5 CONCLUSIONS AND FUTURE WORK

5.1 Experimental System

The experimental system is totally operational and very reliable. It is also very flexible. Almost any scan geometry can be accomplished. Variable array geometry can be used on receive and on transmit. Also, any pulse can be generated with the help of the waveform generator. Therefore, the experimental system is a very useful tool for the investigation of the subsurface acoustic imaging problem.

5.1.1 Experimental system improvement

The experimental system can still be improved. For example, including force sensors on the transducers would help guarantee a more uniform coupling of the transducers with the sand throughout a scan. The force sensors would give a feedback to the computer of how good the contact of the transducers with the sand is. Therefore, the computer would be able to let the transducers make contact with the sand with a constant force. This will definitively help have a more uniform contact and therefore coupling throughout a scan. The inclusion of force sensors would be necessary if the system were to be used in real sites where the ground is not level.

The system could also be improved by modifying the transducer properties. The transducers are responsible for the transmission and reception of the direct wave (DW). This is probably because they are omnidirectional devices. Improvement would hence consist in using devices able to transmit higher frequencies with good power transmission through the sand. The use of higher frequencies would result in making the beamwidth of the transducer narrower. However, the use of the array in receive requires the beamwidth to be wide enough so that signals can be received at large angle (with respect to the transducer axis). There is hence a trade-off between the ability of modeling large arrays and the use higher frequencies. Also using a higher center frequency would lead to an improved axial resolution and to higher attenuation of the waves. Particularly, the DW would be more attenuated because its attenuation is probably also increasing with frequency. Of course, the counterpart would be in the diminution of the depth of penetration because of higher attenuation of the wave traveling through the medium as well.

Another idea would be to modify the radius of the MST so that its beam pattern has a null perpendicular to the axis. We are interested in having a null in this direction because the direct wave is a wave traveling in a direction normal to the transducer axis. Therefore, the direct wave might disappear if the MST is such that it does not transmit energy in directions perpendicular to its axis. This would happen if we choose the radius a, to be such that $2\pi a/\lambda$ =3.83 [12]. This leads to a=6.10 cm assuming $\lambda = 10$ cm. Therefore, modifying the radius of the MST to a value of 6.10 cm at a frequency of 2 kHz might prevent the propagation of the direct wave.

To use an array on receive we need to have transducers with omnidirectional beam patterns, so that they are able to receive signals even at large angles. The beam patterns of MST and Terr are essentially spherical with their actual radii and a frequency of operation of 2 kHz. The change of the radius of MST to a value of 6.10 cm will transform this spherical beam pattern to a nonspherical beam pattern. The new beam pattern, however, will still be omnidirectional [12]. Therefore, changing the radius of a MST to a value of 6.10 cm should not lead to any major drawbacks in terms of imaging with arrays. The first reason is that Terr would still have a mostly spherical beam pattern; therefore, it would still be able to receive signals at large angles. The second reason is that the new theoretical beam pattern of MST described in [12] is such that power is still transmitted almost in every direction.

5.2 Imaging

The image techniques presented in this thesis are interesting. The B-mode and delay-and-sum beamforming techniques presented in Chapter 3 are direct adaptations of successful techniques used in ultrasound [1]. However, the very high attenuation of the sand limits the success of these techniques to the subsurface acoustic imaging problem.

Nevertheless, results using these techniques have been obtained and have been presented. They gave us an idea of the resolutions obtainable and also demonstrated the existence of a direct wave propagating directly from the source to the receiver.

5.2.1 Resolutions

We would like to have a high-resolution system for which the resolutions are smaller than 5 cm in both directions (axial and lateral) because the goal of the system is to be able to detect small artifacts (1-10 cm in size). Therefore, the results showed that resolutions were not good enough.

The axial resolution, related to the pulse length, is around 20 cm on the B-mode images because we use a two-cycle, 2-kHz pulse in a medium whose speed of propagation is 200 m/s. However, we have seen that using an array on receive, and reconstruction with delay-and-sum beamforming can lead to an improved axial resolution of around 10 cm.

The lateral resolution is related to the beamwidth of the transducer when no array is modeled. Our transducers have large beamwidth because they are essentially omnidirectional. Results obtained in Chapter 3 showed the possibility of resolving objects at a distances of 7 cm from each other in the lateral direction. However, when a receiving array is modeled, the lateral resolution is related to the width of the main lobe of the beam pattern of the array. And the width of the main lobe decreases when the number of elements in the array increases [12]. However, experimental images reconstructed using arrays did not show an improved lateral resolution compared to images reconstructed using a single receiver. This is probably due to the high attenuation in sand leading to small echo signals at large angles because in our geometry larger angle also implies a longer distance of propagation of the pulse, and therefore a higher attenuation.

