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A LABORATORY STUDY OF THE TRANSMISSION OF SIGNALS THROUGH  
SOLID MATERIAL WITH POSSIBLE APPLICATION TO  
SEISMIC COMMUNICATION

BY

RONALD WILLIS CARTER, 1944-

A THESIS

Presented to the Faculty of the Graduate School of the

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1971

Approved by

William H. Travis (Advisor)

David Cunningham

General B. Rupert

## ABSTRACT

The problem of transmitting acoustic signals through solid material channels is investigated using piezoelectric transducers for generation and detection of the signals. Laboratory experiments are performed in which a solid material channel is modeled by a block of Berea sandstone.

The magnitude of the frequency response for the sandstone and transducer combination is obtained over the frequency range of approximately 0 Hz to 500 kHz. Various electrical waveforms are utilized as driving sources for the transmitting transducer. It is found that the best received waveform is obtained when a gated sinewave whose frequency is approximately equal to the resonant frequency of the transducer is used as the driving source. Based on the experimental results obtained, a communication system is proposed in which seismic noise is assumed to be negligible in the frequency range of interest.

## ACKNOWLEDGEMENT

The author wishes to express his appreciation and thanks to Dr. W. H. Tranter and Dr. G. B. Rupert for their assistance and guidance throughout this project. The author also wishes to extend his thanks to Dr. C. J. Haas for his suggestions concerning some of the methods and equipment used in this investigation.

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## I. INTRODUCTION

The purpose of this investigation was to test the feasibility of transmitting signals through solid materials such as rock. It was hoped that some insight into the problem of reliable communication through solid material channels such as the earth might be gained.

The capability of reliable communication through the earth could be quite useful in some mining operations, especially in mine rescue work. Systems with a high survivability factor are of interest to the military. If the communication system could be completely underground, its reliability during attack would be improved over a system which has some of its components such as antennas aboveground.

There are principally two methods of transmitting signals through the earth. One method employs electromagnetic energy and the other employs acoustical energy. Acoustical energy was chosen for this project because it seemed to lend itself well to laboratory investigation. Also, less work appears to have been done on systems which use acoustical energy than those using electromagnetic energy.

The problem of transmitting information through the earth using acoustical energy is analogous to some of the methods of seismic prospecting used by the oil companies. One method consists of coupling acoustical energy into the ground and observing the reflected signals. These signals are then processed in such a manner that certain underground geologic conditions can be inferred from the results. In communications, one would be interested in reproducing the transmitted signal as nearly as possible rather than observing certain

characteristics of the signal which were indicative of underground geologic conditions.



## II. LITERATURE REVIEW

Acoustical energy is used quite extensively for underwater communication. Miller [1] has described an underwater communication system which uses acoustical energy to transmit speech. This system uses single-sideband suppressed-carrier modulation and has a range of 5000 yards when operating between a submerged submarine and a hovering helicopter. The transmitted power is 20 watts and the carrier frequency is 8.087 kHz. Thanos and Hubbard [2] have described a hydroacoustic communication link for an ocean-bottom seismograph. This system is used to transmit data from a seismograph on the ocean floor to a ship overhead. The data from the seismograph is used to generate a pulse amplitude modulated waveform which in turn frequency modulates a 10.5 kHz carrier. Commands to the seismograph and associated instruments are transmitted in the form of a pulse position code on a 14 kHz carrier. This system operated satisfactorily with the seismograph at a depth of 2350 fathoms (14,100 feet) with an acoustic output power of 2.5 watts.

Much investigation and research concerned with the transmission of signals through the earth has involved the use of electromagnetic energy [3] - [6]. Wundt and Boots [6] discuss two types of systems employing electromagnetic energy. In one case the electromagnetic wave propagation is totally subterranean and in the other case the wave propagates from the transmitting antenna to the surface of the earth where it is propagated in the air space along the ground and through space as a sky wave. At the receiving site, the receiving antenna picks up the portion of the energy which penetrates from the

surface down to the antenna. Wundt and Boots call this last method of propagation "up-over-down transmission". With the up-over-down transmission method, Wundt and Boots report that ranges of 40 to 1,000 miles have been achieved and they calculate that ranges on the order of 500 miles might be possible using the subterranean method at frequencies below 50 kHz when a path attenuation of 160 decibels is allowed. They report that in 1942 V. Fritsch and R. Wundt were able to establish voice communication over a distance of 9.5 miles in a salt mine. This was done by using a 5 watt transmitter operating at 8.8 MHz with amplitude modulation.

Ikrath and Schneider [7] have built and tested an earth communication system which is based on the use of acoustical energy. This system uses transducers which have a resonant frequency of approximately 80 Hz to transmit and receive signals. By using pulse amplitude modulation, Ikrath and Schneider were able to achieve a communication range of 1,000 meters (3,280 feet) when transmitting through rock in mountainous terrain. The transmitter power required to produce a signal-to-noise ratio of at least 3 decibels over this distance was about 60 watts.

### III. BACKGROUND MATERIAL

The experimental methods used in this investigation apply to the study of a solid material channel which is modeled by a 1 foot cube of Berea sandstone. The transducers used differed greatly from those used by Ikrath and Schneider which were electrodynamic whereas those employed in this investigation were piezoelectric. Piezoelectric transducers were chosen because they convert electrical energy to acoustical energy and vice versa. This characteristic allows one to work exclusively with electrical signals external to the transducers. The fact that one may work with electrical signals makes interfacing the transducers with various types of measuring equipment quite easy. Small piezoelectric transducers are also easily attached to and removed from the specimen under study.

The piezoelectric elements used were manufactured by the Clevite Corporation and designated PZT-4. The elements were disks  $3/4$  inch in diameter designed to vibrate in a thickness mode, in which the fundamental frequency of operation is governed by the thickness of the disk. Each piezoelectric disk has a certain natural frequency of oscillation but this is not to say that under the particular conditions of loading in any given experiment it will necessarily vibrate at this frequency. The disks were manufactured from a ceramic material known as Lead Titanate Zirconate [8]. These piezoelectric elements were used because they were readily available, have fairly low dielectric losses, possess good temperature stability over a wide temperature range, and can be used quite successfully as either transmitters or receivers.

#### IV. EXPERIMENTAL PROCEDURES AND RESULTS

The equipment for a typical test is as shown in Figure 1. When it was desired to display signals in the time domain on the 549 oscilloscope, a 1A1 plug-in unit was substituted for the 1L5 spectrum analyzer plug-in unit. The storage capability of the 549 oscilloscope was used when determining the spectra of various signals. A Polaroid camera, which is not shown in Figure 1, was employed for obtaining photographs of various oscilloscope displays.

##### A. The Transducers

Hereafter, when the word "transducer" is used, it will denote the combination of the piezoelectric element and its associated holder. As a means of identification, each transducer will be referred to by stating the natural frequency of oscillation of the piezoelectric element which it contains. Magnesium holders for the piezoelectric elements were constructed as shown in Figure 2. Magnesium was used in an effort to obtain a reasonable acoustical match between the piezoelectric element and various materials to which it might be attached. Some of the ideas developed by Deatherage [9] and Thill, McWilliams, and Bur [10] were considered in designing the holders.

