A Subsurface Acoustic Imaging System

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Abstract— **In this study, we demonstrate an acoustic system for high-resolution imaging of objects buried in soil. Our goal is to image cultural artifacts in order to assess, in a rapid, highly sampled manner, the historical significance of a potential construction site. In a preliminary study conducted at the Bioacoustics Research Laboratory, the acoustic propagation properties of six types of soil were evaluated. The current study will describe the imaging system and present preliminary images produced from data collected from a soil phantom. We have built the imaging system, which incorporates a single element source transducer and a receiver array, both obtained from the Applied Research Laboratory at Pennsylvania State University. The source and receiver array are moved together along a linear path to collect data to form a B-mode image. The source is well approximated as a point source. The transmitted signal is a cosine weighted pulse of 6 cycles at a center frequency of 6 kHz. A 52-element sonar array (8x8, 3.56 cm^2 close-packed elements with 3 elements missing from each corner) acts as the receiver and allows for beamforming on receive, which is accomplished off-line using delay-and-sum beamforming. This system is in operation at the U.S. Army Construction Engineering Research Laboratory (CERL) in Champaign, IL, where the data are collected in a controlled volume (120 x 120 x 60 cm) of dry sand. Using this system, we have obtained B-mode images of several targets buried up to 13 cm deep.**

I. INTRODUCTION

This study proposes an acoustic system for imaging buried artifacts. Once a cultural or archaeological resource site is identified, it must be assessed in order to determine its significance and eligibility for National Registry of Historic Places (Executive Order 11593). The cost of complete assessments is prohibitive; therefore, there is an urgent need to significantly reduce the cost of data recovery at sites with an unknown probability of containing significant cultural or archaeological resources.

Existing technologies in seismic exploration and borehole techniques are not designed to meet the resolution requirements for imaging cultural artifacts [1]. Ground penetrating radar has had some success in identifying underground structures; however, the success is site specific, depending on the moisture content of the soil [2].

At the same time this system was being developed, Smith et al [3] developed an acoustic system for localizing reflections from a buried object on a natural beach. The center frequency of their transmitted pulse is 100 Hz, and they are interested in propagating distances up to 10 m. Our system is intended to be used up to a maximum distance of 2 m and to detect smaller objects; therefore, we propagate a much higher frequency pulse.

In this paper, we present a system that demonstrates the feasibility of imaging small objects buried in dry sand. In the next section, our system is described. In Section III, the characteristics of the soil used in our tests are presented. The image formation is described in Section IV. Finally two images are presented.

II. SYSTEM

A photograph and schematic of the system are shown in Figure 1 and Figure 2. A torpedo head, which

Figure 1: Photograph of imaging system

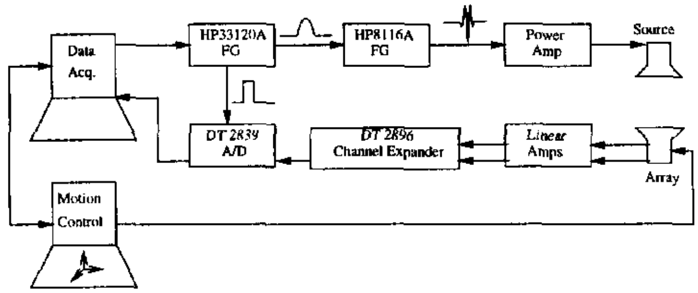

Figure 2: Block diagram of imaging system

contains a two-dimensional, close-packed array (8x8 3.56 cm^2 with three elements missing in each corner), is used as the receiver. The source is a single element, well-approximated by a point source. Due to the size of the torpedo and the source, the smallest possible center-to-center spacing of the source and receiver array is 33 cm.

Movement of the array is accomplished by a motion control system with three translational axes. Only the two horizontal axes, with positional accuracy of 3 μm, are used for the scans. Position control is achieved through a PC-based control card using LabView software to create the interface. The motion control program allows manual positioning or automatic control by the data acquisition computer, which uses the serial port to send position coordinates to the motion control computer.

The data acquisition program runs on a ZEOS Micron Millenia computer with an Intel Pentium 133 MHz processor. An HPIB interface card is used to communicate with the HP33120A function/arbitrary waveform generator to set up initial parameters for the excitation signal. The excitation signal is generated by an HP33120A function/arbitrary waveform generator modifying the signal (AM modulation) from an HP8116A pulse/function generator. The resulting signal is a cosine-weighted pulse of 6 cycles at 6 kHz. The signal is amplified by either a 3000-W amplifier (Industrial Test Equipment, Co.) or 1000-W amplifier with variable output impedance capability (Instruments, Inc. Model L10).

Signals from the 52 elements are captured individually so that processing may be done off-line. A separate transmit pulse is used for each signal captured, so that at each position of the source and receiver array, 52 pulses are transmitted. Before the received signal is digitized, it is amplified by an in-line linear amplifier with a gain of 330.