An axial resolution of 10 cm and a lateral resolution of 7 cm are encouraging, but these values are still not good enough to resolve small artifacts or small land mines buried in soil close to each other.

5.2.2 Improvement of the delay-and-sum beamforming technique

A possible improvement would consist of adapting the matched filter method. This method is essentially adapted from communications engineering. It consists, in order to maximize the signal-to-noise ratio, of convolving the signals detected at the output of a noisy channel by the input signal. In our case the matched filter technique might result in an improvement of resolution. Convolving corresponds to linear filtering; therefore, the matched filter term refers to the fact of filtering with the input signal filter. In our problem, one can consider the medium of sand as a communication channel and therefore try to adapt this method. Usually in communications the problem is that we do not exactly know the input signals. However, even though in our problem we exactly know the pulse we are transmitting, we cannot directly convolve the received signals with the transmitted pulse. In our project the matched pulse is distorting with depth, because of the attenuation. The attenuation makes the shape of the pulse change as the pulse propagates deeper into the medium. Therefore, the match filter is depth-dependent and the method cannot be directly applied.

5.2.3 New imaging approaches

Synthetic aperture (SA) processing could, for example, yield higher resolutions than the B-mode and delay-and-sum beamforming technique. Cadalli [17] explains how he used a modified synthetic aperture technique to reconstruct images from simulated data. His algorithm is an adaptation of synthetic aperture radar (SAR) to subsurface imaging. The main difference between SAR and subsurface imaging is the high attenuation of the signal in sand. The images obtained using the SA algorithm for subsurface imaging from simulated data showed good resolution (around 4 cm in both direction). However, results obtained with experimental data were not satisfying, probably because this algorithm was unstable in the presence of noise.

Another technique is the so called $\omega - k$ algorithm. This technique is better than the SA technique because it takes into account wavefront curvature. This technique is therefore particularly efficient near the transducers, where the field is very curved. Cadalli [17] showed how to develop a 3-D version of the $\omega - k$ algorithm for subsurface imaging. However, this technique assumes a chirp transmitted pulse. Our transducers are designed to transmit shaped sinusoidal pulses but cannot transmit chirp efficiently. Therefore, using this reconstruction technique would require more broadband transducers, which would be able to transmit chirp pulses efficiently. Finally, we can easily model a chirp pulse in our simulation. Therefore, we should be able to develop a 3-D $\omega - k$ algorithm able to reconstruct images from simulated data.

5.2.4 Direct wave problem

The presence of the direct wave (DW) is responsible for the limited quality of the images obtainable with the experimental system. The DW generates strong signals precisely in the depth range (around 10-50 cm) where the system has to be efficient. Therefore, dealing with the direct wave is very important. The direct wave is composed of around four cycles and is centered at 2 kHz when the transmitted pulse is a two-cycle, 2-kHz pulse. The fact that its center frequency is the same as the transmitted pulse eliminates the possibility of filtering in the frequency domain.

The other techniques for mitigating its effect presented in this work have been either unsuccessful (use of a water layer and SOABs) or only partially successful (destructive summation).

Based on the idea of modifying the coupling of the transducers with the sand, we could try to use some materials other than SOABs. For example, we could use a layer of a material having a high attenuation in one direction only. If we use this material such that the attenuating direction is that of the DW then, it might help in mitigating its effect. However, the use of such a material would also have consequences in terms of imaging. This material would probably have an attenuation factor dependent upon the angle of propagation with respect to the transducer. Therefore, echoes coming from different directions would be attenuated differently because of the material layer.

The idea of destructive summation was shown to be partially successful; therefore, we could try to improve the simple scan scheme we presented in Chapter 4. We could, for example, design a scan scheme such that the delays computed to focus the receiving elements of a line array at a certain depth regularly cover one cycle (or one wavelength) of the direct wave. This should in theory give better results than the technique used in Chapter 4, but only at the considered depth. However, since the delays to focus at a nonzero depth are nonlinear the resulting line array would not be linear.

