Mechanical and electronic design for the U of C Seismic Physical Modelling Facility

Joe Wong, Kevin W. Hall, Eric V. Gallant and Malcolm B. Bertram

ABSTRACT

The University of Calgary Seismic Physical Modelling System has undergone significant upgrades. These upgrades include the implementation of a precise eight-axis positioning system based on modern linear electric motors, smaller piezoelectric transducers for ultrasonic sources and detectors, design of arrays of receiving and transmitting transducers, better high-voltage circuits for driving the source transducers, and improved amplifier electronics for the receivers. The various essential components have been combined mechanically and electronically in order to form a complete system that is able to automatically run acquisition experiments simulating high-fold 3D marine and land seismic surveys. Testing of the system, and integration with a master program for system control, are on-going.

INTRODUCTION

The University of Calgary Seismic Physical Modelling Facility was first designed and constructed in the mid-1980's (Cheadle et al., 1985; Lawton et al., 1989). Recently, the facility has undergone extensive upgrading to take advantage of precision positioning systems made possible by finely controlled motors (Bland et al., 2006; Wong et al.; 2007). With a scaling factor of 10,000, a laboratory experiment over a model with horizontal dimensions of 1000 mm by 800 mm and a vertical dimension of 600 mm using dominant frequencies of 300 kHz to 1 MHz simulates a real-world seismic survey covering an area of 10 km by 8 km by 6 km in depth having dominant frequencies of 30 to 100 Hz.

The earliest version of the Physical Modelling Facility was suitable for generating and receiving ultrasonic pulses in water, and was used to simulate marine-type surveys. Transducers sizes were about 1.0 cm in diameter, which scaled to unrealistically large source and geophone footprints of 100 m. Stepper motors driving carriages along aluminum tracks were used to position source and receiver transducers. Rotary motion of the stepper motors was translated into linear motion by sprocket-and-chain mechanisms that had limited repeatability and precision.

Just as seismic acquisition technology has evolved and improved tremendously over the past two decades, so the U of C Seismic Modelling Facility has grown in its sophistication and capability. This report describes the modernized hardware and electronic features of the facility in its current state. A companion report in this volume documents the software designed and written by CREWES personnel to control and synchronize the workings of the hardware. Tight integration of mechanical and electronic hardware with user-friendly software will enable rapid, automated collection of thousands or tens of thousands of seismic traces in scaled-down 3D surveys.

The positioning system

The positioning system for the Seismic Physical Modeling System is constructed using components from Parker-Hannifin Corporation of California. These components were purchased through Landel Controls Limited, Parker Motion Control's sales representative in Calgary. Table 1 shows the components used in the positioning system. Each motor/encoder/drive combination is capable moving and positioning with a precision and repeatability of 0.1 millimetre.

Table 1. Components of the positioning system.

Component Type	Number of Components	Parker Model Number
Precision Linear Motor	4	406T12LXR + encoder, 1450 mm travel
Precision Linear Motor	2	404T15LXR + encoder, 800 mm travel
Precision Linear Motor	2	404T02LXR + encoder, 150 mm travel
Motor Drive	8	AR-04AE
Breakout Module	1	RBC-8408-06
Drive Control Board	1	ACR8020/PC/E8/D4/D4/A8/0/0
Software	3	ACRView, Aries Support Tool, SDK

The eight motors/encoders/drives are configured in a two-gantry orthogonal motion system. Each gantry has 4 motors. Two of these motors move the gantry in the X direction. The two remaining motors are mounted on the gantry so as to move an equipment carriage in the Y and Z directions.

The eight motors on two gantries constitute an eight-axes system. On Gantry A, the axes AXIS0, AXIS1, AXIS2, and AXIS4 are given the aliases XAA, XA, YA, and ZA. On Gantry B, the axes AXIS4, AXIS5, AXIS6, And AXIS7 are given the aliases XBB, XB, YB, and ZB. Transmitting and receiving transducers can be mounted interchangeably on the two gantry carriages and be moved independently in three orthogonal directions.

Figure 1 shows the two gantries, AC power switches and fuses, the eight motor drives, and the breakout box, all mounted on a steel frame. After installation on the frame, the maximum ranges of motion for the X, Y, and Z motors are 1000 mm, 800 mm, and 160 mm, respectively.

Piezoelectric Transducers

Currently, we use two types of piezoelectric transducers for generating and detecting ultrasonic seismic waves. The first type of transducers are small hemispheric shells (6 mm diameter, 0.6 mm thickness) mounted on the tips of thin metal tubes. Figure 2 is a photograph of two such transducer assemblies attached to RG174/U coaxial cables terminated by standard BNC connectors. These hemispheric shells can be used as either transmitters or receivers for modeling of marine surveys. In water, the hemispheric transducers have natural dominant frequencies of about 320 kHz.

The second type of transducer used is called a piezopin. A piezopin consists of a very small cylindrical piezoelectric element (approximately 1 mm diameter by 0.5 mm long) bonded to the tips of thin metal tubes (about 1.6 mm diameter by 150 mm or 19 mm long). These also are wired to RG174/U coaxial cables terminated by standard BNC connectors. In water, the piezopins have natural dominant frequencies of about 1.0 MHz, and can be used as either transmitters or receivers.

Assuming a modeling scale factor of 10^4, the 1 mm diameters of the piezopins mimic real-world source/receiver footprints of 10 m. Because of their small size, the piezopin is well-suited for constructing arrays of multiple transducers. In any model experiment, moving transducers to their desired positions is the most time-intensive operation. By employing multi-channel receiver and transmitter arrays, we can decrease the number of transducer moves significantly, and so increase the efficiency of conducting experiments that simulate high-resolution 3D surveys.

Figure 3 is a photograph of a linear array of ten piezopins mounted on a carriage attached to Gantry A. The piezopins are spaced 10 mm apart, and each one can be connected either as a receiver (Rx) or a transmitter (Tx). Each piezopin is spring-loaded vertically, so that by moving the ZA motor down, the array can be coupled consistently to a solid surface for modelling land-type surveys (the solid surface must be covered by a very thin layer of silicon grease or hydraulic fluid to improve coupling).

