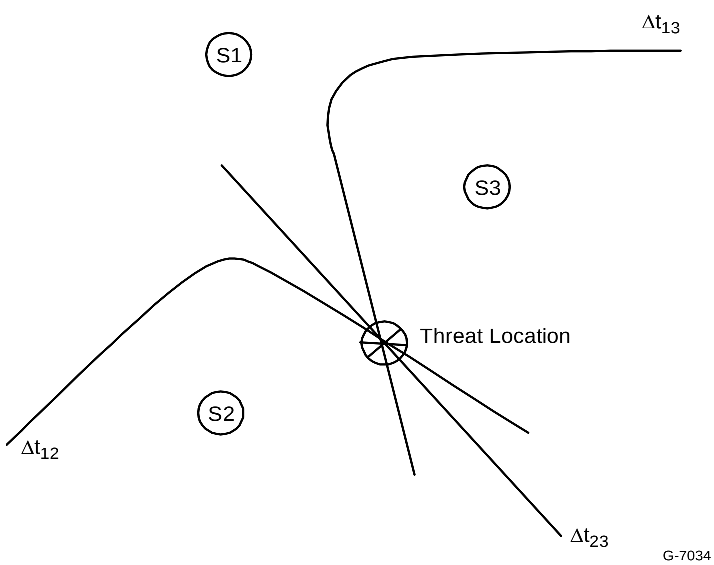


Figure 18. With multiple sensors, the threat is localized to a point (a region once uncertainties are included).

To qualify the triangulation accuracy, we acquired data on multiple sensors for sledgehammer impacts and a jackhammer. The threat positions were located at various points within the sensor grid. The threat positions and the sensor position were surveyed with an accuracy of ± 1 yard. We used three or four sensors in the analysis. Table 2 shows the results from our triangulation measurements.

Table 2. Results of Triangulation Accuracy Measurements

	Surveyed (± 1 yd)		**PIGPEN measurement**	
	X	**Y**	**X**	**Y**
Sledgehammer – U	24.7 yd	23.4 yd	27.8 ± 0.8 yd	25.9 ± 1.1 yd
Sledgehammer – V	65.1 yd	47.9 yd	64.4 ± 1.4 yd	53.5 ± 1.0 yd
Sledgehammer – X	125 yd	-4.5 yd	128 ± 0.6 yd	4.2 ± 1.0 yd
Jackhammer	-22.5 yd	62.4 yd	-18 ± 1.0 yd	64 ± 1.0 yd

Each point represents about ten individual hammer strikes (or about 6 separate 30 second acquisitions of jackhammer data). The precision of the triangulation determination is comparable to the surveyed accuracy (± 1 yard). The accuracy of the triangulation varies from 1 to 9 meters. The rms accuracy for triangulation is 3.5 m. The nominal range of the threat from the sensors is 150 yards. This derived accuracy is in agreement with the project goal listed in Table 1, although at reduced range.

2.5 PIGPEN EP-2 Field Testing

PSI deployed a PIGPEN Experimental Prototype-2 (EP-2) unit with digital signal processor (DSP) at a site near PSI's Andover, MA facility. We acquired background and threat (jackhammer) data. Those data are summarized in Figures 19 and 20 and Tables 3 and 4.

The DSP executed an algorithm to identify the type of threat present based on the threats unique seismic signature. The algorithm first uses a filter bank to create a coarse, normalized, power spectrum and then analyzes that spectrum to determine the type of threat present (or if no threat is present). Figure 19 compares the conventional power spectrum calculated in MATLAB with the DSP filter-bank output.

Figure 20 shows the DSP power spectra output for periods of background and periods when a jackhammer was present. The spectra are normalized for a total power = 100.

Table 3 shows the activities over a period of a few hours and the EP-2 algorithm output. When the threat is present (in this case a jackhammer), the automatic processing correctly identifies it. When the threat is not present, however, the algorithm dithers between background, jackhammer, backhoe and unknown assignments (see Table 4). This result indicates that the overall threshold on the algorithm was set too low, resulting in false positives. We refined operation based on these observations.

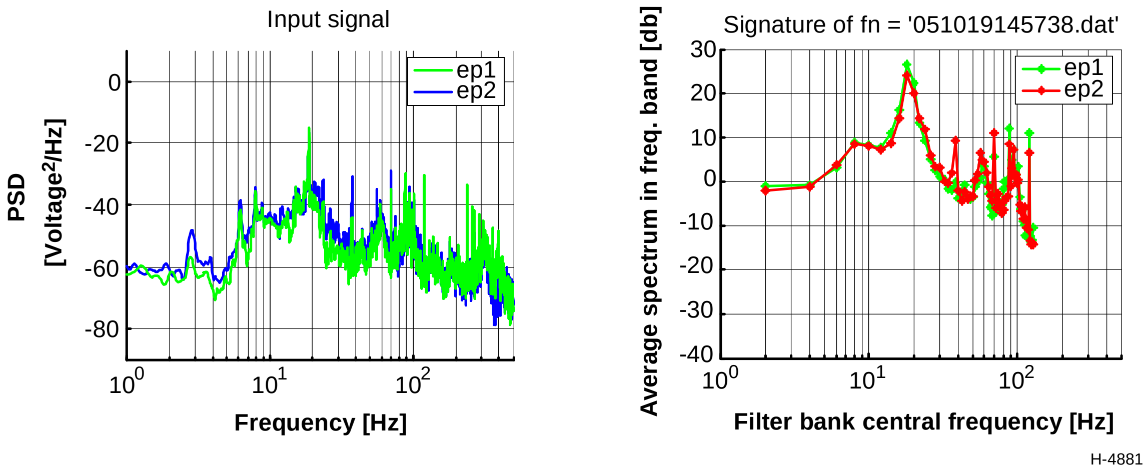


Figure 19. Conventional power spectrum of PIGPEN data calculated by MATLAB (left). Algorithm filter bank output calculated by EP_2 DSP (right).

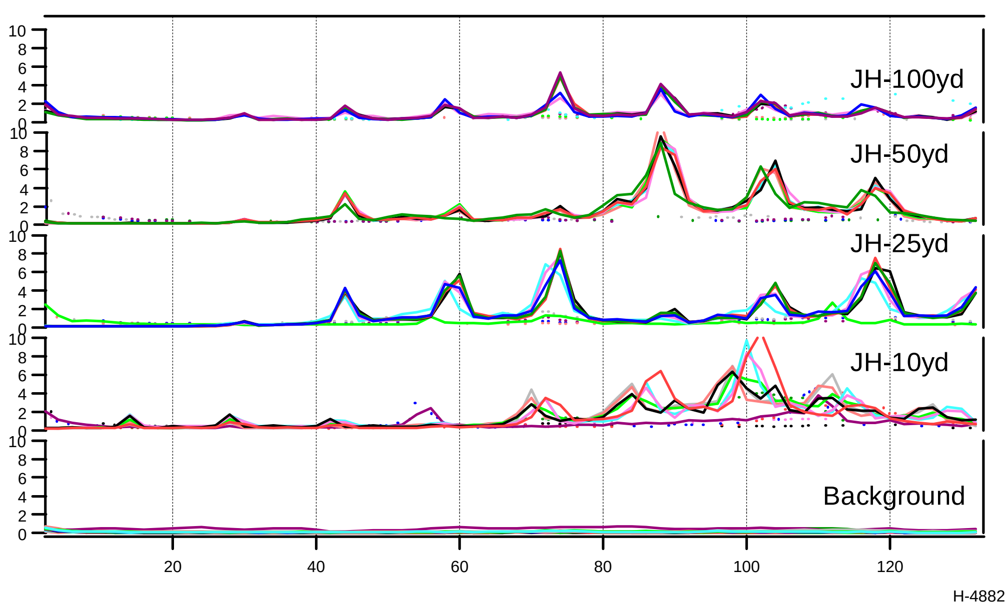


Figure 20. DSP intermediate output of power spectra with and without a jackhammer present.

Table 3. Summary of Data Acquired on 30 September 2005 and EP-2 DSP Algorithm Result

Distance (yards)	**Event**	**EP-2 Event ID**	**Distance (yards)**	**Event**	**EP-2 Event ID**
5	Noise	Backhoe	50	Noise	Noise
5	Noise	Backhoe	50	Noise	Noise
5	Generator??	Jackhammer	50	Noise /gen	Noise
5	Generator	Jackhammer	50	Generator	Backhoe
5	Gene/Jackham	Jackhammer	50	Jackhammer	Jackhammer
5	Jackhammer	Jackhammer	50	Jackhammer	Jackhammer
5	Jackhammer	Jackhammer	50	Jackhammer	Jackhammer
5	Jackhammer	Jackhammer	50	Jackhammer	Jackhammer
5	Jackhammer	Jackhammer	50	Jackhammer	Jackhammer
5	Jackhammer	Jackhammer	50	Jackhammer	Jackhammer
5	Jackhammer	Jackhammer	50	Jackhammer	Jackhammer
5	Jackhammer	Jackhammer			
5	Jackhammer	Jackhammer	100	Noise	Backhoe
			100	Noise	Noise
25	Noise	Noise	100	Generator	Noise
25	Noise	Noise	100	Generator	Backhoe
25	Noise	Noise	100	Jackhammer	Jackhammer
25	Gen/Jack	Jackhammer	100	Jackhammer	Jackhammer
25	Gen/jack	Jackhammer	100	Jackhammer	Jackhammer
25	Jackhammer	Jackhammer	100	Jackhammer	Jackhammer
25	Jackhammer	Jackhammer	100	Jackhammer	Jackhammer
25	Jackhammer	Jackhammer	100	Jackhammer	Jackhammer
25	Jackhammer	Jackhammer	100	Jackhammer	Jackhammer
25	Jackhammer	Jackhammer			
25	Jackhammer	Jackhammer		Pd=100	
				Pfabhoe=3/9	backhoewhennoise

Table 4. Background Data Files for EP2

Run#	**Identity**	**Run#**	**Identity**	**Run#**	**Identity**
1	Backhoe	8	Backhoe	15	Unknown
2	Jackhammer	9	Jackhammer	16	Noise
3	Noise	10	Backhoe	17	Jackhammer
4	Noise	11	Backhoe	18	Jackhammer
5	Jackhammer	12	Backhoe	19	Jackhammer
6	Noise	13	Jackhammer		
7	Backhoe	14	Jackhammer		
Noise	**Unknown**	**Jackhammer**	**Backhoe**	**Jackhammer**	**Backhoe**
4	1	8	6	8	6

3.0 Refinement of Algorithms

3.1 Triangulation

Before beginning the AP engineering development effort, we internally reviewed the initial data and identified two issues that required further investigation to enable AP and product development:

a) The triangulation accuracy required by the gas industry (target customer community)

b) The interface specification and system architecture for AP and for the future commercial system

3.1.1 Triangulation Accuracy

After extensive discussions NYSEARCH and PSI it was recommended that the goal for the baseline performance for triangulation accuracy should be improved to an accuracy of 10 feet at a range of 300-500 yards. Initial testing had demonstrated a triangulation accuracy of 3.5 m at a range of roughly 150 m. This tighter requirement shaped much of the effort in the rest of this SBIR program. We continued to work to achieve this accuracy through test for the rest of the program.

3.2 Communication Interface

After an investigation of SCADA network standards, we concluded that a communication system for AP based on RS-485 would be the sensible choice. In the development of AP, we wished to focus on the system performance (for detecting 3d party damage) and not on developing a network protocol. At the same time, we wished to develop a system that is likely to be forward-compatible so that we may minimize redesign in future systems.

The transmission of information collected by remote sensors may be over a physical pairs of wires, telecommunication circuits, wireless radios or satellites. Some definitions of the most common remote data acquisition systems first follow.

Telemetry: This is an automated communications process by which data is collected by remote instruments or inaccessible points and transmitted to receiving equipment for measurement, monitoring, display, and recording.

Supervisory Control and Data Acquisition (SCADA): This is a measurement and control system consisting of a central host (or Master) and one or more remote units/stations (e.g., PIGPEN) controlled by standard and/or custom software. SCADA systems often cover large geographic areas, and rely on a variety of communications systems. They use sophisticated database, provide graphing and reporting functions, offer a human-machine interface, and have software initiated alarms to alert control engineers to specific conditions. Distributed Control Systems (DCS) are similar to SCADA systems but they often cover smaller geographic areas (e.g., factories and treatment plants) and typically communicate over a Local Area Network (LAN). SCADA networks are used in almost all (gas and oil) pipeline monitoring systems. Some of the information collected and transmitted through existing SCADA networks are: flow rate, operation status, pressure, and temperature.

Many companies offer various SCADA networking packages using a variety of proprietary and open-standard protocols. However, the one thing that most SCADA protocols have in common is that they are designed to use RS-232 or RS-485 as communications network.

Protocol: A protocol is an agreed-upon format for transmitting data between devices. They can be implemented in software or hardware. Protocols used in SCADA (or Telemetry) networks determine the essential communication elements, such as:

- Network node address format (a node is a terminal in the network)
- How the sending device will indicate that it has started or finished sending a message
- How the receiving device will indicate that it has received (or not received) a message
- The data compression method (if any)
- The type of error checking the devices will use

Examples of such SCADA network protocols are: BSAP (Bristol Babcock), DNP3, DF1 (Allen Bradley), Fisher (ROC & FloBuss), Mercury (Mercury), Modbus (ASCII), Opto-22, Sixnet, SNP (GE Fanuc).

3.2.1 Device to Device Transfer

The most basic SCADA/Telemetry applications involve data transfer from a remote device to a central facility. Two of the most common means of connecting the devices are detailed below.

Unsolicited Reporting

In this case, a remote device (e.g., PIGPEN sensor) is set to send data to a host server (e.g., NIB) in a continuing basis. This is often the case with remote devices that don't have a communications protocol, and can only stream data out of a serial interface.

Figure 21 shows the architecture for this configuration. In this architecture, a modem is required to interface the remote device to the SCADA network.

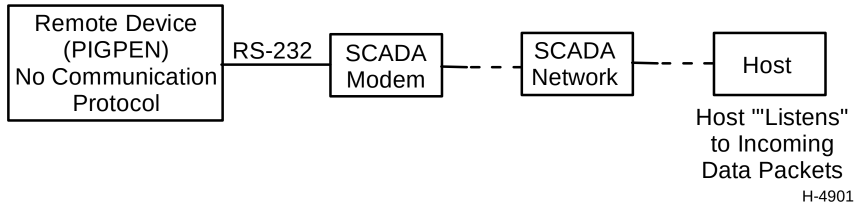


Figure 21. Architecture for unsolicited data transmission.

Solicited Reporting: Terminal, Telnet or Serial-Based Software Connections

Many devices have an internal menu-driven data collection mechanism accessible with a simple terminal emulation program such as HyperTerminal. Others may have vendor-provided software that communicates to the device via a serial interface. In either scenario, connecting the device to a SCADA network is often quite simple. Figure 22 shows the architecture for this configuration. In this architecture, no modem is required and the device can be directly connected to the SCADA network through an RS-232 or RS-485 line.

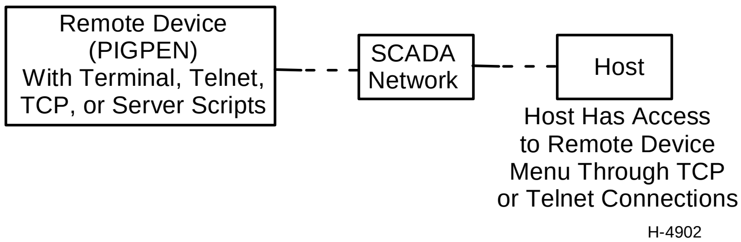


Figure 22. Architecture for solicited data transmission.

3.2.2 Examples of SCADA Systems in Use by Pipeline Companies

A few examples of pipeline companies, their SCADA systems, and the manufacturers of the systems are given in Table 5.

Table 5. SCADA Systems

Company	**Network System in Use**	**Manufacturer**
Texas Gas (part of Williams Companies Inc., Tulsa, OK)	Citect 5.21 SCADA (384-kbps over a WAN of 68,480 control and 129,827 data points)	Ci Technologies (Charlotte, NC)
Alyeska Pipeline Services (Canada & USA)	UCOS SCADA (wired network for 100-mile pipeline, 4,121 input points, 813 control points)	Control Systems International (USA)
Duke Energy Gas Transmission (BC, Canada)	SR500 SCADA (wireless network, 64-kps, 511 remote nodes)	SR Telecom (QC, Canada)
Alliance Pipeline (Canada & USA)	Plantscape SCADA (Satellite-based, Bristol BSAP protocol)	Honeywell Inc.

3.2.3 Technical Drivers for PIGPEN Communication Selection

The AP DSP is based on the Analog Devices ADSP-218X family. It includes 2 Single ended Serial Interfaces with a minimum serial speed 20 Mbps. The DSP performs threat identification on 30 second data set and transmits to central node threat warning and type. The type of data transmitted includes:

- Type of threat and time stamp of detection
- Reduced data set (example time stamp and 2 sec. data)
  - Identify threat transient using frequency analysis then transmit data recording transient event only (backhoe shovel impact)
  - Time window data for periodic threats (jackhammer)

Issues with the data transmission include:

- Data time stamping
  - Have Central node periodically broadcast a universal time
  - Have Central node simultaneously initiate data collection on multiple sensors
- Local sensor DSP will need to sample and hold data for transmission

Possible transmission modes include wired or wireless networks. For wired networks RS-485 is a common standard and supports 100 kbit/s at 1200 m and higher bandwidths at shorter distances. However, the standard does not specify data protocol and the number of supported nodes is protocol and hardware dependent. For example sample hardware from TI supports speeds of 500 kbit/s @ 1000 m with 256 nodes).

For wireless solutions, there are several options including: 300 MHz, 433 MHz, 900 MHz, 2.4 GHz, Cellular, and satellite. Previously, we investigated wired network solutions. In this period, we have investigated the various wireless solutions.

We also developed interface specifications to permit possible inclusion with the Automatika, Inc. and NYSEARCH-developed GasNet system. GasNet is a suite a sensors and a communication system that measures a variety of gas pipeline parameters. PIGPEN would provide a complement to the GasNet suite.

3.3 PIGPEN Network Communication

In parallel with the investigation of system architecture and system communication interface requirements, we began developing an algorithm to extract and transmit sensor data required to perform the triangulation calculations at the Network Interface Box.

The triangulation algorithm is based on a cross-correlation between pairs of sensors. From several pair-wise combinations, one determines differences in arrival times of the signals. From those differences, the algorithm then determines the source location.

In the simplest scheme, all sensor data is transmitted to the network interface box, where the algorithm is executed – a total 960 kbytes of data for a sixteen sensor subnet. Transmitting that amount of data is not feasible for a simple, low-power network.

Techniques for extracting the critical segments of data at each sensor for transmission to the Network Interface Box were explored to reduce the data transmission to 8 kbytes total (4 sensors x 1 sec of data). To develop the algorithm, we must decide what information to transmit. Ideally, the exact time of arrival (TOA) of threat signal. Practically, the data frame containing time-of-arrival (TOA) for cross-correlation calculation. Once the amount of data is determined, we can formalize the sensor to NIB communication. This assumes/requires that all sensors in the network have the current time.

We investigated two methods for finding smallest data frame containing TOA:

- Method 1: Apply threat ID algorithm to test for threat presence in fractions of original data frame.
- Method 2: Compare signal energy in fractions of original data frame.

Those approaches are shown graphically in Figure 23.

Step 1: Run threat ID on 30-sec. data frame.
Step 2: Test for threat presence in left-half of data frame.
Step 3: If frame size > 30/2n and threat detected in left-half go to step 2 with left-half frame, otherwise go to step 2 with right-half frame.
Step 4: Transmit reduced data frame.

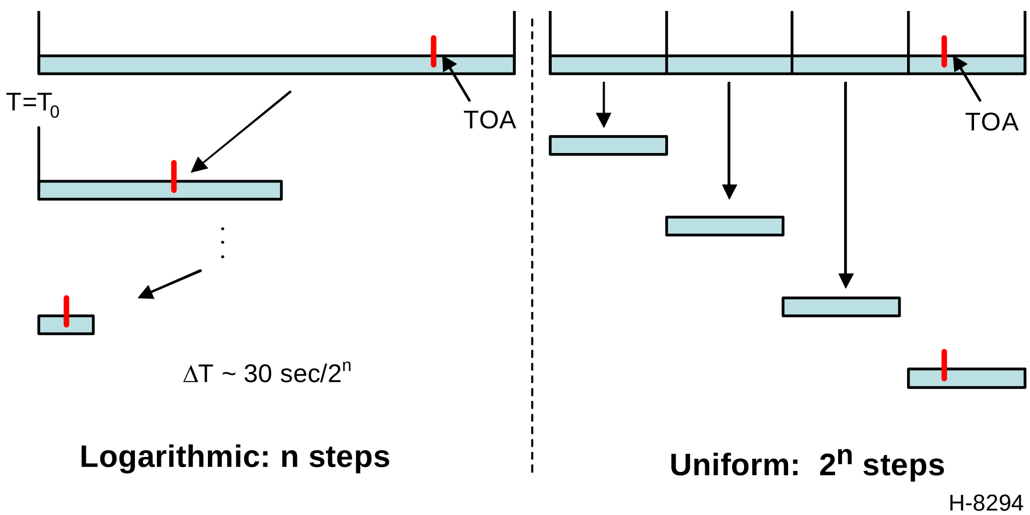


Figure 23. Methods of identifying critical time of arrival data by successive analysis: successive factor-of-two reductions in data, or uniform divisions.

We developed an algorithm that automatically sorts a 30 sec data file to determine the ideal minimum data segment to transmit for cross-correlation analysis. The algorithm makes decisions on successive factor of 2 reductions in the data segment length. Figure 24 shows two examples. The blue curves are the time series data from a sensor that was measuring jackhammer activity. The blue curves are the full 30 sec data set (30,000 points). The red curves are the data segments selected for transmission by the sorting algorithm (940 points). The data reduction is 32x.

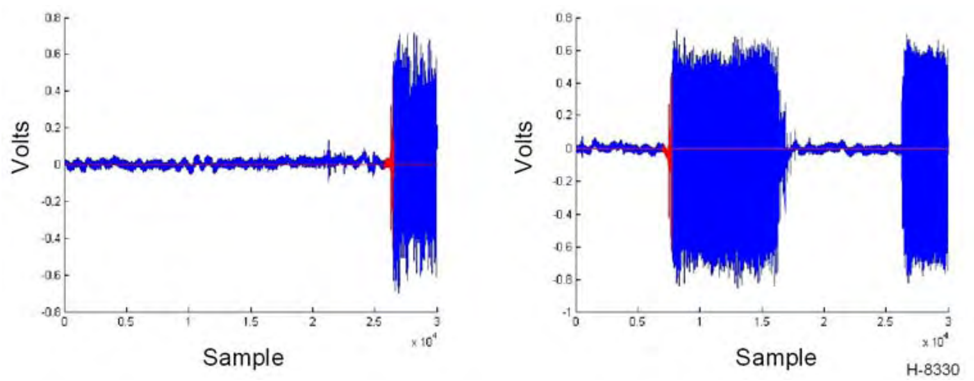


Figure 24. Examples of data sorting algorithm results. The blue curves are the full data set. The red curves are the data selected by the sorting algorithm.

Figure 25 shows a comparison of the cross-correlation analyses for the full data set and the reduced data set. The lower left figure shows the cross-correlation result for the full data sets. The lower right figure shows the cross-correlation result for the reduced data sets. Both correlation results show similar widths and result in the same calculated time lag (182 msec). There is no degradation in accuracy caused by the reduced data set.

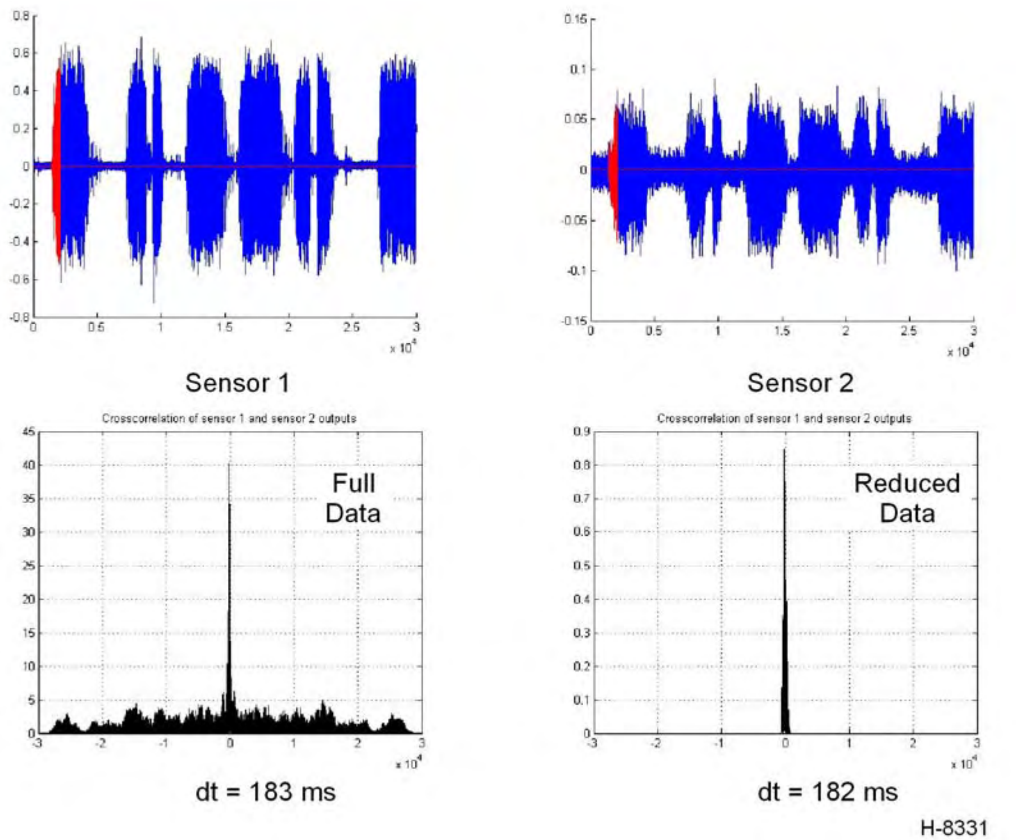


Figure 25. Comparison of the cross-correlation analyses for the full data set and the reduced data set. The lower left figure shows the cross-correlation result for the full data sets. The lower right figure shows the cross-correlation result for the reduced data sets.

3.4 Assessment of System Error

Based on the acquired critical data demonstrating triangulation feasibility, we created a system model to guide future PIGPEN development. The system model helped identify critical error terms, guided further data acquisition and field tests, optimized sensor grid configuration and operations, and optimized the algorithms.

A mathematical model is required as the triangulation uncertainty is a complex, non-linear function of threat position and sensor grid geometry. The errors cannot be determined in closed form. The total error depends on propagation of errors through triangulation algorithm, error and uncertainty in time lag determination and processing, and errors and uncertainty caused by complex soil conditions.

Figure 26 shows an example of the error field calculated for a three-sensor grid. There are clearly regions of low error and regions of higher error. The errors vary spatially. The model proved valuable for predicting and comparing to field test results of triangulation accuracy.

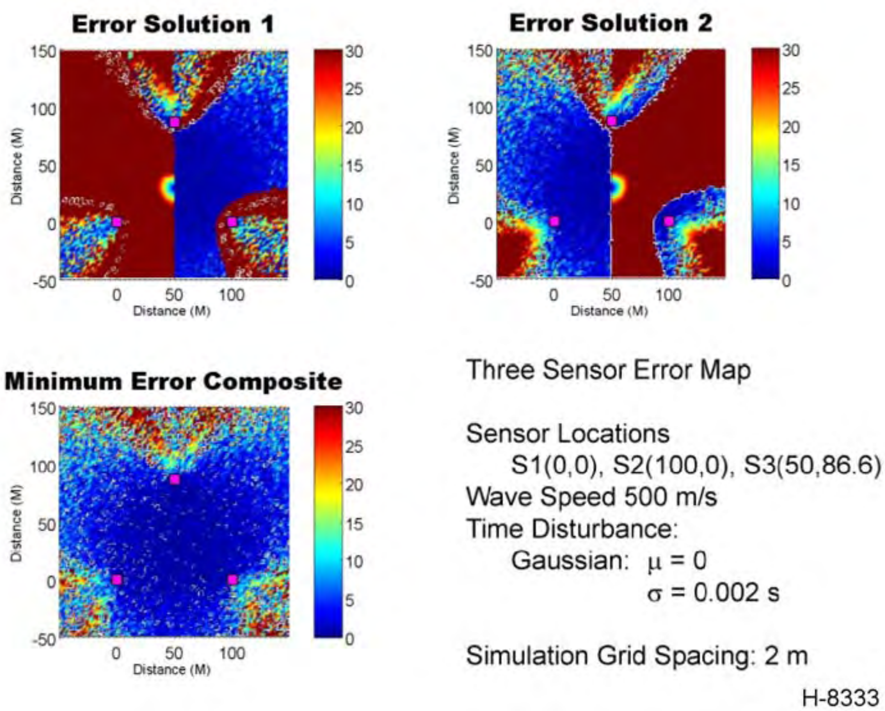


Figure 26. Calculated error grids for a 3-sensor grid.

3.5 PIGPEN Network Architecture

We conducted a thorough system design study and investigation several architectures for the PIGPEN AP and for future commercial systems. We concluded that there are three system drivers.

- How to *Power* each sensor
  - How much power?
- How to *Communicate Data* across network
  - How much data in how much time?
- How to *Synchronize Time* across network
  - How precise must the synchronization be?

We concluded that the AP should be battery powered, have wireless communication from each sensor directly to the Network Interface Box, and have local time synchronization.

All three system drivers are commercialization issues and not fundamental science issues. Nor are they internal product definition issues, but they do drive system performance. The commercialization issues vary by application and the amount of existing infrastructure. Therefore, the AP development should be robust enough to enable PSI to demonstrate the system performance and be flexible enough to accommodate future interface changes. Our baseline architecture is shown in Figure 27. Each sensor node includes a sensor and power and communications adaptor (PCA). Each sensor communicates wirelessly to the Network Interface Box. The sensor and NIB are constant regardless of application. The PCA enables adaptation to different power and communication protocols.

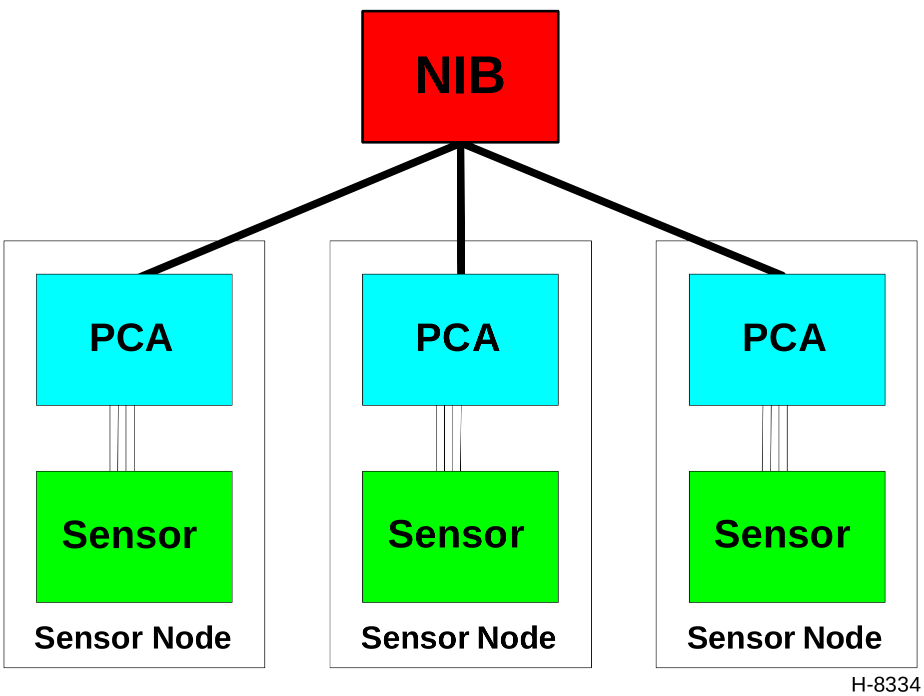


Figure 27. PIGPEN system architecture.

4.0 Extended Field Data Collections of the EP System

4.1 Background Stability Data

PSI deployed PIGPEN sensors in urban and suburban environments to collect 24 hour data segments. These data segments provide sensor drift and comprehensive background data.

Some of those data acquired in a suburban environment are shown in Figure 28. Figure 29 shows the total power in the sensor data as a function of time. Figure 30 shows the total power from an urban environment. In the urban data, we were able to correlate peaks with specific activities (trains, airplanes, traffic, etc.)

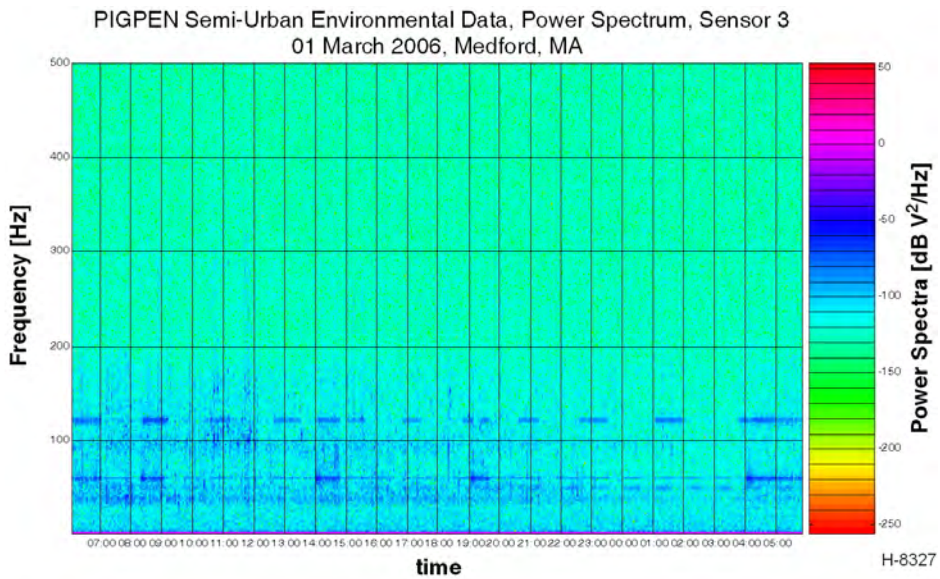


Figure 28. Power Spectral density of PIGPEN sensor data as a function of time for a suburban environment.

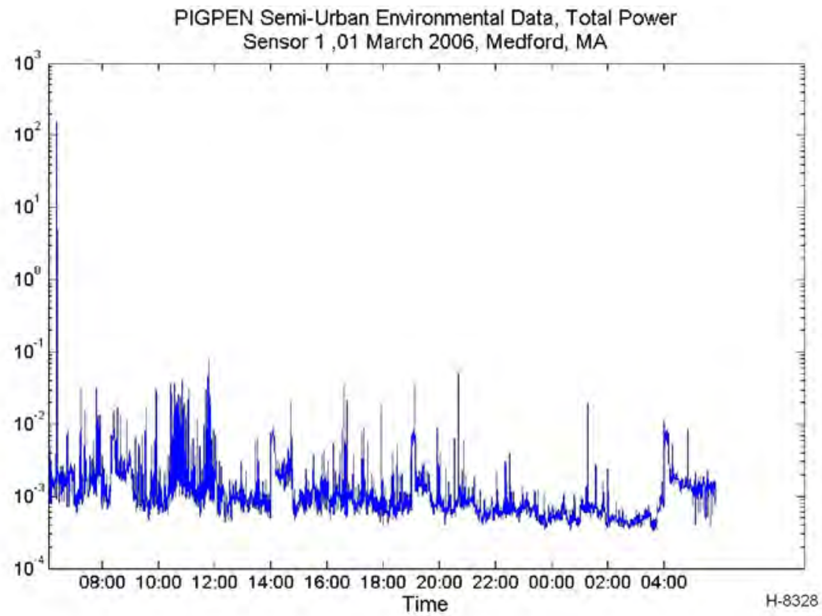


Figure 29. Total power in the PIGPEN sensor data as a function of time (suburban).

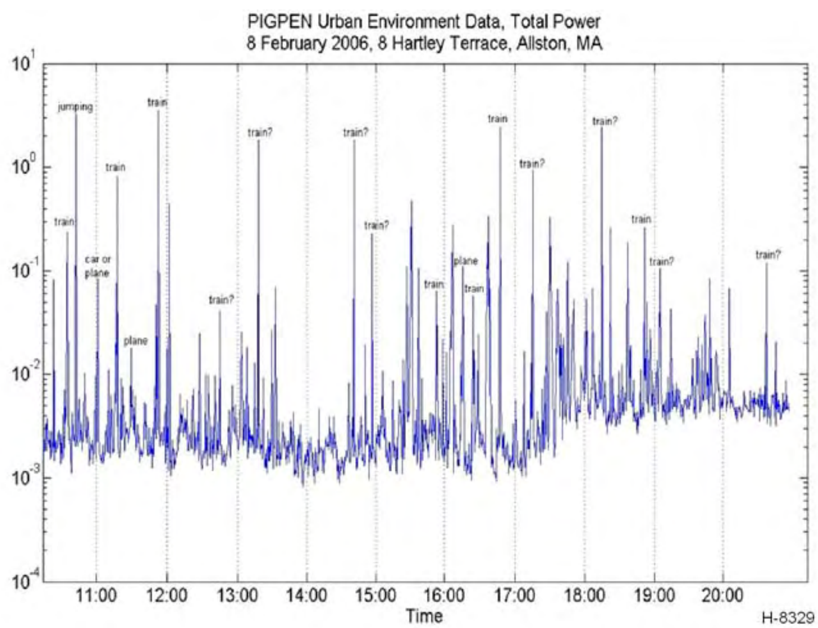
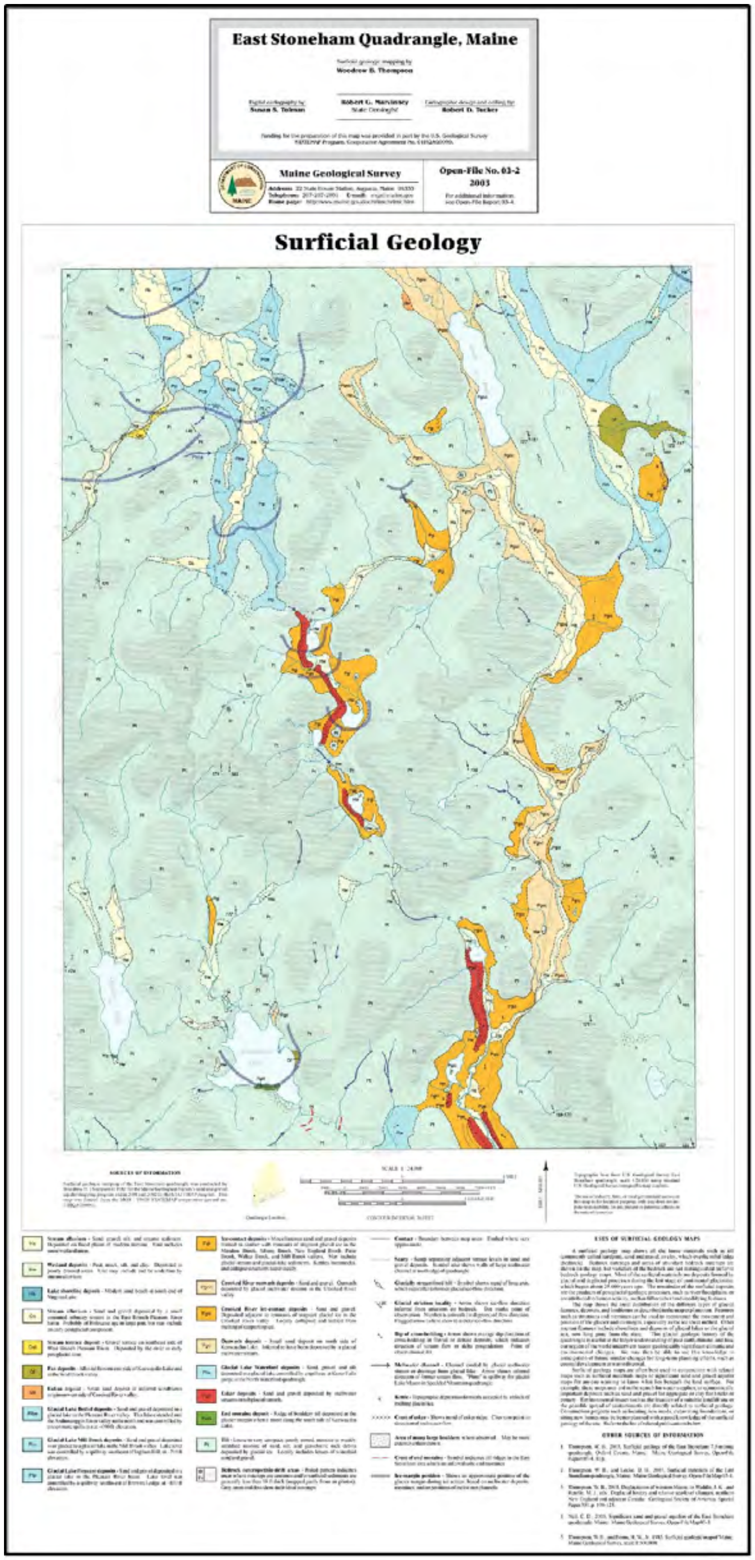


Figure 30. Total power in the PIGPEN sensor data as a function of time (urban).

We also acquired 11 hours of data in a rural setting (Stoneham, ME) to complement the urban and suburban data already acquired. A map of the surface geology is shown in Figure 31.



J-4945

Figure 31. Surface Geology near Stoneham Maine test site.

Figure 32 shows the spectral-temporal profile of data collected at that location. Figure 33 shows the total power as a function of time. The large feature (>10^{-2} total power) is the result of activity at the sensor site by the PIGPEN team.

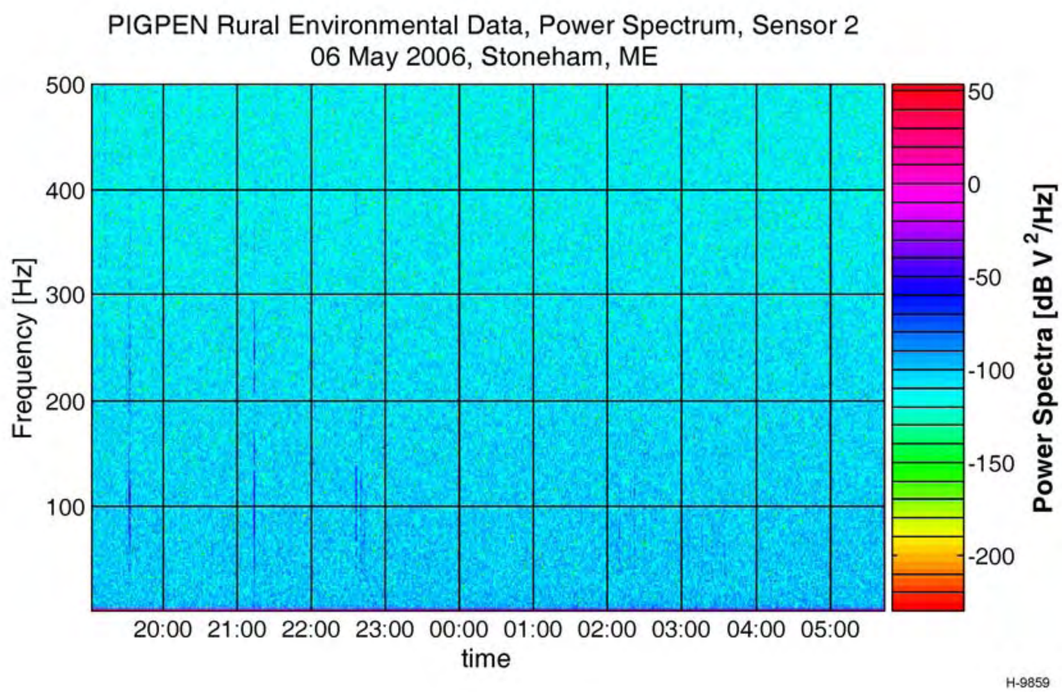


Figure 32. Spectral-temporal profile of rural PIGPEN data.

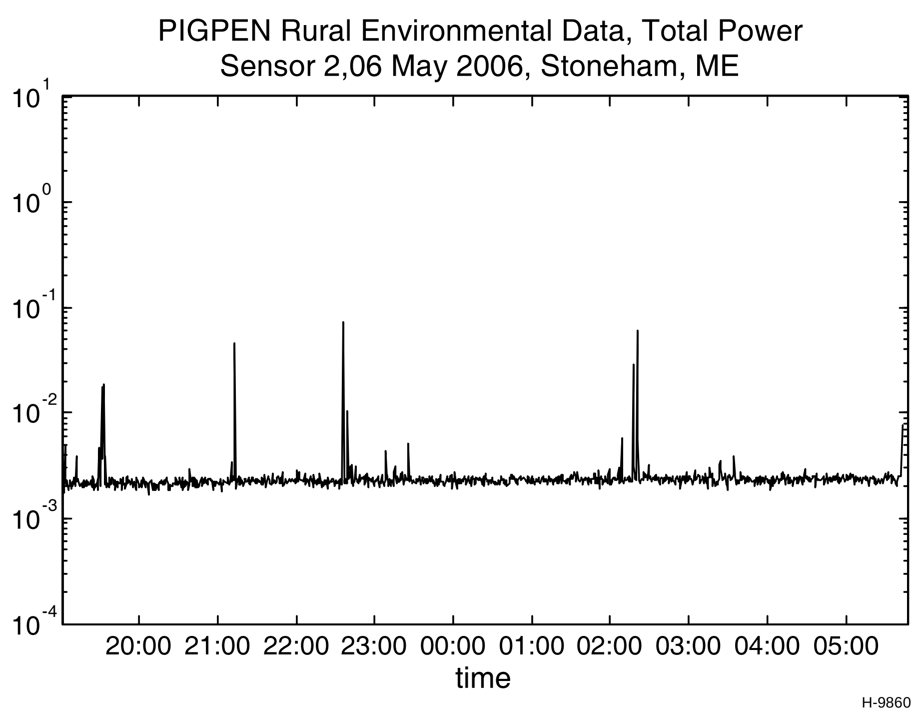


Figure 33. Total power vs time of rural PIGPEN data.

4.2 Acoustic Test Source Acquisition for Triangulation Database and Algorithm Development

We developed a very controlled experimental configuration to acquire a database of triangulation data used to refine an automated triangulation algorithm. We acquired data on 1 June 06 and 27 June 06 at 35 New England Business Ctr, Andover, MA – a site close to PSI. The test configuration is shown in Figure 34. We used a sledgehammer to excite the ground repeatedly at fixed distances along the 320 foot leg. As sensors S2 and S3 are equidistant from any point along the long leg, the time lag for signals arriving at those sensors should be zero. The dispersion and spreading of the received signal will change for S2 (or S3) and S1 as a function of position as well. We will compare the performance of the triangulation algorithm on the S1 and S2 (or S3) signals as a function of that dispersion.

Figure 34. June 2006 triangulation test configuration.

We had three objectives for this test:

1. Assess triangulation algorithm performance as a function of signal-to-noise ratio.
2. Acquire sufficient data to develop and test an automated triangulation algorithm.
3. Assess triangulation algorithm performance as the dispersion in the received signal changes as a function of threat position.

Figure 35 shows the signal-to-noise ratio for each of the sensors as a function of distance from each sensor.

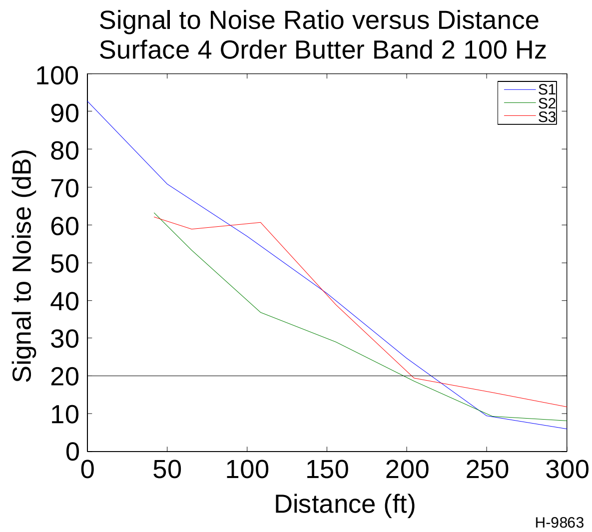


Figure 35. Signal-to-noise ratio as a function of distance for each sensor.

Figure 36 shows the cross-correlation functions between S3 and S3 as a function of distance with no post-processing. Note that the correlations are centered about zero time lag as expected. They correlations remain distinct until a distance of 250 feet (SNR=10 dB for S2 and S3).

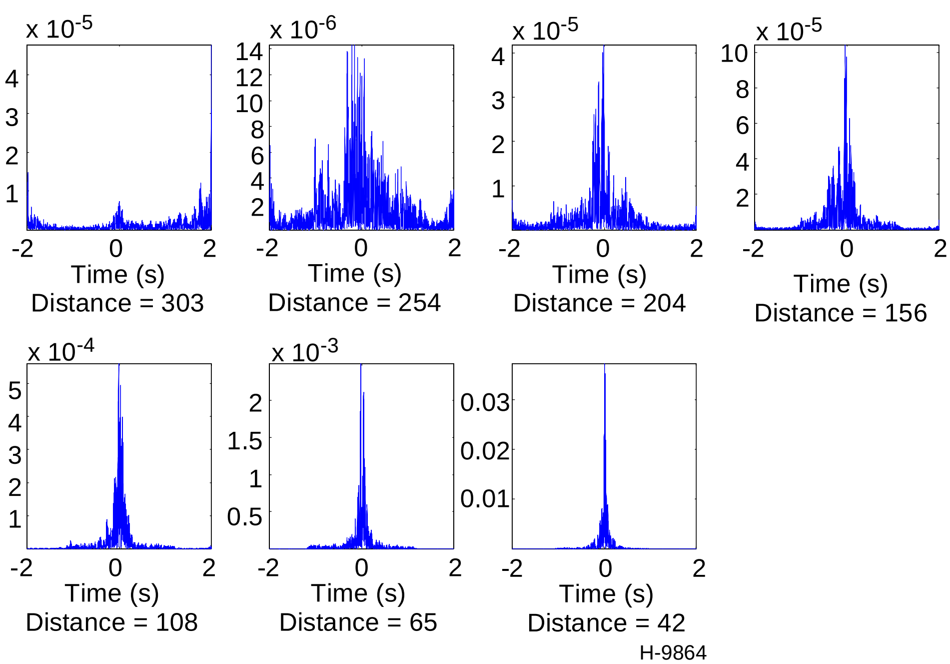


Figure 36. Correlation functions as function of distance – no post-processing.

Although the correlation functions are sharp and easily distinguished by eye, the fluctuations in the correlation make it difficult to select the best value through an autonomous process. By filtering the data, the correlations are smoothed and lend themselves more easily to an autonomous peak-selection algorithm (Figure 36). We used a 200th order Finite Impulse Response filter with at cutoff frequency of 10 Hz.

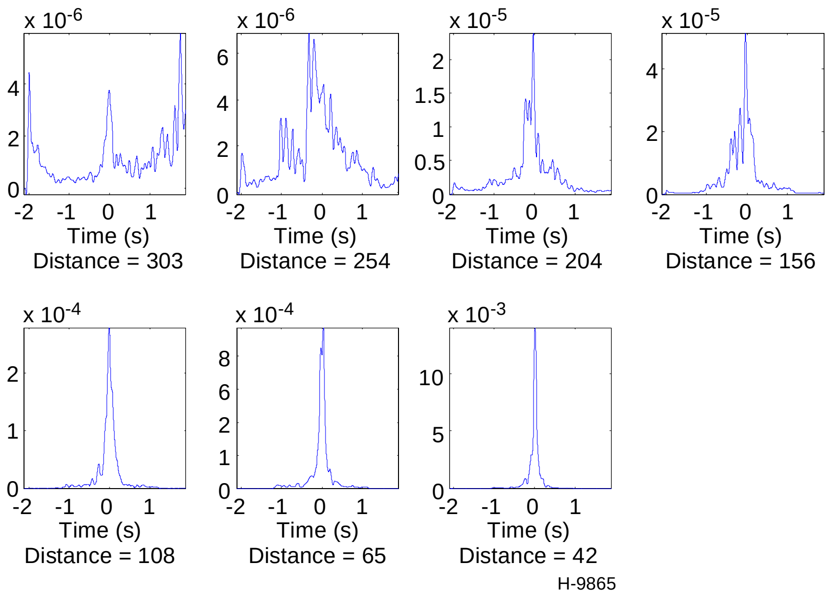


Figure 37. S2-S3 cross-correlation functions after filtering with a 10 Hz cutoff filter.

Table 6 summarizes the results in numerical form. At each distance there are 12 hammer strikes taken at 4 separate times. The tables summarize the time lag determined by the automated process for the unfiltered case and two different filters (20 Hz cutoff and 10 Hz cutoff). The right-most columns are the means and standard deviations of the cross-correlations at each distance.

Table 6. Results of Automated Cross-Correlation Algorithm for 12 Hammer Strikes at Each Distance for the Unfiltered and 2 Filtered Cases

200th order Low Pass FIR filter, breakpoint 20 Hz

Distance From S2 - S3	Strike 1	2	3	4	5	6	7	8	9	10	11	12	Mean	Stdev
303	0.349	0.003	-0.004	0.002	-0.003	-0.004	0.063	0.003	NaN	0.001	0.063	0.07	0.0494	0.1039
254	-0.2	-0.163	-0.198	-0.165	-0.202	-0.163	-0.315	0	-0.315	-0.32	NaN	-0.321	-0.2147	0.0985
204	-0.022	-0.024	-0.025	-0.023	-0.031	-0.027	-0.028	-0.031	-0.027	-0.029	-0.029	-0.029	-0.0271	0.0030
156	-0.035	-0.034	-0.034	-0.034	-0.035	-0.032	-0.035	-0.033	-0.032	-0.035	-0.032	-0.034	-0.0338	0.0012
108	0.02	0.018	0.016	0.014	0.012	0.011	0.015	-0.011	-0.008	-0.012	0.015	0.001	0.0076	0.0118
65	0.035	0.035	0.034	0.035	0.035	0.033	-0.026	-0.026	0.039	0.038	-0.026	0.04	0.0205	0.0281
42	0.011	0.01	0.011	0.01	0.011	0.013	0.01	0.01	0.013	0.011	0.008	0.01	0.0107	0.0014

200th order Low Pass FIR filter, breakpoint 10 Hz

Distance From S2 - S3	Strike 1	2	3	4	5	6	7	8	9	10	11	12	Mean	Stdev
303	0.334	0.001	-0.013	0	-0.009	-0.004	0.06	0.008	NaN	-0.001	0.058	0.07	0.0458	0.1003
254	-0.196	-0.176	-0.186	-0.184	-0.189	-0.192	-0.311	-0.324	-0.32	-0.231	NaN	-0.193	-0.2275	0.0600
204	-0.028	-0.027	-0.026	-0.027	-0.03	-0.028	-0.03	-0.032	-0.028	-0.028	-0.029	-0.029	-0.0285	0.0016
156	-0.034	-0.033	-0.034	-0.033	-0.034	-0.033	-0.034	-0.033	-0.032	-0.034	-0.033	-0.034	-0.0334	0.0007
108	0.011	0.01	0.007	0.001	0.002	0.003	0.001	-0.002	-0.002	-0.002	0.001	0	0.0025	0.0045
65	0.031	0.034	0.033	0.032	0.036	0.031	0.034	0.034	0.04	0.039	0.037	0.041	0.0352	0.0034
42	0.015	0.014	0.015	0.014	0.014	0.017	0.011	0.012	0.016	0.012	0.01	0.011	0.0134	0.0022

No Filter

Distance From S2 - S3	Strike 1	2	3	4	5	6	7	8	9	10	11	12	Mean	Stdev
303	-0.057	-0.001	NaN	0.063	0.063	0.064	NaN	NaN	NaN	NaN	0.064	0.063	0.0370	0.0479
254	-0.195	-0.159	-0.194	0.003	0.002	0.057	NaN	0.003	-0.16	-0.098	NaN	-0.043	-0.0784	0.0942
204	-0.019	-0.02	-0.019	-0.019	-0.039	-0.019	-0.019	-0.038	-0.02	-0.019	-0.019	-0.02	-0.0225	0.0075
156	-0.035	-0.035	-0.035	-0.035	-0.036	-0.035	-0.035	-0.035	-0.035	-0.035	-0.035	-0.035	-0.0351	0.0003
108	0.022	0.023	0.022	0.022	0.022	0.022	0.023	-0.012	-0.012	-0.012	0.023	-0.011	0.0110	0.0168
65	0.032	0.032	-0.028	-0.028	-0.028	0.031	-0.028	-0.029	-0.028	-0.028	-0.029	-0.028	-0.0133	0.0271
42	0.007	0.007	0.007	0.007	0.007	0.008	0.006	0.007	0.008	0.006	0.005	0.007	0.0068	0.0008

4.2.1 Andover Testing in August 2006

On 17 August, PSI conducted another series of field tests at a local site using sledgehammers and jackhammers as sources. The configuration was identical to the earlier field tests on 1 June and 27 June. We repeated the measurements with sledgehammer sources as well as used a jackhammer as a source. Figure 38 shows the test site and configuration. Our goal was to investigate repeatability, and any climatic effects of soil temperature and dampness.

During the 17 August field test, we demonstrated that PIGPEN and its algorithm could determine the location of a jackhammer threat. Figure 39 shows the sensor and threat locations for the test. Figure 40 shows raw sensor data from a jackhammer threat. Each burst is the signal from the jackhammer operating for several seconds. Figure 41 show the cross-correlations for all the sensors for the jackhammer data. In this experiment, the threat is always equi-distant from sensors 2 and 4; therefore the peak of the cross-correlation is centered at zero lag as expected. Figure 42 shows the time lags determined from the sensor2 and sensor 4 data. The time lags range from 0 to 40 msec. These time lags correspond to distance accuracies of 8 meters at the worst.

J-2456

Figure 38. 17 August 2006 test site and configuration.

J-2460

Figure 39. Sensor and threat locations for the 17 August field test.

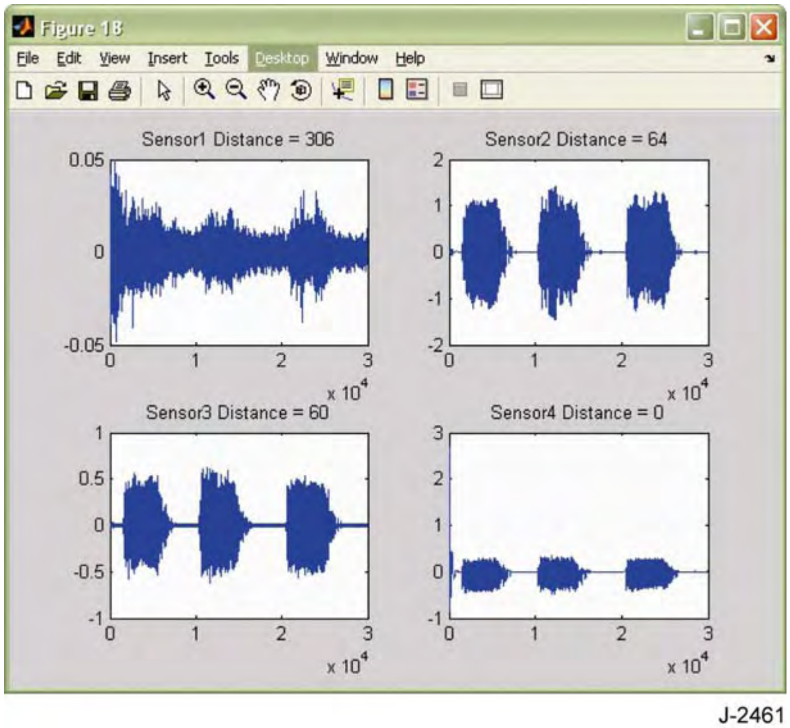


Figure 40. Sensor data from a jackhammer threat.

