2 EXPERIMENTAL SYSTEM

2.1 Description

The experimental system is present at the Bioacoustics Research Laboratory at the University of Illinois at Urbana-Champaign. It is composed of a cubic wooden box of 1.2 m per side. Only the top 60 cm are filled with sand because it has a false bottom. The experimental system uses two different transducers, one to transmit pulses and one to receive the signals.

A motion system has been designed to control the motion of both transducers. Their motions are independent, which gives us flexibility in terms of scan schemes. Figure 2.1 shows a picture of the experimental system. All figures appear at the end of each chapter.

A PC-based software system has been designed to control the motions of the transducers. The computer (Industrial and Communication Products) has a Pentium II processor, 128 MB of RAM and a 2.4 GB hard drive.

Figure 2.2 shows a block diagram of the experimental system. The system is a usual data acquisition system. The main difference here with most other systems (particularly ultrasonic imaging systems) is the use of two different transducers. One is used to transmit and the other is used to receive. The scan files are simple text files that are used as inputs to describe the geometry of the scan to be ran. They basically contain the locations where the transducers have to go to acquire the data.

The purpose of the experimental system consists of providing control for six axes of motion, waveform generation, and data acquisition. Three axes are in a rectangular coordinate system (x, y, z), to control the carriage movement (transmitter). The three others axes are in a cylindrical coordinate system (r, θ, z') to control the radial arm movement (receiver motion with respect to the transmitter). The x-y plane corresponds to the soil surface, and the z coordinate indicates the depth into the sand. Figure 2.3 shows the coordinate systems in the $x - y$ plane; therefore, z and z' are orthonormal to the plane of the figure.

The computer program is developed in Visual Basic under the Windows NT environment. It is responsible for sending command via the various interfaces to generate waveforms, position the carriage and radial arm and acquire data. Motion is controlled by the computer through two National Instruments PCI-7344 cards.

A waveform generator (Hewlett Packard HP 33120S) is used to generate the pulse. The waveform generator is triggered by the computer. The pulse is then amplified by a 40-dB amplifier (POWERTRON 3000S, Industrial Test Equipment Co.) before going into the transmitter. Received signals are then acquired by a National Instruments PCI-6052E card and saved on the computer. An oscilloscope (FLUKE PM 3084) is also used to display transmitted and received waveforms. Figure 2.4 shows a picture of the console of the system, including the oscilloscope, the waveform generator and the three National Instruments cards.

2.2 Sand Properties

The values obtained in [11] with the sand present in the sandbox are

- A speed of propagation c of 200 m/s
- An attenuation, A proportional to frequency, of 0.6 dB/cm/kHz

These values are the ones that will be used throughout this project. An error on c has important consequences because it is used to range targets, whereas A is mostly used to gain an idea of the expected depth of penetration. Also knowing the exact value of A is helpful toward the goal of compensating for the attenuation of the signals.

2.3 Transducers

2.3.1 Transmitters and receiver

In the beginning of this project, we used a transmitter designed at the Penn State Applied Research Laboratory. It will be referred as the Penn State transmitter (PST). We then received a magnetostrictive transducer developed at IMS (Industrial Measurements Systems Inc., West Chicago, IL 60185), it will be referred to as MST.

We have only one receiver. It was also developed at the Penn State Applied Research Laboratory, and it is called terraphone and will be referred to as Terr. Figures 2.5 and 2.6 show pictures of the three transducers.

MST, PST, and Terr exhibit the same center frequency of 2 kHz. Hence, working with a frequency of 2 kHz is the logical choice to maximize the energy transmitted into the medium and then received from the medium.

A frequency of 2 kHz and a speed of propagation of 200 m/s (Section 2.2) yield a wavelength of $\lambda = 10$ cm.

The radii of the transducers are $a_{PST} = 3.8$ cm, $a_{MST} = 3.75$ cm and $a_{Terr} = 2.55$ cm. The definition of the border between the near field and the far field of a circular transducer is given by [12]: $r > r_a$ where r is the distance from the source and r_a is defined by

$$r_a = a/\lambda - \lambda/4a \tag{2.1}$$

Using $\lambda = 10$ cm and the values of the radii given above, one can see that at a frequency of 2 kHz, MST, PST, and Terr do not have a near field (that is, $r_a < 0$ for the three transducers). Therefore, at that frequency of operation these transducers are very close to omnidirectional devices.

2.3.2 Combined beam patterns

Before using a transducer, particularly for making images, it is important to have an idea of its beam pattern. The beam pattern describes the variation of the transmission amplitude as a function of the angle between the observation point and the normal to the transducer surface.

To evaluate the beam pattern of the transducers, we buried the terraphone into the sandbox. It was buried at a depth of 18 cm. Then, we acquired signals on a square pattern centered on the position where Terr was buried. We completed this procedure with both MST and PST in order to compare their beam patterns.

The transducers were basically spanning a 61 cm x 61 cm square whose center was right above where Terr was buried. The transmitted pulse was composed of two cycles at 2 kHz. At each of the receiving position the signal was sent 32 times with a pulse repetition frequency (PRF) of 10 Hz, and received signals were averaged before being saved. This averaging was meant to help remove some of the noise.