Transmitter Driver Electronics

Figure 4(a) shows the basic circuit for driving a transmitting transducer. In operation, a control signal, (250-Hz, 0 to 15V square wave) causes two power MOSFET devices, MTP 2P50 and MTP 2N50, to switch the 325 VDC supply voltage, producing a high-voltage square-wave output. The HV square wave is applied to a source piezoelectric transducer, which responds to the filtered derivative of the square wave and produces an ultrasonic seismic pulse. The dominant frequency of the seismic pulse is strongly dependent on the physical shape and dimensions of the particular piezoelectric transducer, as well as the acoustic impedance of the material being coupled to. If the material is a liquid such as water, the dominant frequency is about 330 kHz for a hemispheric transducer, and about 1 MHz for a piezopin transducer.

A multiplexing circuit is needed to select an individual transducer in a multi-channel array. We have designed such a selection circuit using CMOS integrated circuits (ICs) that connects to the Parker-Hannifin RBC breakout module. The module has eight open collector outputs (Bits 48 to 55) that can be turned on or off by software. The selection circuit uses two of these outputs to sequentially select one transducer from the multi-channel array.

Figure 5 is a schematic diagram showing a multiplexing circuit that can select one of eight transmitters. The multiplexing circuit is connected to use Bits 48 and 49 from the RBC board to select the desired transmitter. The ACR-8020 motor controller board operates in the application program ACRView. This application controls the breakout module and the linear motor drives through a proprietary language called AcroBasic. Issuing the AcroBasic command sequence

SET48 DWL0.5 CLR48

causes pin 3 of the MC14011 (CMOS NAND gate) to go to +15 V, wait 0.5 seconds, and then sets it back to 0 V. This generates a RESET signal that forces the outputs Q3, Q2, Q1and Q0 of the MC14520 (CMOS counter) to a binary value of 0000. The value 000 for Q2, Q1, and Q0 connects the 250 square-wave signal at pin 3 of the MC14051 (CMOS one-of-eight multiplexor) to gate G-0, activating the high-voltage switch driving transmitter Tx-0. The other seven transmitters are not activated because they have no signal on their gates.

The AcroBasic command sequence

SET49 DWL0.5 CLR49

sets the pin 4 output of the MC14011 first to +15 V and then to 0 V. This increments the counter, and Q3, Q2, Q1, and Q0 now have the binary value 0001. The square-wave control signal at pin 3 of the MC14051 multiplexor is now connected to gate G-1, activating the high-voltage switch driving the transmitter Tx-1. Each time the command sequence SET49 DWL.05 CLR49 is issued, the circuit selects the next transmitter in sequence. Issuing the command sequence

SET48 DWL0.5 CLR48

at any time will reset the counter to 0000, and thus select Tx-0.

Bit Q3 of the MC14520 counter currently is not used. However, in an expanded circuit with added components, Q3 can be used with a second MC14051 multiplexor IC to select one of sixteen transmitters or receivers. The MC14520 is a dual 4-bit counter, and the second counter can be connected to the first counter to obtain an eight-bit counter. In principle, this can be used with 32 MC14051 multiplexor ICs to select one of 256 transmitters or receivers. Details on how to connect the CMOS ICs together properly in the multiplexing circuit may be deduced by consulting data sheets that can be found on the web.

A prototype transmitter multiplexing circuit constructed following the design of Figure 5 is shown in Figure 6. Figure 7 is a photograph of the interior of the transmitter electronics module, showing the prototype transmitter selection/driver circuit board and components of the high-voltage supply.

Receiver Amplifier Electronics

Figure 4(b) shows the amplifier circuit for a single receiver transducer. The amplifier design is based an OPA-353A operational amplifier manufactured by BurrBrown/Texas Instruments. These are fast operational amplifiers with gain-bandwidth products of 50 MHz. An important design consideration using these operational amplifiers is that they require power supply voltages that are within the 0 to 5 V range for single-ended supplies, or -2.5 to +2.5 V for split supplies.

The op-amp is connected in a non-inverting, low-input impedance configuration to minimize electric motor noise. The linear electric motors and their AR-04AE drives use high-frequency (5 MHz) communications signals. When the motors are activated, electromagnetic pickup of the communication signals by the receiving transducers and the long coax cables connected to them causes serious interference with received seismic signals. This electromagnetic interference manifests itself as short bursts of 5 MHz noise which must be attenuated.

Reducing the input impedance of the amplifier by using small values of the input and feedback resistors R_i and R_f in the first stage amplifier reduces the pickup noise relative to the transducer signal. Further reduction of the 5 MHz noise bursts is done with the feedback capacitor $C_{f,}$ and in the second stage, two-pole active filter designed with a high-cut frequency of 2.0 MHz and a roll-off of 6 dB per octave. Our standard sampling interval for digitization is 0.1 microseconds, so the high-cut corner is well below the Nyquist frequency.

A receiver multiplexer circuit (almost identical to the transmitter selection circuit shown in Figure 5) can be built to select one of eight amplified received signals. The receiver selection circuit is shown in Figure 8. The outputs of eight receiver amplifiers are connected to the X0 to X7 pins of an MC14051. One of these outputs is selected to feed through pin 3 and to connect with the input of the CompuScope CS-1450 digital data acquisition board.

The selection is again done by using MC14011, MC14520, and MC14051 ICs controlled by two bits from the Parker-Hannifin breakout module. The receiver selection circuit is connected so that bits 50 and 51 are the control bits. The command sequence

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SET50 DWL0.5 CLR50
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resets the counter and forces pin 3 of the MC14051 IC to connect to channel X0, or the first receiver. A subsequent command sequence

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SET51 DWL0.5 CLR51
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increments the counter and selects the next receiver channel.

AcroBASIC commands can be sent via the application program ACRView to configure and test the linear motors and multiplexing circuits. However, in order to synchronize motor motion, transmitter/receiver selection, and digital data acquisition, we need to write customized software. The Aries software development kit (SDK) is used to write customized software in C/C++. A detailed description of the design of the control and acquisition software for the Physical Modelling Facility is described by Wong et al. (2008).

Transmitter and Receiver Electronics Modules

The transmitter driver and receiver amplifier circuits are housed in metal cases to form electronics modules for the Physical Modelling facility. Figure 9 shows the front of the receiver electronics module and the transmitter electronics module in their current forms.