The shielded wire shown in Figure 2 was run to a metal junction box where the shield and ground lead were grounded and a transition from shielded wire to coaxial cable was made. Shielded wire was attached to the transducer because the coaxial cable could not readily be attached directly to the transducer. The use of coaxial cable allowed easy connection between the junction box and whatever piece

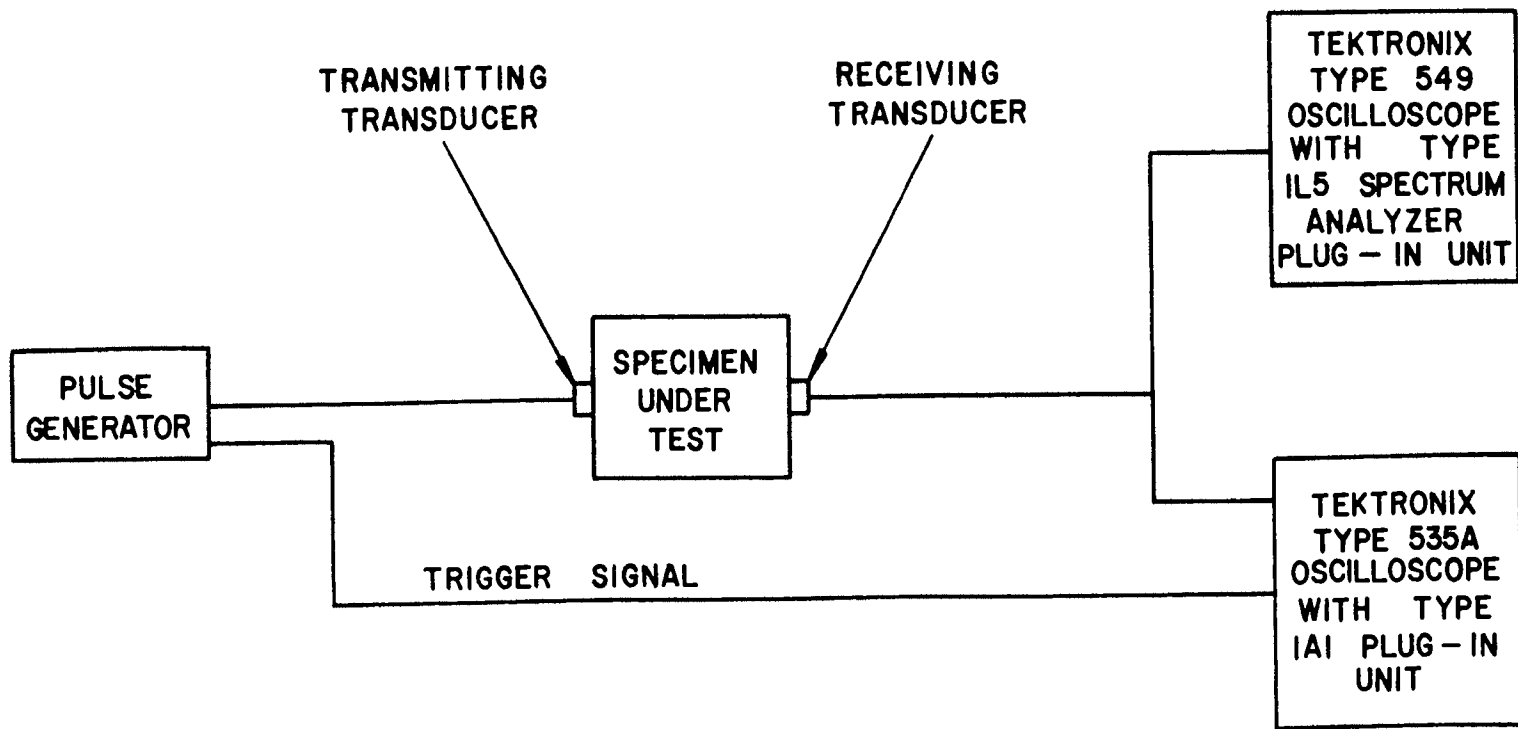


Figure 1. Typical Test Set-Up.

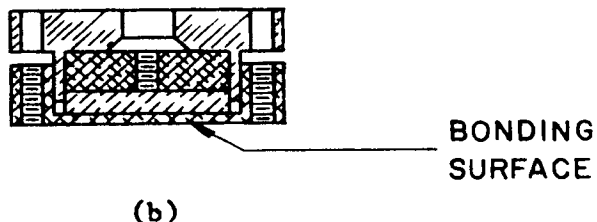
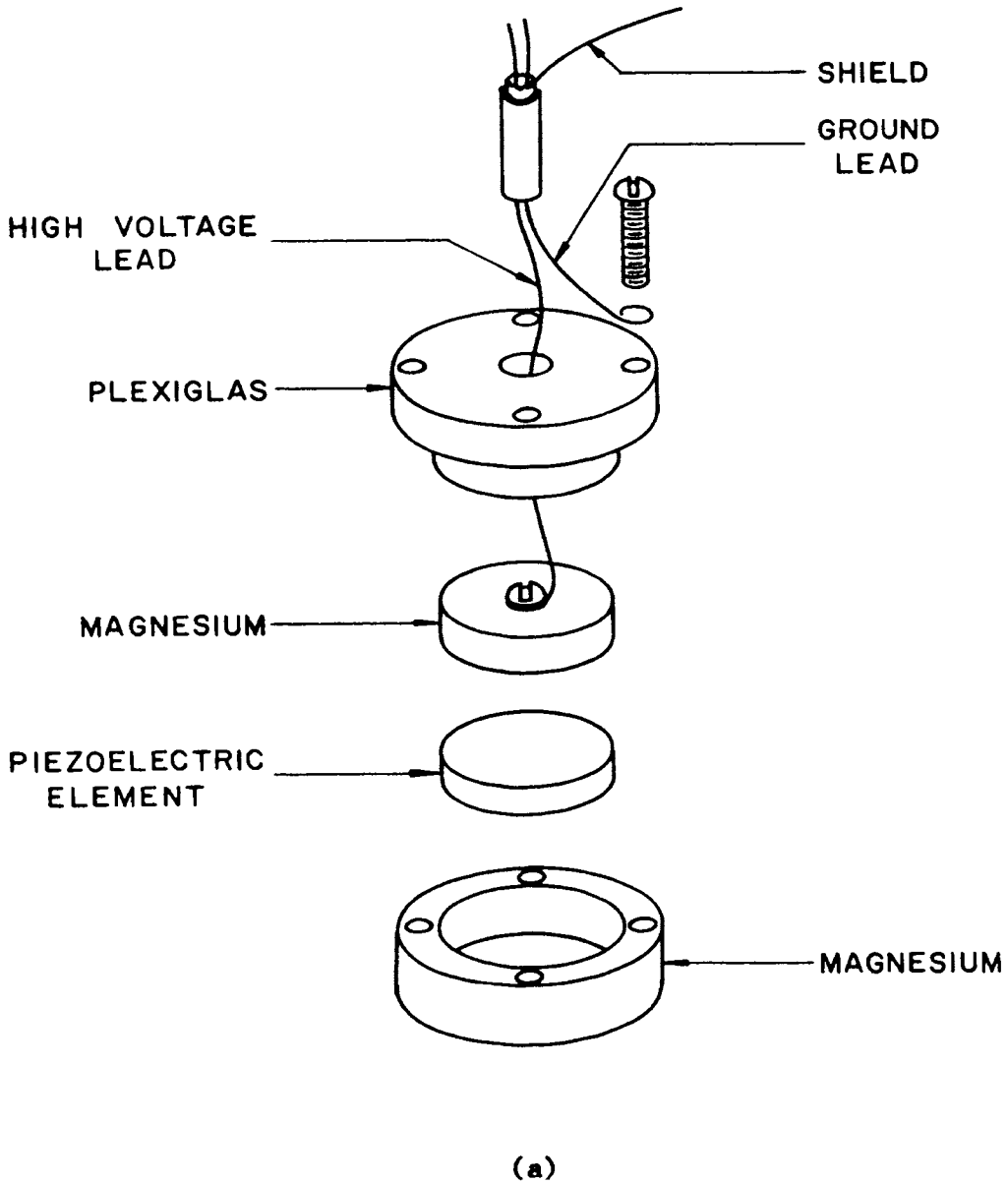


Figure 2. The Transducer. (a) Exploded view. (b) Sectional view.

of test equipment was being used at any given time. Shielded wire and coaxial cable were necessary to prevent the low-level output signals from being contaminated by unwanted signals.

