

Hyperlocal Seismic Soil Characteristic Measurements for Unexploded Ordnance Detection

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Hyperlocal Seismic Soil Characteristic Measurements for Unexploded Ordnance Detection

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Abstract

Explosive Remnants of War (ERW) range from small plastic landmines to unexploded cannon shells to bombs that weigh hundreds of kilograms. They kill and maim thousands of people each year, make otherwise productive real estate unusable, and exist worldwide. Their variability and the variability of the soil in which they exist defeat and delay cleanup efforts.

Current search technology treats soil as a problem or nuisance variable.

We propose to measure soil properties hyperlocally (meter by meter) with a foundational approach that exploits broadband seismic stimulus and commercial off the shelf (COTS) instrumentation to characterize detection capability in site-specific soil context.

Field experiments were conducted at three widely spaced geographic locations and in four soil types to research the feasibility of hyperlocal seismic measurements that include P-wave velocity, attenuation, and frequency content.

Consistent target-related spectral signature changes were observed across two independent test sites and in different soil types, though the detailed spectral structure differed between sites. These preliminary results indicate that soil-adaptive detection using soil characterization as the primary data layer rather than an afterthought offers a path toward safer, more predictable, and more efficient ERW clearance operations.

We conclude that further research into this technology is needed.

1 Introduction

1.1 The Scale of the Problem

We are under no illusions about the scope of the unexploded ordnance (UXO) problem. In the United States alone, *“The UXO cleanup problem ... 10 million acres of land at some 1400 sites. Estimated clean-up cost of ... tens of billions of dollars. ... instruments that can detect the buried UXOs also detect numerous scrap metal objects and other artifacts”*. While things have improved since 2003, the Defense Science Board’s assertion that *“Typically 100 holes may be dug before a real UXO is unearthed! ...”* remains too close to reality [1].

We are under no illusions about the human cost of UXO and landmines. According to Landmine Monitor 2024 [2], there were 4,335 civilian casualties in 2023 with 1,498 of them children.

We are under no illusions about the breadth of the UXO and landmine challenge. According to “To Walk the Earth in Safety 2023” [3], 38 African nations, 12 East Asia and Pacific nations, 22 European nations, 12 Middle East and North African nations, 9 South and Central Asian nations, and 16 Western Hemisphere nations other than the United States were actively engaged in ERW cleanup activities.

One hundred and fifteen nations worldwide.

We are under no illusions about the trajectory of this threat. One need only read the headlines about wars—the Russia-Ukraine war, conflicts in the Middle East—to know that the challenge is growing rather than decreasing.

We are under no illusions about the methodology available to detect ERW. It is directly tied to human effort: one person, one detector, possibly operating in an organized group. This is an artisanal process akin to the hand loom weavers who produced cloth before the Industrial Revolution.

We are under no illusions about the availability of bombs and cannon shells and landmines. The means to manufacture and distribute ERW advanced into the industrial age in the mid-nineteenth century or almost 200 years ago. Given the artisanal versus industrial competitive landscape, it is little wonder that the scale of the ERW problem is increasing.

- **Technology.** Threat detection technology focuses on the common characteristic of unexploded ordnance and landmines of a quarter century ago: metal. Metal detectors and magnetometers, each operated by a single human, are the site search state of the art. Other detectors, such as ground penetrating radar (GPR) are also human operated.
- **Trained Animals.** Dogs and rats have been trained to search for subterranean threats. While they offer a different sensing system than the metal detectors, a different technology, the one human one detector ratio remains constant.
- **Trained Humans.** It is not uncommon for sappers to search for ERW using the simplest of all technologies, a simple probe with which to search beneath the surface of the Earth.

We are under no illusions about the challenge of the environment in which ERW is hidden. Soil is incredibly complex and variable. The hyperlocal mixture of sand, clay, and silt varies rapidly in the three obvious dimensions of north-south, east-west, and up-down. Its moisture content and temperature can vary in hours as the sun warms the surface and in minutes as rain adds water. Its chemistry is also complex as, for example, volcanic soils often have very high iron content. Life changes the soil with root structures and tunnels. War changes the soil with a variety of metallic debris, only a small part of which remains a hazardous explosive device.

1.2 Current Approaches and Their Limitation

One size cannot fit all nor can one technology. Every detection technology—electromagnetic, acoustic/seismic, magnetic—propagates energy through soil. The soil’s hyperlocal properties determine how that energy travels, attenuates, reflects, and scatters. And how it returns information to that technology’s user.

The underlying mathematics is simple: the minimum directly detectable object size is proportional to the wavelength; the maximum detection range is determined by the remaining wave energy at the sensor. Both depend entirely on soil properties that vary at scales of meters and hours.

These are not minor calibration issues. In a seismic technology example, P-wave velocity ranges 180-420 m/s across soil types; attenuation varies by orders of magnitude [4]. Moisture absorbs GPR’s microwaves. Laterite confounds detectors focused on magnetism and metals. These factors so limit the

effectiveness of electromagnetic and mechanical search technologies that trained dogs and rats remain in service today.

In some cases, incremental improvements have been achieved. Modern sensor fusion approaches such as the AN/PSS-14 Mine Detection System, magnetometer arrays, and towed multi-sensor platforms have made incremental improvements in detection range and target discrimination. In other cases, progress has been elusive. For example, seismology using acoustic-to-seismic coupling [5, 6] and nonlinear soil-mine resonance [7] has been shown to work well in controlled conditions but could not achieve reliable performance across varying soil types and field environments.

The limit these approaches share is their view of the soil and its place upon the Earth. In some cases, it is a nuisance variable to be overcome. In others it is a fixed parameter. Sometimes it is information to be “looked up” as a reference.

This view of the medium in which the search is to be conducted, a foe rather than a friend, is the common thread.

1.3 The Proposed Shift: Soil as Partner

We propose a fundamental shift in how the soil is viewed: it is a friend and colleague in the search for ERW rather than a foe or a nuisance. It is the primary data layer on which all sensor data is interpreted. It is an informant that, coaxed to do so, will reveal a great deal about what it is and what it holds.

This paper reports on field experiments testing the feasibility of detecting seismic P-waves, S-waves, and Rayleigh waves using hyperlocal COTS instrumentation. It further reports on whether those waves have frequencies and are traveling at velocities that can support the ERW detection mission.

Based on these test results, we propose using broadband rather than forced frequency stimulus and hyperlocal—i.e., meter by meter—near real-time wideband sensing to let the soil answer us in its own way, to reveal what it is willing to reveal.

And it is willing to reveal quite a lot.

2 What We Measure: Six Hypotheses

The seismic subsurface object location technology described in this paper rests on six hypotheses that are based on a foundational observation: real soil, when excited by a broadband impulse, contains and transmits seismic energy at frequencies high enough to be compatible with detecting objects of ERW scales. The field experiments reported here include measurements of energy at frequencies exceeding 900 Hz.