An improvement of this previous technique would consist in using a linear receiving array consisting of many elements (for example a 10 x 10 array). Then during the focusing procedure we could choose to use only a part of all the acquired signals such that the resulting delays regularly cover a wavelength of the direct wave. This technique would have the advantage of dealing with any depth of focus. Therefore, dynamic focusing should lead to images where the DW should be cancelled at every depths of focus.

Another idea would be to modify the size of the transducers. This could avoid the transmission or reception of the DW. The idea is to have a beam pattern a null perpendicular to the axis. It is possible to modify the radius of the MST as described in Section 5.1.1 to reach this goal.

Based on the same idea of designing beam patterns with a null in the direction of propagation of the DW, one could think about designing a receiving array having this feature. For example, an N x N square array whose pitch is d in both directions would have that property if $\sin(\frac{N}{2}\frac{2\pi}{\lambda}d) = 0$ [12]. For example if we use N=8 (an 8 x 8 array) and with λ=10 cm, one solution is d=$\lambda/2$ leading to a square array whose side is 4λ=40 cm.

5.3 Simulation

The simulation model developed in this work is very simple. It consists of assuming a uniform medium with a speed of propagation c and an attenuation α. This is essentially an elastic propagation model even though the medium considered is porous.

Chapter 4 showed that the simulation has been a very useful tool in the development and testing of reconstruction techniques. It particularly helped in validating the inclusion of time gain compensation and dynamic focusing in the delay-and-sum beamforming technique. Moreover, simulated images gave an insight in terms of resolutions and point spread function of the system.

Knowing the point spread function can be helpful because one can see the reconstructed image as a 2-D linear convolution of the medium with the 2-D point spread function of the system. Therefore, knowledge of the point spread function can be very helpful toward the goal of deconvolving the conventional image in order to reconstruct the medium features.

5.3.1 Improvement of our model

Many improvements of the simulation methodology could be done. A model of noise should be included, so that reconstruction algorithms could be tested under different signal-to-noise ratios. However, the usual Gaussian white noise would be insufficient to model noise due to slight variation of the acoustical properties of the medium. Slight variation of acoustic parameters can lead to small reflections that have to be modeled as noise. These low-noise small reflections can be referred to as scattering noise. Therefore, a more correct noise model than the Gaussian model would consist of assigning to each point in the sampled 3-D space that is not an object a random reflection coefficient.

The attenuation due to the propagation of the pulse in our model is only an approximation. The attenuation coefficient varies with frequency, and our transmitted pulse is not composed of a single frequency component. Therefore, the correct attenuation model would consist of attenuating in the frequency domain. In that case each frequency component of our pulse would be attenuated differently and in accordance with the frequency-dependent attenuation.

Another idea would be to try to incorporate properties of the actual transducers (MST and Terr) into our model. One can, for example, think about their frequency responses and beam patterns. This would definitively help in the goal of testing reconstruction techniques efficiently. If we can accurately simulate the system, then the results obtained from simulations would give more information and help us in the design of new scan schemes and processing techniques.

Finally, more interestingly, one could try to include the direct wave in the simulation. This would help in the investigation to mitigate its effect. New processing techniques or scan schemes could be easily tested by simulation before being tried on the experimental system. However, here also the problem is to accurately include the direct wave in the simulation. The waveform of the direct wave is consistent in the sense that it is always composed of around four cycles. However, the DW signal is not a simple four-cycle sine wave, and relative amplitudes between the four cycles do not seem consistent. Measurements showed a speed of propagation of around 150 m/s, but to accurately simulate the DW one needs to have an idea of the attenuation factor as well as its dependence upon frequency. This has yet to be determined; therefore, more experiments need to be conducted in order to asses the attenuation properties of the direct wave. Once the acoustic properties of the DW are available, adding it into the simulator as a four-cycle sine wave would be easy and should lead to interesting results even if the four-cycle model is not totally correct. Another possibly more correct solution would be to record one of the experimental waveforms and include it in the simulator in place of the four-cycle sine wave.

5.3.2 New simulation approach

Finally, one could use a totally different technique to simulate the echo signals. Research is now moving forward using the finite-difference time-domain (FDTD) method [18]. Unlike our model, this model incorporates the interactions of waves and the fluid-saturated pore space. This method does not assume an elastic propagation and derives all the dynamic equations directly from Biot's theory [6],[7],[8]. This technique is hence more accurate. Having a more accurate model will help in the developing of new imaging techniques. Therefore research into the FDTD simulation methodology could also be conducted.