

Field Testing and Development of a Seismic Landmine Detection System

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Abstract

A technique for the detection of buried landmines, which uses a seismic probing signal in conjunction with a non-contact radar-based surface displacement sensor, has been studied for several years at Georgia Tech. Laboratory experiments and numerical models have indicated that this technique shows great promise for imaging a large variety of mine types and burial scenarios. In order to develop a detection system based on this technique, recent studies have focused on transitioning the experimental work from laboratory models to realistic field environments, which poses several challenges for system development. Unknown soil properties at field sites as well as the presence of local inhomogeneities, vertical stratification, and surface variations make the propagation and the modal content of the seismic probing signal more difficult to predict. This complicates the processing required to image buried mines. The small-scale surface topography and naturally-occurring ground cover impede the function of the system's non-contact sensor, which must be capable of looking through the ground cover and spatially averaging its measurement over the irregular surface. A prototype detection system has been tested at several field sites with widely disparate soil properties. Problems were encountered that required modifications to the system sensor, scanning technique, and signal processing algorithms. Following these changes, system performance comparable to that observed in laboratory models was demonstrated during field testing.

Keywords: Mine Detection, Seismic Waves, Elastic Waves, Electromagnetic Waves.

1. Introduction

Landmine detection research at Georgia Tech has led to the development of a seismic landmine detection technique^{1,2} which excites elastic waves in the ground with a surface-contacting seismic source and measures the resulting surface displacements with a non-contacting radar sensor. A conceptual drawing of the current experimental system is shown in Figure 1 with the seismic source and a two-element array of independent radar sensors. The ground-contacting seismic source has been coupled to the ground so as to preferentially excite Rayleigh surface waves; other waves are also excited by the seismic source^{1,3,4} but the Rayleigh surface wave is the most valuable for interrogating the near-surface layers due to the exponential decay of the amplitude of the Rayleigh wave with increasing depth. As the waves travel through the region of interest, they generate surface displacements that can be measured using the non-contact radar sensor. The waves interact strongly with the buried mines as landmines are complex mechanical structures with flexible parts, air chambers, and trigger mechanisms. Scattered waves and resonances of the mine soil system are clearly evident from the experiments. The interaction of the buried landmine with the surrounding soil produces a resonator which is easily excited by the Rayleigh waves. The resonator causes an enhanced motion of the soil above the mine due to the compliance of the mine^{2,3,5,6}.

The radar sensor has been designed as a non-contact sensor that operates at distances of 10 to 30 cm from the ground to allow detection of mines beneath surface clutter and variations in the surface contour^{2,7,8}. Buried landmines have been detected using this sensor when the ground was covered by 15 cm of pine straw. While the current

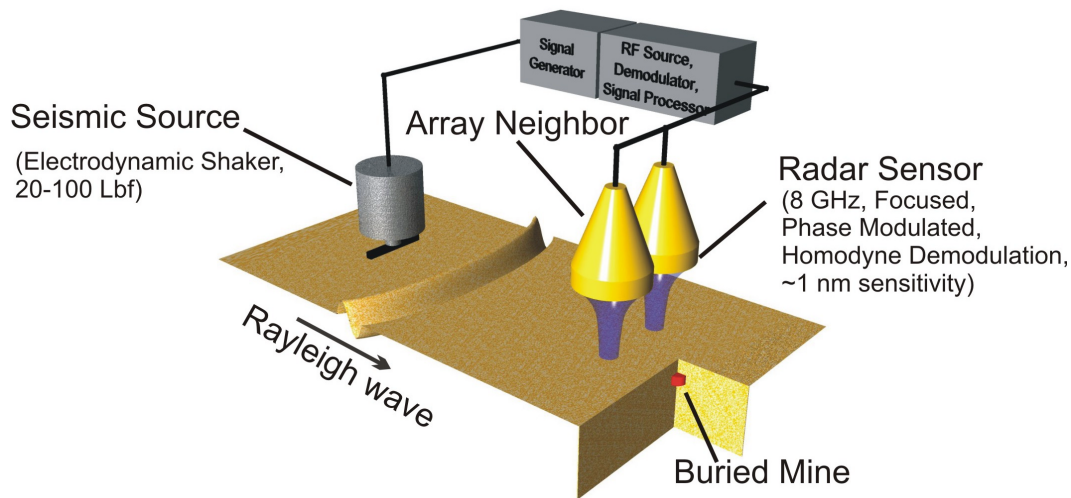


Figure 1: Prototype Seismic Landmine Detection System Using Two Radar Sensors.

experimental system uses two radar sensors, much larger sensor arrays are envisioned; multiple sensors would increase the system's scanning speed with no loss of measurement accuracy.