Phenyl Salicylate, which is a crystalline compound that melts at approximately 43°C, was used in bonding the transducers to the specimen. The transducer was attached to the specimen in the following manner: Phenyl Salicylate was melted in a beaker. The base of the transducer was dipped in the molten material and pressed against the specimen until the Phenyl Salicylate recrystallized.

The holder had to be held in the beaker until it became warm enough so that the Phenyl Salicylate did not begin to recrystallize before the holder was firmly pressed against the specimen. If the Phenyl Salicylate did recrystallize slightly before the holder was pressed against the specimen, the layer of bonding material between the holder and the specimen would be thicker than necessary thus causing an excess loss of energy before the acoustic wave entered the specimen. A weak bond also forms when recrystallization occurs prematurely.

#### B. Preliminary Check of Equipment Operation

As a check on equipment operation and the reliability of the bond between transducer and specimen, the velocity of elastic wave propagation in an aluminum bar was measured. The bar was 4 inches in diameter and 31.75 inches long. The velocity of propagation was found to be 20,670 feet per second. It was felt that this figure was close enough to the published figure of  $6.4 \times 10^5$  centimeters per second

(21,000 feet per second) [11] for the bulk or plate velocity of aluminum to indicate that the equipment was working properly.

The velocity of propagation was determined by bonding a transducer to each end of the bar as shown in Figure 1. The transmitting transducer was driven by an Arenberg Ultrasonic Laboratory Inc. Model PG-652C signal generator which produced a gated sinewave output. The output of the receiving transducer was fed directly into the 549 oscilloscope operating with the 1A1 plug-in unit. The transmitter and receiver were both 780 kHz transducers. The travel time through the specimen was determined by measuring the time between the initiation of the pulse input to the transmitting transducer and the occurrence of an output signal at the receiving transducer. The travel time was determined directly from the oscilloscope display. The velocity of propagation was then determined by dividing the length of the specimen in the direction of propagation by the travel time.

After the equipment was found to be operating properly, the transducers were removed from the aluminum bar and bonded to a 1 foot cube of Berea sandstone. Velocity of propagation for the sandstone was also measured and found to be 7,870 feet per second.

### C. Frequency Response of the System

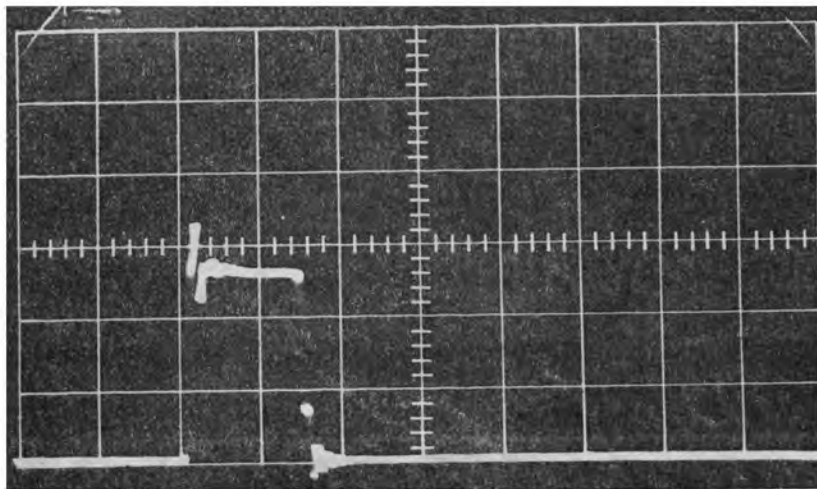
The magnitude of the frequency response of the system comprised of a 1 foot cube of Berea sandstone and the transducers was measured. A 780 kHz transducer was bonded in the center of one face of the specimen. Three transducers (1.5 MHz, 780 kHz, and 310 kHz) were arranged in a horizontal line and bonded to the opposing face of the



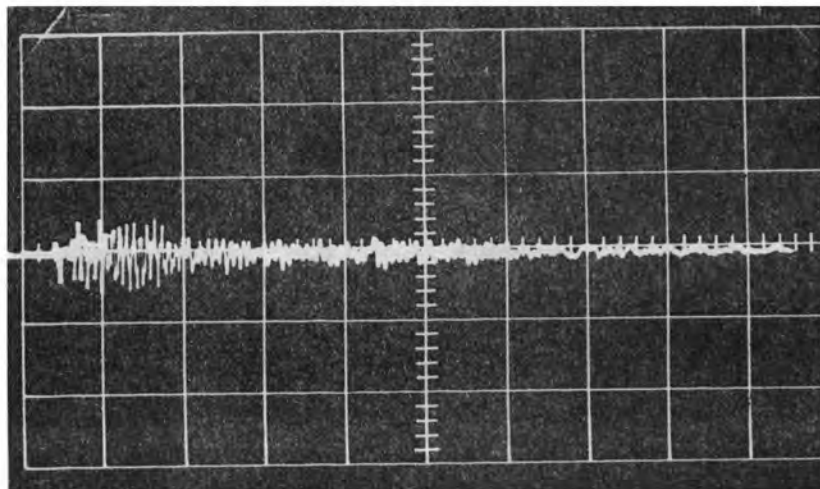
specimen. The 780 kHz transducer was mounted in the center of the face with the 1.5 MHz and 310 kHz transducers mounted 1 inch either side of it.

The test equipment was arranged as shown in Figure 1 with a Hewlett-Packard Model 212A pulse generator driving the transmitting transducer at a pulse repetition frequency (PRF) of 215 Hz. Figures 3 and 4 show time and frequency domain representations of the results obtained with the 310 kHz transducer transmitting and the 780 kHz transducer on the opposing face of the specimen receiving. The input pulse length was chosen such that a further decrease in pulse length only served to reduce the amplitude but not the shape of the received waveform. The fact that only the amplitude changed as the pulse length was decreased means that the chosen pulse can be thought of as representing an impulse to the system. The magnitude of the output spectrum is then essentially the magnitude of the Fourier transform of the impulse response. Similar measurements were made using the 780 kHz and 1.5 MHz transducers as transmitters. The role of transmitter and receiver was then reversed and the same measurements were again made.

