1 INTRODUCTION

The work reported in this thesis concerns the project of using acoustic wave propagation through a highly attenuating material in order to construct images of subsurface features. The highly attenuating material concerned throughout the experimental work of this thesis is sand. Sand is known to be a very attenuating material that is a limiting factor for the goal of producing images. In this work the term “acoustic” concerns the audible range of frequencies (20 Hz−20 kHz), whereas usually this term also includes lower frequencies, or infrasound frequencies, and higher frequencies, or ultrasound frequencies.

Usually ultrasonic waves are used to produce medical images, as explained in [1], because resolution improves when the frequency increases. However, the attenuation of a material also increases with the frequency of the traveling wave. Therefore, ultrasonic waves cannot be used to image in a highly attenuating material because their high frequency yields high attenuation. High attenuation makes the wave difficult to penetrate deep into the medium.

There is hence a trade-off between the depth of penetration and the resolution of the reconstructed image. To have a greater depth of penetration one would like to use a low frequency so that the wave does not attenuate too fast, but to achieve a better resolution one would like to use a high frequency.

However, with the high attenuation in sand, the frequency that we will be using throughout this project will be in the kilohertz range and not in the megahertz range.

Finally, acoustic waves do not alter the medium. The acoustic technique is hence a nondestructive evaluation method. This last fact is very important because we are interested in knowing what is inside the medium without damaging it as it might have valuable or dangerous objects.

1.1 Imaging in Sand

1.1.1 Goal

The goal is the production of high-quality images of subsurface properties without digging. In this project we are interested in imaging to a depth of approximately 50 cm.

Imaging in sand allows us to assess the archaeological resource of a new site in a faster manner than the usual technique that consists of small-scale digs. Moreover, a system able to detect cultural artifacts might also be used to find buried land mines. In order to permit the detection of small objects, the resolution requirements are high. We need to be able to achieve a resolution on the order of 1 to 10 cm.

Sand is the medium chosen because it has similar properties as the usual medium where the system would be used, either to detect land mines or cultural artifacts. The main common property is the very high attenuation of soil-like media.

1.1.2 Existing techniques

Subsurface imaging has generated a lot of interest, particularly in helping with the worldwide effort of finding land mines. Many different approaches have been tried, but acoustic imaging is probably the most recent one.

Ground penetrating radar (GPR) was tried as a solution to the subsurface imaging problem. GPR can be defined as a radar whose goal is to detect and identify structures within the ground. It is basically a time-domain reflectometer of electromagnetic energy. This technique had some success, but this success was extremely site dependent [2]. Electromagnetic waves suffer attenuation that is very medium-dependent. In most media the attenuation factor in Np/m is

$$\alpha = \frac{1}{2}\sigma\sqrt{\frac{\mu}{\epsilon}} \tag{1.1}$$

where μ is the permeability, ϵ the permittivity, and σ the conductivity of the medium. The conductivity is often a frequency-dependent parameter which makes the value of α frequency-dependent as well. The frequency of operation of GPR is in the range 100 MHz$-$500 MHz. The technique described [2] is particularly efficient in dry soil, where the attenuation factor is very small. But in moist soil the electromagnetic attenuation is too high and the wave does not propagate a sufficient distance to do imaging.

Seismic techniques have also been used for the purpose of subsurface imaging [3]. This technique can image deeper (10 m), but does not meet the requirements in terms of resolution necessary to detect cultural artifacts (1−10 cm). Reference [4] provides a comparison of seismic and GPR techniques mostly focused on the variations of the attenuation values and speed of propagation values for different type of materials and for both types of waves. In [4] we find a speed of propagation of electromagnetic waves of 1.5 10^8 m/s in dry soil and 0.5 10^8 m/s in water-saturated soil. The attenuation is 0.14 dB/m for dry soil and 2.3 dB/m for water-saturated soil at 100 MHz. The case of seismic propagation at 10 kHz [4] shows a speed of propagation of 4300 m/s and an attenuation of 3.91 dB/m in sandstone. The drastic variation of electromagnetic properties between dry soil and moist soil shows how the GPR constitutes a technique that will not give consistent results in media such as sand. Also, the properties of seismic waves lead to a wavelength of around 43 cm. This value does not provide a satisfying resolution for the goal of our project.