Testing at realistic field sites has been done as the first step in determining the required system parameters for a field-operable landmine detection system. Surface topology, soil stratification, inhomogeneities, and unknown soil properties have affected the propagation and detection of the Rayleigh surface wave at the field sites. Field experiments are currently being conducted to determine soil properties pertinent to landmine detection for use in system and modeling efforts; a range of probable soil types and environmental conditions for demining operations are being studied⁹⁻¹¹. A 3-D numerical model³ has also been developed and is being used to interpret and understand the field experiments. Measurement techniques and signal processing algorithms developed based upon laboratory and numerical models are being refined based upon field testing of the experimental system. In the following sections, field measurements at a road-bed site at a temperate U. S. Government test facility of several anti-personnel and anti-tank mines will be presented. Additionally, system development issues such as scanning speed, possible system configurations, and an audible data presentation method for a hand-held scanner will be discussed. Future experiments will be conducted to define system parameters for a field-operable landmine detection system based upon realistic demining scenarios.

2. Field Measurements

The numerical model and experimental measurements have indicated the necessity of testing the system in a variety of soil types under differing environmental conditions. In addition to variations of the mean soil properties at a given site, the depth-dependence of material properties has been shown to be of great importance to accuracy and reliability of numerical modeling^{3,6}. To transition the system testing and evaluation from the laboratory experimental model to typical field environments, several field measurements have been conducted at a variety of sites with differing soil and environmental conditions^{2,10,11}. The latest field measurements were conducted at the road-bed site; tests included a VS-2.2 anti-tank (AT) mine buried one inch deep, a PMD-6 anti-personnel (AP) mine buried 1.75 inches deep, an M19 AT mine buried two inches deep, an M19 AT mine buried three inches deep, a TMA-4 AT mine buried one inch deep, and a TM62M AT mine buried four inches deep. Both one-dimensional and two-dimensional scans were conducted for comparison with scans over areas not containing landmines or buried clutter objects.

Figure 2 shows the prototype system at two different field sites, the Georgia Tech Research Institute's Cobb County Research Facility in Smyrna, Georgia, and the road-bed site. The positioner can scan a 2m by 1m region with



Figure 2: Field Measurement System with Two Radar Sensors at (a, b) Georgia Tech Research Institute – Cobb County Research Facility in Smyrna, Georgia, and (c) a road-bed site at a temperate U. S. Government Test Facility.

two radar sensors. An automated PC-based measurement system featuring amplification and filtering electronics, data acquisition hardware, motion control hardware, and software are used for data acquisition and motion control. The system's operation consists of moving the sensor to a measurement location, exciting elastic waves in the ground, and measuring the resulting surface displacements. The system typically scans either in one dimension at points evenly spaced along a line extending away from the seismic source (linear scans) or in two dimensions at points in a regularly spaced grid in a region adjacent to the seismic source (area scanning). At each measurement point, a broadband signal is used to interrogate the ground; swept-frequency chirps from 50 Hz to 2 kHz are typically used. A transfer function is recorded which relates the measured surface displacements to the input broadband signal. Convolution of the transfer function with a narrowband pulse in the post-processing presents the data in the time domain for analysis.

In Figure 3, 1-D images are presented for each landmine and a region that did not contain any landmines or clutter objects. The images represent a measure of the strength of the resonances and the scattered waves¹². All data are presented on a 30 dB scale in reference to the measurement of the VS-2.2 AT mine buried one inch deep as shown in Figure 3(b); this particular test case exhibited the largest surface displacements of these test cases. In Figure 3(a), the measurement noise floor can be identified at greater than 30 dB below the reference level. The increased noise level near the ends of the scan in Figure 3a is due to the artifacts in the imaging algorithm. It should be possible to improve the algorithm to remove these artifacts, and, thus, lower the noise floor significantly. In all of the test cases, the measured surface displacement over the buried landmines was greater than the noise floor as seen in Figure 3. The responses of both the VS-2.2 mine and the PMD-6 mine are very strong; the response of the VS-2.2 is 30 dB greater than the noise level. The mines with the weakest response are the TMA4 and the TM62M; both of these resonate