The output spectrum varied depending on what frequency transducers were used, however, in no case was an output observed which contained appreciable energy at frequencies above 450 kHz. This does not imply that the system does not pass signals above 450 kHz because the energy in the input waveform decreases as frequency increases as may be seen by examining Figure 4a. If more energy at higher frequencies could be introduced into the system, it might be found that the system response is appreciable over a wider range of frequencies than

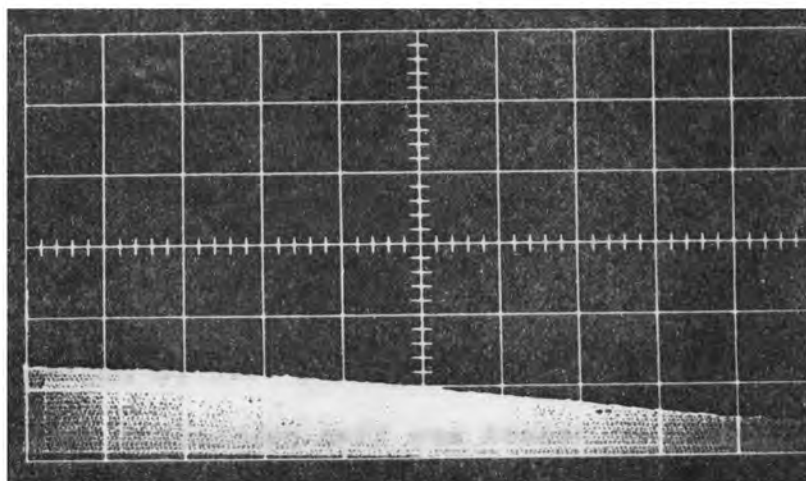


(a)

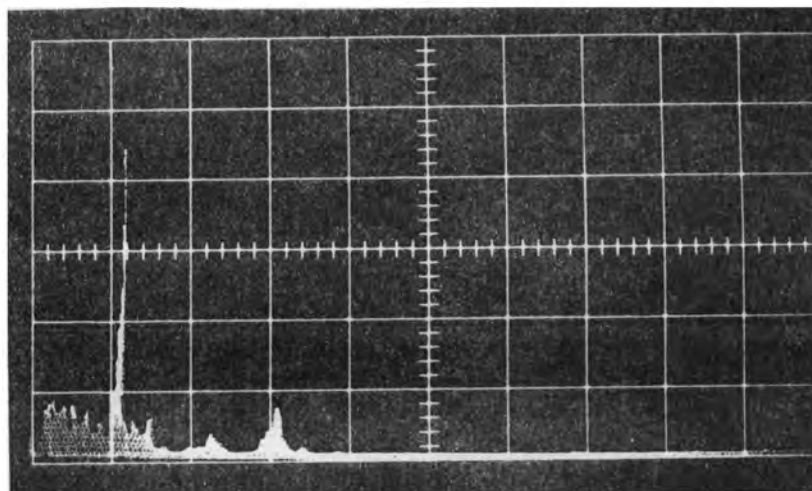


(b)

**Figure 3. Pulse Input and Corresponding Output.**  
(a) Pulse input. Scale - horizontal:  
0.5  $\mu$ sec/major div.; vertical: 20 v/major div.  
(b) Corresponding output. Scale - horizontal:  
100  $\mu$ sec/major div.; vertical: 5 mv/major div.



(a)



(b)

Figure 4. Spectra of Pulse Input and Corresponding Output.  
 Center frequency = 500 kHz. Scale - horizontal:  
 100 kHz/major div.  
 (a) Pulse input. Scale - vertical: 50 mvrms/major div.  
 (b) Corresponding output. Scale - vertical:  
 50  $\mu$ vrms/major div.

is indicated by these tests. Regardless of which transducer combination was used, it was found that there was always a large component of the observed output in the frequency range of 100 to 160 kHz. This was also observed when another sample of Berea sandstone was tested. The second sample was similar to the first except that the dimension in the direction of wave propagation was 6 inches rather than 1 foot. Only a 780 kHz transducer pair was tested on the second sample. It may be seen by examining Figure 4b that the output spectrum contains several peaks. The peak near 310 kHz occurred regardless of which pair of transducers was transmitting and receiving which seems to indicate that this is a property of the sandstone rather than the transducers. It is not known how much the transducers contribute to the peaks in Figure 4b; however, Auberger and Rinehart [12] observed relative maxima and minima in curves of attenuation versus frequency in the range of 250 kHz to 1 MHz for various rocks. More detailed data concerning the frequency response of the system is presented in Appendix A.

#### D. The Driving Waveform

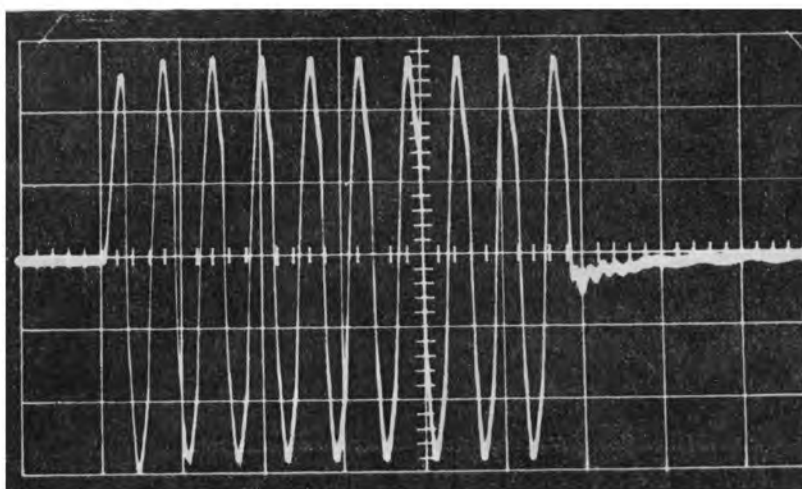
Voltage waveforms of various types were tried as the driving source for the transmitting transducer. The only criterion for the driving voltage when making velocity of propagation measurements is that it be of sufficient amplitude to produce a detectable signal at the receiver and the trailing end of one received signal not overlap into the beginning of the succeeding one. Rectangular pulses with low repetition rates work very well for this as do gated or pulsed sine-waves where the "off" time is sufficient to prevent overlap at the

receiver. Pulse inputs present some problems for communication work, however, because the transmitting transducer has a tendency to "ring" long after the driving pulse has been removed. In order to avoid overlap between a signal and the one succeeding it, a long "dead" time must be provided by the transmitter which limits signaling rate.

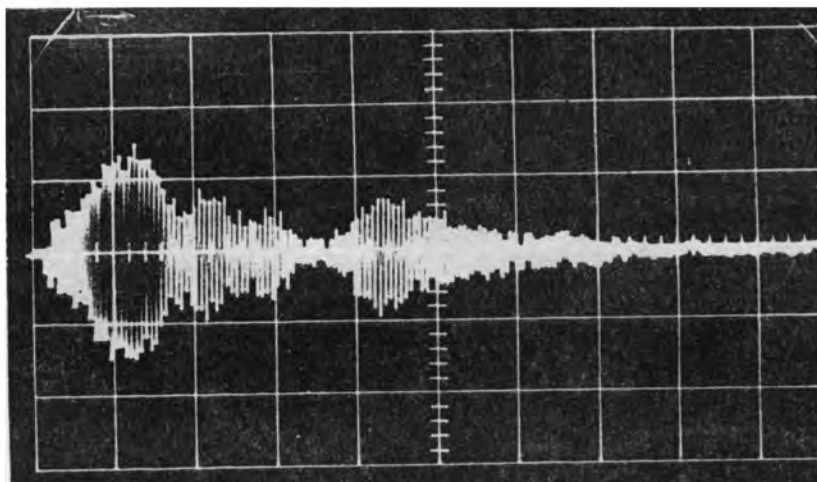
Rykunov and Feofilaktov [13] have reported the construction of a piezoelectric transducer which, when excited by a rectangular pulse of duration equal to the period of oscillation of the transducer, exhibits negligible residual vibration after removal of the pulse. They accomplished this by constraining the transducer so that it could vibrate in one mode only. One method of avoiding ringing of the transmitting transducer is discussed by White [14] whereby a step input with an exponential decay is assumed to cause the transducer to produce damped oscillations of frequency  $f_n$ . A step input with exponential decay is applied to the transducer;  $1/f_n$  seconds later a step input of opposite polarity with exponential decay is applied which cancels all succeeding oscillations. The acoustical waveform generated by the transducer under these circumstances consists of one cycle of an exponentially damped sinusoid of frequency  $f_n$ . Driving the transducer with the two step inputs each with exponential decay is equivalent to using an exponentially decaying pulse whose duration is equal to the period of oscillation of the transducer. More than one cycle of a sinusoid may be generated by making the duration of the pulse equal to a multiple of the period of oscillation. Rykunov and Selyuminov [15] have reported the construction of a pulse generator which produces a pulse with approximately exponential decay. By carefully adjusting the pulse amplitude and duration, they were able to

reduce residual vibration of the transducer. The author attempted to test the idea of using an exponentially decaying pulse as a driving source with the transducers attached to the sandstone. Due to the lack of availability of an amplifier capable of satisfactorily driving the transducer with the required waveform, no conclusive results were obtained.