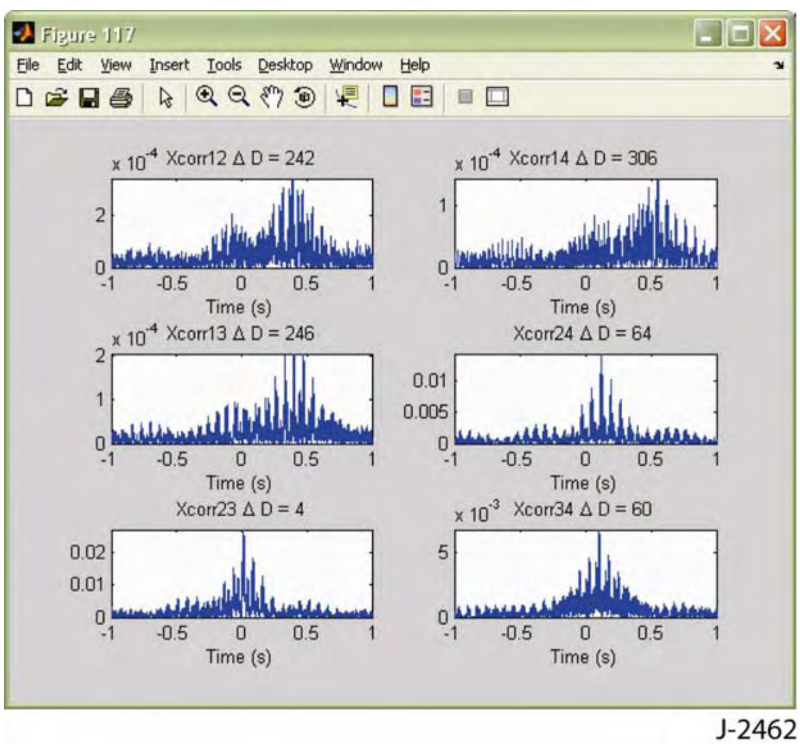
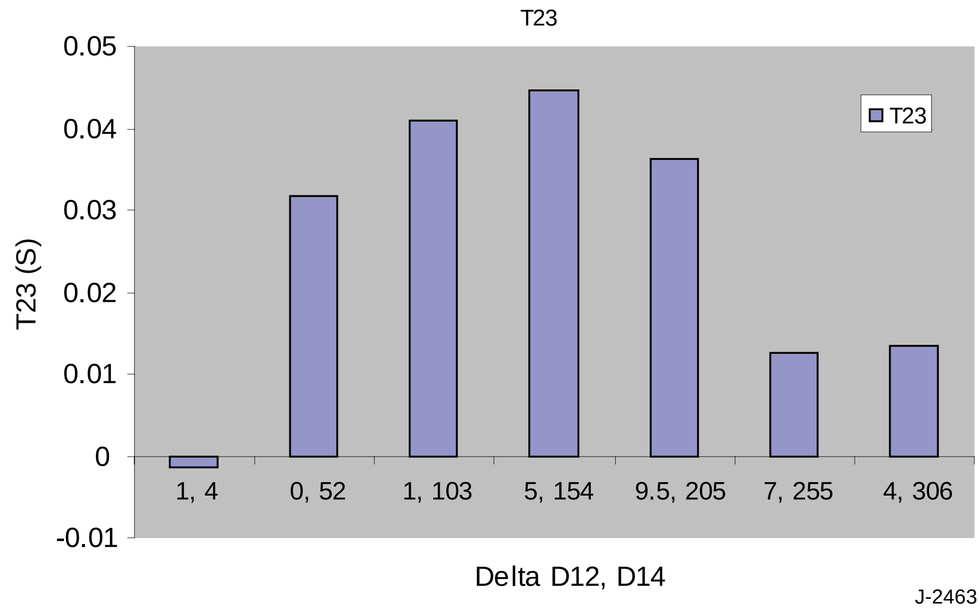


Figure 41. Cross-correlations from the jackhammer data. The threat is always equi-distant from sensors 2 and 4; therefore the peak of the cross-correlation is centered at zero lag as expected.



J-2463

Figure 42. Range of time lags between sensor 2 and sensor 4 for jackhammer threats.

4.2.2 October 2006 Field Testing

In October 2006, PSI conducted a field test in Bronx, NYC to acquire data from a horizontal directional drill (HDD). The HDD is an important threat source to the gas industry infrastructure. NYSEARCH and ConEd arranged for our participation in the HDD jobsite. Figures 43 through 46 show the jobsite, equipment and test setup. We acquired data to permit this threat to be added to our library.

J-2450

Figure 43. HDD jobsite it Bronx, NY.

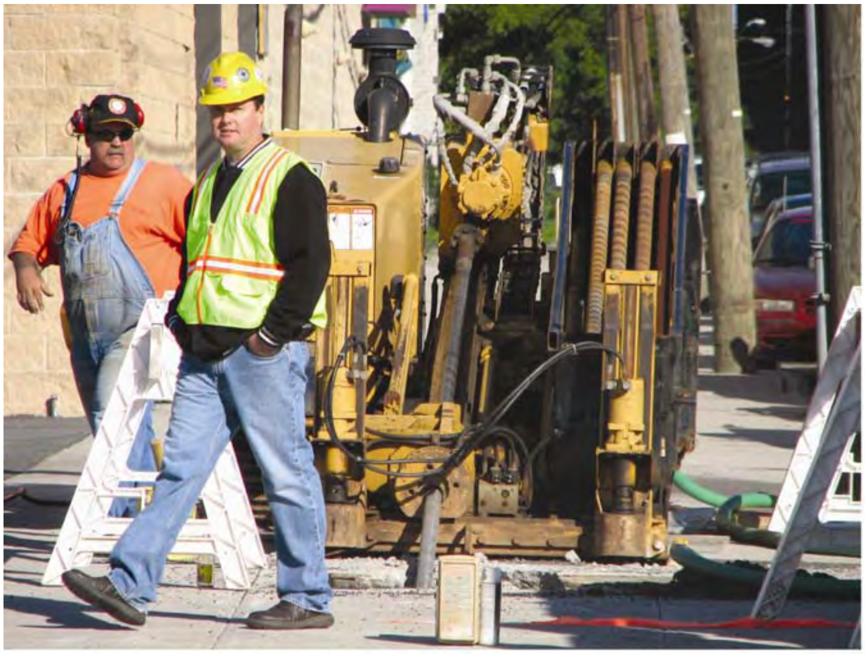


Figure 44. HDD equipment.

Figure 45. Location of PIGPEN sensors.

Figure 46. One PIGPEN sensors was buried approximately 5 feet below grade in the trench shown. A second sensor was located on the sidewalk in a box of soil.

4.3 November 2006 Field Testing in Lawrence, KS

PSI conducted an extensive data collection and analysis of that data collected during a field test in near Lawrence, Kansas. This location was chosen because it possessed a clear discontinuity in the soil types – sandy loam to shale. PSI in complete agreement with the user community felt it necessary to demonstrate the performance of the PIGPEN technology across a soil discontinuity. The analysis of this four day data set took several months, and has resulted in the following conclusions:

1. PIGPEN detected a 30-06 down-hole rifle to a range of 400 ft in sand/loam.
2. PIGPEN detected a 30-06 down-hole rifle to a range of 200 ft in limestone/shale.
3. Threat signatures are degraded 20-30 dB (depending on initial signal strength) as they transition from limestone to sand. We were able to observe attenuated threat signatures across this discontinuity in both directions.
4. Under certain conditions when the arrival times matched geometric distance expectations, PIGPEN localized threats repeatably to ±7 ft in sand/loam. However, in many cases the accuracy was far worse, and only ± 75 ft accuracy was observed. (A 27 foot error in accuracy was observed in the more uniform soils of the Andover test site.) The decreased accuracy was not predictable, but rather (we believe) dependent on the site. The data is not statistically random (as is noise), but is tightly clustered around an incorrect answer. This indicates to PSI that a physical process is giving rise to the incorrect position determinations.

5. Under certain conditions when the arrival times matched geometric distance expectations, PIGPEN localized threats reproducably to ±9.6 ft in slate/limestone. However in many cases the accuracy was far worse, and only ± 300 ft accuracy was observed. The decreased accuracy was not predictable, but dependent on the site.
6. We were able to observe the unique signature and repeated strikes from a Backhoe across the discontinuity at all sensors.

Due to the signal degradation across the soil discontinuity, PSI has not been able to establish the positional accuracy across the soil transition for the down-hole rifle acoustic source. In addition, positional accuracy may be degraded by steep slopes within soil types. Significant algorithm development in conjunction with on-site calibration will be required to correct for non-uniform soil conditions.

4.3.1 Kansas Test Geography and Test Configuration

On 5-11 November 2006, PSI conducted the field test in a soy bean field outside of Lawrence, KS. Sensors were deployed in four configurations and three excitation sources were used:

– Configuration 1A. 3 Sensor T formation in sandy loam, sledgehammer and down-hole-gun

– Configuration 1B: 3 Sensor T formation in shale/limestone, sledgehammer and down-hole-gun

– Configuration 2: 4 sensor ShortField (2 sensors in loam, 2 sensors in rock), down-hole-gun and backhoe

– Configuration 3: 4 Sensor LongField, shotgun and down-hole-gun

We also acquired serendipitous background data on trains and vehicles.

Figure 47 shows an aerial view of the site overlaid with the sensor and threat positions for Configurations 1A and 1B. The "A" region comprises sandy loam. The "B" region comprises shale/limestone. The purpose of Configurations 1A and 1B is to determine the acoustic velocity in each soil type and to determine the signal strength versus range in each soil type. Figures 48 and 48 show the sensor and threat positions for Configurations 1A and 1B. Configuration 1A consists of three sensors and eight threat locations. Configuration 1B consists of three sensors and six threat locations. In both configurations, the sixth threat location (T6) is placed 10 feet from sensor 1 to prevent sensor saturation.

Figure 49 shows an aerial photograph overlaid with the sensor and threat positions for Configuration 2 and Configuration 3. In Configurations 2 and 3, the threats were positioned along roughly N-S lines with respect to the sensor positions. Each threat line was labeled with a unique designator. Each threat position was label by the threat line and the distance in feet from the northernmost position along that line: e.g. BE-0, BE-60, BE-120, … , BE-420.

The threat positions were chosen to characterize the triangulation performance both inside and outside of the sensor grid and to allow a comparison of performance with each soil type as well as across a soil boundary. All the positions on the BW line are equidistant from sensors S1 and S2 (nominally zero delay between signal arrival times at S1 and S2). All the positions along the BE line are equidistant from S3 and S4. The C line runs directly through the center of the grid. The AW line is completely outside the sensor grid. The AE line is partially inside and partially outside the sensor grid.

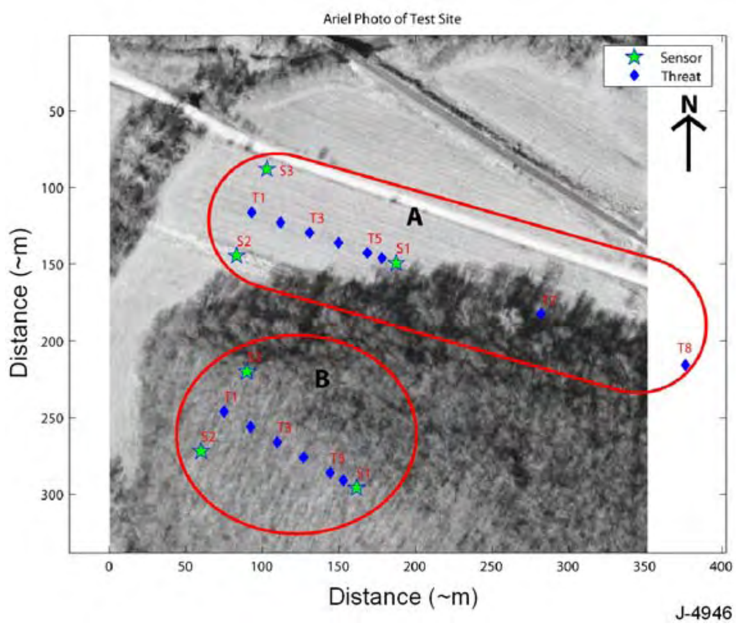


Figure 47. Aerial photograph of the site and sensor configurations 1A and 1B. The “A” region comprises sandy loam. The “B” region comprises shale/limestone.

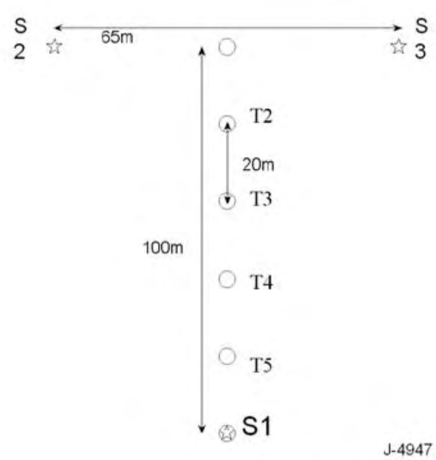


Figure 48. Sensor and threat positions for Configurations 1A and 1B.

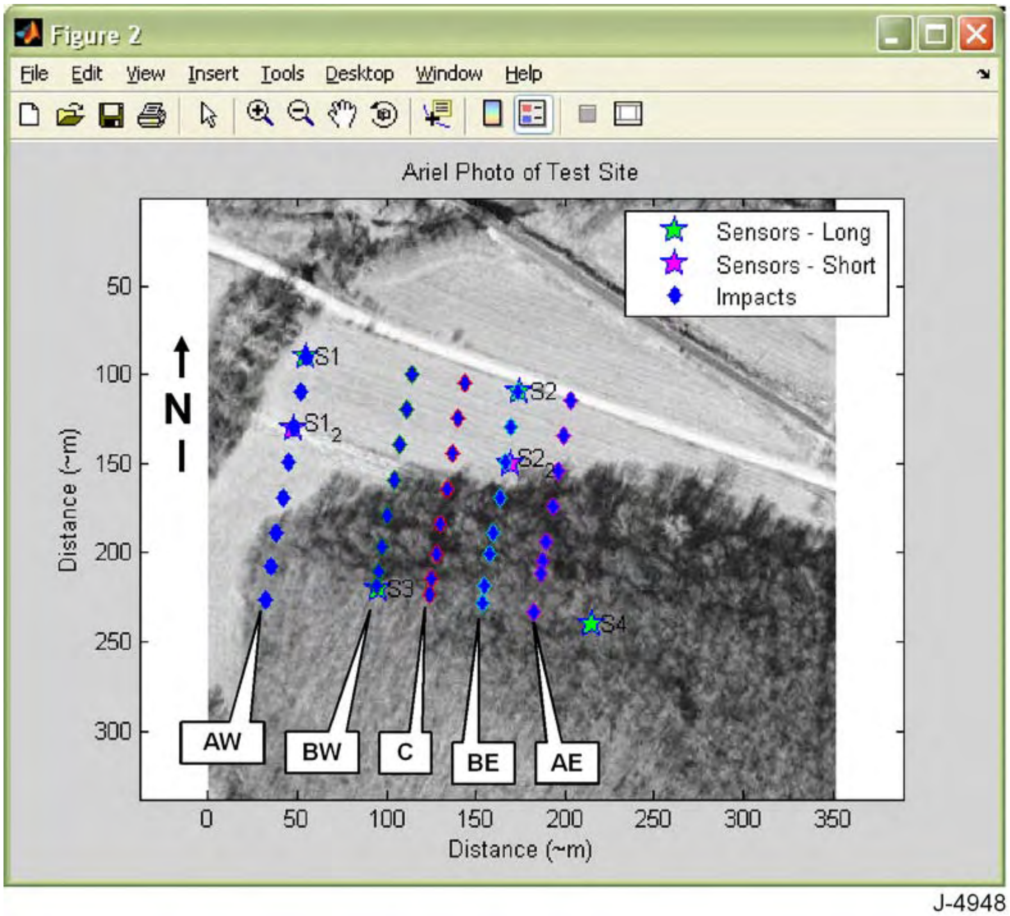
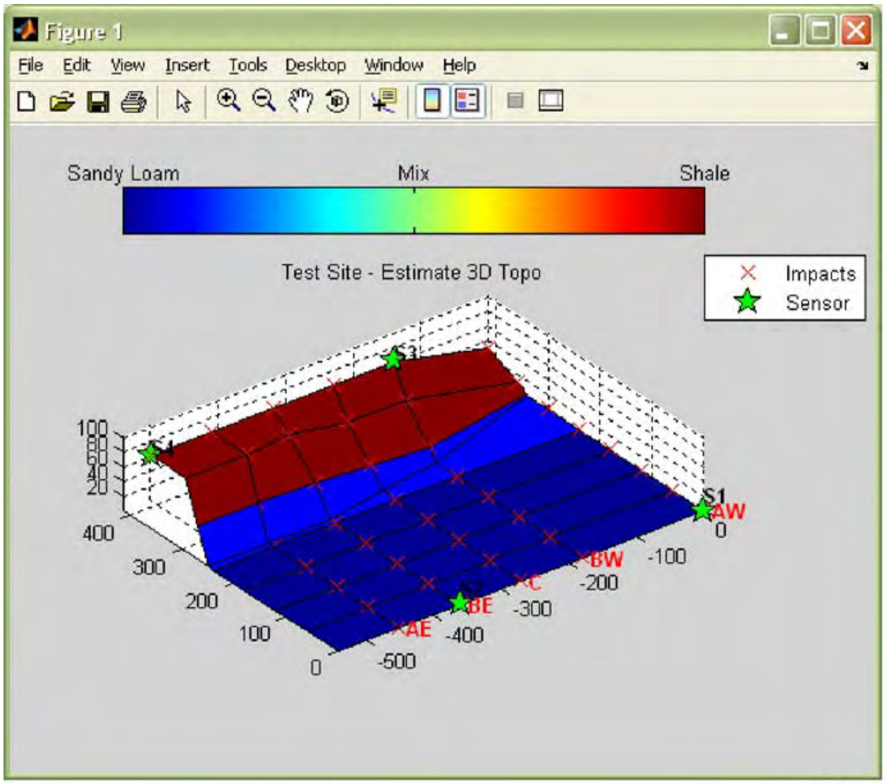


Figure 49. Aerial photograph of the test site overlaid with the sensor and threat positions for configurations 2 and 3.

Figure 50 shows the elevation contour of the site. The shale/limestone ridge rises to about 100 feet above the lower field. The side of the ridge is approximately a 50% grade. Figure 51 shows a photograph of the sight looking south. The lower field is in the foreground and the shale/limestone ridge is in the background.



J-4949

Figure 50. Elevation contours of the site.

J-4950

Figure 51. Photograph of the Kansas site looking south. The field is in the foreground. The shale/limestone ridge is in the background.

4.3.2 Acoustic Sources

We used three primary sources to excite the ground: a sledgehammer and steel plate; a downhole gun (Figure 52); and a backhoe (Figure 53). The downhole gun fires a standard 30-06 rifle cartridge. The 180 grain projectile travels at 2700 feet/sec resulting in an impact energy of 2900 ft lbs. The backhoe was a Case 580 Super L loader weighing roughly 15000 lbs. The backhoe driver created an acoustic signal by repeatedly striking the ground with the backhoe bucket.

J-4951

Figure 52. The downhole gun close-up (left) and in operation (right).

J-4952

Figure 53. Case 580 Super L backhoe.

4.3.3 Sensor Network Performance Data

In the following sections, we will evaluate the data from five different tests configurations and sources.

1. Configuration 1A (T-loam), down hole 30-06
2. Configuration 1B (T-shale), down hole 30-06
3. Configuration 2 (Longfield), down hole 30-06
4. Configuration 3 (Shortfield), down hole 30-06
5. Configuration 3 (Shortfield), Backhoe

All of the data was analyzed using the same basic process. First, the raw data is passed through a 500th order finite impulse response (FIR) 5 to 100 Hz band-pass filter. A relatively high order FIR filter was used in this situation because FIR filters are linear phase. This means that all signals regardless of spectral content are phase shifted equally as they are passed through the filter. Lower order infinite impulse response (IIR) filters, such as Butterworth filters, do not have linear phase, which result in a temporal distortion of the filtered data. The 5-100 Hz pass-band was selected in consultation with Prof. Don Steeples as a good balance between maximizing relevant seismic data, and minimizing background noise and air acoustics. The filtered data was then plotted.

Once the data is plotted, an analyst identifies both the time window in the data containing the threat signature and a portion of the data from which to calculate the background noise. Once the time windows are identified, the power within both the threat signature and background data samples are calculated to determine the signal to noise ratio. The time sequences containing threat signatures are then cross-correlated. Next the cross-correlation output is low pass filtered to smooth the correlation output. The time difference of arrival is determined from the filtered cross-correlation output. Additional analysis such as spectrographs is performed as necessary.

4.3.3.1 Configuration 1A – Sandy Loam Calibration

In configuration 1A three sensors were placed in the sandy loam for the purpose of characterizing the properties of the sandy loam. A total of 8 threat locations were excited with the down-hole 30-06 gun. Four shots were fired at each location. The distance from the sensors ranges from 10 ft to 900 ft. Each threat location is equidistant from sensors 2 and 3 such that the nominal time difference of arrival should be 0 s. The expected wave speed for this soil type is nominally 1000 ft/s. The data presented here utilizes a minimum of 3 of the four shots at each location. [At two of the locations a car was passing in close proximity to sensors 1 and 2 thus degrading the signal to noise ratio. To keep the results consistent these data points were not included.]

All of the data presented here was band-pass filtered using a 500th order FIR filter with breakpoints of 5 and 100 Hz. All of the cross-correlation results have been low pass filtered through a 100th order FIR filter with a stop band starting at 20 Hz. The cross-correlation outputs have been generated using a Matlab function which automatically selects the maximum correlation value between -1 and 1 second.

Past data has demonstrated that we nominally need a signal to noise ratio of 20dB or greater to obtain an accurate time difference of arrival measurement using either the cross-correlation method or a manual selection of time of arrival. Figure 54 shows the average signal to noise ratio for each of the sensors at each of the threat locations (the x-axis notes the threat location number). As can be seen in Figure 54, all of the sensors have sufficient signal strength at threat locations 1 thru 6, while there is insufficient signal strength for analysis at threat locations 7 and 8.

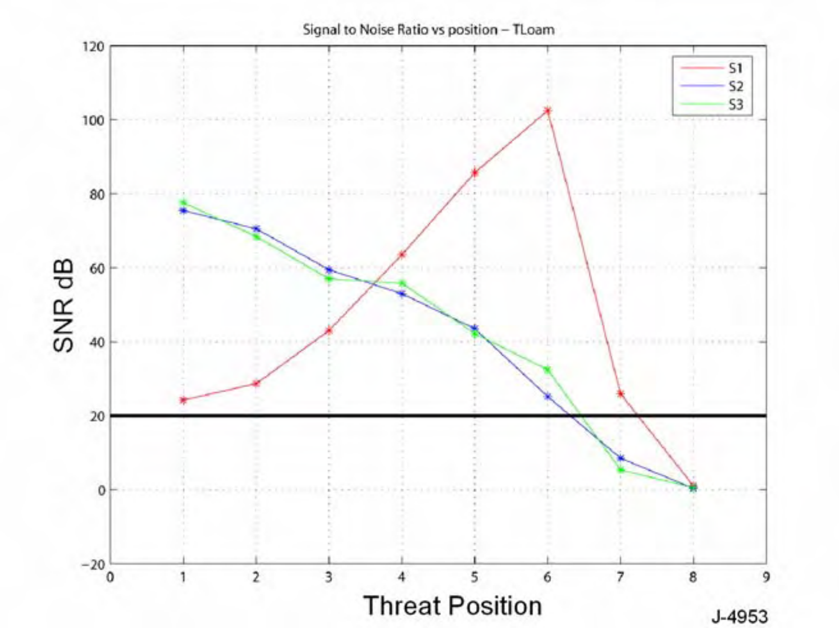


Figure 54. Average Signal to Noise ratio vs Threat Position in sandy loam. (Solid black line indicates the minimum SNR required for analysis).

Figure 55 shows the average signal to noise ratio versus threat distance for the sandy loam. This plot was generated using the data from all three sensors. As we can see, the approximate detection distance for the down-hole 30-06 rifle is 400 ft in the sandy loam.

Figure 56 shows the average time difference of arrival between sensors 1 and 2 (X12), and sensors 1 and 3 (X13) versus path length difference for threat locations T1-T6. The time difference of arrival was determined using the cross correlation. As we can see in Figure 55, with the exception of the data gathered from threat location T2, the cross-correlation outputs form a line with a slope of 0.0024 sec/ft. This corresponds to a wave speed of 410 ft/sec which is lower than expected. However, the observed speed corresponds well to the soil speeds observed at the Andover, MA field site which is also composed of alluvial deposits.

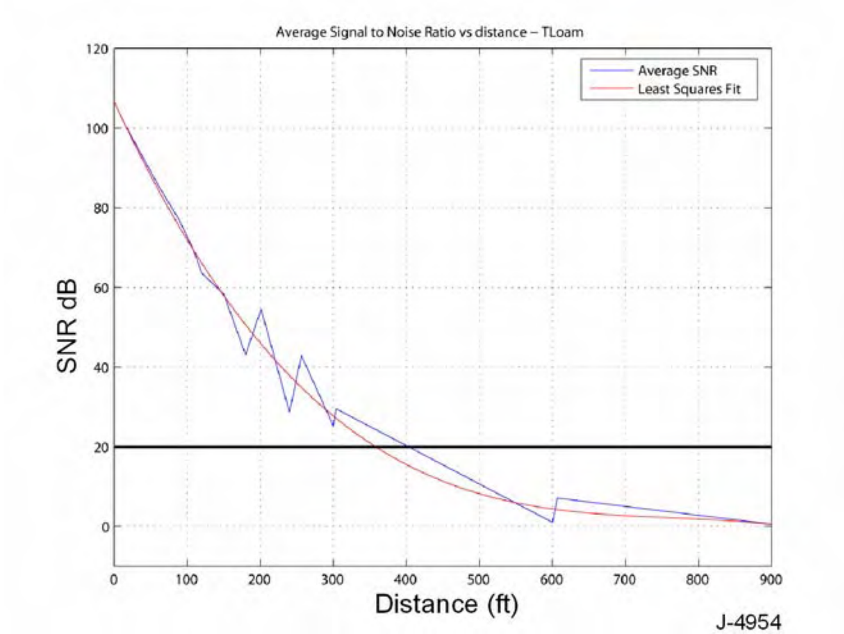


Figure 55. Average Signal to Noise ratio vs Threat Distance in sandy loam.

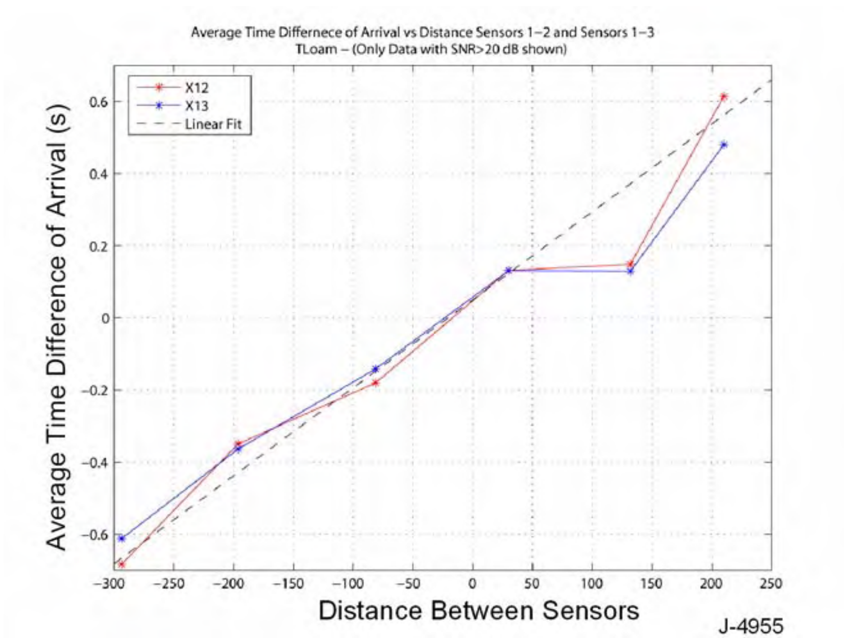


Figure 56. Average Time Difference of Arrival between Sensors 1 and 2, and Sensors 1 and 3 versus path length difference.

Figure 57 shows the average time difference of arrival between sensors 2 and 3 versus threat location (T1 through T6). In addition to displaying the average time difference of arrival, we have also displayed the time differences of arrival for each shot at each threat location. There are four shots shown at locations 2, 4, 5, and 6. There are three shots at locations 1 and 3. Thus at locations 2, 4, 5, and 6 a minimum of two shots are co-located on the plot. The expected time difference of arrival for all of the threat locations is 0 sec. As we can see in Figure 56, there is some deviation from the expected result. Specifically, as we progress from T1 to T6 there is linear increase in the time difference of arrival between sensor 2 and sensor 3. This likely indicates that the wave speed between the threats and sensor 2 is slightly slower than the wave speed between the threat and sensor 3. If we make the assumption that the wave speed for the entire field is 410 ft/s, the actual variations in the field will result in a positional error of ±6.5 ft. The maximum variance at any one the threat locations is 0.0025 s, which corresponds to a position error of ±1 ft.

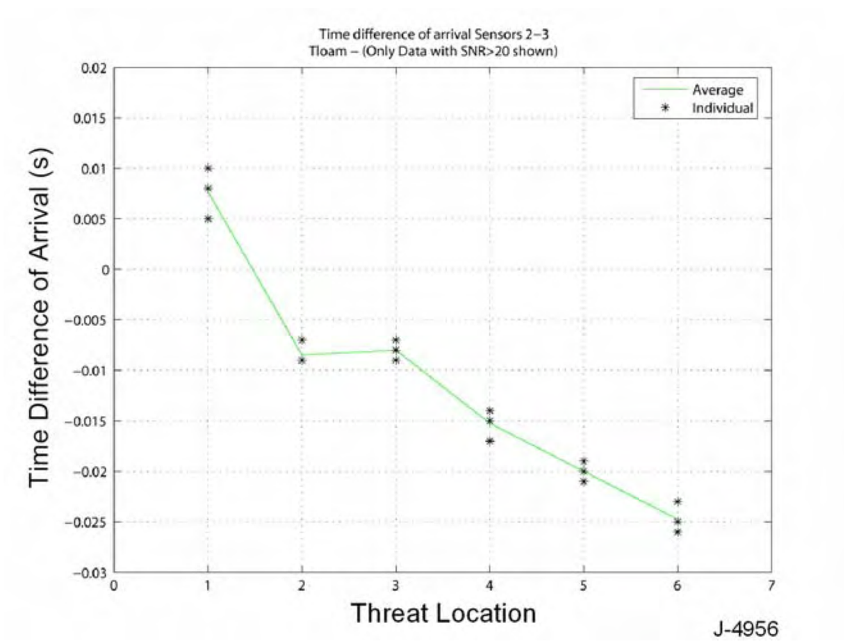


Figure 57. Time difference of arrival between sensors 2 and 3 versus threat location.

Similarly Figure 58 shows both the average time difference of arrival and the individual time difference versus path length difference for sensors 1 and 2, and sensors 3 and 4. Eliminating the outlying data point gathered at T6, we see that the maximum variance at each location is ±0.028 sec, which corresponds to a position error of ±11 ft. If we ignore all of the data collected at position T6, the maximum variance is ±0.018 sec, which corresponds to a position error of ±7 ft. The large variance seen in the T6 data is due to the saturation of sensor 1 (the threat is only 10 feet from sensor 1 at threat location 6). The saturation of sensor 1 results in a non-linear distortion of the measured waveform which then does not correlate well with the more distance signals. PSI also experienced this problem with data collected at the Andover test site. Similarly, there are some issues with the X13 correlation at T1.

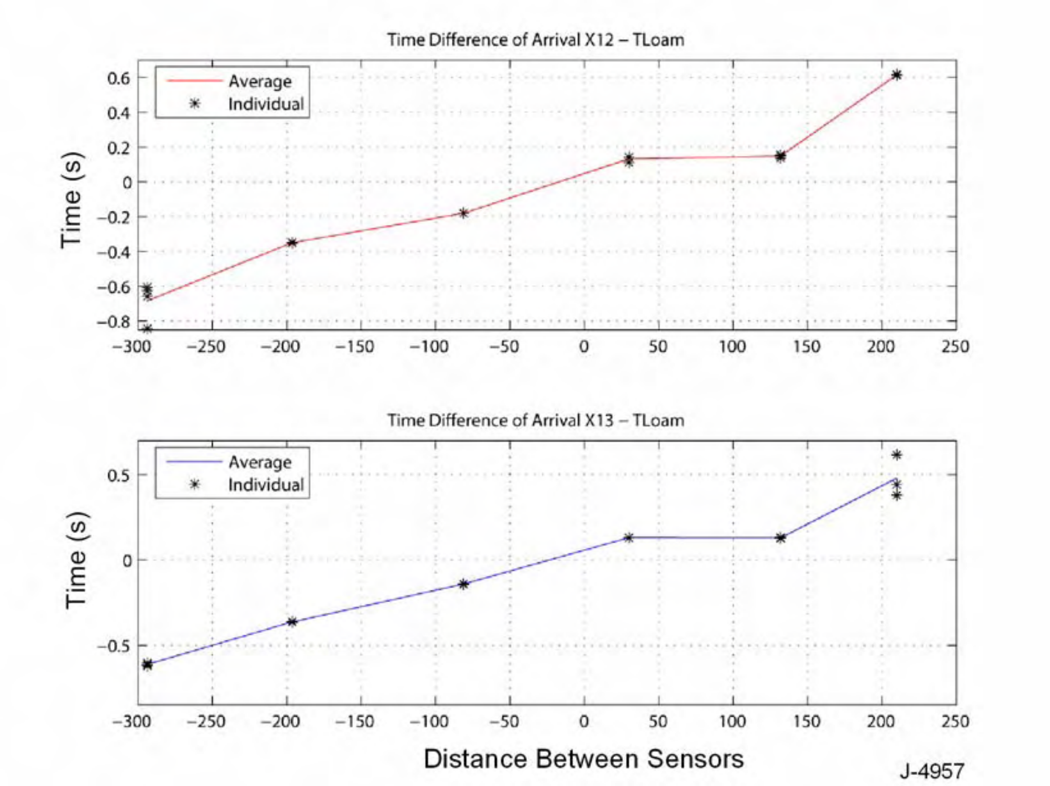


Figure 58. Time difference of arrival between sensors 1 and 2, and sensors 1 and 3 versus threat location.

Next we discuss the acoustic spectral signatures observed. Figure 59 shows example data of the down-hole gun signature measured in the sandy loam at a distance of 108 feet (sensors 2 and 3) and 240 feet (sensor 1). Figure 60 shows the corresponding power spectral density (Figure 60A shows the PSD of the raw signal while Figure 60B shows the PSD of the filtered signal). Note that sensor 4 is not connected to the data acquisition system and then represents the electrical noise floor of the data acquisition system. Note also the different temporal profile at the longer distance. The PSD reflects this with sensors 2 and 3 having similar peaked spectral features and sensor 1 having a broader distribution.

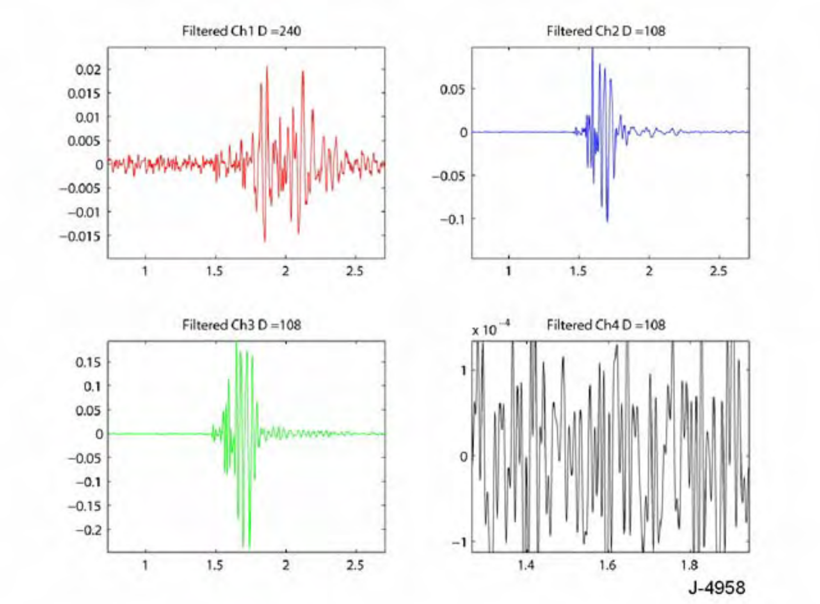


Figure 59. Down-hole gun signature in sandy loam.

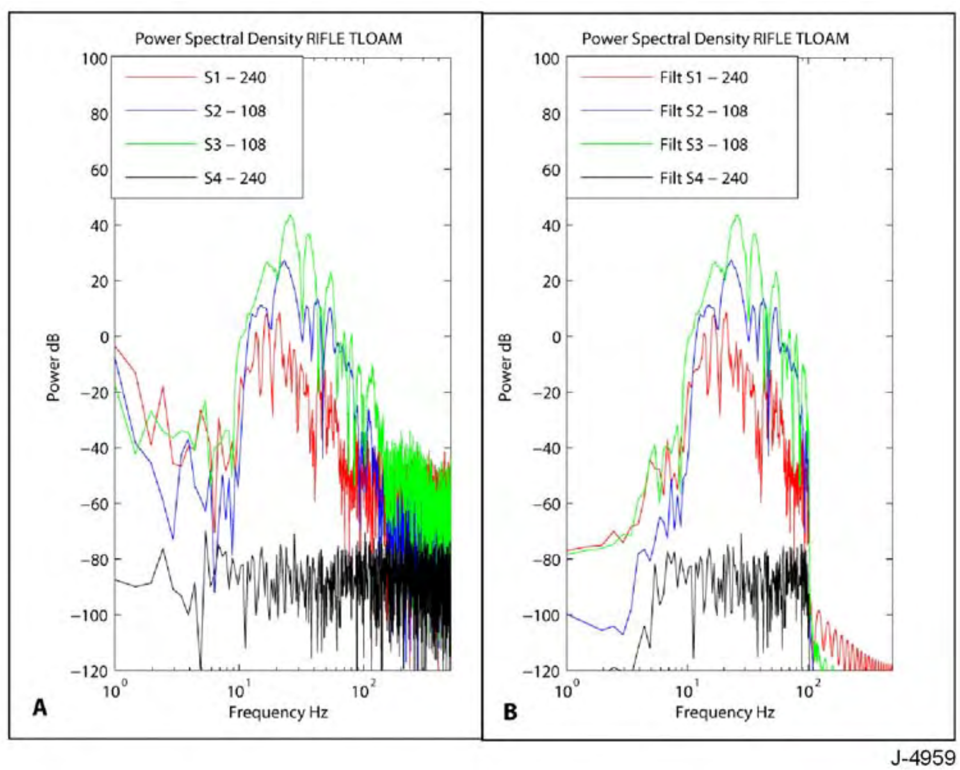


Figure 60. Down-hole gun power spectral density signature in sandy loam. (A – Raw data, B-Filtered Data)

Table 7 shows the individual and average cross-correlation outputs for all of the data points where all the signals have a signal to noise ratio greater than 20 dB for Configuration 1A.

Table 7. Cross-Correlation output for TLoam

	X12	X13	X23
T1	0.617	0.443	0.010
	0.612	0.380	0.008
	0.613	0.617	0.005
mean	**0.614**	**0.480**	**0.008**
T2	0.137	0.132	-0.007
	0.150	0.129	-0.009
	0.152	0.128	-0.009
	0.154	0.127	-0.009
mean	**0.148**	**0.129**	**-0.009**
T3	0.111	0.131	-0.007
	0.142	0.131	-0.008
	0.141	0.130	-0.009
mean	**0.131**	**0.131**	**-0.008**

	X12	X13	X23
T4	-0.181	-0.144	-0.017
	-0.180	-0.142	-0.015
	-0.180	-0.140	-0.015
	-0.180	-0.140	-0.014
mean	**-0.180**	**-0.142**	**-0.015**
T5	-0.348	-0.361	-0.019
	-0.352	-0.365	-0.020
	-0.350	-0.365	-0.020
	-0.349	-0.364	-0.021
mean	**-0.350**	**-0.364**	**-0.020**
T6	-0.843	-0.616	-0.026
	-0.626	-0.621	-0.025
	-0.658	-0.606	-0.025
	-0.606	-0.605	-0.023
mean	**-0.683**	**-0.612**	**-0.025**

4.3.3.2 Configuration 1B – Shale/Limestone Calibration

In configuration 1B three sensors were placed in the shale at the top of the hill for the purpose of characterizing the properties of the shale/limestone soil properties. A total of 6 threat locations were excited with the down-hole 30-06 rifle. Four shots were fired at each location. The distance from the sensors ranges from 10 ft to 310 ft. Each threat location is equidistant from sensors 2 and 3 such that the nominal time difference of arrival should be 0 s. The expected wave speed for this soil type is nominally 10,000 ft/s.

All of the data presented here was band-pass filtered using a 500th order FIR filter with breakpoints of 5 and 100 Hz. All of the cross-correlation results have been low pass filtered through a 100th order FIR filter with a stop band starting at 20 Hz. The cross-correlation outputs have been generated using a Matlab function which automatically selects the maximum correlation value between -1 and 1 second. As we will discuss and show later in this section, temporal and frequency distortions of the waveforms lead us to utilize and alternate method of deriving the time difference of arrival. In this method the analyst selected the point in the time sequence of each sensor in which the threat was clearly present. The time difference of arrival was then determined from the difference between the relative arrival time.

Figure 61 shows the average signal to noise ratio for each of the sensors at each of the threat locations (the x-axis notes the threat location number). As can be seen in Figure 61, in the shale the signal propagation is significantly attenuated. For this configuration in fact we only have sufficient signal strength to confidently compare all three sensors at threat locations 3 and 4. We also have sufficient signal strength to compare the signals from sensors 2 and 3 at locations

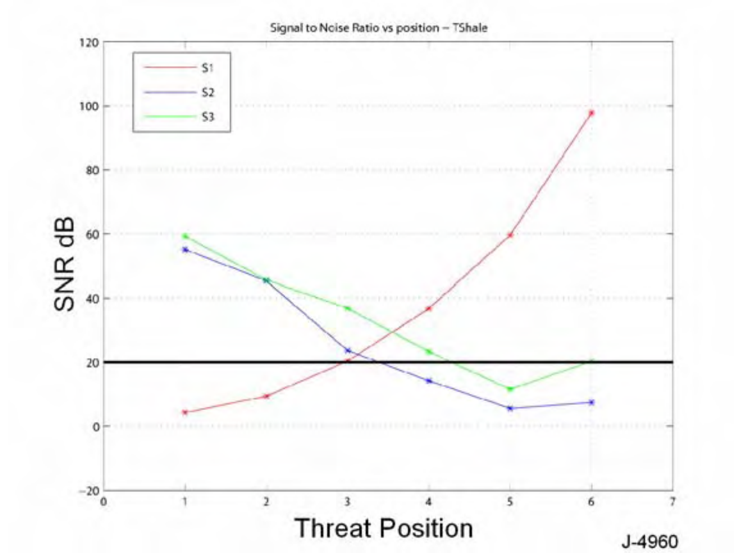


Figure 61. Average signal to noise ratio versus threat position for configuration 1B (TShale).

1 and 2. Figure 62 shows the average signal to noise ratio versus threat distance for the shale. This plot was generated using the data from all three sensors. As we can see, the approximate detection distance for the down-hole 30-06 rifle is 200 ft in the shale.

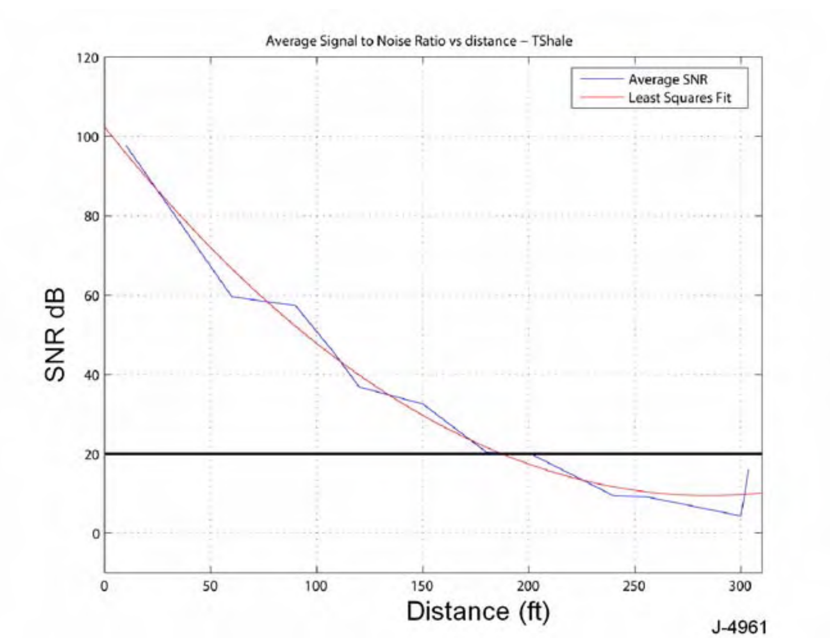


Figure 62. Average signal to noise ratio versus distance for configuration 1B (TShale).

Figure 63 shows the average time difference of arrival between sensors 1 and 2 (X12), and sensors 1 and 3 (X13) versus path length difference for threat locations T1-T6. The time difference of arrival was determined using the cross correlation. As we can see in Figure 63, while the general data trend is correct but the cross-correlation output for sensor locations T3 and T4, which is suppose to have a high level of confidence, trend the wrong way. A linear fit of this data results in a soil velocity of 2000 ft/sec. Figure 64 shows the both the average time difference of arrival and each of the individual cross-correlation results. As we can see, the cross-correlation results have a significant variance from shot to shot. For example the X12 cross-correlation at T3 (Δ-81 ft) has a variance of ±0.065 s which corresponds to a position variance of ±125 ft at a soil speed of 2000 ft/s.

Figure 65 shows the average time difference of arrival between sensors 2 and 3 versus threat location (T1 through T6). In addition to displaying the average time difference of arrival, we have also displayed the time differences of arrival for each shot at each threat location. As can be seen in Figure 19, while the shots at T1 through T4 are tightly grouped (this ignores the single outlier for T4) the locations are well offset from the expected zero mean. In fact the mean cross-correlation for the T1 location is -0.077 s which corresponds to an offset distance of 154 ft at a soil speed of 2000 ft/s (this is greater than the distance to sensors 2 and 3). This indicates that there is either a problem with the cross-correlation method or very non-uniform soil properties.

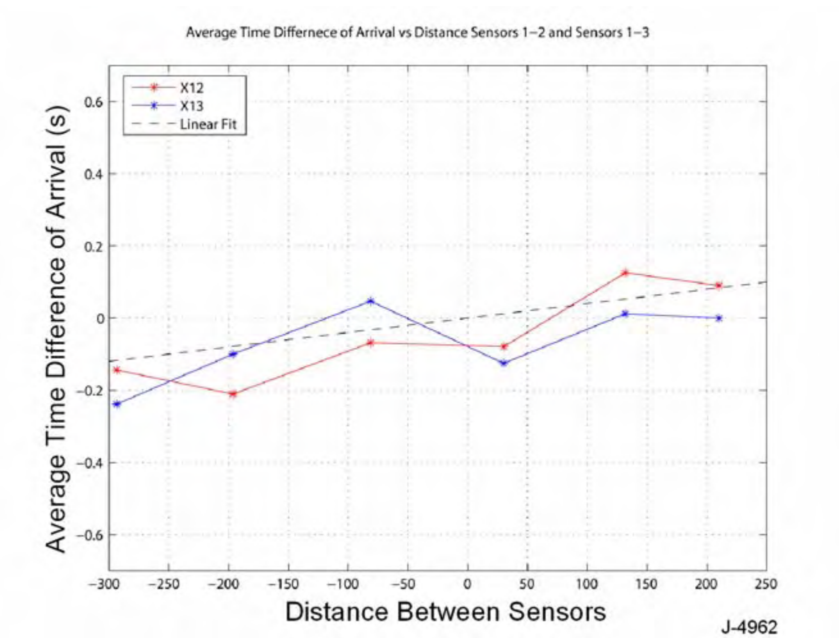


Figure 63. Average time difference of arrival for sensors 1 and 2, and sensors 1 and 3 versus path length difference. Time difference determined from cross-correlation.

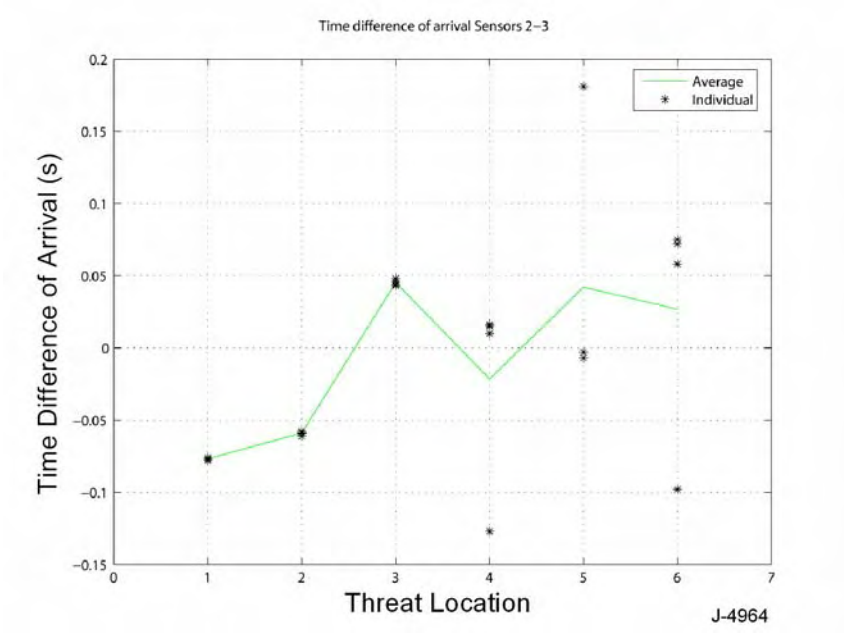


Figure 64. Time difference of arrival between sensors 1 and 2, and sensors 1 and 3 versus threat location.

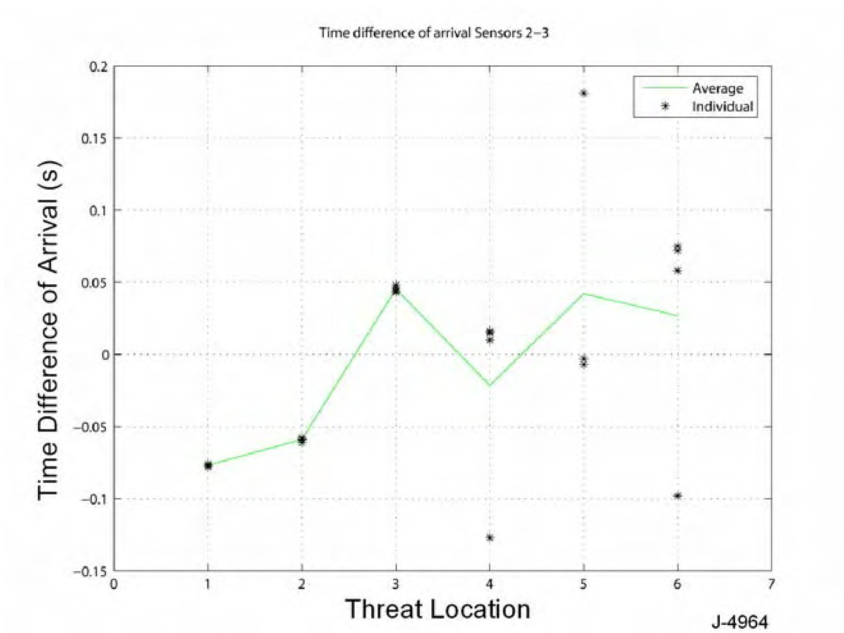


Figure 65. Time difference of arrival between sensors 2 and 3 for threat positions 1 through 6 in shale.

To try and resolve the issue with the cross-correlation output, PSI looked in detail at both the temporal and spectral signatures recorded at sensors 2 and 3 as well as the complete cross-correlation output. Figure 20 shows the temporal signatures for sensors 1, 2, and 3 for a test shot at location T1 in the shale (once again sensor 4 is displayed but not connected). As we can see in Figure 66, while sensors 2 and 3 are equal distances from the threat the recorded signatures are quite different. Specifically, the signature recorded by sensor 3 includes a low frequency component which persists approximately 0.3 seconds longer than the lower frequency component recorded at sensor 2. Figure 21 shows the power spectral density for this signature (the left hand plot shows the PSD for the unfiltered data while the right hand plot shows the PSD of the filtered data). As we can see, the spectral signatures for sensor 2 and 3 are quite similar so one would expect that they could be correlated (Note: the 5-100 Hz band-pass filter has eliminated a significant acoustic signature in the 200 Hz region).

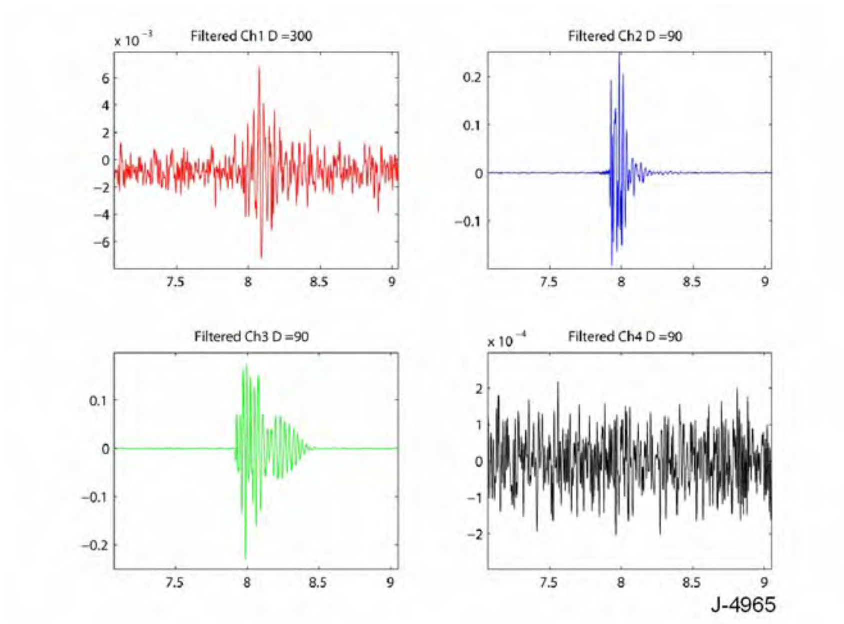


Figure 66. Time signature for a rifle shot at threat position T1 in the shale (Sensor 4 not active).

Since the power spectral density plot shown in Figure 67 did not capture the temporal differences between the sensor 2 and sensor 3 signatures, we utilized an alternate method of viewing spectral data called a spectrograph. In a PSD plot, we achieve high resolution in the frequency axis by looking at a signal over a long time period. In a spectrograph, we trade off time and frequency resolution. By reducing the length of the time series which is transformed in to the frequency domain, we increase the time resolution of the frequency data but at the expense of frequency resolution. Figure 68 shows the spectrograph of the time series shown in Figure 66. For this spectrograph, we have divided the 2 second (2000 point) data series into thirty two 128 point packets. The packets have 50% overlap. This results in a series of frequency transforms with a spectral resolution of 8 Hz per data point and a temporal resolution of 64 ms.

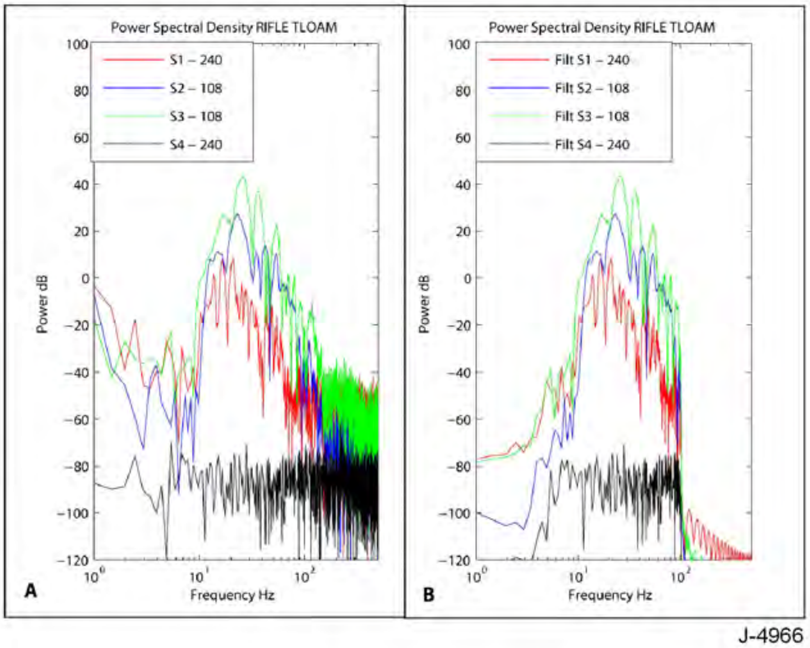


Figure 67. Power spectral density plot for a rifle shot at threat position T1 in the shale (time series shown in Figure 66).

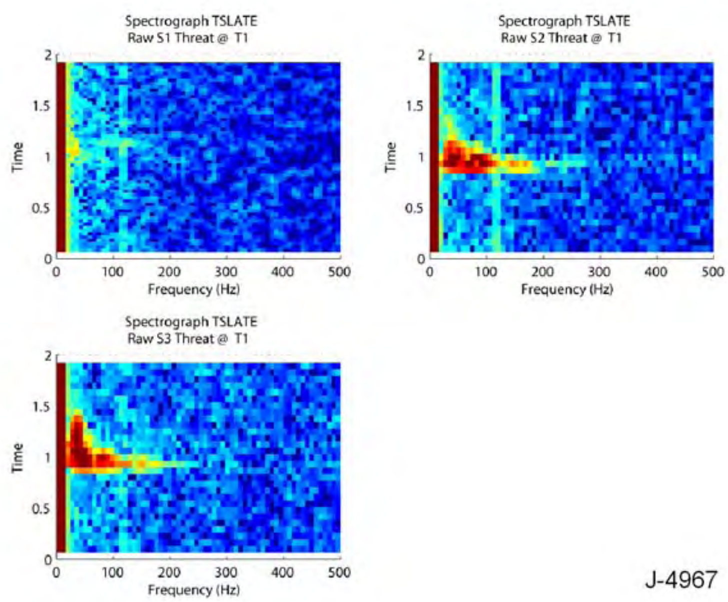


Figure 68. Spectrograph for a rifle shot at threat position T1 in the shale (time series shown in Figure 66).

As we can see in Figure 68, the signals from sensors 2 and 3 have a sharp onset at 0.83 seconds, and consist of a high frequency (80-88 Hz) and a low frequency component (32-48 Hz). At sensor 2, the high frequency component decays in 180 ms while the low frequency component decays in 384 ms. In comparison, the high frequency component at sensor 3 decays in 180 ms while the low frequency component persists for 512 ms (30% longer than the same component at sensor 2). Clearly these signals are different in both time and frequency. Since cross correlation is a mathematical tool developed to determine when two signals are most alike comparing signals which are significantly different often gives unanticipated results. Figure 69 shows the low pass filtered cross-correlation output for a shot at threat location T1 in the shale. As we can see there is a clearly defined peak at -77 ms and a much smaller peak at 51 ms. Neither of these peaks can be associated with the distinctive arrival wave front apparent in Figure 66.

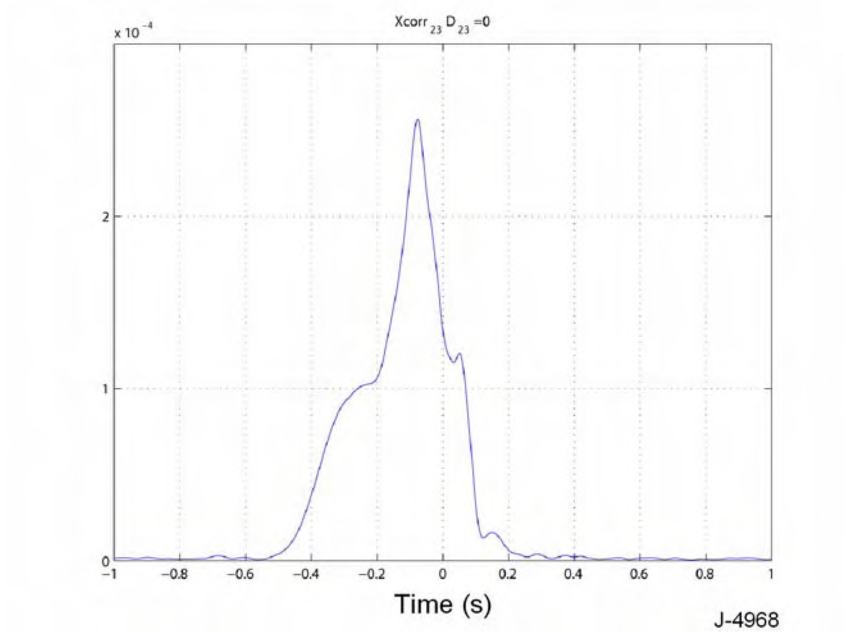


Figure 69. Low pass filtered cross-correlation output for a shot at threat location T1 in the shale.

To correct for this uncertainty PSI alternately chose to specify the time difference of arrival based upon the arrival time of the wave front. There are a number of ways to automatically select the wave front arrival. One is to specify a trigger threshold from which we automatically mark the arrival wave front. There are a number of problems with this method. The most prominent is that it is unable to scale the threshold for the wave magnitude. Thus for conditions where the sensor is quite close to the threat, the high speed p-wave would be sufficient to trigger the threshold limit (we are interested in the slower propagating s-wave). Alternately, we could use a shorter sequence/higher overlap spectrograph to measure changes in the signal power over a narrow time window. This approach is both computationally intensive and as noted earlier a compromise between temporal and spectral resolution. Rather than try and develop and automatic algorithm PSI elected as a temporary expedient to have the analyst manually identify the arrival time of the wave front. For this process to be accurate the signal amplitude needs to be sufficiently above the background noise so that the analyst has a clear arrival wave front. In practice, this requires a signal to noise ratio of approximately 20 dB which is equivalent to the limits observed for cross correlation.

Figure 70 shows the average time difference of arrival for sensor 1 and 2, and sensors 3 and 4 versus distance using the wave front arrival time technique. As can be seen in the figure, this more linear than the data shown in Figure 62 with a significantly shallower slope. Based upon the highest confidence data recorded at the T3, T4, and T5 locations, the measured wave speed is 4800 ft/s. Figure 71 shows the time difference of arrival for each of the individual shots. Looking at the highest confidence data (T3 and T4), we find that this method gives a variance of ±2 ms which corresponds to a position error of 9.6 ft at a wave speed of 4800 ft/s. The lower confidence data (T2 and T5) has a variance of ±20 ms which corresponds to a position error of 96ft at a wave speed of 4800 ft/s.