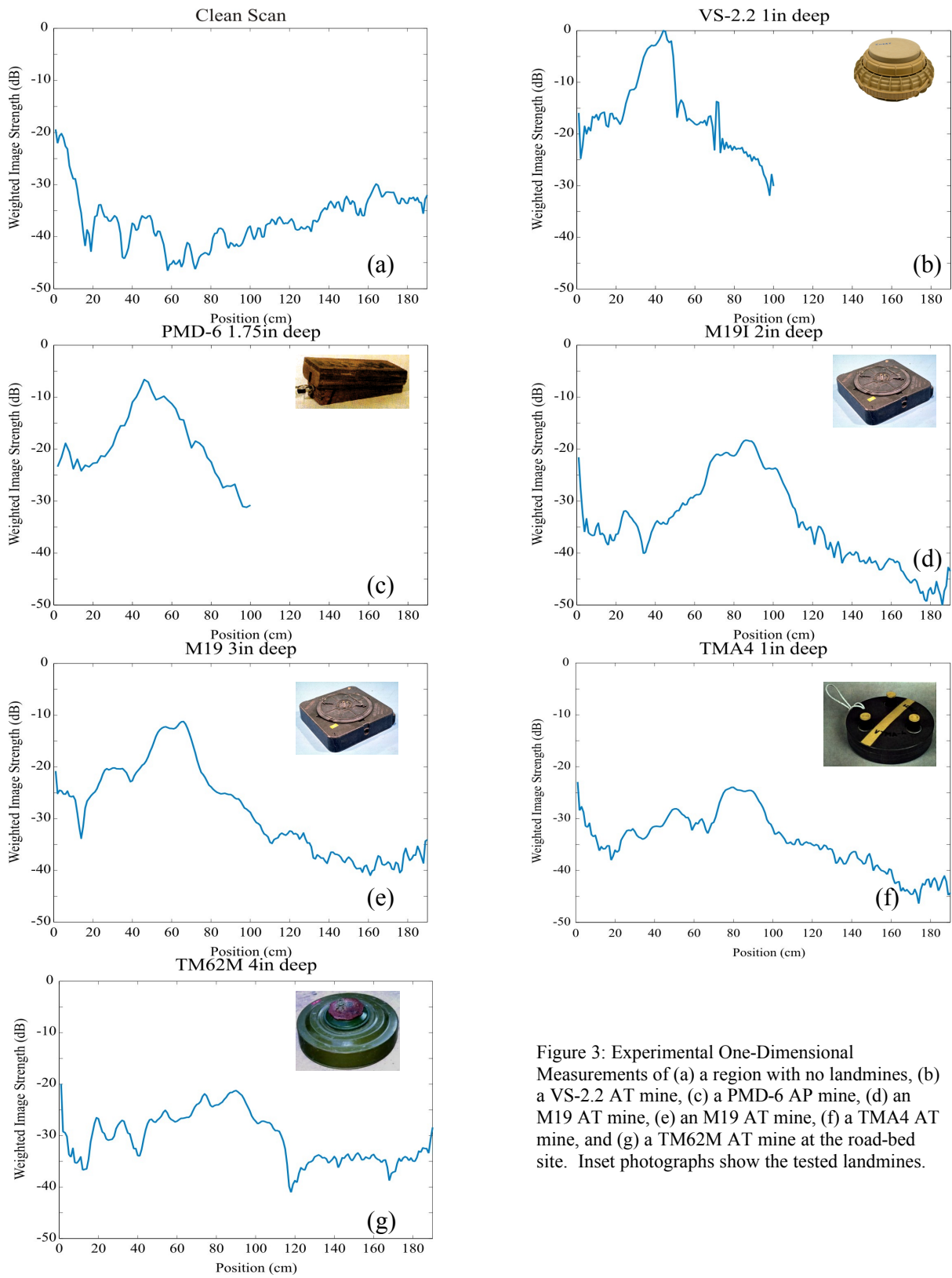


Figure 3: Experimental One-Dimensional Measurements of (a) a region with no landmines, (b) a VS-2.2 AT mine, (c) a PMD-6 AP mine, (d) an M19 AT mine, (e) an M19 AT mine, (f) a TMA4 AT mine, and (g) a TM62M AT mine at the road-bed site. Inset photographs show the tested landmines.

poorly due to their very stiff tops. This increased response at the landmine burial location can be attributed to the mine-soil system resonance as previously mentioned.