Since this technique essentially involves the beam patterns of both receiving and transmitting devices, it can be called a combined beam pattern. After the signals were all acquired, their energies were then expressed in dB. Energies were computed by summing the squares of the signal amplitudes at every time sample.

Figure 2.7 shows the result when MST was transmitting and Figure 2.8 when PST was transmitting. Figures 2.7 and 2.8 show very similar plots. In both figures, the dynamic range of the energies of the received signals is the same, around 40 dB. Also, the 10-dB beamwidth is about the same for both transducers. It is about a circle of radius 19 cm for both transducers. Actually, the 10-dB contour looks more like an ellipse with a small eccentricity; this might be due to the buried Terr not pointing exactly to the top. But the similarities between Figures 2.7 and 2.8 only mean that both transducers have similar beam patterns. These plots do not give any information in terms of the relative performance of MST with respect to PST because Figures 2.7 and 2.8 are in a normalized dB scale without any absolute values.

2.3.3 Transmitters comparison

The beam patterns of MST and PST shown in Figures 2.7 and 2.8 are not sufficient to compare the two devices. We need to have an idea of the power transmission of both devices. The methodology used was to transmit the same pulse with the same peak-to-peak voltage into both transducers. The peak-to-peak voltage used in that experiment was only 1 V, and the pulse was a two-cycle 2-kHz sine wave. Terr was kept buried at a depth of 18 cm and MST and PST were touching the sand and located on the top of the buried Terr at the time the pulse was emitted. Then we acquired the received signals and computed their energies. Energies were computed by summing the squares of the amplitudes of the sampled signals. This experiment showed that the energy acquired when the MST was transmitting was 17 dB higher than when PST was used.

Based on the same idea of comparing the power transmission of both devices, and using the same procedure (MST or PST on the top of the buried Terr), we compared the minimum peak-to-peak voltage necessary to slightly saturate the received signal. The pulse sent was the same as in the previous experiment, a two-cycle 2 kHz pulse. We found that the necessary peak-to-peak voltage was 1.7 V for MST and 14 V for PST. It means that a voltage 18 dB higher was necessary to produce the slight saturation in the same conditions. These two experiments show that at 2 kHz the MST is transmitting more energy into the sand than PST.

Experiments were needed to compare the frequency response of both transducers to complete their comparison. The methodology used consisted in sending pulses with both transducers, at four different frequencies (1 kHz, 2 kHz, 3 kHz or 4 kHz) with either four cycles or 15 cycles. We then looked at the spectra of the received signals. The variation in frequency was simply meant to give us an idea of the frequency response of the device, whereas the variation in the number of cycles was meant to help transmit more energy in the center frequency of the pulse. Sending 15 cycles yields more energy around the center frequency than sending four cycles. This is why normally any kind of resonating system should be more likely to resonate at the frequency of the pulse when more cycles are sent. Actually, in theory if you send a continuous wave at a certain frequency, then the system will oscillate at that frequency independently of how far it is from the center frequency. So a 15-cycle pulse is closer to a continuous wave than a four-cycle pulse. The purpose of varying the number of cycles was hence to look at the ability of the device to transmit energy at a certain frequency as a function of the number of cycles.

Figures 2.9, 2.10, 2.11, and 2.12 display the spectra of the received signals. For Figures 2.9 and 2.10 the pulses are composed of four cycles and for Figures 2.11 and 2.12 the pulses are composed of 15 cycles. In Figures 2.9 and 2.11, top curves are obtained with a 1-kHz pulse and bottom curves with a 2-kHz pulse. And on Figures 2.10 and 2.12, top curves are obtained with a 3-kHz pulse and bottom curves with a 4-kHz pulse. Finally, on all four figures the left curves correspond to the case where MST was transmitting and the right curves to the case where PST was transmitting.

On all four figures the numerical values of the amplitudes are not comparable because all the signals were not acquired using the same peak-to-peak voltage, because PST needed more voltage and also because the voltage had to be changed with frequency in order to receive nonzero signals.

The results shown in Figure 2.9 are very different for both transducers; the left side (MST) shows peaks at 2 kHz for both 1-kHz and 2-kHz pulses. The right side (PST) shows peaks at 1 kHz for the 1-kHz pulse (top right curve) and at 2 kHz for the 2-kHz pulse. The same phenomenon is shown on Figure 2.11, where the only difference is the use of 15 cycles. MST always peaks at 2 kHz independently of the frequency, whereas PST peaks at the transmitted frequency. However, in Figure 2.11 the peaks are thinner; this is because transmitting 15 cycles makes the energy concentrate more around the center frequency.

The top curves of Figure 2.10 do not show a single peak. The transmitted pulse was a four-cycle, 3-kHz pulse. It seems like the devices have many peaks at that frequency. The MST (top left curve) shows four main peaks, at 1.6 kHz, 1.8 kHz, 2 kHz, and 2.8 kHz. The PST (top right curve) shows five main peaks at 1.1 kHz, 2 kHz, 2.6 kHz, 3.1 kHz, and 4 kHz. However, the bottom curves of Figure 2.10 obtained with a four-cycle, 4-kHz pulse show a phenomenon as in Figures 2.9 and 2.11: the MST peaks at 2 kHz, whereas the PST peaks at 4 kHz, which is the transmitted frequency.

