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Transducer Design Experiments for Ground-Penetrating Acoustic Systems

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19 March 1996



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1 Introduction

Acoustic sounding in soil offers a viable alternative to excavation for the purpose of identifying shallow, subsurface inhomogeneities such as archeological sites, pipelines, and tunnels [1, 2]. Due to the attenuative nature of high-frequency sound propagation in soil, and the relatively small amount of backscatter from buried targets, the majority of successful subsurface imaging experiments have utilized a source (Tx) and receiver (Rx) configuration in which signals produced by a transmitter at the soil surface were measured by an array of receive transducers placed down a vertical borehole [2, 3]. While there are obvious advantages to such a design (e.g., deeper penetration for a given transmit frequency, minimal coupling between the transmitter and receiver via induced surface waves), there are operational reasons to favor the development of a system in which both transducers are positioned at the soil surface. This report summarizes an investigation into the coupling of pulse-waveform acoustic signals, generated and received at the soil surface, into a volume of soil.

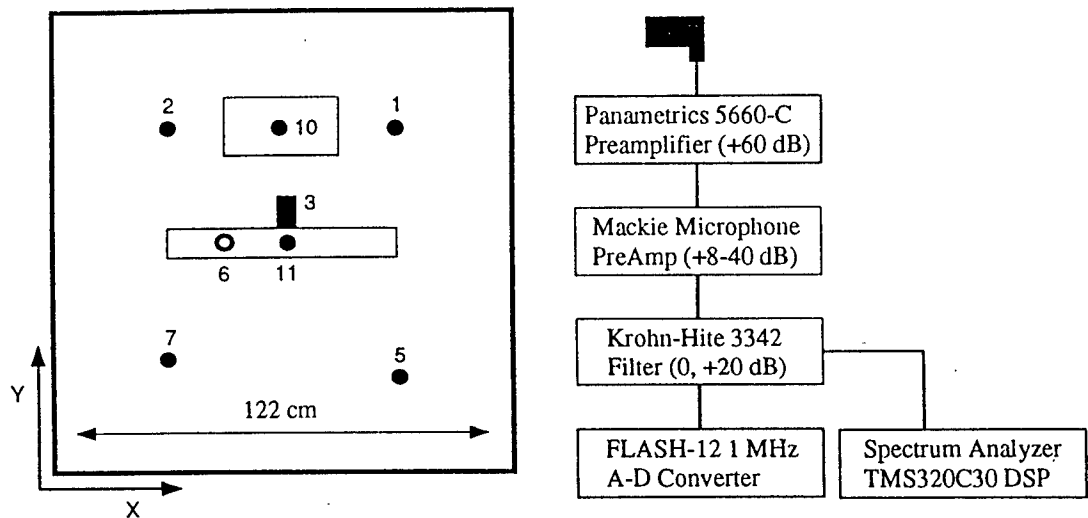
The results of this work may be summarized as follows:

- Acoustic sources such as hydrophones, loudspeakers, and piezoelectric drivers are capable of transmitting impulsive signals into the soil.
- Acoustic signals which propagate within the soil are subject to a high degree of attenuation. The attenuation increases with increasing frequency.
- Each of the acoustic sources tested was found to produce surface waves at the air-soil interface whose amplitude was large in comparison to the expected amplitude resulting from scattering by subsurface targets.
- The amplitude of the surface waves was found to be inversely proportional to the transmit frequency.
- A prototype receiver designed to minimize the direct-path coupling between the transmitter and the receiver via surface waves was successfully tested.

2 Experiment Design

Figure 1 shows a diagram of the soil container and instrumentation used in the acoustic propagation experiments. The measurements were conducted within a test box whose length was approximately 1.2 m on each side. Reflections of acoustic signals from the floor and walls of the soil container were minimized through the use of sound-absorbing foam. The soil, nominally composed of 50% sand, 25% clay, and 25% silt compacted at near 100% saturation, was chosen to be representative of a typical site at which a ground-penetrating acoustic (GPA) imaging system may be successfully utilized. Two sections of steel pipeline (2-in-diameter and 7-in-diameter) were buried within the soil volume.

In order to assess the degree to which acoustic energy was transmitted into the soil, eight piezoelectric receivers (CTI-30 broadband accelerometers) were placed within the soil volume at the time of compaction. The CTI-30 accelerometers were also used to measure the surface waves at the air-soil interface. The output of each accelerometer was amplified in two stages using Panametrics 5660-C preamplifiers (60 dB gain, 500 Hz low-frequency cutoff) and Mackie microphone amplifiers (0-48 dB variable gain). The acoustic signals were digitized using an STI FLASH-12 A/D converter that provided an



Sensor:	1	2	3	5	6	7	10	11
X (cm):	91	30	61	94	51	31	61	61
Y (cm):	91	91	61	24	61	28	91	61
Z (cm):	61	43	30	32	00	32	91	61

Figure 1. Diagram of the soil box and data acquisition system used in the acoustic sounding experiments. The cubic soil box is shown projected onto the horizontal plane; the coordinate origin is at the lower left corner of the box at the floor level. The z-coordinates of the buried transducers are given in cm from the floor of the box with the soil surface at $z=117$ cm.

aggregate sample rate of 1 MHz with 12-bit resolution. Krohn-Hite 3342 active filters were used to both minimize the effects of low-frequency (≤ 500 Hz) ambient noise and to prevent aliasing of the signals during digitization.