Area scans were conducted with two landmines, a VS-2.2 AT mine buried one inch deep and a PMD-6 AP mine buried 1.75 inches deep. The VS-2.2 AT mine is a predominantly plastic mine that measures 24 cm across its diameter and 11.5cm in height. The PMD-6 AP mine is wooden and measures 19.6cm by 8.7cm by 5.0 cm; the top surface is hinged at one end. Images plotted on a 30 dB scale relative to the maximum surface displacement measured during each scan, shown in Figure 4 for each of these test cases, clearly identify the locations of the buried landmines in the scan regions, each a 1.2 m by 0.8 m area. The source was located along the centerline of the scan region, just to the left of the regions shown in Figure 4. The clutter immediately in front of the source in both of the images in Figure 4 can be attributed to interactions in the near-field of the source with a small plastic pipe used to mark the test site.

3. System Development

While testing the prototype system at various field sites to improve its detection capabilities, several system development issues have received attention, specifically scanning speed, signal-to-noise ratios required for mine detection, soil properties, and methods of displaying measured data to a user of a field-operable detection system. One of the most significant issues that must be overcome to make a practical seismic mine detection system is measurement speed. The prototype system employs a four second measurement time in order to optimize data integrity for laboratory-based measurements in a noisy environment without regard for scanning speed. Based upon noise measurements made at several field test sites⁹, background noise levels for field operations are expected to be lower than those in the laboratory; comparisons of ambient seismic noise in the experimental model and at a field site in a coastal area on Skidaway Island, Georgia, indicated that the laboratory noise levels were 30 to 50 dB higher than those at the field site. Experimental measurements in the damp, compacted sand in the laboratory have shown nonlinear propagation effects¹¹. However, several field sites have demonstrated much more linear behavior at higher drive levels; at one test site, the maximum drive level was limited by the amount of energy the seismic source could couple into the ground instead of nonlinearity considerations. Additionally, lower signal-to-noise ratios are adequate for the detection of buried landmines. Thus, these factors indicate that lower signal-to-noise ratios can be used in the field operation of this landmine detection system resulting in decreased scanning times.

To evaluate the possibility of decreasing the measurement times, data from the road-bed site were used to synthesize measurements with shorter duration chirps as the interrogation signal. In the data acquisition process, measured data are recorded as transfer functions of the measured surface displacement relative to the input drive signal in the frequency domain. By decrementing the data in the frequency domain, multiplying by the desired test signal in the frequency domain, and taking the inverse Fourier transform to display the data in the time domain, shorter duration interrogation signals can be synthesized from existing data sets. Thus, the surface displacement as a function of time at a particular measurement location can be compared by synthesizing shorter chirps based upon an existing data set. Using experimental data from a region that did not contain a buried landmine, the measured surface displacement 95 cm from the seismic source using a four second chirp was compared to synthesized measurement times of shorter durations, as shown in Figure 5. The original measurement time of four seconds was synthetically reduced to measurement times of one, $\frac{1}{4}$, and $\frac{1}{16}$ seconds. The measured surface displacement was not degraded by the use of shorter measurement times; however, as expected the noise level is seen to increase with the decreasing measurement time. But even for the shortest measurement time, the signal is clearly evident.

The effect on the images of using shorter measurement times was synthesized using the two-dimensional data already presented in Figure 4. Four images are shown on a 30 dB scale in Figure 6 using different duration chirps to measure the resulting elastic waves: (a) the original 4 second chirp, (b) a synthesized 1 second chirp, (c) a synthesized $\frac{1}{4}$ second chirp, and (d) a synthesized $\frac{1}{16}$ second chirp. Further reductions in the duration of the chirp were not possible because of the propagation times. The images in Figure 6 all indicate the location of the VS-2.2 AT mine clearly with no loss in detection capability with the shorter measurement times in spite of the increased noise levels due to the decreasing measurement time as shown in Figure 5.