The top curves of Figure 2.12 obtained with a 15-cycle, 3-kHz pulse show a peak at 3 kHz (transmitted frequency) for MST (top left curve) and a peak at 2 kHz for PST (top right curve). But the bottom plots of Figure 2.12 show once again the PST having a peak at 2 kHz and the MST having a peak at the transmitted frequency of 4 kHz.

These four figures helps us understand the behavior of MST and PST when the frequency varies from their 2-kHz resonant frequency. In most of the figures, the MST has most of its energy located around 2 kHz independently of the number of cycles or of the frequency of the transmitted pulse. Only the 3-kHz curves (top left curves of Figures 2.10 and 2.12) showed different responses.

The behavior of PST is different. It admits a peak at the transmitted frequency. Once more, only the 3-kHz case is different (top right curves of Figures 2.10 and 2.12). These results basically show that the PST is able to transmit energy far from its center frequency of 2 kHz, whereas the MST is essentially transmitting energy around its center frequency of 2 kHz independently of the frequency of the excitation signal.

The energy study showed that at 2 kHz the MST performs better. It transmits around 18 dB more power into the sand than the PST with the same peak-to-peak voltage applied. Therefore, MST should be the transmitter used when using a pulse at 2 kHz. However, the frequency experiments showed that MST is basically unable to transmit energy far from 2 kHz. This last fact means that it is useless to use MST with an excitation frequency different of 2 kHz. But PST is able to transmit energy at frequencies other than 2 kHz; specifically, we obtained good responses at 1 kHz and 4 kHz. This last fact demonstrates that PST should definitively be used if one decides to operate at a frequency other than 2 kHz.

However, to maximize the transmission and reception of energy it is very natural to use pulses centered at the center frequency of the devices, in our case 2 kHz. This is why the MST has been chosen to be the exclusive transmitting device used in this project; it is the one that will help us receive the best signals.

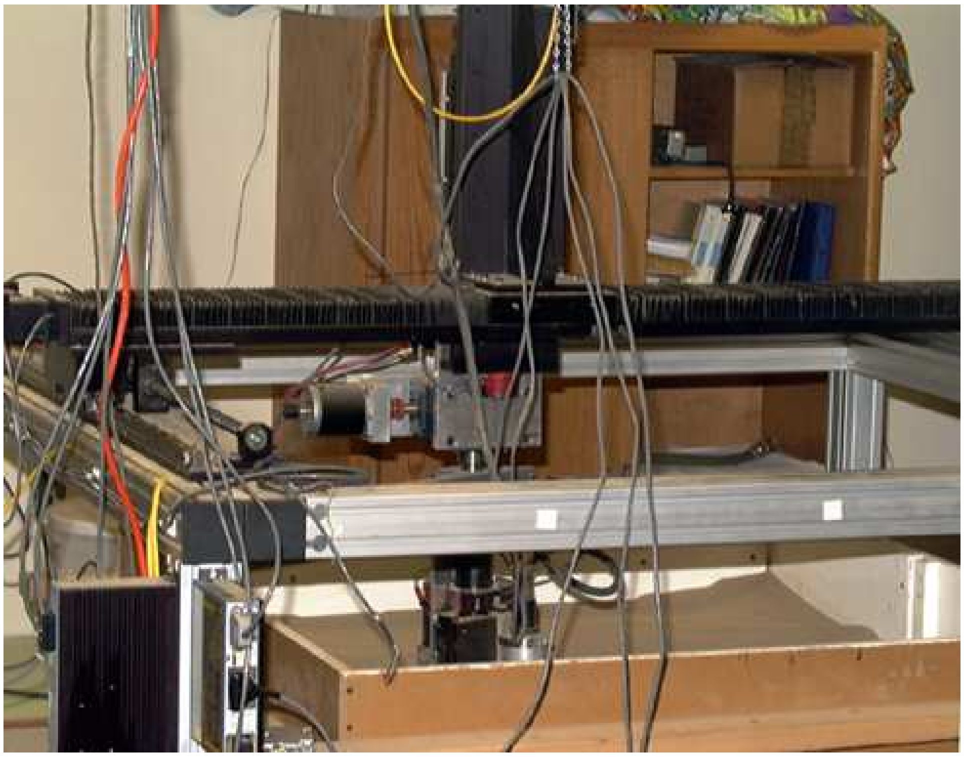

Figure 2.1: Picture of the experimental system.