The first four of these hypotheses address specific gaps in the soil property data that have prevented effective use of seismic technology for ERW detection [4]. All the measurements are made of hyperlocal, i.e., meter by meter, soil properties using simple, COTS instrumentation.

Hypothesis 1: It is possible to measure P-wave velocity, which is the most conservative approach to calculating the sensitivity of ERW location using seismic technology.

Hypothesis 2: It is possible to measure seismic frequency content, which is the second key variable in calculating ERW location sensitivity.

Hypothesis 3: It is possible to use the seismic frequency content from Hypothesis 2 to calculate the temporal attenuation coefficients for each seismic frequency. This determines the minimum time between stimulus events and the time during which useful data may be acquired after each event.

Hypothesis 4: It is possible to use the seismic frequency content from two sensors at known relative positions as obtained under Hypothesis 2 to calculate the spatial attenuation coefficients for each seismic frequency. This information describes the potential instrument sensing range.

Hypothesis 5: It is possible to use the hyperlocal seismic wave frequencies and velocities to calculate the smallest object detectable through frequency shifts within range of a sensor. This is the critical performance criterion for an operational ERW detection system.

Hypothesis 6: It is possible to use the hyperlocal seismic waves to detect a change in the nearby soil's hyperlocal properties that indicate a soil anomaly. Such anomalies are likely to indicate the presence of an object that cannot be detected directly.

We note that inadequate sample rates have a major effect on successful seismic measurements as discussed in Section 4.2.

3 Technical Approach

3.1 Methodological Foundation: Let the Soil Speak

This approach originated from a first-principles analysis of seismic instrumentation for a lunar regolith characterization concept that some of the coauthors supported. Applying the calculations involved to the challenge of detecting subsurface terrestrial objects seemed simple enough.

3.1.1 Initial Testing at the Brady Residence

The first principles calculations led to a recognition that the wave frequencies below 100 Hz, even for low velocity S- or Rayleigh waves, would be of limited value in a search for most ERW sized objects. Discussions among the coauthors and preliminary investigations into the literature describing soil frequency response, seismic P-, S-, and Rayleigh wave velocities, and energy attenuation [4] led to a very informal test series focusing on what, if any, frequencies of interest might be found and how far such frequencies might propagate. Further coauthor discussions identified a low-cost, high-frequency COTS inertial measurement unit (IMU) instrument and evaluation kit for a single channel data acquisition (DAQ) approach and the owners of a convenient site were willing to support the effort by donating the use of their property.

3.1.2 Test Procedure Development and Data Acquisition at Bally Cliff Farm

The Brady Residence experience led to several general changes in test procedures. The most important of these, adding a multi-channel DAQ for simultaneous data acquisition from multiple IMUs with a common time reference, failed unexpectedly when we attempted to implement it on July 9.

Testing resumed on August 7 using the two single channel DAQ systems as the multi-channel DAQ remained inoperative despite a continuing software development effort. This test series occurred on August 7, 8, 11, and 12 in a small copse of trees on Bally Cliff Farm. The results of those tests, described in Section 4, established the methodological foundation for subsequent testing at the Bush Combat Development Complex (BCDC) Innovation Proving Grounds (IPG).

The test procedure changes implemented at Bally Cliff included:

1. The addition of a second single channel DAQ
2. A "whack it and wait" stimulus strategy to allow the soil to respond in its own way
3. A down select on surrogate sensor to soil interface hardware
4. The addition of targets, seismic ERW simulants, for some runs
5. The addition of more distant sensor positions.

3.1.3 Multi-soil Testing at the Bush Combat Development Complex

The stimulus cycles developed at Bally Cliff Farm were fully implemented at approximately 0.5 Hz based on success using that cadence. The test instrumentation and DAQ configurations were adapted to the exigencies of actual test operations as described in Section 4.1.3.

3.2 Detection Geometry: Volume vs. Area

The scope of the ERW problem is often expressed in terms of the area of the soil's surface, square meters or kilometers, that is affected. This is misleading because the issue is volumetric. Landmines covered by centimeters of soil are a different problem than unexploded bombs several meters below the surface. This difference in characteristics slows down ERW clearance by requiring a search for suspected landmines to be completed before a search for unexploded ordnance can begin [12].

Our operational concept addresses this in a way that is fundamentally different from conventional seismic survey methods. Rather than a single sensor or linear array that is repositioned sequentially across a site, we deploy sensors continuously in an evolving two-dimensional array. Each sensor position contributes to the coverage volume immediately upon deployment. Low-energy automated stimulus allows data acquisition to proceed exactly where it is needed as the array grows. Sensor spacing is adapted to measured hyperlocal soil conditions—sensors are closer together where attenuation, detection requirements, or imaging objectives demand, wider apart where soil conditions and threat characteristics permit.

The robotic deployment strategy that is a fundamental building block of our approach allows coverage rates to scale rather than be constrained by the pace of human operations. Near real-time data processing for key parameters allows robot path replanning as needed for safe operations and to maintain productivity.

Surface coupled sensors such as handheld magnetometers and GPR, are used to search an area defined by their footprint and the ribbons of soil they examine as the sensor moves. This requires careful, systematic surveys with the sensor's path precisely controlled because gaps lead to unexamined volumes while overlaps are merely duplications of prior results. The search volume is the area of the ribbon of soil searched and the sensor's ability to penetrate the soil being examined, which is driven by hyperlocal soil conditions that are often unknown.

Seismic sensing can offer significant advantages, especially for initial survey operations.

Seismic searches are volumetric with hemispherical search volumes. The research reported here indicates that seismic energy propagates usefully for distances exceeding 5 m in favorable soil conditions. This suggests effective search volumes on the order of hundreds of cubic meters for a single source/sensor combination may be possible depending on the hyperlocal soil characteristics. Overlaps in this volume from closely spaced sensors are not duplicative, they are complementary because the energy's path from the stimulus to the object and from the object to the sensor varies, which produces additional knowledge.

The spectral analysis reported here operates on temporal signals at individual sensor positions and does not require spatial phase coherence across the array. Therefore, the sensor spacing does not limit the detectable frequency content; that is constrained by the temporal sample rate of the individual sensor. The planned operational system deploys sensors at spacings determined by measured, hyperlocal soil properties. This allows the spatial sampling density to be adjusted as needed to address productivity or needed analysis inputs as conditions require.

Importantly, measuring the hyperlocal spatial attenuation of the seismic energy for each frequency in near real-time during the search allows the detectable object size to be known as a function of distance from the sensor, rather than assumed based on reference data. This allows the seismic source and detector array to be optimized for both productivity and efficacy in the expected threat environment and simplifies automated emplacement.