Smith et al. [5] developed an acoustic subsurface system to localize reflections from a buried object on a natural beach. They used a pulse with a very low center frequency of 100 Hz, so they could image to a depth of 100 m. The speed of propagation they observed was around 115 m/s and the attenuation value observed with a pulse centered at 100 Hz was 0.912 dB/m. The resolution they achieved was on the order of tens of centimeters. This value does not meet the requirements necessary to find a small land mine or a small archaeological object. Moreover, the technique requires the subtraction of a background image with no targets, making this technique unsuitable for the situation where no target-free data can be collected. This is a main disadvantage and results in the impossibility of using this technique to achieve the goal of our project.

1.1.3 Acoustic imaging

None of the techniques tried to accomplish subsurface imaging met the objectives of our project, that is, a high-resolution system (1−10 cm), but a small depth of penetration (50 cm). The acoustic project described in [5] confirmed that acoustic waves could be successfully used at higher frequencies to increase the resolution and also decrease the depth of penetration. Therefore, using acoustic waves should bring advantages over the other techniques.

The acoustic technique would lead to a better resolution in sand-like media than the seismic and GPR techniques. It is also an inexpensive technique compared to small-scale digs. This last fact would make this technique available on sites where the probability is very low of finding land mines or cultural objects. Also, the acoustic propagation is shown to be better in moisture-saturated sand, which would make an acoustic system complementary to a GPR system.

1.2 Acoustical Properties of Sand

The acoustical properties of sand are not easy to determine. First, it is important to understand that acoustic propagation in a porous medium is far from the ideal case of wave propagation through a uniform medium. Biot [6],[7],[8] first theorized this part of acoustics.

Biot's theory was developed in 1956. The goal was to describe the propagation of stress waves in a porous elastic solid containing a compressible fluid.

This theory predicts the propagation of two compressional waves and one shear wave, each having very different properties [6],[7]. The first compressional wave is referred to as the fast wave because it often has a higher speed of propagation and is characterized by a particle motion in phase with the fluid. The other compressional wave, or slow wave, has its particle motion out of phase with the fluid motion. Also, the theory shows that the slow wave has a higher attenuation. The shear wave is shown to have the slowest speed and the greatest attenuation. However, the slow wave is very difficult to observe because of its high attenuation.

Biot's theory was confirmed by Burridge and Keller [9] based on the dynamic equations governing the behavior of a medium on a microscopic scale. Experiments conducted by Plona [10] also confirmed Biot's theory.

In our experimental study we will be dealing with the fast wave because it is the one that has the lowest attenuation. It can therefore penetrate deeper, allowing us to form images of deeper features. It is actually the only one we have been able to observe.

The problem of determining the acoustical properties of sand is essentially reduced to evaluating the speed of propagation and the attenuation of the fast wave. Speed of sound is needed to range targets in the field of the imaging system. Because the echo from a target appears in the signal at a certain time, we then need to convert this time to a depth to multiply by the speed of propagation.

Attenuation is necessary to determine the magnitude of the return echo from a target and to determine the maximum depth of penetration. The smaller the attenuation, the greater the depth at which the system should be able to detect targets.

1.2.1 Experimental measurements

Oelze et al. [11] describe and explain some measurements that were made in different kinds of sand and soils. Their experimental study includes samples from six different soils, with two compaction levels and four moisture levels.

Through-transmission experiments were conducted to measure attenuation and speed of propagation. A transmitting transducer was placed on one side of one of the soil sample and a receiving transducer on the other side. The source transducer was an NRL F56 Serial 58 (Transducer Branch, U.S. Naval Research Laboratory's Underwater Sound Reference Detachment, Orlando, FL) and the receiver transducer a hydrophone, NRL F42C Serial 28 (Transducer Branch, U.S. Naval Research Laboratory's Underwater Sound Reference Detachment, Orlando, FL).