The receiver module currently has only two channels, while the transmitter module has only eight channels. In future, we plan to design and construct expanded versions to accommodate arrays of 16 or more Rx and Tx transducers.

Oscilloscope and Signal Generator

Support instrumentation makes up part of the Seismic Modelling Facility. A Tektronix TDS 2014B digital oscilloscope is used to monitor received signals and to check proper operation of the multiplexing circuits. The 250 Hz square wave used to repetitively fire a selected transmitter transducer is produced by a BK Precision 4040A signal generator. Figure 10 is a photograph showing both instruments.

Orthogonal Alignment of Transducer arrays

To achieve added flexibility for setting up survey geometries, the mounting of linear transducer arrays on the gantry carriages was designed so that the arrays can be oriented horizontally in orthogonal directions. Figure 11 shows a 10-element array aligned parallel and perpendicular to the y-direction.

The Digital Acquisition System

Receiver seismic signals are digitized and recorded by a Compuscope CS-1450 A/D board installed in a desktop computer. The board functions as a digital oscilloscope with two input channels. It can digitize each channel at a rate as fast as 25 megasamples per second producing 14-bit samples. Software for the board includes GageScope, a Windows application that makes the CS-1450 board a computer-controlled oscilloscope, and a software development kit (SDK) for the C/C++ language. The SDKs for the 8020 motor controller and the CS-1450 board enable us to write customized software to automatically record large high-resolution, 3D seismic datasets.

System Computer

The AR-8020 motor controller board and CS-1450 digital acquisition boards are installed in two PCI slots in a desktop computer running the Windows XP Professional operating system. These are non-standard, oversized boards, so the interior of the computer case had to modified in order to create enough room to accommodate them. An external one terabyte mass storage device is connected to the system computer for archiving acquired data. Figure 12 is a photograph of the modelling system computer beside a Tektronix 2014 digital oscilloscope, which can be used to visually monitor received signals.

Water tank

Modelling marine-type surveys requires a tank large enough to enclose solid models immersed in water. Currently, we are using small plastic containers similar to the one shown in Figure 2. However, for larger more complex models, we need to purchase or build a leak-proof tank approximately 800 mm long by 800 mm wide by 600 mm deep.

Lift Table

Solid models in a water-filled tank can easily weigh 250 kg or more. Material handling equipment is required to maneuver heavy objects into and within the frame of the positioning system. The physical layout of the positioning system and the other components of the Modelling Facility prevent us from using an overhead hoist system. For the present, we are using the movable lift table shown in Figure 10. This apparatus uses a hand-operated hydraulic pump to lift a platform from a bottom height of 17 cm to a top height of 36 cm. It is able to lift 450 kg, and has brakes to prevent inadvertent rolling.

Noise due to motor communications signals

We have referred to the noise in our received signals due to electromagnetic pickup of the motor communications signals.The resulting bursts of 5 MHz pulses are asynchronous to the received seismic signals, but they are quite strong, even with the electronic filtering. Vertical stacking of up to 512 repeated traces reduces this noise in the final data. However, in situations where the received signals are weak, we must disable the communications signals from the motor drives before acquiring data.

Figure 14 compares seismograms recorded with the motor communications signals both on and off. The gathers were recorded with the same transmitting and receiving transducers and no change in geometry. The receiver transducer is at a position of 80 mm, and the eight transmitters are at 0 to 70 mm with a 10 mm separation between adjacent transmitters. AGC, hi-cut filtering, and trace normalization have been applied for display. Even after vertically stacking 500 repeated shots, the four traces to the left, with the largest Rx-Tx separations, are much degraded when the motors are enabled. The obvious conclusion is that the linear electric motors must be disabled before recording survey data. Because mechanical relays are involved, disabling and enabling the motors requires a few seconds for each operation, and this significantly slows acquisition speed for large surveys using single transducers. However, when multichannel Rx and Tx arrays are used, the time overhead for switching relays is minimal because motor motion is relatively infrequent.

SUMMARY AND DISCUSSION

We have described the various essential components that make up the modernized version of the U of C Seismic Physical Modelling Facility. These components have been assembled and configured to fit into the overall design concept of the facility.

The high-precision positioning system has been assembled and commissioned for accurate and precise location of transmitting and receiving transducers.

Small-radii (1.0 mm) piezopin transducers have been chosen and tested for both transmitting and receiving ultrasonic seismic signals. Spring-loaded mechanical arrays of multiple transducers have been built and can consistently couple to the surfaces of solid models with reasonably flat surfaces. High-voltage switching circuits have been devised for driving individual transmitting transducers.

High-gain amplifier circuits were designed with –6 dB bandwidths of 2 MHz. These amplifiers were designed to meet a specific problem caused by the linear motor drives. When the linear motors are enabled, they generate strong 5 MHz pulses that are the basis of the motor control and feedback system. These pulses interfere with the ultrasonic signals detected by receiving transducers, and it has been a difficult problem to minimize this interference. This has not been fully solved as yet. One option is to turn all the motors off before acquiring data. This decreases survey efficiency, but may be a viable solution when multi-channel transmitter and receiver arrays are used.

A multiplexing circuit has been built to sequentially activate one of eight transmitters in an array. A second similar circuit has been built to sequentially select one of eight received signals from eight receiving transducers. The selection of both transmitting and receiving transducers can be done by commands issued from a computer program, making automated selection possible. Automatic selection of multiple transmitters and receivers greatly improves survey efficiency arrays receiver, especially when collecting data for high-fold 3D surveys.

A control and acquisition software package for automatically conducting simple 3D high-fold surveys has been written, and was used to collect sample data presented in this report.

The University of Calgary Seismic Physical Modelling System is now in a state where it can be used to do automatic surveys simulating both marine and land surveys. However, optimization of the system is an on-going process. In some situations, transducers more responsive than the piezopins will be needed. We will explore possible improvements to the transmitter drive and receiver amplifier circuits. Expansion of the transmitter and receiver arrays to 16 or 32 elements is definitely desirable. We will seek to purchase suitable A/D boards with more input channels that can record an increased number of received signals.