3.3 Multi-Physics Convergent Evidence

Our seismic sensor platform is expected to provide sufficient size, weight, power, and data resources to accommodate other sensors. Several orthogonal sensing technologies have been examined, and notional configurations have been developed for some. We plan to incorporate a selected orthogonal technology in next-generation test hardware, but no detailed designs, strawman hardware configurations, or test articles have been developed.

Seismic sensing is an attractive candidate for multi-physics sensor fusion because it is an acoustic impedance phenomenon while most detectors are based on magnetic, electromagnetic, or electromagnetic radiation physics. Magnetometry senses the magnetic fields associated with ferromagnetic materials. Metal sensing uses transmitting and receiving coils to detect eddy currents that result from the presence of conductive materials such as metal. Both are orthogonal to seismic phenomena, so fusing either of them with seismic sensing would bring information from disparate physics. Multi-sensor fusion that combines orthogonal physics has been shown to improve detection probability and reduce false alarm rates in UXO applications [9].

Similarly, soil characterization provides important information for electromagnetic technologies operating on separate platforms. Hyperlocal soil characterization can include moisture data to indicate the likely GPR signal penetration depth [13], since soil moisture is a primary factor governing GPR attenuation. Seismic area searches can also identify specific anomaly locations that are appropriate for detailed investigations with orthogonal technologies such as GPR.

4 Field Experiments and Results

4.1 Test Sites and Instrumentation

Tests were performed at three sites—the Brady Residence in Pennsylvania, Bally Cliff Farm in Maryland, and the Bush Combat Development Complex in Texas as shown in Figure 1. Testing took place over the two-month period beginning on June 23, 2025, and ending August 21, 2025 [14].

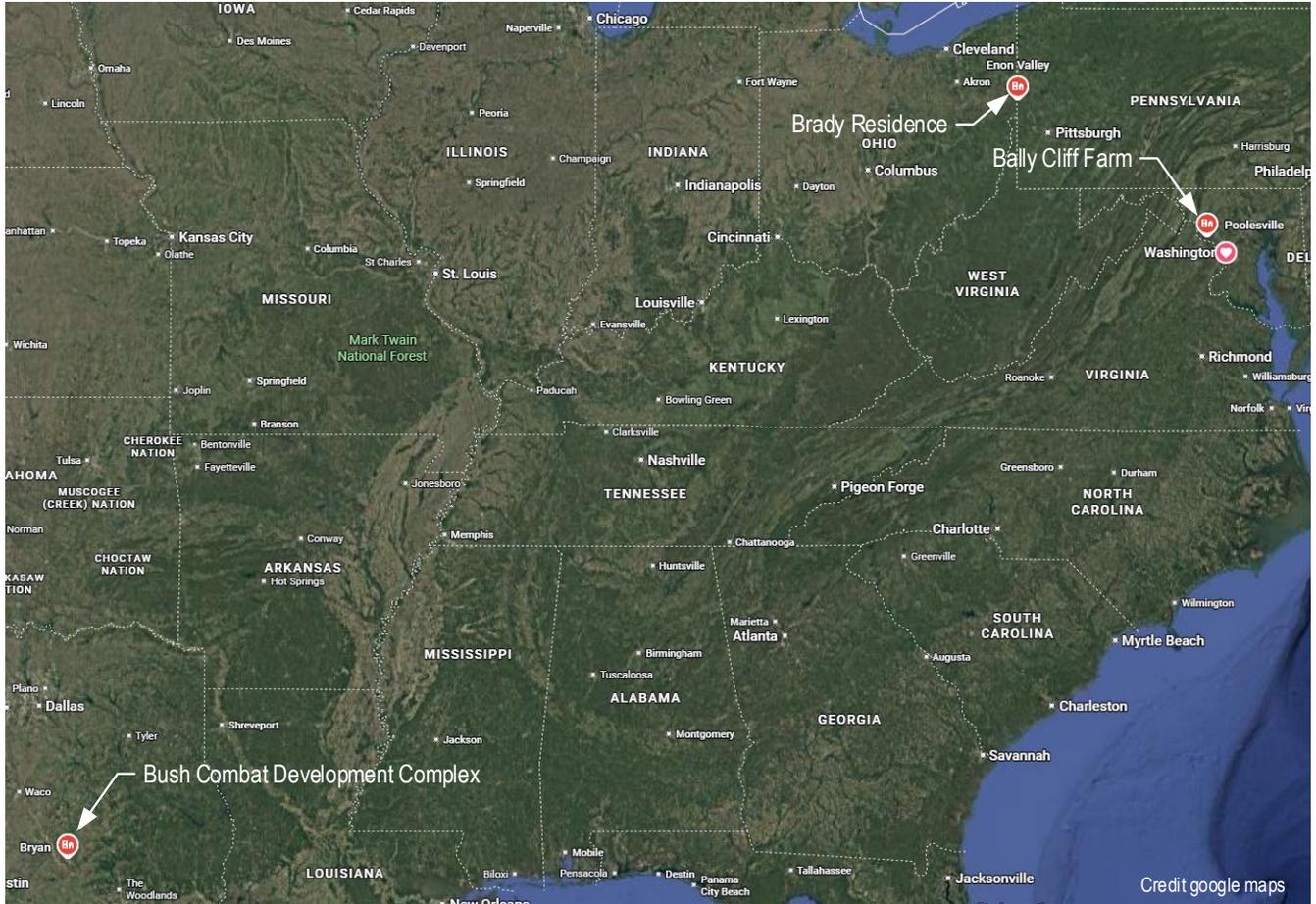


Figure 1. Test locations were dispersed over a wide geographical area.

The general test geometry consisted of a seismic source and a series of IMUs arranged along a single axis as illustrated in Figure 2. The grid is shown as 2 m squares, but the sensors were arranged at 1 m spacing for many tests. Similarly, while the simulated targets are shown at both + and -y locations, testing was generally conducted with the target at a +y position for convenience and because the arrangement was generally symmetrical about the x-axis centerline.