The synchronization signal from the HP33120A is used to trigger data collection by the Data Translation A/D board (DT 2839, 12 bit, 1 MHz). The DT 2839 has 8 channels, so we used a DT 2896 channel expander (Data Translation) to allow us to capture the 52 channels individually.

The targets are buried in a controlled volume of soil. The soil is contained in a 1.2 m^3 box with a false bottom, such that only the top 60 cm are filled. A child's pool with 3 cm depth of water is used to couple the transducers to the medium since the transducers are designed for underwater applications. The water also provides uniform coupling to the sand over the range of the scan.

Simulations of the results of collecting data in this configuration are used to test the image formation algorithms to be described.

III. SOIL PROPERTIES

The sand was gathered from the University of Illinois Sand Farm in Mason County, Illinois. Physical characterization of the soil was performed by Professor Robert Darmody of the University of Illinois. The sand content was 94%, most of which was evenly divided between the medium and fine sand subclasses. Because of the low clay content, the soil was non-plastic. Organic carbon content was low, as was the soil moisture.

Acoustic properties of soil are described by the Biot theory for sound propagation in a porous medium [4], [5]. The theory predicts the propagation of two compressional waves and a shear wave in the porous medium. The first compressional wave is characterized by particle motion in phase with the fluid motion. The second compressional wave is characterized by particle motion out of phase with the fluid motion. The first wave is often referred to as the fast compressional wave because it generally has a higher speed than the wave of the second type, or slow compressional wave. Also, the slow compressional wave generally has much higher attenuation than the fast compressional wave.

The wave speed and attenuation of the propagated wave were determined using the experimental system described above. The source and receiver were positioned above a steel plate. Pulses with center frequencies ranging from 2 kHz to 6 kHz were transmitted and received at the 52 elements. The array was then moved an additional 2 cm away from the source and the data collection was repeated. Data were collected for a total of five positions of the array in increments of 2 cm. This data collection differs from the data collection for images, where the relative position of the source and receiver remained constant.

The total distance traveled by the pulse was calculated using geometric acoustics. It was assumed that the speed of sound was constant in the first 12 cm of sand, so the sound travels over a linear path from the source to the plate and from the plate to the receiver element. The sound speed was measured by correlating the signal received by each element with the signal received by the same element after the array had been moved to a different position. The difference in distance the pulse has to travel was then divided by the difference in time of arrival. Results showed that the speed of sound in the sand was 166 ± 27 m/s.

The attenuation was measured by first finding the log power spectrum of the received signals. The first position of the array was used as a reference for comparison with the four other positions. The log decrements for the four positions were calculated and fitted to a line for the 52 elements giving 52 estimates of the attenuation per cm at one frequency. The average slope was then taken as the attenuation in dB/cm at that frequency. Finally a line was fit to the data for different frequencies. The results showed that for our sand, the attenuation was approximately 0.65 dB/cm/kHz in the frequency range from 500 Hz to 2 kHz. These results are in agreement with the results for unconsolidated sand by Hickey and Sabatier [6]. They measured a phase velocity of 143 m/s for the slow wave and 240 m/s for the fast wave. The slow wave attenuation was measured to be 35 Np/m (3.0 dB/cm) at 1 kHz and the fast wave attenuation was measured to be 10 Np/m (0.87 dB/cm) at 1 kHz. For the slow wave, both phase velocity and attenuation increased with frequency.

IV. Image Formation

Focusing the 52 individual signals is accomplished through delay-and-sum beamforming on receive using dynamic focusing. The coordinate system and positions of the source and receiver array are shown in Figure 3. The source is centered at position $(x_s, 0, 0)$. The elements

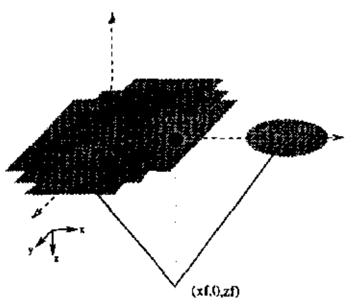

Figure 3: Source-receiver geometry

of the receiver array are at positions $(x_i, y_i, 0)$, where the subscript i varies from 1 to 52 and is used to enumerate the elements. The center of the array lies on the y-axis, so that half of the elements are in the region where $y > 0$ and half are in the region $y < 0$. The synthetic element is centered at $(x_f, 0, 0)$. For desired focal point, $(x_f, 0, z_f)$, the delays are calculated as follows.

$$g(t) = \sum_{i=1}^{52} s_i(t - t_t - t_{ri}) \tag{1}$$

$$t_t = (z_f - \sqrt{(x_s - x_f)^2 + z_f^2})/c \tag{2}$$

$$t_{ri} = (z_f - \sqrt{(x_i - x_f)^2 + y_i^2 + z_f^2})/c \tag{3}$$

The delay, t_t, is the same for each element. It compensates for the difference in travel time from the actual source to the focal point and from the synthetic source to the focal point. The delay, t_{ri}, is different for each element. It compensates for the difference in travel times from the focal point to the actual receivers and from the focal point to the synthetic receiver. In our case, the synthetic element is both transmitter and receiver. The $g(t)$ are envelope-detected using the Hilbert Transform.