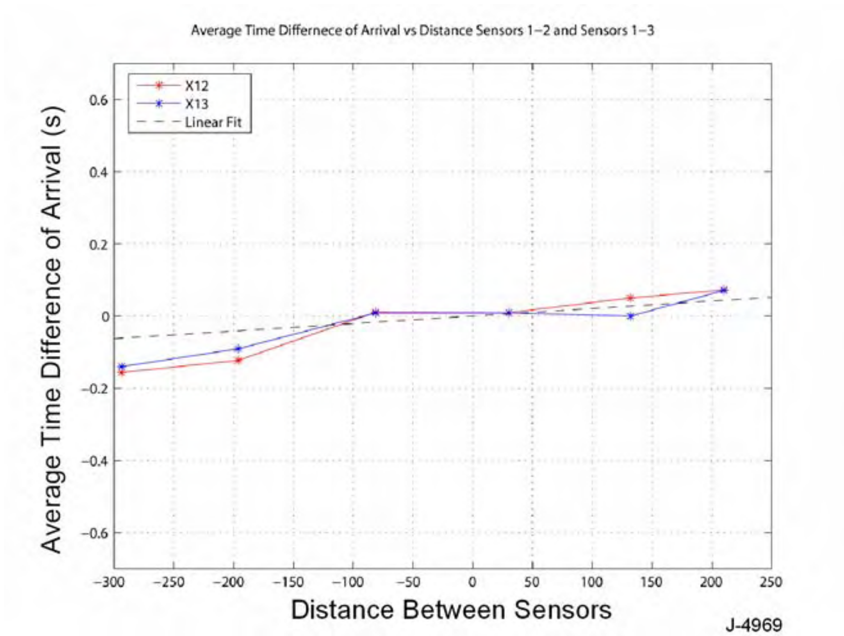


Figure 70. Average time difference of arrival for sensors 1 and 2, and sensors 1 and 3 versus distance. Time difference determined from wave front arrival.

Figure 72 shows the average time difference of arrival for sensors 2 and 3 versus distance using the wave front of arrival technique. As we can see, this technique has moved the average time difference of arrival much closer to the anticipated zero mean for locations T1, T3, and T4 (we should disregard the data for locations T5 and T6 since the signal strength at these locations is below our confidence limit of 20 dB). Unfortunately, the data for location T2 is still at -0.05 s, only nominally different than the answer arrived at by cross-correlation (Figure 19). This offset represents a 240 ft difference in the measure position versus the actual position for a wave speed of 4800 ft/s. PSI has not been able to develop a physical explanation for this apparent difference. The maximum variance for high confidence data with this method is ±1.5 ms which corresponds to a position error of ±7.2 ft at a wave speed of 4800 ft/s. Figures 73, 74, 75, and 76 show the time signature, PSD, cross-correlation, and spectrograph for a shot at threat location T2.

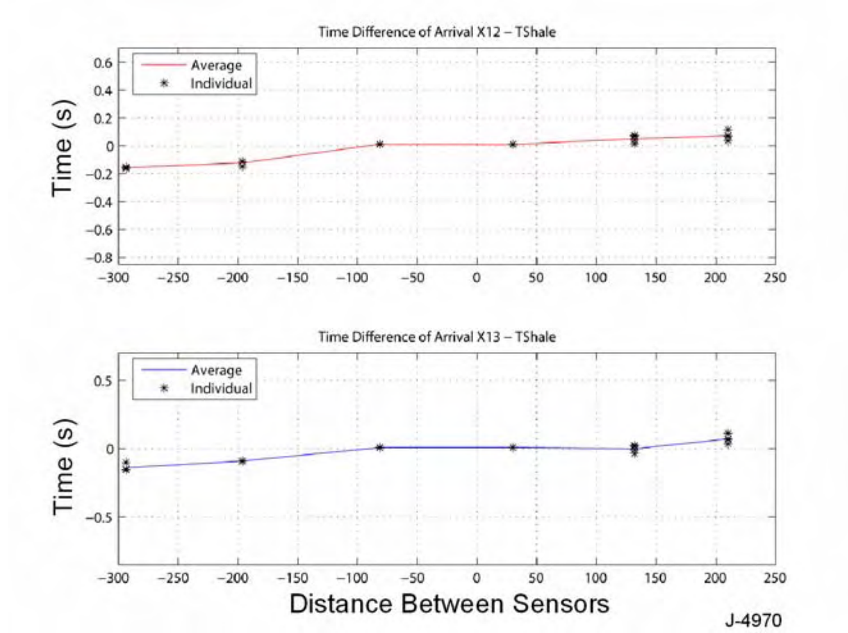


Figure 71. Average time difference of arrival for sensors 1 and 2, and sensors 1 and 3 versus distance. Time difference determined from wave front arrival.

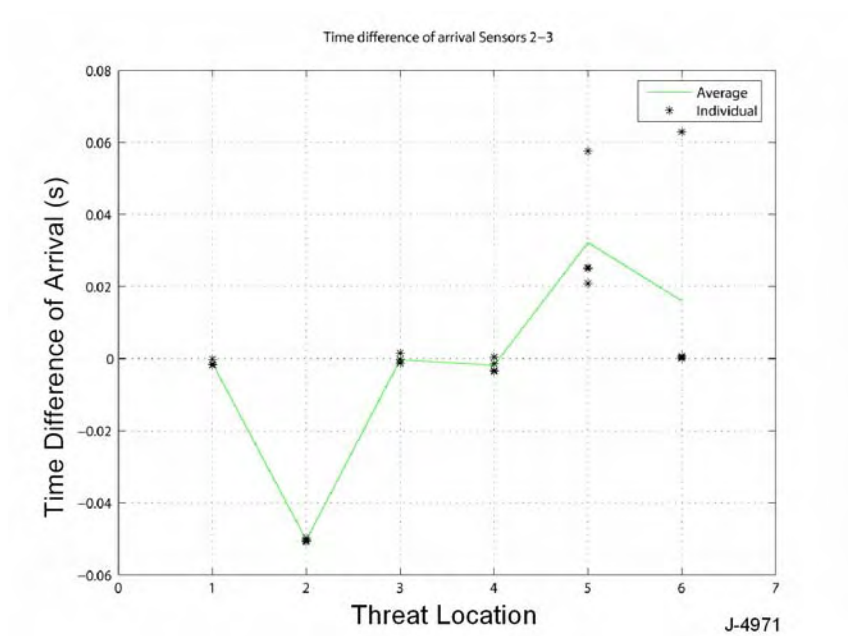


Figure 72. Average time difference of arrival for sensors 2 and 3 versus distance. Time difference determined from wave front arrival.

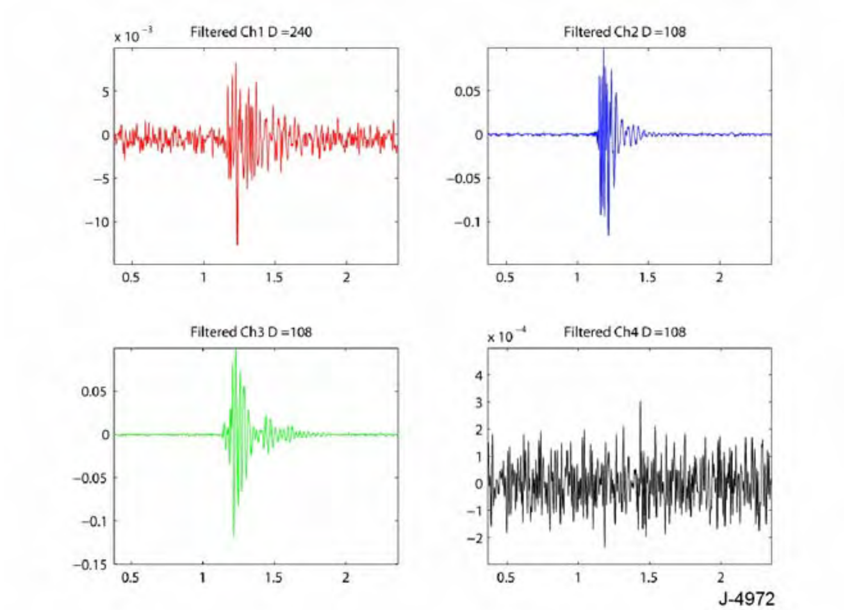


Figure 73. Time signature for a rifle shot at threat position T2 in the shale (Sensor 4 not active).

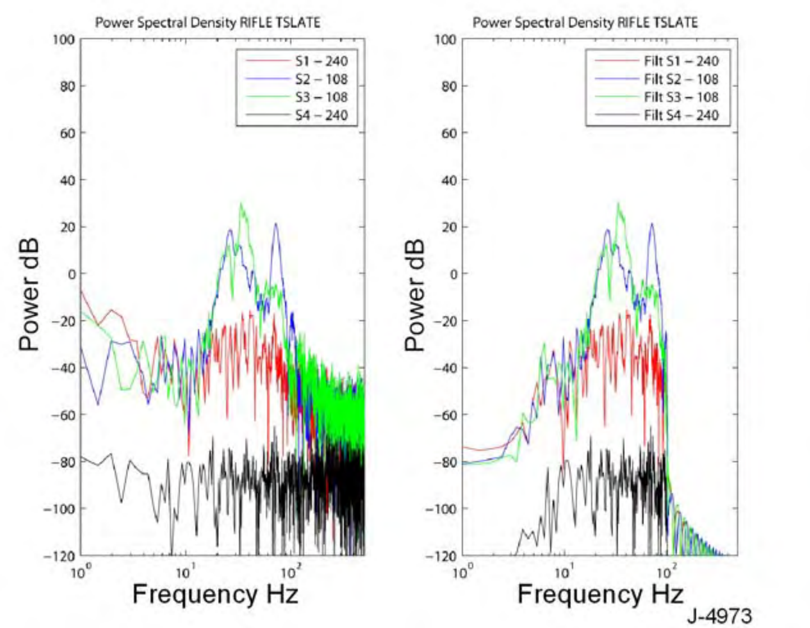


Figure 74. Power spectral density plot for a rifle shot at threat position T2 in the shale (time series shown in Figure 73).

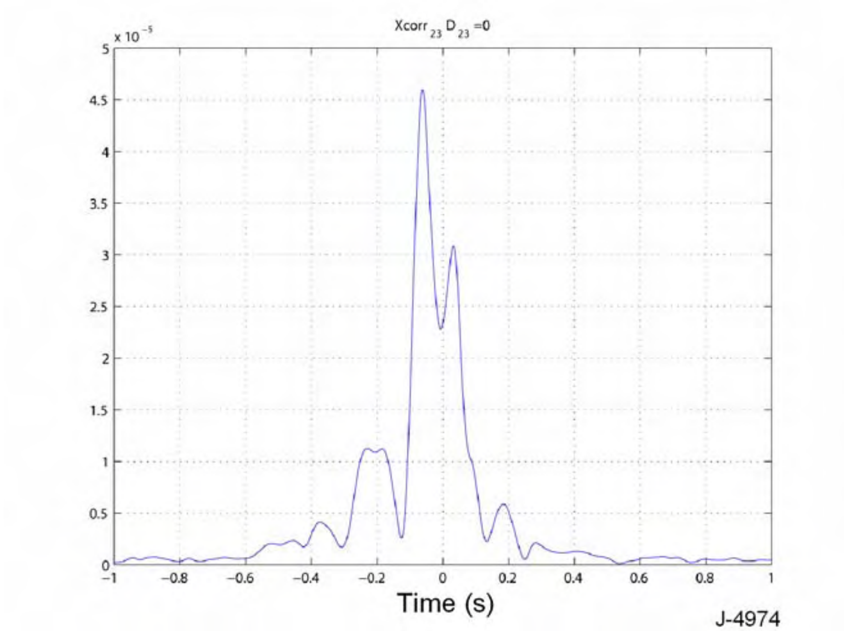


Figure 75. Low pass filtered cross-correlation output for a shot at threat location T1 in the shale.

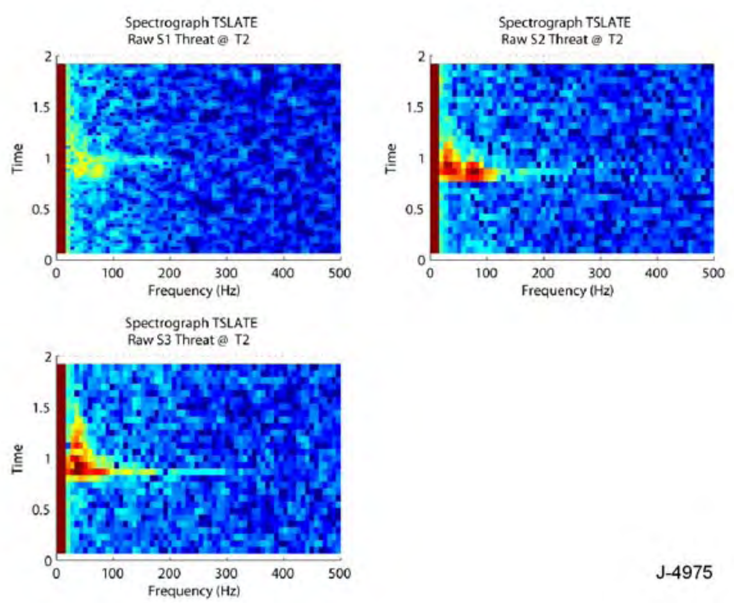


Figure 76. Spectrograph for a rifle shot at threat position T2 in the shale (time series shown in Figure 73).

Table 8 shows all of the cross-correlation and manual time difference of arrival results for configuration 1B.

Table 8. Cross-Correlation and Manual Time Difference of Arrival values for Configuration 1B.

	X12	X13	X23	M12	M13	M23
T1	0.109	0.002	-0.076	0.071	0.071	0.000
	0.018	-0.001	-0.078	0.037	0.035	-0.002
	0.138	0.000	-0.076	0.067	0.066	-0.002
	0.094	-0.003	-0.077	0.115	0.113	-0.002
Mean	**0.090**	**0.000**	**-0.077**	**0.073**	**0.071**	**-0.001**
T2	0.015	-0.037	-0.061	0.015	-0.036	-0.051
	0.163	-0.038	-0.059	0.069	0.019	-0.051
	0.161	0.158	-0.058	0.074	0.023	-0.050
	0.163	-0.035	-0.058	0.042	-0.008	-0.050
Mean	**0.126**	**0.012**	**-0.059**	**0.050**	**0.000**	**-0.050**
T3	-0.032	-0.063	0.043	0.010	0.009	-0.001
	-0.120	-0.062	0.048	0.009	0.010	0.002
	-0.132	-0.191	0.046	0.010	0.009	-0.001
	-0.033	-0.185	0.044	0.008	0.008	0.000
Mean	**-0.079**	**-0.125**	**0.045**	**0.009**	**0.009**	**0.000**
T4	-0.102	0.040	0.015	0.011	0.010	-0.001
	-0.101	0.047	0.016	0.010	0.010	0.000
	0.031	0.050	-0.127	0.010	0.007	-0.003
	-0.102	0.050	0.010	0.010	0.007	-0.004
Mean	**-0.069**	**0.047**	**-0.022**	**0.010**	**0.008**	**-0.002**
T5	-0.178	-0.081	-0.003	-0.114	-0.089	0.025
	-0.163	-0.078	-0.007	-0.115	-0.090	0.025
	-0.335	-0.150	0.181	-0.149	-0.091	0.058
	-0.165	-0.091	-0.003	-0.113	-0.092	0.021
Mean	**-0.210**	**-0.100**	**0.042**	**-0.123**	**-0.091**	**0.032**
T6	-0.157	-0.237	0.072	-0.164	-0.101	0.063
	-0.159	-0.230	0.058	-0.152	-0.151	0.001
	-0.128	-0.246	-0.098	-0.155	-0.154	0.000
	-0.132	-0.241	0.075	-0.154	-0.154	0.000
Mean	**-0.144**	**-0.239**	**0.027**	**-0.156**	**-0.140**	**0.016**

4.3.3.3 Configuration 2 – LongField Down-hole 30-06 Rifle

In configuration 2, two sensors (S1 and S2) were placed in the sandy loam near the north edge of the soy bean field and two sensors (S3 and S4) were place in the shale at the top of the limestone ridge. The east-west separation of the sensors was 360 feet and the north-south separation of the sensors was 420 feet (Both distances are quoted as the distance measured along the surface of the soil. As the crow fly distances are shorter). The east-west sensors lines are staggered by 180 ft. Three north-south threat lines were tested BE (aligned with sensor 2 and equidistant to sensors 3 and 4), C (aligned with the center of the test site), and BW (aligned with sensor 3 and equidistant to sensors 1 and 2). A minimum of two shots were fired at each location. As many as four shots were taken at the threat locations with in the soil discontinuity (BE300, C300, and BW 300). Figures 49 and 50 show the aerial photo and elevation contours for this test configuration.

This test configuration was laid out and tested prior to doing any analysis of the data gathered at the site. During a preliminary data analysis while we were onsite in Kansas, we realized that we were not getting the signal strength we desired across the transition for two reasons: the poor signal transmission characteristics of the limestone/shale soil; the large signal drop across the soil transition.

As a result, we elected to modify this configuration to the short-field configuration (Configuration 2) with the goal of maximizing the data with a high confidence factor. A similar approach was taken with regards to data analysis, with the bulk of the analysis effort being spent on configurations 1A, 1B, and 3.

Figure 77 shows the signal to noise ratio versus distance along the BE threat line (i.e. the distance is measured from threat location BE0) for all four sensors. As we can see from Figure 77 there are only three locations on this threat line where we have cross-correlations with a high confidence factor. In this case the X12 correlations are valid at BE0 and BE60, while the X34 correlation is valid at BE420. Figure 78 shows the signal to noise ratio versus distance for sensors 1 and 2 (solid lines) as well as the expected to signal to noise ratio as derived from Configuration 1A (dashed line).

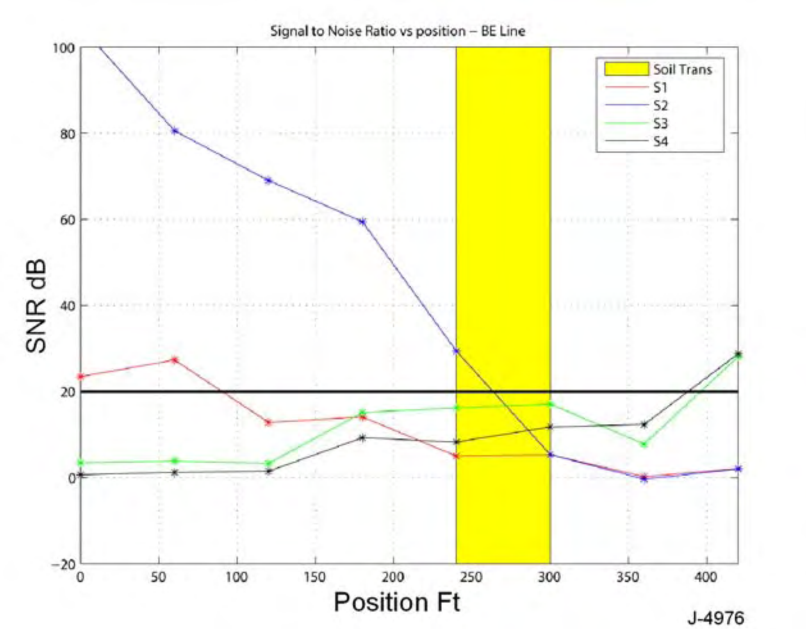


Figure 77. Signal to noise ratio vs distance along the BE threat line.

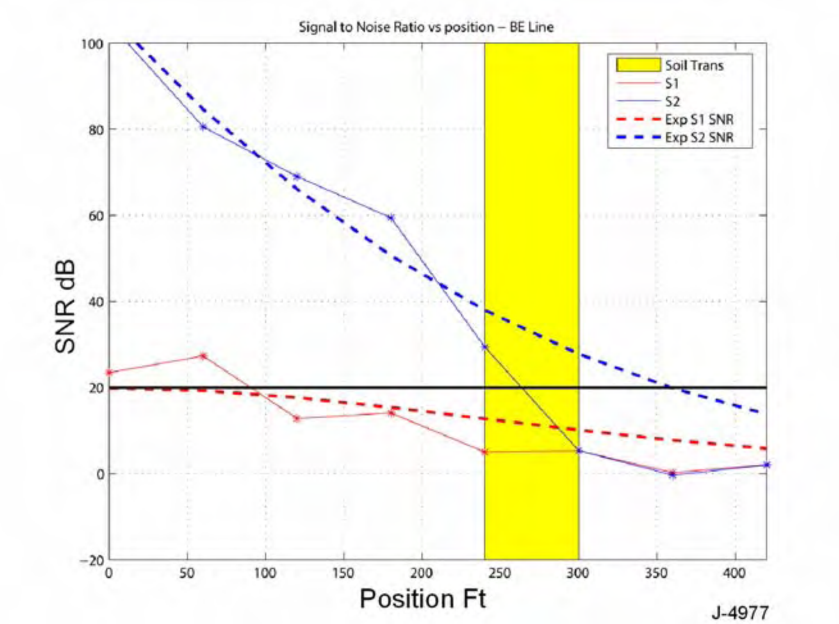


Figure 78. Signal to noise ratio for sensors 1 and 2 versus distance along BE threat line.

In Figure 78, the actual signal to noise ratio for sensor 2 is 20 dB lower than the expected value across the soil transition. The drop in the sensor 1 SNR ratio is much lower since the expected value is of the signal is already below our confidence level of 20 dB. Figure 79 shows the measured SNR for sensors 3 and 4 as well as the expected SNR value as derived from Configuration 1B (Note: since the sensors are equidistant from the BE line the expected SNR for sensors 3 and 4 are identical). Table 9 shows the cross-correlation and manual time difference of arrival values for the data above the confidence level.

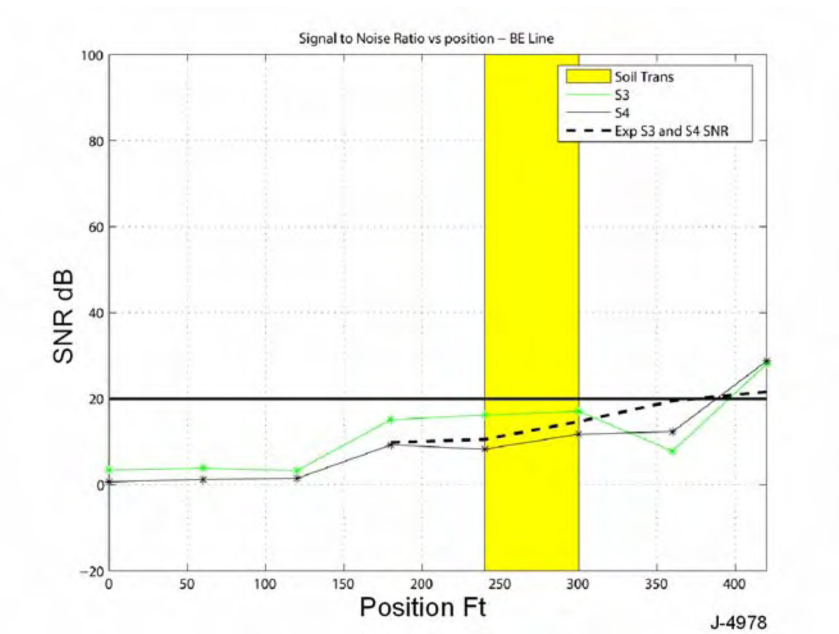


Figure 79. Signal to noise ratio for sensors 3 and 4 versus distance along the BE threat line.

Table 9. Cross-Correlation and Manual Time Difference of Arrival for Longfield BE Threat Line

	X12	M12
BE0	0.657	0.674
	0.660	0.679
mean	**0.659**	**0.677**

BE60	0.581	0.533
	0.534	0.534
mean	**0.558**	**0.533**

	X12	M12
BE0	-0.132	-0.002763
	-0.131	0.00023
mean	**-0.132**	**-0.001**

Figure 80 shows the signal to noise ratio versus distance for the longfield configuration along the C threat line. Now there is a larger range of high confidence data. Specifically, we can have high confidence in the sensor 1-2 correlation at positions C0 through C180 and marginal confidence in the C240 correlation. Similarly, we can have marginal confidence in the sensor 2-3 correlation at positions C180 through C300, and marginal confidence in the sensor 1-3 correlation at positions C180 and C240.

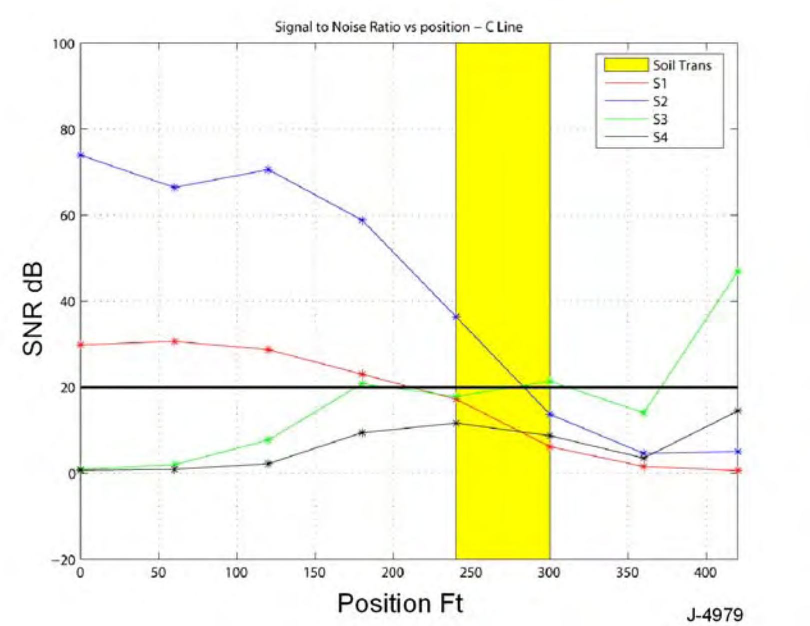


Figure 80. Signal to noise ratio vs distance along the C threat line.

Figure 81 shows the signal to noise ratio versus distance for sensors 1 and 2 (solid lines) as well as the expected to signal to noise ratio along the C threat line. The magnitude drop in sensor 2 across the transition is 15 dB while the sensor 1 magnitude drop is 10 dB. Figure 82 shows the actual and expected SNR versus distance for sensors 3 and 4. The most notable result of this plot is the consistently lower SNR for sensor 3. Since the SNR for sensor 3 is consistently below the expected value it is difficult to estimate how much the signal is degraded as we cross the soil transition boundary.

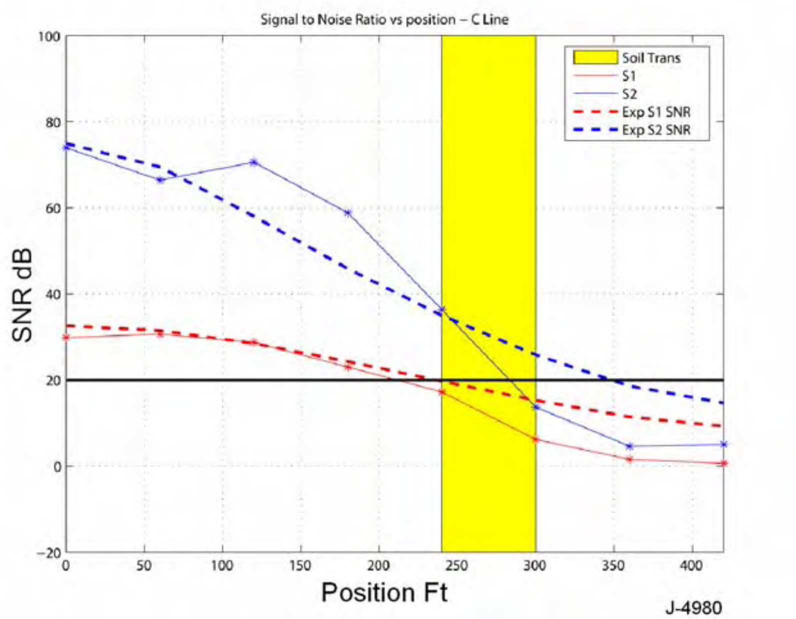


Figure 81. Signal to noise ratio for sensors 1 and 2 versus distance along C threat line.

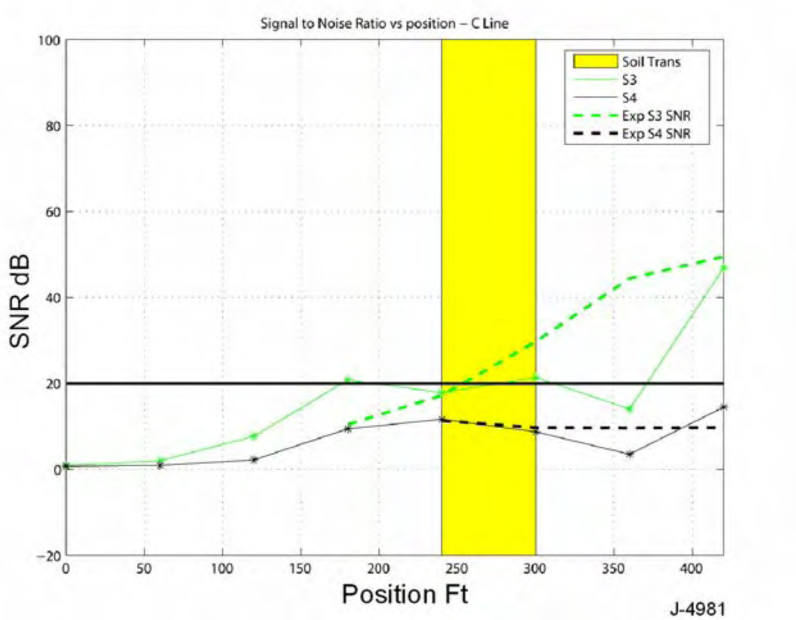


Figure 82. Signal to noise ratio for sensors 3 and 4 versus distance along the C threat line.

Table 10 contains all high and marginal confidence cross-correlation and manual time difference of arrival results for the longfield C threat line.

Table 10. Cross-Correlation and Manual Time of Arrival for Longfield C Threat Line

	X12	M12	X13	M13	X23	M23
C0	0.312	0.316				
	0.317	0.293				
mean	0.315	0.305				
C60	0.508	0.531				
	0.509	0.494				
mean	0.509	0.512				
C120	0.129	0.255				
	0.300	0.255				
mean	0.215	0.255				
C180	0.218	0.121	0.588	0.289	0.294	0.170
	0.300	0.225	0.491	0.245	0.233	0.223
mean	0.259	0.173	0.540	0.267	0.264	0.196
C240	-0.142	0.119	0.417	0.318	0.492	0.236
	-0.146	0.023	0.434	0.323	0.485	0.240
mean	-0.144	0.071	0.426	0.320	0.489	0.238

The SNR ratio along the BW threat line is shown in Figure 83. Since the BW threat line is equidistant from both sensors 1 and 2, the SNR ratios are roughly equal. As we can see from the figure, we should have a high degree of confidence in the sensor 1-2 correlations at threat locations BW 0 through BW 180, the sensor 2-3 correlation at location BW 240, and marginal confidence in the sensor 1-2 correlation at C300, the sensor 1-3 and sensor 2-3 correlation at location BW 180. The actual and expected SNR for sensors 1 and 2 is shown in Figure 84. Along the BW threat line, we are seeing a 10 dB drop across the soil transition. Figure 85 shows the measured and expected SNR ratios for sensors 3 and 4 along the BW threat line. In this case there is a 15 dB gap between the expected and measured values. It is unclear if this is due to the soil transition or other factors since the measure SNR at location BW360 is already 30 dB below the expected value. Table 11 contains the high and marginal confidence cross-correlations and manual time of arrival data for the longfield BW threat line.

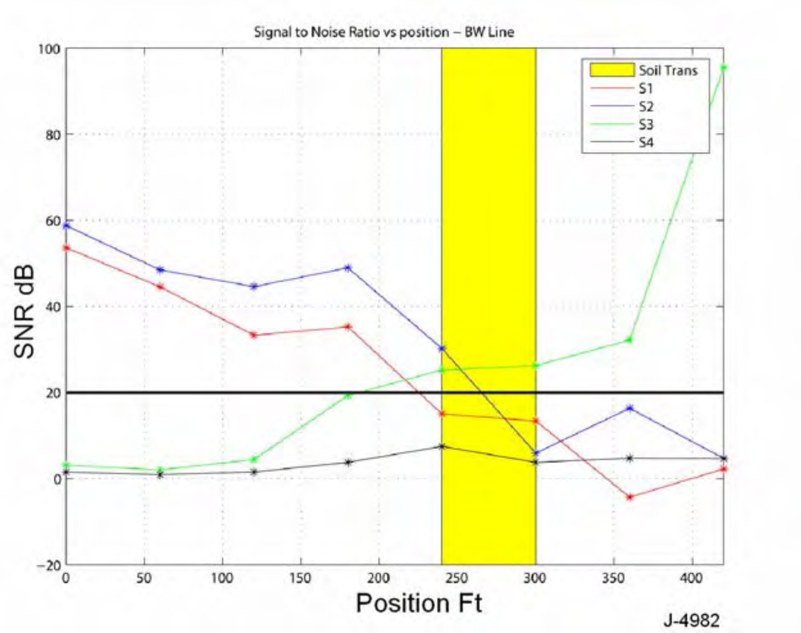


Figure 83. Signal to noise ratio vs distance along the BW threat line.

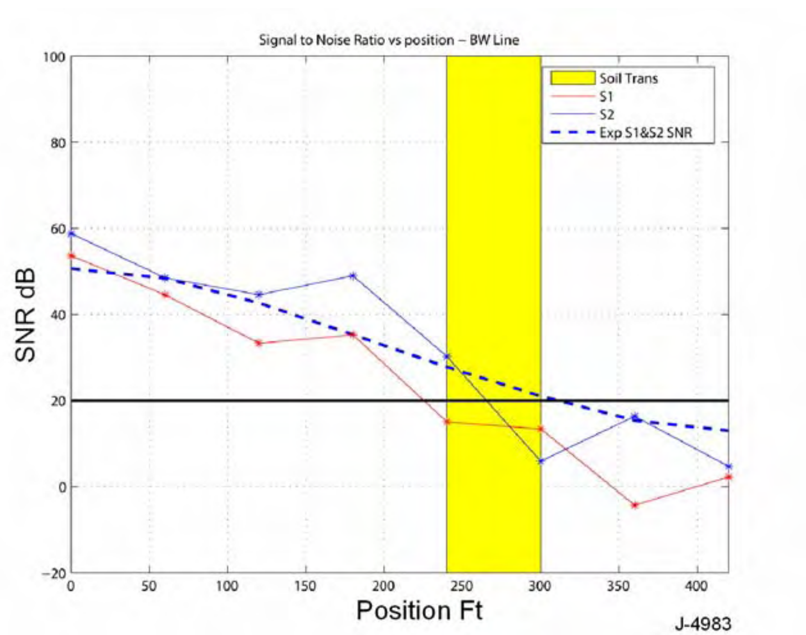


Figure 84. Signal to noise ratio for sensors 1 and 2 versus distance along BW threat line.

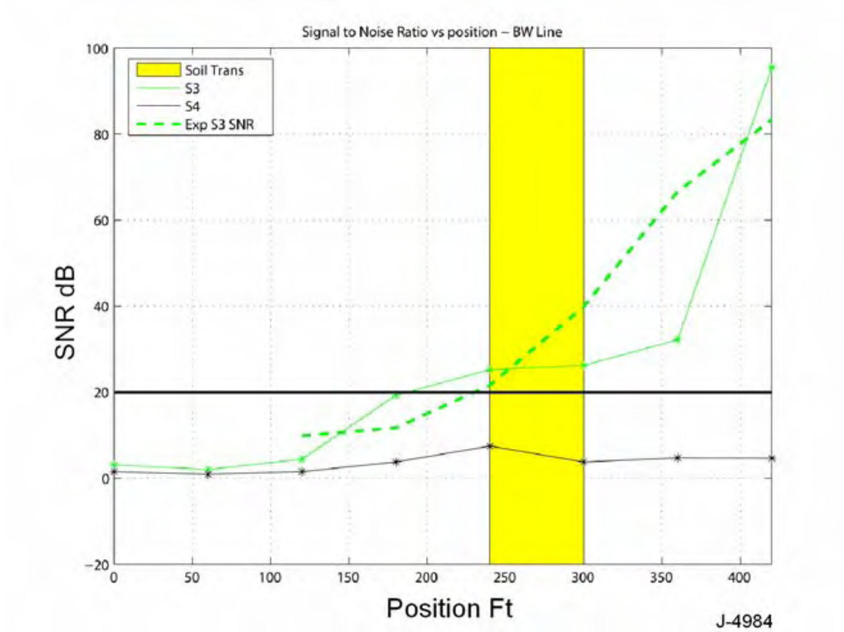


Figure 85. Signal to noise ratio for sensors 3 and 4 versus distance along the BW threat line.

Table 11. Cross-Correlation and Manual Time of Arrival for Longfield BW Threat Line

	X12	M12
C0	0.001	-0.059
	0.005	-0.060
mean	0.003	-0.059

C60	-0.029	-0.008
	-0.025	-0.018
mean	-0.027	-0.013

C120	0.060	-0.009
	0.055	-0.009
mean	0.058	-0.009

			X13	M13	X23	M23
C180	0.025	-0.157	0.169	0.098	0.602	0.374
	0.026	-0.151	0.171	0.198	0.602	0.370
mean	0.026	-0.154	0.170	0.148	0.602	0.372
C240	-0.023	-0.059	0.301	0.409	0.292	0.466
	0.044	-0.012	0.299	0.382	0.555	0.231
mean	0.011	-0.035	0.300	0.396	0.424	0.348

4.3.3.4 Configuration 3 – ShortField down-hole 30-06 rifle

Configuration 3 is identical to that of Configuration 2 except that sensors one and two have been move closer to the soil transition. Specifically sensor 1 has been moved from the AW0 position to the AW120 position while sensor 2 has been moved from the BE0 position to the BE120 position. Sensors 3 and 4 remain in the shale at the top of the limestone ridge. The east-west sensors lines are staggered by 180 ft. Five north-south threat lines were tested: AE (90 feet east of the BE sensor line), BE (aligned with sensor 2 and equidistant to sensors 3 and 4), C (aligned with the center of the test site), BW (aligned with sensor 3 and equidistant to sensors 1 and 2), and AW (aligned with sensor 1). A minimum of two shots were fired at each location. As many as four shots were taken at the threat locations with in the soil discontinuity (BE300, C300, and BW 300). Figures 48 and 49 show the aerial photo and elevation contours for this test configuration.

Figure 85 shows the SNR ratio versus distance along the AE threat line. As we can see, the signal strengths are such that there is no position along the AE threat line with a high or marginal confidence correlation. The measured and expected values for the SNR ratio of sensors 1 and 2 are shown in Figure 86. Along the AE line, we see a 20 dB gap between the expected and measured SNR ratios for sensor 2. Figure 87 shows the expected and measured SNR ratios for sensors 3 and 4. As was the case for configuration 2, it is impossible to tell how much the signals measured by sensors 3 and 4 are degraded by the soil transition.

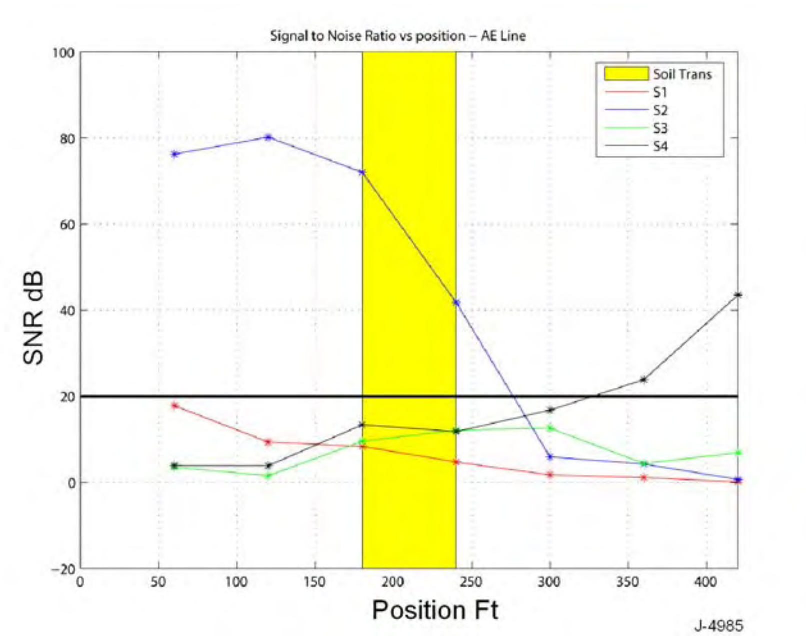


Figure 86. Signal to noise ratio vs distance along the AE threat line.

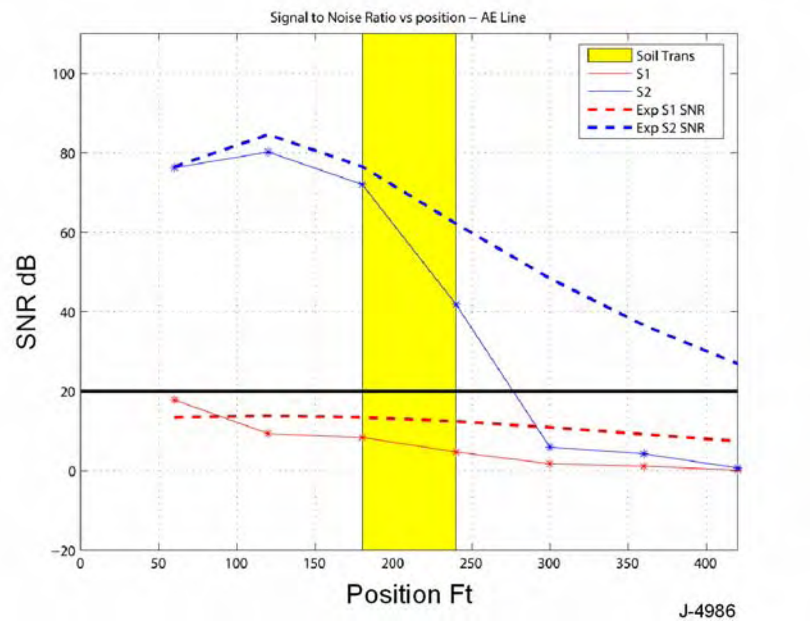


Figure 87. Signal to noise ratio for sensors 1 and 2 versus distance along AE threat line.

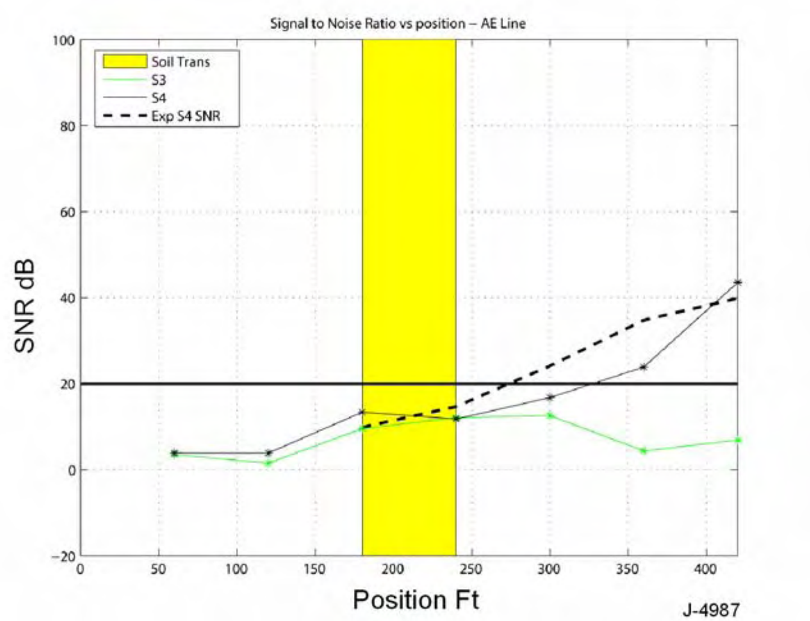


Figure 88. Signal to noise ratio for sensors 3 and 4 versus distance along the AE threat line.

Figure 89 shows the SNR ratio versus distance along the BE threat line. As was the case for the AE threat line, there is not threat position with sufficient signal strength to yield a high confidence correlation. Figure 90 shows the expected and measured SNR for sensors 1 and 2. There is a 30 dB drop across the transition for this threat line, with Figure 91 presenting the data for sensors 3 and 4.

Figure 92 shows the SNR versus distance for the C threat line. For the C threat line we have sensor 1-2 correlations with a high degree of confidence at locations C0 through C240, sensor 1-3 correlation with marginal confidence at C180 and C240, and sensor 2-3 correlations with marginal confidence at locations C180 can C240. Figure 93 show the measure and predicted sensor 1 and 2 SNR versus distance for the C line. There is a 40 dB difference between the expected and measured SNR for sensor 2 and a 20 dB difference between the measured and expected SNR for sensor 1. Figure 94 shows the measured and expected SNR for sensors 3 and 4. Again there is a 20 db difference between the expected and measured values for sensor 3, but it is unclear if this difference is due solely to the soil discontinuity.

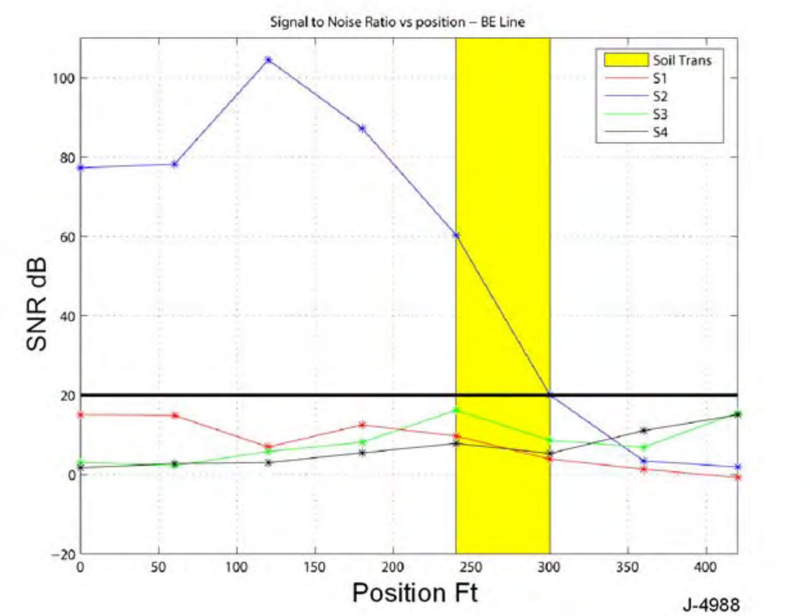


Figure 89. Signal to noise ratio vs distance along the BE threat line.

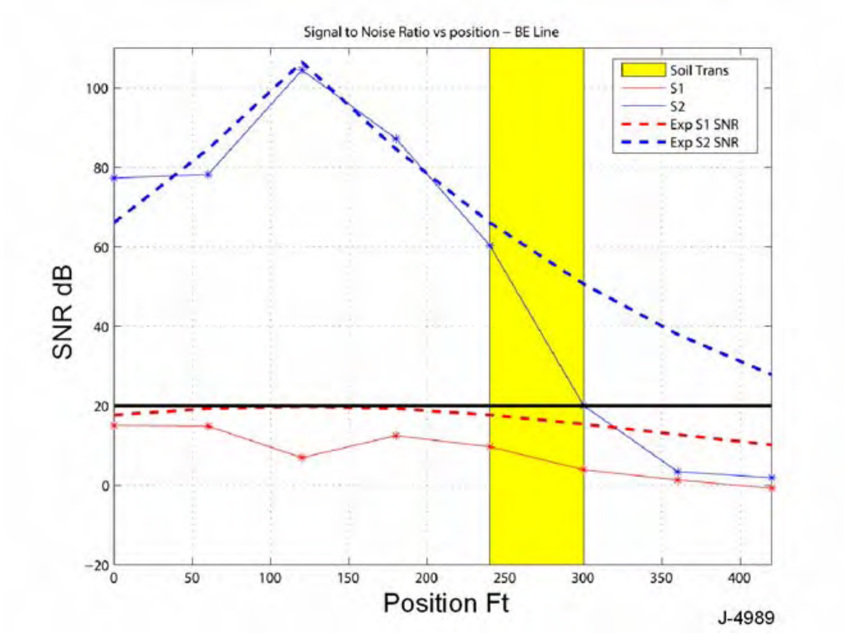


Figure 90. Signal to noise ratio for sensors 1 and 2 versus distance along BE threat line.

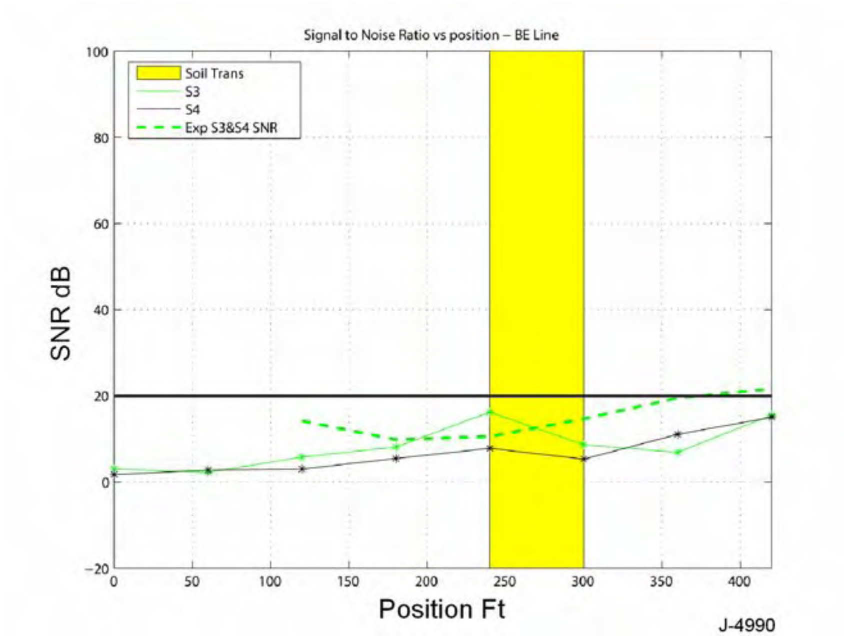


Figure 91. Signal to noise ratio for sensors 3 and 4 versus distance along the BE threat line.

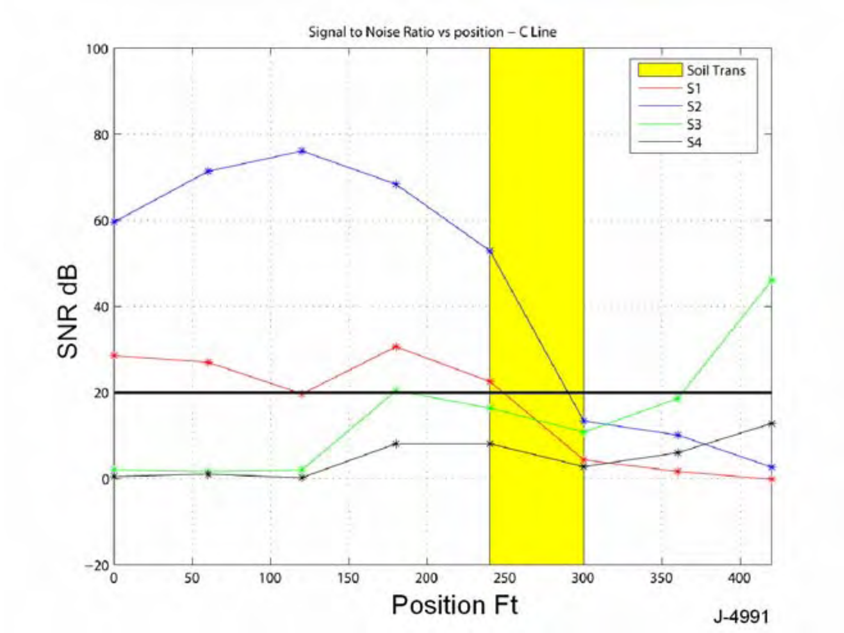


Figure 92. Signal to noise ratio vs distance along the C threat line.

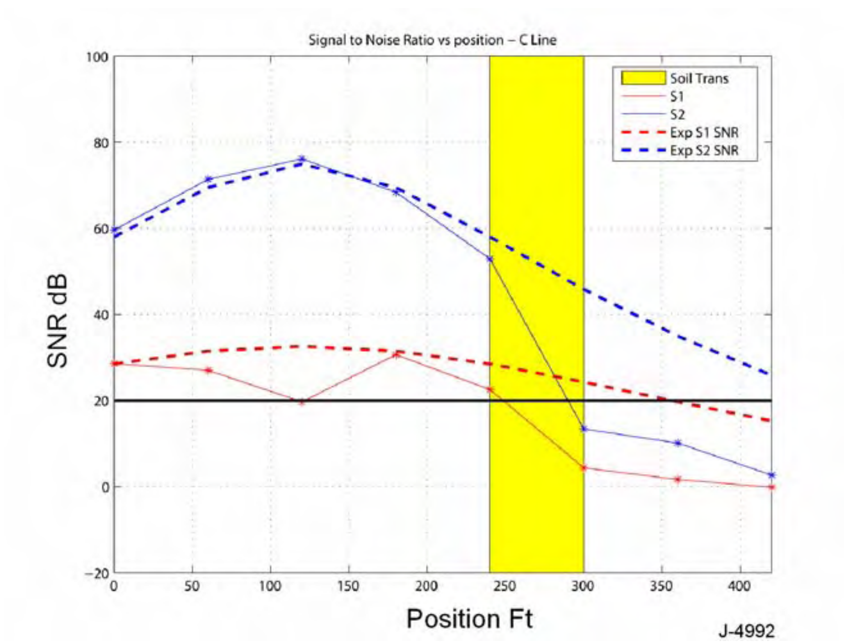


Figure 93. Signal to noise ratio for sensors 1 and 2 versus distance along C threat line.

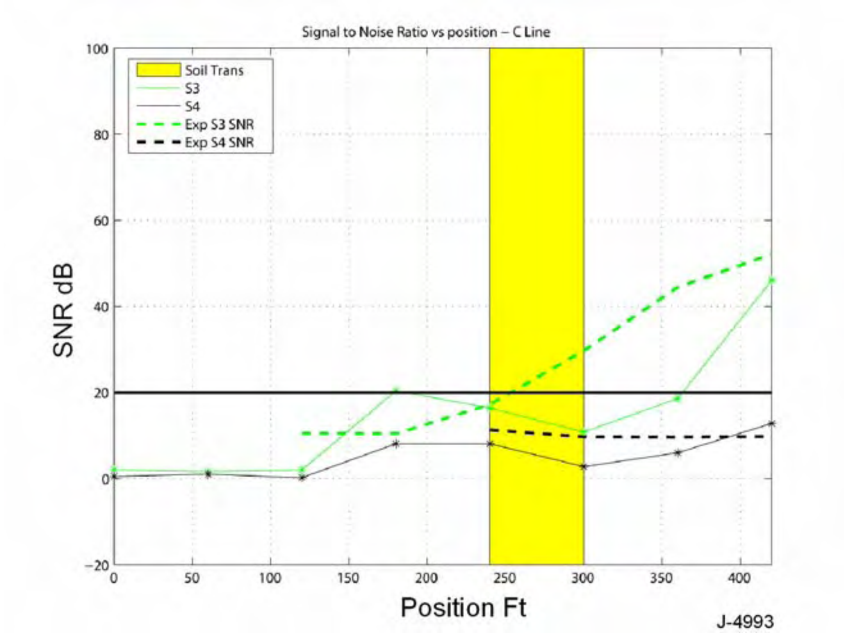


Figure 94. Signal to noise ratio for sensors 3 and 4 versus distance along the C threat line.

Figure 95 shows the average time difference of arrival for sensors 1 and 2 versus distance along the C threat line. In addition to the measured values, there is a line indicating the expected time difference. This expected time difference is determined using the method described in Appendix E. As we can see in the plots of the individual results, the correlation and manual results are tightly grouped at each location but do not match well with the expected values. The maximum variance in the high confidence correlation outputs (C0-C240) is ±10 ms which corresponds to a position error of ±4 ft at a soil speed of 400 ft/s (both sensors are located in the loam). Similarly, the maximum variance for the manually determined time difference is ±1.5 ms which corresponds to a position error of ±0.6 ft. There are a number of possible explanations for the discrepancy between the measured and predicted values. First, there is potentially a problem with how we are comparing signal. Since the spectral and temporal signature shifts as it travels through the soil, we are not really comparing apples to apples. Because the signals really are different, the comparisons that we are making to derive the time of arrival are not necessarily accurate. An alternate reason that our approach is not working well is that the soil conditions truly are not uniform and thus distort our results.

Table 12 contains the high and marginal confidence cross-correlation data for the C threat line.

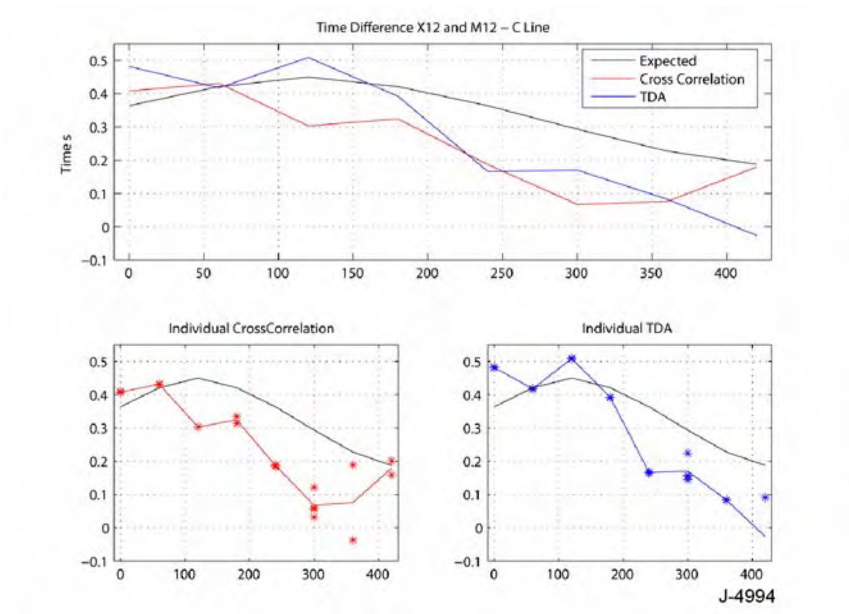


Figure 95. Average time difference of arrival for sensors 1 and 2 versus distance C threat line. Time difference determined from both wave front arrival and cross correlation.

Table 12. Cross-Correlation and Manual Time of Arrival for Shortfield C Threat Line

	X12	M12	X13	M13	X23	M23
C0	0.407	0.483				
	0.409	0.481				
mean	0.408	0.482				
C60	0.432	0.418				
	0.430	0.416				
mean	0.431	0.417				
C120	0.303	0.510				
	0.303	0.507				
mean	0.303	0.509				
C180	0.334	0.393	0.428	0.465	0.080	0.072
	0.314	0.391	0.434	0.464	0.082	0.072
mean	0.324	0.392	0.431	0.464	0.081	0.072
C240	0.188	0.165	0.398	0.460	0.269	0.296
	0.183	0.166	0.400	0.392	0.262	0.226
	0.188	0.167	0.405	0.339	0.270	0.172
	0.189	0.166	0.398	0.392	0.272	0.226
mean	0.187	0.166	0.400	0.396	0.268	0.230

Figure 96 shows SNR versus distance along the shortfield BW threat line. As was the case for the C threat line, we have sensor 1-2 correlations with a high degree of confidence at locations C0 through C240, sensor 1-3 correlation with marginal confidence at C180 and C240, and sensor 2-3 correlations with marginal confidence at locations C180 can C240. Figure 97 shows the expected and measured SNR for sensors 1 and 2 along the BW threat line. Since the two sensors are equidistant from the threat line the expected SNR's are equal. As we can see from the figure, the both signals are degraded 30 dB across the soil transition. Figure 98 shows the measured and expected SNR for sensors 3 and 4. As has been the situation for all of the sensor 3 and 4 data taken in the long and short-field configurations, it is unclear whether the large difference between the expected value and the measured SNR is a result of the soil transition or some other effect.

Figure 99 plots the average and expected time difference of arrival between sensor 1 and 2 along the BW threat line. In addition Figure 99 individually plots the cross-correlation and manual time difference of arrival results. The results shown in Figure 99 are mixed. On the positive side we see that the automatic cross-correlation results are tightly grouped (maximum variance ±1.5 ms / ±0.6 ft @ 400 ft/s) but there is a significant offset (-50 ms / -20 ft @ 400 ft/s) ignoring the data at C240) from the expected time difference (expected value at locations C0-C240 = 0 s). As we have noted earlier this likely indicates non-uniform soil conditions. This means that even in soils such as the loam in the soy bean field that we will need to calibrate the installation to accurately establish position. Table 13 contains the high and marginal confidence cross-correlation data for the BW threat line.

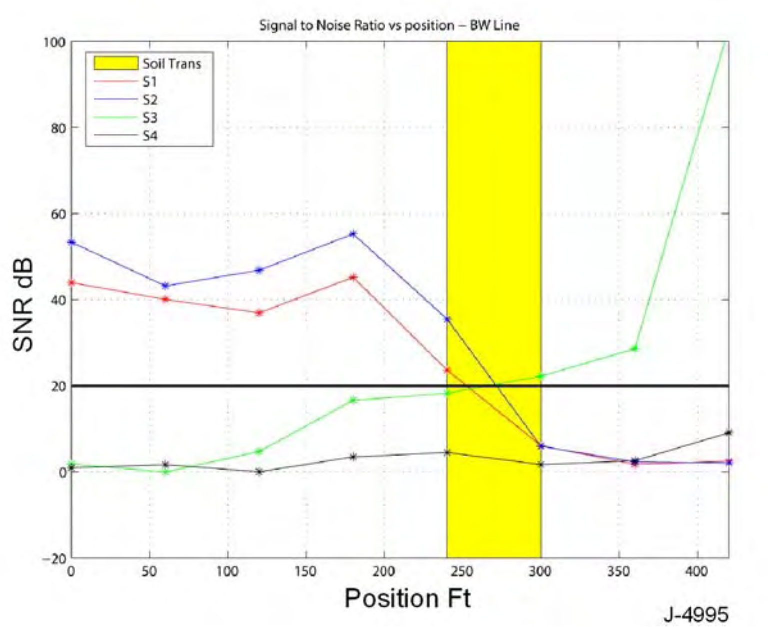


Figure 96. Signal to noise ratio vs distance along the BW threat line.