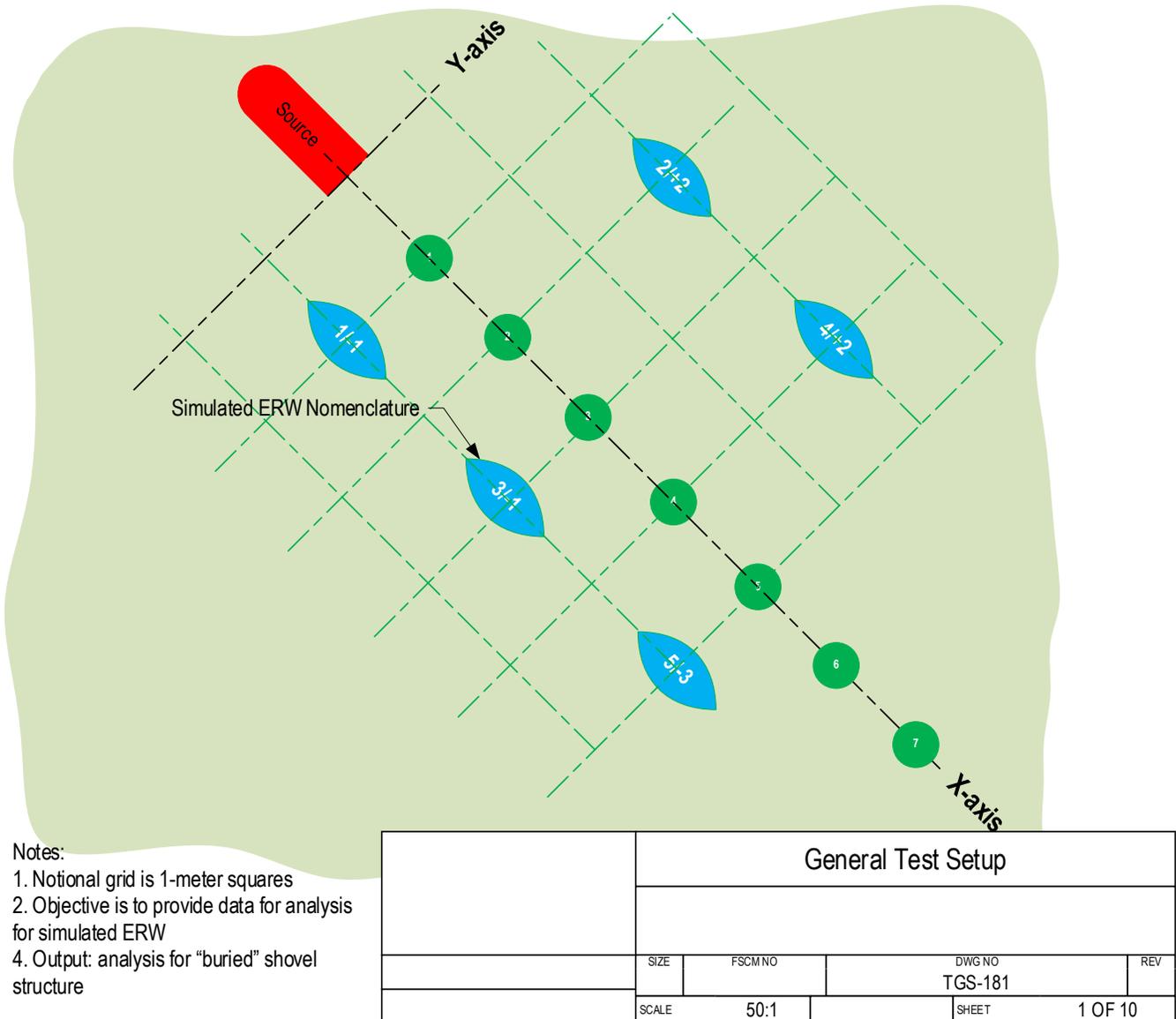


Figure 2. Typical seismic stimulus source, IMU, and simulated ERW locations.

Two primary instrumentation systems—a microelectromechanical systems (MEMS) IMU that delivered three-axis accelerometer data and a contact microphone that provided a single energy level output—were used. Each of these instruments was mechanically coupled to the soil using surrogate tooling.

Three data acquisition systems were used—a dedicated single board computer (SBC) based system sold by the IMU manufacturer, a COTS DAQ designed to support 8 independent instrument channels, and a recording oscilloscope.

The seismic stimulus energy ranged from 3 to 6 joules at stimulus frequencies from 130 to 0.5 Hz. This energy is compatible with automated delivery mechanisms.

4.1.1 Brady Residence Testing

Testing at the Brady Residence in Enon Valley, Pennsylvania took place on June 23 through 25, 2025. The primary work included test setup experiments, testing tooling concepts, observing general test results, and examining a variety of test site characteristics. Digital data was acquired during six test runs. The soil in the test area was not examined beyond general observations but is believed to be a combination of organic material, silt, and loam.

A motorized hammer operating at ~ 130 hammer impacts per second was used based on the assumption that a controlled-frequency stimulus would produce an interpretable soil response at a frequency high enough to be of value. Instead, the continuous stimulus flooded the soil with overlapping signals. This finding led to the subsequent development of the broadband impulse seismic stimulus methodology. A conservative view of the soil's attenuation characteristics led to limiting planned testing to sensor distances from the stimulus of ~ 0.5 , 1, 2, and 3 m.

This early test series validated the selection of the MEMS IMU as a primary sensor.

4.1.2 Bally Cliff Testing

A COTS DAQ able to acquire multiple COTS IMU channels appeared to be functional during software development but failed to operate in the field on July 9 and no data was taken. Testing was suspended at that point in the hope that the DAQ issues could be resolved. The DAQ issues proved to be more difficult to resolve than expected and testing resumed on August 7, 2025, with the two parallel COTS SBC data pipelines.

Testing at Bally Cliff Farm in Poolesville, Maryland, took place between August 7th and August 12, 2025.

The testing was generally performed in a copse of trees penetrated by farm lanes connecting three fields. The soil in the test area was not examined beyond general observations but is believed to be a combination of organic material, silt, and loam with substantial subsurface organic material such as tree roots throughout.

In addition to tests designed to measure soil characteristics, surrogate ERW items, or targets, were included in the testing. A total of 34 runs (23 no-target, 11 with-target) were conducted with sensor distances of 3 to 7 m from the seismic energy source.

The whack it and wait stimulus strategy was put into practice. Listening to the soil's response to a broadband stimulus rather than interrogating it at predetermined frequencies [5, 6, 7, 8] provided data useful for ERW detection.

4.1.3 Bush Combat Development Complex Testing

The BCDC IPG contains designated test areas identified as CLAY and SAND named for the soil type in each facility. We adopted the BCDC capitalization structure to identify our NATIVE SOIL test location adjacent to SAND.

The BCDC test plan was based on full multi-channel DAQ availability at the beginning of testing. It was baselined as an intense one-day effort with multiple sensor locations along a single axis in each BCDC location. With those tests complete, a series of ERW simulants were to be added at various positions.

A total of 39 runs were conducted including 3 unofficial “setup” verification tests. Seventeen of these runs, including the 3 setup runs, were conducted in CLAY, 16 in SAND, and 6 in NATIVE SOIL. Fifteen runs included ERW simulants.

CLAY and SAND are homogeneous layers of the stated soil in a constrained pit approximately 27.5 m (90 ft) in diameter and 0.9 m (36 in) deep. The NATIVE SOIL was not examined in detail but is generally believed to consist of acidic sandy loam, loamy fine sand, some gravel, and limited organic material.

Despite expectations about its availability and ability to provide data acquisition rates above 2 kHz range, the multi-channel DAQ was not available on the first day of testing.

The two single-channel IMU-DAQ systems were set up in the CLAY facility and testing began at a much-reduced cadence on August 20 with the stimulus cycles targeted to be at 0.5 Hz.