The transducers used to generate the acoustic signals included a piezoelectric driver (Motorola midrange/tweeter driver), a broadband hydrophone, and a standard loudspeaker. The impulsive acoustic waveforms were produced by either the ± 5 V transition of a square wave input, or by the pulse-waveform output of a Spectrum Signal Processing TMS320C30 DSP card. Sinusoidal waveforms used to measure the frequency dependence of the signal attenuation in soil and the angular distribution of acoustic energy were produced by driving the transducers with the sine wave output of a signal generator.

3 Results

The attenuation of acoustic signals which propagate through the soil was estimated by comparison of the signal strength measured by identical, buried receivers separated vertically by 48 cm. The acoustic source used to conduct the attenuation measurements was the hydrophone placed in direct contact with the soil surface. The hydrophone was driven by the continuous, sine-wave output of a signal generator. Figure 2 shows the attenuation values at frequencies between 1 and 8 kHz. Since the attenuation estimate is performed using two identical receivers, any frequency dependence of the transmitter output signal is effectively eliminated. The data shown in Figure 2 have been corrected to include an assumed signal spreading loss proportional to $1/r^2$.

The angular dependence of transmitted acoustic energy in soil was characterized for both the hydrophone and piezoelectric driver sources. In order to reduce the effects of surface-wave coupling between the source and the receiving probe, the source was buried at a depth of 20 cm from the soil surface. At this depth, the distance between the receiving

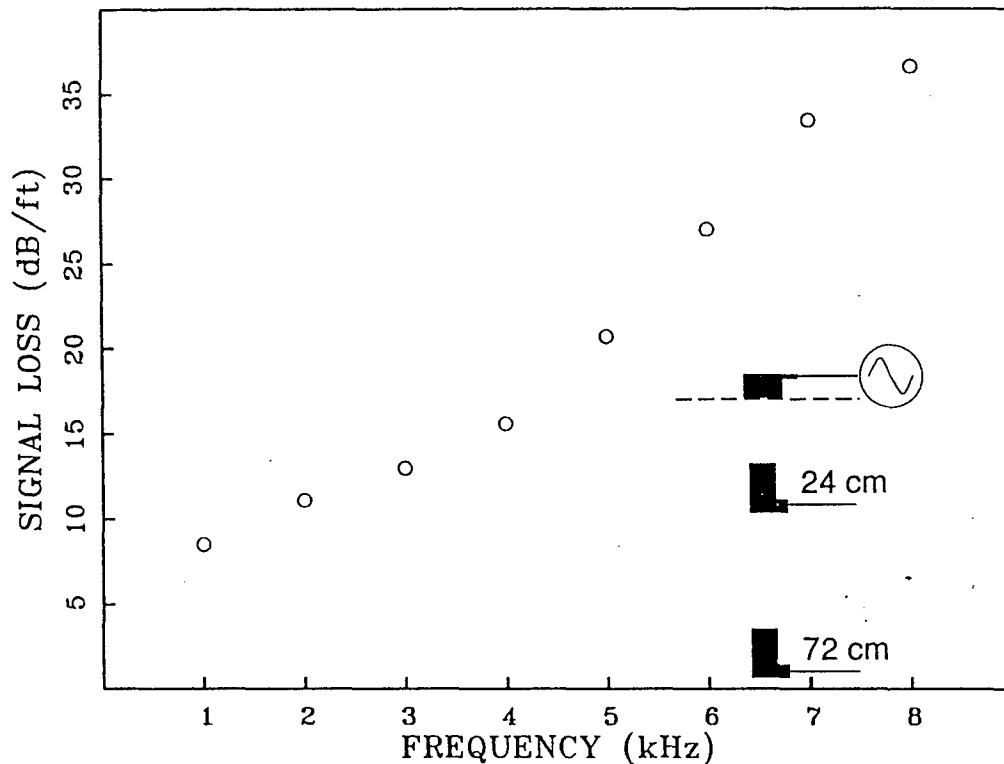


Figure 2. Attenuation resulting from the propagation of 1- to 8-kHz plane-wave acoustic signals through the soil. The data were obtained using the hydrophone source and identical receivers separated vertically by 48 cm.