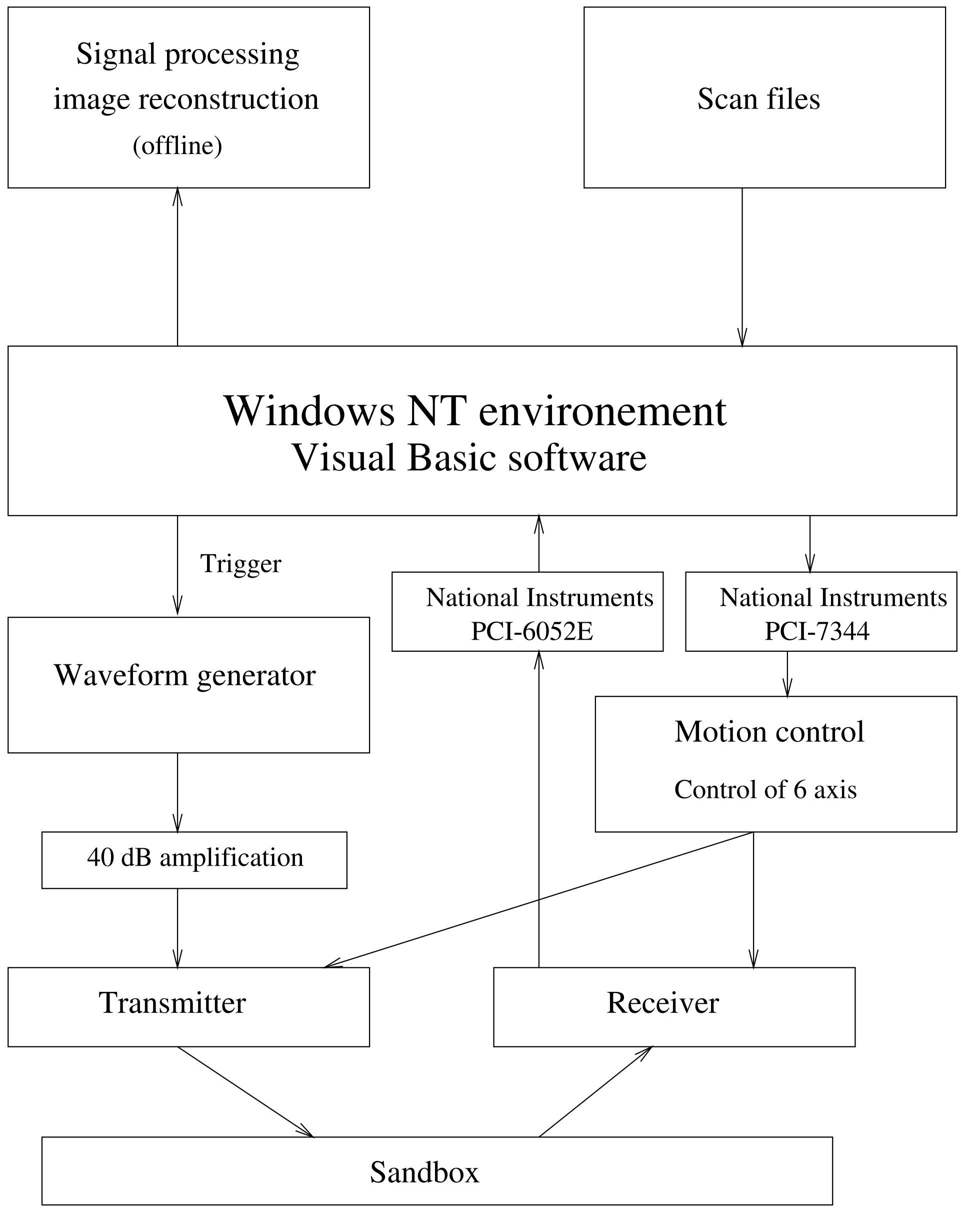

Figure 2.2: Block diagram describing the experimental system.

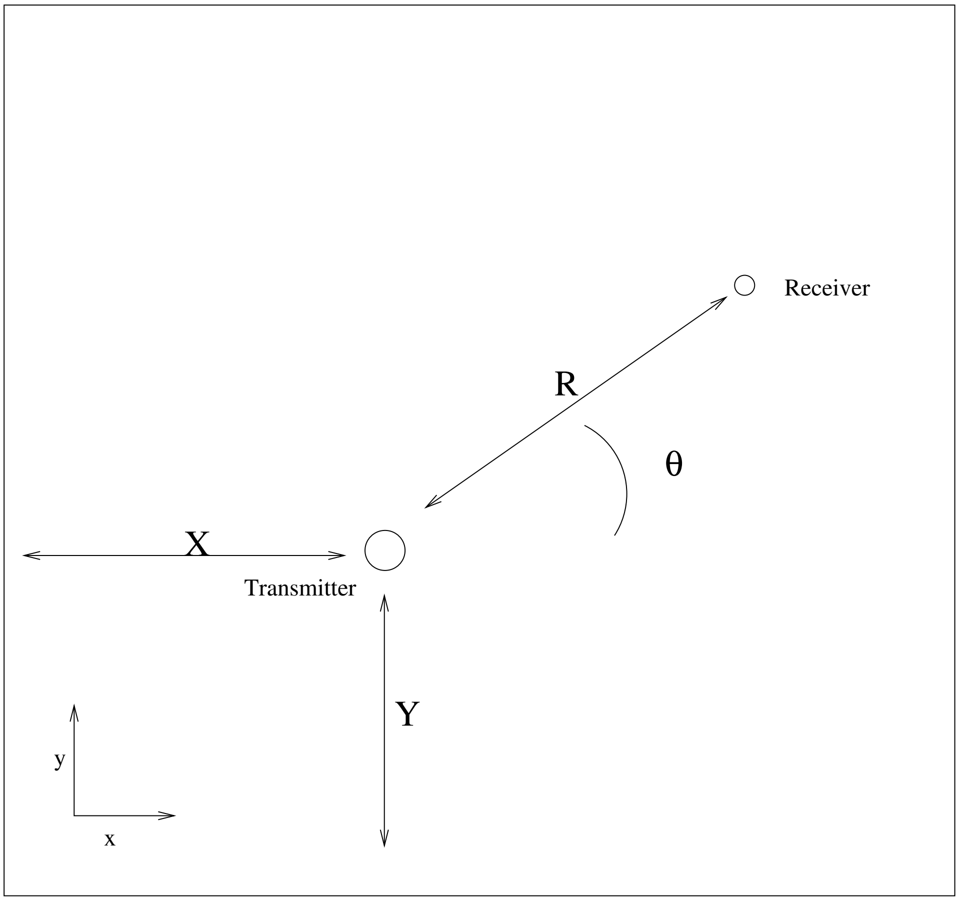

Figure 2.3: Figure describing the axis conventions of the experimental system. The figure is in the x-y plane, which is the soil surface.