ACKNOWLEDGEMENTS

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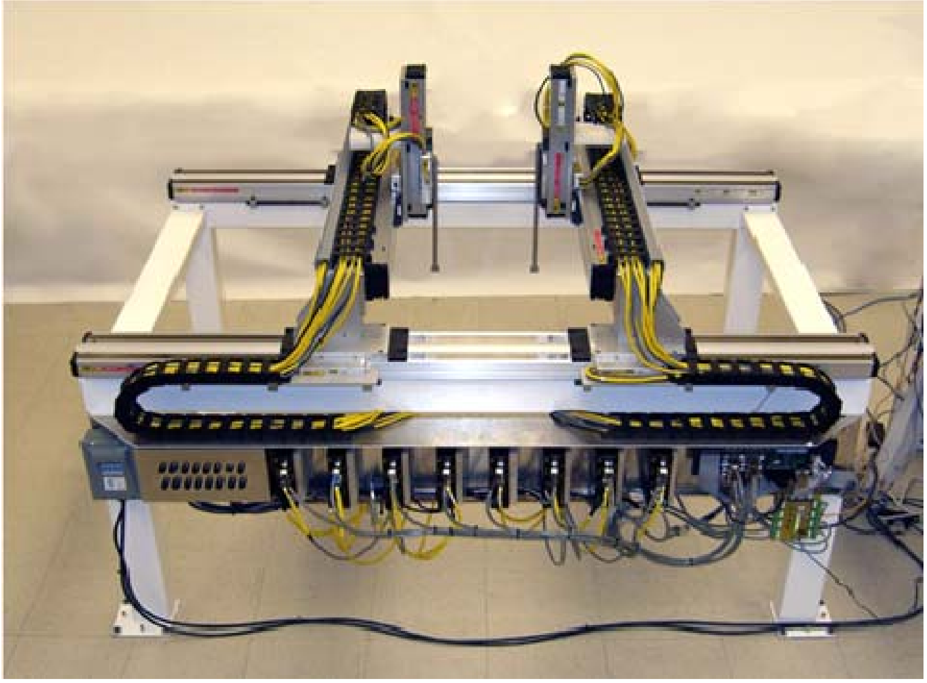


FIG. 1. The eight-axis 3D positioning system. Gantry A is to the left; Gantry B is to the right.

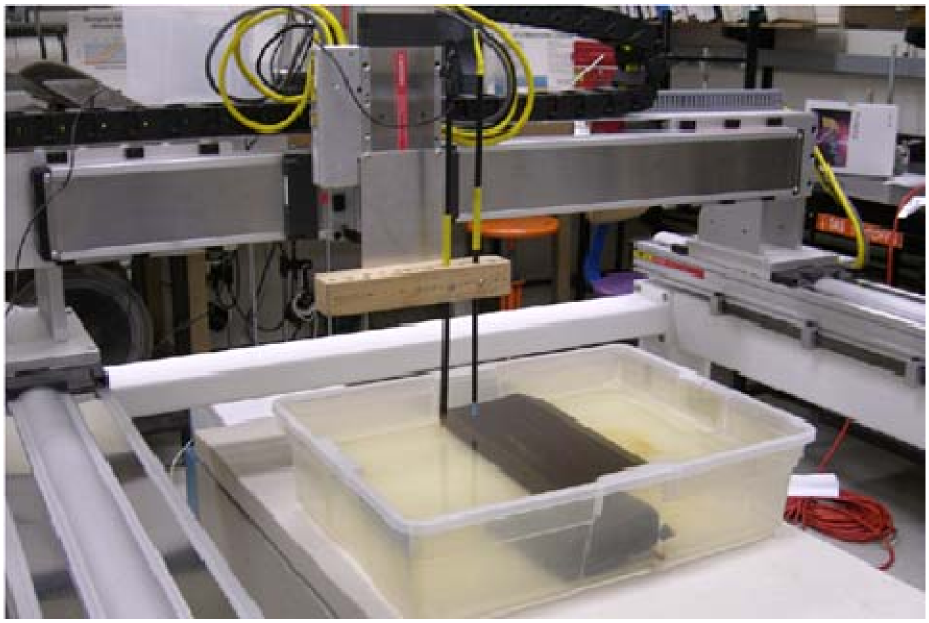


FIG. 2. Two hemispheric transducers attached to the carriage mounted on Gantry A. The transducers are glued to the bottom of thin metal tubes, mounted vertically.