Testing continued on the 21st. A contact microphone and digital data logger, a third instrumentation-DAQ option, were added for some testing in CLAY to partially address the difficulties with the multi-channel DAQ. Testing began in SAND with the multi-channel DAQ. Despite manufacturer’s literature performance specifications, it was only able to support 6 data channels at a data acquisition rate slightly above 300 Hz.

The multi-channel DAQ system and instrumentation were moved to NATIVE SOIL when the runs planned for SAND were completed. A weather event forced an early end to test operations.

4.2 The DAQ Lesson

Multi-channel data acquisition at the Texas test site relied on COTS interface hardware that could not meet performance expectations based on manufacturer literature. The resulting effective sample rate of slightly over 300 Hz—versus the above 2 kHz sample rate achieved with the single-channel SBC DAQ—all but eliminated useful frequency content at the SAND and NATIVE SOIL test areas by reducing the Nyquist frequency to approximately 150 Hz. Coarse P-wave velocity estimates may be possible from arrival-time analysis, and analytical work to recover them is ongoing, but the desirable spectral characterization of these soil types will require retesting with adequate data acquisition equipment.

This experience confirmed that data acquisition bandwidth is not a peripheral concern but a first-order system requirement for hyperlocal seismic characterization. The design of, and planning for a purpose-built, widely expandable, Raspberry Pi-based DAQ with GPS-synchronized timing is underway to address this limitation in planned future testing.

4.3 P-wave Velocity

P-wave velocity was measured as 272 m/s in BCDC IPG CLAY using two contact microphones separated by 3 m, a digital oscilloscope acquiring data from them at 10 kHz, and identifying the first break in values from the background noise. This value is close to the midpoint for the P-wave velocity range Oelze [4] reports, i.e., from 180 to 420 m/s, across soil types, and is used in the detection limit calculations in Section 4.8.

Data analysis is continuing for the lower bandwidth data acquisition system used in the BCDC SAND and NATIVE SOIL locations and for an ad hoc approach to synchronizing the two single pipeline, high bandwidth instruments. This work will continue and be reported as a part of future research.

4.4 Frequency Content and Spectral Characterization

Energy was detected at frequencies above 900 Hz at both Bally Cliff Farm and BCDC IPG CLAY using the SBC DAQ and COTS instrumentation. The data shows a rich spectral response at both locations and coherent signals at distances from the seismic source to the instrument of up to 7 m. The successful recovery of coherent data at Bally Cliff Farm is more impressive because data from only about 5 stimulus events were available for signal to noise enhancement.

Testing was not extended beyond 7 m because a literature review (Oelze [4]) had indicated that detecting meaningful signals was unlikely. The lessons learned include placing instrumentation at greater distances and making greater use of signal to noise enhancement methodologies.

Figure 3 shows the variation in normalized signal amplitude (/Hz) versus frequency for instrumentation placed at distances from 3 to 7 m from the seismic source during testing at Bally Cliff Farm. The effect of increasing distance is as expected. The 3m curve (blue) has sharp peaks, the 5m curve (pink) is lower, and the 7m (yellow) spectrum is almost flat. All runs were accomplished with only about 5 stimulus events, so signal to noise improvement during data processing was limited to a factor of about 2.2.

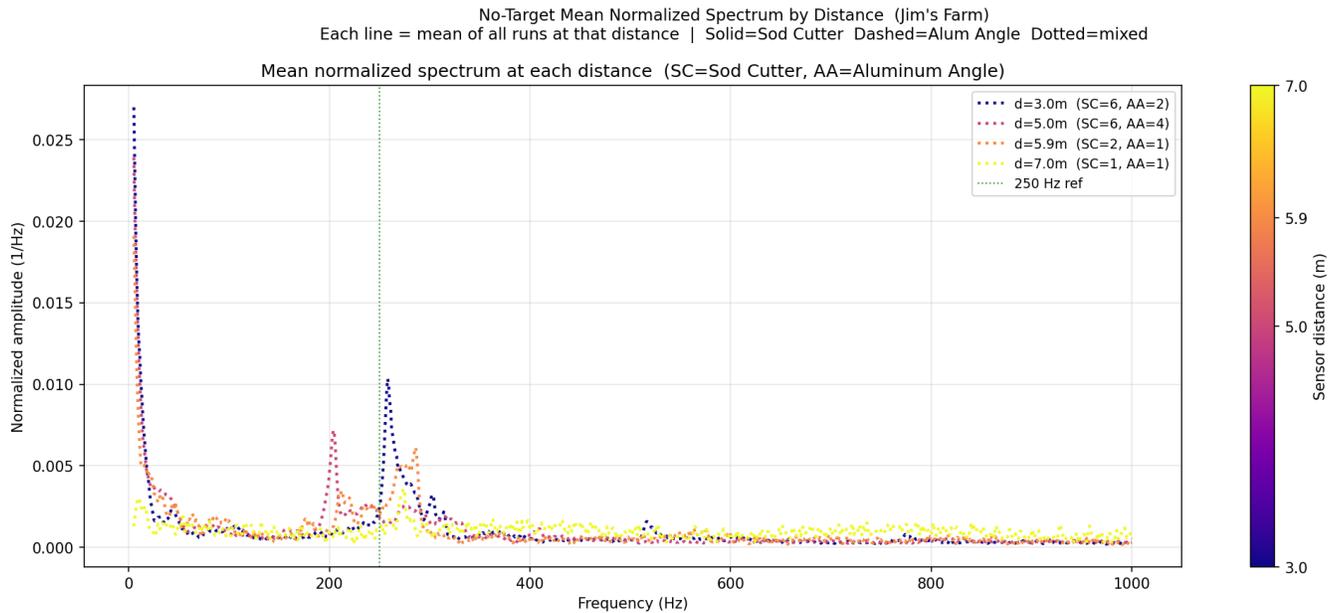


Figure 3. Spectral trend versus distance at Bally Cliff Farm.

The data shows that higher frequencies attenuate more quickly than lower ones. This is as expected based on the literature ([4]), is consistent with soil physics, and supports the COTS instrumentation's ability to capture soil properties.

Visual examination of a spectrogram of the 7 m data at Bally Cliff Farm, not included here, shows structured bands of energy persisting hundreds of ms after initial stimulus arrival. This warrants further investigation with test configurations designed to capture the data with enhanced signal to noise ratio, added instrumentation, and properly designed test conditions.

4.5 Temporal and Spatial Attenuation

Data supporting attenuation measurements was acquired at Bally Cliff Farm and in the IPG CLAY facility. Both temporal and spatial attenuation are soil-type-dependent and reference or average values are insufficient for ERW detection through seismic operations.