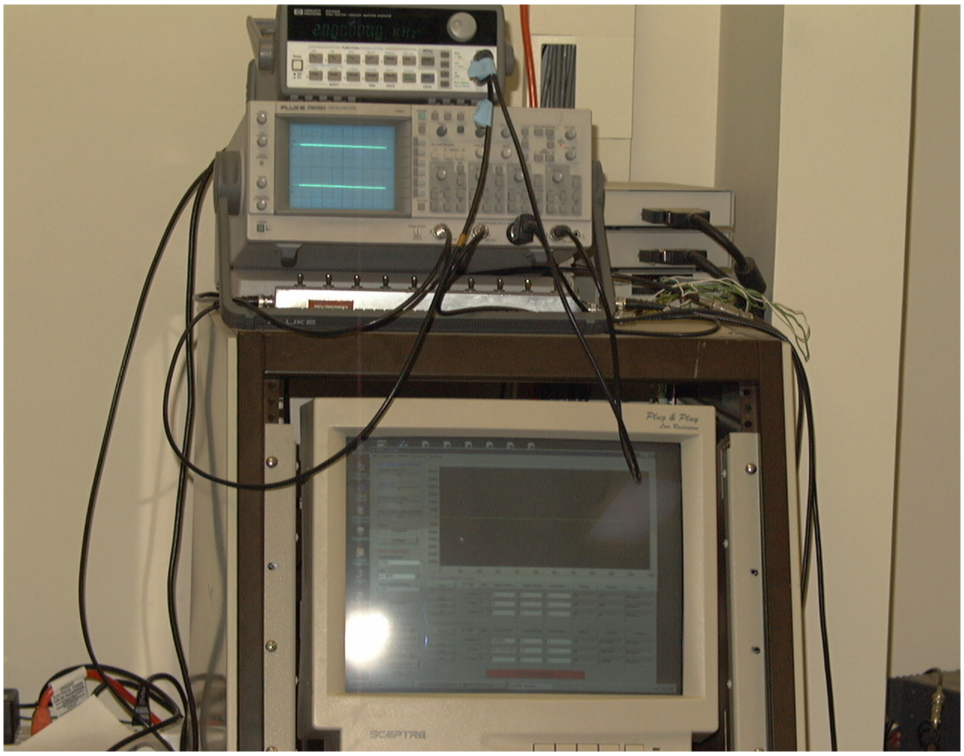

Figure 2.4: Picture showing the monitor of the computer, the oscilloscope, the waveform generator, and the three National Instruments cards (top right).

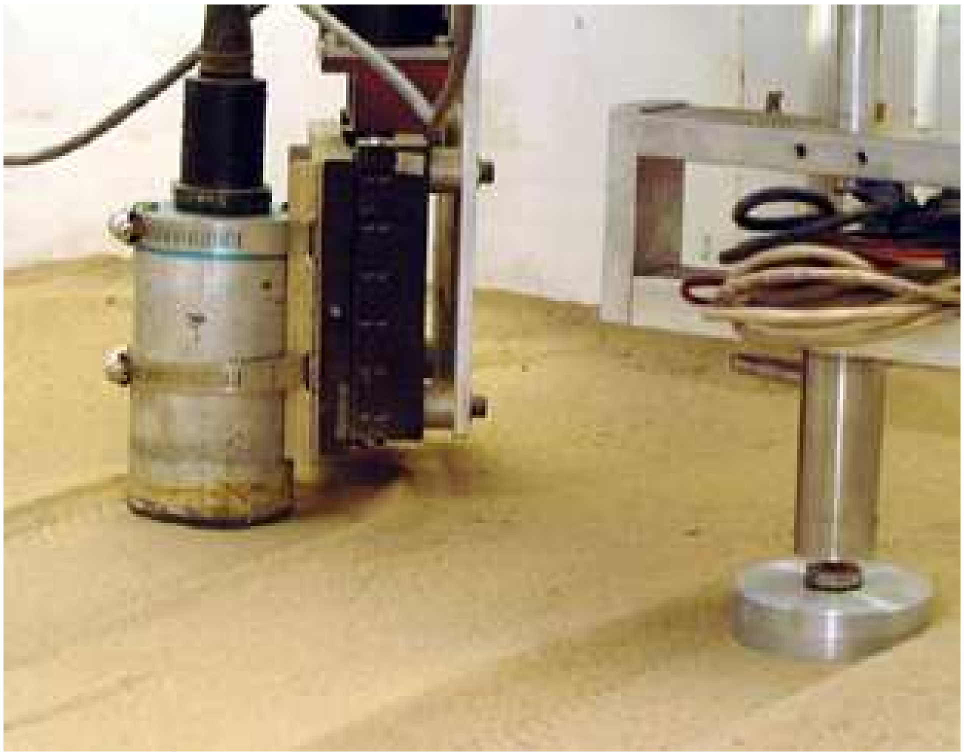

Figure 2.5: Picture showing MST (right) and Terr (left).