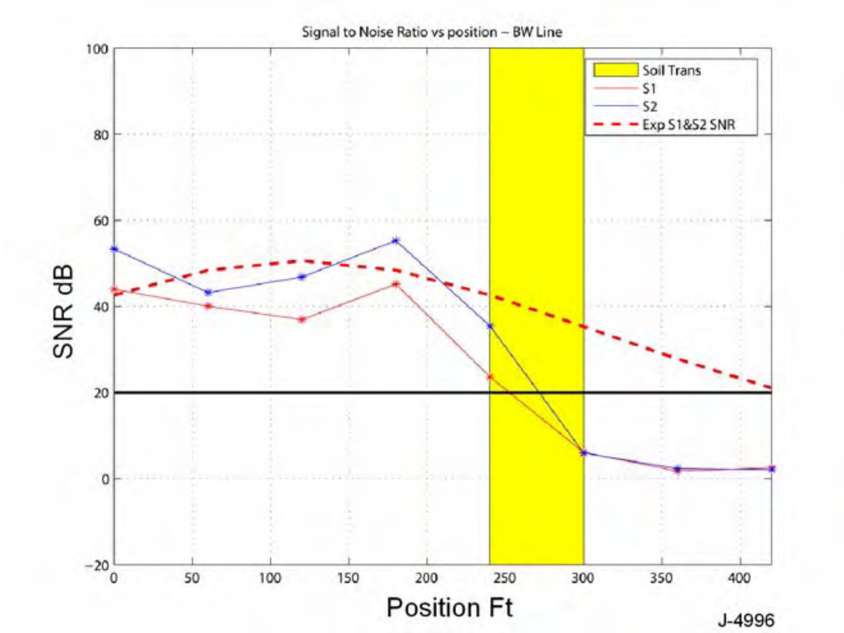


Figure 97. Signal to noise ratio for sensors 1 and 2 versus distance along BW threat line.

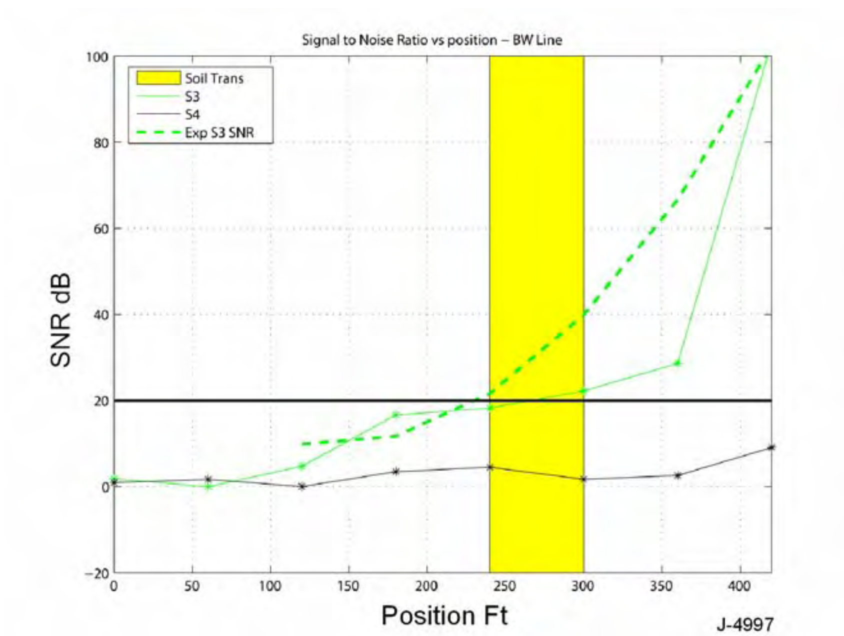


Figure 98. Signal to noise ratio for sensors 3 and 4 versus distance along the BW threat line.

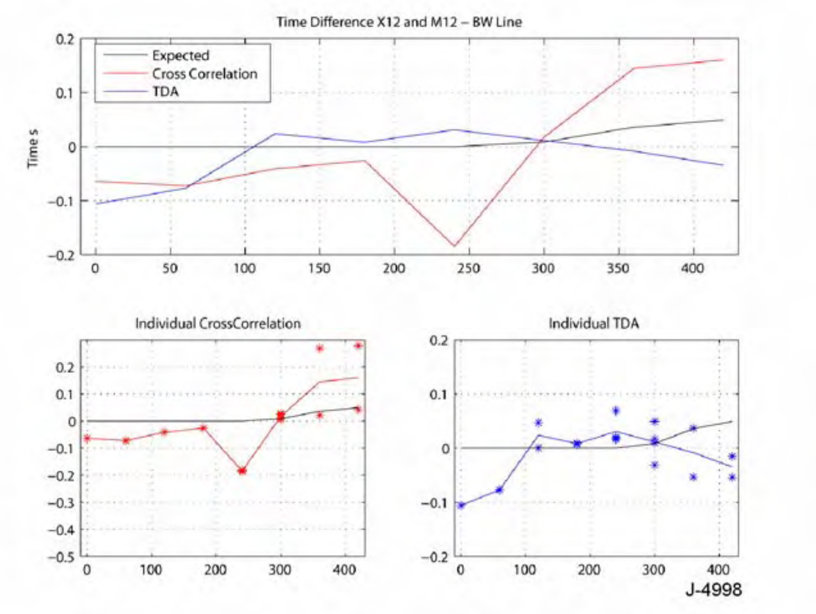


Figure 99. Average time difference of arrival for sensors 1 and 2 versus distance BW threat line. Time difference determined from both wave front arrival and cross correlation.

Table 13. Cross-Correlation and Manual Time of Arrival for Shortfield BW Threat Line

	X12	M12
C0	-0.064	-0.106
	-0.064	-0.106
mean	-0.064	-0.106
C60	-0.072	-0.077
	-0.073	-0.077
mean	-0.073	-0.077
C120	-0.041	0.047
	-0.041	0.000
mean	-0.041	0.024

			X13	M13	X23	M23
C180	-0.026	0.009	0.165	0.084	0.244	0.075
	-0.026	0.007	0.166	0.083	0.246	0.076
mean	-0.026	0.008	0.166	0.084	0.245	0.076
C240	-0.185	0.020	0.203	0.051	0.474	0.031
	-0.182	0.016	0.301	0.046	0.387	0.030
	-0.185	0.019	0.413	0.049	0.472	0.030
	-0.186	0.069	0.412	0.100	0.477	0.031
mean	-0.185	0.031	0.332	0.061	0.453	0.031

Figure 100 plots the measured SNR along the shortfield AW threat line which is aligned with sensor 1. As was the case for the AE and BE threat lines, there is marginal signal on three of the four sensors. As a result, we only have marginal sensor 1-2 correlation data at locations AW0 through AW240. Figure 101 plots the expected and measured SNR for sensors 1 and 2. There is a 20 dB drop in the sensor 1 signal magnitude across the soil transition. Figure 102 shows the average time difference of arrival versus expectation for both the cross-correlation and manual time difference of arrival measurements. Table 14 contains the cross-correlation numbers for the shortfield AW threat line. As we can see from the variance in the numbers, all of these correlations are marginal. Similarly, there is a wide discrepancy between the expected correlation values and the measured time of arrivals.

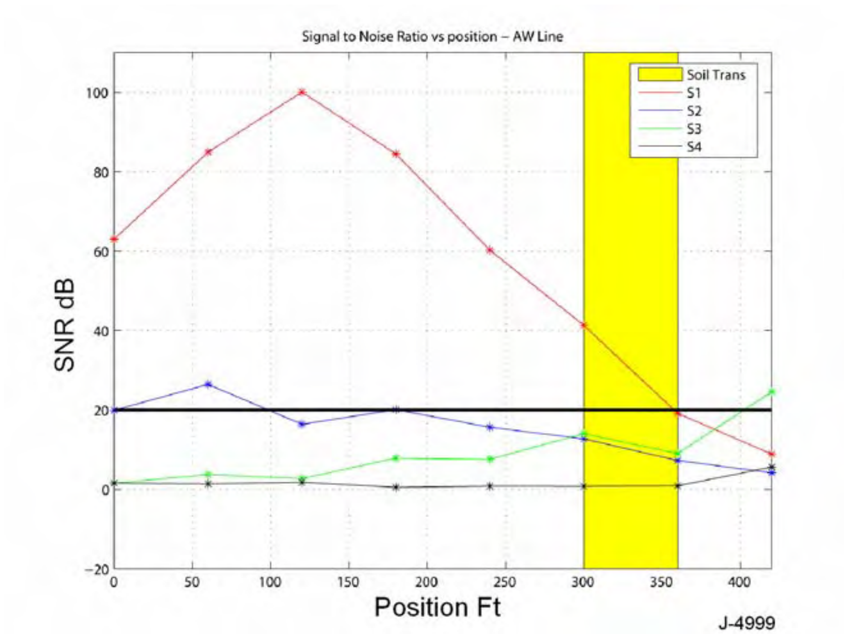


Figure 100. Signal to noise ratio vs distance along the AW threat line.

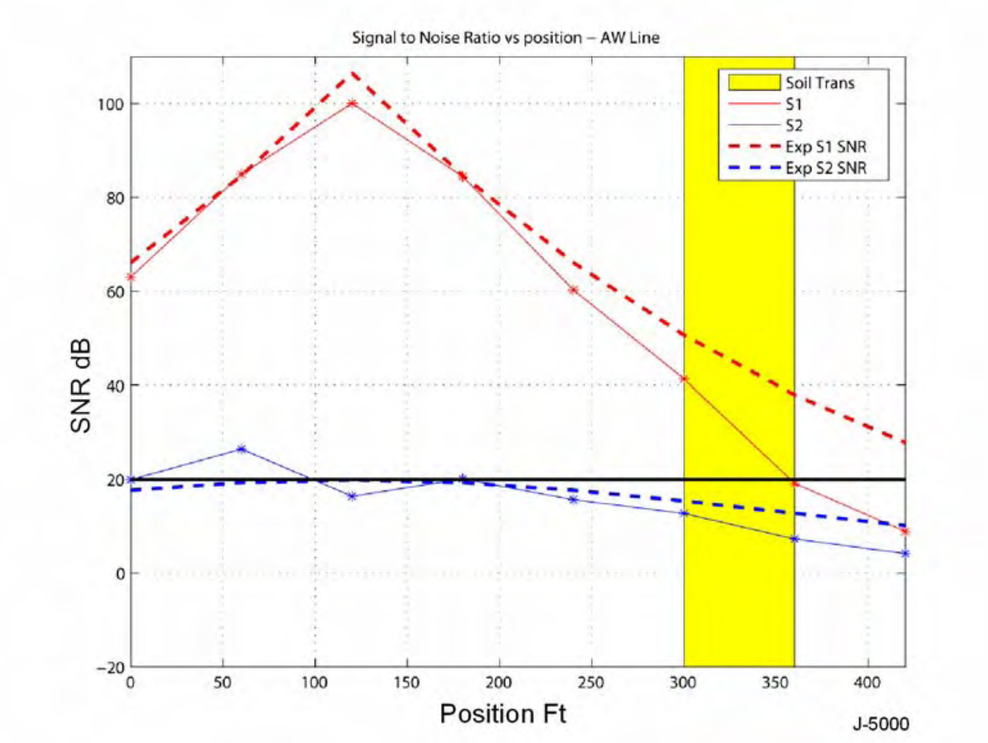


Figure 101. Signal to noise ratio for sensors 1 and 2 versus distance along AW threat line.

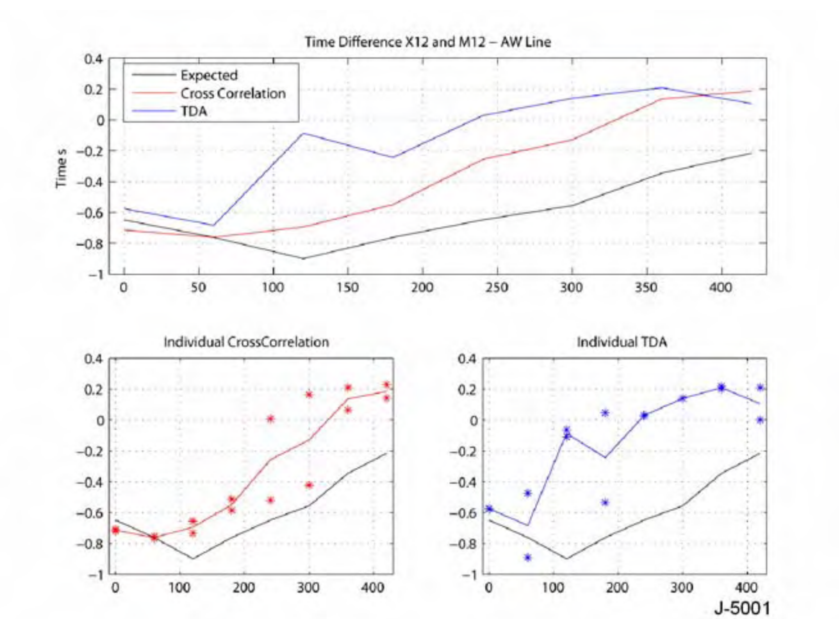


Figure 102. Average time difference of arrival for sensors 1 and 2 versus distance AW threat line. Time difference determined from both wave front arrival and cross correlation.

Table 14. Cross-Correlation and Manual Time of Arrival for Shortfield AW Threat Line

	X12	M12
C0	-0.720	-0.577
	-0.709	-0.575
mean	-0.715	-0.576

C60	-0.755	-0.892
	-0.769	-0.475
mean	-0.762	-0.684

C120	-0.734	-0.065
	-0.656	-0.109
mean	-0.695	-0.087

	X12	M12
C180	-0.586	-0.535
	-0.513	0.046
mean	-0.550	-0.244

C240	0.007	0.027
	-0.521	0.029
mean	-0.257	0.028

4.3.3.5 Configuration 4 – ShortField Backhoe

Configuration 4 is identical to Configuration 3, the only change is that instead of using the down-hole rifle as a source we are using a 15,000 lb backhoe as the threat source. Due to the geography of the test site, the backhoe could only be deployed to the edge of the soy bean field. This means that data could only be collect with the threat in the loamy soil (locations 0 through 180 for all 5 threat lines). Since we were not allowed by the land owner to dig in the field, the backhoe was used as an impact source. Specifically, the backhoe was driven to a location 8-10 feet from each of the threat locations (orientation of the tractor relative to the threat location varied) where the side support legs and front bucket were lowered to stabilize the tractor. The backhoe then extended the bucket arm and struck the bucket multiple times (5-7 times per data file) against the ground at the threat location. A minimum of three data files were recorded at each threat location.

Figure 103 shows the power spectral density for a typical backhoe impact. As was the case for the down-hole rifle, the majority of the signal energy is contained within the 5-100 Hz band, thus we utilized the same 500th order 5-100 Hz band-pass filter employed on all of the previous analysis. As we would expect, there is a strong acoustic signature from the backhoe in the 200-400 Hz band. As we can see in Figure 103, the 5-100 Hz filter does an excellent job attenuating this acoustic energy.

One of the issues with analyzing the backhoe data is defining exactly how the signal to noise ratio is determined. In all of the previous analysis, we have determined the signal to noise by calculating the power in a short time segment which includes the down-hole rifle shot, and comparing that power to the power of another time segment within the same data file which does not contain the rifle shot. In this way, we are able to determine the signal strength of the threat signature versus the current background/sensor conditions. In the case of the backhoe impacts, the analysis is complicated by the fact that the tractor is always running. Since the tractor is quite noisy, this results in a significant increase in the background "noise" (Note: Since the seismic signature from the tractor running is one of the tools we use to identify threat types, it can be argued that this background noise is in fact threat and not noise). Figure 104 shows the power

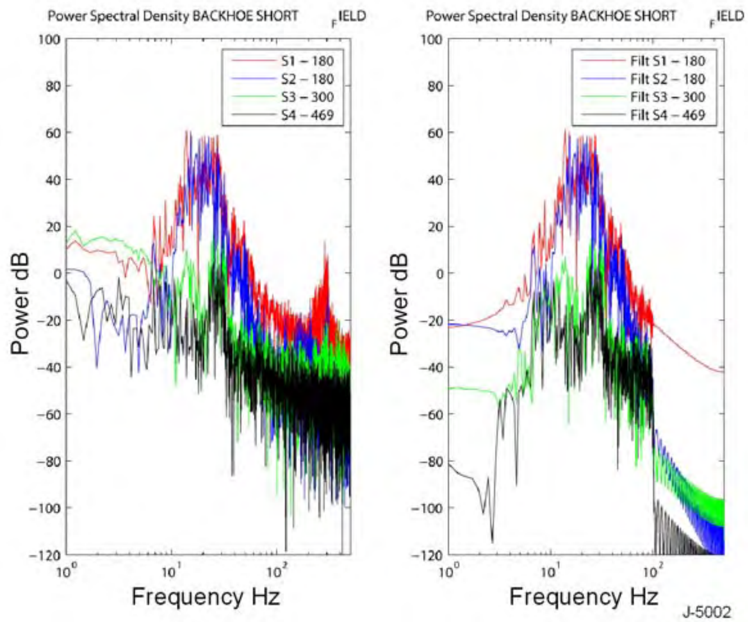


Figure 103. Power spectral density for the backhoe during bucket impact (Location AE180).

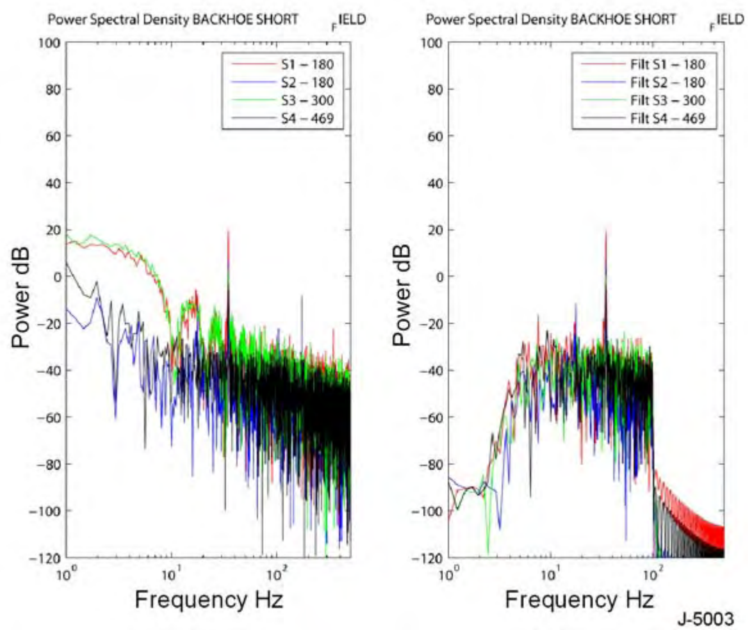


Figure 104. Power spectral density for the backhoe idling (Location BW120).

spectral density of the backhoe idling. As we can see, there is a very sharp peak at 30 Hz (likely directly associated with the engine idle speed) and a 20 dB increase in the broad spectrum signature. To account for this uncertainty, we will present the signal to noise in three forms:

1. Bucket impact power versus backhoe idle background.
2. Bucket impact power versus quiet* background.
3. Backhoe idle power versus quiet background.

Figure 105 shows all three forms of average SNR versus distance for the backhoe. In Figure 105(A), we see that for the two sensors located in the loam that the backhoe impacts are 40-60 dB above the backhoe background idle out to a range of 400 ft, while at sensors 3 and 4, located in the shale, the impact is 20 dB above the backhoe background out to a range of 600 ft. As can be seen, there is a large variance in the magnitudes of the signals with respect to range. This is largely due to the variance in the strength of the bucket impact with the ground. Figure 106 shows the SNR of the individual data points. As we can see, there is a large (as much as 60 dB) variance in the signal strength at any threat location. Thus it is not surprising that there is a large variance in the average data. This variance makes it impossible to estimate the maximum detection range of the backhoe impacts in each of the soil conditions.

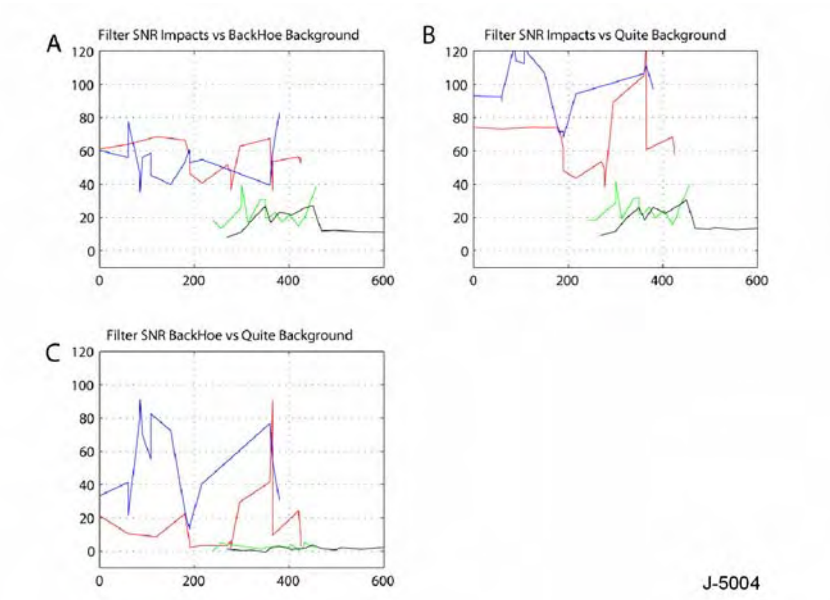


Figure 105. Backhoe signal to noise ratio versus distance. 104(A) Impact versus Backhoe Idle. 104(B) Impact versus quite background (no equipment). 104(C) Backhoe idle versus quite background.

* For this case, we have taken the background data from one of the Configuration 3 data files and used it as a sample background for all of the backhoe data.

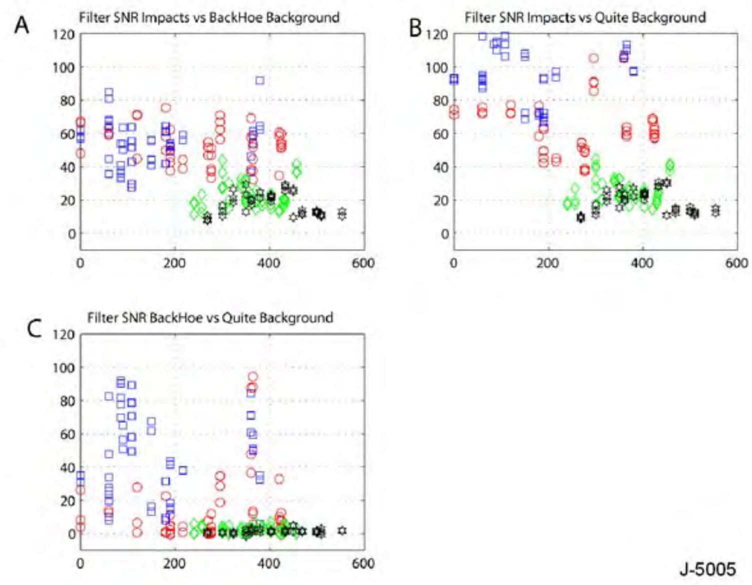


Figure 106. Backhoe signal to noise ratio versus distance. 105(A) Impact versus Backhoe Idle. 105(B) Impact versus quiet background (no equipment). 105(C) Backhoe idle versus quiet background.

Returning to Figure 105(B), we see that comparing the bucket impact power with respect to a quiet background results in a 20 dB increase of the SNR for sensors 1 and 2 while there is only a minimal increase in the SNR for sensors 3 and 4. This essentially means that the backhoe idle is not present in the sensor 3 and 4 data. When comparing the strength of signals in the loam and shale, we see that there is roughly a 60 dB strength advantage for the signal propagation in the loam. It is difficult to determine how much of this signal drop is due to the soil transition and how much is due to other factors. To try and estimate the power drop across the transition, we can compare the expected power drop versus distance in the various soil conditions. Using the data from the 240 ft range, we see that the signal strength in the loam is roughly 70db and the signal strength in the shale is 20 dB. Since sensors 3 and 4 are a minimum of 120 ft from the soil transition boundary, we can estimate from Figure 62 that there is a 60 dB attenuation of the signal while traveling through the shale. Similarly from Figure 55, we can estimate that the 80 feet the signal travels through the loam results in 20 dB of attenuation for a total signal attenuation of 80 dB. The same signal traveling 200 ft through loam only would be attenuated 60dB. If there were no attenuation due to the soil transition, we would expect a 20 dB difference between the signals measured in the loam versus the sensors in the shale. Thus we can estimate that the soil transition attenuates the signals 30-40 dB, which is comparable to the attenuation seen in Configurations 2 and 3.

Figure 107 shows a spectrogram for a series of backhoe impacts at location BW180. As we can see from the figure, the individual bucket strikes are clearly visible as large magnitude low frequency wave packets. What is interesting is that we can clearly pickup the variation in engine speed as the bucket is maneuvered by looking at the high frequency acoustic signature at 300 Hz. Figure 108 shows a spectrogram of the backhoe idling. As we can see from the figure,

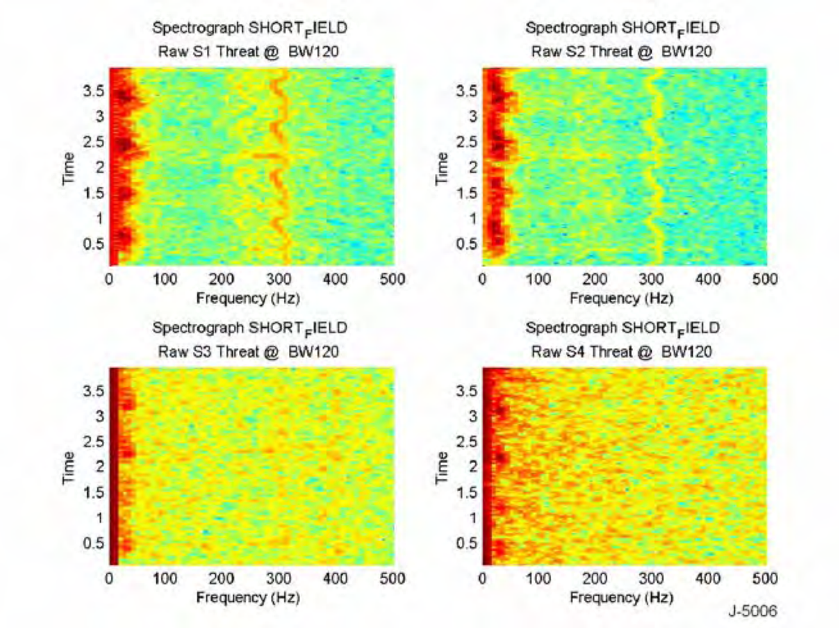


Figure 107. Spectrogram of the Backhoe impacts.

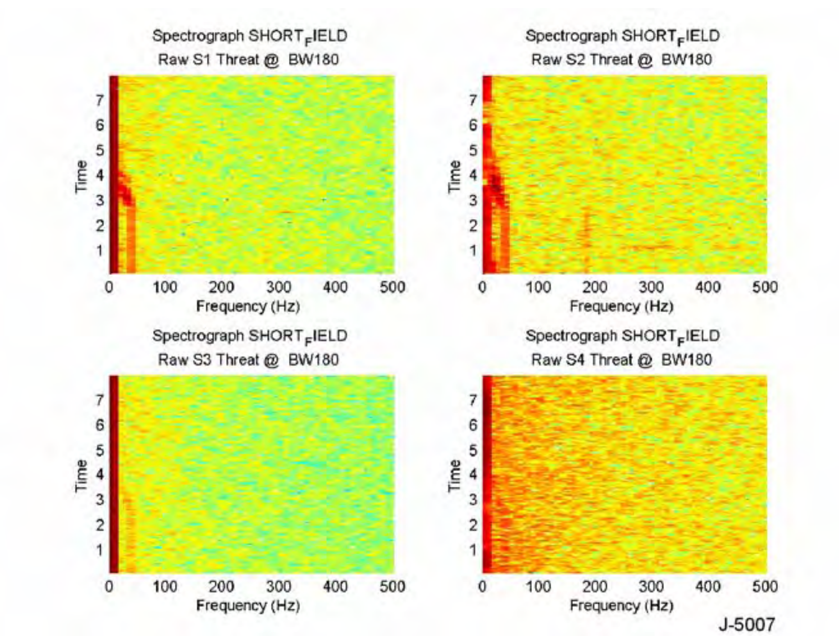


Figure 108. Spectrogram of the backhoe idling.

we can clearly pickup a strong seismic signature of the engine running at approximately 30 Hz. In fact, we can clearly see the changes in engine idle speed as the motor is further idled down.

We have conducted some preliminary cross-correlation analysis of the backhoe data. Table 15 contains the preliminary sensor 1-2 correlation for the BW line and Table 16 contains the preliminary sensor 3-4 correlations for the BE line. In the case of the BW line, since sensors 1 and 2 are equidistant from the threat, we would expect that the time difference would be 0 s. Similarly, we would expect the sensor 3-4 correlation to be 0 s for the BE line. As we can see from the preliminary data, this is not true for all of the data.

Table 15. Preliminary Cross-Correlation Backhoe BW Threat Line

Backhoe BW Line

D1	D2	D3	D4	S1-S2 time lag (sec)
216	216	420	553	-0.009
190	190	360	509	-0.027
180	180	300	469	0
190	190	240	433	0

Table 16. Preliminary Cross-Correlation Backhoe BE Threat Line

Backhoe BE line

D1	D2	D3	D4	S3-S4 time lag (sec)
379	120	457	457	-0.147
365	60	402	402	0.067
360	0	350	350	0.004
365	60	300	300	-0.191

There are many potential sources for this inconsistency. First, the correlation method we are using for this analysis is the same used for evaluating the down-hole rifle shots. Specifically, we are taking time segments 2 seconds in length and correlating them. Since the backhoe data consist of multiple strikes, the number of strikes recorded at a given sensor may be different at each location due to transmission lags. Thus the correlations may be off due to the signals being different.

Alternately, we may be running into the situation that we experienced in configuration 1B, where the actual time and spectral signatures were different enough that it results in a poor correlation. Figure 108 shows the time signature of a series of impacts at location BE180. As we can see, while all of the signals meet our 20 dB criteria, the signature recorded for sensor 1 lacks the distinct peaking seen in the other 3 signals. While this may not preclude the use of correlation, it will reduce the fidelity of the correlation result.

Thirdly, the variance in the correlation results may be a direct result in our uncertainty in the origin location of the threat. As described earlier, the backhoe was driven near each of the threat locations at which point the bucket and side stabilizers where deployed to stabilize the vehicle. When the backhoe bucket is impacted with the ground, there are equal and opposite forces applied against the ground at the bucket and stabilizer contact points. Since the tractor is approximately 10 feet wide and 15 feet long, this results in a roughly 25 by 10 footprint for the source (the backhoe is 8-10 feet from the bucket impact point). Looking at the data for the BW line, we see that the position uncertainty is approximately 10 ft which could easily be accounted for by this uncertainty.

Lastly, as we have noted earlier, we could simply be documenting actual artifacts of the site geology.

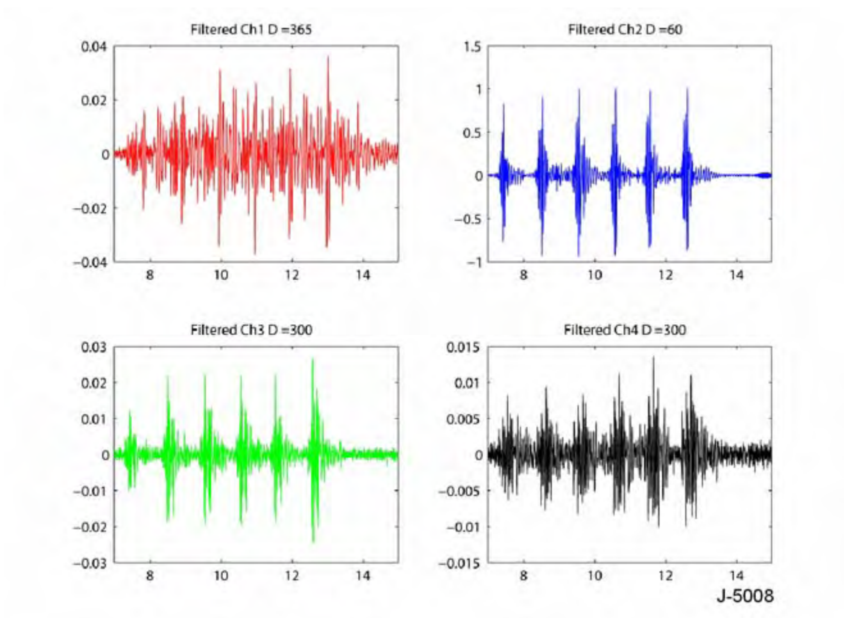


Figure 109. Time signature of the backhoe impacts at BE180.

We have presented the temporal signatures and acoustic frequency spectra acquired over the test site. Frequencies are not uniformly attenuated with distance as they propagate through the loam and shale, complicating time-of-arrival and PSD analyses. Loam attenuates the down-hole-gun signal less than shale. Acoustic signatures were observed in both directions across the soil discontinuity, but an attenuation of about 20-30 dB in signal strength was observed in the transition. The correlated arrival times at different sensors were tightly clustered for many shots (to within a millisecond) indicating that precise measurement was possible (physics was not against us), however the propagation time was not as expected indicating that better understanding of the propagation is required. Both manual peak selection and automated cross-correlation approaches show promise. The derived arrival times are tightly clustered, with outliers often representing one acoustic cycle shift. Multiple strikes (in real world applications) would permit precise arrival time determination (just as the multiple shots in this field test did). However the accuracy remains to be determined. Neither algorithm is sufficiently robust presently to permit automatic triangulation. The system has demonstrated adequately low and invariant operating noise under a variety of environmental conditions (warm, cold, windy). The backhoe displayed a very strong acoustic signature that was observable across the soil discontinuity in all four sensors at distances up to the maximum 700 feet in this test site.

Upon further improvement, we believe that the installed sensor network could be "calibrated" with an acoustic source to permit the time-of-arrival and propagation to be characterized and train the Pigpen sensors for that location.

5.0 Advanced Prototype Development

In parallel with the extensive testing of the EP-1 and EP-2 hardware, PSI developed the next engineering development model, the Advanced Prototype (AP). The AP will make use of the mature sensor head (acoustic transducer) configuration and analog electronics, as proven in earlier programs and the DOT BAA with NYSEARCH, with improved digital electronics, processing and threat recognition software, and changing the communication between the sensors from wired to wireless. These changes are presented as a flow diagram in Figure 110.

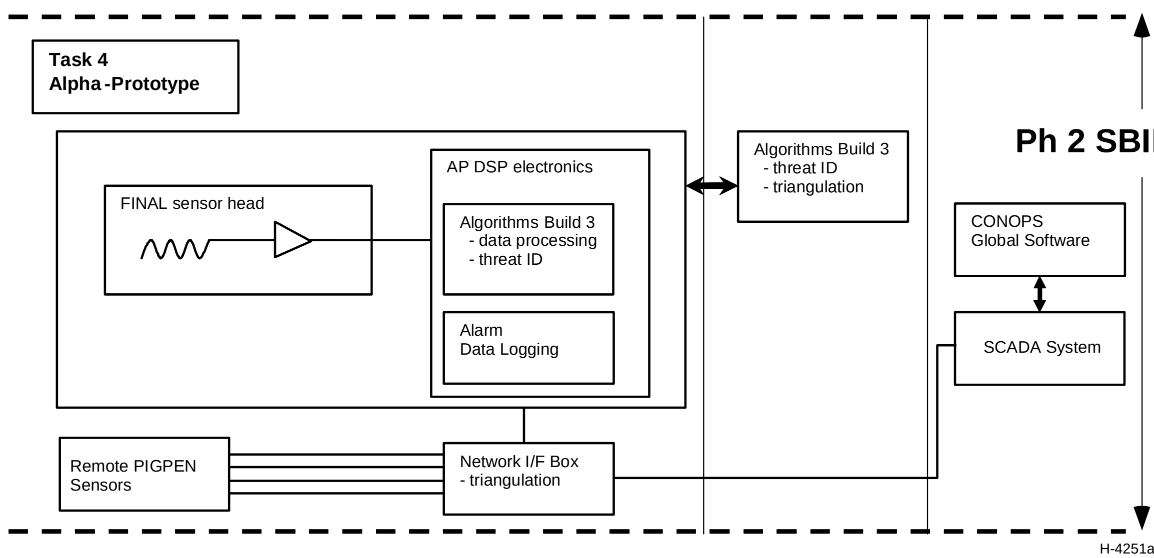


Figure 110. Advanced Prototype development components.

We undertook a study of the AP system design drivers, such as communication bandwidth, range, power, sensitivity and likely local support structure (power, communication) starting after the kickoff meeting (Appendix A), met with the user community to obtain their insight (as part of the Data Review in Appendix B), and presented a status and recommended configuration nine months into the Phase 2 program in March 2006 (Appendix C). By May 2006 we had completed the detailed electrical design for the digital signal processor approach and created schematics. PSI worked closely with its subcontractor VTech Engineering Corp. to form and review the electronics design for the PIGPEN AP. By June of 2006 we had completed the electrical layout of the PIGPEN AP meeting the design specifications. We held an internal layout review to formally approve the electronics layout. The electronics documentation package was sent out for quotation and fabrication. In July 2006, we completed the electrical fabrication of PIGPEN AP. The PIGPEN processor board and Power and Communication adaptor (PCA) board were fabricated and populated. Figure 111 shows the AP electronics boards with a PIGPEN sensor.

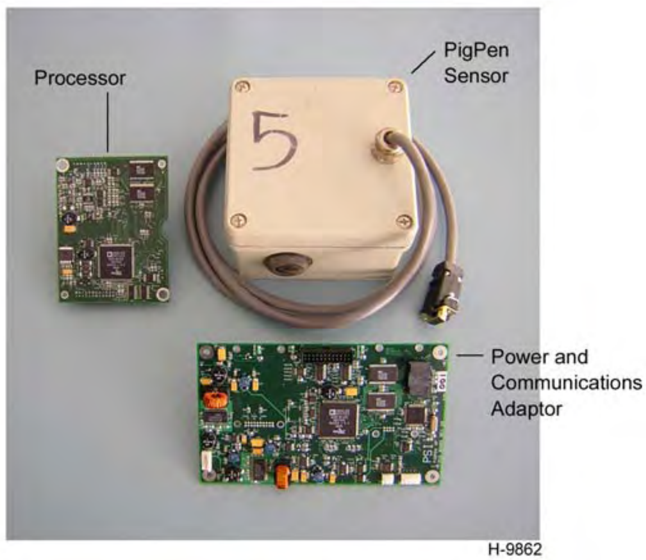
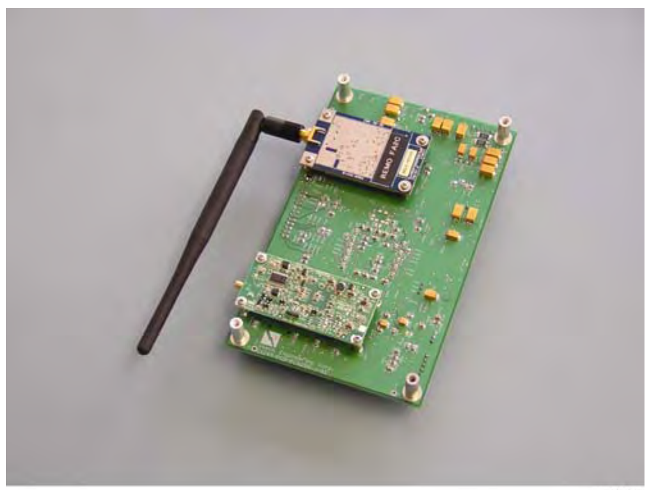


Figure 111. The PIGPEN AP electronics boards with the PIGPEN sensor.

During August 2006 we were able to complete the development of DSP Board firmware and PCA board firmware and began testing. We also developed test interface to laptop computer. We reviewed the Design Specification to reflect information needed to implement the central command system interface we call the Network Interface Box. These development and testing efforts proceeded smoothly so that by the end of October we were able to verify performance on the first AP unit. Figures 112 and 113 show the top and bottom sides, respectively, of the Power and Communications Adaptor Board (PCA). The GPS and Radio units are clearly visible in the bottom side view. Figure 114 shows the sensor chassis and DSP board, which is installed inside the chassis. Testing on the first AP unit showed good electrical test performance, so we proceeded to build the next 5 AP sensor units and preamplifier boards, chassis, housings, and cabling that were components of the AP system. We completed this activity early in 2007 and began integration and assembly of the AP units. We integrated the GPS receivers into each AP sensor node to enable precise time determination. We next assembled the sensors into a network and demonstrated communication with the central node (below). This bench test demonstration was the level of maturity we reached at the end of this Phase 2 program.

J-2457

Figure 112. PIGPEN AP Power and Communications board. Top view.

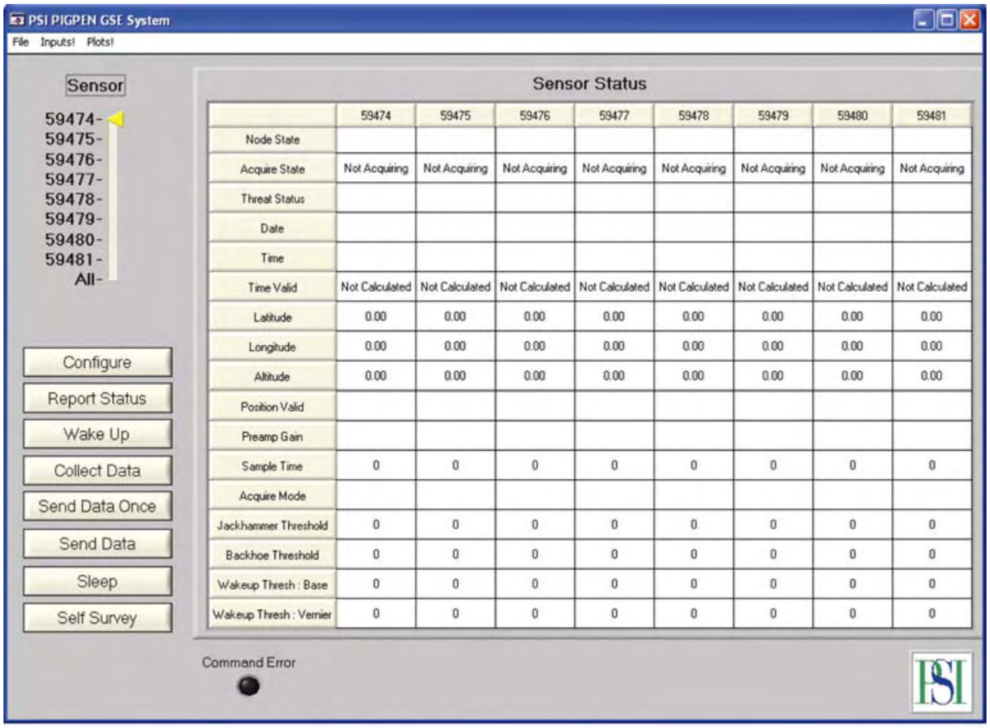


J-2458

Figure 113. PIGPEN AP Power and Communications board. Bottom view.

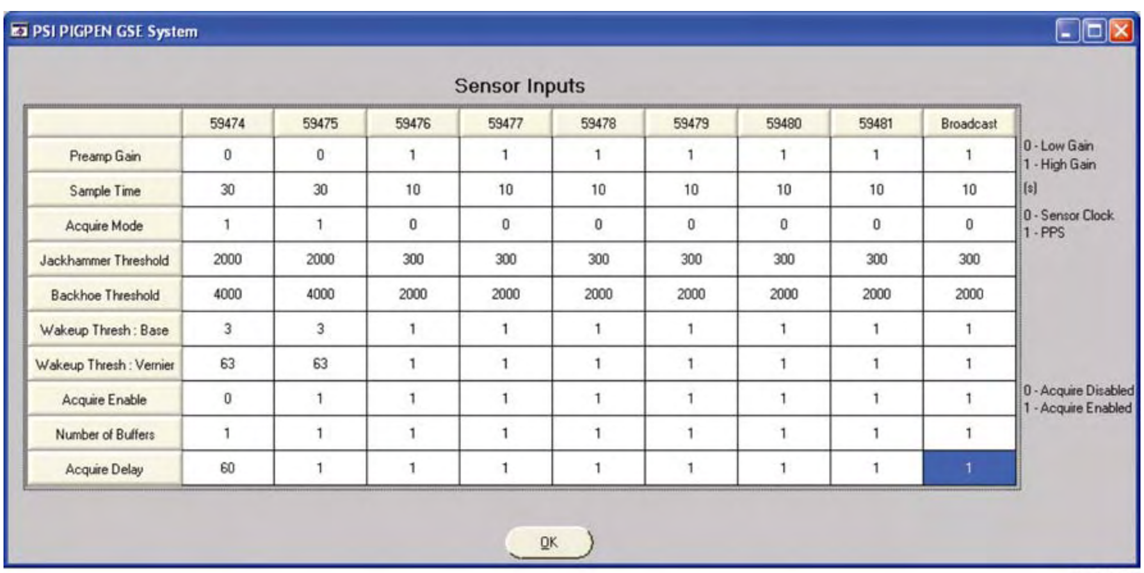
Figure 114. Sensor chassis and DSP board before installation in the chassis.

We also developed control system software for the AP units. The software runs on a laptop computer that acts as the Network Interface Box for the AP system. From that laptop, or remotely through the laptop, we can acquire data, change settings, and check the health status of the system. Figures 115 and 116 show the control system software display.



J-2454

Figure 115. AP control system software main display.



J-2455

Figure 116. AP control system software configuration screen.

6.0 Technology Development Status and Summary

We successfully collected a large amount of data at the Kansas field test site. We collected data in a grid covering loam and shale/hillside using a down-hole gun as our primary stimulant threat acoustic source. This source was very reproducible and permitted repeated testing. The signature it generated was not as strong as many real threats and as a result it did not produce signals with large SNR at all the sensors, limiting the number of data sets where we were able to attempt triangulation. Nevertheless, the PIGPEN sensors detected nearly every acoustic event (approximately 397 out of 400 shots) presented to the sensors, even with interference from strong background sources such as trucks and trains. With the Kansas data we have demonstrated PIGPEN detection of relevant events in over a half dozen field tests performed in a variety of weather, soil and background acoustic conditions. PIGPEN is a robust and dependable sensor system.

After the preparation of the above draft of the Kansas data testing and results, we sent copies of this section of the report to Daphne D'Zurko and the NYSEARCH Consultant for comments. They provided many good observations and requested clarifications and expansions in the text. We have not included those amendments here. Those revisions are included in the related final report submitted by the NYSEARCH with PSI as co-authors.

Unfortunately the extensive field testing to establish the capability of this technique consumed significant resources. As a result we were unable to extensively test the AP units developed under this program. They are available for testing and further development as further funding for this technology becomes available. We are in discussion with NYSEARCH, the PRCI, and our partner American Innovations to move this technology to further development. PSI's activity in commercial partner development is outlined in the next chapter of this report.

We presented a summary of the technical status on this project to Jim Merritt in March 2007. The time difference of arrival approach while offering the potential for high time resolution and spatial location accuracy, did not seem capable of delivering that accuracy in complex real world conditions. Discussions with Mr. Merritt in March identified other analysis approaches based on relative signal amplitude. This summary presentation and a suggested new detection and localization approach are presented in Appendix F. During the last months of this program PSI performed a re-analysis of Kansa data and the Andover triangulation data using internal funds. We presented this new approach to our partner/ customer – the NYSEARCH committee in early June 2007. That briefing is included in this report as Appendix G. In it we identified that the Remote Power Localization (RPL) approach performed robustly and reproducibly in several soil conditions, and provided 20 to 50 foot localization accuracy of the cases examined. PSI intends to continue to seek support from our partners to couple the PIGPEN sensor technology – matured in this SBIR program – with the RPL algorithms into a robust affordable pipeline intrusion detection product.

7.0 Technology Commercialization

PSI performed an initial market search for potential commercialization partners. Table 17 summarizes four potential commercialization partners investigated by PSI during the first year of the program.

Table 17. Four Companies Identified as Potential Commercialization Partners in a Preliminary Search

Company	Type	Services	Product Mfg.	URL
Mears Group Inc.	International service provider	X		www.mears.net
Metrotech	International leak detection instrument manufacturer		X	www.metrotech.com
Rosen USA	International service provider	X	X	www.roseninspection.net
T.D. Williamson Inc.	International service provider	X	X	www.tdwilliamson.com

Rosen and TD Williamson are organizations that are service providers and product manufacturers. The services that they offer are heavily pipeline inspection via internal sensors and robots. Both companies are manufacturers but it is not clear they are the types of organizations that might be interested in the PIGPEN technology.

Mears Group is more of an engineering firm that provides a wide variety of pipeline services including pipeline laying. They might be interested in adding PIGPEN capability – but they are not a manufacturer.

Metrotech is a manufacturer of pipeline locating equipment but they are not a service provider.

7.1 Profiles of Initial List of Companies (SBIR Year 1)

7.1.1 Rosen: http://www.roseninspection.net/RosenInternet/

Profile: 25 year old Swiss based multi-national company. US Headquarters in Houston, TX.

From the home page:

Inspection & Services	ROSEN’s inspection services and tools are built in a modular fashion that can be combined or operated independently to collect the highest quality data for piggable or unpiggable pipelines, tanks, coiled tubing and other facilities.
Data Services	ROSEN’s main product is information that is based on accurate data. It is important to you – and to us – that the information is always reliable.
Asset Integrity Management	ROSEN provides customer-specific solutions for all of the key applications in Asset Integrity Management (AIM).
Products for Sale	ROSEN sells many of the same tools used for Inspection Services, guaranteeing that the latest available technology is received.
Customized Solutions	ROSEN is there to meet every pipeline customer need – wherever and however they may show up.

Rosen manufactures electronic test instrumentation as well as their internal pipeline sensor robots. There business appears to be centered around internal pipe inspection – primarily large transmission pipelines (20,000 km)

7.1.2 T.D. Williamson: http://www.tdwilliamson.com

Profile: An 85 year old privately held piping maintenance company. TDW designs and manufactures engineered systems for monitoring, pigging, tapping, plugging, and inspecting essential piping systems, and also provides these services. TDW markets its products and services through a worldwide network of sales offices and representatives and from strategically located international service and/or manufacturing facilities in the United States, Belgium, England, India and Singapore. The company is headquartered in Tulsa, OK.

7.1.3 Mears Group Inc.: http://www.mears.net

Profile: A 30 year old pipeline engineering organization, privately held, based in Michigan with offices throughout the US, Europe, Mexico, and South America.

Capabilities: Horizontal Directional Drilling; Engineering/Technical Services: Turnkey External Corrosion Direct Assessment (ECDA); Data Integration/Management (Rapsheets); Bellhole/NDT Inspections and Documentation; Smart Pig Retrofit and Analysis Construction Services: Bellhole Excavation; Pipeline Repair; Pipeline Maintenance Support; Anodeflex Installation; In-Line Inspection Support and Anomaly Digs; Pipeline Coating Reconditioning

7.1.4 Metrotech: http://www.metrotech.com

Profile: Metrotech Corporation designs and manufactures buried utility locating instruments. Metrotech web site says they are "advanced as a leader in locating technology through design innovations that increase productivity for the user of our instruments". Metrotech is part of Germany based company, Seba Group. (http://www.sebakmt.com). Metrotech's US location is in Silicon Valley.

Metrotech products locate buried cables and pipes and detect leaks in water and sanitary pipes. The markets they serve include: Municipal water and sanitary districts, military facilities, gas and petroleum pipeline companies, plumbing contractors, industrial facility maintenance departments, railroad companies, golf courses, electric power and telecommunication firms of all sizes.

Metrotech's web site indicates that they see tremendous opportunity in the market for underground locator technologies. Deregulation and privatization trends demand more efficient construction methods. At the same time, technological advances offer ways to meet this rapidly emerging market demand. Metrotech is in the process of expanding our own infrastructure, particularly in the areas of R&D and new product design. They intend to leverage their Silicon Valley vantage point to stay on the cutting edge of innovations in software, processing power, miniaturization, materials, GPS, EMF research, and supply chain management

7.2 Partner Search Performed in Conjunction with NYSEARCH

PSI also worked closely with NYSEARCH in the identification of commercialization partners for PIGPEN. NYSEARCH also performed an independent search for potential commercialization partners for both PIGPEN and their GasNet technology. Table 18 summarizes the results of NYSEARCH's preliminary investigation.

Table 18. Candidate Commercialization Partners (NYSEARCH)

Company	Type	Services	Product Mfg.	URL
LaBarge, Inc.	Electronic systems		X	www.labarge.com
Sensor Technology Limited	Manufacturer of piezoelectrics		X	www.sensortech.ca
CorPro Inc.	Distributor			www.corpro-inc.com
MetroTech Corporation			X	www.metrotech.com
Bullhorn Remote Monitoring	Wireless telemetry services	X		www.aimonitoring.com
Bristol Babcock	Supplier of measurement and control systems		X	www.bristolbabcock.com
Ashcroft (Dresser Incorporated)	Manufacturer of flow switches, transducers, etc. for industrial applications		X	www.ashcroft.com
Fisher (Rosemount)	Process instrumentation & control provider	X	X	www.fisher.com www.rosemount.com
Druck (GE Infrastructure)	Manufacturer of flow switches, etc. for industrial applications		X	www.druck.com
ULC Robotics	Development and testing of robotic and non-robotic repairs to gas mains and instruments to view gas pipeline			www.ulcrobotics.com
Honeywell	Process instrumentation & control provider		X	www.honeywell.com
ABB	Process instrumentation & control provider		X	www.abb.com
Mears Group, Inc.	Specializes in underground pipe evaluation, rehabilitation and replacement	X		www.mears.net

As part of the vetting process, PSI developed the following list of questions for potential commercialization partners.

1. Does the partner currently provide pipeline maintenance and inspection services?
2. Does the partner develop products that are used for pipeline maintenance and inspection?
3. Does the partner support products that they sell for pipeline maintenance and inspection?
4. Does the partner derive revenue from providing infrastructure (IT) support to users of pipeline maintenance and inspection services?
5. What percentage of partner's profit derives from new products on a 5 year basis?
6. Does the partner invest in new technologies for new product development?
7. Does the partner possess a culture that supports new product development partnerships?
8. Does the partner have complimentary skills to PSI to bring a product to market?

In addition, PSI began a self-evaluation of the role our company could fill to transition the technology. As an experienced transitioner of SBIR technology, PSI has learned to use its wide skills to fill any gaps in the candidate partners' skills to ensure successful creation of a commercial product. We identified potential roles we could play:

1. PSI could manufacture (or have contract manufactured) the PIGPEN sensor.
2. PSI could manufacture (or have contract manufactured) the PIGPEN electronics.
3. PSI is not credible to sell or service the PIGPEN into the pipeline community.
4. Thus we will require a partner to either manufacture or sell PIGPEN to the community.
5. Is this a "large" market or a "niche" market?

PSI has on-staff a Manager of Technology Transition whose primary job function is help facilitate SBIR technology transfer to commercial entities. His activity is performed at no cost to this SBIR project. The following decision tree summarizes our analysis of the companies suggested by NYSEARCH and by PSI. Fundamentally, there are two issues that PSI must decide. These are: 1) Will PSI undertake the manufacturing of PIGPEN? 2) Is the market opportunity a large or small market?

We have reviewed the PSI candidates and the NYSEARCH candidates. It is important to note that the NYSEARCH list factors in whether or not a company will be a suitable partner for GasNet commercialization as well as PIGPEN.

The decision tree in Figure 117, allows PSI to pick appropriate partners depending on how PSI answers the above questions. The decision tree highlights which companies could be approached from the combined PSI and NYSEARCH lists.

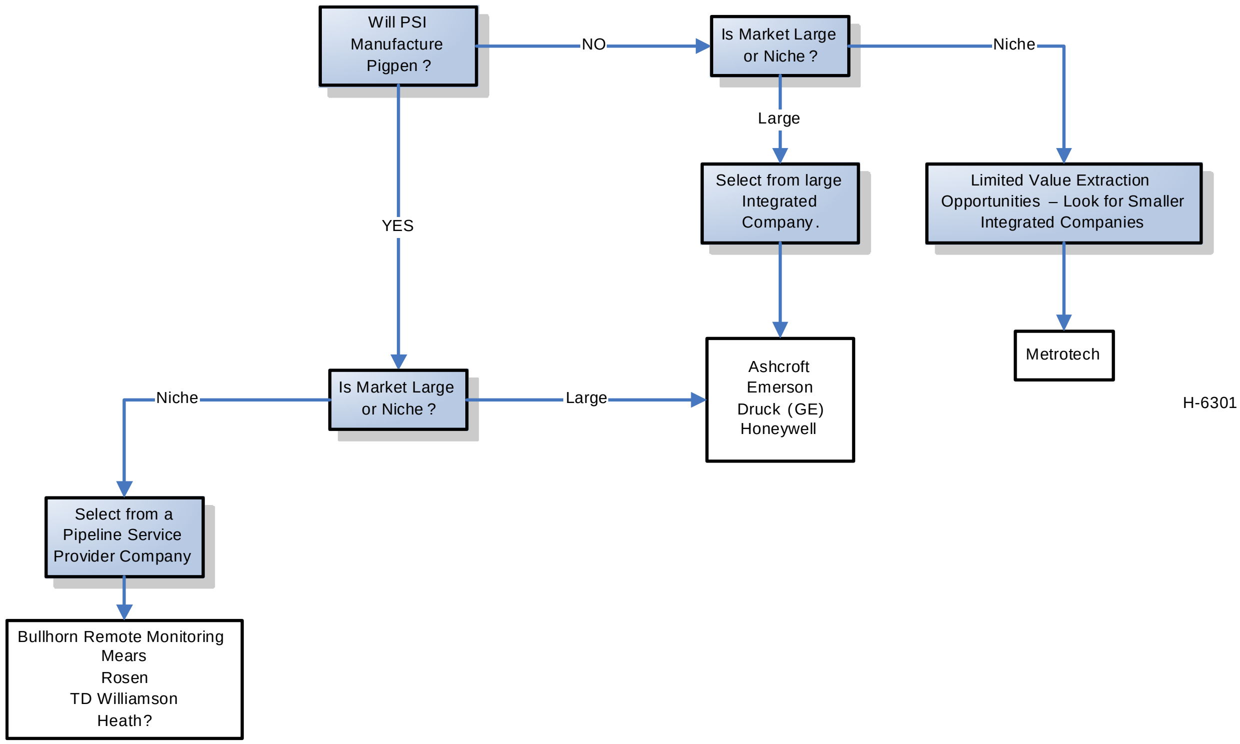


Figure 117. Decision tree.

With this categorization of the several potential partners, we began the vetting process at the end of Year 1 and the start of year 2. We have prepared a non-proprietary description of PIGPEN and will distribute it to interested parties as we begin contacting the potential partners. Subsequently, we will hold teleconferences and face-to-face meetings to establish interest and suitability for partnership.

7.3 Outreach to Potential Partners

As a result of the above analysis and vetting process, we contacted two companies: Bullhorn Remote Monitoring and Corrpro Companies Inc.

Bullhorn Remote Monitoring builds, installs and maintains wireless communication networks for monitoring Cathodic Protection Systems. Their system monitors a substantial fraction of the transmission pipelines in North America. Their skills and technology are complementary to PSI's and they have presence in the gas industry. They seem accepting of new technology.

Overall, the initial teleconference was positive and we agreed to meet to continue discussions.

Corrpro provides corrosion control, cathodic protection design, materials, installation, monitoring and maintenance services and pipeline integrity management. Corrpro has over 50 offices located throughout the world. Corrpro was interested in the PIGPEN technology for transmission pipelines in particular. Given Corrpro's size, financial condition, and recent reorganization, PSI felt that Corrpro would not be a suitable commercialization partner.

We also identified another potential partner included within the pipeline services industry: EDM Services Inc., Simi Valley, CA. Manufacturers of the Trip Wire® third-party intrusion detection system (a "broken wire" type system). We also undertook a market survey into the more general business area of Remote Terminal Units(RTUs) and Programmable Logic Controllers (PLCs).

There are many manufacturers of RTUs and SCADA equipment (wireless, wired, ethernet, cell based, internet-based). For PIGPEN, PSI's approach is to develop the sensing and locating technology, and leave the SCADA work to that industry. Examples of RTU and SCADA companies include:

- Bentek Systems http://www.scadalink.com
- Data-Linc Group http://www.data-linc.com

There are a few SCADA integrators that service the gas and petroleum industries that we reviewed as possible partners:

- Metrix Networks http://www.metrixnetworks.com
- Emerson Process Management http://www.emersonprocess.com
- PSI Control Systems http://www.pipesys.com

PSI contacted each of these companies with our prepared material. We did not find a suitable level of capability, interest, new technology acceptance or financial strength to continue discussions.

In November 2006 we attended the Remote Monitoring Conference. The primary objective in attending the conference was to seek out potential partners for commercialization of the PIGPEN technology and to identify other applications for PIGPEN. Five contacts were of relevant to PIGPEN:

FreeRange Technologies: FreeRange is a small company in Irvine that serves the utility industry. They are primarily a systems engineering firm. They are a small, young company; however, the founder, Jim Gilbert, has a good track record in his previous endeavors (successful and bought by larger companies, etc).

Smarter Security Systems focuses on perimeter protection and covert video surveillance systems. Spoke with Mark Ellsworth. They are located in Austin, TX. Ellsworth was intrigued by the potential of seismic sensing for perimeter protection.

Critical Wireless is a generic SCADA system company that manufactures hardware, integrates, and provides data services. They target the industrial process control sector – similar to American Innovations, but in a different niche market. They were interested in seismic for infrastructure protection. Also located in Austin, TX.

Data Online: Similar model to American Innovations, except they target the tank farm market. They are teamed with Endress+Hauser as their sensor provider. These folks expressed no interest in continuing discussions.