If the transmitting transducer could be excited at its resonant frequency, it would seem that large amplitude waves of nearly a single frequency could be introduced into the specimen. This idea was tested and found to work quite well. For this test, a 780 kHz transducer mounted in the center of one face of the 1 foot cube of Berea sandstone acted as the receiver and a 310 kHz transducer mounted in the center of the opposing face acted as the transmitter. The Arenberg generator was used to drive the transmitting transducer with a gated sine wave at a PRF of 206 Hz. The generator was adjusted so that the frequency of the sine wave was approximately equal to the resonant frequency of the 310 kHz transducer. The time and frequency domain descriptions of the input and output for these conditions are shown in Figures 5 and 6. The frequency of resonance was assumed to be that frequency at which the received waveform attained its maximum amplitude for fixed input amplitude. It is doubtful that the exact resonant frequency of the transducer was reached, because as the frequency of the sine wave was reduced to the minimum attainable, the output amplitude was still increasing. The minimum attainable frequency of the sine wave was approximately 320 kHz. From Figure 6b, it appears that the resonant frequency of the transducer was about 310 kHz which is approximately the natural frequency of vibration of the piezoelectric

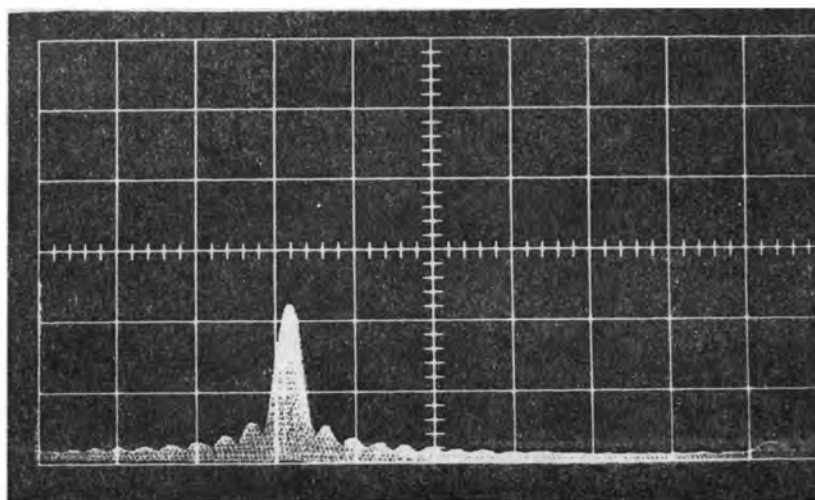


(a)

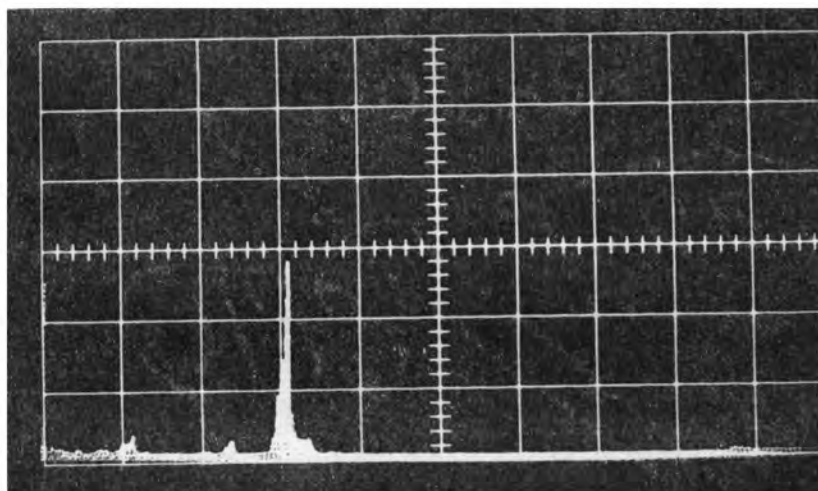


(b)

Figure 5. Gated Sinewave Input and Corresponding Output.  
(a) Gated sinewave input. Scale - horizontal:  
5  $\mu$ sec/major div.; vertical: 20 v/major div.  
(b) Corresponding output. Scale - horizontal:  
50  $\mu$ sec/major div.; vertical: 5 mv/major div.



(a)



(b)

Figure 6. Spectra of Gated Sinewave Input and Corresponding Output.  
 Center frequency = 500 kHz. Scale - horizontal:  
 100 kHz/major div.  
 (a) Gated sinewave input. Scale - vertical:  
 0.5 vrms/major div.  
 (b) Corresponding output. Scale - vertical:  
 0.2 mvrms/major div.



element. If the generator could have been adjusted to this frequency, it is probable that a larger output amplitude could have been obtained. It may be seen from Figure 6b that a large portion of the energy in the output is contained in a very narrow frequency band.

## V. SOME ASPECTS OF A SEISMIC COMMUNICATION SYSTEM

### A. Attenuation

Acoustic attenuation in earth materials appears to be quite high. Attewell and Ramana [16] determined the attenuation,  $\alpha$ , to be  $1.012 \times 10^{-5} f^{0.911}$  decibels per centimeter ( $3.08 \times 10^{-4} f^{0.911}$  decibels per foot) in the frequency range 1 to  $10^5$  Hz. This is a composite figure obtained by considering data presented by many researchers for several different types of earth materials. At a frequency of 10 kHz  $\alpha$  equals 1.34 decibels per foot and at a frequency of 1 kHz,  $\alpha$  is 0.165 decibels per foot. It can readily be seen that even at a frequency of 1 kHz the attenuation is quite high. The actual loss of signal energy incurred in some geologic conditions might be greater than that indicated by the calculated value of  $\alpha$  for the appropriate frequency. If two rock materials with quite different velocities of propagation were in the signal path, a certain amount of the signal energy incident on the interface between the two materials would be reflected. This would produce the net result of a greater loss in signal energy than would be predicted by considering only the attenuation constant of the two materials.

The apparent high attenuation in earth materials might seem to indicate that acoustical methods of transmitting signals through the earth except at very low frequencies is nearly impossible. There may be natural features of the earth such as sound ducts which would permit the transmission of acoustic signals over long distances.

Ryerson [17, p. 193] says, "Nature has provided a number of media in which propagation occurs by the inverse first power of range. This comes about when

the material composing the earth and its atmosphere occurs as spherical shells. Transmission through these natural ducts is very desirable because of the great ranges which may be obtained with low-powered transmitters." On the same page Ryerson further states, "It is possible to conduct sound and radio waves through appropriate rock strata by reflection from their boundaries and it is also possible to conduct sound along underground water."

It may be possible to exploit these natural phenomena in such a manner as to keep signal loss within manageable proportions.