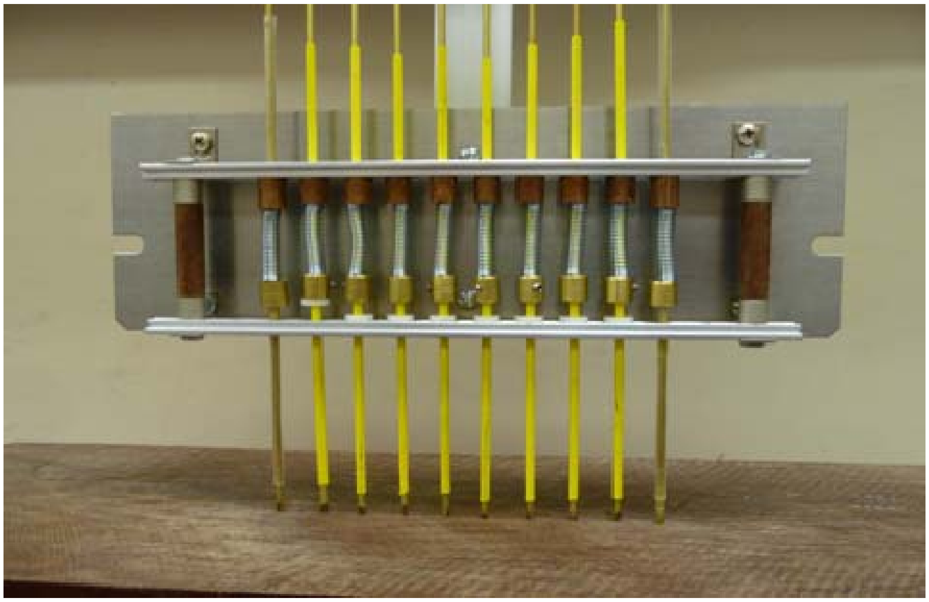
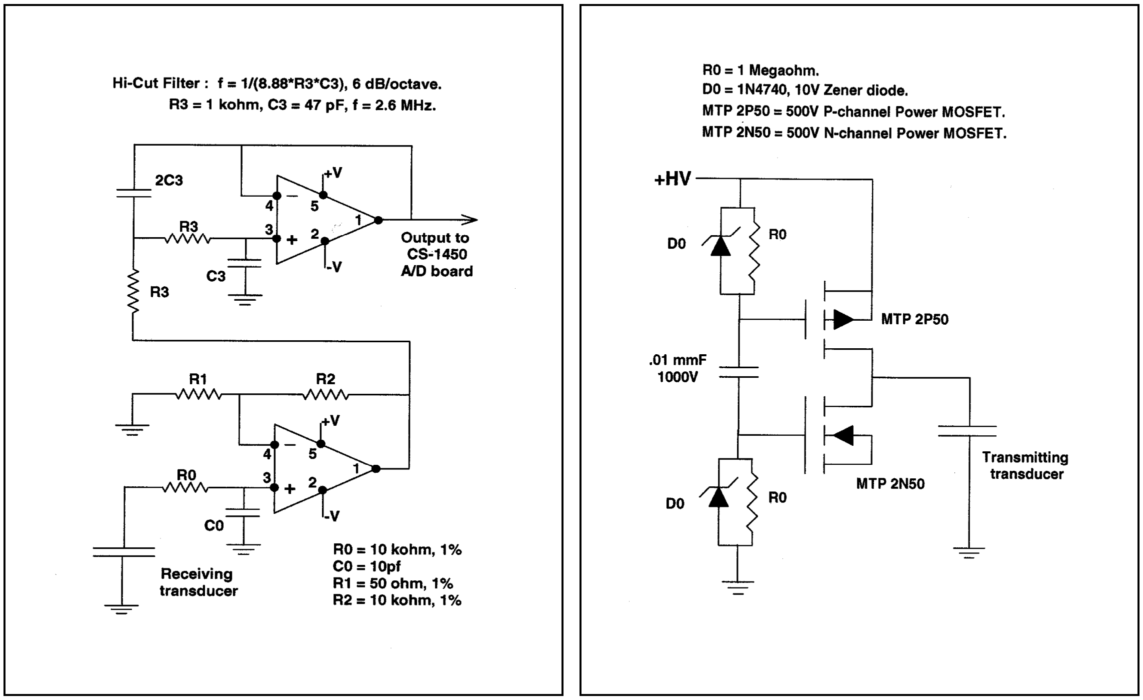


FIG. 3. A linear array of ten piezopin transducers. The small piezoelectric elements are located on the bottom tips. Adjacent transducers are separated by 10 mm.



Hi-Cut Filter : f = 1/(8.88*R3*C3), 6 dB/octave.
R3 = 1 kohm, C3 = 47 pF, f = 2.6 MHz.

R0 = 10 kohm, 1%
C0 = 10pf
R1 = 50 ohm, 1%
R2 = 10 kohm, 1%

R0 = 1 Megaohm.
D0 = 1N4740, 10V Zener diode.
MTP 2P50 = 500V P-channel Power MOSFET.
MTP 2N50 = 500V N-channel Power MOSFET.

FIG. 4. (a) Left: Schematic diagram of a high-voltage switch circuit driving a single transmitting transducer; (b) right: schematic diagram of an amplifier circuit for a single receiving transducer. Component values are provisional.