Sensicast: Similar model again. Sensicast is located in Needham, MA.

7.4 Bullhorn Remote Monitoring

Bullhorn Remote Monitoring builds, installs and maintains wireless communication networks for monitoring Cathodic Protection Systems. Their system monitoring a substantial fraction of the transmission pipelines in North America. We held a first telephone discussion with them in the Spring of 2006. Their skills and technology are complementary to PSI and they have presence in the gas industry. They seem accepting of new technology. Overall, the initial teleconference was positive and we agreed to meet to continue discussions.

In summer 2006 PSI had a follow-up teleconference with American Innovations the parent company of Bullhorn, to further explore their interest in becoming the PIGPEN commercialization partner. At that teleconference, we agreed to have a meeting at the American Innovations facility in Austin TX to continue discussions. The objectives for that meeting were defined as:

1. Determine if PIGPEN and AI's remote sensing system are a good fit technologically.
2. Determine if PSI's and AI's technologies and companies are a good fit from a business standpoint.
3. If PSI and AI agree that the fit is good, begin to define how we move forward to transition the technology (in short, begin to define a commercialization plan).
   - define strawman business models
   - define how we would work together through the technology maturation process.

At that meeting in Austin TX, PSI described PIGPEN in more detail, what it does, and its level of maturity. AI provided the same information about their technologies. These discussions showed very complementary capabilities. AI agreed to begin a survey of market interest and acceptance criteria. They also contacted their field installation division to begin to develop a plan for installation and service.

During the meeting and subsequently, there were discussions and an investigation of competitive systems and their installation cost relative to PIGPEN. We estimated that the cost per mile for the PIGPEN system installed was below $10,000/ mile.

7.4.1 Competitive System

Most existing systems involve some form of trip wire which detects that the pipeline has likely been damaged. For comparative analysis, a competitive system is the FFT/PSE&G fiberoptic system which allows for detection prior to pipeline damage. In addition to the cost below, the estimated electronics cost of $150,000 which can be used for up to 8 miles must be included.

Cost Per Mile	New	Retrofit
Fiberoptic cable @ $3/ft.	$15,840	$15,840
Installation @ $3/ft. new and $10/ft. retrofit	$15,840	$52,800
Equipment and Installation Subtotal	$31,680	$68,640
Electronic Cost (Assumes best case of 8 miles)	$18,750	$18,750
Total Installed Cost	$50,430	$87,390

GE is releasing a system to monitor pipeline strikes. It must contact the pipeline and only reports when damage has been done – it is not a warning and prevention system.

7.4.2 PIGPEN Cost Estimate

Cost Per Mile	New or Retrofit
Equipment ($4 to 6K per mile)	$6,000
Installation ($1.5K to 2K per mile)	$2,000
Communication (Bullhorn at $1300 every 2 miles)	$650
Total Installed Cost	$8,650

PIGPEN has a compelling cost position compared to the competition. However, can the market afford this technology? Based on the current costs of $4800/mile/yr., it appears that a solid financial argument can be made. When one adds in the additional risk of operating in HCA's, the financial viability escalates.

7.4.3 Potential Market

The total potential market is all oil & gas transmission pipeline, though HCA pipeline could be the key target market initially. We will try to get a gauge from IMD on the amount of pipeline in HCA. There would be one Bullhorn, one NIB and 16 sensors for every two miles of pipe.

7.4.4 Communication

Upon each alarm condition that must be communicated, the PIGPEN will interface with the Bullhorn SDT (likely via contact closure), and the SDT will communicate through the Bullhorn solution all the way to the customer via email, fax, page, voice or FTP. PIGPEN will have to be modified to interface using the Modbus serial protocol. Expected packet will include the GPS location of the threat, a risk identifier, and the time of occurrence. Packet size is expected to be 20 bytes. Communication time from the field to the customer is expected to be 6 to 7 minutes maximum.

7.4.5 Actions Resulting from the September 2006 Meeting

1) Get better estimate on current costs per mile for incidents. Obtain data from the industry and/or clients. Canvas NE Gas Assoc. members to see if they have more current or more accurate data. This action is aimed at trying to determine the value proposition.
2) Discuss the benefits of this system with clients. Try to determine if the system is attractive at <$10,000 per mile installed. Determine whether there is a niche for the technology in HCA.
3) Inquire whether there are clients that have a particular interest in such a system.
4) Assess competitive system installed costs.
5) Identify modifications of the PIGPEN hardware to make it compatible with AI SDT16-GSM so that AI can participate in the long term field testing.
6) Identify clients that would be interested in offering opportunities for alpha & beta field testing. PSI contacted NE Gas Association member companies. AI discussed with its client base.

7.5 Commercialization Summary

At the conclusion of this program we presented a status summary to Mr. Jim Merritt. American Innovation traveled to that meeting at no cost to this contract and presented company capabilities, a summary of the preliminary market analysis, and the most important remaining issues to be addressed in follow-on activities to help ensure product acceptance. There were enthusiastic about the need for this technology and were committed to work with PSI to continue its testing, productization and market insertion.

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Appendix A

VG05-264

Infrasonic-Frequency Seismic Sensor System for Pipeline Integrity Management

Phase II SBIR Kickoff Meeting

14 July 2005

G.E. Galica and B.D. Green
Physical Sciences Inc., Andover, MA

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

Kickoff Meeting Objectives

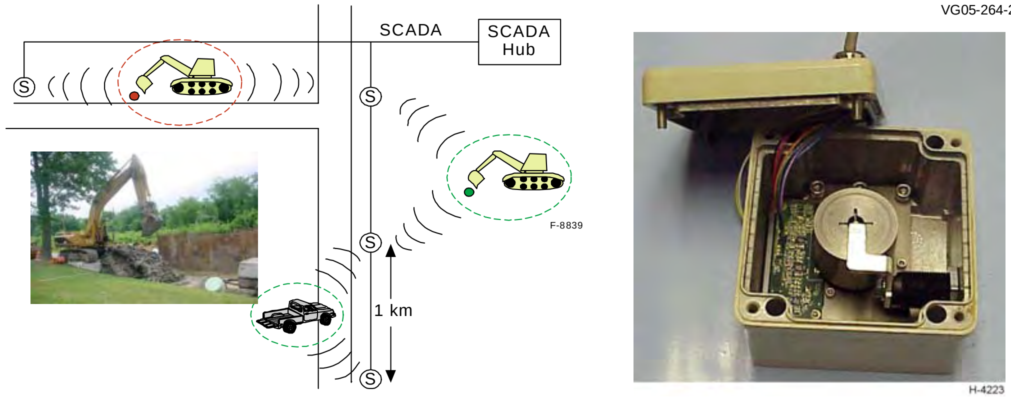
VG05-264-1

- **Summarize technology development status**
- **Review Phase 2 SBIR program objectives and schedule**
- **Discuss DOT requirements and objectives**
- **Discuss overall technology development plan**
  - interleaving of BAA & NGA-funded efforts

PROPRIETARY

***P**roactive **I**nfrasonic **G**as **P**ipeline **E**valuation **N**etwork PIGPEN*

VG05-264-2



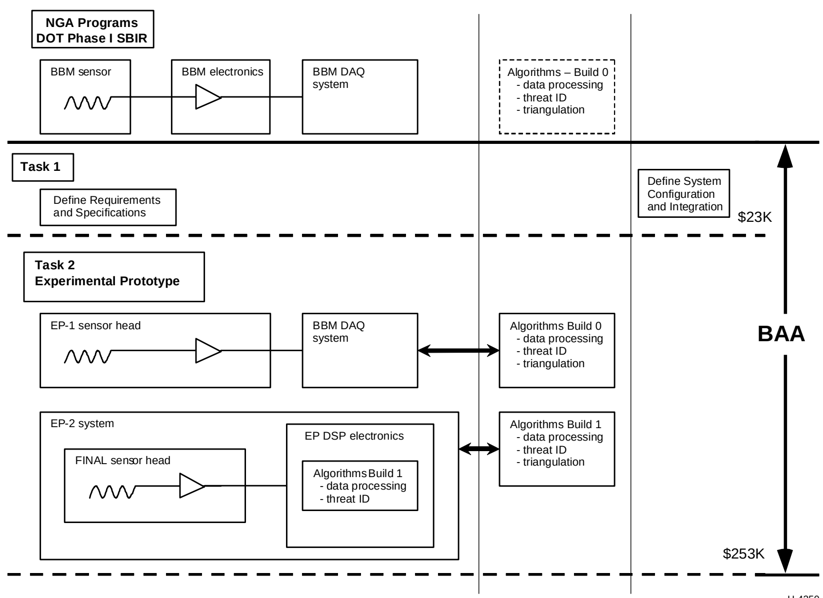
- Smart Sensors placed at 0.5 to 1 km spacing along the pipeline
- PIGPEN sensors determine threat status based on signature (backhoe or bus)
- PIGPEN system determines range and direction of potential threats
- Only true threats that are close to the pipe trigger a warning

PROPRIETARY

PSI Physical Sciences Inc

Technology Development Plan

VG05-264-3



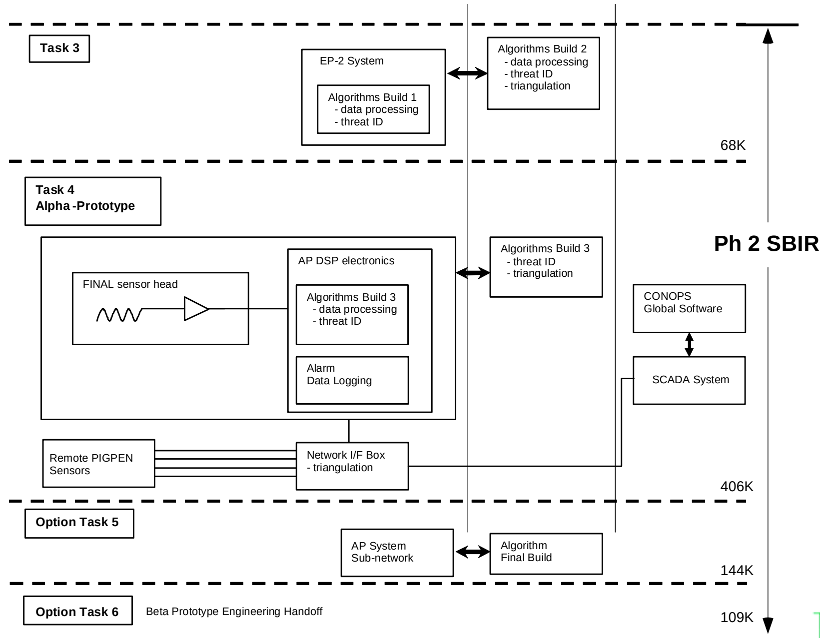
PROPRIETARY

PSI Physical Sciences Inc

SBIR Rights in Data / ITAR Restricted

Technology Development Plan (continued)

VG05-264-4



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PROPRIETARY

PSI PHYSICAL SCIENCES INC

Current BAA Tasks

VG05-264-5

- **Develop PIGPEN Experimental Prototype (EP)**
  1) Develop EP sensor head and analog electronics
  2) Establish performance of EP sensor head, analog electronics and preliminary algorithms through field testing
  3) Refine EP-1 design to develop final version hardware for sensor head and analog electronics. Refine algorithms and implement on an EP digital signal processor (DSP) that is consistent with the form factor and design limitations of the PIGPEN system
  4) Establish performance of EP-2 PIGPEN system through acquisition of laboratory and field test data
  5) Work with NGA to identify an appropriate commercialization partner
  6) Establish requirements and specifications for the Advanced Prototype PIGPEN sensor and system

PROPRIETARY

PSI PHYSICAL SCIENCES INC

PIGPEN Technology Status

VG05-264-6

- **Six Experimental Prototype-1 (EP-1) units fabricated**
- **EP-1 sensor head meets its design criteria**
  - resonance frequency >1000 Hz (1100 Hz measured)
  - calibrated response of EP-1 is 12 dB greater than the NGA-Ph2A sensor (3-10 dB goal)
  - noise reduced by more than 20 dB below the NGA-Ph2A system (10 dB goal)
  - no effect in the EP-1 response for installation at angles up to 30 deg (PDR action item)
- **We acquired three days of field data at two test sites**
  - Somerset, MA
  - NGA-sponsored test at Johnson City, NY
- **EP-1 range detection extrapolated to 1750 m with SNR=16 dB under quiet conditions**
  - all excavating equipment detected with high SNR at 175 m
  - EP-1 performance exceeds range goal of 1000 m
- **The preliminary algorithm correctly identified the backhoe data.**
  - algorithm optimization in process
  - performance with the jackhammer and tamper data needs improvement
- **Triangulation accuracy not yet established**
  - EP-1 field test data timing corrupted by data acquisition system - Must retest during EP-2 testing
- **We developed a preliminary algorithm for triangulation**
  - cross-correlation technique
- **EP-2 integration in process**

PROPRIETARY

PSI Physical Sciences Inc

BAA Remaining Tasks

VG05-264-7

- **Optimize Algorithm – ongoing**
- **Complete triangulation testing of EP-1 – 31 Aug 05**
- **Complete EP-2 integration and lab testing – 15 Sep 05**
- **Complete EP-2 preliminary checkout – 30 Sep 05**
- **EP-2 field test – Oct-Nov 05**
- **Define AP specifications – 15 Dec 05**
- **Identify potential commercialization partners – 15 Dec 05**

PROPRIETARY

PSI Physical Sciences Inc

Phase 2 SBIR Program Objectives

VG05-264-8

- **Transition the PIGPEN technology from its present Experimental Prototype stage to a commercially viable prototype system**
  1) Demonstrate a PIGPEN sensor that meets the performance requirements of a third-party damage early warning system
  2) Demonstrate threat identification and threat location algorithms as an enabling technology for a third-party damage early warning system
  3) Develop a PIGPEN Advanced Prototype system that forms a basis for a commercially viable product that meets both the performance and market requirements of a third-party damage early warning system
  4) Transition the PIGPEN technology to a commercialization partner in cooperation with NGA

PROPRIETARY

PSI PHYSICAL SCIENCES INC

Phase 2 SBIR Tasks

VG05-264-9

- **Task 1. Program Kickoff**
  - 1.1 Interface and requirements definition
  - 1.2 Program kickoff meeting
- **Task 3. Assess PIGPEN EP Performance and Refine Algorithms**
  - 3.1 Acquire database of performance data with EP-2 in a long-term deployment
  - 3.2 Develop Build-2 algorithms, based on EP-2 assessment data
- **Task 4. Develop PIGPEN Alpha Prototype (AP)**
  - 4.1 Develop and fabricate integrated sensor head and customized digital signal processor as AP
  - 4.2 Develop and implement Build-3 software algorithms
  - 4.3 Establish AP performance by laboratory and field testing
- **Task 5. Assess Long-Term PIGPEN AP Performance**
  - 5.1 Deploy small network of PIGPEN AP sensors
  - 5.2 Assess performance by long term acquisition
- **Task 6. Transition PIGPEN Technology to Beta Prototype (BP)**
  - 6.1 Develop commercialization plan
  - 6.2 Transition PIGPEN technology to commercialization partner

PROPRIETARY

PSI PHYSICAL SCIENCES INC

Task 1. Program Kickoff

VG05-264-10

- **1.1 Interface and requirements definition**
  - as part of the EP (BAA) effort, we will establish requirements and specifications for the Advanced Prototype PIGPEN sensor and system
  - we have begun the process of defining the concept of operations and the interface options
  - **Interface meeting tentatively scheduled for early September**
- **1.2 Program kickoff meeting**
  - align DoT and program objectives
  - discuss program objectives
  - discuss schedule

PROPRIETARY

PSI PHYSICAL SCIENCES INC

Task 3. Assess PIGPEN EP Performance and Refine Algorithms

VG05-264-11

- **3.1 Acquire database of performance data with EP in a long-term deployment**
  - ready to begin with EP-1 immediately
    - variations with soil moisture, temperature, seasonal
    - long term deployment in fixed geometry
    - continue testing long-term triangulation accuracy – synergy with BAA
    - assess reproducibility
    - assess long term drift
    - assess long term backgrounds
  - assess real-time algorithm performance with EP-2 – robustness, Pd, Pfa
- **3.2 Develop Build-2 algorithms, based on EP-2 assessment data**
  - refine signature identification
  - build triangulation algorithm **(already begun in EP program)**
  - build sleep control algorithm **(already begun in EP program)**

PROPRIETARY

PSI PHYSICAL SCIENCES INC

Task 4. Develop PIGPEN Alpha Prototype (AP)

VG05-264-12

- **4.1 Develop and fabricate integrated sensor head and customized digital signal processor as AP**
  - design custom DSP (based on EP-2) for AP
  - completely integrate DSP with EP-1 sensor head and chassis to create AP
    - transfer EP sensor head and chassis directly to AP – no redesign
  - develop AP Network Interface Box (NIB)
  - build sub-network of AP sensors
- **4.2 Develop and implement Build-3 software algorithms**
  - incorporate Build-3 algorithms into AP DSP
  - develop NIB software – triangulation and communication
- **4.3 Establish AP performance by laboratory and field testing**
  - two phases of preliminary field testing planned
    - individual AP units
    - entire sub-network
  - perhaps NGA affiliate sites would be available for AP field testing

PROPRIETARY

PSI Physical Sciences Inc

Task 5. Assess Long-Term PIGPEN AP Performance

VG05-264-13

- **5.1 Deploy small network of PIGPEN AP sensors**
  - deploy sub-network of 4-8 AP sensors with NIB in suitable location
  - perhaps NGA affiliate sites would be available for long-term AP field testing
- **5.2 Assess performance by long term acquisition**

PROPRIETARY

PSI Physical Sciences Inc

Task 6. Transition PIGPEN Technology to Beta Prototype (BP)

VG05-264-14

- **6.1 Develop commercialization plan (in cooperation with NGA)**
  - potential commercialization partners identified by NGA and PSI during EP program
  - down-select best commercialization partner
  - develop commercialization plan
    - market study
    - cost
    - engineering
    - partner contribution

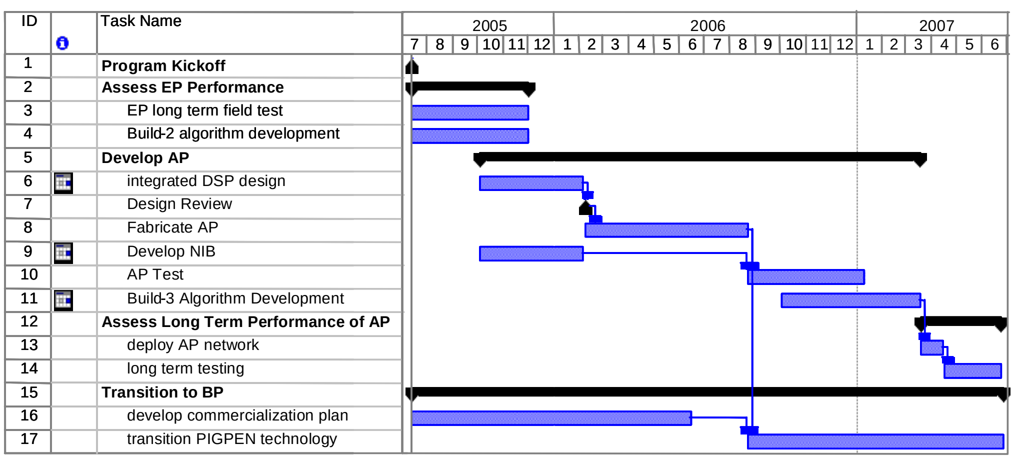
- **6.2 Transition PIGPEN technology to commercialization partner**
  - in past programs, PSI need to remain involved fairly long into the BP development
  - under the Phase 2 SBIR, this task enables PSI to participate in technology transfer only
  - further development work by PSI would be paid by a third party

PROPRIETARY

PHYSICAL SCIENCES INC

Milestone Schedule

VG05-264-15



H-4224

- **PSI and NGA are maintaining an aggressive schedule**
- **AP ready for field testing in late summer 2006**

PROPRIETARY

PHYSICAL SCIENCES INC

PIGPEN Preliminary System Specifications

VG05-264-16

Parameter	Target	Actual
Detection range	1000 yards, in quiet conditions	1900 yards (SNR=16 dB) Extrapolated
Triangulation accuracy	10 yards at 300 yard range	Not yet verified
Unit mass	2.5 lbs	4-5 lbs
Unit size	6.5 x 3.5 x 2.5 $in.^3$	5 x 5 x 4 $in.^3$
Unit power	1 watt (max) Less with sleep mode	1 watt (max) baseline Less with sleep mode
Unit cost	<$300 Target	No change to BOM

- **Triangulation accuracy will be verified by end of BAA program**
- **Specifications will be revised by end of BAA program**
- **EP-1 sensor performance has met or exceeded predictions**
- **EP-1 design (sensor head, front-end electronics, chassis) directly transferrable to AP program**

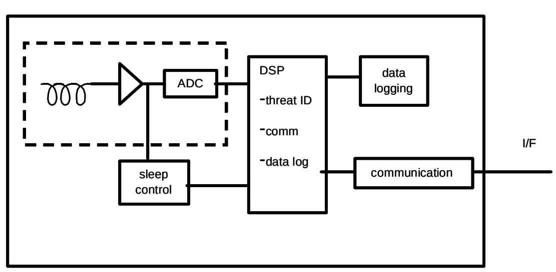
PROPRIETARY

PSI Physical Sciences Inc

PIGPEN Preliminary Block Diagram

VG05-264-17

- **PIGPEN comprises:**
  - sensor head and low noise preamplifier – EP
  - data acquisition electronics – EP
  - threat identification algorithm/warning system – EP/AP
  - data logging – AP
  - interface to existing SCADA system – AP/BP
- **DAQ, processor and threat ID accommodated in an inexpensive digital signal processor**
- **Scale <5 lb, <5 in. cube**
- **Target cost $300/unit**
- **Preliminary EP-1 results still support this PIGPEN concept**



PROPRIETARY

PSI Physical Sciences Inc

Commercialization Partner

VG05-264-18

- **PSI and NGA are working together to identify a suitable commercialization partner**
- **PSI an NGA have negotiated terms for future commercial development of PIGPEN**
- **PSI has a strong R&D focus**
  - PSI has a small Pilot Manufacturing Area for fabricating limited runs of prototype and product instrumentation (AP, BP)
  - PSI does not have the capabilities for economical, high-volume production of commercial products
- **NGA and PSI are cooperatively identifying an appropriate commercialization partner**
  - strong presence in the utility industry
  - strong sales and marketing support
  - capable engineering staff
  - acceptors of new technology
  - resources to undertake new product introduction
- **Commercialization partner participation is extremely important during AP development**
  - definition of system architecture and interfaces
  - insight on commercialization & manufacturing issues to guide the design

PROPRIETARY

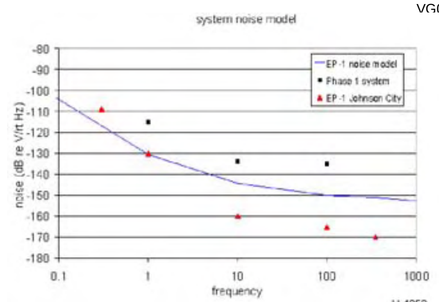
PSI
PHYSICAL SCIENCES INC

EP-1 Data Review

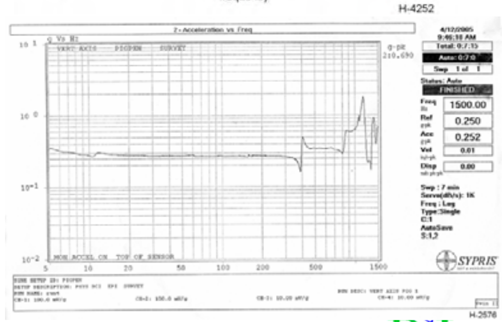
EP-1 Calibration

VG05-264-20

- **EP-1 performance meets design goals**
- **Resonant frequency of 1100 Hz**
  - meets design goal >1000 Hz
- **EP-1 sensitivity 12 dB greater than Phase-1 sensor**
  - 3-10 dB goal
- **EP-1 noise more than 20 dB less than Phase-1 system**
  - 10 dB goal



H-4252



H-2576

PROPRIETARY

PSI Physical Sciences Inc

Field Testing

VG05-264-21

- **Two field tests conducted**
  - Somerset, MA, private contractor – field checkout
  - Johnson City, NY, sponsored by NGA
- **NGA-sponsored test**
  - several types of equipment available over 2 days
- **In total more than 3 days of data collected**

Equipment	Manufacturer & Model Number
Backhoe	Caterpillar 10-200 416D
Trackhoe	Caterpillar 225 BLC
Jackhammer	Attachment to Cat 225 BLC
Tamper	Wacker 2_103

PROPRIETARY

PSI Physical Sciences Inc

Trackhoe and Backhoe – Johnson City

VG05-264-22

H-4226

PROPRIETARY

PSI Physical Sciences Inc

Tamper and Jackhammer Attachment

VG05-264-23

H-4227

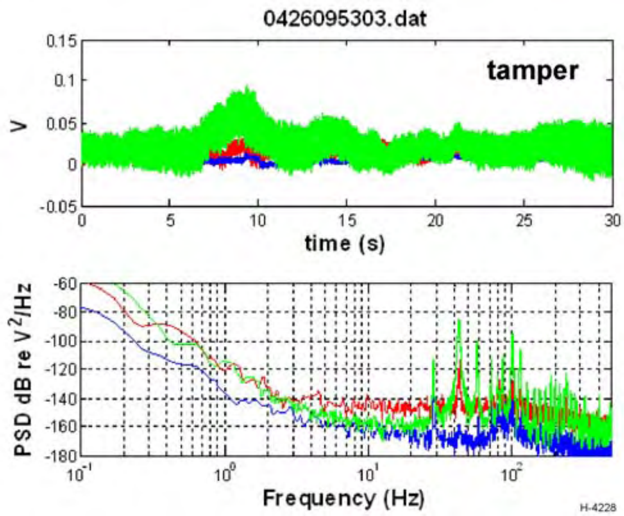
PROPRIETARY

PSI Physical Sciences Inc

Signatures

VG05-264-24

- Signatures of all equipment acquired at ranges up to 175 m
- High SNR at all ranges
- Signatures similar to data acquired in Phase 1



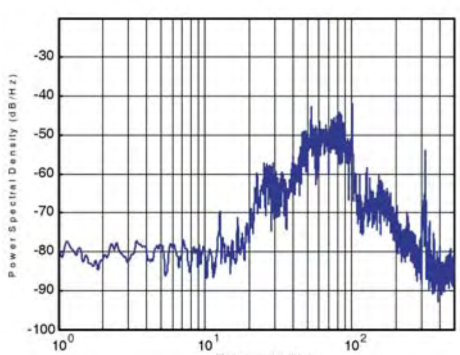
PROPRIETARY

PHYSICAL SCIENCES INC

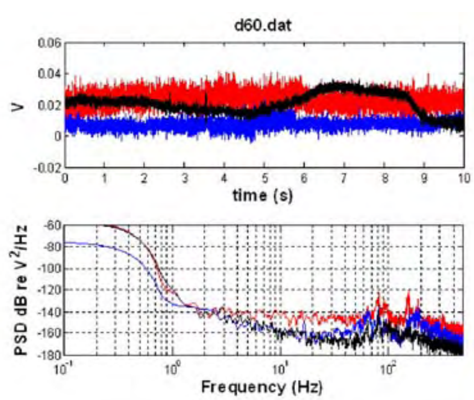
Signatures (2)

VG05-264-25

- EP-1 measured signatures comparable to early phase measurements
- Basic algorithm approach is sound – optimization required



NGA Phase 1



EP-1

H-4229

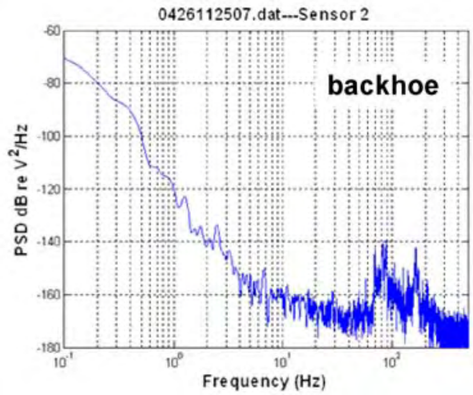
PROPRIETARY

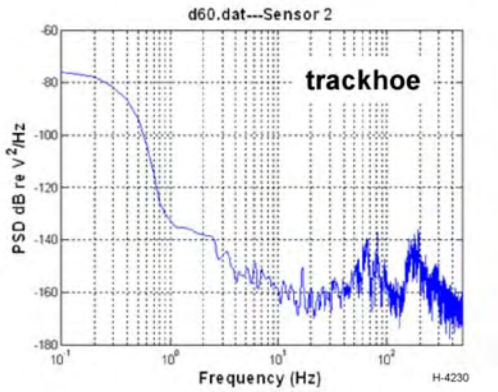
PHYSICAL SCIENCES INC

Signatures of Similar Equipment

VG05-264-26

- Signatures of backhoe and trackhoe qualitatively similar
- Some variability – algorithm logic still satisfied
- We will use these results to refine the algorithm





H-4230

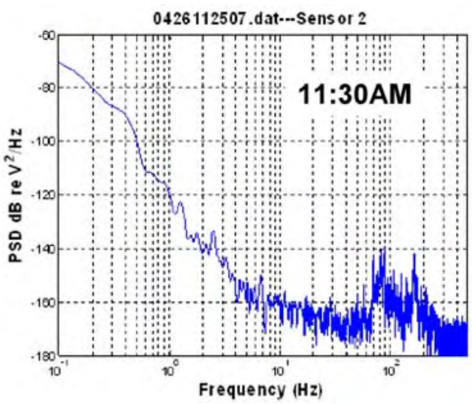
PROPRIETARY

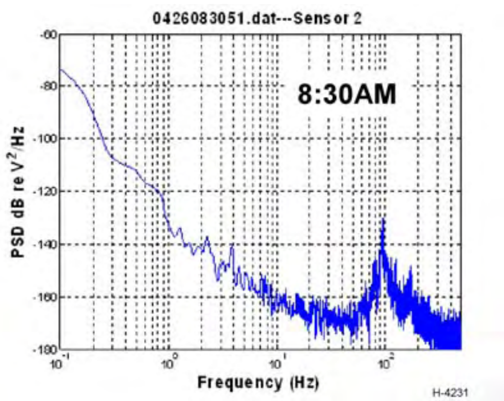
PSI Physical Sciences Inc

Signatures at different times

VG05-264-27

- Signatures of the same equipment acquired at different times
- Some variability – algorithm logic still satisfied
- We will use these data to refine algorithm





H-4231

PROPRIETARY

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Extrapolated EP-1 Range

VG05-264-28

- **Maximum sensor range at Johnson City site is 175 m**
- **We used range dependence of the signal to extrapolate a maximum range (under quiet conditions)**
- **Signals falls as roughly 1/R**
- **1750 m extrapolated range (SNR=16 dB)**

Sensor	Range	Signal
S3	25.5 m	-113 dB
S1	80 m	-122 dB
S2	175 m	-131 dB
Extrapolated limit	**1750 m**	**-151 dB (SNR=16 dB)**

PROPRIETARY

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Build-1 Algorithm Performance

VG05-264-29

- **PSI developed the Build-1 algorithm using NGA-Phase 1 data as the training set**
  - filter-bank creates sparse spectra
  - logical comparison to library spectra
- **We exercised the Build-1 algorithm with EP field test data (Somerset and and Johnson City)**
- **Backhoe identification results are reasonably good**
- **Jackhammer (tamper) data resulted in many false-positives**
  - EP sensors have better (but different) performance than NGA-Phase 1 sensors
  - data drop-outs may be affecting algorithm performance
- **We are currently optimizing the algorithm**

PROPRIETARY

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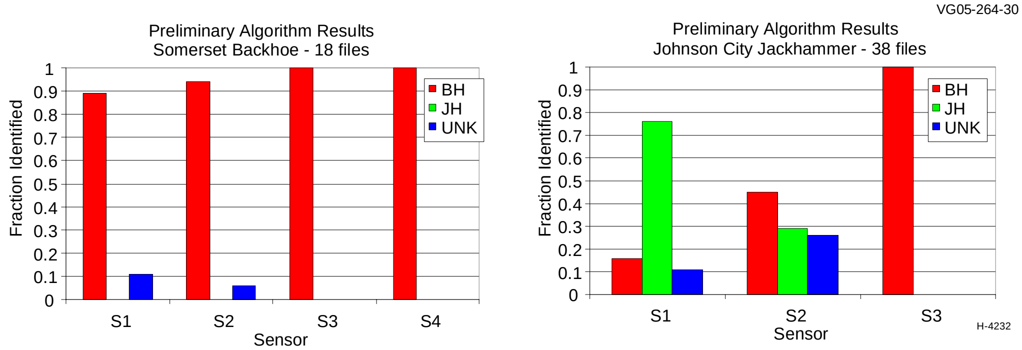
Build-1 Algorithm Examples

VG05-264-30



- **Backhoe**
  - 18 files of backhoe from Somerset test (9 minutes)
  - algorithm correctly identifies nearly all files on all sensors
- **Jackhammer**
  - 38 files of jackhammer data
  - S1 correctly identifies most jackhammers, S2 and S3 results mixed
  - jackhammer equipment is quite different than conventional pavement breaker

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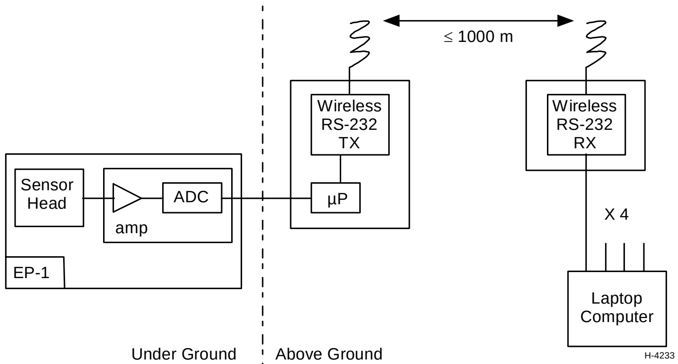
Data Timing and Triangulation

VG05-264-31

- **At Johnson City, the sensors were configured to acquire triangulation data**
- **The relative timing of the data streams from the 4 sensors was corrupted by the data acquisition system**
  - the DAQ system is based on wireless serial communication
  - internal buffering in the computer introduced variable and non-reproducible time lags in the data streams



PROPRIETARY

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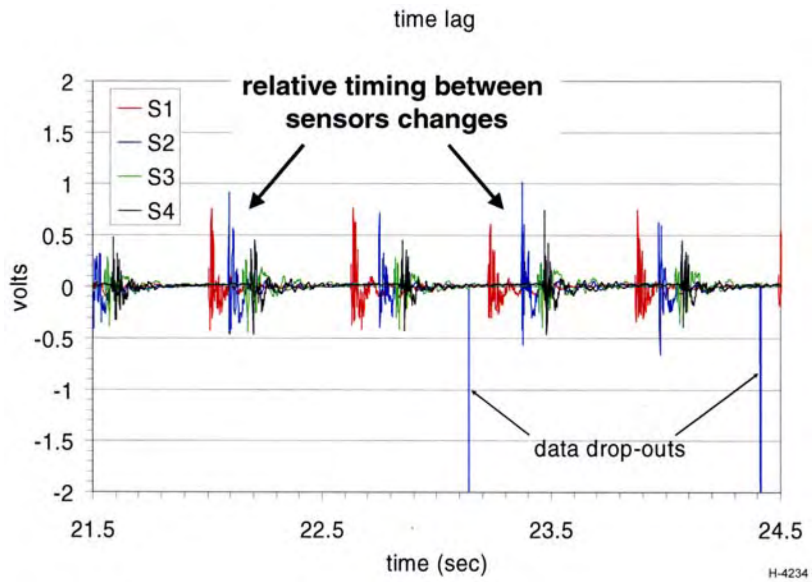
Time Lag Example
- all sensors co-located -

VG05-264-32



PROPRIETARY

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Plan To Acquire Triangulation Data

VG05-264-33

- **PSI has developed a work-around for the data acquisition system**
  - use NGA-Phase 1 DAQ recording analog data with dedicated DAQ system
  - higher noise likely, but time lags will not be present
- **PSI has a suitable site near its facility for the testing**
  - site is also suitable for long-term deployment
- **We will rent appropriate equipment to use as sources (tamper, jackhammer, etc.)**
- **Repeat site characterization measurements**
- **Acquire triangulation data**
- **Acquire long term deployment data for Phase 2 SBIR**

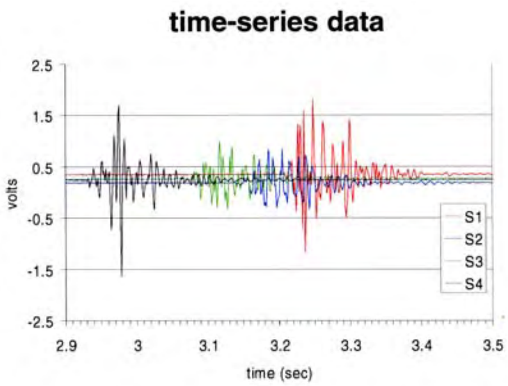
PROPRIETARY

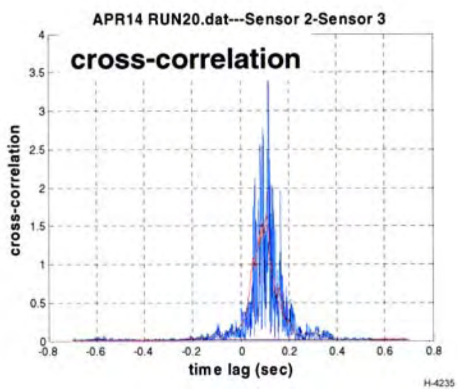
PSI Physical Sciences Inc

Triangulation Algorithm

VG05-264-34

- **We developed a preliminary algorithm for triangulation based on cross-correlation of the time-series data**
- **Preliminary results are promising**





PROPRIETARY

Backups

Additional Effort in BAA

VG05-264-36

- **Two areas were underestimated in EP program**
  - design and laboratory test of EP-1 sensor head
  - preparation for field test 1
- **Progress made in several areas that will save effort in AP**
- **Extra design, modeling and testing of EP-1 enhanced data quality, sensor performance and portability to future programs**
  - FEA modeling ensured resonance freq. > 1000 Hz
  - fully weather-tight and rugged package directly transferable to AP
  - full calibration of EP-1
- **Field test preparation**
  - more complicated DAQ system needed to support the near-ideal field test conditions provided by NGA
  - we did not acquire all the data we wished; however, the data quality is significantly better than in earlier phases
- **Algorithm development**
  - preliminary triangulation algorithm developed – needed for AP
  - preliminary sleep-control algorithm developed – needed for AP

PROPRIETARY

PSI PHYSICAL SCIENCES INC

Proposed Milestones (1/2)

VG05-264-37

Item No.	Task No. (per proposal)	Activity/Deliverable ACTIVITY/DELIVERABLE	Expected Completion Month After Award	Payable Milestone TITLE
1	1.1	Kickoff meeting	0.5	Project kickoff with funders and contractors
2	1.2	EP-1 design	3	Initial design of system completed
3	1.3	Preliminary algorithm development	3	Design Review-1 conducted. Sponsors review initial design
4	1.4	NYSEARCH project management	3	Project management performed
5	1.5	Utility project requirements-NYSEARCH	3	System specifications developed
6	1.6	NYSEARCH technical & financial reporting	3	Technical & Financial reporting accomplished
7	1.7	Quarterly Status Report	3	Quarterly report outlining preliminary sensory system and algorithm design submitted
		First Payable Milestone	**3**	**SUBTOTAL**
8	1.8	EP-1 fabrication	4	Fabrication of initial system completed
9	1.9	Laboratory test	5	Lab testing of initial system conducted
10	2.1	Field Test EP-FT1	6	Field testing of initial system conducted
11	2.2	Quarterly Status Report	6	Second quarterly report outlining results of laboratory and field tests submitted
		Second Payable Milestone	**6**	**SUBTOTAL**
12	3.1	Optimize algorithm	9	Encroachment identification algorithms optimized
13	3.2	EP-2 design	ongoing	Design of second generation system completed
14	3.3	Quarterly Status Report	9	Third quarterly report outlining second design and optimized algorithms submitted
15	3.4	NYSEARCH project management	9	Self explanatory
16	3.5	Utility project requirements-NYSEARCH	9	System specs (2nd generation) developed by utility personnel
17	3.6	NYSEARCH planning & prep for field tests	9	Self explanatory
		Third Payable Milestone	**9**	**SUBTOTAL**

PROPRIETARY

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Proposed Milestones (2/2)

VG05-264-38

Item No.	Task No. (per proposal)	Activity/Deliverable ACTIVITY/DELIVERABLE	Expected Completion Month After Award	Payable Milestone TITLE
18	3.7	EP-2 design	10	Design Review 2 completed by sponsors
19	3.8	EP-2 fabrication	11	Fabrication of 2nd generation system completed
20	3.9	Implement algorithms in EP-2 DSP	12	Optimized algorithms implemented in 2nd generation system
21	3.1	NYSEARCH technical & financial reporting	12	Self explanatory
22	3.11	NYSEARCH -implement field tests	12	Preparation for field testing 2nd generation system
23	3.12	Quarterly Status Report	12	Fourth quarterly report outlining results of algorithm implementation in second design submitted
		Fourth Payable Milestone	**12**	**SUBTOTAL**
24	4.1	Laboratory test	13	Lab testing of 2nd generation system conducted
25	4.2	Field test EP-FT2	14	Field testing of second generation system conducted
26	4.3	NYSEARCH -implement field tests	14	Preparation for additional field testing 2nd generation system
27	5.1	Define AP specifications	15	AP specifications & requirements document delivered
28	5.2	NYSEARCH technical & financial reporting*	15	Self explanatory
29	5.3	NYSEARCH project management	15	Self explanatory
30	5.4	Final Report	15	Final report detailing entire project effort submitted
		Fifth Payable Milestone	**15**	**SUBTOTAL**

PROPRIETARY

Suggested Revised Schedule

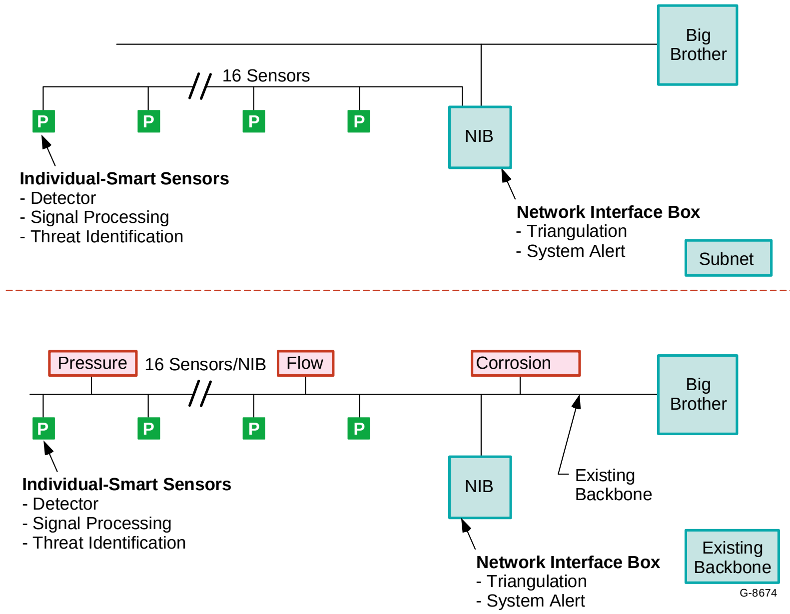
VG05-264-39

	Proposed		Revised (15 Nov Start)		Other Actions
Kick-Off Meeting	0.5 MAC	15 -OCT-04	9-NOV-04	1.5 MAC	-
Design Review-EP-1	3	31-DEC-04	31-JAN-05	4	Begin F-T1 Planning
EP-1 Fabrication Complete	4	31-JAN-05	28-FEB-05	5	-
Field Testing EP-1 Complete	6	31-MAR-05	30-APR-05	7	Commercialization Partner Selected
Design Review - EP-2	10	31-JUL-05	15-AUG-05	10.5	Begin FT-2 Planning
EP2 Fabrication Complete	11	31-AUG-05	15-SEP-05	11.5	-
Field Testing EP-2 Complete	14	30-NOV-05	30-NOV-05	14	AP Preliminary Specifications Review
AP Specifications Document	15	31-DEC-05	31-DEC-05	15	-
Final Report	15	31-DEC-05	31-DEC-05	15	-

PROPRIETARY

System Architecture Alternatives

VG05-264-40

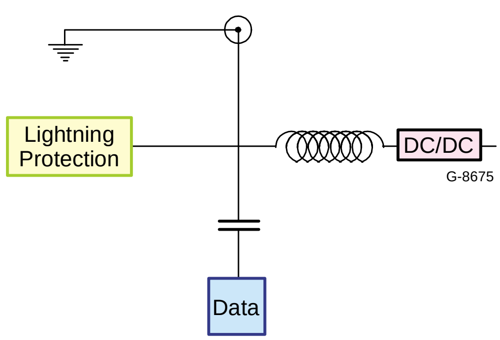


PROPRIETARY

PHYSICAL SCIENCES INC

Power and Data Interface

VG05-264-41



- **Power and data transmitted on a single shielded cable**
- **Lightning protection circuitry**
- **Bit rate - subnet**
  - 100 bps - average
  - 1000 bps - burst

PROPRIETARY

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Appendix B

VG05-263

Infrasonic-Frequency Seismic Sensor System for Pipeline Integrity Management

Data Review

21 September 2005

G. E. Galica and B. D. Green
Physical Sciences Inc.
20 New England Business Center
Andover, MA 01810-1077

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

Data Review Meeting Agenda

VG05-263-1

- **Data Review**
  - sensor performance and calibration results
  - Apr 05 field test results (signatures, sensitivity)
  - algorithm optimization
  - PSI additional field test results (triangulation)
- **Commercialization**
- **Field Test plans**
  - EPFT-2
  - future field tests
- **EP-2 Design & Status**
- **System interface and CONOPS**

PIGPEN Technology Status

VG05-263-2

- **Six Experimental Prototype-1 (EP-1) units fabricated**
- **EP-1 sensor head meets its design criteria**
  - Resonance frequency >1000 Hz (1100 Hz measured)
  - Calibrated response of EP-1 is 12 dB greater than the NYSEARCH-Ph2A sensor (3-10 dB goal)
  - Noise reduced by more than 20 dB below the NYSEARCH-Ph2A system (10 dB goal)
  - No effect in the EP-1 response for installation at angles up to 30 deg (PDR action item)
- **We acquired three days of field data at two test sites**
  - Somerset, MA
  - NYSEARCH-sponsored test at Johnson City, NY
- **We acquired additional four days of field data under the Phase 2 SBIR**
  - Andover, MA
  - triangulation & long-term stability
- **EP-1 detection range extrapolated to 1750 m with SNR=16 dB under quiet conditions**
  - EP-1 performance exceeds range goal of 1000 yards
- **Algorithm has been optimized to correctly identify two common threats**
- **Triangulation accuracy established**
  - Triangulation demonstrated with sledgehammer and jackhammer at Andover site
  - We developed an algorithm for triangulation
- **EP-2 fabrication and integration complete**
  - Laboratory checkout ongoing
  - EP-2 checkout complete by early October

PROPRIETARY

PSI Physical Sciences Inc

EP Data Review

VG05-263-3

- **EP-1 Calibration**
- **EPFT-1 results**
  - signatures
  - range & sensitivity
- **Algorithm performance**
  - Build 1
  - optimization
- **Triangulation**
  - EPFT-1 difficulties
  - algorithm development
  - Ph 2 SBIR field test results

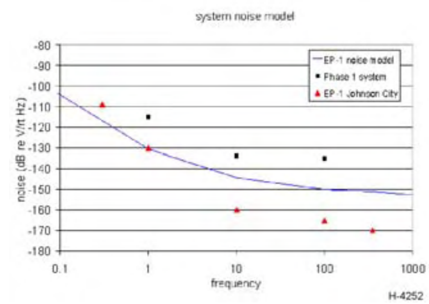
PROPRIETARY

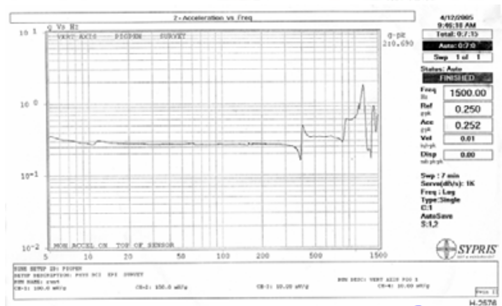
PSI Physical Sciences Inc

EP-1 Calibration

VG05-263-4

- **EP-1 performance meets its design goals**
- **Resonant frequency of 1100 Hz**
  - Meets design goal >1000 Hz
- **EP-1 sensitivity 12 dB greater than Phase-1 sensor**
  - 3-10 dB goal
- **EP-1 noise more than 20 dB less than Phase-1 system**
  - 10 dB goal
- **Calibrated at vibration test facility and at PSI**
  - Bell Technologies, Burlington MA





PROPRIETARY

Field Testing

VG05-263-5

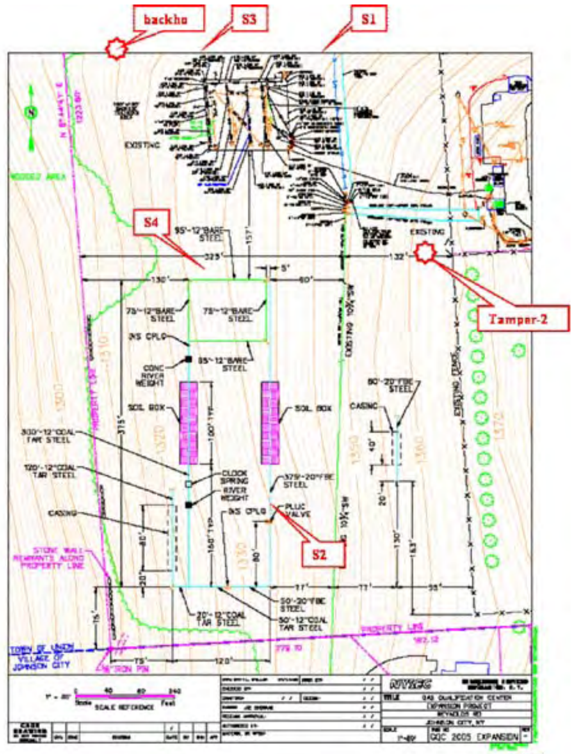
- **Multiple field tests conducted**
  - Somerset MA, private contractor - field checkout
  - Johnson City, NY, sponsored by NYSEARCH
  - Andover MA, long term deployment & triangulation under Ph 2 SBIR
- **In total more than 7 days of data collected**
- **NYSEARCH-sponsored test**
  - Several types of equipment available over two days

Equipment	Manufacturer & Model
Backhoe	Caterpillar 10-200 416D
Trackhoe	Caterpillar 225BLC
Jackhammer	Attachment to Cat 225 BLC
Tamper	Wacker 2-103

PROPRIETARY

- **Johnson City, NY site**
- **4 sensors deployed**
- **175 m maximum range from threat**

-6



H-4236

Trackhoe and Backhoe – Johnson City

VG05-263-7

H-4226

PROPRIETARY

Tamper & Jackhammer Attachment

VG05-263-8

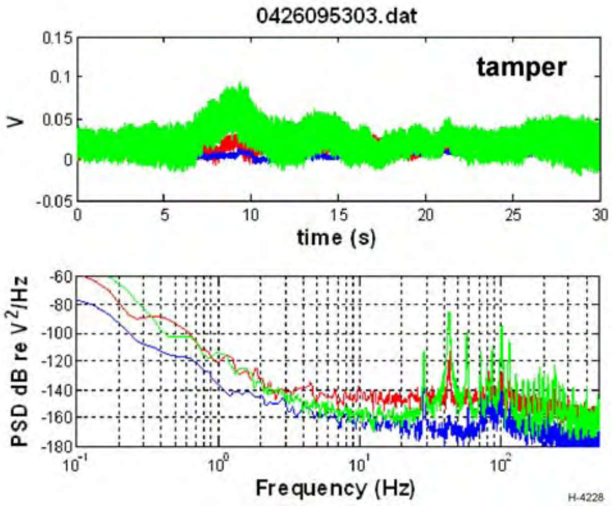
H-4227

PROPRIETARY

Signatures – Johnson City

VG05-263-9

- **Signatures of all equipment acquired at ranges up to 175 m**
- **High SNR at all ranges**
- **Signatures qualitatively similar to data acquired in NYSEARCH Phase- 1 program**



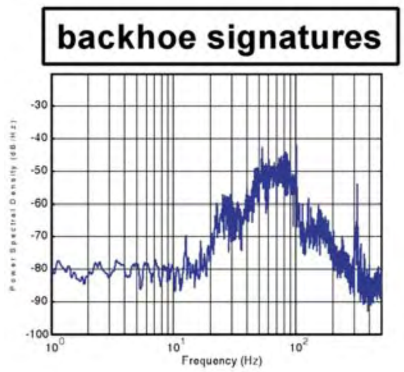
H-4228

PROPRIETARY

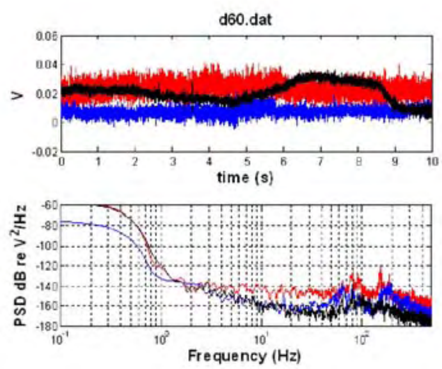
Signatures (2)

VG05-263-10

- **EP-1 measured signatures comparable to early NYSEARCH Phase-1 measurements**
- **Basic algorithm approach is sound**
- **Algorithm optimization now complete**



NYSEARCH Phase 1



EP-1

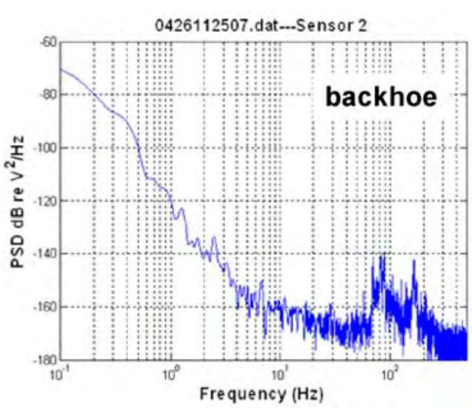
H-4229a

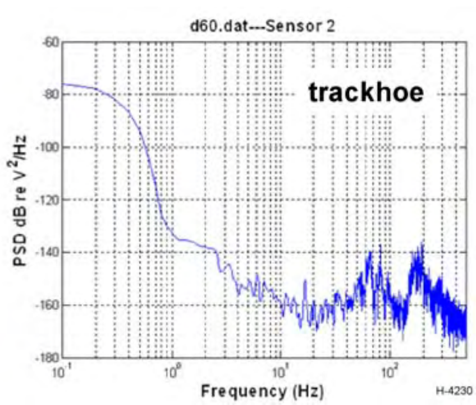
PROPRIETARY

Signatures of Similar Equipment

VG05-263-11

- **Signatures of backhoe and trackhoe qualitatively similar**
- **Some variability, but overall robust signature – Build-1 algorithm logic still satisfied**
- **We have used these results to refine the algorithm**





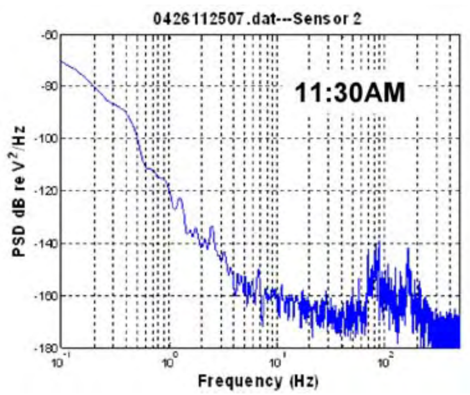
H-4230

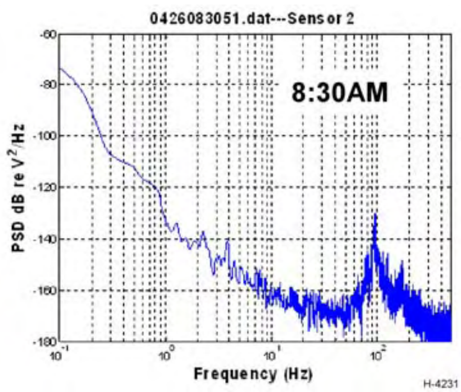
PROPRIETARY

Signatures at Different Times

VG05-263-12

- Signatures of the same equipment acquired at different times are comparable
- Some variability - as expected
- algorithm logic still satisfied





H-4231

PROPRIETARY

PHYSICAL SCIENCES INC

Extrapolated EP-1 Range

VG05-263-13

- Maximum sensor range at Johnson City site is 175 m
- We used range dependence of the signal to extrapolate a maximum range (under quiet conditions)
- Signals falls as roughly 1/R

- 1750 m extrapolated range (SNR=16 dB)
- EP-1 exceeds detection range specification (1000 yards)

sensor	range	signal
S3	25.5 m	-113 dB
S1	80 m	-122 dB
S2	175 m	-131 dB
Extrapolated limit	1750 m	-151 dB (SNR=16 dB)

PROPRIETARY

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Algorithm Performance

VG05-263-14

- **PSI developed the Build-1 algorithm using NYSEARCH-Phase1 data as the training set**
  - filter-bank creates sparse spectra
  - logical comparison to library spectra
- **Build-1 algorithm provides good results for backhoe identification**
- **Optimized algorithm provides good results for jackhammer identification**
- **The algorithm is now at Build-2**
- **Build-2 is implemented and functional on the EP-2 DSP**

PROPRIETARY

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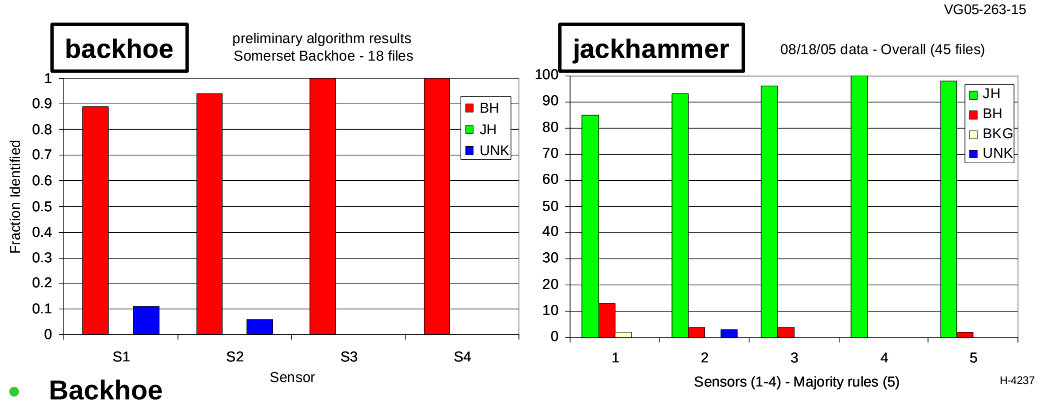
Algorithm Performance (2)

VG05-263-15



- **Backhoe**
  - 18 files of backhoe from Somerset test (9 minutes)
  - algorithm correctly identifies nearly all files on all sensors
- **Jackhammer**
  - Optimized Algorithm correctly identifies 85-100% of jackhammer files (45 files – 20 minutes)
  - better performance achieved when multiple sensors are used for identification

PROPRIETARY

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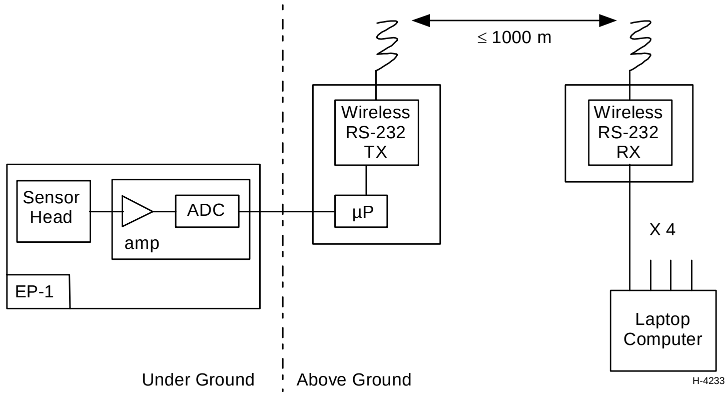
Triangulation & Data Timing

VG05-263-16

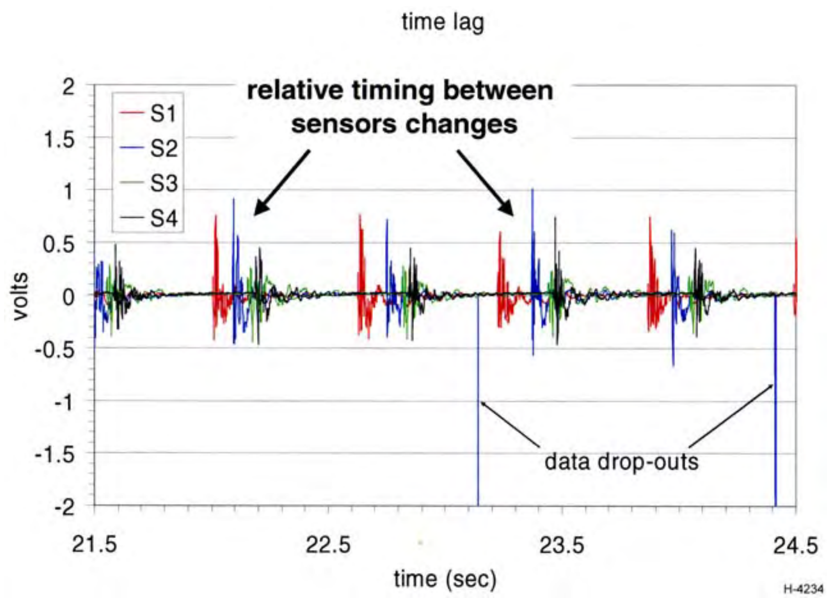
- **At Johnson City, we failed to acquire accurate triangulation data**
- **The relative timing of the data streams from the 4 sensors was corrupted by the data acquisition system**
  - At the Johnson City test, we used wireless serial DAQ system – wireless facilitates acquisition of remote sensor data at long range
  - internal buffering in the computer introduced non-reproducible time lags in the data