For communication through the atmosphere, sea water, rock strata, and underground water employing energy in the form of audible sound, Ryerson suggests the frequency range of 16 Hz to 10 kHz as perhaps worthy of consideration. For the same propagation media employing ultrasonic energy, he suggests the frequency range 10 kHz to 100 kHz. It appears at this time that considerable research is necessary to establish the practicality of these frequency ranges. For purposes of design, it will be assumed that the frequency range 1 kHz to 10 kHz is suitable for the transmission of signals by acoustic methods. The transducers required for this would probably be relatively high-power devices. Reasonably high-power, low-frequency piezoelectric transducers have been built. For example, Maropis [18] has described a 4.2 kW transducer which operates at 15 kHz and Minchenko [19] has described a 10 kW, 10 kHz transducer. The transducer described by Maropis used the same type of ceramic piezoelectric element (PZT-4) as was used for the transducer shown in Figure 2. It may be that by using transducers of this type and the ducting phenomena, that practical seismic communication systems using piezoelectric transducers could be built.

## B. Seismic Noise

Seismic noise appears to be a relatively low-frequency phenomenon [20] - [25]. Concerning seismic noise of short period (high frequency) Brune and Oliver [20, p. 351] say, "For periods shorter than  $10^{-2}$  seconds little information is available in the literature, but there is no evidence to suggest that the amplitudes do not continue to fall off rapidly with decreasing period." The amplitudes referred to are the amplitudes of ground particle displacement at various frequencies. Frantti, Willis, and Wilson [21] found that, except for an anomalous effect near 2 or 3 Hz, the ground particle motion curves exhibited a smooth decrease with increasing frequency. The rate of decrease was found to be approximately proportional to the second power of frequency in the range of 2 to 31.5 Hz. The data only covered frequencies up to 31.5 Hz. The material presented by Brune and Oliver excludes obvious local sources such as industrial activity and waterfalls. The data presented by Frantti [22] does include some noise due to human activity and natural sources and varies considerably between various recording locations in some cases. The majority of the data obtained by Frantti yields maximum and minimum curves somewhat less than those of Brune and Oliver. It is interesting to note that Frantti found the noise level on the ocean beach near Oxnard, California, to be 20 to 40 decibels above that at other California sites which were situated farther inland. He indicates that his analysis of the data suggests that a substantial portion of high frequency seismic noise originates at the earth's surface and is propagated at or near the surface. If this is actually the case, one

would want the communication system underground to improve performance as well as for protection as in military applications. Most of the data discussed here deals with the vertical component of seismic noise.

Considering the decrease of noise with frequency, it seems that the noise might be treated as arbitrarily being negligible above 1 kHz. This assumes that above 100 Hz the noise continues to decrease at the same rate as it does in the region of 2 to 100 Hz [20]. Assuming that the noise is negligible in the frequency range of interest in a particular communication system, leaves one essentially with the problem of overcoming attenuation and scattering between transmitter and receiver. These problems might be overcome by using a high-power transmitter, use of sound ducts in the earth, and use of a sensitive receiver.

### C. A Proposed Communication System

Considering the results of the experiment performed in which the transmitting transducer on the sandstone specimen was driven at or near its resonant frequency, it seems reasonable to propose a communication system which employs amplitude modulation. Only digital communication will be considered, i.e., each message is represented by a single timelimited waveform at the input to the transmitter. These restrictions result in an ASK (amplitude shift keyed) system. Referring to the gated sinewave in Figure 5a, it may be seen that each different message could be represented by a different amplitude sine-wave driving the transmitting transducer. At the receiving end of the channel, one would require a receiving transducer plus some means of

deciding which message had been transmitted. A system satisfying these requirements is shown in Figure 7. The amplitude modulated driving source shown in Figure 7a produces a gated sinewave the amplitude of which depends on the message to be transmitted.

The decision portion of the receiver will now be considered. Referring to Figure 6b, it may be seen that the major portion of the received energy is in a very narrow frequency band about  $f_c$  where  $f_c$  is assumed to be the resonant frequency of the transmitting transducer. The fact that the received energy is in a narrow frequency band about  $f_c$ , would indicate that one would want to use a bandpass filter in the receiver centered at  $f_c$  to eliminate the low frequency noise discussed earlier. This assumes that  $f_c$  is high enough that seismic noise is negligible in the frequency band about  $f_c$ . According to the assumption that seismic noise is negligible, the signal out of the filter should be relatively noise free. This fact, coupled with the fact that amplitude modulation is assumed, would indicate that an envelope detector might be used. The receiver portion of the system might be represented as shown in Figure 7b. Figure 7b assumes that the receiver is synchronized with the transmitter and that 1 of 2 equally likely messages will be transmitted. The comparison threshold for the comparator is determined from (1).

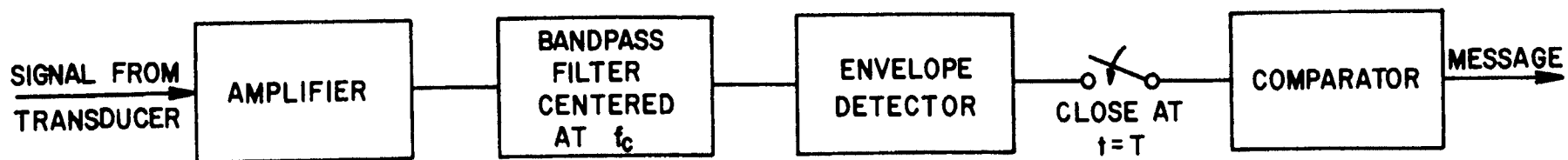
$$b = \frac{a_0 + a_1}{2} \quad (1)$$

where:  $b$  = comparison threshold

$a_0$  = amplitude of the signal out of the envelope detector at time  $t = T$  when the signal corresponding to message  $m_0$  has been transmitted



(a)



(b)

Figure 7. Proposed Communication System.  
 (a) Complete system. (b) Receiver.

$a_1$  = amplitude of the signal out of the envelope detector at time  $t = T$  when the signal corresponding to message  $m_1$  has been transmitted.

The time  $T$  at which the sample is taken should be that time at which the output of the envelope detector is maximum. This time would of necessity be determined experimentally. Assume that when the input to the comparator is less than  $b$ , the output is negative and for the input greater than  $b$ , the output is positive. Under these conditions, the decision process is quite simple. If  $a_0$  is less than  $a_1$  and the output of the comparator is negative,  $m_0$  is the correct choice of message; otherwise, it is  $m_1$ . The expression for the threshold  $b$  was picked as the most logical one in the absence of information concerning the statistics of the noise. If the noise were not negligible in the frequency range of interest and if the statistics were known, more sophisticated techniques such as correlation might be used to detect the signal [26]. The receiver may be extended to process more than 2 possible messages merely by making the comparator capable of distinguishing more thresholds.

Another modulation technique which might be used is FSK (frequency shift keying). An FSK system might be implemented by utilizing a different transmitting transducer for each message. Each transmitter would have a different resonant frequency so that when a particular message was to be transmitted, the corresponding transducer would be excited at its resonant frequency. The receiver could be structured as shown in Figure 7b except that a bandpass filter and envelope detector would be required for each different received signal [27]. The comparator would be replaced by a decision device which would



determine the envelope detector and consequently the filter that has the largest amplitude output at time  $t = T$ . The message corresponding to the signal which this filter would pass would then be chosen as the message which had been transmitted.

## VI. CONCLUSION

The transmission of acoustic signals through solid material employing piezoelectric transducers as transmitters and receivers presents two problems. The first is how to drive the transmitting transducer and the second is to determine the frequency response of the propagation medium. The voltage waveform used for driving piezoelectric transducers is important when the form of the received signal is of primary interest. Exciting the transmitting transducer at its resonant frequency provides a means of generating acoustic signals of known frequency. A gated sinewave whose frequency approximately equaled the resonant frequency of the transducer worked satisfactorily for the system studied in this investigation. Another waveform which has possibilities as a driving source for the transmitting transducer is an exponentially decaying pulse. Using this as an input, it may be possible to generate signals which contain a predetermined number of cycles of a sinusoid. If this type of signal could be generated, signaling rates could be obtained which are greater than those possible where the transducer vibrates after the driving waveform is removed.