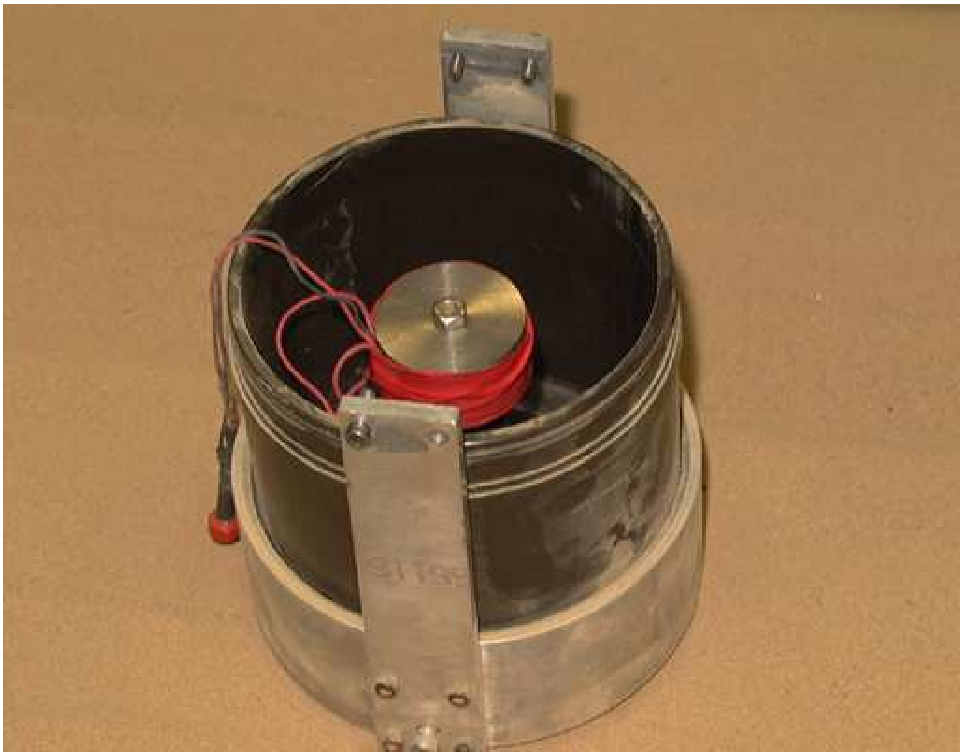

Figure 2.6: Picture showing the PST.

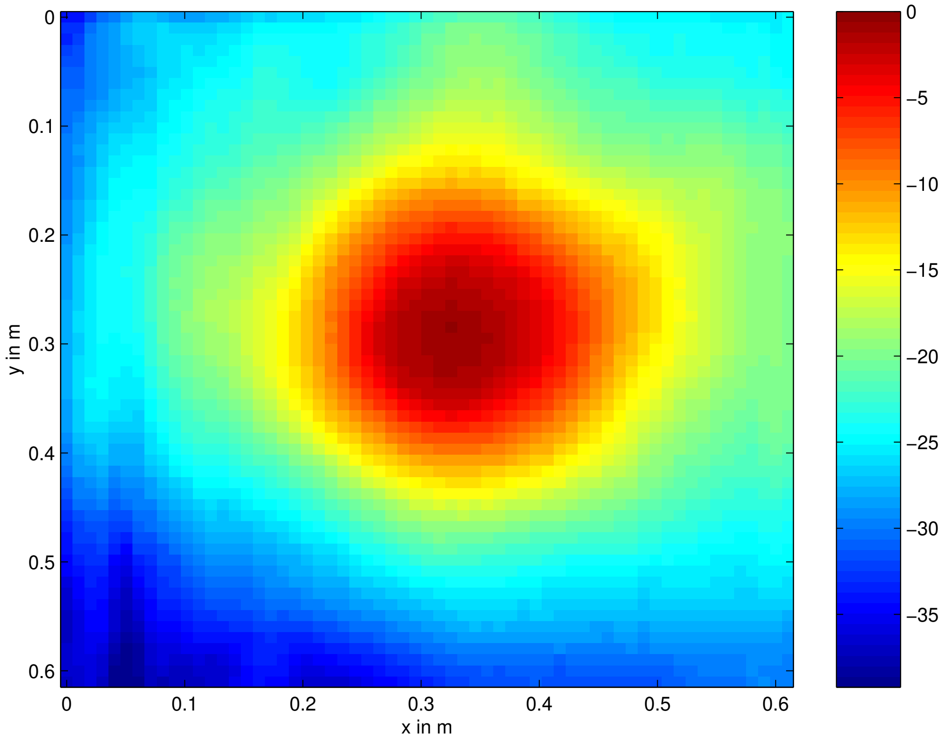

Figure 2.7: Beam pattern of MST in the sand. MST is transmitter, Terr is receiver. Terr is buried 18 cm deep. Transmitted signal: 2 kHz, two cycles and PRF 10 Hz.