PROPRIETARY

Time Lag Example – Johnson City - all sensors co-located -

VG05-263-17



PROPRIETARY

Triangulation - Andover, MA Field Testing

VG05-263-18

- **PSI developed an alternative data acquisition system**
  - no time lags
  - acquisition system range limited to 250 yards
- **PSI deployed 4 EP-1 sensors at a site in Andover, MA**
  - 250 m sensor separation – comparable in size to Johnson City site
  - deployed 3 August 05 in a long-term installation (still operational)
- **We have rented equipment to use as sources (e.g. jackhammer)**
- **We have completed 4 additional days of field testing**
  - repeated site characterization measurements (supporting Don Steeples)
  - acquired triangulation data & demonstrated performance
  - acquiring long term deployment data for Phase 2 SBIR

PROPRIETARY

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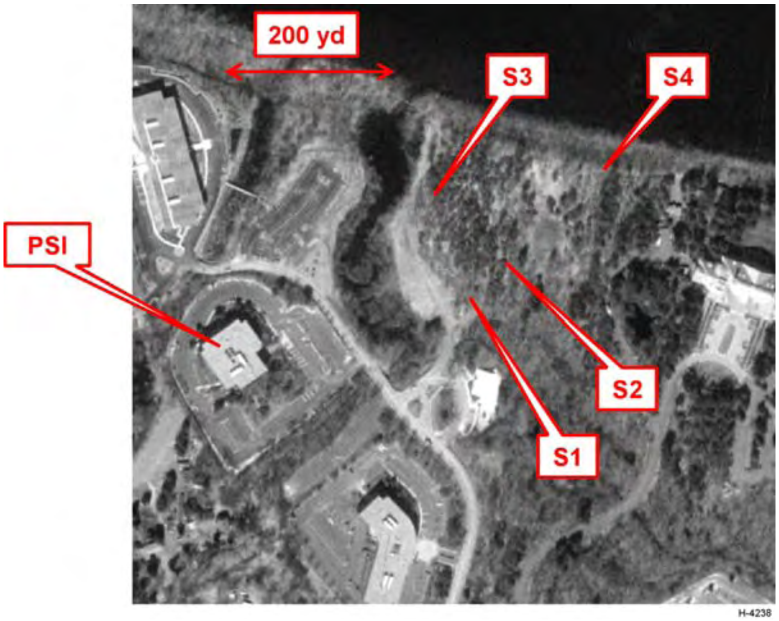
Andover Test Site

VG05-263-19



PROPRIETARY

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Andover Test Site Sensor Layout

VG05-263-20

H-4239

Arial view with location of sensors for triangulation and long-term deployment shown in red

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Andover Test Site (2)

VG05-263-21

G-4634

PROPRIETARY

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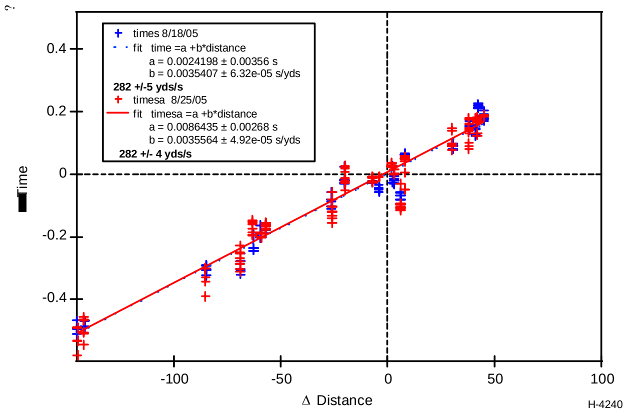
Velocity Calculation- Sledgehammer Impacts

VG05-263-22

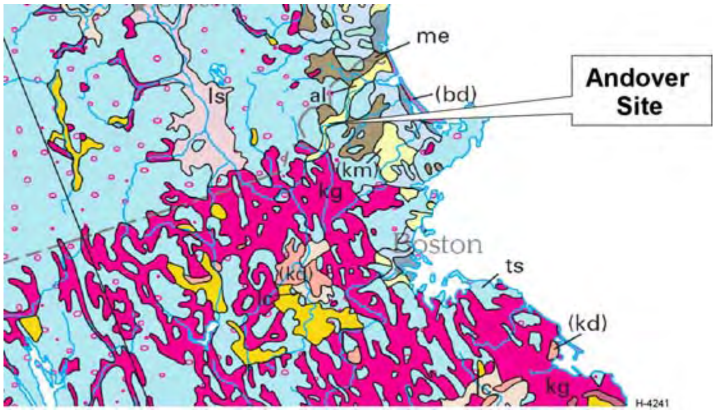
- **Velocity calculated from 2 different days data using sledgehammer impacts at varying locations at Andover site**
- **Excellent agreement day-to-day: 282 +/- 4 yards/sec**
- **consistent with NEHRP Class D soil**



PROPRIETARY

Geologic Conditions - Andover

VG05-263-23



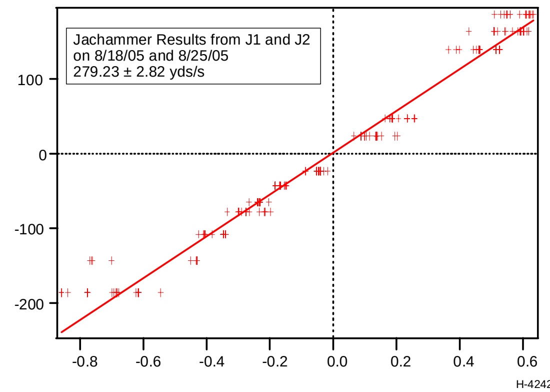
- **Soil is predominantly alluvium**
- **Measured velocity is 256 m/sec**
- **Typical velocities in alluvium range from 120 – 430 m/sec**
- **predictive model (Nottis) yields 324 m/sec for depth of 30 m**

PROPRIETARY

Velocity Calculation- Jackhammer Impacts

VG05-263-24

- **Velocity Calculated on 2 different days using jackhammer impacts at varying locations**
- **Good agreement day-to-day**
- **Good agreement with sledgehammer results**
  - 279 +/- 3 yards/sec (JH)
  - 282 +/- 5 yards/sec (SH)
- **Andover, MA site**

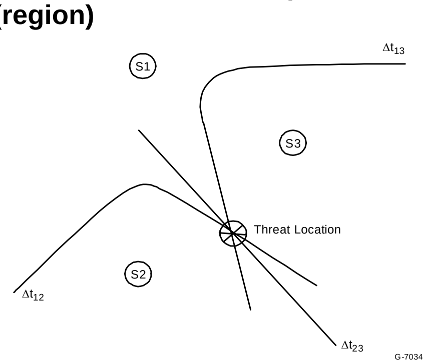


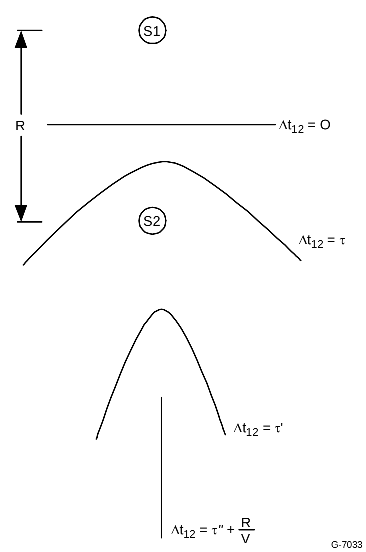
PROPRIETARY

Triangulation Methodology

VG05-263-25

- **PSI is following the formalism of Moore, Glover and Peck [2002] for determining source location with multiple sensors**
- **Any two sensors locate a threat on a hyperbola**
- **Additional sensors (up to 4) localize the threat to a point (region)**



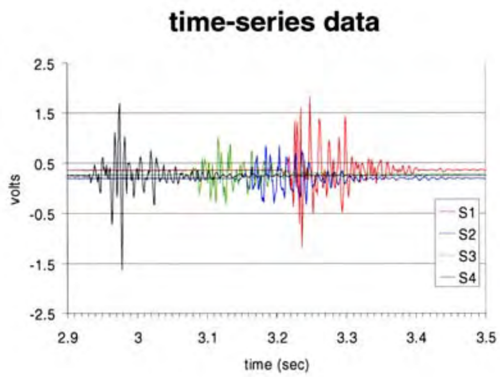


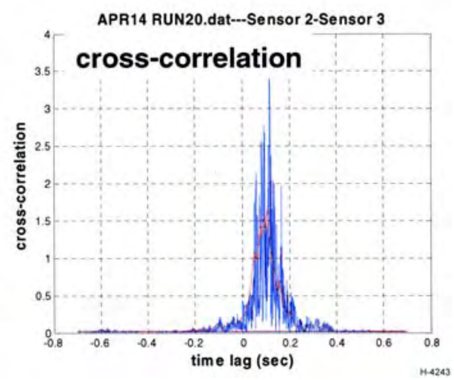
PROPRIETARY

Triangulation Algorithm

VG05-263-26

- We developed an autonomous algorithm for triangulation based on cross-correlation of the time-series data
- Preliminary results are good
- Algorithm allows easy incorporation of filtering (air-coupled vs ground-coupled)
- Algorithm is suitable for implementation on DSP



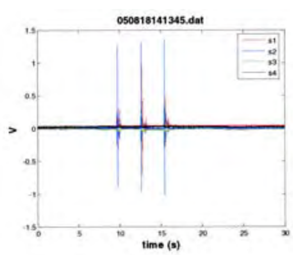


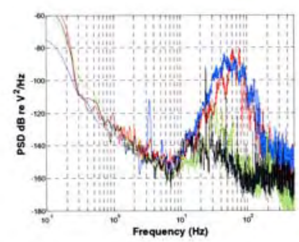
H-4243

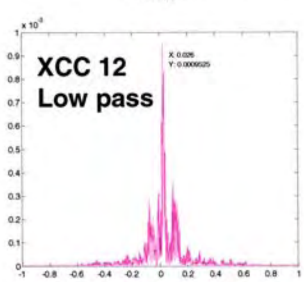
PROPRIETARY

Results from Filtered Data

VG05-263-27

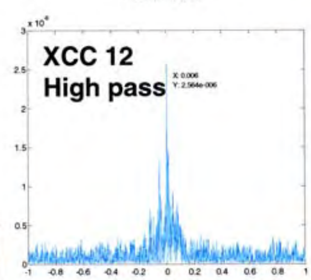






Position from XCC:
x = 28.0 y = 23.8

Real location
24.66, 23.4 yds



Position from XCC:
x = 24.2 y = 21.6

H-4244

PROPRIETARY

Triangulation Results

VG05-263-28

- **PSI deployed 4 EP-1 sensors at a site in Andover, MA under Phase 2 SBIR**
- **Triangulation data acquired with sledgehammer and jackhammer sources**
- **Position determination are precise to +/- 1yd**
- **Position accuracies are +/- 3.5 yards (vary from 1 – 9 yd and are range independent)**
- **Jackhammer location has same accuracy as sledgehammer location**

	Surveyed (+/- 1 yd)		PIGPEN measurement	
	X	Y	X	Y
Sledgehammer - U	24.7 yd	23.4 yd	27.8 ± 0.8 yd	25.9 ± 1.1 yd
Sledgehammer - V	65.1 yd	47.9 yd	64.4 ± 1.4 yd	53.5 ± 1.0 yd
Sledgehammer - X	125 yd	-4.5 yd	128 ± 0.6 yd	4.2 ± 1.0 yd
Jackhammer	-22.5 yd	62.4 yd	-18 ± 1.0 yd	64 ± 1.0 yd

PROPRIETARY

PSI Physical Sciences Inc

PIGPEN Preliminary System Specifications

VG05-263-29

Parameter	target	actual
Detection range	1000 yards, in quiet conditions	1900 yards (SNR=16 dB) Extrapolated
Triangulation accuracy	10 yards at 300 yard range [3.3 yds at 100 yard range] [33 yds at 1000 yard range]	3.5 yards at 150 yard range accuracy is a non-linear function of range
Unit mass	2.5 lbs	4-5 lbs
Unit size	6.5 x 3.5 x 2.5 in^3	5 x 5 x 4 in^3
Unit power	1 watt (max) Less with sleep mode	1 watt (max) baseline Less with sleep mode
Unit cost	<$300 Target	No change to BOM

- **EP-1 sensor performance has met or exceeded predictions**
- **EP-2 processor has met timing requirement with no optimization**
- **EP-1 design (sensor head, front-end electronics, chassis) directly transferrable to AP program**
- **EP-2 DSP forms baseline for AP processor**

PROPRIETARY

PSI Physical Sciences Inc

Numerical Modeling

VG05-263-30

- **We have acquired critical data that demonstrates triangulation feasibility**
- **A system model is required to guide future development**
  - Identify critical error terms
  - Guide future data acquisition and field tests
  - Optimize sensor grid configuration and CONOPS
  - Optimize algorithm
- **Triangulation uncertainty is a complex, non-linear function of threat position and sensor grid geometry**
  - Propagation of errors through triangulation algorithm
  - Error and uncertainty in time lag determination and processing
  - Error and uncertainty caused by complex soil conditions
- **Field test data used to validate model**
- **Validated model guides system development**
  - A vast range of soil conditions, configurations, threat scenarios etc. can be explored
  - Optimize data acquisition - cost effective field tests
  - Optimize system design, configuration and CONOPs

PROPRIETARY

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BAA Remaining Tasks

VG05-263-31

- **Complete EP-2 preliminary checkout**
  - laboratory checkout complete - 30 Sep 05
  - preliminary field checkout complete – mid Oct 05
- **EP-2 field test – Oct-Nov 05**
- **Define AP specifications – 15 Dec 05**
- **Identify potential commercialization partners – 15 Dec 05**

PROPRIETARY

PSI PHYSICAL SCIENCES INC

Data Review Summary

VG05-263-32

- **EP-1 sensor head meets its design criteria in responsivity, noise performance and resonance frequency**
- **We acquired seven days of field data at three test sites**
  - Somerset, MA
  - NYSEARCH-sponsored test at Johnson City, NY
  - Andover, MA
- **EP-1 extrapolated detection range exceeds goal of 1000 m (1750 m with SNR=16 dB under quiet conditions)**
- **Triangulation accuracy of +/- 3.5 yards at 150 yards demonstrated – consistent with goal of +/-10 yards at 300 yards range**
- **Threat identification algorithm is optimized to correctly identify two common threats**
- **We developed and demonstrated an automated algorithm for triangulation**
- **EP-2 fabrication and integration complete – ready for field testing in mid October**

PROPRIETARY

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Commercialization Partner

VG05-263-33

- **PSI and NYSEARCH have negotiated terms for future commercial development of PIGPEN**
- **PSI has begun working with NYSEARCH to identify a suitable commercialization partner**
- **We solicit your suggestions……**

- **Commercialization partner participation is extremely important during AP development**
  - definition of system architecture and interfaces
  - insight on commercialization & manufacturing issues to guide the design

- **Commercialization partner criteria**
  - strong presence in the utility industry
  - strong sales and marketing support
  - capable engineering staff
  - acceptors of new technology
  - resources to undertake new product introduction

PROPRIETARY

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EP-2 Status

PROPRIETARY

EP-2 Design & Status

VG05-263-35

- **EP-2 based on existing DSP hardware**
  - using slightly modified DSP board for other application
- **Hardware fabrication, integration and test complete**
- **Build-2 algorithm implemented and verified in DSP**
  - excellent agreement between DSP and MATLAB intermediate results
- **DSP Hardware integrated with EP-1 sensor head**
  - laboratory testing ongoing (complete 30 Sep)
  - field checkout (1-15 Oct)
- **Field test target date 15Oct-15Nov**

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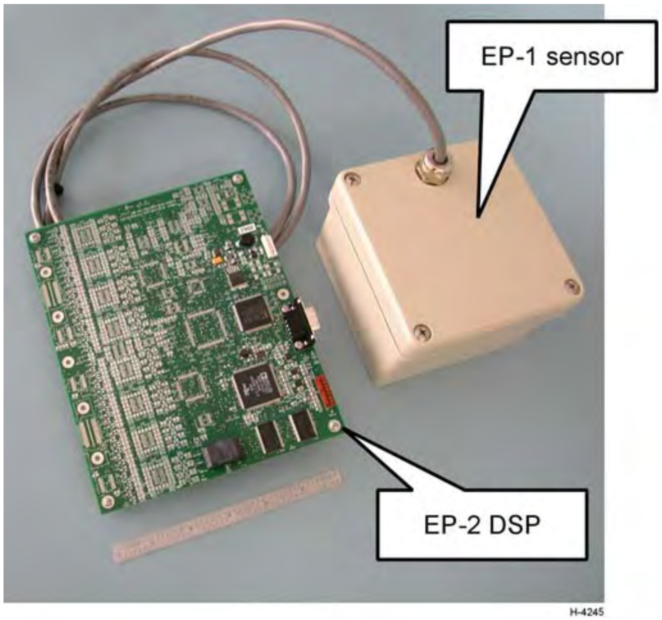
EP-2 Hardware

VG05-263-36



PROPRIETARY

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Algorithm Implementation

VG05-263-37

- **Algorithm first developed in Matlab programming environment (The Mathworks Inc,)**
- **Vtech Inc., transferred Algorithm to C++ and verified operation using sample input files provided by PSI.**
  - Results compared to Matlab results
- **Vtech Inc., implemented C++ code onto DSP board and verified operation using sample EP-1 sensor data input files provided by PSI**

PROPRIETARY

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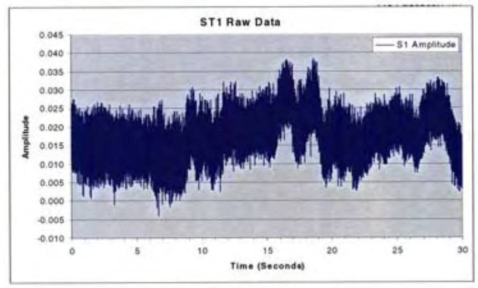
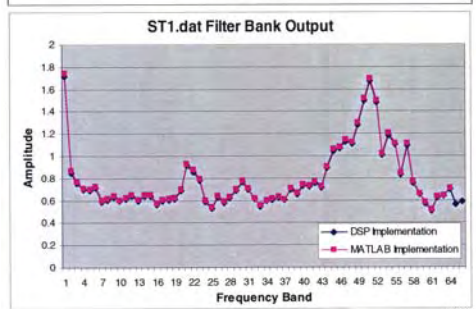
Pigpen Filter Bank Verification

VG05-263-38

- **Analog signals from preamp collected by DAQ card on PC during field testing to produce reference input data**
- **Input data processed by reference algorithm in MATLAB**
- **Input data downloaded to Pigpen EP+ DSP board into same buffer that is filled by data collection from preamp**
- **Reference algorithm implemented in DSP applied to downloaded data in input buffer**
- **Filter bank results compared to reference results from MATLAB:**
  - 6 Reference Files Compared
  - Point-by-Point Error = 1.2%
  - Overall Correlation = 100%





H-4246

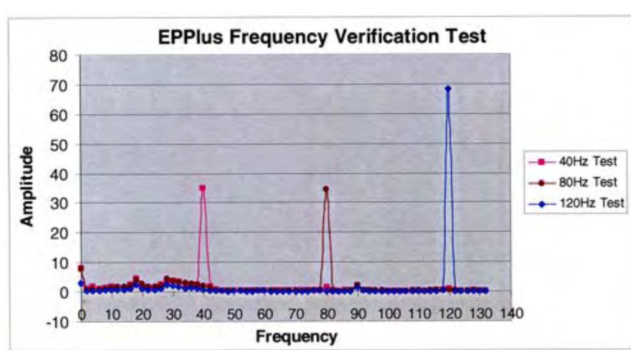
PROPRIETARY

PSI Physical Sciences Inc

Lab Test - Filter Bank Frequency Verification

VG05-263-39

- **Complete System Assembled**
- **Audio speaker driven by waveform generator at known frequencies (1/4W into speaker load)**
- **Vibration coupled to Preamplifier through aluminum plate**
- **Data read by DSP and processed**



H-4247

*Coupling between speaker and preamplifier highly frequency dependent. Data normalization also affects amplitudes

PROPRIETARY

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EP-2 Field Test

PROPRIETARY

EP-2 Field Test (EPFT2 in BAA)

VG05-263-41

Objective: Verify EP-DSP is functioning properly

- Assess automatic threat identification.
- Assess triangulation performance (COMPLETE)
- The EP-2 sensor will be tested on a series of realistic threats (perhaps in conjunction with NYSEARCH and LDCs)
- One to two day test - deployment of one PIGPEN EP-2 unit and one PIGPEN EP-1 unit .
- Deployment on a site with active excavations.
- PSI will prepare a written test plan

PROPRIETARY

PSI
PHYSICAL SCIENCES INC

EP-2 Field Test - Preliminary Test Plan

VG05-263-42

- Johnson City (EPFT1) or Somerset/Andover sites acceptable
- Target test dates 15Oct – 15Nov
- Two sensors deployed
  - **EP2 – containing onboard DSP**
    - **Real time output and threat identification**
  - **EP1- allow for collection of raw signals to verify EP2 performance**
  - **Sensors co-located.**
  - **Sensors deployed 100 yards from threat**
- Series of Threats:
  - **Determine P_d and P_fa**
  - **Excavators**
  - **Pavement Breakers**
  - **Compactor (optional)**
- Acquire Background Data
  - **Determine false alarm rate**
- If NYSEARCH cannot support EPFT2, PSI has identified potential local test sites for a 1-2 day assessment of EP-2

PROPRIETARY

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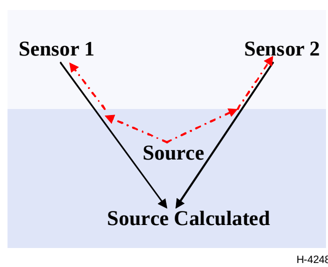
Recommendations from "Seismic techniques for locating threats to buried utilities: Some Limitations and Challenges" by Don Steeples.

VG05-263-43



- **Surface waves refract at interfaces of differing soil types leading to erroneous calculation of source location**
- **Recommendations:**
  - Develop and test a sufficient velocity model
  - Numerical modeling to determine limits of location accuracy and critical parameters
  - Analysis of air coupled wave as a additional location constraint for threat sources.
- **PSI Response – based on recent field test data:**
  - Currently modeling time delay of arrival and accuracy
  - Currently optimizing sensor deployment configuration
  - Analyzing utilization of air coupled waves
  - Planning potential future field test to address triangulation issues associated with non- uniform site geology.

PROPRIETARY

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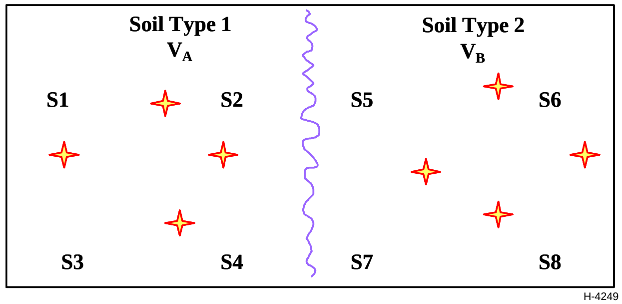
Future Testing of EP Inhomogeneous Soil Performance

VG05-263-44



- **Field test specifically designed to address the issues of performance in inhomogeneous soils**
  - per discussion with NYSEARCH and geological consultant
- **Field test with EP-1 sensors**
  - Non-uniform site with multiple known soil conditions
  - At least 4 EP-1 sensors needed 8 preferred.
  - Multiple threat locations to map velocity field
- **Currently not in the program plan for BAA or DOT Phase II**
- **PSI would welcome the assistance of NYSEARCH in coordinating this test**

PROPRIETARY

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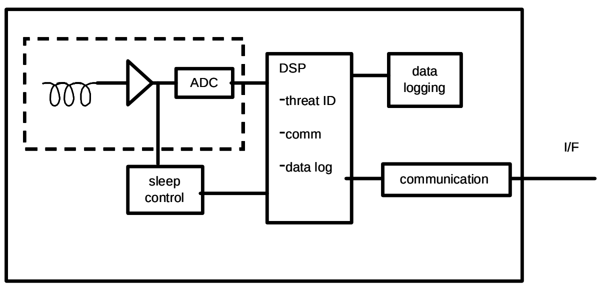
PIGPEN Interface & Operational Concept

PROPRIETARY

PIGPEN Preliminary Block Diagram

VG05-263-46

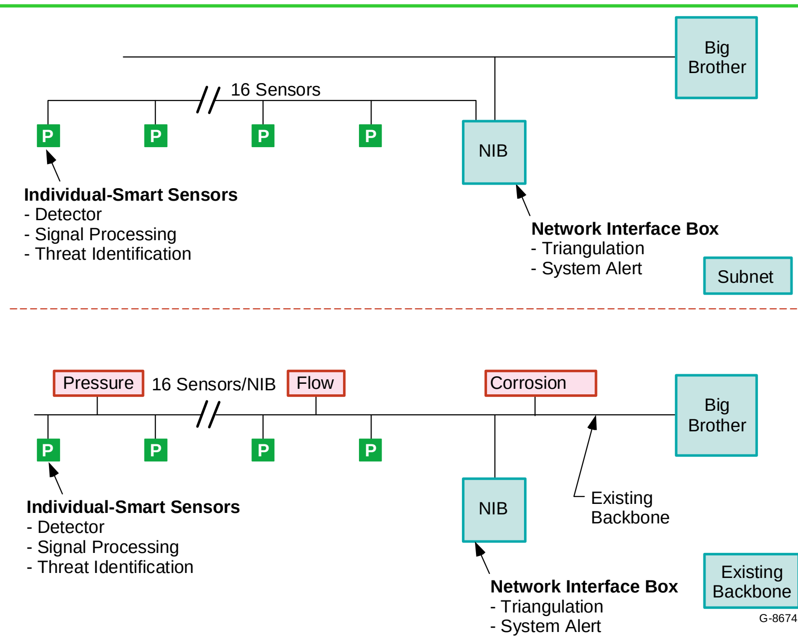
- **PIGPEN comprises:**
  - sensor head and low noise preamplifier - EP
  - data acquisition electronics - EP
  - threat identification algorithm/warning system - EP/AP
  - data logging - AP
  - interface to existing SCADA system - AP/BP
- **DAQ, processor and threat ID accommodated in an inexpensive digital signal processor**
- **Scale <5 lb, <5 in. cube**
- **Preliminary EP-1 results still support this PIGPEN concept**



PROPRIETARY

System Architecture Alternatives

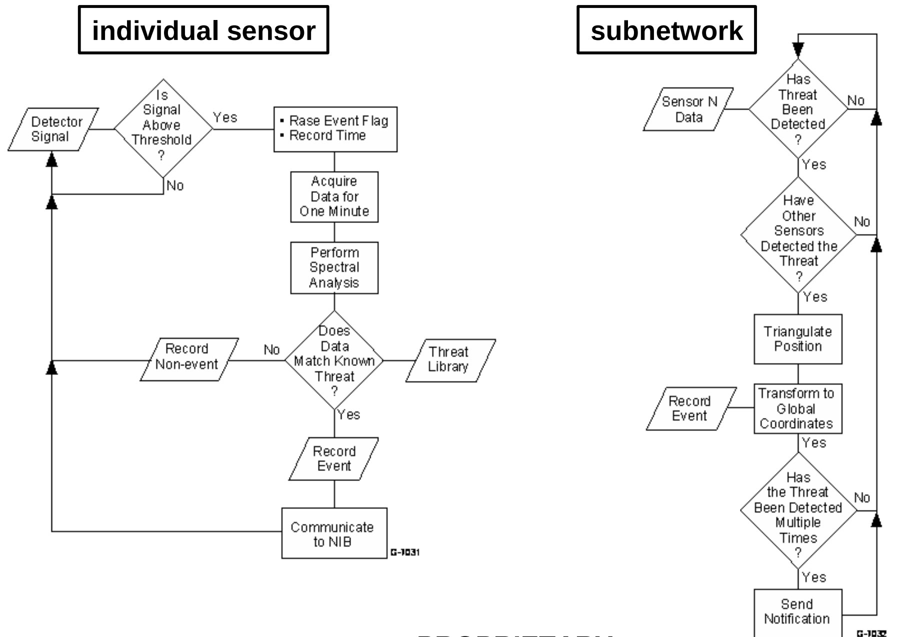
VG05-263-47



PROPRIETARY

PIGPEN Processing Flows

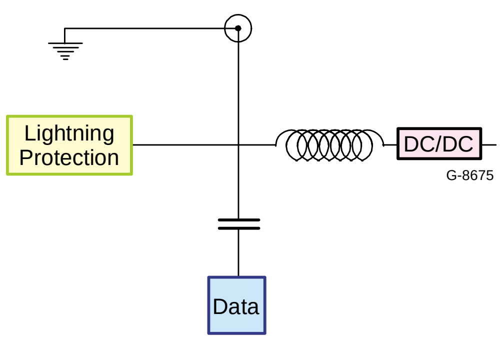
VG05-263-48



PROPRIETARY

Power and Data Interface

VG05-263-49



- **Power and data transmitted on a single shielded cable**
- **Lightning protection circuitry**
- **Bit rate - subnet**
  - 100 bps - average
  - 1000 bps – burst
- **We will revise the interface specifications as we revise the algorithms**

PROPRIETARY

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VG06-073

Infrasonic-Frequency Seismic Sensor System for Pipeline Integrity Management

Phase II SBIR Status Meeting

9 March 2006

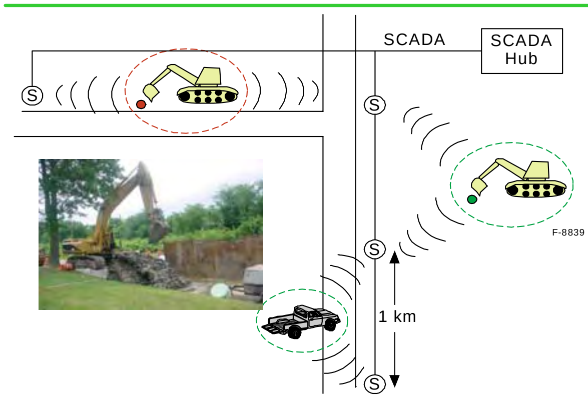
G.E. Galica, W.B.G. Agassounon, M.F. Byl,
S.K. Paintal, and B.D. Green
Physical Sciences Inc.

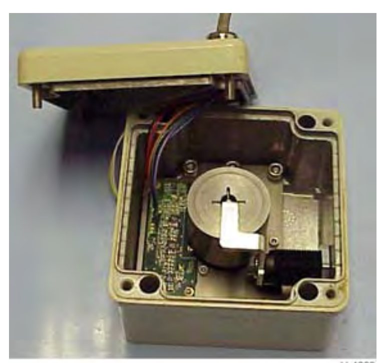
D. D'Zurko
NYSEARCH, Northeast Gas Association

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

Proactive Infrasonic Gas Pipeline Evaluation Network PIGPEN

VG06-073-1





H-4223

- **Smart Sensors placed at 0.5 km spacing along the pipeline**
- **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**

PROPRIETARY

EP (BAA) Summary

VG06-073-2

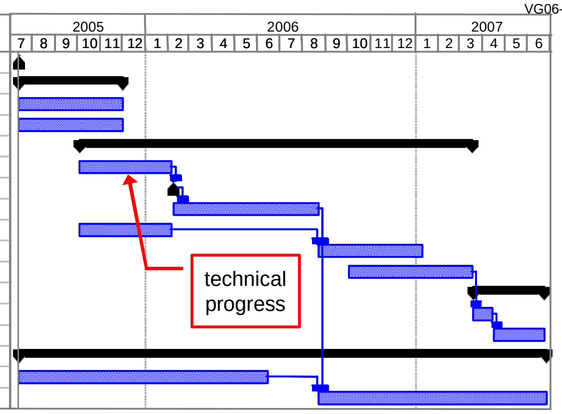
- **EP-1 sensor head meets its design criteria in responsivity, noise performance and resonance frequency**
- **We acquired ten days of field data at three test sites**
  - Somerset, MA; Andover, MA; Johnson City, NY (NYSEARCH test)
- **EP-1 extrapolated detection range exceeds goal of 1000 m (1750 m with SNR=16 dB under quiet conditions)**
- **Triangulation accuracy of +/- 3.5 yards at 150 yards demonstrated**
  - consistent with proposed goal of +/-10 yards at 300 yards range
  - Triangulation accuracy does not meet NYSEARCH requirements (10 feet at 300 yards)
- **Threat identification algorithm is optimized to correctly identify two common threats**
- **Automated, real-time threat identification demonstrated**
- **Developed and demonstrated an algorithm for triangulation**

PROPRIETARY

Proposed Milestone Schedule

VG06-073-3

ID		Task Name
1		**Program Kickoff**
2		**Assess EP Performance**
3		EP long term field test
4		Build-2 algorithm development
5		**Develop AP**
6		integrated DSP design
7		Design Review
8		Fabricate AP
9		Develop NIB
10		AP Test
11		Build-3 Algorithm Development
12		**Assess Long Term Performance of AP**
13		deploy AP network
14		long term testing
15		**Transition to BP**
16		develop commercialization plan
17		transition PIGPEN technology

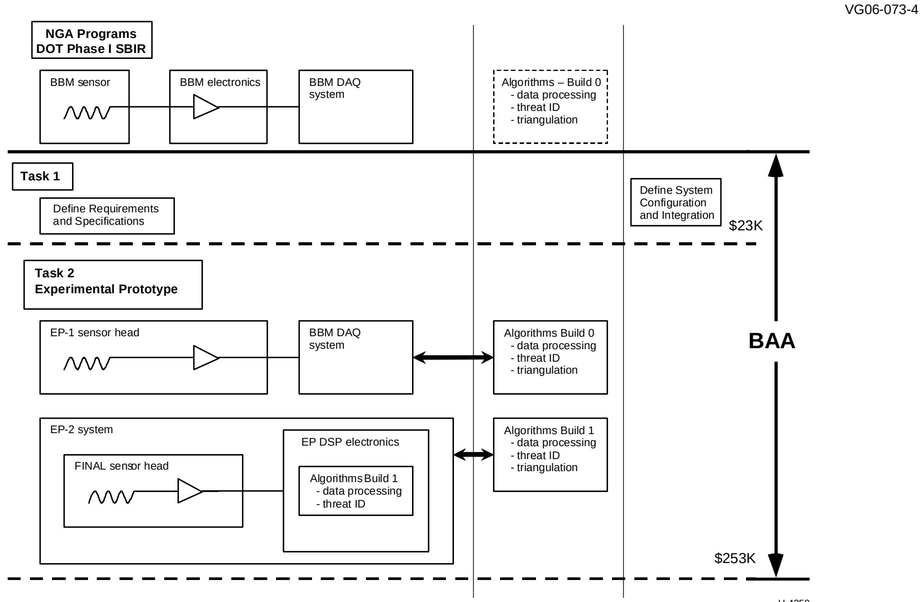


H-4224

- **AP development roughly 2 months behind schedule**
- **EP Testing and triangulation discussions continued into Nov 05**
- **Dec/Jan activities**
  - (re)defined AP architecture
  - triangulation accuracy modeling
- **Spending is commensurate with technical progress**

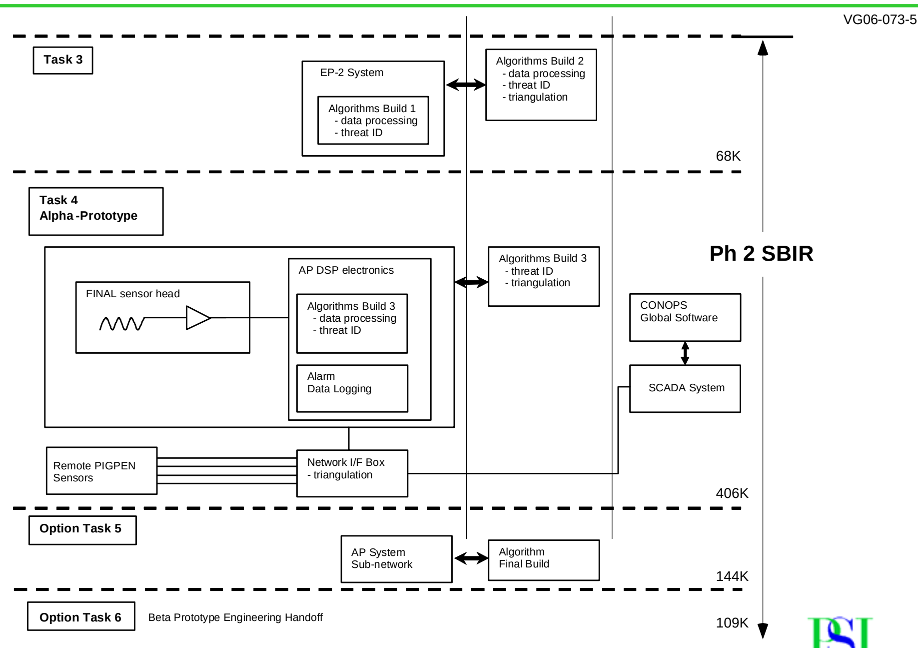
PROPRIETARY

Technology Development Plan



PROPRIETARY

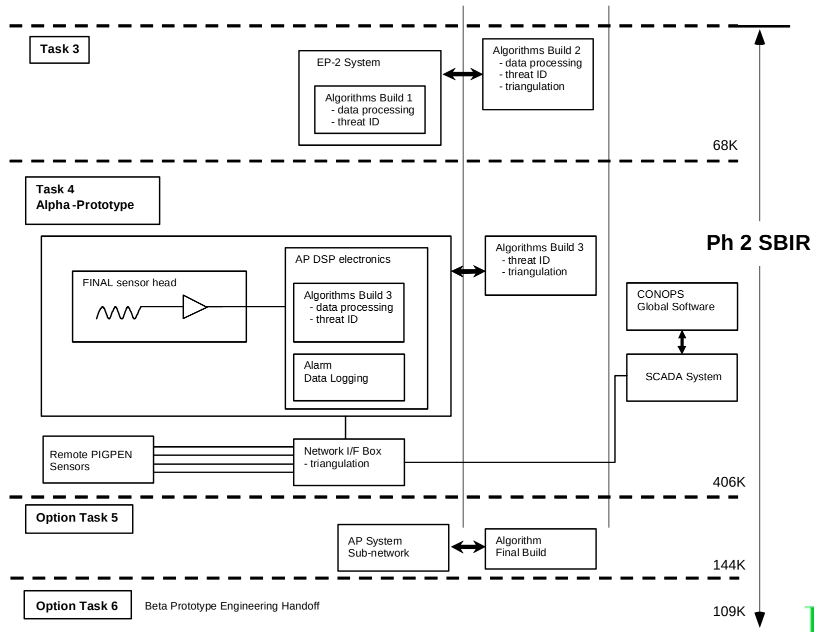
Technology Development Plan (continued)



PROPRIETARY

Technology Development Plan (continued)

VG06-073-5



H-4251

PROPRIETARY

Phase 2 SBIR Program Objectives

VG06-073-6

- **Transition the PIGPEN technology from its present Experimental Prototype stage to a commercially viable prototype system**

  1) Demonstrate a PIGPEN sensor that meets the performance requirements of a third-party damage early warning system

  2) Demonstrate threat identification and threat location algorithms as an enabling technology for a third-party damage early warning system

  3) Develop a PIGPEN Advanced Prototype system that forms a basis for a commercially viable product that meets both the performance and market requirements of a third-party damage early warning system

  4) Transition the PIGPEN technology to a commercialization partner in cooperation with NYSEARCH

PROPRIETARY

Phase 2 SBIR Tasks

VG06-073-7

- Task 1. **Program Kickoff**
  - 1.1 Interface and requirements definition
  - 1.2 Program kickoff meeting
- Task 3. **Assess PIGPEN EP Performance and Refine Algorithms**
  - 3.1 Acquire database of performance data with EP-2 in a long-term deployment
  - 3.2 Develop Build-2 algorithms, based on EP-2 assessment data
- Task 4. **Develop PIGPEN Alpha Prototype (AP)**
  - 4.1 Develop and fabricate integrated sensor head and customized digital signal processor as AP
  - 4.2 Develop and implement Build-3 software algorithms
  - 4.3 Establish AP performance by laboratory and field testing
- Task 5. **Assess Long-Term PIGPEN AP Performance**
  - 5.1 Deploy small network of PIGPEN AP sensors
  - 5.2 Assess performance by long term acquisition
- Task 6. **Transition PIGPEN Technology to Beta Prototype (BP)**
  - 6.1 Develop commercialization plan
  - 6.2 Transition PIGPEN technology to commercialization partner

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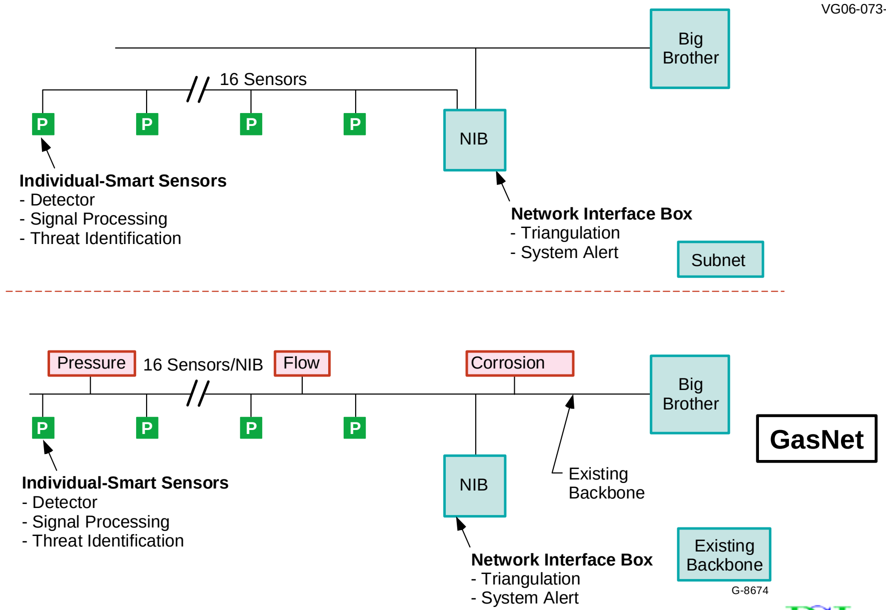
AP System Design

Proposed AP System Architecture Options

VG06-073-9



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System Architecture Drivers (AP & future)

VG06-073-10

- **1) How to *Power* each sensor**
  - How much power?
- **2) How to *Communicate Data* across network**
  - How much data in how much time?
- **3) How to *Synchronize Time* across network**
  - How precise must the synchronization be?
- **All 3 drivers are *Commercialization* issues**
  - Not fundamental science issues
  - Not internal product definition issues
  - But they do drive system performance
- **Commercialization decisions vary by application**
  - How the boxes get powered
  - How the boxes communicate
  - Customer's existing infrastructure affects decisions
- **Develop an interface-agnostic AP compatible with a wide range of customer interfaces**
- **Develop a simple infrastructure to enable AP-level system evaluation in the absence of a specific customer interface**

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3 Case Studies

VG06-073-11

- **AP Development System**
  - DC power is preferable, battery life less important
  - Wired vs. wireless communication driven by cost
  - Synchronization is critical for proof-of-concept
- **Rural Application**
  - Continuous power not available, battery replacement costly
  - Networking favors wireless system over burying miles of cable but makes synchronization difficult and wires may be needed for power anyway
  - Client less likely to have existing infrastructure that can support system
- **Urban Application**
  - Continuous power likely accessible but batteries easy to change too
  - Networking favors wired system over interference-susceptible wireless, making synchronization easier as well
  - Client probably has existing infrastructure – anything we pick is likely to be incompatible

PROPRIETARY

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Driver #1: Power Supply

VG06-073-12

- **Critical Specifications**
  - What is the maximum power during processing?
  - What is the minimum power during sleep?
  - What will the duty cycle (average power) be?
  - What external power will be provided?
- **Alternatives**
  - 1) System is ultra-low power and is completely battery operated
  - 2) System has power wires to every node
- **If System Power is wired . . .**
  - Power requirements dictate unrealistic cable sizes and/or voltages
  - Increased installation cost
- **Recommend battery power for AP**
- **Future system compatibility**
  - multi-year battery life for low duty cycle system
  - solar power (or other) supplementation for higher duty cycles

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AP System Power

VG06-073-13

- **Sensor Power**

Sensor Power	Active	Sleep
– Preamplifier	6 mW	6 mW
– Sensor Board	1000 mW	50 mW
– PCA Board	1000 mW	100 mW
– Radio	3650 mW	43 mW (1 sec cycle)
– GPS	600 mW	100 mW
Total:	6.3W	300 mW

- **Use 4 D-Cells for power (90WH):**
  - At 1% Duty Cycle → 360 mW avg. (10 days)
  - At 50% Duty Cycle → 3.3 W avg. (1 day)

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Driver #2: Communications

VG06-073-14

- **Critical Specifications**
  - How much data must be collected per block?
  - How much latency before localization is permitted?
  - How long is the longest link?
- **Alternatives**
  - 1) Each sensor can see directly back to NIB (high power)
  - 2) Sensors must retransmit each other's messages
- **Recommend direct communication to NIB for AP**
  - greatly simplifies protocol
- **Future System compatibility**
  - wireless direct communication likely best for rural/suburban installation
  - urban installation may favor hardwired installation

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AP System WLAN

VG06-073-15

- **UART-Serial Radio Survey**
  - Range up to 20 miles with high-gain antenna
  - Expected throughput ˜ 38.4kbps – 115.2kbps
  - 1W RF output power
  - Active power = 3 to 6 W, Sleep < 50 mW
  - Cost per unit = $200 to $1000 + Antenna

- **Conclusion:**
  - Bandwidth becomes system constraint
  - Low BW needed for other application anyway

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Driver #3: Synchronization

VG06-073-16

- **Critical Specifications**
  - Data Registration Accuracy
    - Worst case is fastest speed (800 m/sec)
    - Requested localization accuracy = 10 feet (3.1 m)
    - With 10x margin to account for geometry, etc.→ 400 microsec
  - Synchronization Accuracy
    - 400 μsec error, 30 seconds of collection → 13 ppm
    - Watch crystals have 20 to 200 ppm drift (temperature dependent)
    - TCXO's have 2-8 ppm drift (burn more power)
    - Communication latencies drive synchronization error
- **Alternatives**
  - 1) Global synchronization
  - 2) Local synchronization
- **Recommend local synchronization via inexpensive GPS for AP and future systems**
  - triangulation accuracy drives synchronization requirement
  - errors induced by local clock drift and communication latencies preclude global synchronization

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AP System GPS

VG06-073-17

- **Single Point Survey = Garmin 25LP**
  - 1 PPS Output = ±1 usec of GPS Time
    - Only provided when position fix is valid
  - 45 seconds acquisition (known location, unknown ephemeris (15 seconds with ephemeris known)
  - OEM compatible
- **Synchronization Process**
  - RTC provides rough timestamp (1 second)
  - PPS kicks off ADC sampling through interrupt

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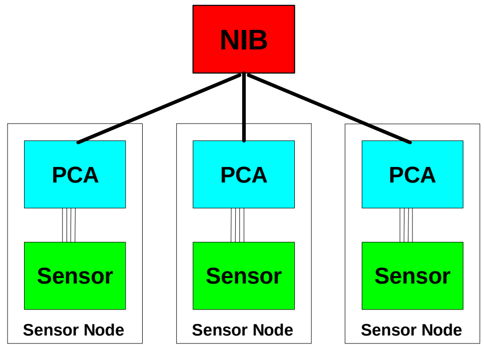
AP Architecture Breakdown

VG06-073-18



- **Add Power/Communications Adapter (PCA) Module**
  - Fixed interface to "final" sensor
  - PCA module to be customized for different applications
- **AP PCA**
  - battery power
  - local GPS synchronization
  - wireless serial interface to NIB

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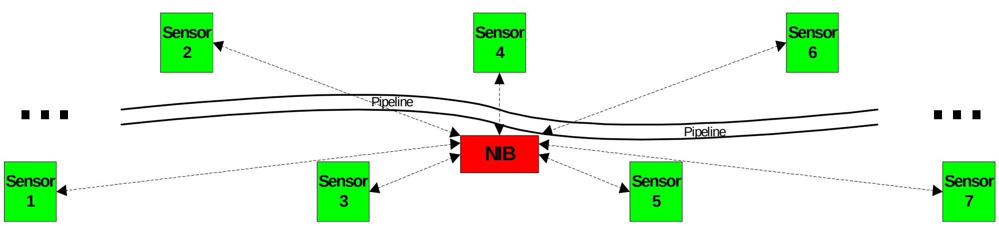
Network Architecture

VG06-073-19

- **Individual sensors straddle the pipeline in the ROW**
- **Sensor spacing 300-500 m**
- **Up to 16 sensors communicate with the NIB**

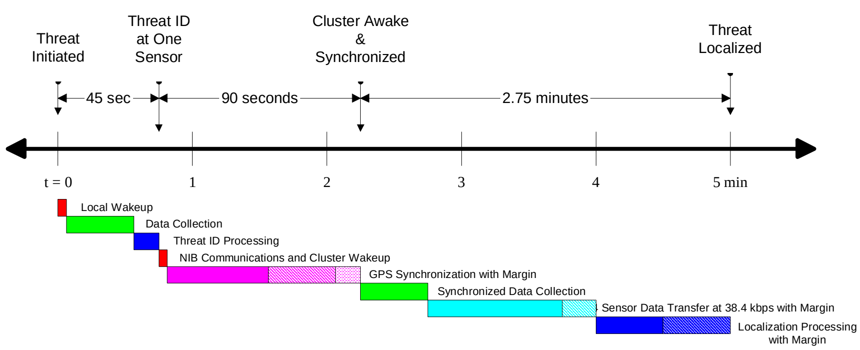


PROPRIETARY

CONOPS & Timeline

VG06-073-20

- **Within 5 minutes, the system detects, identifies and locates threats**
- **All sensors in sleep mode to begin (listening only)**
- **Sensor #1 detects a threat – performs threat ID**
- **If valid threat, then Sensor #1 awakens cluster – local sync starts**
- **After sync, all sensors acquire data for TBD minutes, send threat identification, time, and data samples to NIB every 30 sec.**
- **NIB performs triangulation – NIB warns BigBrother if threat is close to pipe**



PROPRIETARY

Triangulation Accuracy

Triangulation - Andover, MA Field Testing

VG06-073-22

- **PSI built a synchronized data acquisition system**
- **PSI deployed 4 EP-1 sensors at a site in Andover, MA**
  - 250 m maximum sensor separation
  - deployed 3 August 05 in a long-term installation (operational through 30 November 05)
  - We used sledgehammer impacts and a jackhammer as sources
- **We have completed 4 additional days of field testing**
  - repeated site characterization measurements (supporting Don Steeples)
  - acquired triangulation data & demonstrated performance
  - acquiring long term deployment data for Phase 2 SBIR

PROPRIETARY

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Andover Test Site

VG06-073-23

- **PSI deployed 4 EP-1 sensors at a site in Andover, MA**
  - 250 m sensor separation
  - deployed 3 August 05 in a long-term installation (operational through 30 November 05)
  - We used sledgehammer impacts and a jackhammer as sources

PROPRIETARY

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Andover Test Site (2)

VG06-073-24

PROPRIETARY

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Triangulation Results

VG06-073-25

- PSI deployed 4 EP-1 sensors at a site in Andover, MA under Phase 2 SBIR
- Triangulation data acquired with sledgehammer and jackhammer sources
- Position determination are precise to +/- 1yd
- Position accuracies are +/- 3.5 yards (vary from 1 – 9 yd and are range independent)
- Jackhammer location has same accuracy as sledgehammer location

	Surveyed (+/- 1 yd)		PIGPEN measurement	
	X	Y	X	Y
Sledgehammer - U	24.7 yd	23.4 yd	27.8 ± 0.8 yd	25.9 ± 1.1 yd
Sledgehammer - V	65.1 yd	47.9 yd	64.4 ± 1.4 yd	53.5 ± 1.0 yd
Sledgehammer - X	125 yd	-4.5 yd	128 ± 0.6 yd	4.2 ± 1.0 yd
Jackhammer	-22.5 yd	62.4 yd	-18 ± 1.0 yd	64 ± 1.0 yd

PROPRIETARY

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Triangulation Accuracy - Numerical Modeling

VG06-073-26

- We have acquired critical data that demonstrates triangulation feasibility
- We have created a system model to guide future PIGPEN development
  - Identify critical error terms
  - Guide future data acquisition and field tests
  - Optimize sensor grid configuration and CONOPS
  - Optimize algorithm
- Triangulation uncertainty is a complex, non-linear function of threat position and sensor grid geometry
  - Propagation of errors through triangulation algorithm
  - Error and uncertainty in time lag determination and processing
  - Error and uncertainty caused by complex soil conditions
- We have used field test data to validate the model
- We are using the validated model to guide system development
  - A vast range of soil conditions, configurations, threat scenarios etc. can be explored
  - Optimize data acquisition - cost effective field tests
  - Optimize system design, configuration and CONOPS

PROPRIETARY

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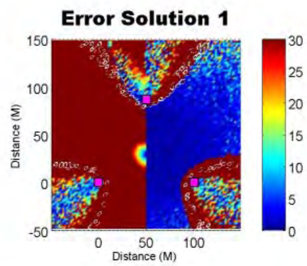
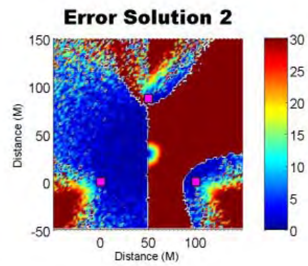
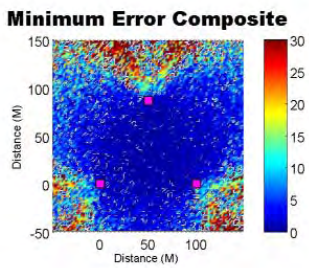
Triangulation Accuracy Modeling
3 Sensor Square Grid

VG06-073-27





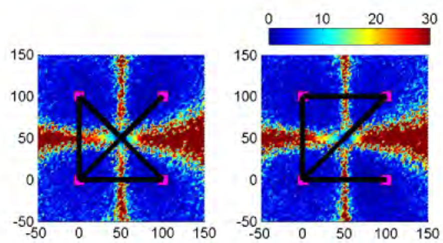


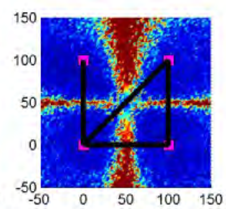
- **model includes:**
  - sensor position error
  - gaussian distributed time errors
- **future upgrades:**
  - nonuniform soil velocity
- **model provides a tool for interpreting field data and optimizing grid configurations**

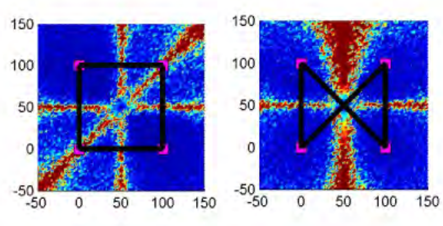
PROPRIETARY

4 Sensor Square Grid

VG06-073-28







Four Sensor Error Map
    5 Trial Mean
    5 of 16 possible solutions
Sensor Locations
    S1(0,0), S2(0,100)
    S3(100,0), S4(100,100)

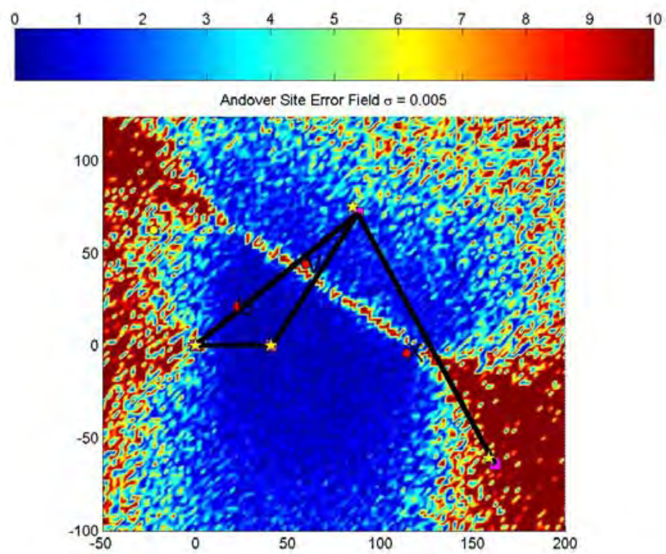
Wave Speed 500 m/s
Time Disturbance:
    Gaussian: $\mu = 0$
    $\sigma = 0.002$ s

Simulation Grid Spacing: 2 m

PROPRIETARY

Andover Field Test – Error Analysis

VG06-073-29



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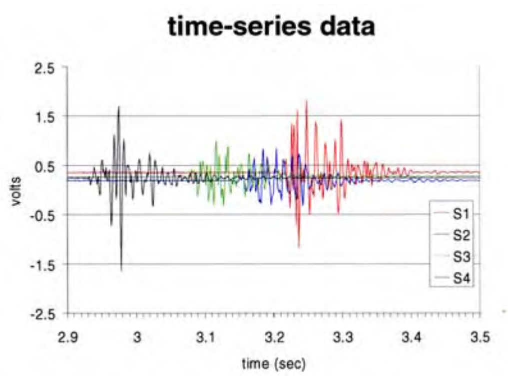
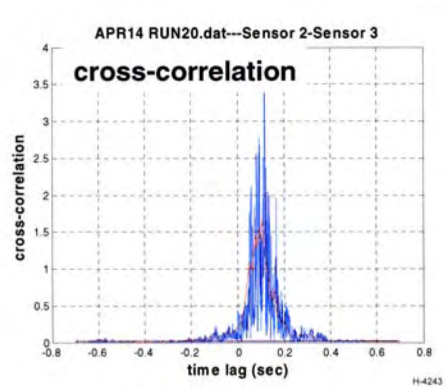
Triangulation Algorithm

VG06-073-30

- **We developed an basic autonomous algorithm for triangulation based on cross-correlation of the time-series data**
- **Preliminary results are good**
- **Algorithm allows easy incorporation of filtering (air-coupled vs ground-coupled)**
- **Algorithm is suitable for implementation on DSP**





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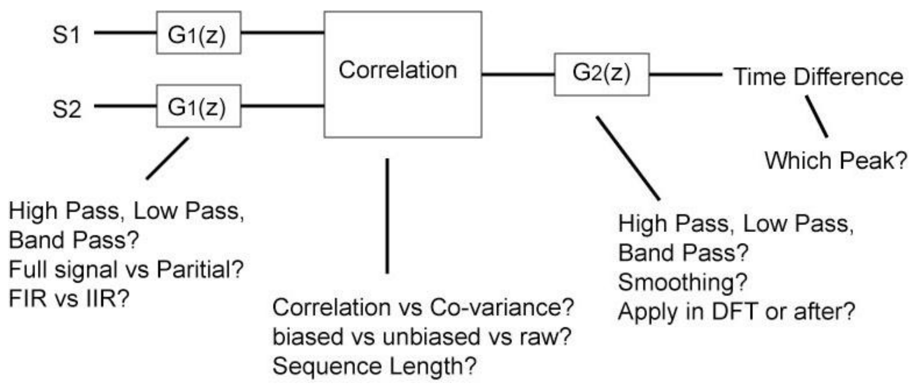
Triangulation Algorithm Optimization

VG06-073-31

- **We are currently optimizing the triangulation algorithm**

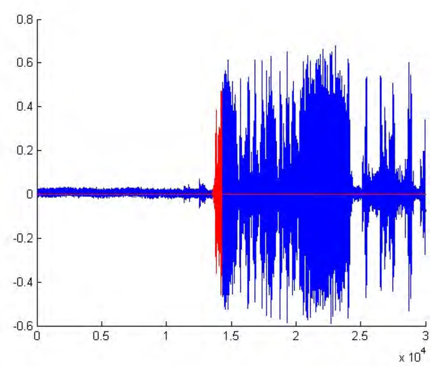


PROPRIETARY

Data Rates for Triangulation

VG06-073-32

- **Triangulation determination requires higher level processing than initially proposed**
- **NIB performs triangulation algorithm**
- **Algorithm requires raw data transfer from local sensor to NIB**
- **We have developed an algorithm to automatically minimize the transferred dataset**
  - Vout (Blue): 30,000 values
  - Vsent (Red): 30,000/25 ~ 940 values (to be sent to Base Station)

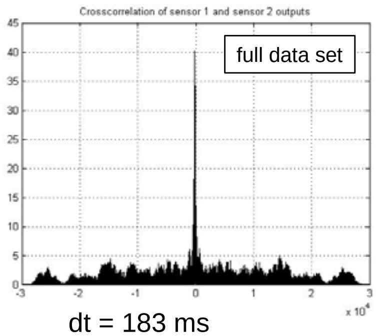


PROPRIETARY

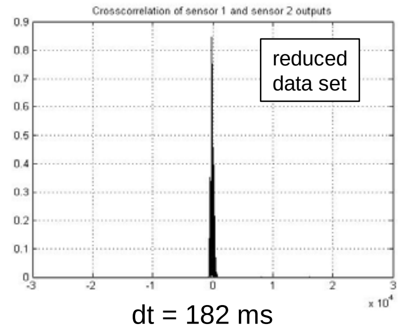
Cross-correlation on Reduced Dataset

VG06-073-33

- **No degradation in cross-correlation performance with reduced dataset**



dt = 183 ms



dt = 182 ms

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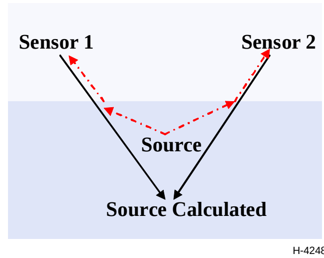
Complex Soil Conditions

Recommendations from “Seismic techniques for locating threats to buried utilities: Some Limitations and Challenges” by Don Steeples

VG06-073-35



- **Surface waves refract at interfaces of differing soil types leading to erroneous calculation of source location**
- **Recommendations (Steeples):**
  - Develop and test a sufficient velocity model
  - Numerical modeling to determine limits of location accuracy and critical parameters
  - Analysis of air coupled wave as a additional location constraint for threat sources
- **PSI Response – based on recent field test data:**
  - Currently modeling time delay of arrival and accuracy
  - Currently optimizing sensor deployment configuration
  - Analyzing utilization of air coupled waves
  - We are currently evaluating the cost of geophysical modeling (McMecham, UT-Dallas)
  - Planning potential future field test to address triangulation issues associated with non- uniform site geology.