probe and the floor of the soil box (approximately 40 cm at normal incidence) was sufficient to avoid reflections of the transmitted signal from the boundaries of the soil box. The acoustic signal emitted from the source was measured using a small-diameter, omnidirectional microphone placed down a series of boreholes. The boreholes were positioned such that the received signal could be measured at a constant source-receiver separation of 60 cm. Figure 3 shows the ratio of the received signal strength to the maximum observed signal strength as a function of angle for a 2-kHz transmitted signal. The hydrophone is relatively omnidirectional, while the piezoelectric driver exhibits a strong diffraction null at an angle of 60°. The angular dependence of the piezoelectric driver is determined by the geometric properties of the driving element, the cavity within which the element is mounted, and the aperture through which the acoustic signals are emitted, and on the wavelength of the radiated energy. For both the hydrophone and the piezoelectric driver, the aperture length is small in comparison to the wavelength of the radiated acoustic energy. Thus, within a frequency band suitable for propagation in soil (e.g., 1 to 3 kHz), these transducers are relatively omnidirectional. A directional radiation pattern, in which the majority of acoustic energy is concentrated in a narrow beam at normal incidence, can be obtained through the use of a wide-aperture transmitter.

Impulsive acoustic signals were successfully coupled into the soil using three types of acoustic sources: the piezoelectric driver, the broadband hydrophone, and a standard loudspeaker. The signal coupling was verified by placing each source in direct contact with the soil surface, emitting an impulsive acoustic signal from the source, and measuring the signal after propagation through approximately 80 cm of soil. In order to attain the best coupling between the hydrophone source and the soil, the hydrophone was pressed tightly onto the soil surface. This method of coupling is discussed in greater detail below. Figure 4 shows examples of time series of the acoustic signal produced by each source when driven by identical input signals (the ± 5 V transition of a square-wave

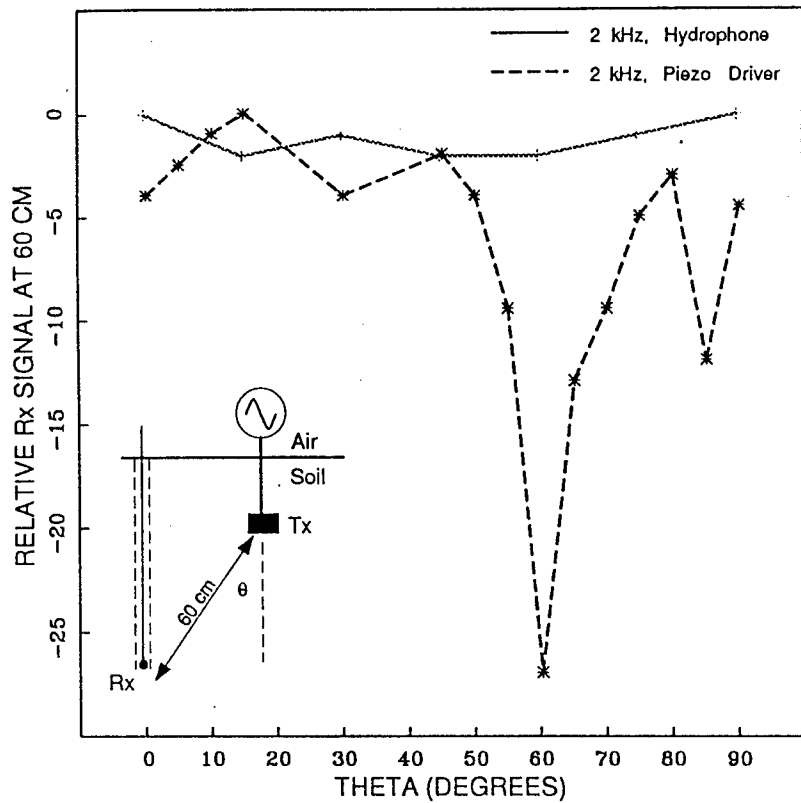


Figure 3. The angular dependence of acoustic signals transmitted by the hydrophone (solid line) and piezoelectric driver (dashed line) sources. The data for each source have been normalized against the strongest received signal. The received signals were measured using a microphone placed down a series of vertical boreholes.