Temporal attenuation is the energy decay rate in each frequency band over time after the energy first arrives at the sensor. The decay rate (s^{-1} or Alpha) measured in CLAY was approximately constant in the $25 s^{-1}$ to $30 s^{-1}$ range over the 50 Hz to 1 kHz range except for a pronounced drop below $20 s^{-1}$ in the 400 to 450 Hz band. The corresponding decay time (ms or Tau) was generally below 40 ms except for a pronounced rise to above 60 ms in the 400 to 450 Hz range.

Spatial attenuation, the ratio of spectral amplitudes between two sensors at known distances from the same source, is the decay over distance. The corresponding spatial attenuation results are functions of frequency as expected. They range from approximately 10 dB/m at low frequencies to about 20 dB/m at 200 Hz, then fall to approximately 0 dB/m at about 400 Hz. The attenuation rate then recovers to about 20 dB/m at 1 kHz. The anomalous attenuation behavior near 400 Hz may be related to the concrete floor at about 1 m depth. A second harmonic at 1 m depth falls near 408 Hz.

4.6 Soil-Type Spectral Differences

Wave spectral responses were successfully developed for the Bally Cliff Farm and in the IPG CLAY facility, both with and without surrogate targets located at various distances normal to the line through the seismic source and sensor positions.

This spectral data showed changes in the 250 Hz range at both sites when a surrogate target was added but had significant differences as well. BCDC shows a trough at 250 Hz plus peaks at 510, 710, and 830 Hz; Bally Cliff shows peaks at 260 and 330 Hz with no higher-frequency features.

In a “like to like” comparison, the 3 m no-target Bally Cliff Farm and the 3 m no-target IPG CLAY data show clearly different spectral shapes. This difference is a demonstration of the importance of hyperlocal soil characterization data.

4.7 Target (ERW Simulant) Detection: Preliminary Observations

Testing included runs with and without a target, or ERW simulant, at both Bally Cliff Farm and at BCDC. The Bally Cliff Farm and BCDC IPG CLAY data were taken at a high data rate while the SAND and NATIVE SOIL data were taken at slightly more than 300 Hz.

Hand shovels were used as metallic ERW simulants. They were forced into the soil to convenient depths and not dimensionally characterized during testing. A lesson learned is that future experiments will use targets of known dimensions to enable direct comparison with calculated detection limits.

The upper part of Figure 4 compares root-sum-square data for three without-target runs (blue) with three with target-runs (orange) by superimposing the normalized amplitude ($/\text{Hz}$) of the signals and their averages on a single chart. A close examination of the figure reveals that the blue lines are tightly overlaid on one another, and the orange lines are similarly superimposed. The average lines are only detectable as separate from the individual runs on close examination. The data repeatability was very good.

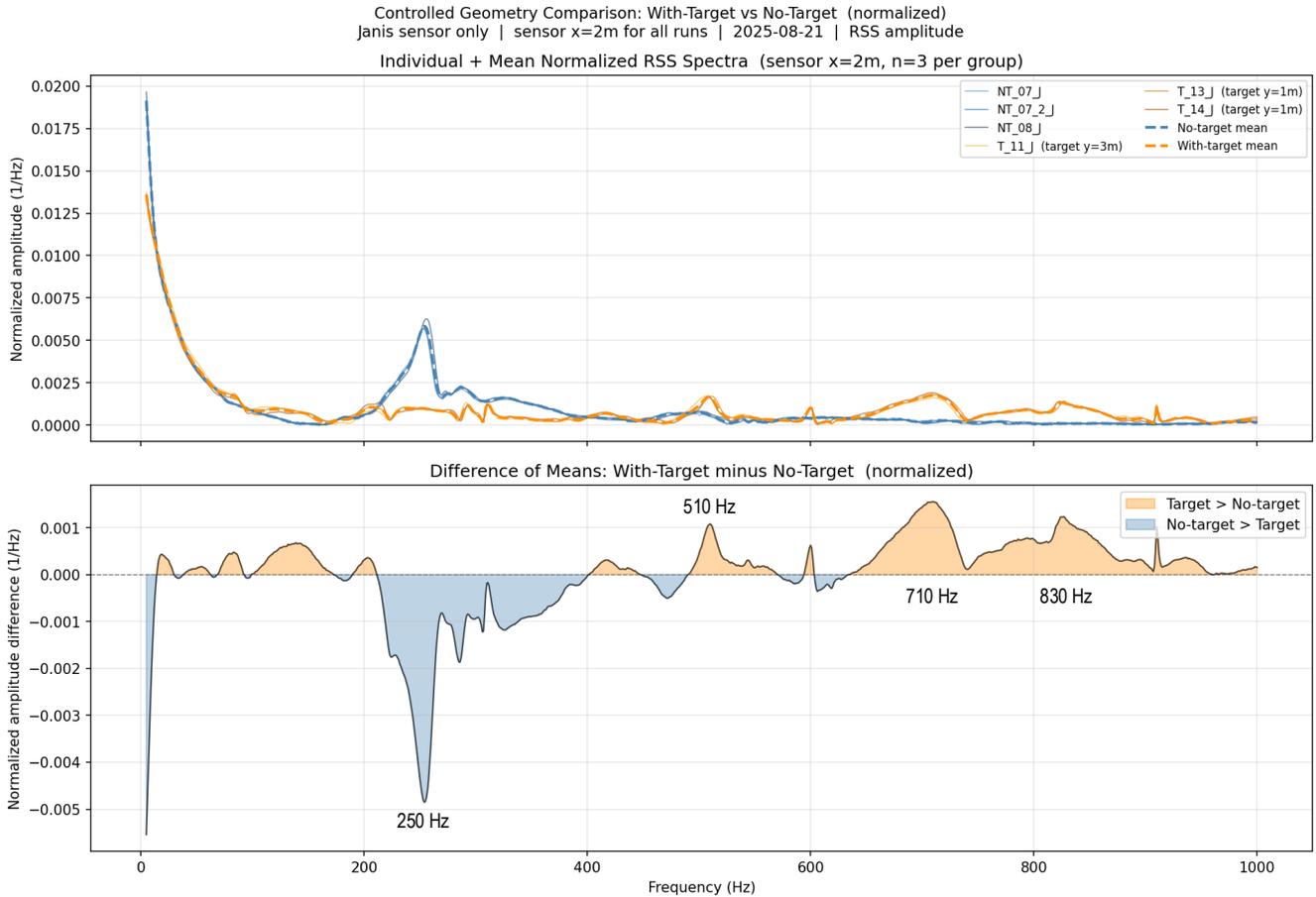


Figure 4. No-ERW simulant and with-ERW simulant BCDC IPG CLAY direct comparisons.

The lower portion of Figure 4 is a graphical representation of the difference between the means of the two groups shown in the upper portion. The key observation is not the nature of the differences but that they are clearly and consistently present—a distinct trough centered near 250 Hz and clear peaks near 510, 710, and 830 Hz. These differences suggest that meaningful energy is available at frequencies approaching 1 kHz and that the hyperlocal frequency spectrum changes measurably when an ERW simulant is placed nearby.