PROPRIETARY

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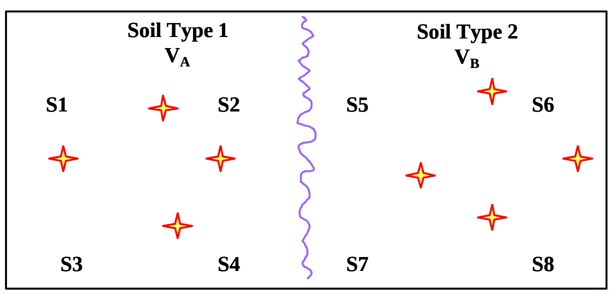
Future Testing of EP Inhomogeneous Soil Performance

VG06-073-36



- **Field test specifically designed to address the issues of performance in inhomogeneous soils**
  - per discussion with NYSEARCH and geological consultant
- **Field test with EP-1 sensors**
  - Non-uniform site with multiple known soil conditions
  - At least 4 EP-1 sensors needed 8 preferred.
  - Multiple threat locations to map velocity field
- **Currently not in the program plan for BAA or DOT Phase II**
- **PSI would welcome the assistance of NYSEARCH in coordinating this test**

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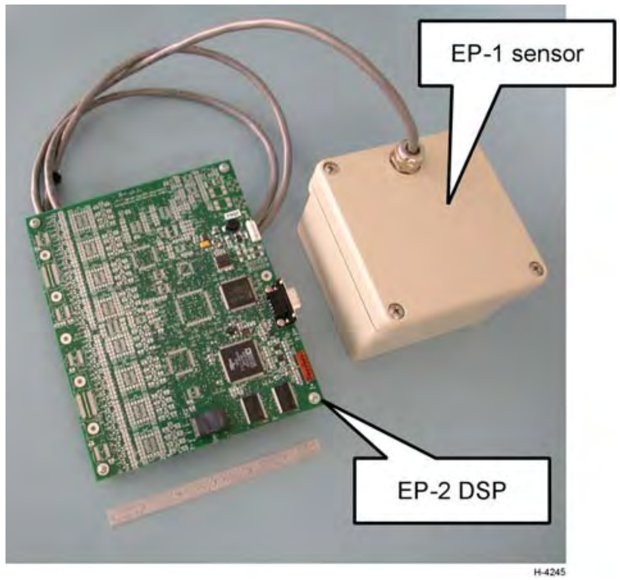
EP-2 Hardware

VG06-073-37



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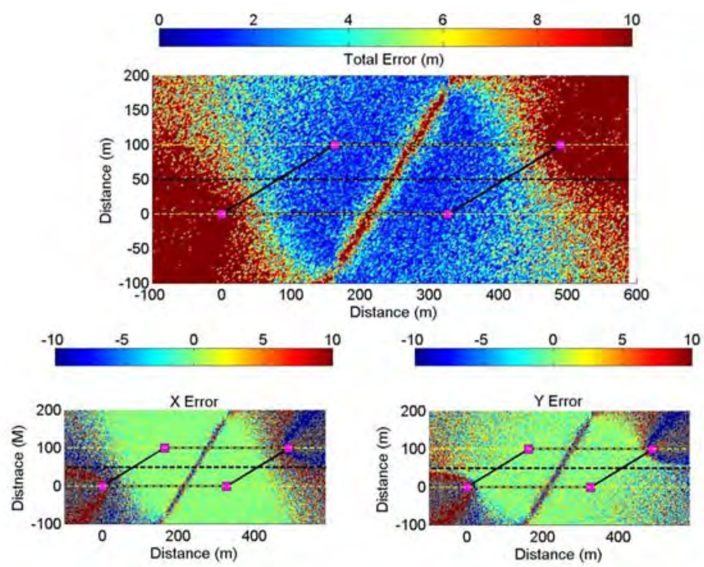
ROW Sensor Grid Layout

VG06-073-38



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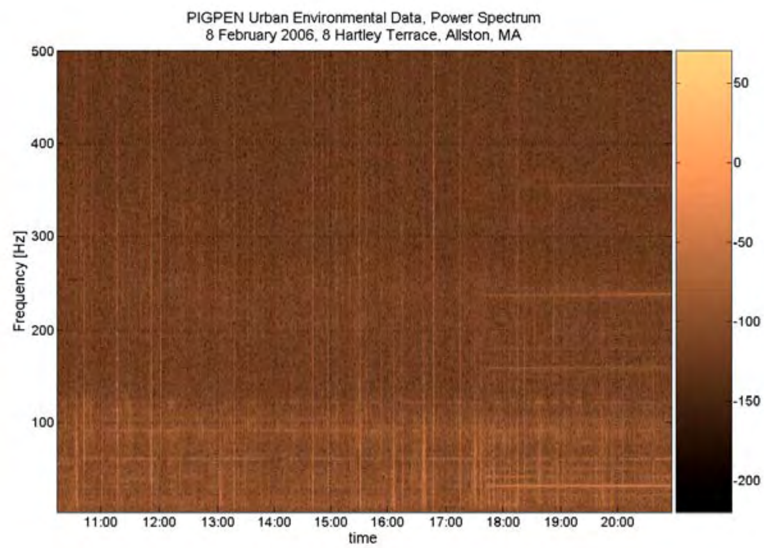
URBAN: Spectral – Temporal Profile

VG06-073-39



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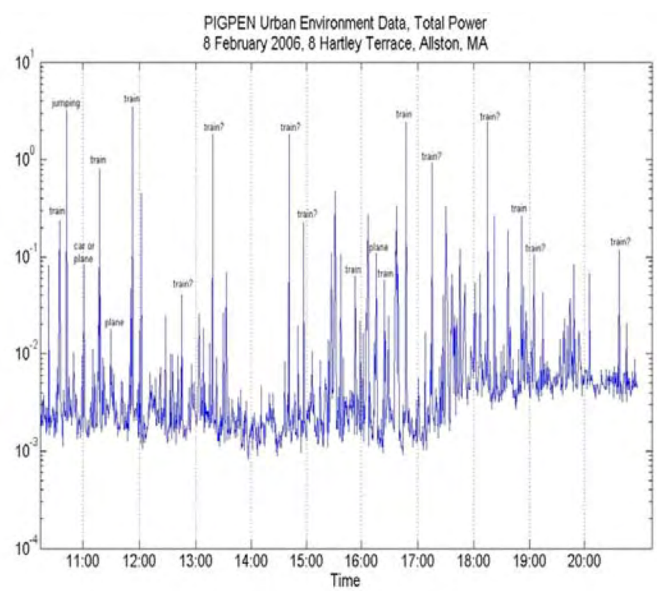
URBAN: Total Power (no DC)

VG06-073-40



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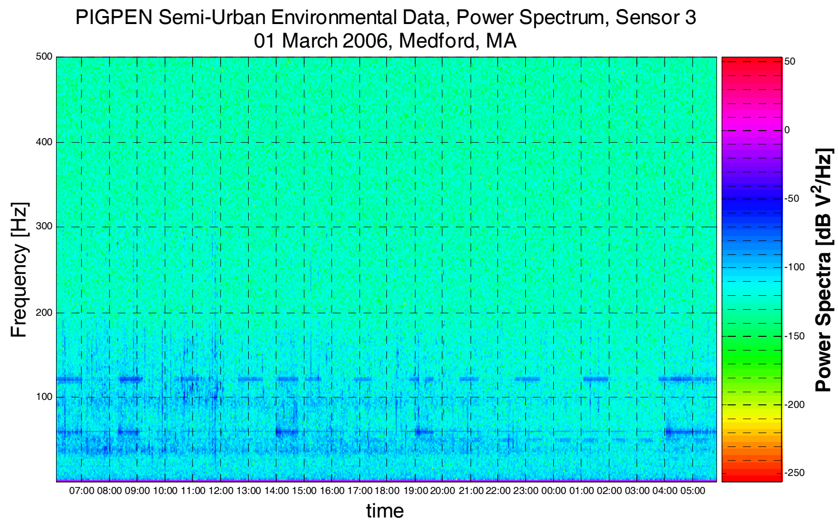
SUBURBAN: Spectral – Temporal Profile (S1)

VG06-073-41



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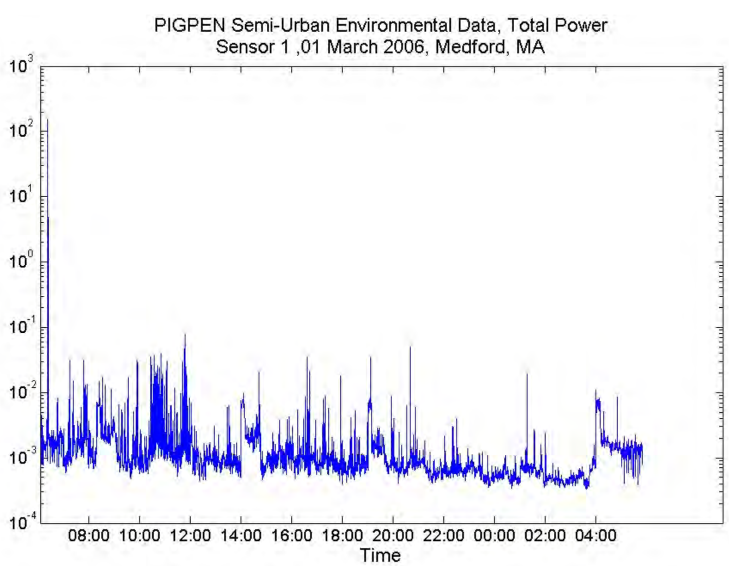
VG06-073-42



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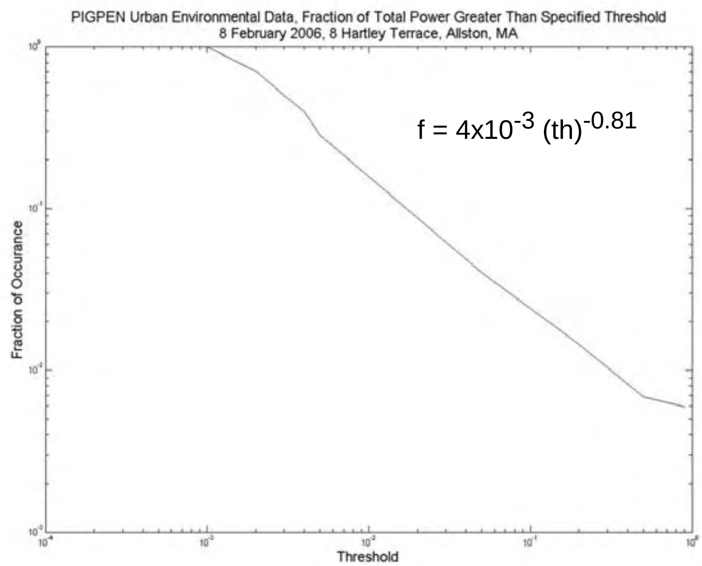
URBAN: Exceedances vs Threshold

VG06-073-43



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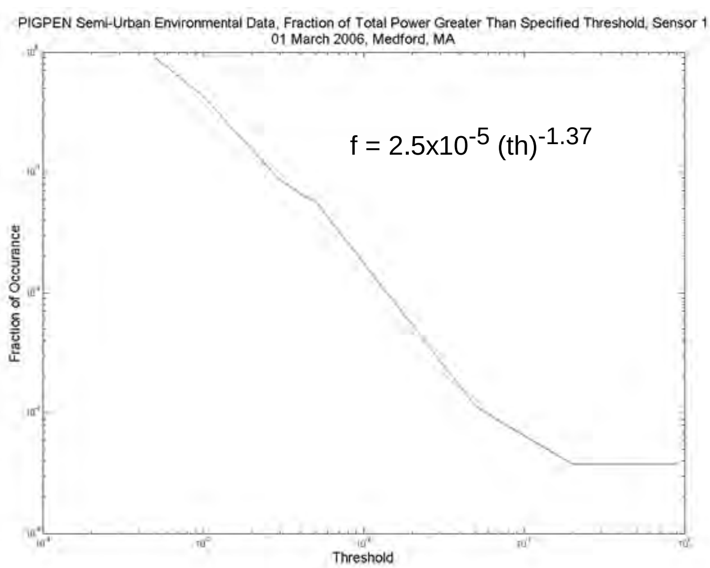
SUBURBAN: Exceedances vs. Threshold

VG06-073-44



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Commercialization Activities

VG06-073-45

- **PSI and NYSEARCH have negotiated terms for future commercial development of PIGPEN**
- **NYSEARCH has conducted a preliminary market survey focusing on both PIGPEN and their GASNET technologies**
  - NYSEARCH wishes to link PIGPEN with commercialization of their GASNET system
- **We have independently researched the firms identified by NYSEARCH as well as others identified by PSI**
- **We have initiated discussions with Bullhorn Remote Monitoring**
- **Currently we are proceeding with AP development independent of the commercialization activity**
  - AP is designed to be "interface-agnostic" and flexible in its installation
  - As soon as a commercialization partner is identified, we will involve them in the technology development

PROPRIETARY

PSI PHYSICAL SCIENCES INC

NYSEARCH Preliminary Market Study

VG06-073-46

Company	Type	Services	Product Mfg.	URL
LaBarge, Inc.	Electronic Systems		X	www.labarge.com
Sensor Technology Limited	Manufacturer of piezoelectrics		X	www.sensortech.ca
CorPro Inc.	Distributor			www.corpro-inc.com
MetroTech Corporation			X	www.metrotech.com
Bullhorn Remote Monitoring	Wireless telemetry services	X		www.aimonitoring.com
Bristol Babcock	Supplier of measurement and control systems		X	www.bristolbabcock.com
Ashcroft (Dresser Incorporated)	Manufacturer of flow switches, transducers, etc. for industrial applications		X	www.ashcroft.com
Fisher (Rosemount)	Process instrumentation & control provider	X	X	www.fisher.com www.rosemount.com
Druck (GE Infrastructure)	Manufacturer of flow switches, etc. for industrial applications		X	www.druck.com
ULC Robotics	Development and testing of robotic and non-robotic repairs to gas mains and instruments to view gas pipeline			www.ulcrobotics.com
Honeywell	Process instrumentation & control provider		X	www.honeywell.com
ABB	Process instrumentation & control provider		X	www.abb.com
Mears Group, Inc	specializes in underground pipe evaluation, rehabilitation and replacement	X		www.mears.net

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Additional Potential Commercialization Partners

VG06-073-47

Company	Type	Services	Product Mfg.	URL
Mears Group Inc.	International service provider	X		www.mears.net
Metrotech	International leak detection instrument manufacturer		X	www.metrotech.com
Rosen USA	International service provider	X	X	www.roseninspection.net
T.D. Williamson Inc.	International service provider	X	X	www.tdwilliamson.com

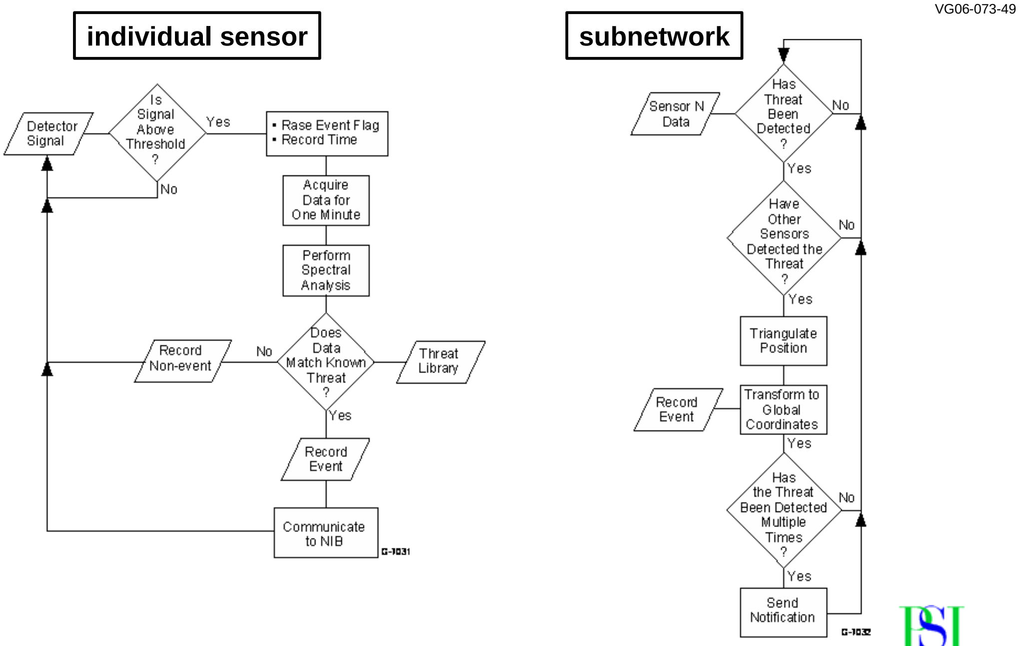
PROPRIETARY

PSI Physical Sciences Inc

Backups

PIGPEN Processing Flows

VG06-073-49



PROPRIETARY

Andover Test Site Sensor Layout

VG06-073-50

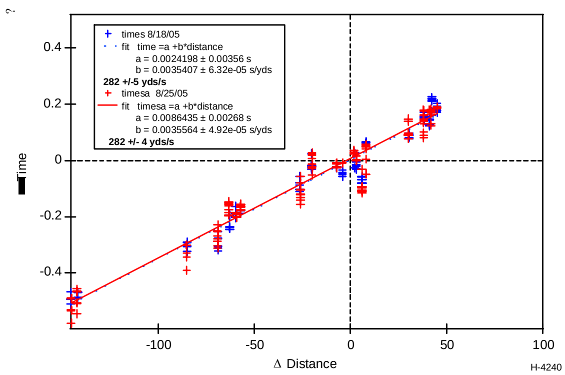
Arial view with location of sensors for triangulation and long-term deployment shown in red

PROPRIETARY

Velocity Calculation- Sledgehammer Impacts

VG06-073-51

- Velocity calculated from 2 different days data using sledgehammer impacts at varying locations at Andover site



- Excellent agreement day-to-day: 282 +/- 4 yards/sec
- consistent with NEHRP Class D soil

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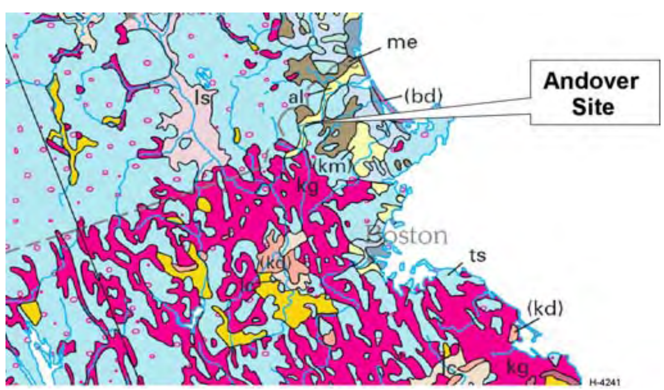
Geologic Conditions - Andover

VG06-073-52



- Soil is predominantly alluvium
- Measured velocity is 256 m/sec
- Typical velocities in alluvium range from 120 – 430 m/sec
- predictive model (Nottis) yields 324 m/sec for depth of 30 m

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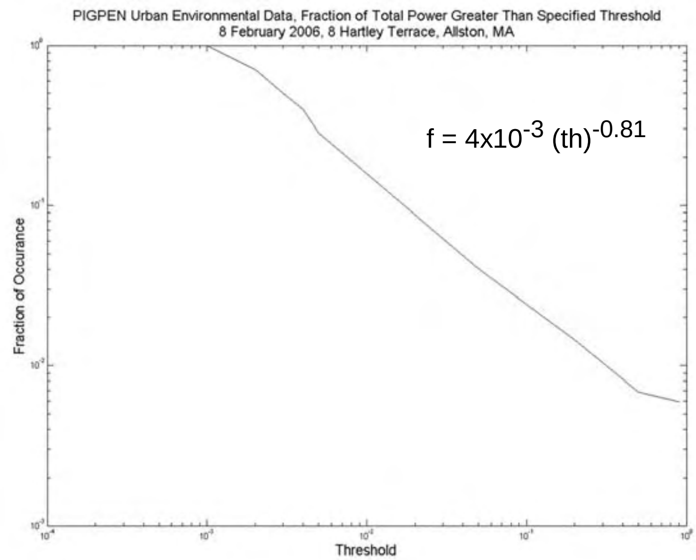
URBAN: Exceedances vs Threshold

VG06-073-53



PROPRIETARY

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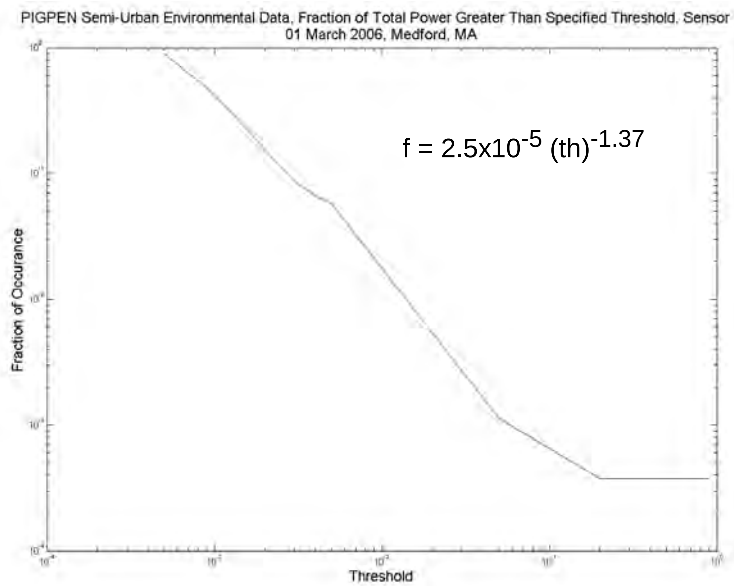
SUBURBAN: Exceedances vs. Threshold

VG06-073-54



PROPRIETARY

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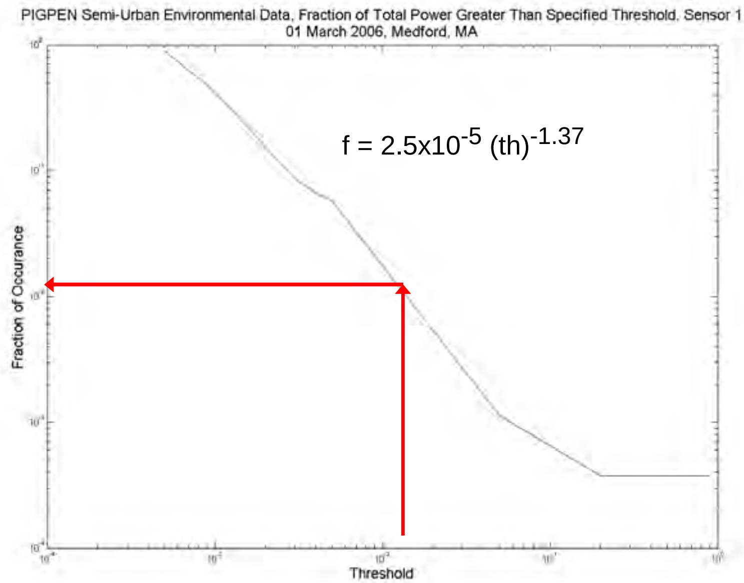
SUBURBAN: Exceedances vs. Threshold

VG06-073-55

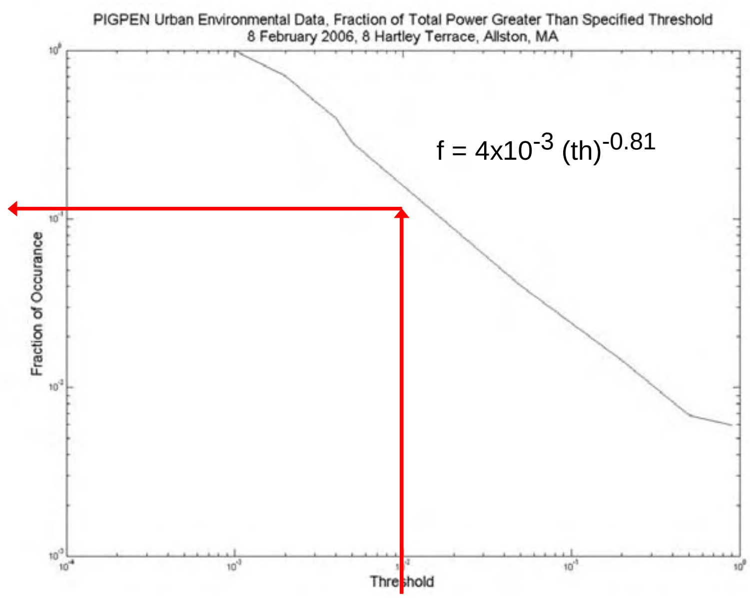


PROPRIETARY

PSI Physical Sciences Inc

URBAN: Exceedances vs Threshold

VG06-073-56



PROPRIETARY

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Appendix D

VG06-218

PIGPEN: Proactive Infrasonic Gas Pipeline Evaluation Network

7 September 2006

G.E. Galica, B.D. Green
Physical Sciences Inc.

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

Introduction & Objectives

VG06-218-1

- **PSI has been developing new technology to detect and warn of potential 3rd party intrusion near gas pipelines (PIGPEN)**
  - Sponsored by DoT Office of Pipeline Safety and gas industry consortium
- **The development funds come with a mandate to transition the technology into the commercial marketplace**
- **PSI is an R&D company; we prefer to team with commercial companies with existing market presence to transition PSI technologies**
- **Based on our previous discussion, Bullhorn may be a good partner for commercialization of PIGPEN**

- **Today's Objectives:**
  - 1. Determine whether PIGPEN and Bullhorn's remote sensing system are a good fit technically
  - 2. Determine whether PSI's and Bullhorn's technologies and companies are a good fit from a business standpoint
  - 3. If so, define how we move forward to transition the technology
    - begin to define a commercialization plan
    - define how we would work together through the technology maturation process
    - define strawman business model

Outline

VG06-218-2

- **What's a PIGPEN**
- **What's a Bullhorn**
- **Discussions**
- **Commercialization Plan**
- **Physical Sciences Inc Overview**

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Third-Party Damage

VG06-218-3

- **Third-party damage is one of the most serious problems faced by natural gas companies.**
  - Punctures by earthmoving equipment are a major cause of pipeline failure
  - Incipient damage caused by an unknown hit can result, over time, in extensive damage and cost to the utility and customers
  - Many contacts made to an underground pipe are not reported: result of improper procedure or risk-taking
- **Costs for third-party damage on transmission lines are particularly high**
  - Low number of incidents, but damage often goes undetected, resulting in delayed catastrophic failure
    - In 2000, 80 incidents over 300,000 miles of transmission pipeline in the US
    - $18M in cost, with 3 fatalities and 7 injuries.
    - For distribution lines, the figures are considerably higher.
- **PIGPEN provides near real-time feedback to the utility, or the excavator, before third party damage occurs**
  - provides a significant benefit to the gas utility industry and to the public

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PIGPEN
Proactive Infrasonic Gas Pipeline Evaluation Network

VG06-218-4

- **PSI is developing the PIGPEN smart seismic sensor network to proactively detect and warn of threats to pipelines before third-party damage occurs**
- **Low frequency seismic/acoustic sensor technology (0.1 to 100 Hz)**
- **Sensors do not need to be installed along the entire length of a service or main**
  - a single PIGPEN unit can monitor a large area from a single point
  - lower cost than other proactive sensors that must be installed along the entire length of the service main
- **A successful PIGPEN sensor will result in great savings through better detection and prevention**

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Benefits

VG06-218-5

PIGEN is a *proactive* system: it detects *impending* damage

- **1) Low Sensor Cost**
  - sensors are simple and inexpensive
  - PIGPEN comprises a compact solid-state sensor, some electronics, and a network connection
- **2) Low Network Cost**
  - infrasonic energy propagates for long distances – sparse sensor array
  - few sensors/mile – reduces cost of purchase, of installation and of maintenance
- **3) Simple to install**
  - "point" installation, does not require installation along entire length of service
- **4) PIGPEN can be retrofit to existing systems**
  - compatible with existing SCADA infrastructure

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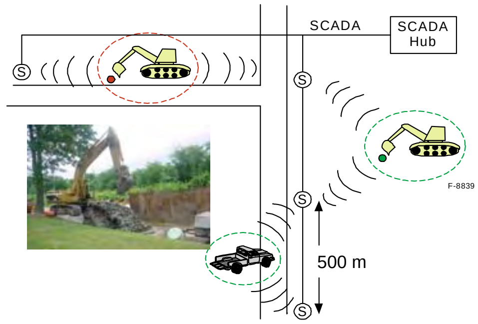
Proactive Infrasonic Gas Pipeline Evaluation Network PIGPEN

VG06-218-6



- **PIGPEN: detect, identify and locate threats to pipeline infrastructure**
- **Detects seismic signatures of excavating equipment at >1000 yards**
- **Automatically differentiates between types of equipment (e. g. backhoe, jackhammer) based on unique spectral seismic signatures**
- **Multiple sensors locate threats with accuracy of <10 yd at 300 yd range**

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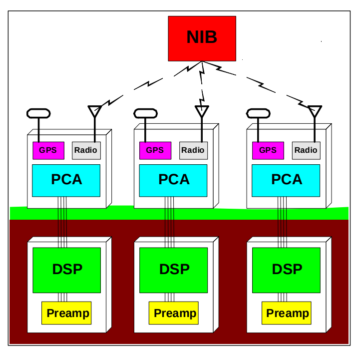
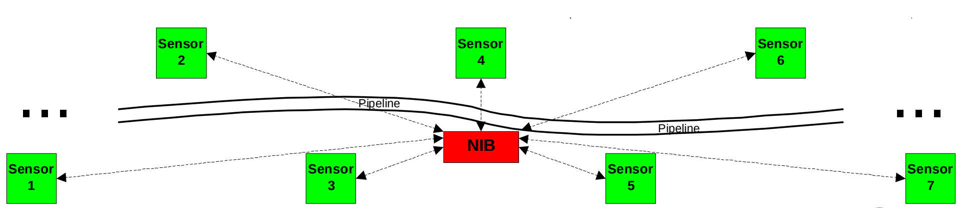
PIGPEN Network Architecture

VG06-218-7

- **Individual smart sensors with power/communication adaptors (PCAs) straddle the pipeline in the right of way**
- **Sensor spacing 300-500 yards**
- **Up to 16 sensors communicate wirelessly with the Network Interface Box (NIB)**
- **The NIB communicates warnings to the home office on existing infrastructure**





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PIGPEN Working Specifications

VG06-218-8

Unit spacing	Sensor: 300-500 yards NIB: 3-5 miles (16 sensors/NIB)
Threat location accuracy	<10 yards at 300 yard range
Unit mass	Sensor: 5 lb PCA: 2 lb + battery NIB: 2 lb
Unit size	Sensor: 5 x 5 x 4 in^3 PCA: 6 x 6 x 2 in^3 + battery NIB: 5 x 5 x 2 in^3
Communication	900 MHz, serial, 1 kbyte/sec
Power	7-18 V (e.g. solar power/battery) Sleep: 0.7 W Active 8 W max
Warning time	5 sec initial detection 30 sec identification 3 minutes triangulation
Equipment cost	$4-6K/mile
Temperature range	-30 to +60 C

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Development Status & Schedule

VG06-218-9

- PSI would like participation by commercialization partner in AP testing
- PSI needs input from commercialization partner on AP design and BP transition

Experimental Prototype (EP) testing	Complete
Advanced Prototype (AP) fabrication	Complete
AP integration & test complete	30 Sep 06
AP testing shakedown test initial system testing long term deployment	 Oct 06 Nov – Dec 06 Mar 07 – Jun 07+
BP transition begins	Jul 07

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Framework of Joint Development Agreement

VG06-218-10

- **PSI is a technology developer – we seek a partner to participate in making PIGPEN technology available to the transmission and distribution community**
- **PSI seeks an active partner to participate in the development of the intrusion detector network**
  - providing insight into the compatibility with their hardware
  - providing insight into industry needs
  - sales, installation and service of the detector network as part of their larger pipeline information network
- **PSI:**
  - continues testing and development of PIGPEN under current funding
  - seeks additional funding from DoT, gas industry, and the partner to support any changes reuiredfor data development
- **The partner:**
  - contributes by providing engineering consulting to guide the physical and data interface of the PSI sensor network to their communication terminal.
  - talks to the potential users to define the information, product performance, and price.
  - helps create test demonstrations of sensor network performance and participates in the performance testing of the alpha units.
  - identifies any safety, compliance, acceptance issues by its association with the pipeline safety and regulatory community
- **PSI & the partner:**
  - support their own costs through the alpha testing stage (June 2007).
  - participate in discussions with the DoT and gas company 'customers' to define changes required for the commercial product, and agree on those changes.
  - Proceed to production model fabrication.
- **We envision that PSI would build the sensors and local network (1-16 sensors) and provide these to the partner at an agreed upon price. PSI would share in a fraction of the incremental revenues produced by the addition of the intrusion sensor into the partner information network.**

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Appendix E – Time difference of arrival estimate across the soil discontinuity:

One of the major goals of the Kansas field test effort was to establish whether PSI could correctly establish position across a soil discontinuity. Since the soil velocities are an order of magnitude different across the boundary, it is necessary to compensate for the velocity differences. In this report, we have plotted the measured time difference of arrival relative to an estimated time difference of arrival. This estimated time difference was determined using the following simple analysis.

Figure E.1 shows a 2 dimensional projection of the test site. The red x's represent the threat locations while the sensor locations are noted by the red and green stars. The solid blue line in Figure E.1 shows a reasonable estimate of where the soil transition occurs. As we can see from the figure, the seismic signals from a threat must travel through different soil types to reach the various sensors. To correct for this, PSI proposed a simple linear model, where we plot the distance between the know threat location and all of the sensors. We then determine how much of that distance is contained in each soil type. Since the soil discontinuity shown in Figure E.1 is not uniform, we created a simplified model shown in Figure E.2.

In Figure E.2, we have simplified the 2D projection making a linear estimate of the soil discontinuity. Now we can easily break the path between a sensor and a know threat location into two segments l_1 (the portion of the path in the loam) and l_2 (the portion of the path in the shale). The estimated time difference of arrival can now be estimated using the following formula

$$\Delta t_{12} = t_1 - t_2$$

where

$t_1 = l_{11}/v_1 + l_{21}/v_2$

$t_2 = l_{12}/v_1 + l_{22}/v_2$

l_{11} = the distance between the threat and sensor 1 in the loam

l_{12} = the distance between the threat and sensor 2 in the loam

l_{21} = the distance between the threat and sensor 1 in the shale

l_{22} = the distance between the threat and sensor 2 in the shale

v_1 = the wave speed in loam

v_2 = the wave speed in shale.

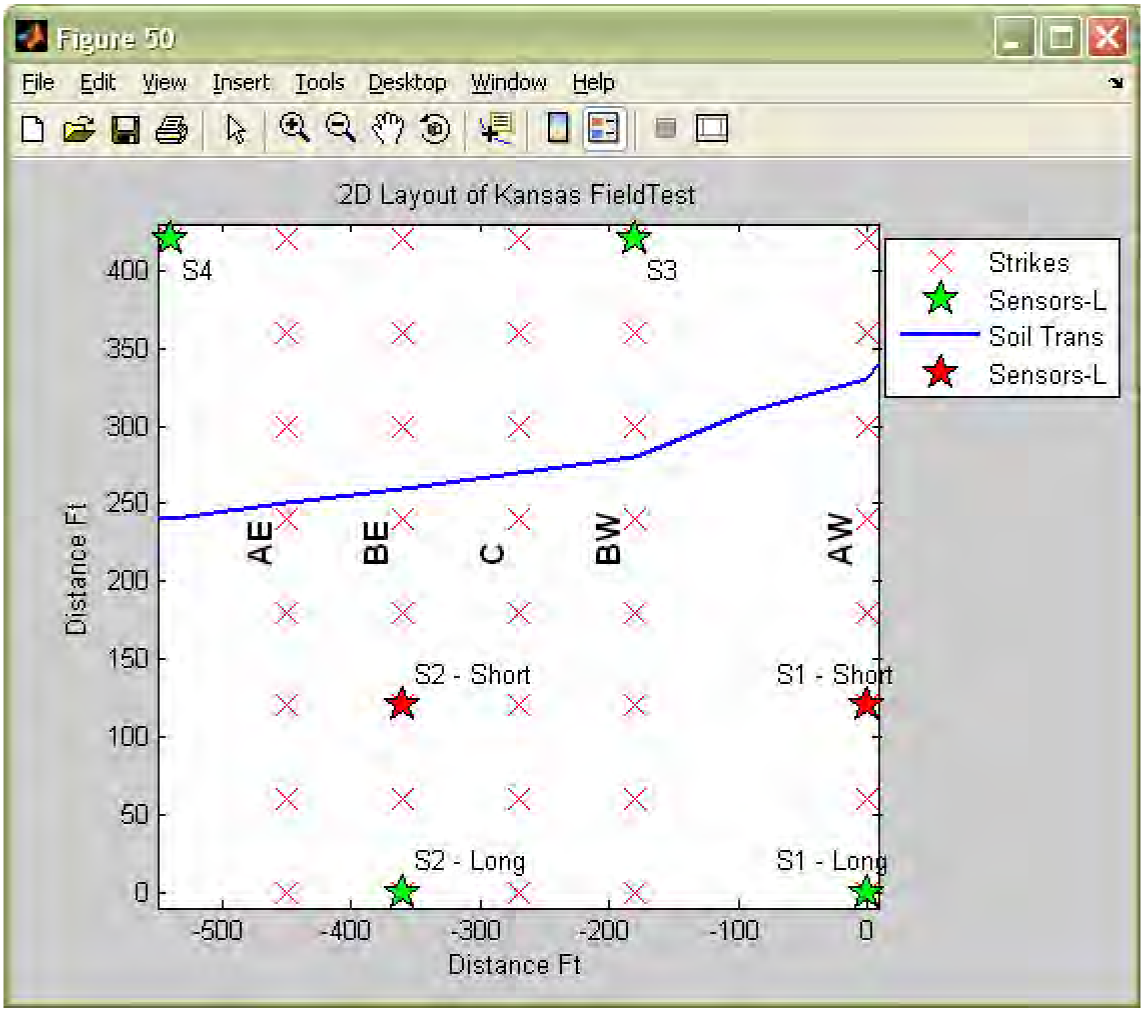

Figure E.1. 2D projection of the Kansas field site. The above the solid blue line the soil is shale while below the blue line the soil is loam.

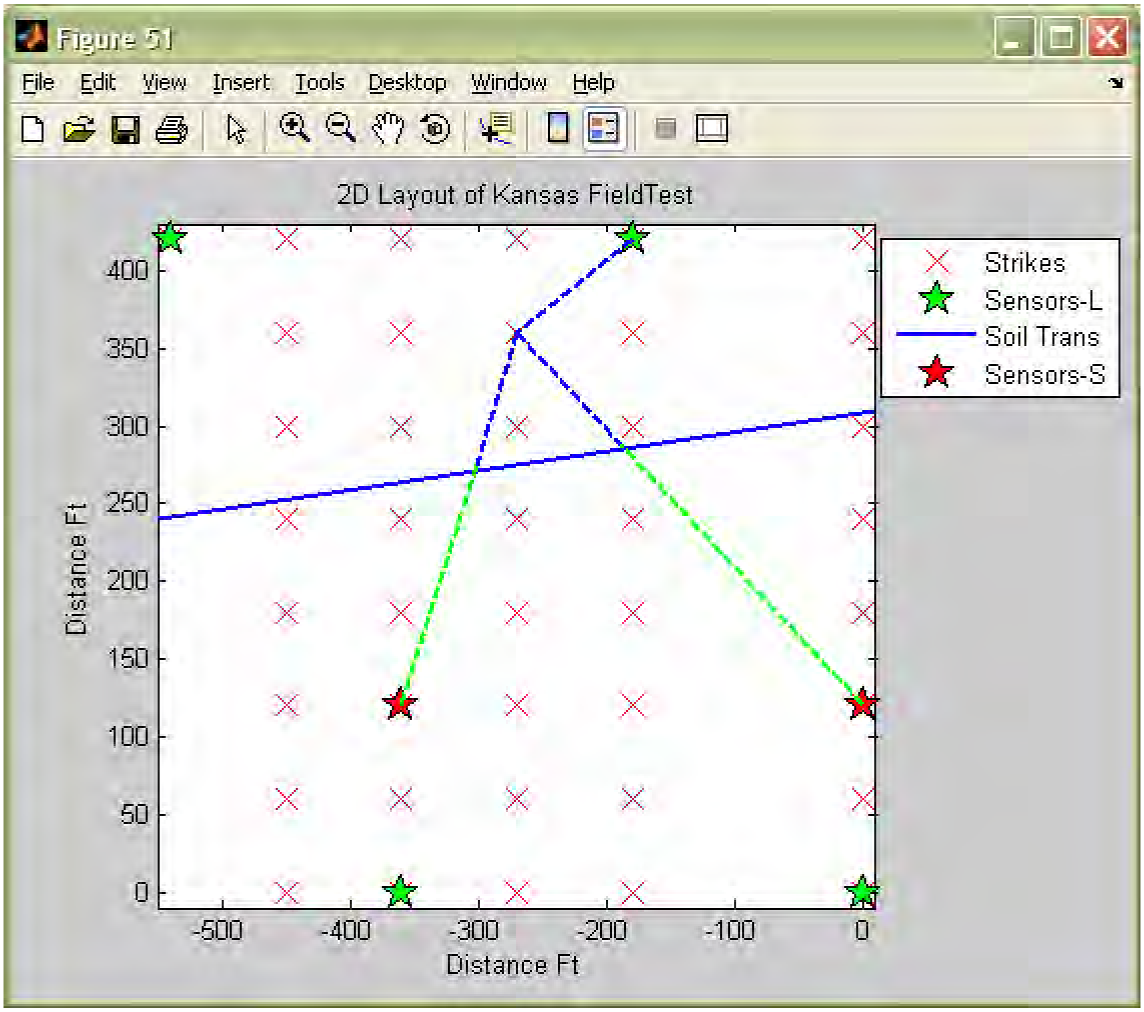

Figure E.2. Simplified 2D projection of the Kansas field site. The above the solid blue line the soil is shale while below the blue line the soil is loam.

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Appendix F

VG07-071

Infrasonic-Frequency Seismic Sensor System for Pipeline Integrity Management

Phase II SBIR Status Meeting

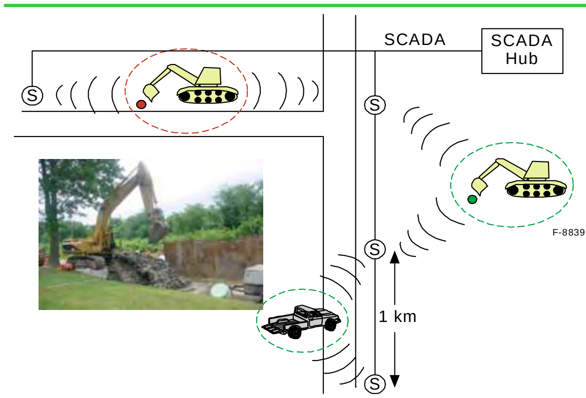
20 March 2007

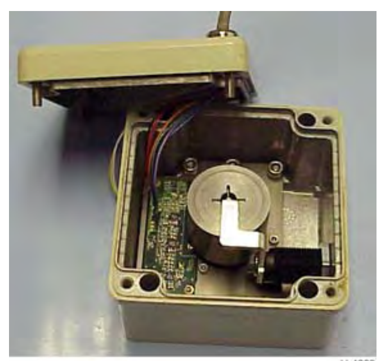
M.F. Byl, M.B. Frish, W.B.G. Agassounon,
S.K. Paintal, G.E. Galica, and B.D. Green
Physical Sciences Inc.

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

Proactive In Ground Pipeline Evaluation Network PIGPEN

VG07-071-1





- **Smart Sensors placed at 0.1-0.5 km spacing around the pipeline**
- **PIGPEN sensors identify potential threat type based on acoustic signature (backhoe or bus)**
- **PIGPEN system determines range and direction of potential threats**
- **Excavating threats that are close to the pipe activate a warning**

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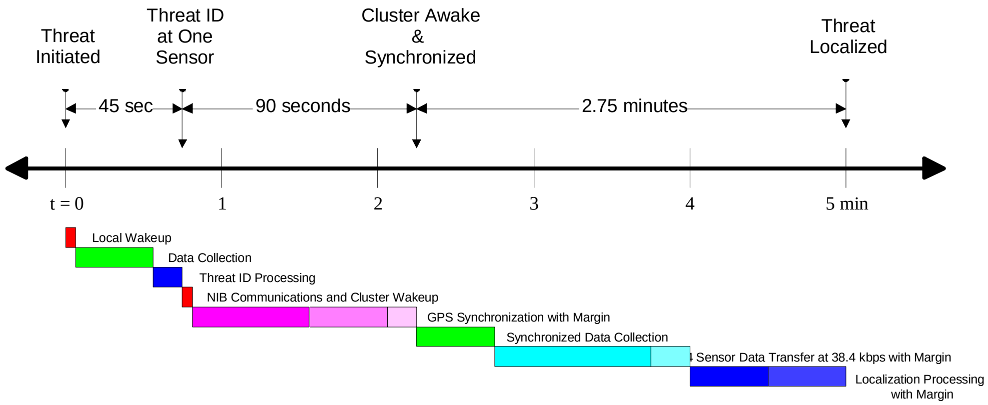
PIGPEN Timing

VG07-071-2

- **Detects, identifies & locates threats within 5 minutes**
- **All sensors in sleep mode to begin (listening only)**



J-0222

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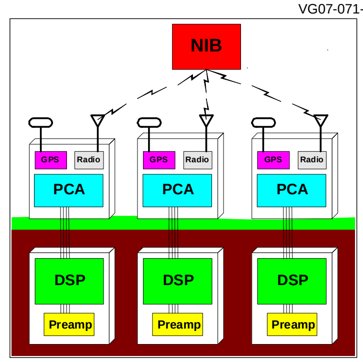
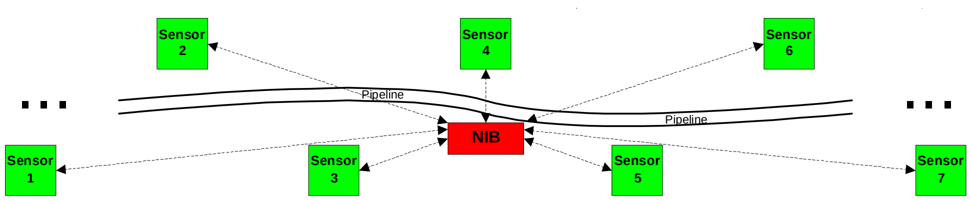
PIGPEN Architecture

VG07-071-3

- **Individual smart sensors straddle the pipeline at 100-500 m intervals (soil dependent)**
- **Up to 16 sensors communicate wirelessly with the Network Interface Box (NIB)**
- **The NIB is connected to the Bullhorn system to report alarms & health check**
- **Alarm notifications are automatically delivered to the end user**





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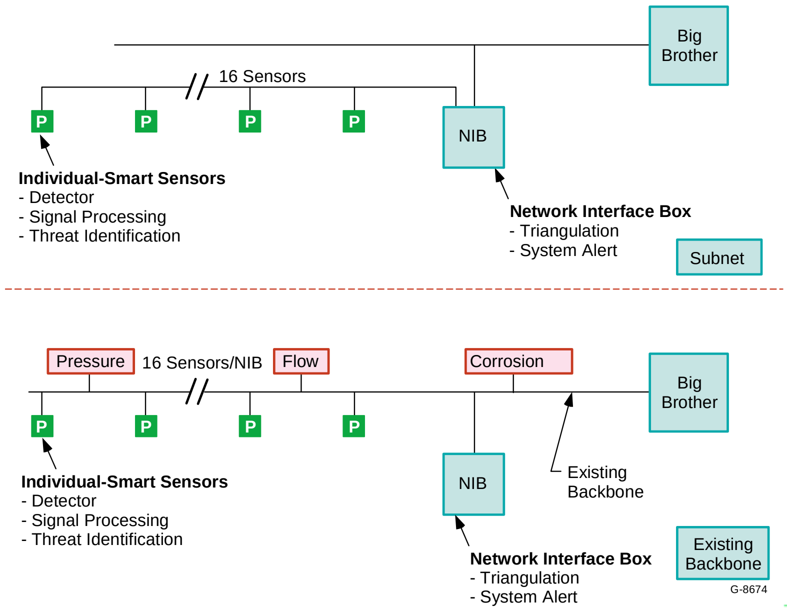
Communication Architecture

VG07-071-4



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Solution - Communications

VG07-071-5

- **Bullhorn remote monitoring system**
- **Leading low cost, reliable remote monitoring system for pipelines – over 10,000 installed to monitor cathodic protection systems**
- **Satellite & digital cellular wireless networks used to monitor the Pigpen system**
- **Web-accessible system for viewing data & configuring alarm notifications**
- **Automatic notifications via fax, page, voice, e-mail with security & escalation**

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PIGPEN Advantages

VG07-071-6

- **Low Sensor Cost**
  - Sensors are simple and inexpensive - compact solid-state sensor, some electronics & a network connection
- **Low Network Cost**
  - Sound energy propagates for long distances so sparse sensor array reduces cost
  - Bullhorn system uses existing low cost wireless networks – it is tested, proven & has low cost automatic notifications
- **Simple to Install**
  - Does not require installation along entire length of service – can be surgically installed wherever justified
  - Can be retrofit to existing systems or used on new service

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Product Performance Specifications and Key Features

VG07-071-7

Application:	Passive third party intrusion monitoring network
Detection range:	>300ft
Threats:	Backhoes, jackhammer, digging, air drill, … demonstrated
Identification:	Threat identified by acoustic signature
Threat detection accuracy:	Threat location to 30 ft
	Probability of detection 99%
	Probability of false alarm 1 per month
Response time:	Detect 30 seconds, alarm 4 minutes
Power requirements:	Self-contained rechargeable battery, 90 days service, w/o solar charging
Placement:	Away from pipe, within right-of-way
Configuration:	**Multiple buried sensors, wireless communication to hub and transmitter**
Alarm notice:	**Transmission from pipeline to customer computer via satellite link**
Target cost:	$10,000/mi installed
Target operating cost:	<$100. per mile
Size and weight:	Sensor: 4 kg (6” cube)
Calibration and fault monitoring:	Characterize site at installation, test yearly, continuous self check, fault notification

Operating Environment

Ambient conditions:	
temperature:	-20° to +120°F
humidity:	0 to 100% RH, non-condensing
Precipitation:	Operation in all weather

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Phase 2 SBIR Tasks

VG07-071-8

- ✓**Task 1. Program Kickoff**
  - 1.1 Interface and requirements definition
  - 1.2 Program kickoff meeting
- ✓ **Task 2. Experimental Prototype**
- ✓ **Task 3. Assess PIGPEN EP Performance and Refine Algorithms** ***(Expanded beyond original scope and plan)***
  - 3.1 Acquire database of performance data with EP-2 in a long-term deployment
  - 3.2 Develop Build-2 algorithms, based on EP-2 assessment data
- **Task 4. Develop PIGPEN Alpha Prototype (AP)**
  - ✓ 4.1 Develop and fabricate integrated sensor head and customized digital signal processor as AP
  - ✓ 4.2 Develop and implement Build-3 software algorithms
  - ✓ 4.3 Establish AP performance by laboratory and field testing
- **Task 5. Assess Long-Term PIGPEN AP Performance**
  - 5.1 Deploy small network of PIGPEN AP sensors
  - 5.2 Assess performance by long term acquisition
- **Task 6. Transition PIGPEN Technology to Beta Prototype (BP)**
  - 6.1 Develop commercialization plan
  - 6.2 Transition PIGPEN technology to commercialization partner

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Year 2 of DOT SBIR

VG07-071-9

Task 3 - Expansion

- **Customer guidance → achieve 10 ft (3m) accuracy**
- **Two significant field tests with EP system to demonstrate accuracy**
  - Variety of threats in real world conditions
  - Prove ability localize in inhomogeneous soils
- **Significant effort and time in analysis of data sets**
  - Time difference of arrival (Cross-correlation, time-of-arrival)
  - Relative acoustic energy detected
- **TDOA**
  - Excellent precision (1 ft), fair reproduciblity (75%), poor localization (30 ft)
  - Have not found best algorithm yet

Task 4 - Expansion

- **Develop AP system permitting high time resolution performance**
  - Drive synchronous Conops

Way Forward

- **Received Power Localization**
  - Demonstrate 20 -40 ft localization
- **Simpler, low power hardware and Conops**

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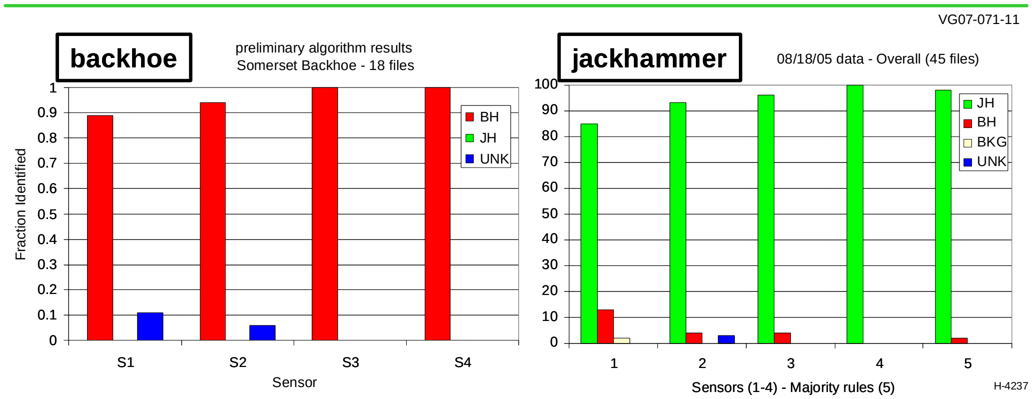
Threat Identification

Algorithm Performance



- **The threat identification algorithm was developed and optimized using PIGPEN field test data**
  - filter-bank creates sparse spectra
  - logical comparison to library spectra
- **Optimized algorithm provides good results for two threat classes (jackhammer & backhoe)**
- **The Build-2 algorithm is now implemented and functional on the prototype DSP**

Additional Threats

VG07-071-12

Horizontal Drilling Machine
Dec. 06 – Bronx, NY

Backhoe Bucket Striking Ground
Nov. 06 – Lawrence KS

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Observed Threats

VG07-071-13

- **Sledgehammer**
- **Jackhammers (2)**
  - Electric
  - Pneumatic
- **Backhoe (3 different brands)**
  - Somerset, MA
  - Johnson City, NY
  - Lawrence, KS
- **Trackhoe**
  - Johnson City, NY
- **Horizontal Drilling Machine**
  - Bronx, NY
- **Shovel digging**
  - Johnson City, NY

H-4226

- **Additional Sources**
  - Freight trains, KS
  - Vehicles (passenger, delivery trucks)
  - 12 gauge shotgun
  - Generator
  - Commuter Rail train, Allston, MA
  - Down-hole 30-06
  - 45 cal. pistol

★ **Signatures Recorded, not all threats integrated into the threat library**

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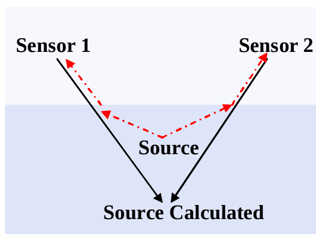
Complex Soil Field Test

Motivation

VG07-071-15

- **Recommendations from "Seismic techniques for locating threats to buried utilities: Some Limitations and Challenges" by Don Steeples.**
- **All waves refract and reflect at interfaces of differing soil types leading to erroneous calculation of source location**



H-4248

- **Recommendations (Steeples):**
  - Develop and test a sufficient velocity model
  - Numerical modeling to determine limits of location accuracy and critical parameters
  - Analysis of air coupled wave as a additional location constraint for threat sources.
- **PSI Response:**
  - Evaluated the accuracy of the time delay of arrival - repeatable but non-uniform
  - Revised sensor deployment configuration – Staggered deployment / multiple calculations
  - Analyzed use of air coupled waves – Minimal utility due to low signal energy
  - Geophysical modeling (McMecham, UT-Dallas) – On-going
  - Conducted extensive field test in Lawrence KS

Complex Soil Testing – Lawrence KS – Nov. 06

VG07-071-16

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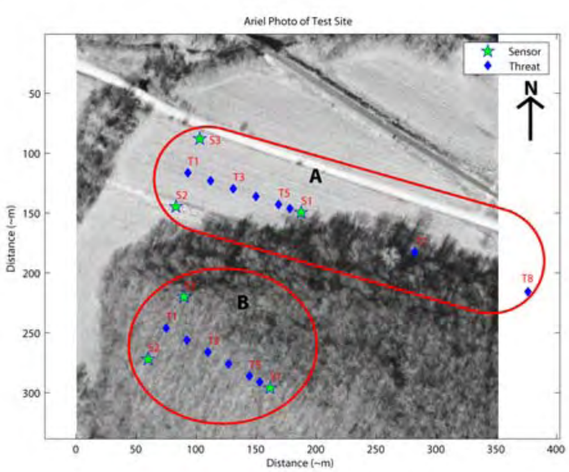
PSI
Physical Sciences Inc

Uniform Soil Testing

VG07-071-17



Site A – Sandy Loam bedrock depth 50 ft
- **Exp. P velocity = 1000 ft/s**
- **Meas. = 410 ft/s**

Site B – Shale/Limestone
- **Exp. P velocity = 10,000 ft/s**
- **Meas. = 4800 ft/s**

Sources tested:
- **down hole 30-06, sledgehammer, shotgun**

Goals
- **Characterize soil properties**
  - Soil speed
  - Signal range/propagation properties
- **Establish baseline accuracy**

T configuration designed to replicate Andover field testing

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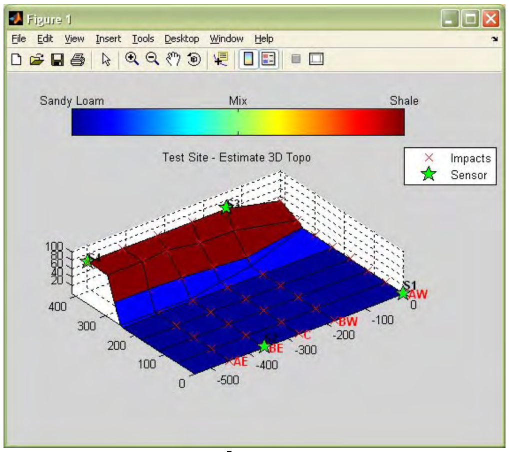
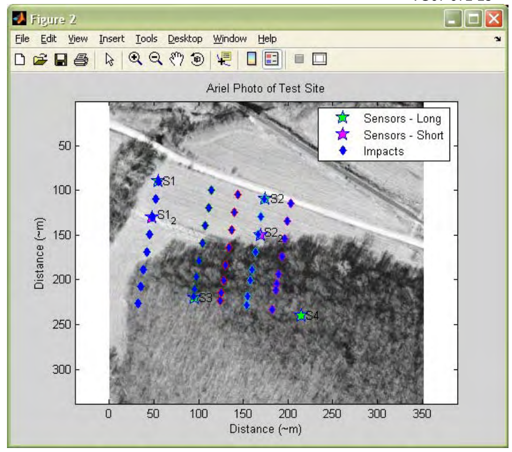
Complex Soil Testing

VG07-071-18



Geology



Aerial Photo

Two Configurations:
- Long Field – S1 @ AW0, S2 @ BE0
- Short Field - S1 @ AW120, S2 @ BE120

Two Threats:
- Long Field – Down Hole Gun
- Short Field – Down Hole Gun, BackHoe

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PSI Physical Sciences Inc

Localization Algorithm Development

Closed Form Localization Algorithm

VG07-071-20

- **Based upon time difference of arrival (TDOA)**
- **Requires four time differences ? 4 sensors**
  - 4 sensors ? 6 time differences ? 15 possible solutions
  - Solution is hyperbolic ? 2 continuous hyperbolic singularities per solution
- **Algorithm is precise – good TDOA in ? precise localization out**
- **Major Limitations**
  - Not uniformly stable (singularities)
  - Assumes uniform soil conditions
  - TDOA calculated using cross-correlation ? assumes signals are similar in time and frequency.

$$
\begin{aligned}
y &= Ax + B \\
y &= Cx + D \\
x &= \frac{D-B}{A-C}
\end{aligned}
$$

$$
\begin{aligned}
A &= \frac{(T_{12}x_{31} - T_{13}x_{21})}{(T_{13}y_{21} - T_{12}y_{31})} \\
B &= \frac{T_{12}(T_{13}^2c^2 + x_1^2 + y_1^2 - x_3^2 - y_3^2) - T_{13}(T_{12}^2c^2 + x_1^2 + y_1^2 - x_2^2 - y_2^2)}{2(T_{13}y_{21} - T_{12}y_{31})} \\
C &= \frac{(T_{12}x_{32} - T_{23}x_{21})}{(T_{23}y_{21} - T_{12}y_{32})} \\
D &= \frac{T_{12}(T_{23}^2c^2 + x_2^2 + y_2^2 - x_3^2 - y_3^2) - T_{23}(x_1^2 + y_1^2 - T_{12}^2c^2 - x_2^2 - y_2^2)}{2(T_{23}y_{21} - T_{12}y_{32})}
\end{aligned}
$$

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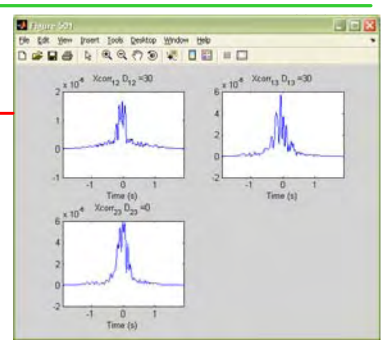
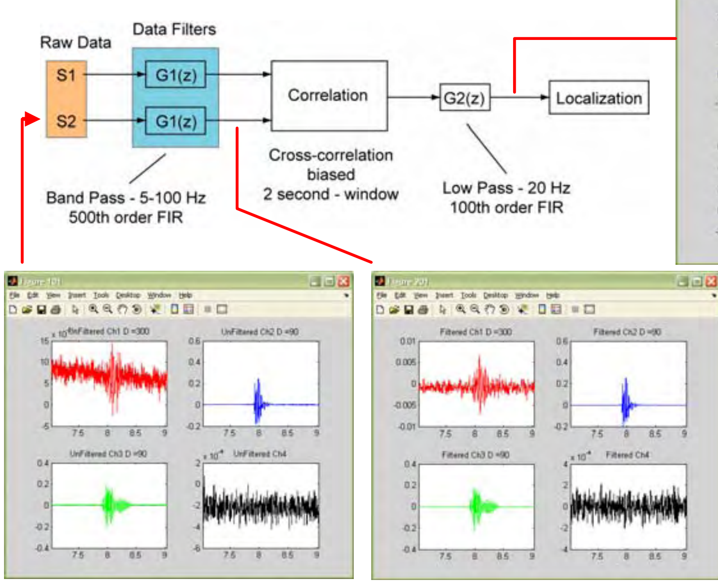
Method 1 -Time Difference of Arrival (TDOA)

- **Cross-Correlation Technique**





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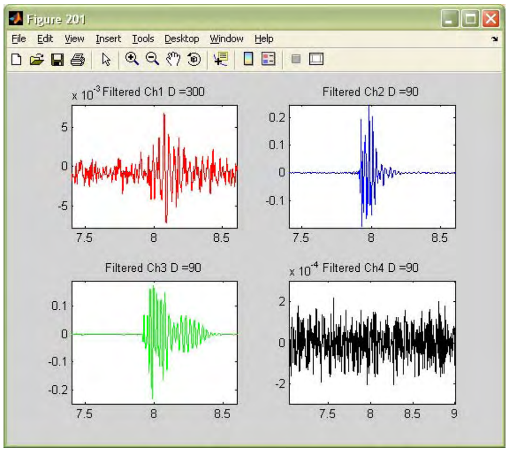
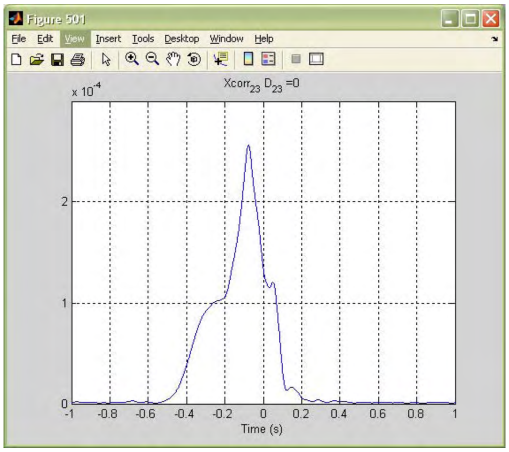
TDOA – Cross-Correlation Distortion

VG07-071-22





Cross-Correlation is degraded by dispersion, reflection, multiple paths, and noise.