In the current prototype system, data are acquired at specific locations by scanning the sensor over the minefield in a raster fashion; after the sensor is stopped at each measurement location, a frequency swept chirp signal, or other suitable interrogation signal, is generated by the seismic source and the normal surface displacement is measured. While reducing the measurement time will increase the system's scanning speed with the current

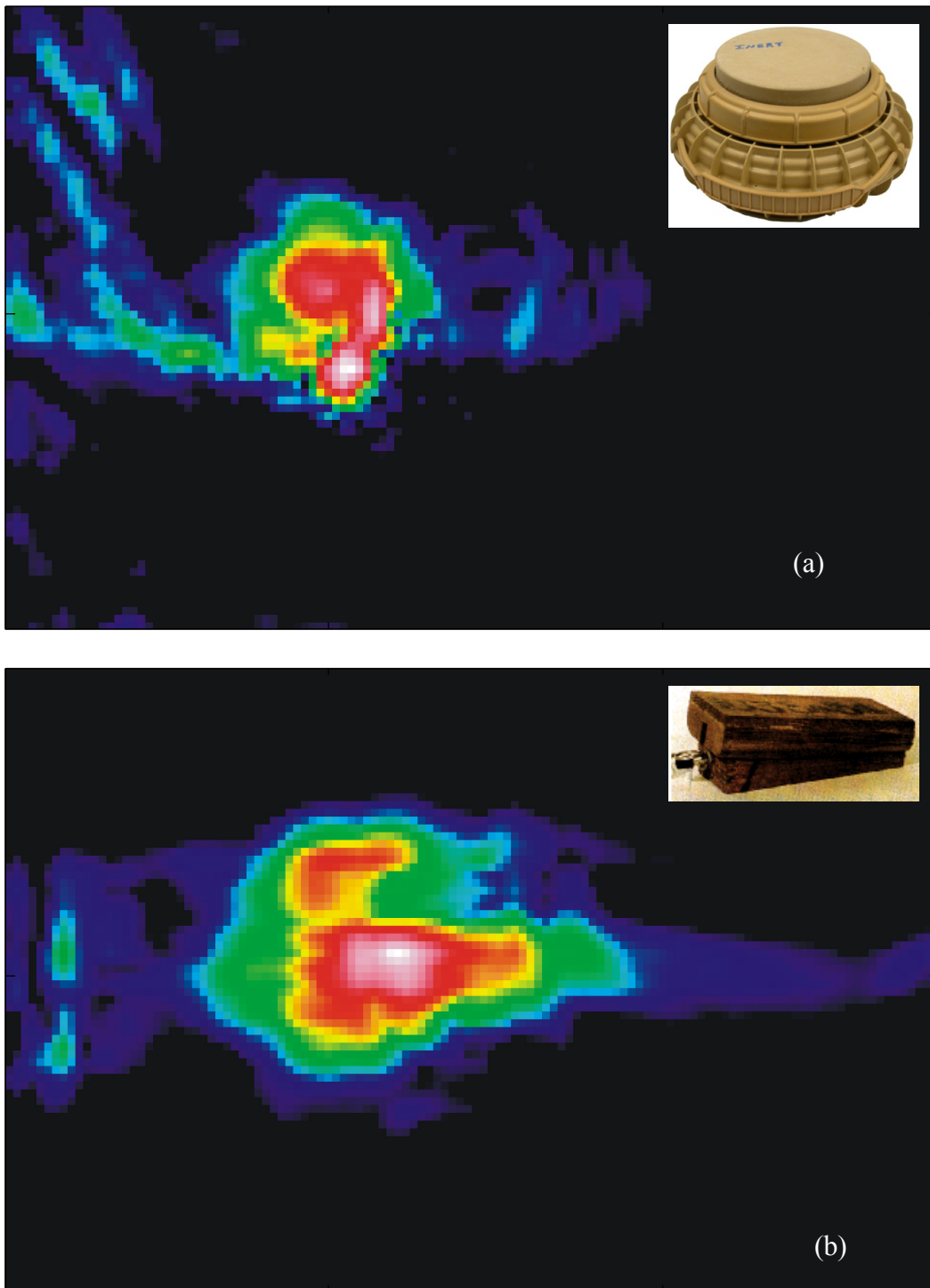


Figure 4: Two-Dimensional Images on a 30 dB scale of (a) a VS-2.2 Anti-Tank Mine Buried 1 inch Deep and (b) a PMD-6 Anti-Personnel Mine Buried 1.75 inches Deep. Both scan regions are 1.2m by 0.8m; the seismic source was located in the middle of the left side of the scan region as shown in these images. Inset photographs show the tested landmines.