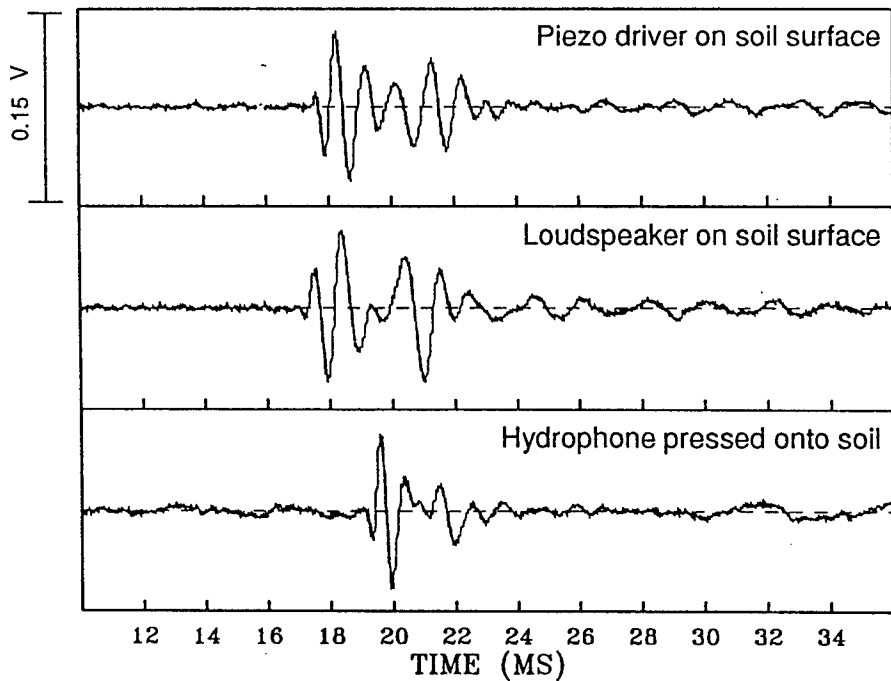


Figure 4. Impulsive acoustic signals generated by surface-mounted piezoelectric driver (top), loudspeaker (center), and hydrophone (bottom) source. The input signals to each source are identical and the propagation path from source to receiver is through 81 cm of soil.

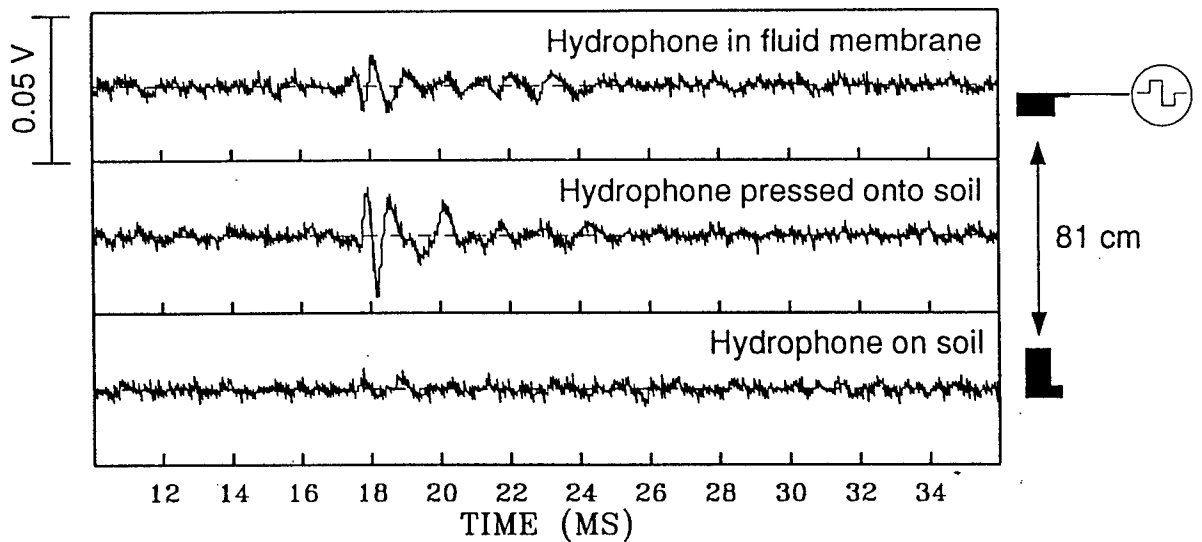


Figure 5. Time series of the acoustic signal transmitted via the hydrophone to a receiver buried at 81-cm depth. The coupling between the hydrophone and the soil surface is achieved by placing the hydrophone lightly on the soil (bottom), pressing the hydrophone tightly onto the soil surface (center), and immersing the hydrophone in a water-filled membrane (top).

input). It should be noted that the apparent difference in arrival time of the impulse produced by the hydrophone is caused by the use of a different number of pre-trigger points in the data acquisition system. As can be seen in Figure 4, the amplitude of the impulsive acoustic signal is nearly the same for each type of transducer. The hydrophone appears to produce a signal which is slightly narrower in time.

The degree to which impulsive acoustic signals produced by the hydrophone source were transmitted into the soil was investigated using three methods of coupling. Figure 5 shows time series of the impulsive signal received by a sensor positioned 81 cm from the soil surface for coupling methods in which the hydrophone was placed lightly on the soil (bottom plot), pressed tightly against the soil (center plot), and immersed in a water-filled membrane which was placed in direct contact with the soil (top plot). The data are scaled such that the root-mean-square (RMS) noise level measured by each sensor is the same. From the figure it is evident that the most efficient coupling is attained when the soil is compacted tightly against the active element of the hydrophone. The signal transmitted by the hydrophone immersed in water is reduced in amplitude by approximately 50% relative to the compressed-soil coupling. The weakest signals result from merely placing the active element of the hydrophone on the soil surface with no applied pressure other than the weight of the transducer.