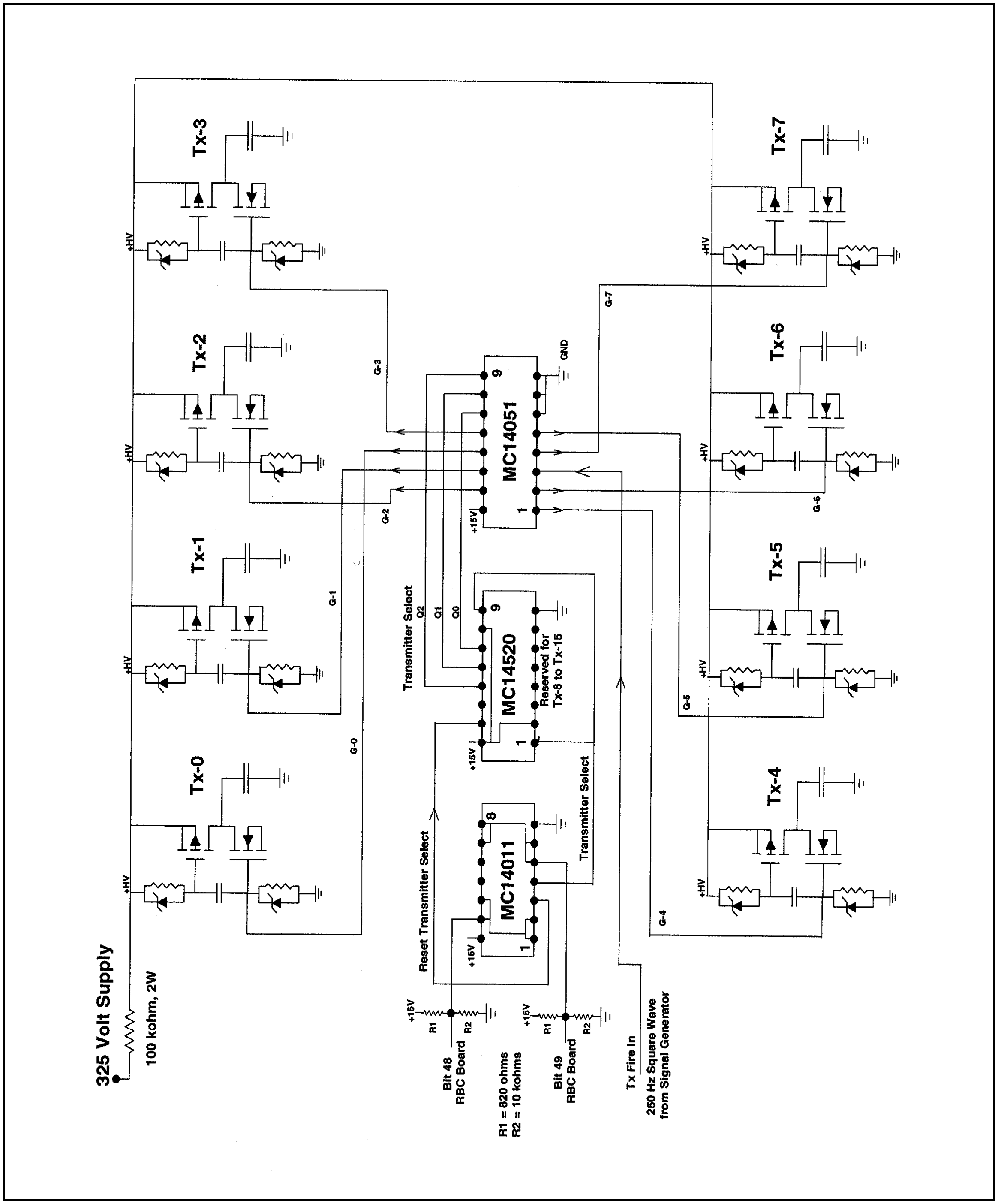


FIG. 5. Multiplexing circuit for sequentially selecting and activating one of eight transmitting transducers. The transmitting transducers are labeled as Tx-0 to Tx-7.

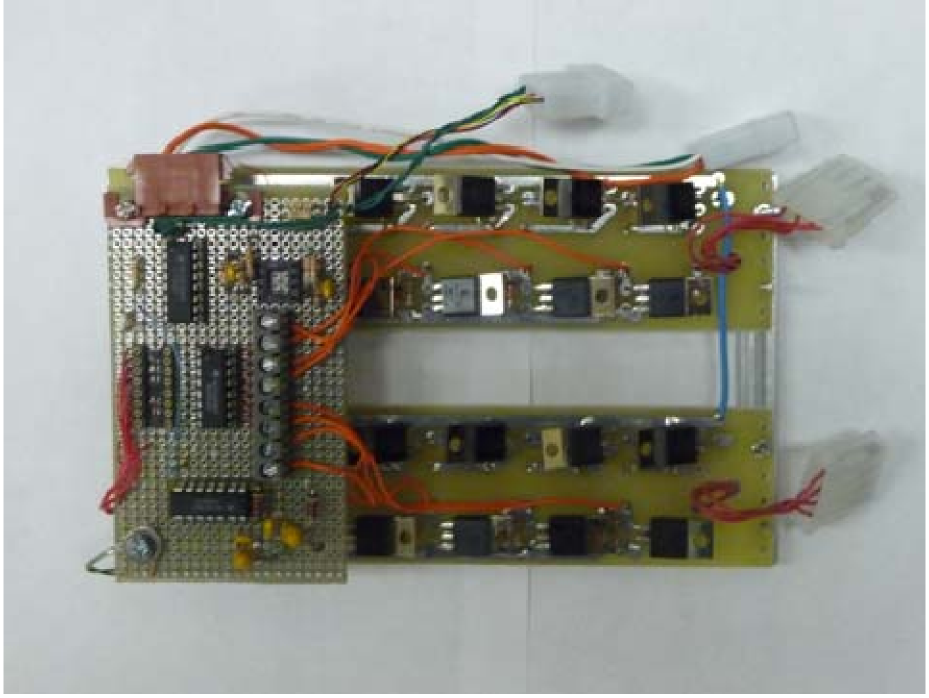


FIG. 6. Prototype multiplexing circuit for selecting one-of-eight transmitter drivers.

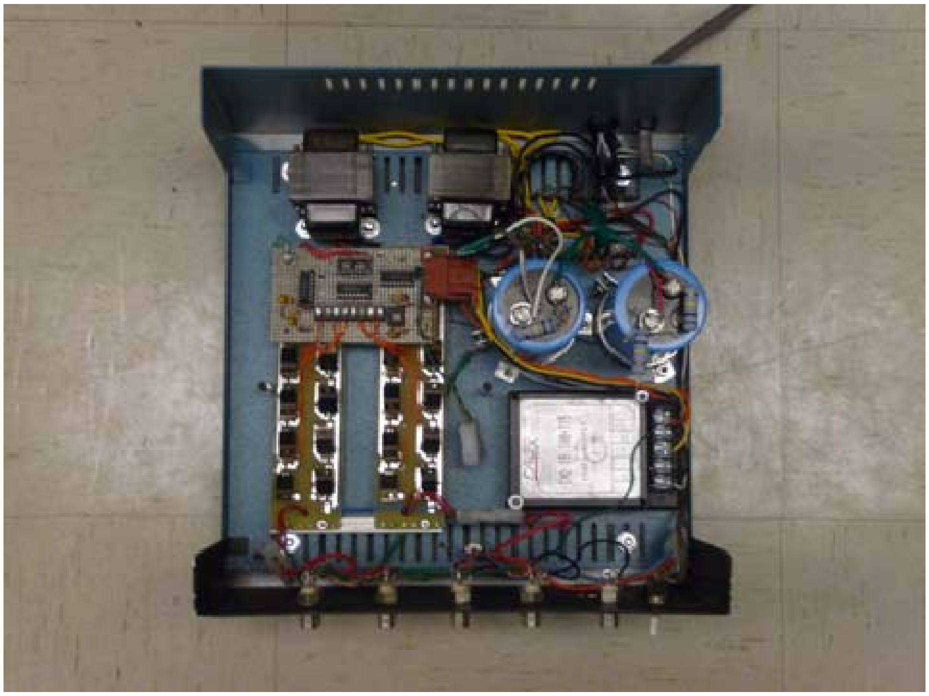


FIG. 7. Interior of the Transmitter Electronics Module showing the one-of-eight Tx selection circuit and components of the 167/325V high-voltage power supply.