Knowledge of the frequency response of earth materials is required when considering the design of a seismic communication system. This knowledge may be useful in fields other than communication such as identification of earth materials by their frequency spectra. From the results of this investigation, it appears that Berea sandstone possesses low attenuation for acoustic waves in a narrow frequency band near 310 kHz for the dimensions studied. If the frequency

spectra of other materials exhibit similar but unique characteristics they could be used for identification. This might be useful for the in situ determination of the composition of earth materials.

Piezoelectric transducers performed satisfactorily for generating and receiving acoustic signals in this investigation; however, considerable further research is necessary in order to determine their practicality for an actual seismic communication system. It may be that piezoelectric transducers are not capable of operating at frequencies low enough to prevent excessive signal attenuation.

## VII. SUGGESTIONS FOR FURTHER STUDY

Further investigation of a seismic communication system will require considerable equipment. Regardless of whether piezoelectric or other type transducers are used, some means of driving them with high power will eventually be required for field tests. A high-power pulse generator capable of producing gated sinewaves and rectangular pulses would be required for piezoelectric transducers. The Arenberg generator used in this investigation is not capable of driving the 780 kHz or the 1.5 MHz transducer at resonance because the shape of the gated sinewave is not preserved as the resonant frequency of either transducer is approached. The 310 kHz transducer could not be driven at its resonant frequency because the minimum attainable frequency of the sinewave was approximately 320 kHz for the particular conditions of loading and it appeared that the resonant frequency of the transducer was slightly less than this. The acquisition of an amplifier capable of driving the transducer is recommended so that various waveforms such as an exponentially decaying pulse can be used to drive the transmitting transducer. A correlator would also be useful for signal analysis.

Considerable research is necessary to determine the practicality of seismic communication systems especially those using piezoelectric transducers. A possible research plan might be as follows: (1) Investigate methods of decreasing or eliminating transducer ringing. (2) Water saturate the sandstone specimen used in this investigation to determine the effect on signal attenuation. (3) Fracture the sandstone specimen to determine the effect of a fracture on signal

propagation. (4) Prepare a specimen of concrete or some other material with imperfections such as glass beads and conduct experiments to determine the amount of signal scattering due to the imperfections. Experiments could be performed to determine the relationship between the size of the glass beads and the signal loss at various wavelengths. The relationship between signal loss, bead size, and wavelength should give an indication of the amount of signal loss due to scattering. (5) Perform attenuation measurements on a variety of different earth materials. (6) Bond two materials together which have widely different velocities of acoustic wave propagation and investigate the amount of signal reflection at the interface between the two specimens. (7) Investigate various aspects of high-power piezoelectric and other transducers and their application to seismic communication. (8) Obtain information concerning seismic noise over a greater frequency range than is now available. (9) Investigate methods of coupling acoustical energy into the earth. (10) Determine if sound ducts exist in the earth which will support acoustic wave propagation for the frequencies of interest. (11) Build and field test a complete seismic communication system.

The use of high-power transducers alone may not be sufficient to overcome the effects of attenuation. There is an upper limit to the amount of power which can be coupled into a medium over a given area and have the resultant deformation stay within the elastic range for that medium. The power which produces inelastic deformation of the medium is essentially wasted for communication purposes. The method of coupling energy into the communication medium is of considerable importance and will require extensive investigation.

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## IX. VITA

Ronald Willis Carter was born on January 23, 1944, in St. Louis, Missouri. He was graduated from Salem High School, Salem, Missouri. He received a Bachelor of Science degree in Electrical Engineering from the University of Missouri-Rolla, in Rolla, Missouri, in May 1967. He was actively employed by the U.S. Navy Electronics Laboratory in San Diego, California, from February 1967 to July 1968 and the McDonnell Douglas Corporation in St. Louis, Missouri, from July 1968 to August 1970. Presently, he is enrolled in the Graduate School of the University of Missouri-Rolla in Electrical Engineering.

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## APPENDIX A

## DETERMINATION OF FREQUENCY RESPONSE

A 780 kHz transducer was bonded in the center of one face of a foot cube of Berea sandstone which will be referred to as specimen number 1. Three transducers (1.5 MHz, 780 kHz, and 310 kHz) were arranged in a horizontal line and bonded to the opposing face of the specimen with the 780 kHz transducer mounted in the center of the face and the 1.5 MHz and 310 kHz transducers mounted 1 inch on either side of it. As a check on the effect of specimen geometry on the spectra obtained, a block of Berea sandstone with dimensions of 1 foot by 1 foot by 1/2 foot which will be referred to as specimen number 2 was also tested. A 780 kHz transducer was bonded in the center of one face of the specimen and another 780 kHz transducer was bonded in the center of the opposing face such that the distance between them was 6 inches. The 780 kHz transducers bonded to specimen number 2 were not the same ones that were bonded to specimen number 1.

The magnitude of the frequency response of specimen number 1 and the attached transducers was determined for various combinations of transmitting and receiving transducers; the results of which, are shown in Figures 8 and 9. The results for specimen number 2 are shown in Figure 10. The driving source for the transmitting transducer in all cases was a Hewlett-Packard Model 212 A pulse generator which produced a 70 volt rectangular pulse of  $7.5 \times 10^{-7}$  seconds duration at a repetition frequency of 215 Hz. This pulse was chosen so that when its duration was decreased, the amplitude of the received signal was reduced but its shape remained unchanged. Under these conditions, the

chosen input represents an impulse to the system. The signal from the receiving transducer was run to the input of a Tektronix Type 535A oscilloscope and the amplified signal from the "Vert. Sig. Out" connector was run to a Tektronix Type 1L5 spectrum analyzer plug-in unit operating in a Tektronix Type 549 oscilloscope. The received signal was amplified by the same amount in all cases and thus the spectra in Figures 8, 9, and 10 may be compared on a relative basis, but the actual amount of energy in the received signal is less than indicated by the amplitudes of the spectra.

By examining Figures 8, 9, and 10; it may be seen that some of the energy contained in the received signal is concentrated near 310 kHz in all cases. To check if this was due to the 780 kHz transducers, they were removed from specimen number 1 and the 310 kHz and 1.5 MHz transducers were bonded to opposing faces of the specimen. The spectrum for either the 310 kHz or the 1.5 MHz transducer transmitting and the other receiving also exhibited the concentration of energy near 310 kHz. From these results, it appears that this concentration is a function of the sandstone rather than the transducers. A large amount of received signal energy in the frequency range of approximately 100 kHz to 160 kHz was observed in all cases and appears to be a function of the sandstone also. The peaks in the spectra at 450 kHz as shown in Figure 8b, Figure 9b, and Figure 10 appear to be due to the 780 kHz transducers because this was observed each time the 780 kHz transducers were used as both transmitter and receiver. The difference in amplitude of the spectra in Figure 10 was found to be a function of which transducer was transmitting rather than the direction of wave propagation.