4 Direct-Path Coupling Via Surface Waves

In order to successfully image subsurface targets, acoustic signals transmitted at the soil surface must be received (also at the surface) after scattering from the target. The scattered signal is measured against the ambient and system noise, and against the acoustic signal which propagates directly from the transmitter to the receiver. In the case of acoustic sounding in soils, this direct-path signal is comprised primarily of surface waves.

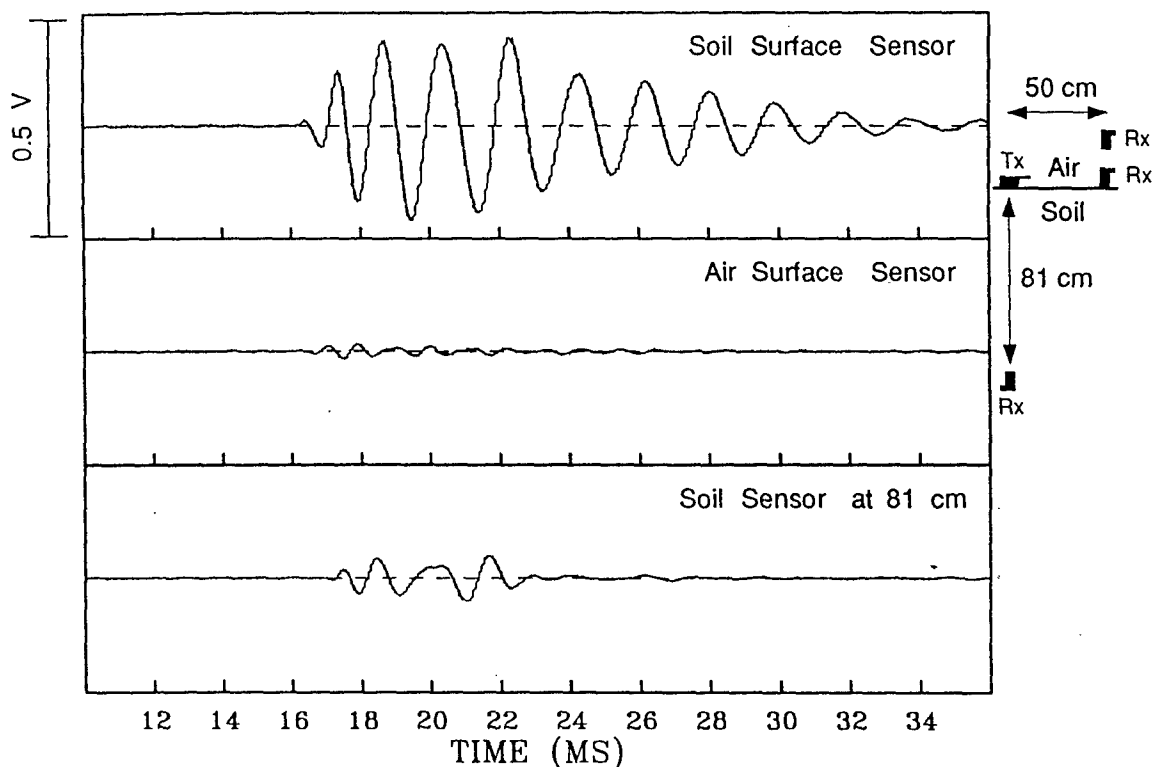


Figure 6. Time series of the acoustic signal transmitted by the hydrophone at the soil surface and received by accelerometers located in soil 81 cm below the source (bottom), in air 50 cm from the source (center), and at the soil/air interface 50 cm from the source.

The surface waves are excited by the displacement of the soil surface that results from the coupling between the transmitter and the soil [4]. The surface wave problem can be demonstrated by comparing a time series recorded by an accelerometer buried within the soil to similar data measured by a surface-mounted transducer.

Figure 6 shows time series of an impulsive signal generated by the piezo driver source as measured by a receiver positioned at 81-cm depth in the soil and an identical sensor at the soil surface located 50 cm from the source. Also shown in Figure 6 is the signal received by an accelerometer suspended in air at a distance of 50 cm from the source. This time series is included as evidence that the majority of energy received by the surface accelerometer in contact with the soil propagates as surface waves. The data of Figure 6 have been scaled such that the RMS noise level measured by each sensor is identical. The surface manifestation of the acoustic impulse is clearly the dominant feature of the time series shown in Figure 6. The peak amplitude of the surface wave is large in comparison to the signal received in soil at a depth of 81 cm. The time required for an acoustic signal to propagate from a surface-mounted source to a target positioned 1 m below the source and back to a surface-mounted receiver is approximately 7 ms (assuming a propagation speed of 300 m/s and a small Tx-Rx separation). Figure 6 shows that the duration of the surface wave (i.e., the time interval over which the surface wave is large in comparison to signals propagated through the soil) is on the order of 20 ms. Thus, signals resulting from scattering from shallow, subsurface targets may be difficult to extract from time series recorded by a transducer (such as an accelerometer) which couples strongly to surface waves. The magnitude of the induced surface wave in relation to the transmitted acoustic wave can be reduced to some extent by transmitting at a higher frequency or increasing the aperture of the transmitter.