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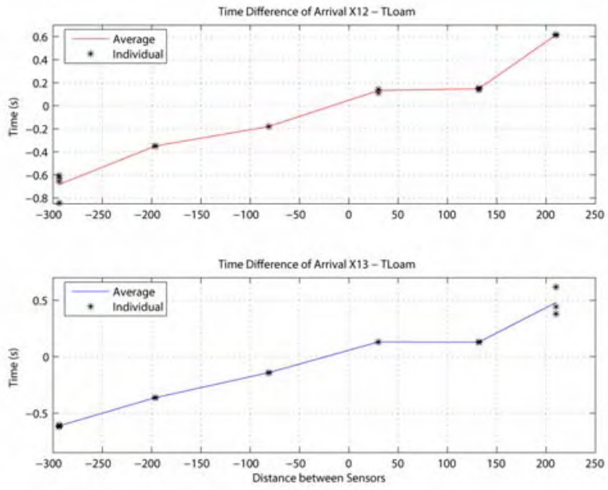
TDOA

VG07-071-23



- **For SNR > 20 dB TDOA are very repeatable**
  - ±18 ms Sand (±7 ft)
  - ±1.5 ms Sand (±10 ft)
- **Major problem is data offsets – this can be as high as 200 ms in uniform soil conditions.**
- **For example X12 and X13 are offset -100 ms, this results in an 80 ft error in the calculated position. In faster soils an offset of -40ms results in a 260 ft error.**

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TDOA Results Summary

VG07-071-24

- PIGPEN can detect the 30-06 down-hole rifle to a range of 400 ft in sand/loam.
- PIGPEN can detect the 30-06 down-hole rifle to a range of 200 ft in limestone/shale.
- Threat signatures are degraded 20-30 dB (depending on initial signal strength) as they transition from limestone to sand. We were able to observe attenuated threat signatures across this discontinuity in both directions.
- In the best cases, PIGPEN can localize threats repeatable to ±7 ft in sand
- In the best cases, PIGPEN can localize threats repeatable ±9.6 ft in slate
- Worst cases exhibited much poorer performance
- We were able to observe the unique signature and repeated strikes from a Backhoe across the discontinuity at all sensors.
- Due to the signal degradation across the soil discontinuity, PSI was not able to establish the positional accuracy across the soil transition for the down-hole rifle acoustic source.
- Further algorithm development in conjunction with on-site calibration will be required to correct for non-uniform soil conditions.

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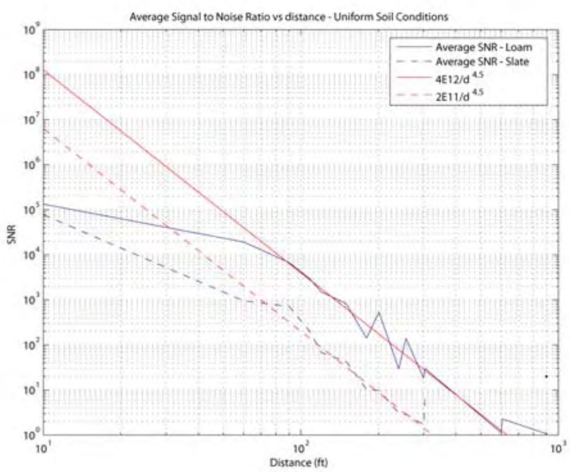
Received Power Localization (RPL)

VG07-071-25



Down-Hole 30-06
Signal Power falling off at ~ $1/d^{4.5}$

- **Library of SNR vs distance for various threats in various soil types**
- **Once threat type identified received signal power can then be used to estimate threat distance**

1. **Identify threat type**
2. **Calculate signal power**
3. **Use signal power to estimate threat distance**
4. **Use estimated distance from multiple sensor to estimate position**

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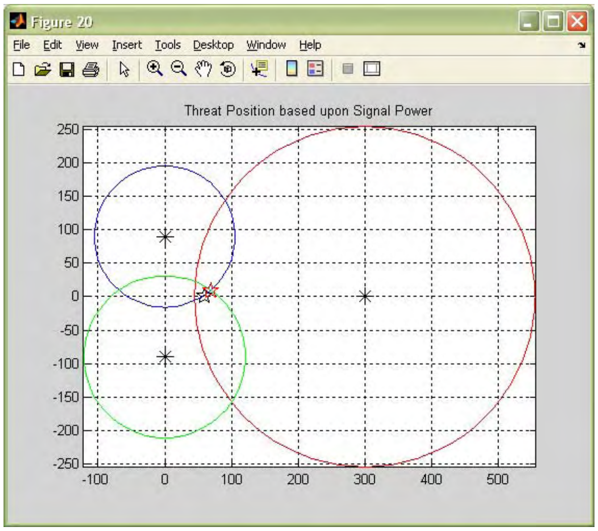
Received Power Localization

VG07-071-26



★ = Actual Threat Location
★ = Estimated Position
* = Sensor Locations

1. Circle intersections
2. Circles prioritized by distance from threat (the closer the signal the higher the priority of the data)
3. Lower priority data used to choose between intersections

Down Hole 30-06 – Kansas, Loamy soil
Distance between estimate position and actual = 15.6 ft

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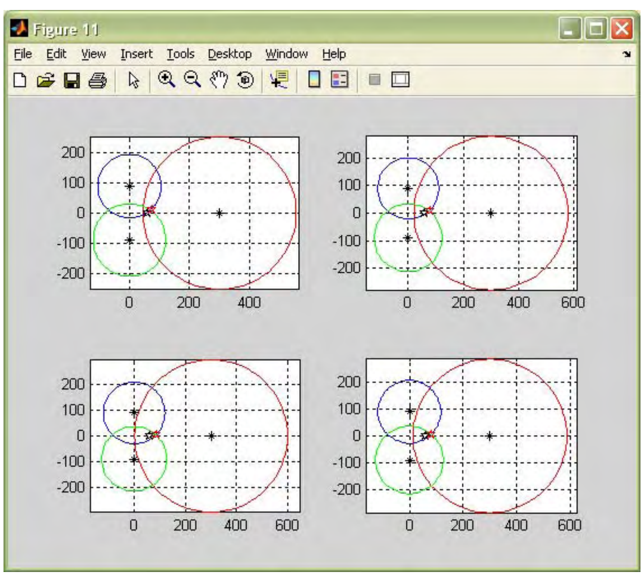
Received Power Localization

VG07-071-27



Repeatable Results:
Four shots at location T2

- **Mean Error = 19.5 ft**
- **σ = 4.11 ft**

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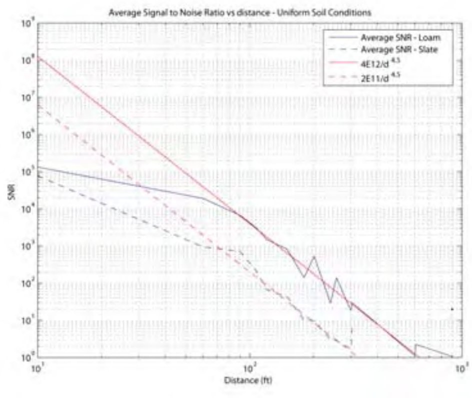
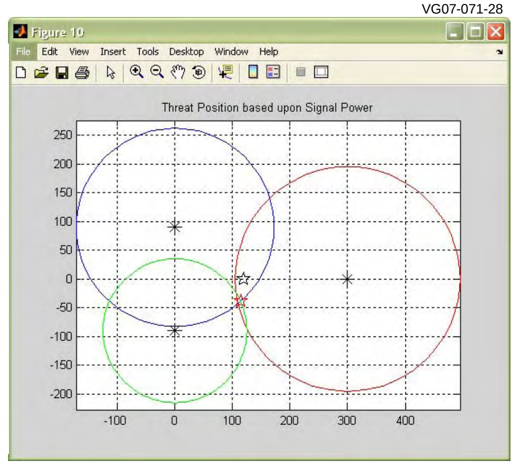
Received Power Localization

VG07-071-28





Method Applied to Slate – Error = 37 ft

Multiple Shots

- **Mean Error = 48.7 ft**
- **σ = 8.2 ft**

- **Larger Error in Slate is due to variance in the SNR vs Distance for the three sensors.**

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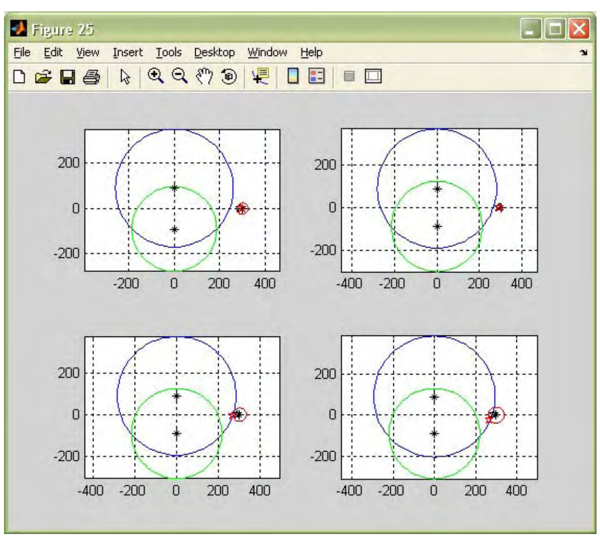
Received Power Localization

VG07-071-29



Shale – Location T6

Overall Accuracy

Loam

22 shots – 6 locations

- **Mean Error = 21.4 ft**
- **σ = 13.2 ft**
- **Max Error = 48.5 ft**
- **Min Error ~ 0 ft (1 ft)**

Shale

24 shots – 6 locations

- **Mean Error = 32 ft**
- **σ = 21 ft**
- **Max Error = 71 ft**
- **Min Error ~ 0 ft (2.6 ft)**

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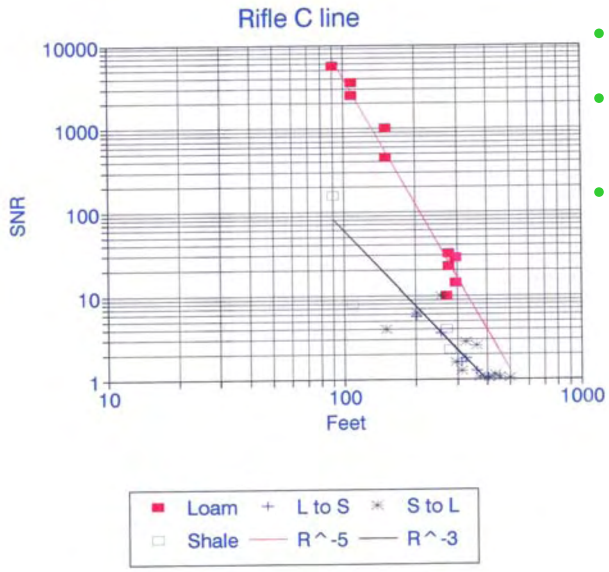
Signal Power Across Soil Discontinuity

VG07-071-30



- **Able to see threat signatures across the soil discontinuity**
- **Acoustic reflection at the soil discontinuity decreases signal strength**
- **Rifle acoustic source detectable at**
  - 150 m in loam,
  - 100m across severe soil discontinuity

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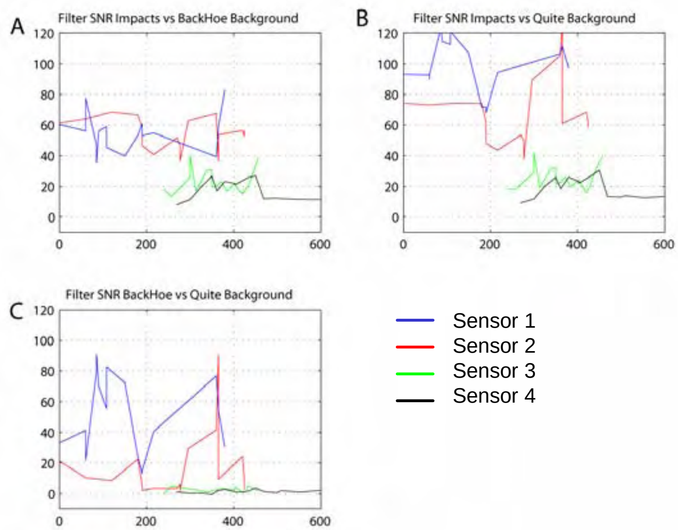
Received Power Localization – Backhoe with Soil Discontinuity

VG07-071-31



- Backhoe strike into ground has very variable energy
- Solution – Scale up the rifle SNR vs distance curves
- Slate data attenuated 20 dB to account for soil transition

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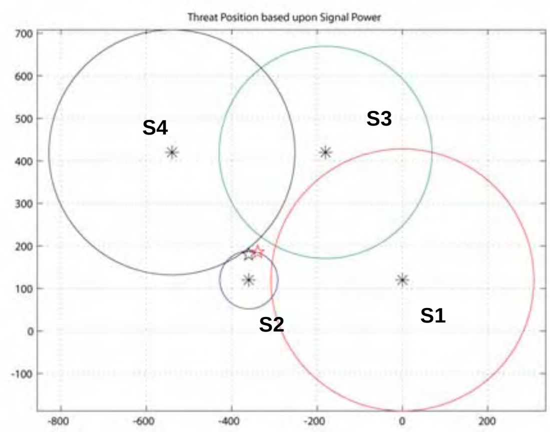
Received Power Localization – Backhoe

VG07-071-32



Backhoe at threat position BE180

- Threat Location BE180 used to calibrate magnitude scaling
- Sensors 1 and 2 use scaled loam data.
- Sensors 3 and 4 use scaled shale data
- Choose logic more complex

RPL method

3 trials

- Mean Error = 26 ft
- σ = 4.1 ft

TDOA

3 trials

- Mean Error = 137 ft
- σ = 1.85 ft

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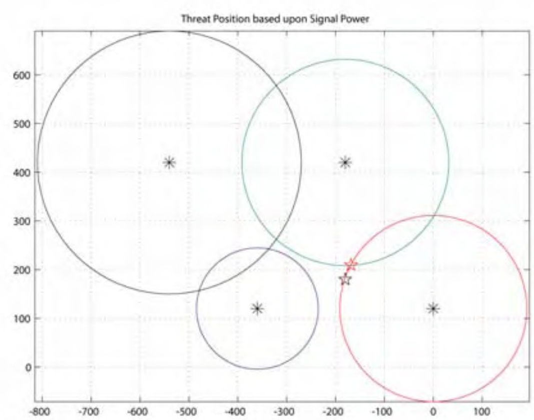
Received Power Localization – Backhoe

VG07-071-33



Backhoe at threat position BW180

RPL method

3 trials

- Mean Error = 38 ft
- σ = 18 ft

TDOA

- Mean Error = 90 ft
- σ = 60 ft

- RPL not optimized
- RPL better than TDOA
- Improvement possible

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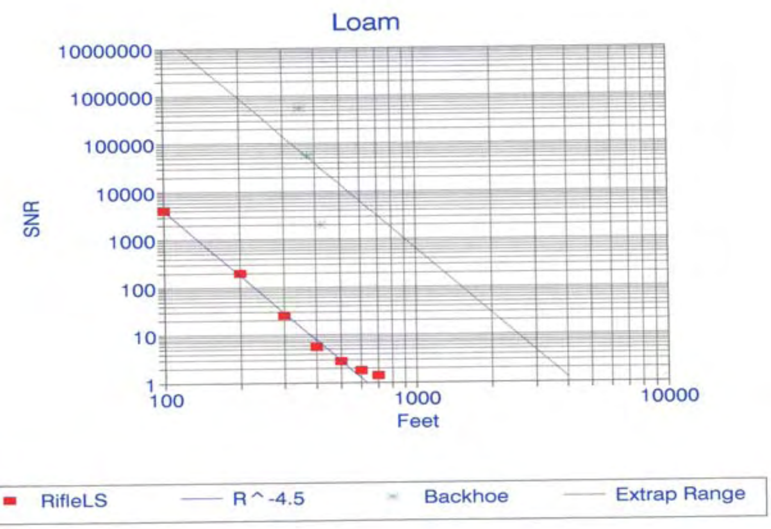
VG07-071-34



Detected signals of backhoe strikes at long range in KS extrapolated with observed scaling would permit 1000 m detection in loam

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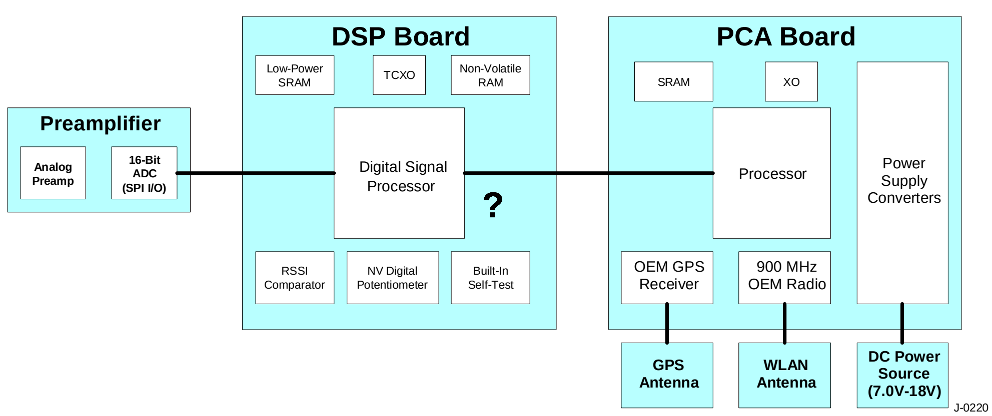
Task 4: AP Sensor Configuration

VG07-071-35



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AP System Status

VG07-071-36

- **AP Sensor Hardware Complete – Battery Power up to 24 Hrs**
  - Sensor & PreAmplifier (includes integrated wake up circuit)
  - DSP
  - PCA
- **AP Network**
  - Network integration is in process
    - Network communication from individual sensors to NIB establish
    - Remote sensor control established (includes ability to update sensor function)
- **Remaining task**
  - Network CONOPS
    - Multi-sensor data management
  - Algorithm integration
  - Reduce power consumption
    - System CONOPS
    - PCA board primary power limitation

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PIGPEN AP Working Specifications

VG07-071-37

Unit spacing	**Sensor: 100-500 yards** **NIB: 3-5 miles (16 sensors/NIB)**
Threat location accuracy	**<10 yards at 300 yard range**
Unit mass	**Sensor: 5 lb** **PCA: 2 lb + battery** **NIB: 2 lb**
Unit size	**Sensor: 5 x 5 x 4 in^3** **PCA: 6 x 6 x 2 in^3 + battery** **NIB: 5 x 5 x 2 in^3**
Communication	**900 MHz, serial, 1 kbyte/sec**
Power	**7-18 V (e.g. solar power/battery)** **Sleep: 0.7 W (currently 2 W)** **Active 8 W max**
Warning time	**5 sec initial detection** **30 sec identification** **3 minutes triangulation**
Equipment cost	**$4-6K/mile**
Temperature range	**-30 to +60 C**

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Path Forward

VG07-071-38

- **Use Received Power Localization approach**
  - Pursue TDOA at low level
- **Simplifies PIGPEN technology**
  - Remove GPS (time synch)
  - Reduce transmission bandwidth
  - Reduce peak and average power requirement (10x)
    - Reduces battery or supplemental power (solar) requirements
- **Place inexpensive sensors closer together**
- **Review OTS technologies**
- **Existing AP units revised to permit rapid field test demonstrations**

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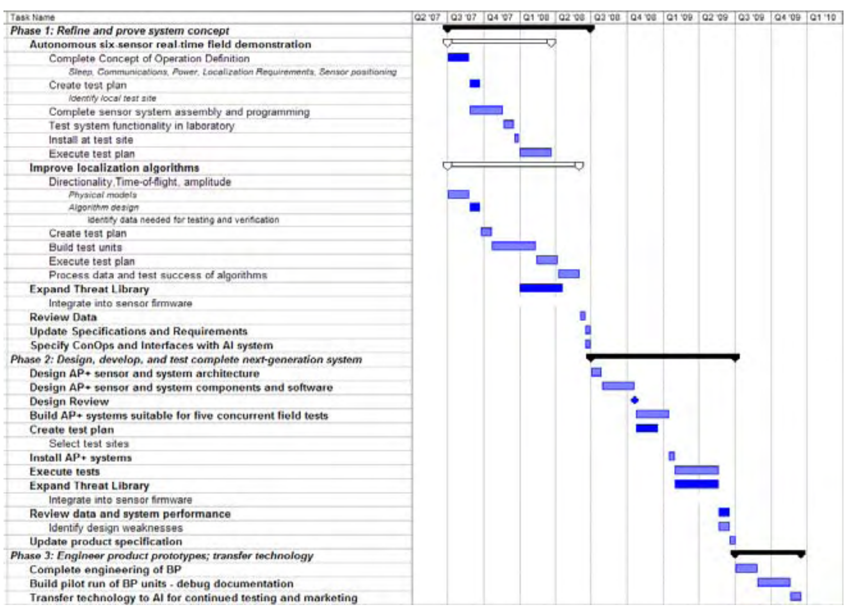
Next Project Recommendation

VG07-071-39

- **Scope: Demonstrate complete system functionality and ready it for production**



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Phase I

VG07-071-40

- **Objectives and Task Summary**
  - Complete an extended (~ 3-month) field test of existing architecture and hardware
    - Demonstrate abilities to sleep for extended periods, awaken upon threat detection, report threat, return to sleep
      - Incorporates relative power localization algorithm and simplified AP hardware
      - Localization accuracy TBD
    - Gather statistics for determining probability of detection and probability of false alarm
    - Expand threat library while system is operating
  - Re-visit and revise methods for localizing threat
    - Refine specifications and requirements
    - Examine several alternative approaches to meeting requirements
      - Include directional (i.e. multi-sensor) nodes and threat signal amplitude to supplement or replace time-of-flight/cross-correlation approach
    - Develop simple but representative physical models of acoustic propagation through target media to guide sensor configuration and signal interpretation
    - Install modified detection algorithms into current AP hardware to test new approaches
    - Install sensors, conduct tests, analyze data
  - Synthesize results of these parallel activities in the form of revised Specifications, Concepts of Operations, and Interface Protocol
- **Year 1, ~ $750K**

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Phases 2 & 3

VG07-071-41

- **Phase 2 Objectives and Task Summary**
  - Integrate results of Phase I into next-generation system
  - Build several (~5) prototype multi-node systems and test them at multiple sites
    - Identify flaws and technical weaknesses
    - Prepare for production
  - Continue threat library expansion
- **Year 2, ~ $500K**

- **Phase 3 Objectives and Task Summary**
  - Update design to correct flaws identified in Phase 2
  - Complete engineering design and documentation for production
  - Complete pilot production run
  - Collaborate with manufacturing partner if appropriate
  - Transfer information and knowledge to marketing and systems integration partner
- **6 months, ~ $250k**

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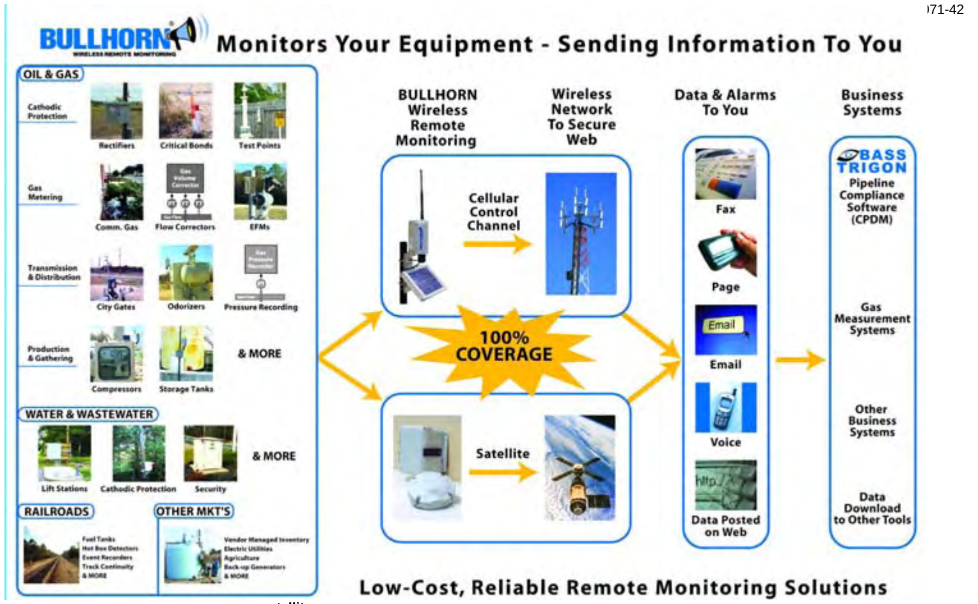
Bullhorn System

071-42



satellite

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Data Security

VG07-071-43

- All packet structures are coded
- SS7 network used for billing by cell providers
- Messages can only terminate at providers hub to eliminate the possibility of theft
- AI is constantly connected to providers NOC
- Bullhorn system uses 128 bit encryption
- Different levels of security access by account

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Key Features

VG07-071-44

- Low cost, reliable, 100% coverage
- Tested, proven, patented
- Analog, digital, accumulator & serial data
- One-way & two-way communications
- Secure web access
- Auto fax/page/email/FTP/voice notifies
- Scheduled and by exception reporting
- False alarm filtering
- Regulatory approvals

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Bullhorn Clients

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AI Company Structure

VG07-071-46

HM International

AMERICAN INNOVATIONS
Minding Your Business

- Accounting / Finance / Capital
- Payroll / HR / Policy / Insurance
- Acquisitions / Contracts / Legal
- Culture / Vision / Mission / Values

Field Data (Austin/45 FTE)

- **Bullhorn® Monitoring** (Including I-Series)
- **MicroMax® Interrupters**
- **Allegro® Field Computer**
- **PCS Software** (Including Popular CPDM Software)

Integrity Mgt. (Denver/35 FTE)

- **IAP / IMP Software**
- **FMP Software**
- **RiskCat™ Software**
- **Engineering Service**

Bass Engineering (Longview/35 FTE)

- **Design, Install & Maintain CP Systems**
- **CP Materials Sales**
- **CIS & Annual Surveys**
- **Enviro. Studies**

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AI Products & Services

VG07-071-47

- **Integrity Management:** Software & engineering services that help gas & liquids pipelines improve safety, efficiency & regulatory compliance
- **Bullhorn Remote Monitoring:** Wireless monitoring for remote equipment, (primarily oil & gas), CP monitoring w/integrated MicroMax interrupter
- **Pipeline Compliance System:** Organize & analyze regulatory data (primarily CP) for more than 1,500 clients in oil & gas pipelines & water
- **Allegro Handheld Computer:** Juniper Systems rugged field computer with proprietary drivers for digital voltmeter + GPS; integrated w/PCS
- **MicroMax Current Interrupters:** Smallest, lowest cost, GPS-synchronized current interrupters; integrated w/Bullhorn monitoring
- **Bass Engineering:** Design, install & maintain CP systems, sales of CP materials, CIS & annual surveys, oil & gas field services, enviro. surveys

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Rectifier Monitoring

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Test Points

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Appendix G

VG07-114

PIGPEN
Proactive Infrasonic Gas Pipeline Evaluation Network
Development and Testing

Marten F. Byl, Mickey B. Frish, Surjeet Paintal, and B. David Green
Physical Sciences Inc.

and

Lee Blankenstein
American Innovations

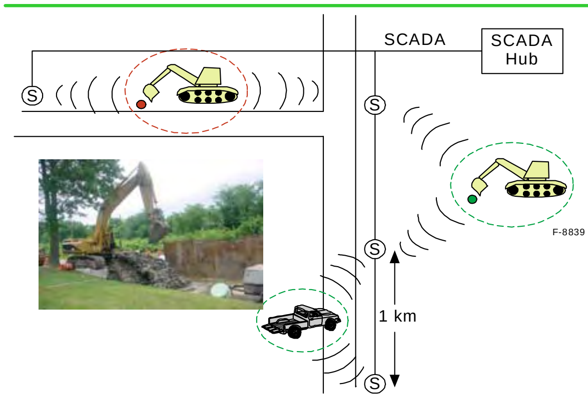
Presentation to NYSEARCH Committee

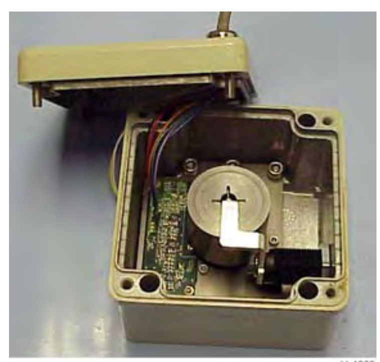
5 June 2007

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

Proactive Infrasonic Gas Pipeline Evaluation Network PIGPEN

VG07-114-1





H-4223

- **Smart Sensors placed at 0.1-0.5 km spacing around the pipeline**
- **PIGPEN sensors determine potential threat type based on signature (backhoe or bus)**
- **PIGPEN system determines range and direction of potential threats**
- **Warning issued upon recognizing a near-pipeline excavation**

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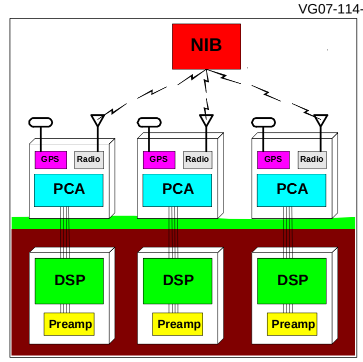
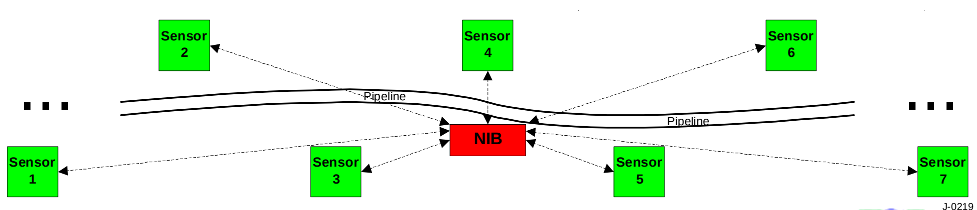
PIGPEN Architecture

VG07-114-2

- Individual smart sensors straddle the pipeline at 100-500 m intervals (soil dependent)
- Up to 16 sensors communicate wirelessly with the Network Interface Box (NIB)
- The NIB connects with the Bullhorn system to report alarms & health check
- Alarm notifications are automatically delivered to the end user





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Solution - Communications

VG07-114-3

- Bullhorn remote monitoring system
- Leading low cost, reliable remote monitoring system for pipelines – over 10,000 installed to monitor cathodic protection systems
- Satellite and digital cellular wireless networks used to monitor the Pigpen system
- Web-accessible system for viewing data and configuring alarm notifications
- Automatic notifications via fax, page, voice, e-mail with security and escalation

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PIGPEN Advantages

VG07-114-4

- **Low Sensor Cost**
  - Sensors are simple and inexpensive - compact solid-state sensor, electronics, and network connection
- **Low Network Cost**
  - Infrasonic energy propagates for long distances so sparse sensor array reduces cost
  - Bullhorn system uses existing low cost wireless networks – it is tested, proven & has low cost automatic notifications
- **Simple to Install**
  - Does not require installation along entire length of service – can be surgically installed wherever justified
  - Does not contact pipeline, not in its trench
  - Can be retrofit to existing systems or used on new service

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Product Performance Specifications and Key Features

VG07-114-5

Application:	Passive third party intrusion monitoring network
Detection range:	>300ft
Threats:	Backhoes, jackhammer, digging, air drill, … demonstrated
Identification:	Threat identified by acoustic signature
Threat detection accuracy:	Threat location to 30 ft
	Probability of detection 99%
	Probability of false alarm 1 per month
Response time:	Detect 30 seconds, alarm 4 minutes
Power requirements:	Self-contained rechargeable battery, 90 days service, w/o solar charging
Placement:	Away from pipe, within right-of-way
Configuration:	Multiple buried sensors, wireless communication to hub and transmitter
Alarm notice:	Transmission from pipeline to customer computer via satellite link
Target cost:	$10,000/mi installed
Target operating cost:	<$100. per mile
Size and weight:	Sensor: 4 kg (6” cube)
Calibration and fault monitoring:	Characterize site at installation, test yearly, continuous self check, fault notification

Operating Environment

Ambient conditions:	
temperature:	-20° to +120°F
humidity:	0 to 100% RH, non-condensing
Precipitation:	Operation in all weather

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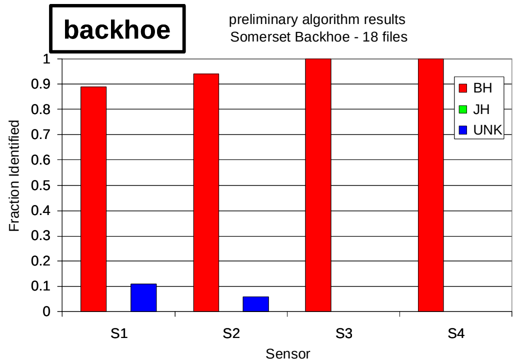
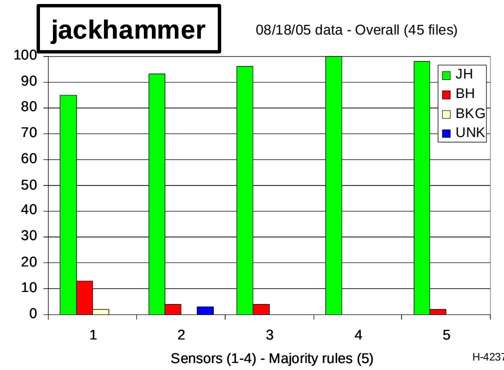
Threat Algorithm Performance

VG07-114-6





- **The threat identification algorithm developed and optimized using field test data**
  - filter-bank creates sparse spectra
  - compared to library spectra
- **Optimized algorithm provides good results for jackhammer and backhoe threat classes**
- **Threat identification occurs at sensor**

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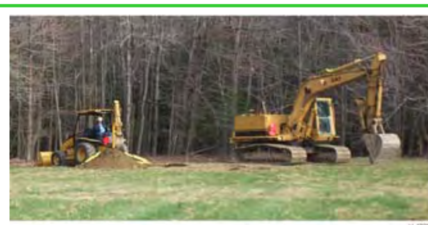
Observed Threats Signatures

VG07-114-7

- **Sledgehammer**
- **Jackhammers (2)**
  - Electric
  - Pneumatic
- **Backhoe (3 different brands)**
  - Somerset, MA
  - Johnson City, NY
  - Lawrence, KS
- **Trackhoe**
  - Johnson City, NY
- **Horizontal Drilling Machine**
  - Bronx, NY
- **Shovel digging**
  - Johnson City, NY
- **Additional Sources**
  - Freight trains, KS
    - Commuter Rail train, Allston, MA
  - Vehicles (passenger, delivery trucks)
    - Down-hole 30-06
  - 12 gauge shotgun
    - 45 cal. pistol
  - Generator



J-3950

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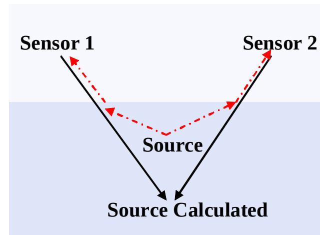
Complex Soil Testing - Motivation

VG07-114-8

- **Motivation: Waves refract and reflect at soil type boundaries**
  - Erroneous calculation of source location
- **Observations:**
  - Velocity is soil dependent
  - Able to observe signals across boundary
    - 20-30 dB attenuation
  - Signal coupling soil dependent
  - Repeatable robust backhoe and rifle signatures



H-4248

- **Further observations:**
  - Sensor precision (1 ms, 2 ft) demonstrated
  - Soil Dispersion limits threat location via TDOA
  - Results not repeatable; limits accuracy
  - Drove development of Received Power Location approach
  - Threat signals detected in 397 of 400 events (P_d = 99.25%)
  - P_{fa} not quantified, small

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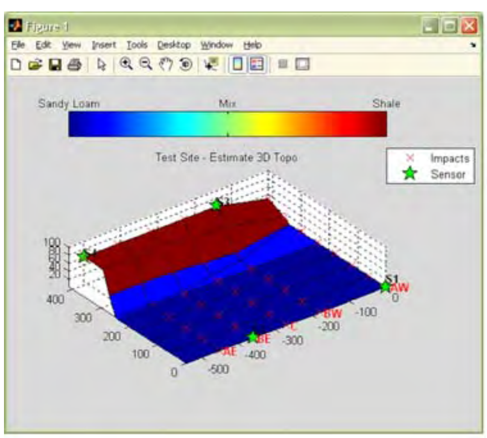
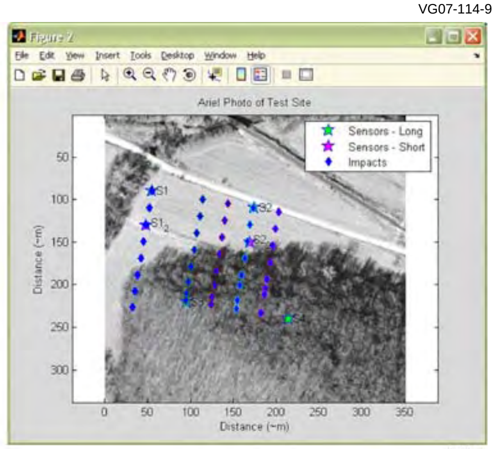
Complex Soil Testing

VG07-114-9



Geology



J-3951

Aerial Photo

Two Configurations:
Long Field – S1 @ AW0, S2 @ BE0
Short Field - S1 @ AW120, S2 @ BE120

Two Threats:
Long Field – Down Hole Gun
Short Field – Down Hole Gun, BackHoe

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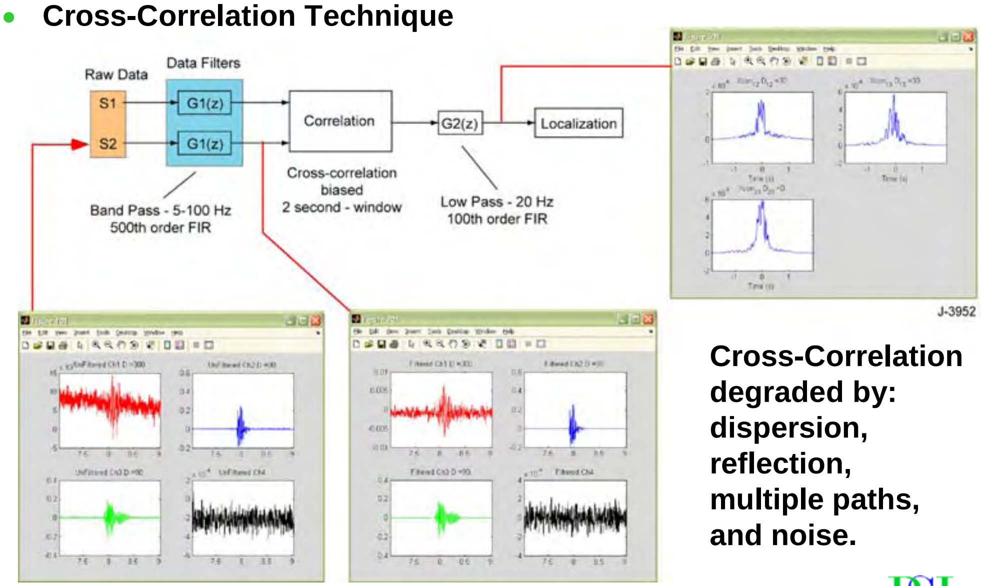
Method 1 - Time Difference of Arrival (TDOA)

VG07-114-10

- **Cross-Correlation Technique**



Cross-Correlation degraded by: dispersion, reflection, multiple paths, and noise.

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Signal Attenuation with Distance

Kansas shale, loam; Andover loam

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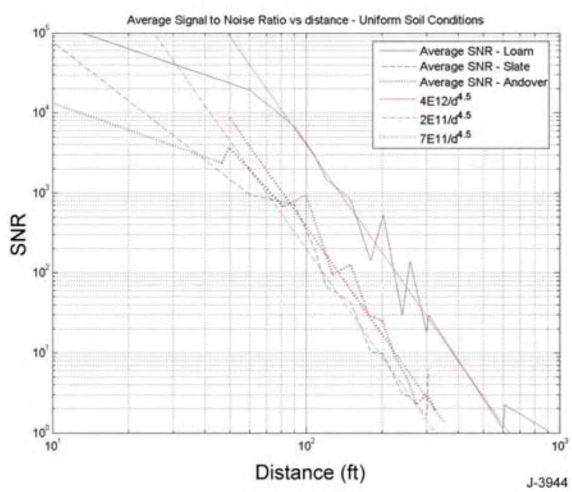

Source magnitude drives detection range
Backhoe $10^{3\text{ to }4}$ larger signal
Backhoe detection range 1 km (>3000 ft)

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Received Power Localization

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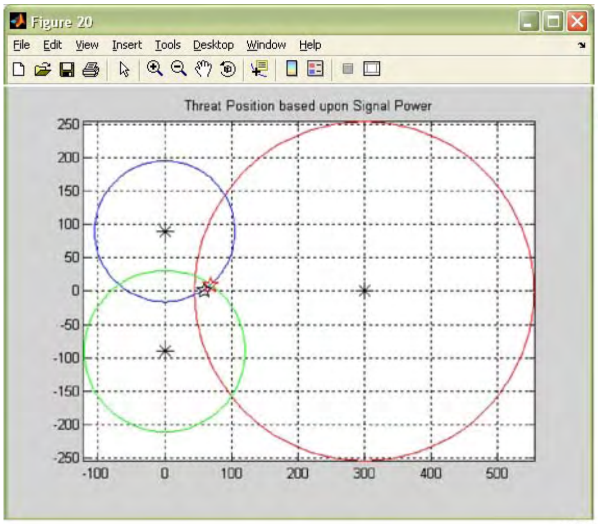

J-3945

★ = Actual Threat Location
★ = Estimated Position
* = Sensor Locations

1. Circle intersections
2. Circles prioritized by distance from threat (the closer the signal the higher the priority of the data)
3. Lower priority data used to choose between intersections

Down Hole 30-06 – Kansas, Loamy soil
Distance between estimate position and actual = 15.6 ft

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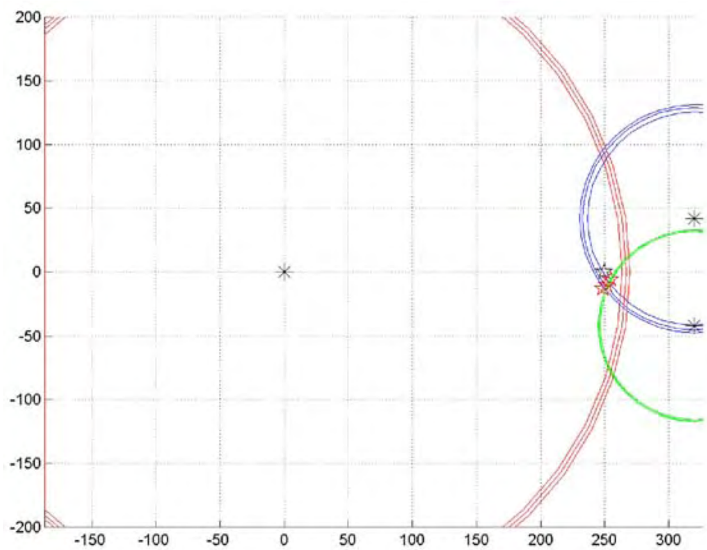
Threat Location for Three Individual Strikes - Andover

VG07-114-13



J-3953

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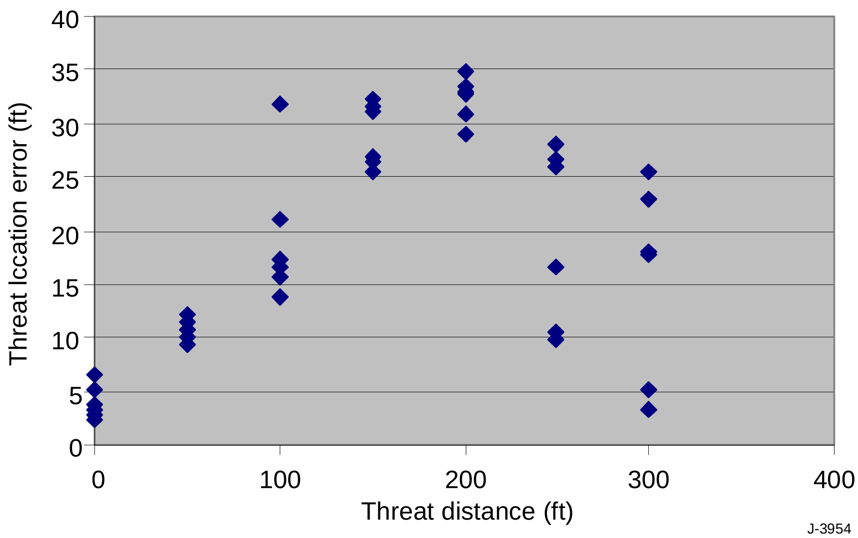
RPL Analysis of Andover Strike Tests

VG07-114-14



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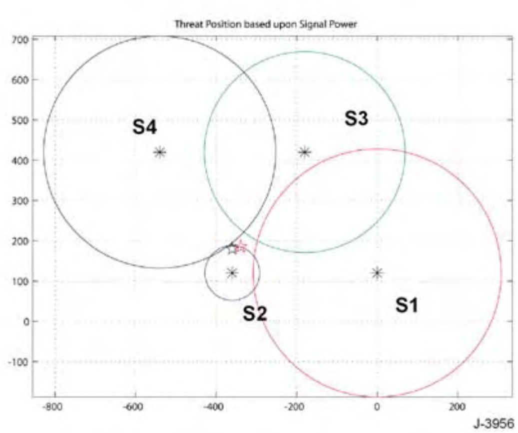
Received Power Localization – Backhoe KS

VG07-114-15



Backhoe at threat position BE180

- Threat Location BE180 used to calibrate magnitude scaling
- Sensors 1 and 2 use scaled loam data.
- Sensors 3 and 4 use scaled shale data
- Choose logic more complex

RPL method

3 trials

- Mean Error = 26 ft
- σ = 4.1 ft

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Localization Data Statistical Summary

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			Received Power Localization		*Time-of Arrival Localization*	
Source	***Soil Type***	***# Tests***	***Accuracy (Mean Error) (feet)***	***Precision (Reproducibility) (feet)***	***Accuracy (Typical Error) (feet)***	***Precision (Reproducibility) (feet)***
Rifle	Loam	22	21	13	80	7
Rifle	Shale	24	32	21	260	10
Backhoe	Discontinuous	9	32	18	114	60

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RPL Summary

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- **Three tested soils show $d^{-4.5}$ scaling**
  - Must be tested on many soils
- **Localization relies upon energy transmitted**
  - Must be tested on many soils
- **Remote Power Localization**
  - Removes precise time (GPS) and high bandwidth requirement
  - Reduces complexity, component cost, power consumption
  - Makes detection more robust
  - Reduces effect of multipath, dispersion
- **Use as baseline going forward**
  - Consider use in conjunction with TDOA
  - RPL constrain TDOA determination
    - proper peak of cycle in cross correlation
- **Full Benefit from PIGPEN development program**
  - Simplify design going forward
- **Focus of next stage field testing**

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Purpose of Proposed R&D

VG07-114-18

- **Demonstrate the complete PIGPEN system, including its sleep/wake routine, communications with the NIB, and its threat response, in realistic extended field tests**
  - Six sensor prototype PIGPEN network hardware is complete
  - Before field testing, must:
    - Write RPL algorithm and install in firmware, and
    - Complete network communications and energy conservation (sleep/wake) software
- **Expand threat identification library and improve algorithm efficiency**
- **Simplify PIGPEN sensor architecture and reduce cost**
  - RPL algorithm, in place of TDOA, eliminate GPS and high-bandwidth radio, along with their associated circuitry, power load, and cost

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Project Goals and Scope

VG07-114-19

- **Goals:**
  - Complete the development of PIGPEN technology
  - Transition the technology to pre-production status
- **Scope - Three Phase, Three Year Project to:**
  - Refine and prove the PIGPEN system
    - Implement RPL algorithm *and verify in diverse geologies*
    - Expand threat library
    - Improve threat detection and false alarm rejection algorithms
    - Evaluate the complete PIGPEN system in field tests
    - Acquire data demonstrating:
      - real-time alarm capabilities in two or more geologic and geographic locations
      - extended operation in semi-permanent installation
  - Develop and test next-generation PIGPEN system
    - simplify sensor hardware
    - improve the packaging
    - reduce cost
    - test AP (next-generation) systems
      - in a controlled environment
      - in five working pipeline scenarios
  - Engineer Beta prototypes; transfer to production at American Innovations

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Program Technical Objectives

VG07-114-20

- **Phase 1: Refine and Prove PIGPEN System (Year 1)**
  - Culminates with field test data acquisition demonstrating:
    - > 95% probability of detecting any known threats within a pipeline right- of-way (Pd>95%)
    - < 10% probability of incorrectly classifying a threat
    - false alarms: fewer than 5% of sensor activation events
      - not due to excavation or are outside of the pipeline right-of-way
    - real-time threat localization with error less than 20 ft; reproducibility better than 15 ft in uniform soil
    - reliable data acquisition and communication at ranges of up to 1 km from the NIB
- **Phase 2: Design, Develop, and Test Next-Generation System (Year 2)**
  - Culminates with field test data acquisition demonstrating:
    - Average power consumption less than 1 W without compromising threat probability of detection and localization
    - 97% probability of detecting any known threats within a pipeline right- of-way
    - less than 5% probability of incorrectly classifying a threat
    - false alarms: fewer than 2% of sensor activation events
      - not due to excavation or are outside of the pipeline right-of-way
    - Real-time threat localization with error less than 20 ft and reproducibility better than 15 ft in complex soils
- *Phase 3: Engineering Product Prototypes and Technology Transition*
  - *Update design based on Phase 2 experience*
  - *Finalize threat detection and localization algorithms*
  - *Transfer documentation and know-how from PSI to AI*
  - ***Not currently requesting NYSEARCH support for this Phase***

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Phase I Plan

VG07-114-21

Task Name	Lead PSI	Lead AI	Support PSI	Support AI	Support NGA
Phase 1: Refine and prove system concept	√			√	√
Kickoff Meeting					
Prepare					
Meet					
Autonomous six-sensor real-time field demonstration	√				
Complete Concept of Operation Definition					
Sleep, Communications, Power, Localization Requirements, Sensor positioning					
Create field test plan	√			√	√
Identify local test site					
Identify data needed for testing and verification					
Complete sensor system assembly, programming, and activation	√				
Build field test units					
Modify Threat Detection algorithm for improved efficiency					
Design algorithm					
Install in firmware and lab test					
Improve Received Power Localization (RPL) algorithms					
Create Theoretical Wave Propagation Models					
Develop improved RPL algorithm					
Install algorithm in firmware and lab test					
Update network communications software					
Test system functionality in laboratory					
Execute field test plan	√				
Install at test site					
Execute test plan					
Expand Threat Library	√				
Collect data					
Integrate into sensor firmware					
Review and Analyze Data	√			√	√
Evaluate RPL performance					
Evaluate Threat Identification Performance					
Evaluate Hardware Performance					
Identify weaknesses and means for improvement					
Update Specifications and Requirements	√			√	√
Specify ConOps and Interfaces with AI system	√	√			
Prepare Report and Review Meeting	√		√		
Meet and Deliver Report	√			√	√

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Phase II Plan

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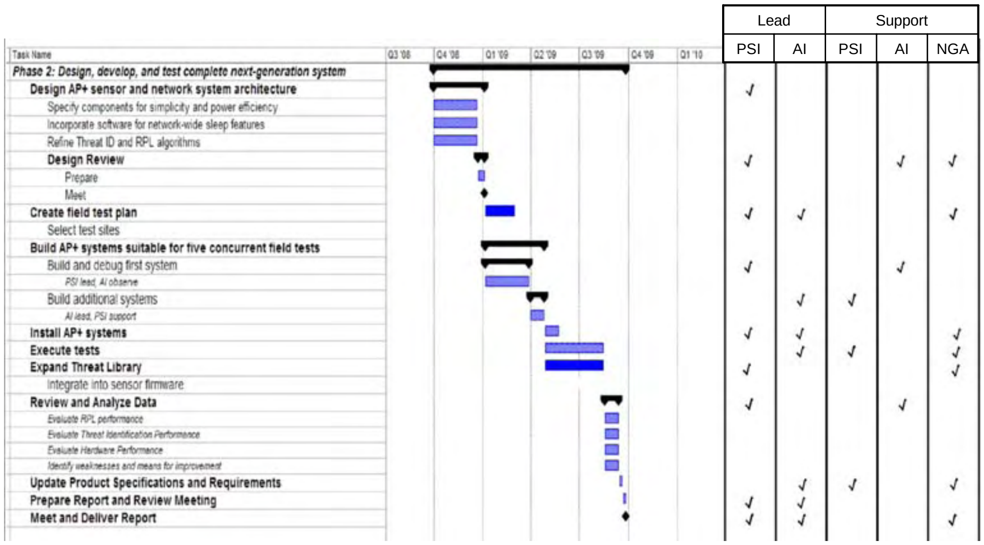

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Project Cost Summary

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	Total Cost	American Innovations In-kind Contribution	*Requested NYSEARCH Support*
Phase 1	$453,607	$74,000	*$379,607*
Phase 2	$849,986	$331,000	*$518,986*
Total:	$1,303,593	$405,000	*$898,593*

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AI Company Structure

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HM International

- Accounting / Finance / Capital
- Payroll / HR / Policy / Insurance
- Acquisitions / Contracts / Legal
- Culture / Vision / Mission / Values

AMERICAN INNOVATIONS
Minding Your Business

Field Data (Austin/45 FTE)	Integrity Mgt. (Denver/35 FTE)	Bass Engineering (Longview/35 FTE)
Bullhorn® Monitoring	IAP / IMP Software	Design, Install & Maintain CP Systems
MicroMax® Interrupters	FMP Software	CP Materials Sales
Allegro® Field Computer	RiskCat™ Software	CIS & Annual Surveys
PCS Software (Including Popular CPDM Software)	Engineering Service	Enviro. Studies

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AI Products & Services

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- **Bullhorn Remote Monitoring:** Low cost, reliable, wireless monitoring for remote equipment; CP monitoring w / integrated MicroMax interrupter
- **Pipeline Compliance System:** Regulatory and inspection data for more than 1,750 clients in O&G / Water pipelines
- **Allegro Field Computer:** Rugged field computer used for CIS and periodic surveys; integrated w / PCS
- **MicroMax Current Interrupters:** smallest, lowest cost, GPS-synchronized
- **Integrity Management:** Software & engineering services that help gas & liquids pipelines improve safety, efficiency & regulatory compliance
- **Bass Engineering:** Design, install & maintain CP systems, AC mitigation, sales of CP materials, pipeline surveys, O&G field services, enviro. surveys

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AI Metrics

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- **Field Data Division**
  - Bullhorn protects over 120,000 miles of O&G pipe
  - PCS: 1750+ seats at over 175 clients worldwide
  - Allegro: 1000+ used for field surveys worldwide
- **Integrity Management Division**
  - Over 250,000 miles of pipeline assessed
  - 80,000+ miles pipe analyzed for HCA
- **Bass Engineering**
  - 40 year anniversary
  - 200+ Clients in Production and Gathering, Transmission, Distribution, Processing & Electric Generation

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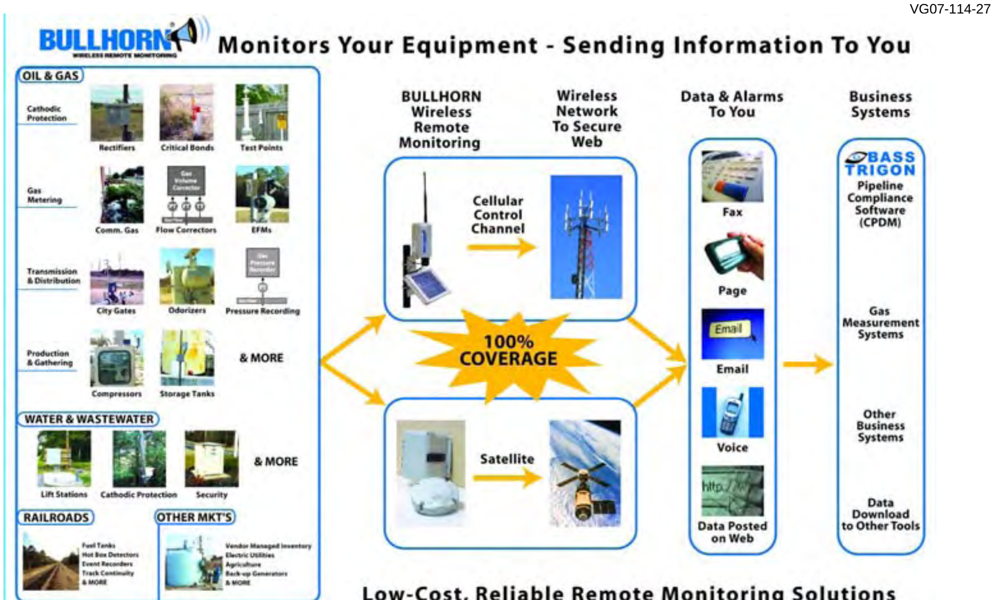
Bullhorn System

VG07-114-27



satellite

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Key Features

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- Low cost
- Reliable
- 100% coverage
- Tested and Proven
- Patented
- One & two-way communications
- Analog, digital, accumulator, serial data
- Scheduled and “By Exception” reports
- Secure web access
- Auto notification: fax, page, email, FTP, voice
- False alarm filtering
- Regulatory approvals

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SUNOCO
AEP
conoco
GIANT INDUSTRIES, INC.
PHILLIPS 66
VECTREN
DYNEGY
CITGO
elpaso
ONEOK
Williams
nicor
Enterprise Products Partners L.P.
ENERGY TRANSFER
ChevronTexaco
ExxonMobil
MIDAMERICAN ENERGY HOLDINGS COMPANY
Duke Energy
KINDER MORGAN
VALERO ENERGY CORPORATION
Xcel Energy
TEPPCO
devon ENERGY CORPORATION
CCO CROSSCOUNTRY

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Rectifier Monitoring

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J-3957

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Test Points

VG07-114-31

J-3958

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