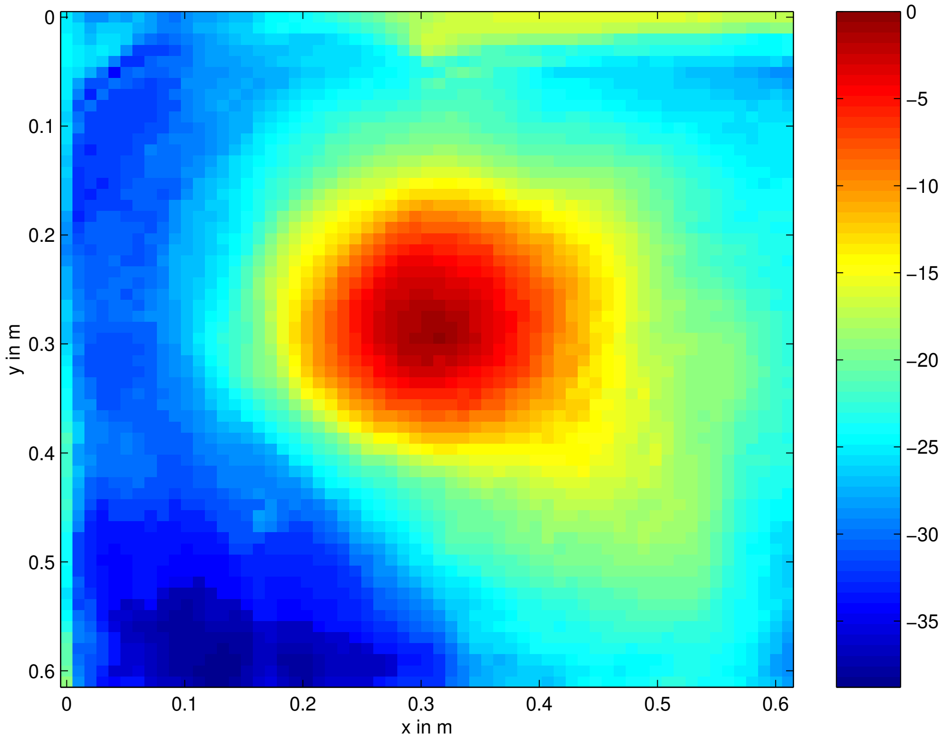

Figure 2.8: Beam pattern of PST in the sand. PST is transmitter, Terr is receiver. Terr is buried 18 cm deep. Transmitted signal: 2 kHz, two cycles and PRF 10 Hz.

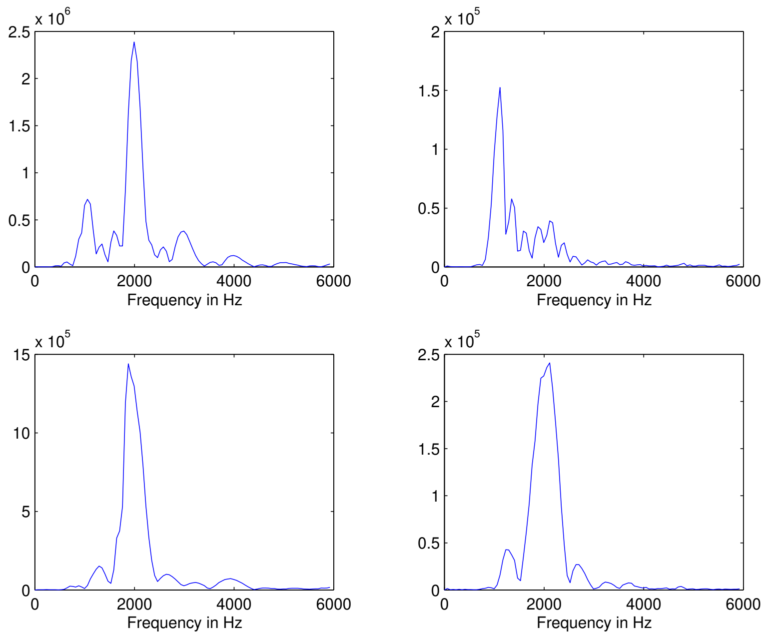

Figure 2.9: Spectra of received signals. Source signal is a four-cycle pulse for all four cases. Top signals were acquired with a transmitted frequency of 1 kHz, and bottom signals with a transmitted frequency of 2 kHz. For the left signals the transmitter was PST, and for the right signals it was MST. The receiver was in all four cases the Terraphone that was buried at a depth of 18 cm.