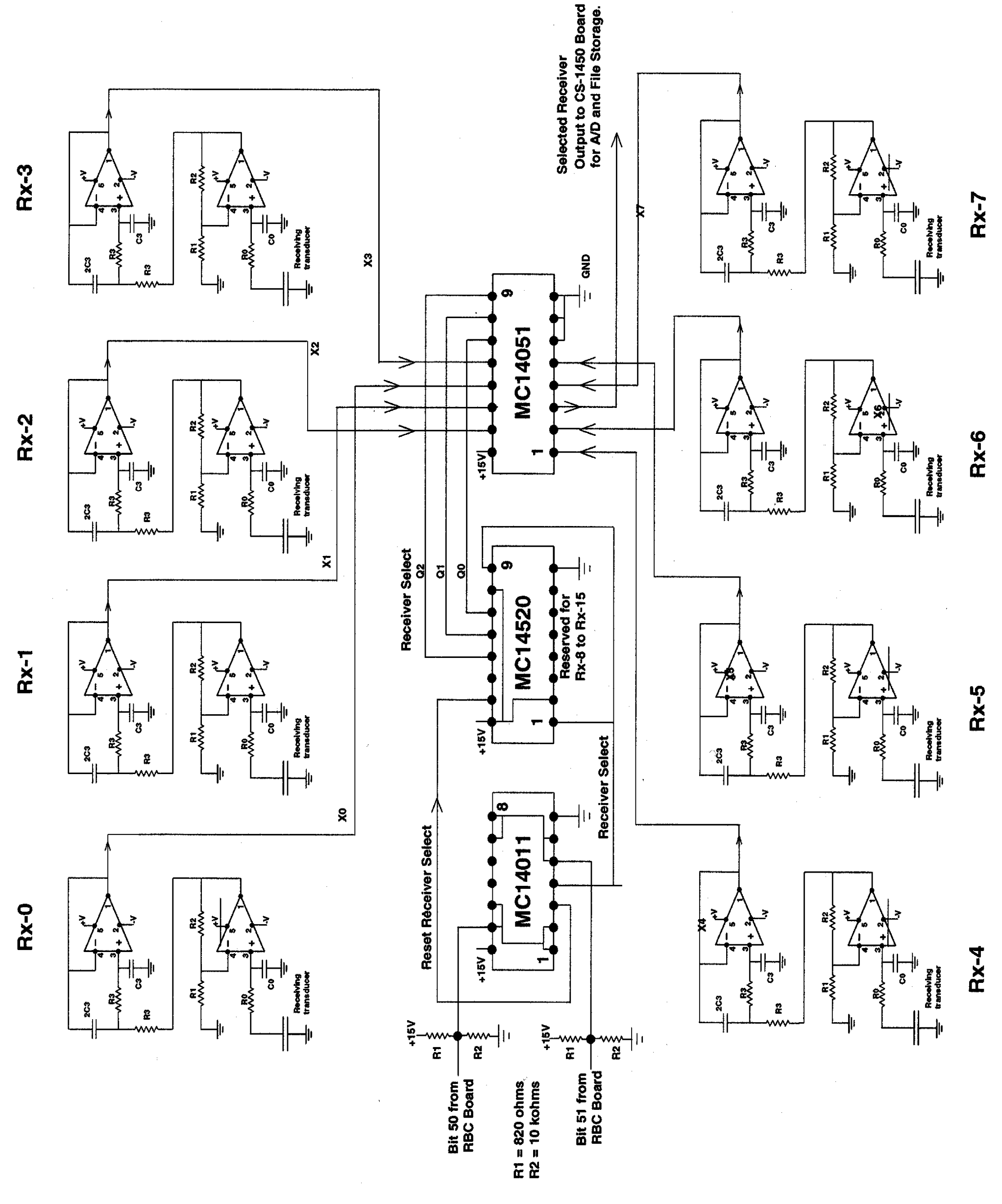


FIG. 8. Multiplexing circuit for selecting one of eight amplified receiver signals. The receiving transducers are labeled Rx-0 to Rx-7. The selected signal is sent to the CS-1450 A/D board.

FIG. 9. Two-channel receiver amplifier module and eight-channel transmitter driver module.

FIG. 10. Tektronix TDS 2014B digital oscilloscope for monitoring received signals (top); BK Precision 4040A signal generator for providing square control signal to activate MOSFET high-voltage switches (bottom).