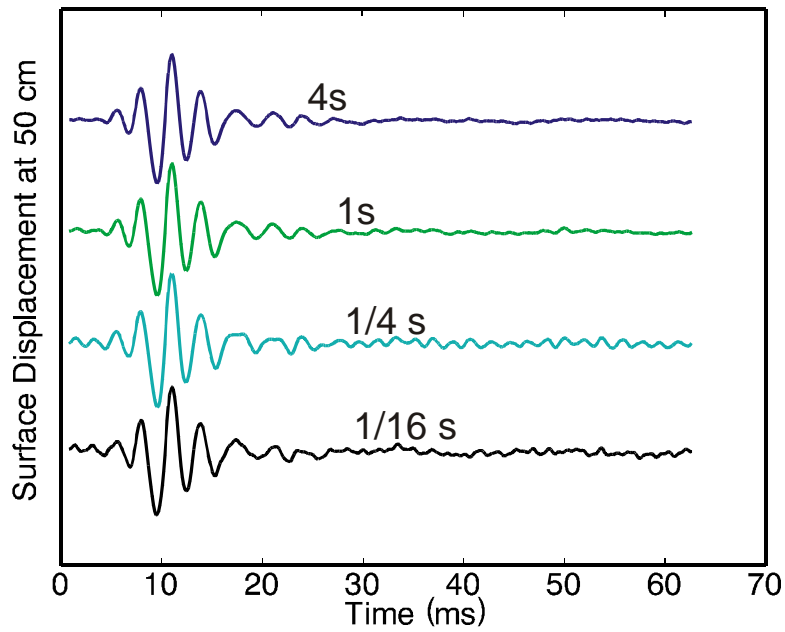


Figure 5: Comparison of Synthesized Measurements Using Four Different Duration Chirp Signals (chirp duration indicated next to each signal).