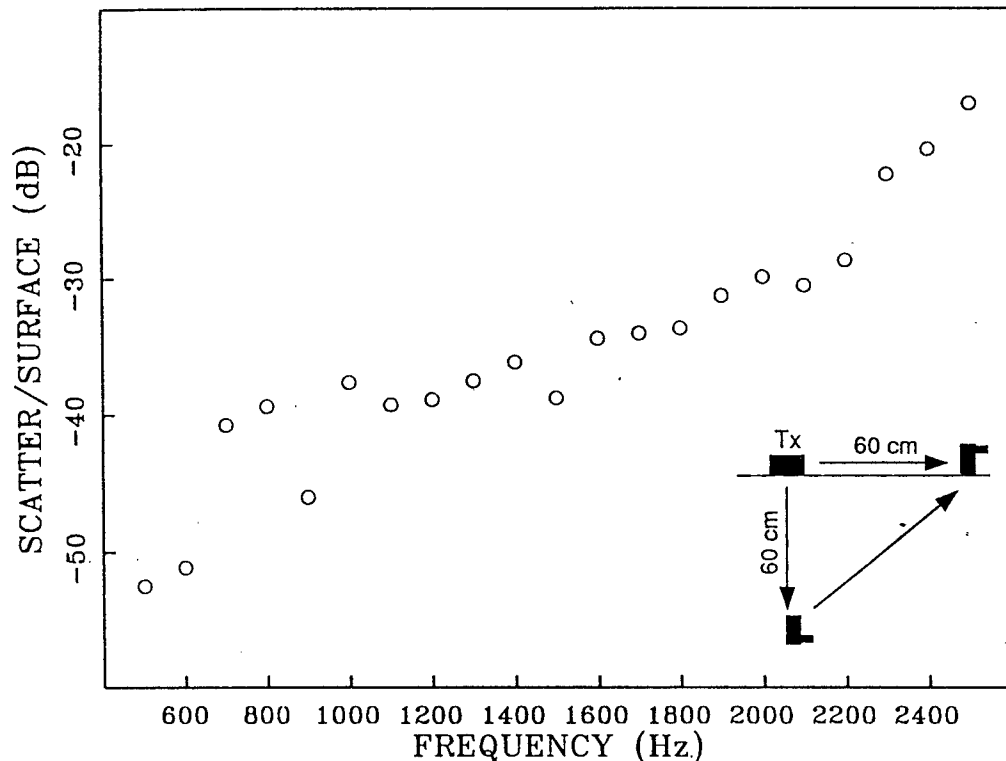


Figure 7. Estimated ratio of the intensity of acoustic waves emitted at the surface and scattered off of a perfectly reflecting target at 60-cm depth to the intensity associated with the direct-path surface waves. The source-to-sensor distance for both the surface and buried accelerometers was 60 cm.

The ratio of the intensity received via subsurface scattering (i.e., a signal transmitted at the surface and received at the surface after scattering from a buried target) to the intensity of the direct-path surface waves was estimated for the case where the target was a *perfect reflector*. Data were recorded at frequencies between 500 Hz and 2500 Hz using a sinusoidal input to the piezo-driver as the source. Accelerometers were positioned directly below the source (in the soil) and at the soil-air interface. The source-to-receiver distance for each transducer was 60 cm. In order to estimate the intensity of the scattered signal received by the surface-mounted transducer, it was assumed that all of the acoustic energy measured by the buried receiver was reflected. The portion of this reflected signal received at the surface was calculated by scaling the intensity measured at 60-cm depth according to the attenuation values shown in Figure 2 (corrected for the $1/r^2$ spreading loss). The ratio of the estimated scattered signal to the measured direct-path signal (comprised mainly of surface waves) is shown in Figure 7. Even at the relatively high transmit frequency of 2500 Hz the intensity associated with surface wave contamination is substantially larger (approximately 20 dB) than the scattered signal. If acoustic scattering from a small cross-section target (e.g., an archeological feature) is considered, the difference in received power between the scattered path and the direct path will be even greater.