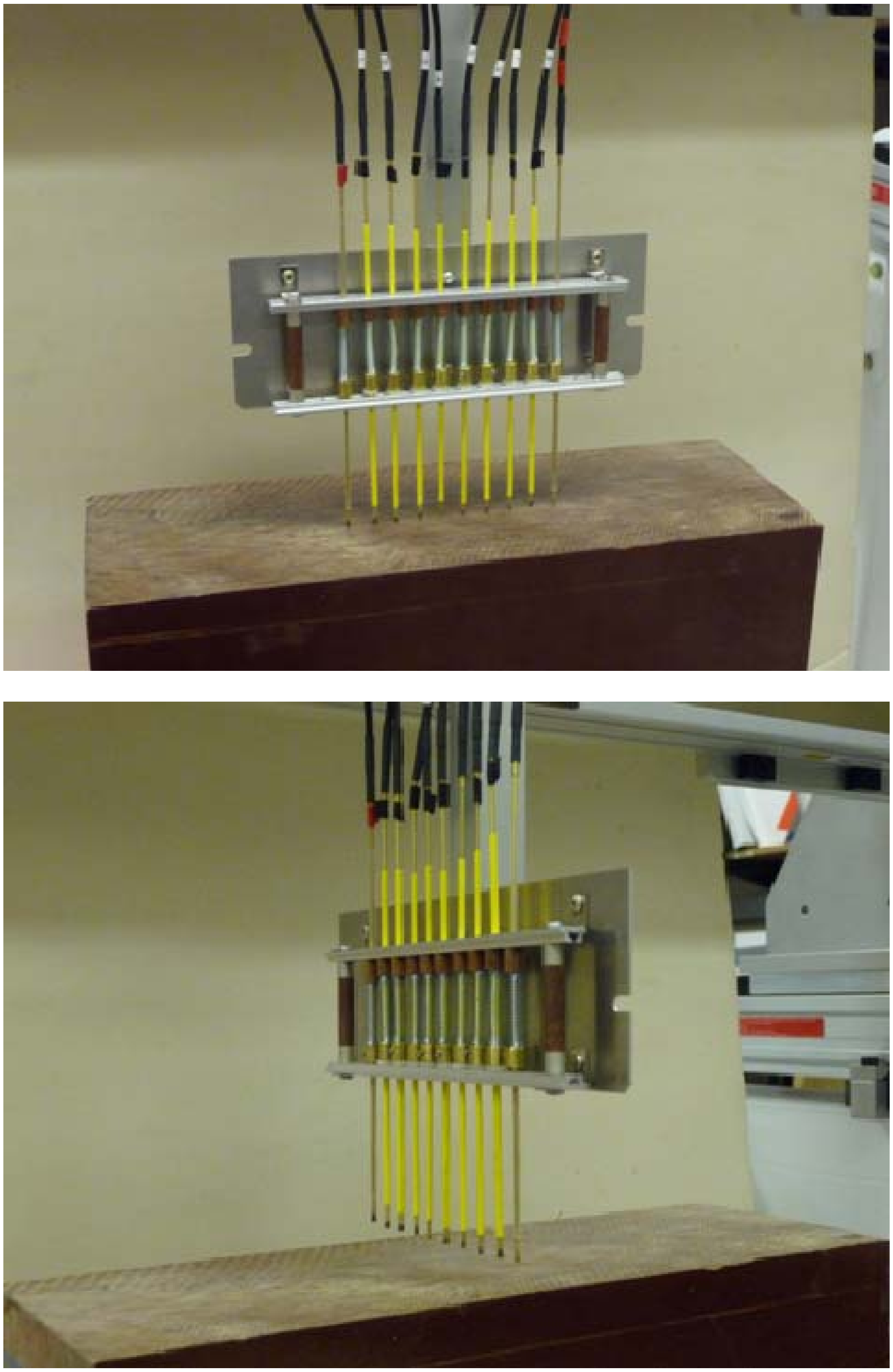


FIG. 11. Linear array mounted parallel (top) and perpendicular (bottom) to y-direction. The ability to mount the array in orthogonal orientations adds flexibility in setting up survey geometries.

FIG. 12. System computer for motion control and acquisition. ACR-8020 and CS-1450 boards are installed inside the tower case.

FIG. 13. Hand-operated hydraulic lift table for moving and positioning heavy models.

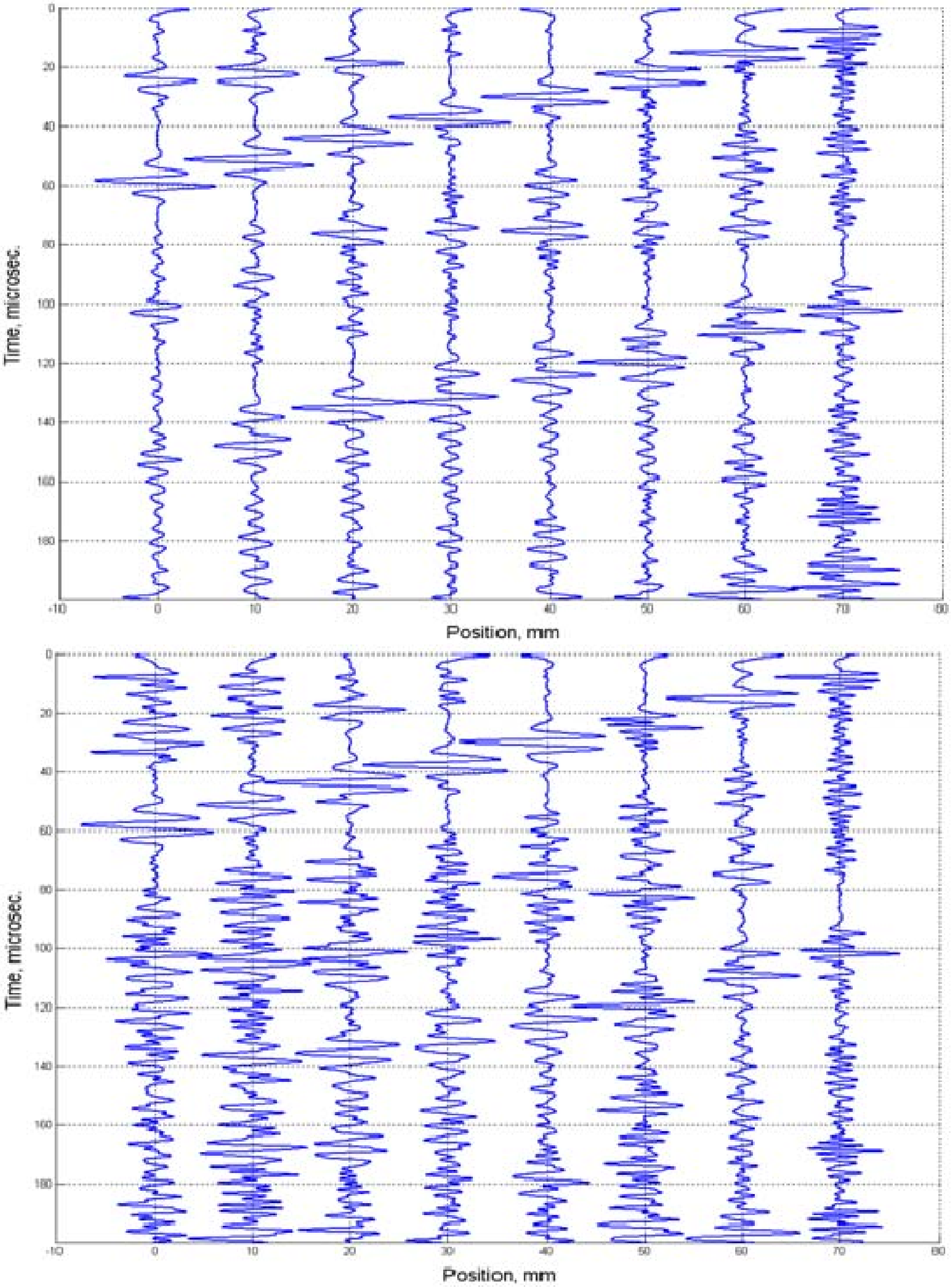


FIG. 14. Effect of electromagnetic pickup of motor communications signals on seismograms. Motor signals are turned off for the top gather; motor signals are on for the bottom gather.