We have also explored synthetic aperture techniques, which are successful in simulations [7]. They have not worked with our experimental data, however, due to limited length of the scan, which limits the achievable resolution.

V. Results

The surprising result in our experiments is that the information about the targets is contained in the frequencies below 1500 Hz rather than the 6 kHz signal we had transmitted. The received signal contains a strong signal at 6 kHz; however, this is most likely reverberation within the pool.

The strength of the frequencies below 1500 Hz can be explained as follows. In the transmitted signal, the energy at frequencies below 2 kHz is 20 dB below the center frequency, as shown in Figure 4. The attenuation in the

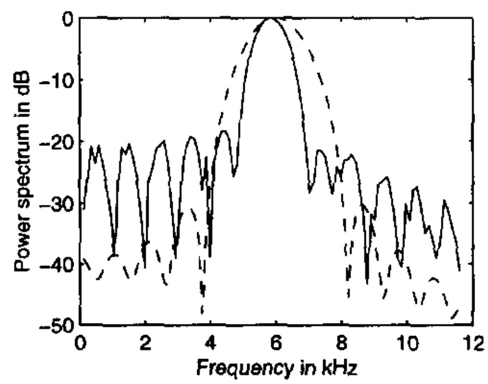

Figure 4: Log Spectra of simulated (dashed) and actual (solid) transmitted signals

soil is measured to be 0.65 dB/cm/kHz for the frequencies between 500 Hz and 2 kHz. The pulse typically must travel 40 cm from the source to the target to the receiver element. In this distance, the 6 kHz signal would be attenuated 156 dB, assuming that the attenuation measurement can be extended to this high frequency. The 1500 Hz signal would be attenuated just 39 dB. Therefore, low frequencies should be more prominent in the received signal. This analysis does not consider the important effect of the transducer impulse response.

The delay and sum imaging algorithm has been modified so that the DC bias of the signal received at each element is removed before any further calculations. The second step in processing the data is to filter the signals such that only frequencies below 1500 Hz are kept, because the SNR is poor at high frequencies.

A reconstructed image of a single target is shown in Figure 5. The target was an air-filled aluminum furnace pipe (7.5 cm diameter, 90 cm length) buried at a depth of 8.5 cm. The pipe appears as the bright spot near the center at the left of the image. The bright spots in the corners are due to reflections from the sides of the box. The bright spot to the right of the pipe is most likely due to a multiple reflection. The image is formed by synthesizing an element 8 cm from the center of the array.

A reconstructed image with multiple targets is shown in Figure 6. The image shows resolution targets buried at approximately 9 cm depth. The resolution target consisted of 5 bars with center-to-center spacings of 3.7, 6.2, 8.8, and 10.1 cm. Each bar is 1.2x7.5x60 cm with the longest dimension perpendicular to the scan, and the smallest dimension parallel to the scan. The total width of the resolution target is 30 cm. The data is focused by forming a synthesized element at a position 2.5 cm from the center of the array. The first bar at the top of the image is less bright than the others. The second bar appears small and is difficult to distinguish. The remaining three bars are bright targets. The axial resolution is 16 cm at best according to the pulse duration and the speed of sound in the soil.

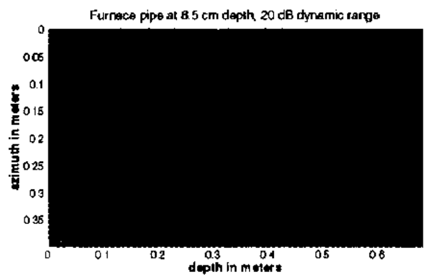

Figure 5: Image of air-filled furnace pipe

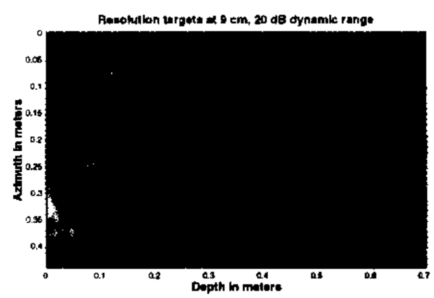

Figure 6: Image of resolution targets

VI. Conclusions

We have shown that an acoustic system can be used to detect buried objects in soil. Objects spaced 5 cm apart can be separated in an image. Objects with a cross-section as small as 1.2 cm by 7.5 cm can be seen as long as they have sufficient length. The system must be tested further to determine the smallest object that can be detected.

Our system operates in the friendly environment of a homogeneous soil sample. The system must also be tested in a more realistic environment. The source and receiver were chosen because of their availability and their ability to transmit high power, shaped pulses and to receive small signals. A more optimal system would use transducers better matched to the impedance of soil and an array that could be focused for transmit.

VII. Acknowledgements

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