A rough estimate of expected reflection frequencies from the 200 mm (8 in) thick concrete floor at a depth of approximately 0.9 m (36 in) yields a fundamental near 149 Hz with higher harmonics near 299 and 448 Hz. Some features in the attenuation data may be influenced by this boundary. The observation of similar target-related spectral changes at Bally Cliff Farm, which has no artificial subsurface boundary, suggests the target-detection findings are not solely attributable to the concrete floor, but controlled experiments in unbounded soil are needed to resolve this question.

Limited per-axis spectral decomposition of individual run target data versus the 3-run average no-target data shows consistent target-induced features across two target positions at different ranges combined with amplitude differences consistent with a distance-dependent relationship.

We measured coherent signal propagation at distances of up to 7 m.

Reduction of the Bally Cliff Farm data showed spectral differences in a partially overlapping frequency range (200–350 Hz), with pronounced peaks at approximately 260 Hz and 330 Hz. The

higher-frequency features observed at BCDC (510, 710, and 830 Hz) were not present at Bally Cliff, which may be due to differences in soil type, ERW simulant configuration, signal-to-noise ratio from fewer stimulus events, or the bounded geometry of the BCDC CLAY facility. No effort has been made to develop similar data for SAND or NATIVE SOIL because the Nyquist limit combined with the data acquisition rate of slightly over 300 Hz limits the frequencies that can be detected.

4.8 Detection Limits

Estimating ERW detection limits for seismic technology is an inherently site-specific exercise because the four key values in the estimates—the relevant seismic velocity (P-wave as worst case), seismic wave frequency, the characteristic dimensions of the ERW threat, and the sensor’s view of that threat—are all controlled by the hyperlocal conditions and are unknown for any general discussion. Thus, this examination is a single example based on the hyperlocal and very limited test data from the six runs in the BCDC IPG CLAY test area discussed in Section 4.7.

The normalized difference of means between the three no-ERW simulant and three with-ERW simulant runs shows a distinct trough at 250 Hz and clear peaks at approximately 510, 710, and 830 Hz. The measured P-wave velocity in the CLAY test area was 272 m/s (Section 4.3). These values produce $\lambda/4$ minimum detection dimensions [15] of 272, 133, 96, and 82 mm for the frequency changes observed. The peak frequencies in the reduced data may reflect soil-target coupling, cavity resonance, or scattering phenomena rather than geometric resolution and are used here for illustrative purposes. The physical mechanism linking spectral perturbation frequency to object dimension requires further investigation.

The lower velocities of S-waves (conservatively estimated as 60% of P-wave velocity in dry, stiff soil or 163 m/s) and Rayleigh waves (estimated as 90% of S-wave velocity or 147 m/s) would indicate the ability to detect proportionally smaller targets.

Unexploded ordnance dimensions vary greatly. For example, hand grenades might be represented as a small cylinder 64 mm in diameter and 89 mm long. Similar dimensions for a 60 mm mortar shell would be 60x300 mm and for a 155 mm artillery round might be 155x750 mm. The potential for detecting such ERW using the worst-case wavelengths associated with the P-wave velocity is summarized by the “X” in the combined dimension and frequency in this table.

Typical Ordnance	Short Dimension	Frequency (Hz)				Long Dimension	Frequency (Hz)			
		250	510	710	830		250	510	710	830
Grenade	64 mm					89 mm				X
60 mm Mortar	60 mm					300 mm	X	X	X	X
155 mm Artillery Round	155 mm		X	X	X	750 mm	X	X	X	X

Note that in actual operation, seismic sensors will be placed such that their hemispherical coverage volume overlap (Section 3.2), thus significantly increasing the likelihood that one or more observations will be made of the long dimension.

This illustrative example is from specific, hyperlocal measurements and demonstrates the value of the hyperlocal measurement approach: Every hyperlocal location on every site has its own measured and calculated detection limits.

5 Discussion

5.1 Implications for ERW Clearance Operations

The seismic search technology reported here benefits ERW search operations in multiple ways.

The most significant benefit is the technology's hyperlocal methodology. The specific search process can be adapted to meet the needs of a specific site. Source-sensor equipment spacing can be adjusted to meet small threat detection needs based on measured capabilities rather than set operating standards. Overlapping sensing volumes add to a rich understanding of the subsurface world through different views of a given volume.

The hyperlocal methodology ultimately produces multiple detection opportunities with a single data stream. Objects, such as the shovels used at Bally Cliff Farm and BCDC, reflect or scatter seismic waves producing a frequency response. Measurements of P-wave velocity and attenuation characteristics at hyperlocal scales also examine the soil itself to detect changes in any characteristic—velocity, for example—over a short distance that may be statistically significant. Future testing will evaluate the use of such differences to address both landmine and UXO hazards in a single pass rather than the repeated examinations that are currently required [12].

The adaptive nature of the hyperlocal deployment allows an algorithm-based balancing of detection sensitivity and search productivity. Hyperlocal soil measurements allow optimization of search parameters—including stimulus count, sensor spacing, and search speed—for each specific area.

Seismic technology is unaffected by soil magnetic characteristics, making it effective in iron-rich volcanic soils and areas heavily contaminated by ferrous debris such as shrapnel—conditions that severely degrade magnetometer and metal detector performance.

Additionally, the seismic technology as planned has the potential for major enhancements.

The technology itself is designed for robotic, rather than human, deployment. This provides many benefits, the most important of which is removing humans from the danger zone. It also leverages human labor for enhanced productivity and can shorten site search timetables through multi-shift work schedules.

The deployment strategy is compatible with other instruments that use orthogonal physics for detection. Integration of an orthogonal sensing modality is now moving from the conceptual phase to the strawman design phase as described in Section 3.3.

The measurement geometry is compatible with tomographic imaging, which would provide subsurface visualization to support detailed investigation—possibly by an orthogonal technology such as GPR—or Explosive Ordnance Disposal operations. Sensor placement requirements and software enhancements to create tomographic images are in the early evaluation stage.

5.2 Limitations

The research reported here is limited by several factors and should be evaluated bearing them in mind.

The research objectives were limited to hyperlocal soil characterization using seismic waves. There was no intent to use those waves to create images nor was any effort made to do so. This is future work.

The test data is from small sample sizes. For example, the BCDC controlled no-target to with-target comparisons are limited to three runs per group. Many more properly controlled experiments with larger sample sizes are required to demonstrate an operational capability.

Our test logs make the presence of many confounding variables during the exploratory testing at Bally Cliff Farm very clear. These included the irregular use of a sound deadening cover or hat, different sensor-to-soil coupling surrogates, occasional hand damping of test equipment vibration, the distance from the seismic source to the sensor, the presence of a target, and the target's position. While distance-controlled comparisons addressed the most critical confound, even these were somewhat obscured by the non-homogeneous nature of the soil between the seismic source and the sensor from undocumented artifacts such as tree roots.