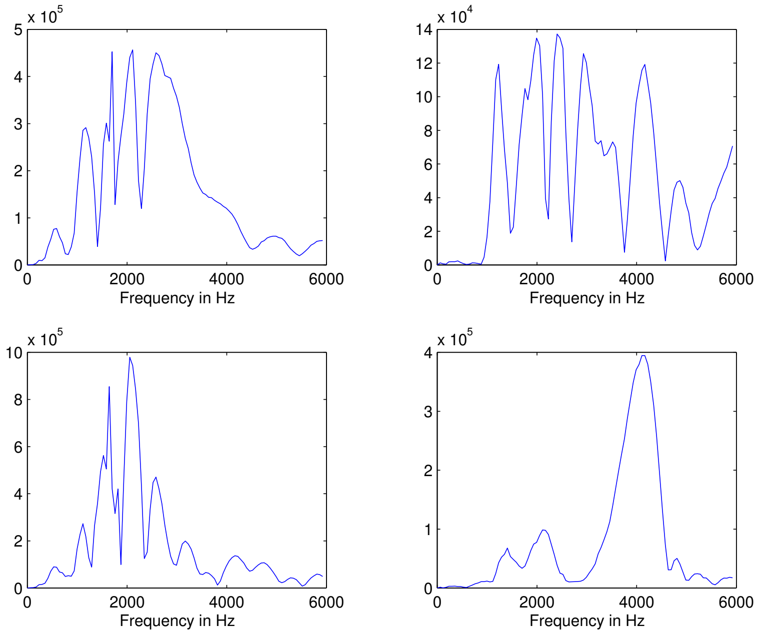

Figure 2.10: Spectra of received signals. Source signal is a four-cycle pulse for all four cases. Top signals were acquired with a transmitted frequency of 3 kHz, and bottom signals with a transmitted frequency of 4 kHz. For the left signals the transmitter was PST, and for the right signals it was MST. The receiver was in all four cases the Terraphone that was buried at a depth of 18 cm.

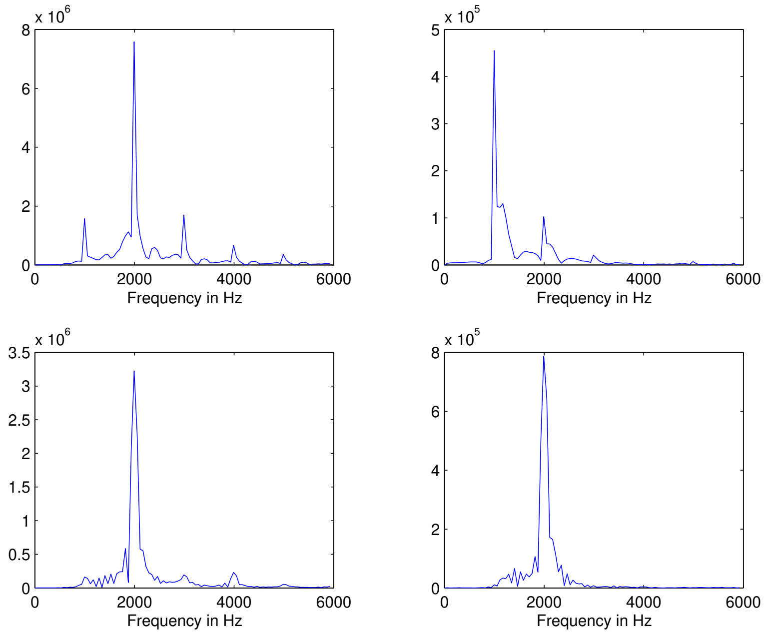

Figure 2.11: Spectra of received signals. Source signal is a 15-cycle pulse for all four cases. Top signals were acquired with a transmitted frequency of 1 kHz, and bottom signals with a transmitted frequency of 2 kHz. For the left signals the transmitter was PST, and for the right signals it was MST. The receiver was in all four cases the Terraphone that was buried at a depth of 18 cm.

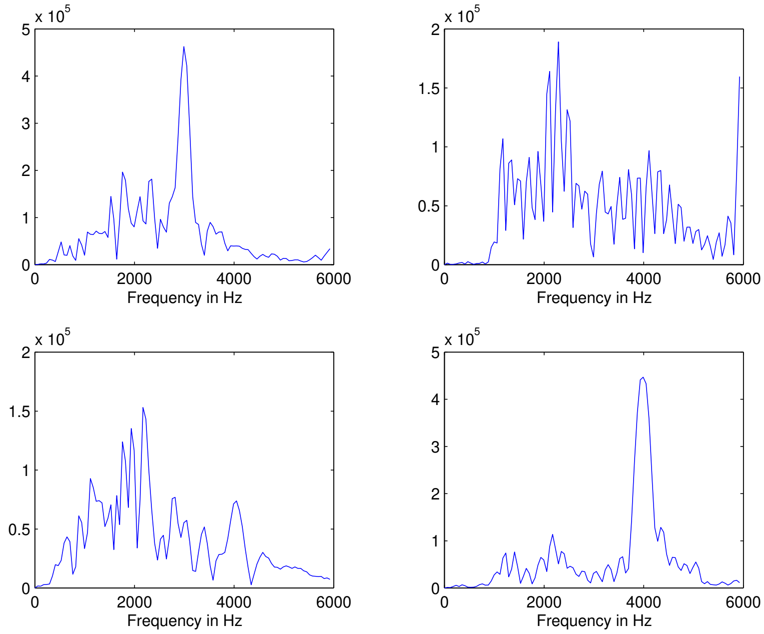

Figure 2.12: Spectra of received signals. Source signal is a 15-cycle pulse for all four cases. Top signals were acquired with a transmitted frequency of 3 kHz, and bottom signals with a transmitted frequency of 4 kHz. For the left signals the transmitter was PST, and for the right signals it was MST. The receiver was in all four cases the Terraphone that was buried at a depth of 18 cm.