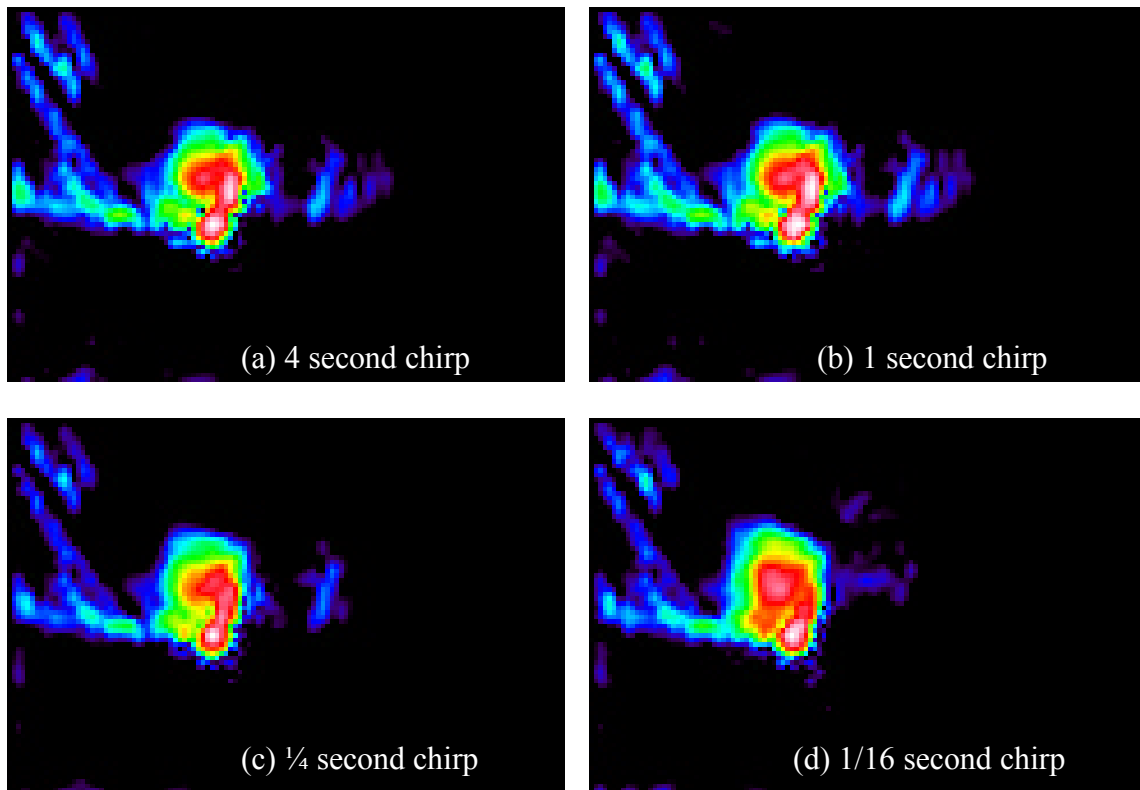


Figure 6: Comparison of Synthesized Measurements Using Four Different Duration Chirps as the Interrogation Signal for the Seismic Landmine Detection System on a 30 db scale).

measurement technique, changing to a continuous scan method where the sensor is moved continuously over the minefield while the seismic source radiates a periodic drive signal will provide the maximum scanning speed. Figure 7 shows a graph of the total time required to scan a 0.8m by 1.2m area using a continuously-scanned radar assuming maximum accelerations of 0.01g and 0.1g for the motion of the radar sensor. In this graph, the measurements were assumed to be made on a 2 cm by 2 cm grid. This total time is plotted as a function of the duration of the drive signal, which is equal to the time it takes the radar to travel 2 cm. As the duration of the interrogation signal decreases, the total measurement time decreases to a minimum value and then increases; this is due to the turning time requirement for the raster scan. Assuming a maximum acceleration of 0.01g for motion of the radar sensor with a 1/4 second chirp, a scan region of 1.2m by 0.8m could be scanned in 10 minutes as shown in Figure 7. Implementing an array of N sensors would decrease the measurement time by a factor of N; if ten radar sensors were used for the above example, the total measurement time would be reduced to one minute.

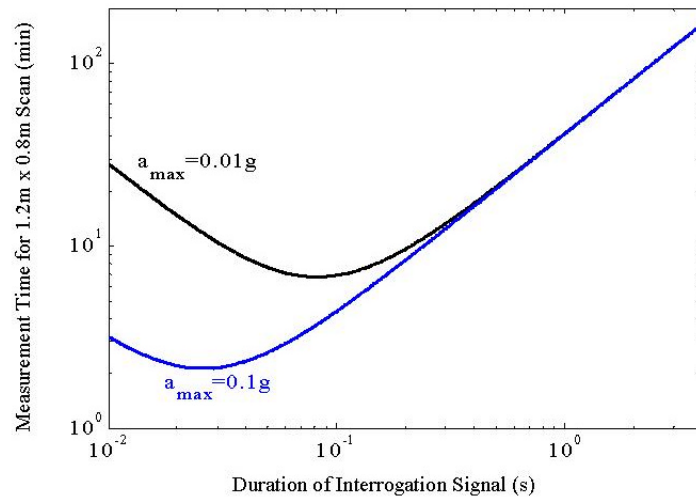


Figure 7: Estimation of Total Measurement Time Required to Scan a 1.2m by 0.8m Region by Continually Scanning with One Sensor with Assumed Maximum Accelerations of 0.01g and 0.1g for the Radar Sensor.

The current prototype's configuration was selected based upon maximum flexibility for research and development purposes; field-operable systems may in fact be configured differently for specific demining scenarios. Possible vehicle-based systems could use an array of non-contact sources or even the seismic noise generated by the vehicle as the source of the surface waves; surface displacements could be detected using an array of sensors mounted in front of the vehicle as shown in Figure 8a. An unmanned configuration as shown in Figure 8b might employ many small, self-propelled sensors moving ahead of a moving seismic source robot; data would be collected and transmitted to a remote site for analysis. A hand-held scanner as shown in Figure 8c presents a new challenge as the operator would analyze data during acquisition; while graphical presentations are not practical for a hand-held system, audible presentations are quite effective for landmine detection and would require minimal training for operators.