DAQ bandwidth is an important limitation. It ranged from a low of somewhat more than 300 Hz for the sensor data acquired through the COTS DAQ to 10 kHz for the data logger used with the contact microphones. This variation in bandwidth is particularly important because having no high-frequency data from SAND or NATIVE SOIL limits seismic frequency extraction and P-wave velocity measurement precision as described in Section 3.

Our testing included only one direct P-wave velocity measurement. That was done in the BCDC IPG CLAY facility as a "one off" implementation of the instrument and DAQ combination involved. This only demonstrates the measurement capability, not an integrated capability from a single instrument-DAQ IMU. Data reduction is ongoing to extract seismic P-wave velocity from SAND and NATIVE SOIL using the severely degraded multi-channel sample rates, but this will have only very limited precision.

The ERW simulants used were informal, simply metallic probes such as hand shovels inserted into the ground, rather than a to-scale UXO model or calibrated surrogate. We plan to include calibrated surrogate ERW simulants in future testing.

While the soil conditions in CLAY and SAND are well documented, the soil composition in NATIVE SOIL, at Bally Cliff Farm, and the Brady Residence is only estimated from superficial visual assessments. The importance of collecting data defining the soil's characteristics as ground truth during each test program is a lesson learned.

Both CLAY and SAND have concrete floors below the well-defined soil. What effect this artificial boundary has on the observed spectral features has not been analyzed.

The inter-stimulus timing of approximately 0.5 Hz is not optimized. It has been inconsistent due to manual operation. Establishing both the optimal stimulus frequency to balance signal decay with operational throughput and optimal energy for sensor function at varying distances are open research questions. We plan to use automated stimulus mechanisms in the future, but these are conceptual in nature.

Spatial sampling at intervals shorter than the wavelengths of interest would be required for wavefield imaging techniques such as tomographic inversion. This would require several closely spaced sensors to study a specific area of interest identified during the site survey. Tests to investigate this are planned for future array configurations.

The sensor fusion concepts described briefly in Section 3.3 have been studied in some detail but remain entirely hypothetical. No instruments were included in these tests and testing of the multi-physics convergent framework described in this paper is in the design and planning stage.

5.3 Relationship to Prior Work

We are far from the first to propose seismic technology for ERW detection.

Sabatier and Xiang [5, 6] demonstrated acoustic-to-seismic coupling using airborne sound as the seismic stimulus and laser Doppler vibrometry as the sensor to detect landmine resonances. Donskoy [7] extended this with nonlinear vibro-acoustic methods. Both approaches used forced-frequency excitation and a remote sensor for surface measurement, a sensing approach that can be degraded if the soil is hidden as with vegetation. Our approach differs fundamentally in two ways: broadband impulse excitation and subsurface-coupled sensors that listen to the soil's natural response.

Park, Miller, and Xia [10, 11] exploited Multichannel Analysis of Surface Waves (MASW) by measuring shear-wave velocity and analyzing Rayleigh wave propagation to image the subsurface volume. While the application domain differs, the dispersive surface wave phenomena that MASW exploits appear to be present in the 7 m spectrogram data taken at Bally Cliff Farm—as mentioned in Section 4.4. Additional research is needed to evaluate how our hyperlocal processes may exploit these measurements.

Current sensor fusion approaches typically combine electromagnetic phenomena—magnetometry with electromagnetic induction, or metal detection with GPR. While effective, these fuse sensors that respond to related physical properties. The sensors are different but the physics they exploit is similar. The sensor fusion now being considered for the seismic sensor uses orthogonal physical phenomena and adds soil characterization as an input to fusion, thus conditioning detection criteria on measured local soil conditions.

6 Conclusions

The results of the work described in this paper can be summarized in six specific achievements that support our six hypotheses. We measured hyperlocal P-wave velocity satisfactorily over short distances in CLAY as well as seismic frequency content both in CLAY and at Bally Cliff Farm. We were able to use that data to calculate temporal attenuation coefficients, spatial attenuation coefficients, and the smallest detectable object within range. We detected nearby anomalies based on consistent spectral differences between no-target and with-target runs at two independent sites.

Our use of broadband impulse excitation produced a variety of soil seismic responses that provide potential ERW detection methodologies.

Per-axis spectral decomposition revealed consistent target-induced features.

We measured coherent signal propagation at distances of up to 7 m.

All of this was achieved with inexpensive COTS instrumentation.

Despite these achievements, our results cannot be broadly interpreted. The limits of the work include small sample sizes, only superficial knowledge of the soil involved in three of the five soil types, and ad hoc ERW simulants.

The work described is preliminary data, not proof that an instrument system based on seismic technology has a broad operational application.

Thus, significant work remains to be done.

We conclude COTS instrumentation and high-frequency, hyperlocal soil characterization have the potential to become the foundation for an economically viable broadly applicable ERW detection system. “Potential” is, however, insufficient and further research into this technology is needed.

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8 Author Biographies

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Stephen Morehouse is a retired professional pilot with 60 years of flying experience. He has a BS degree in Mechanical Engineering from Tri-State University. During his 5-year tour in the Air Force, he

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Janis L. Tabor is a founder and the President and CEO of GoVentures, Inc. She built a career spanning technology policy, science communications, federal government relations, and strategic consulting. Highlights include serving as Executive Director of the Council for Chemical Research, Director of Government Relations for ASME International, and founder and president of EnergyTrack, Inc. She holds a Bachelor of Arts degree from the University of Maryland and is a lifelong learner with graduate and professional studies at institutions ranging from Hood College to Duke University.

Paul Kirchman is a mechanical systems engineer in Aerospace and Nuclear fields. He provided engineering support to Hubble Space Telescope servicing missions, James Webb Space Telescope (JWST), Geostationary Operational Environmental Satellites (GOES), Tracking Data Relay Satellite System (TDRS), and numerous smaller programs. He is a subject matter expert in finite element analysis and software development using MATLAB, Python, and C.

Joseph T. Kujawski is an experienced engineering leader and current IEEE Congressional Fellow with more than two decades of cross-disciplinary accomplishments spanning space systems, electronics, mission architecture, and technology policy. He has delivered complex projects across government, industry, and academia including contributing core electronics to major NASA missions, leading development of space-based weather instruments, and helping transform organizations through AS9100 certification, strategic growth, and multidisciplinary team building. In the U.S. Senate, he provides technical expertise on space, semiconductor, and emerging technology issues, informing legislation, oversight, and constituent engagement. As an engineering executive, consultant, and inventor with multiple patents, he has guided R&D efforts, secured significant grant funding, and mentored the next generation of engineers. He holds an MSEE from Rensselaer Polytechnic Institute and a BSEE from the University of Alabama at Birmingham.

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