The receiver is an hydrophone and therefore is matched to water. It was necessary to use a water layer between the receiver and the sand because the impedance mismatch between water and air is much greater than that between the water and the sand sample. Another concern is the need for a broadband receiver: attenuation is proportional to frequency (or at least increasing with frequency); therefore, the received signal will contain more lower frequencies than the transmitted signal. Since they used a frequency range between 2 kHz and 6 kHz, they chose a hydrophone that had a fairly flat frequency response in the range 100 Hz $-$ 200 kHz.

The results of this study show speed values ranging between 100 m/s and 300 m/s. They also tend to show that the highest propagation speeds were reached in the dry soil with loose compaction. For comparison, from [12] the speed of sound in water is around 1500 m/s and in stainless steel around 5000 m/s.

Attenuation ranged from 0.12 to 0.96 dB/cm/kHz. The lowest attenuation tended to be observed in the loose dry samples. It is important to see at this point that they assumed in their model that attenuation was proportional to frequency, which is not true for all materials or media of course. However, in that case a statistical study showed that this assumption was very reasonable. These values are enormous compared to some other media: in water the attenuation value found in [12] is $2.2 * 10^{-9}$ dB/cm/kHz^2 and in stainless steel the value from [13] is on the order 10^{-20} dB/cm/kHz^2.

A straightforward computation shows that if we assume an attenuation of 0.70 dB/cm/kHz and if we want to image a target located 30 cm deep, the round-trip loss at 2 kHz would be 84 dB. This is a very big loss for an ideal target buried 30 cm deep. Typical imaging systems have a dynamic range of around 140 dB so that basically at 2 kHz our imaging system should be able to image a target up to 50 cm. Of course this limit of 50 cm still assumes a perfect reflector, in the sense that all the energy transmitted bounces back, which will not be true even if the target is, for example, a piece of metal buried in the sand. The pressure reflection coefficient at normal incidence is given by

$$R = \frac{Z_{object} - Z_{soil}}{Z_{object} + Z_{soil}} \tag{1.2}$$

where Z_{soil} is in the range of (1-3)$*10^5$ Pa s/m, assuming the density $\rho = 1000$ kg/m^{-3}, and a speed of propagation in the range $c = 100-300$ m/s. In [12] we find $Z_{steel} = 39 * 10^6$ Pa s/m. These values lead to R=0.857 or a loss of 1.5 dB. Thus, in the extreme case of a piece of steel buried in sand we still do not get a perfect total reflection.

Also, when the pulse hits a target, some of the acoustic energy bounces back and thus does not continue its propagation through the medium. Therefore, if an object at a depth of 10 cm reflects most of the acoustic energy, an object buried right below would not be detected because it would not be hit by enough acoustic energy. This phenomenon is known as masking.

Finally, in such an imaging system, the wavelength would be around $\lambda = c/f = 10$ cm, assuming a speed of propagation of 200 m/s and a frequency of 2 kHz.

1.2.2 Frequency-depth of penetration trade-off

The previous analysis shows the imaging depth is inversely proportional to frequency. The higher the frequency, the higher the attenuation, and therefore the depth of penetration of the waves becomes smaller.

Also, the axial resolution of the system can be approximated by the wavelength $\lambda = \frac{c}{f}$. This last fact comes from the idea that when the pulse hits a target, the same pulse bounces back, and hence it becomes very hard to resolve targets less than one wavelength in the axial direction. This last fact shows that a higher frequency yields a better axial resolution.

The lateral resolution is related to the beamwidth of the transducer. The tighter the beamwitdth, the smaller the shape due to a single target.

Moreover, the beamwidth becomes tighter when the frequency increases [12]. Therefore, a higher frequency yields a better lateral resolution as well.

Hence, there is an important trade-off between depth of penetration into soil and image resolution.

1.3 Organization of this Thesis

This thesis discusses the research accomplished at the Bioacoustics Ressearch Laboratory located at the University of Illinois at Urbana-Champaign to develop subsurface acoustic imaging techniques in soil. This work is a continuation of the previous work accomplished by Frazier et al. [14].

Chapter 2 describes the experimental system that was used to support this research. Chapter 3 explains the methodologies used to reconstruct images. Then Chapter 4 describes the results obtained using the techniques of Chapter 3. Finally, the conclusions and the suggestions for future work are presented in Chapter 5.