Audio presentations of some of the experimental data have been developed to demonstrate the feasibility of audio presentation of the data. Several techniques for presenting the data were developed; simply playing the acquired signal back to the operator with essentially no signal processing seemed to be the best. In this technique, the incident signal is continuously played to the operator giving him feedback about the presence and quality of the incident signal. When the system passes over a mine, the resonance of the mine can be clearly heard; it is a hollow sound that is easily distinguished from the incident signal. This technique is analogous to tapping on a wall to find a stud. In many cases it is possible to tap on the ground and find the mine by listening to the sound of the tapping. Audible signals have been generated for a variety of AT and AP mines. In all of the cases tried, the mine signal could be clearly heard, and in

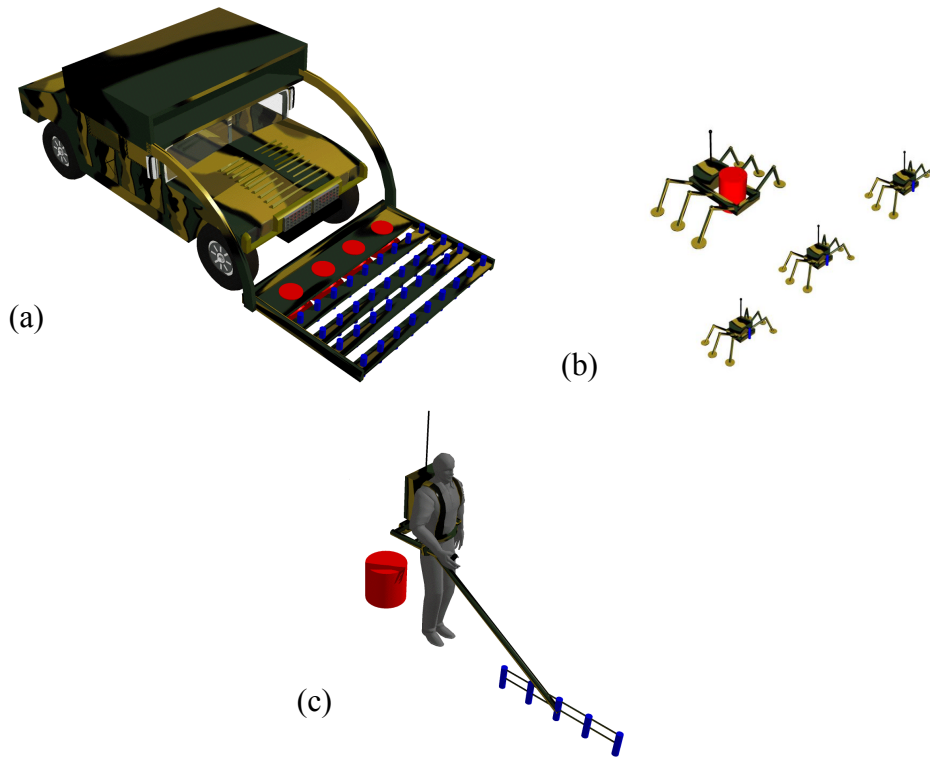


Figure 8: Possible Field-Operable System Configurations for (a) Vehicle-Mounted, (b) Unmanned and (c) Hand-Held Detection of Buried Landmines.

some of the cases the audible representation seemed to be clearer than the visual representation. It may be possible to enhance these audible representations with appropriate signal processing.

4. Conclusions

Field measurements have been conducted at a road-bed site at a temperate U. S. Government test facility with very promising results. The quality of the measurements was considered to be almost as good as that of laboratory measurements with three significant findings: all landmines tested were successfully detected by the prototype system; the soil at the field site was determined to be more linear than the damp, compacted sand of the laboratory experimental model; and the ambient seismic noise was lower at the field site. The linearity of the soil and the reduced noise levels indicate that significant improvements in scanning speeds can be accomplished in a field-operable landmine detection system. Shorter measurement times are possible due to the improved signal-to-noise ratio with the current scanning method; changing to a continuous scanning technique would reduce the measurement time substantially. Vehicle-based and robotic systems could be implemented using image-based representations of acquired data while hand-held scanners would benefit from the clearly heard sound of buried landmines in audible presentations of the acquired data.

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