Based upon the attenuation measurements cited in this work, it is expected that a prototype subsurface acoustic imaging system should operate within an approximate frequency range from 1000 to 3000 Hz. This frequency band is desirable since (a) the 2000 Hz bandwidth gives sufficient range resolution to identify small targets (on the order of a few cm in cross section), and (b) the attenuation within this frequency band is low enough that the scattered signal from a target at 1-m depth may be resolved against the ambient and system noise. The results shown in Figures 6 and 7 suggest that the receiver

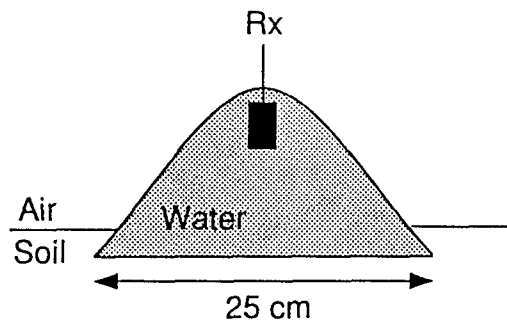


Figure 8. Diagram of the P-wave sensor constructed as part of the experimental program. The sensing element is an accelerometer immersed in a water-filled paraboloid. The receiver is designed to reject surface waves while admitting longitudinal waves at near-vertical incidence.

and transmitter employed in the prototype subsurface acoustic imaging system be designed in such a way as to minimize the degree to which surface waves are generated and received. Such a design has been previously reported in the literature [5, 1]. The characteristics of a prototype sensor designed to couple more efficiently to longitudinal waves than to surface waves is discussed in the following section.

5 Minimization of Surface Wave Effects

Figure 8 shows a schematic diagram of a longitudinal-wave, or P-wave, transducer designed to receive acoustic energy at near-vertical incidence, while rejecting the majority of signals associated with surface waves emitted from the acoustic source. The receiver built as part of the experimental program consists of a thin plastic membrane filled with water placed inside of a parabolic reflector. The sensing element used was an accelerometer placed at the focal point of the paraboloid. The diameter of the paraboloid at the soil surface was 25 cm. Surface waves are rejected by the receiver primarily because the transverse motion associated with the surface waves does not efficiently couple to the fluid in which the sensing element is placed.

Figure 9 shows the results of an experiment in which an impulsive acoustic signal was propagated downward into the soil using the piezoelectric driver. The receivers used to measure the surface waves (and any scattered signals) were an accelerometer placed at the air-soil interface and the P-wave receiver described above. The distance between the source and each sensor was 25 cm. The signal-to-noise ratio of the measurement obtained using the P-wave sensor was raised by averaging together (in the time domain) 82 realizations of the acoustic signal. The difference in intensity of the received surface waves is approximately 30 dB between the two types of sensors. Thus, the P-wave sensor is very effective in terms of its ability to minimize the direct-path coupling between the transmitter and receiver. In addition to reducing the effect of surface waves, the time series recorded by the P-wave sensor contains a component that is consistent with the scattering of the impulsive signal within the soil box. The measured propagation speed of longitudinal waves in the soil was approximately 300 m/s. Acoustic signals scattered from the bottom of the 1.2-m-deep soil box should thus arrive approximately 8 ms after transmission. This predicted delay is consistent with the arrival time of the secondary impulse recorded by the longitudinal-wave sensor. It should be noted that the accelerometer placed on the air-soil interface does not indicate the presence of a scattered signal because the measurement is dominated by surface waves.

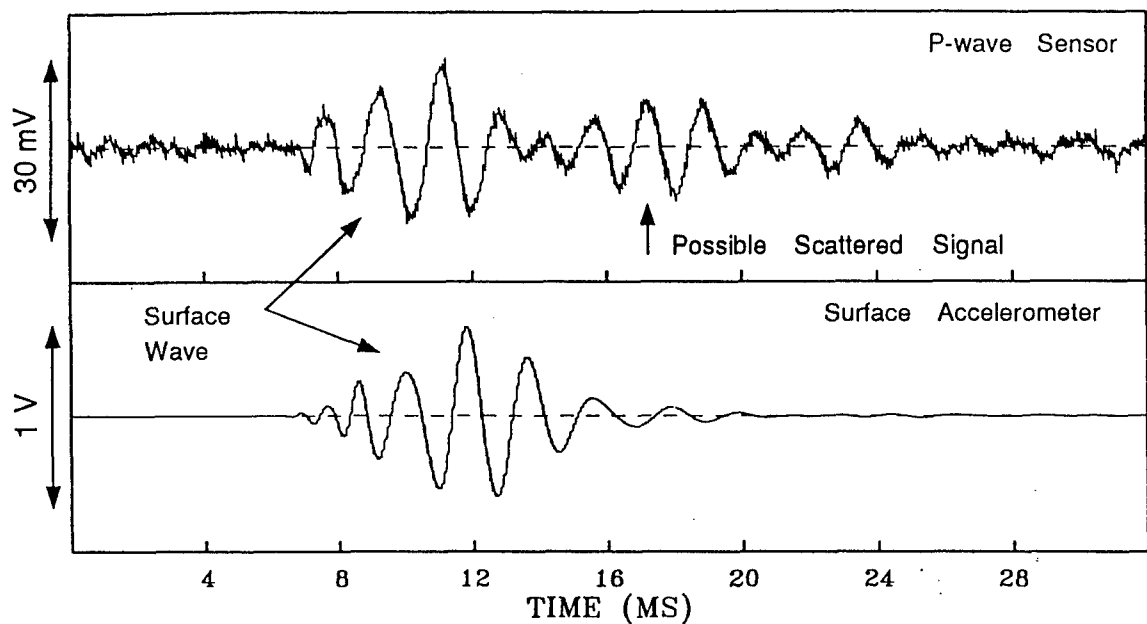


Figure 9. Time series of the signals received by an accelerometer placed at the air-soil interface (lower plot) and the longitudinal-wave receiver (upper plot). The upper time series represents an average (in the time domain) of 82 realizations of the acoustic signal. The response of the longitudinal-wave receiver to surface waves is reduced by approximately 30 dB in comparison to the accelerometer.

6 Conclusions and Recommendations

Experiments performed using a soil box instrumented with buried accelerometers have demonstrated that a variety of acoustic transducers are capable of efficiently coupling sound waves into soil. Impulsive waveforms transmitted by a broadband hydrophone, a piezoelectric driver, and a standard loudspeaker were found to be comparable in terms of both the intensity measured at depth in the soil and the temporal width of the transmitted signal. While there are limits to the amount of acoustic energy that can be emitted in the form of a short-duration pulse from a single transducer, these limits can be overcome by operating the transmitter in a step-chirp mode in which the impulsive signal is synthesized from a series of pure tones.

The attenuation of acoustic signals within the test soil was characterized over a frequency range from 1 to 8 kHz. The attenuation was found to increase with increasing wave frequency. The observed attenuation levels were consistent with those reported in [4].

The most important result of the experimental program is the observation that while each of the transmitters tested produced measurable acoustic waves that were observed to propagate within the soil volume, these sources also produced a level of surface-wave activity that can obscure the acoustic signals resulting from scattering (see Figure 6). This problem of resolving the desired scattered signal against a background of surface waves which propagate directly from the source to the receiver has been previously reported in the literature [1, 4]. Measurements obtained using a sinusoidal transmit waveform over the frequency range from 500 to 2500 Hz showed that the contamination due to induced surface waves is less at high frequencies. However, even at the relatively high transmit frequency of 2500 Hz, the combination of an unshielded transmitter and receiver at the soil surface were coupled via surface waves to the extent that the intensity ratio of the expected scattered signal to the surface-wave signal was -20 dB. Also, the surface waves

were observed to persist for a period of time that was long in comparison to the transit time for scattered signals from shallow (approximately 1-m depth) targets. These results suggest that the scattered signal from weakly-reflecting, shallow targets cannot be detected unless the receiver and/or transmitter are modified to reduce the surface-wave coupling.

A prototype receive transducer designed to reject surface waves while admitting energy associated with acoustic signals was built and tested as part of the experimental program. The longitudinal-wave, or P-wave, receiver consists of a parabolic reflector in which a thin, plastic bag of water is placed. During the tests, the water bag was placed in direct contact with the soil surface and an accelerometer located at the focal point of the paraboloid was used as the sensing element. The experiments conducted using the P-wave receiver showed that the degree of surface-wave contamination was reduced by approximately 30 dB over the level encountered using an unshielded accelerometer at the soil-air interface. Time series of the acoustic signal measured using the P-wave receiver contain an impulsive component whose arrival time is consistent with the reception of an acoustic signal scattered from the floor of the test box (see Figure 9).

Recommendations for further research and development in the field of acoustic subsurface imaging are as follows. First, a transmitter designed to minimize the emission of surface waves, while maintaining efficient coupling of acoustic waves into the soil, should be constructed. The transmitter should be designed to operate either in a pulse or step-chirp mode. A simple prototype of the transmitter could be constructed by replacing the receive accelerometer of the existing prototype P-wave receiver by a high-power projection hydrophone.

Second, data should be obtained using the P-wave transmitter and receiver pair under controlled conditions in which targets of known acoustic cross section are buried in a volume of homogeneous soil (such as the test soil used in the current set of measurements). If the direct-path communication between the transmitter and receiver via surface waves is sufficiently minimized, scattered signals will be detected. The data of Figure 9 suggest that this condition is realized using only the P-wave receiver.

Finally, if the preliminary measurements using the modified P-wave transducers suggest that scattered signals can be detected, scattering measurements should be obtained at a number of grid points on the air-soil interface. This type of data can be processed using a variety of existing signal processing techniques in order to image a subsurface feature. It is possible that reflections of the acoustic signal from the boundaries of a small-scale test box, such as that used in the present experiments, will be large in comparison to the scattered signal from a target. In this case the imaging experiments should be conducted in a test bed of greater volume.

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