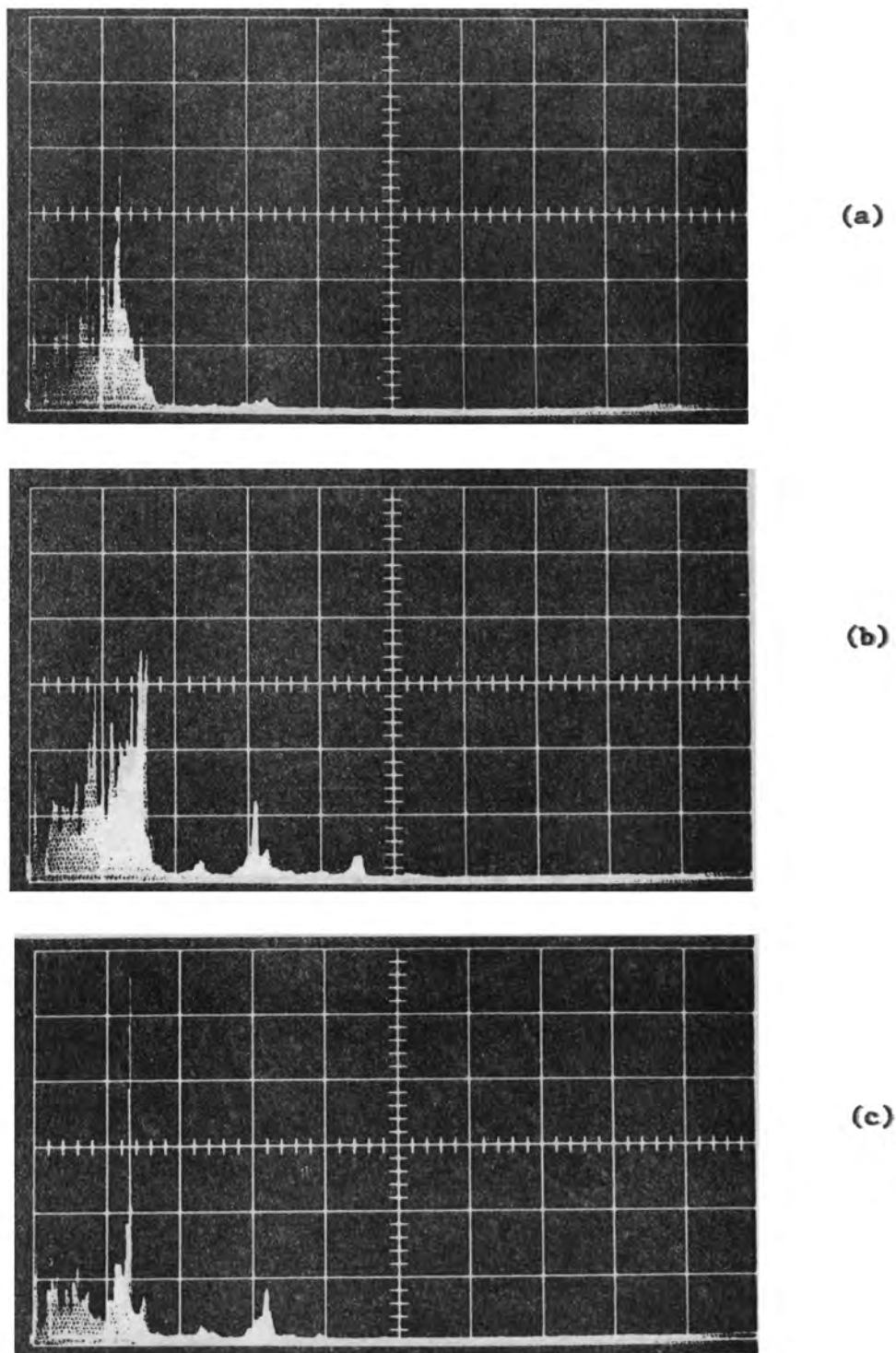


Figure 8. Output Spectra for Specimen No. 1 with 780 kHz Transmitter. Center frequency = 500 kHz. Scale - horizontal: 100 kHz/major div. (a) 1.5 MHz receiver. Scale - vertical: 10 mvrms/major div. (b) 780 kHz receiver. Scale - vertical: 20 mvrms/major div. (c) 310 kHz receiver. Scale - vertical: 50 mvrms/major div.

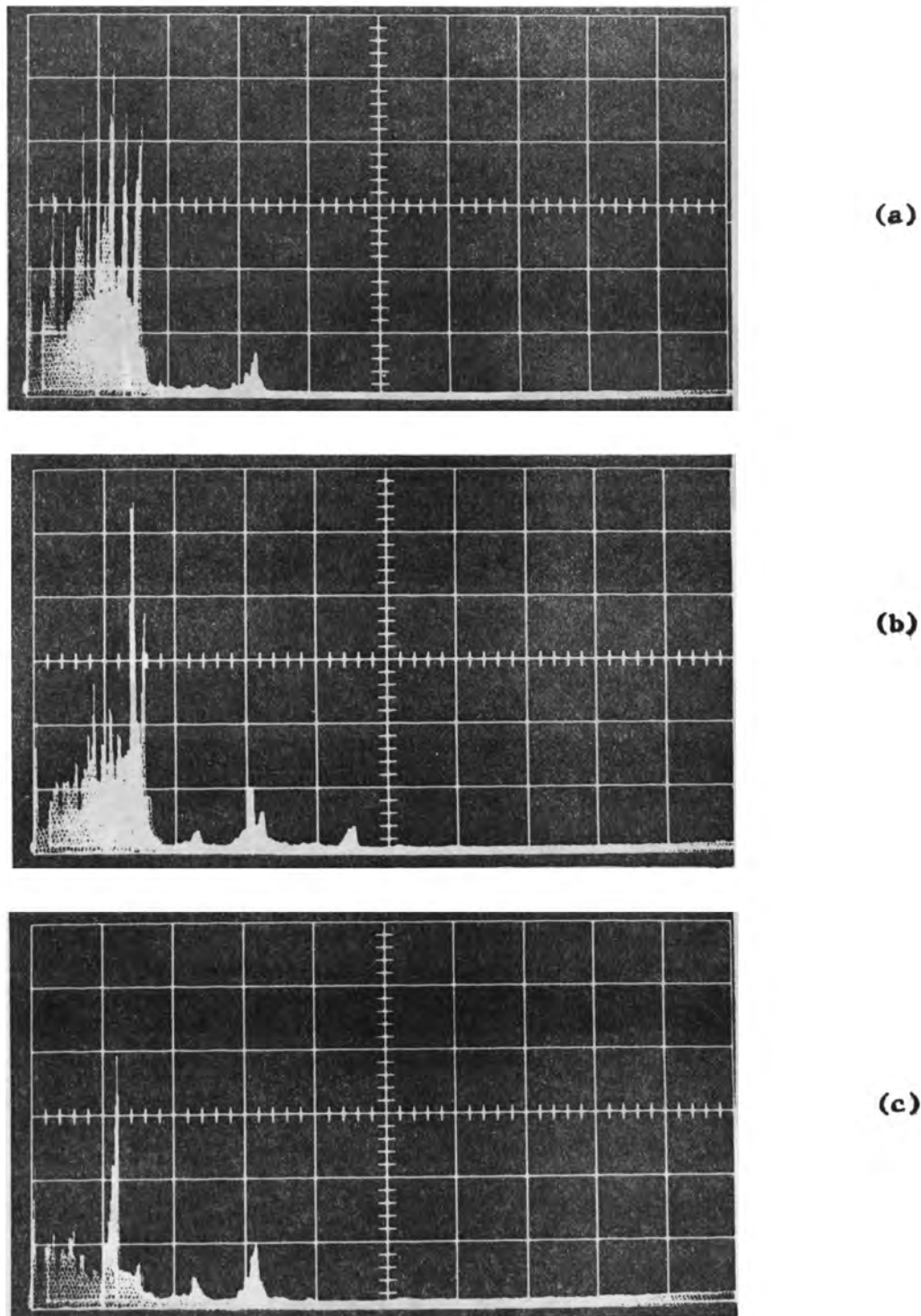
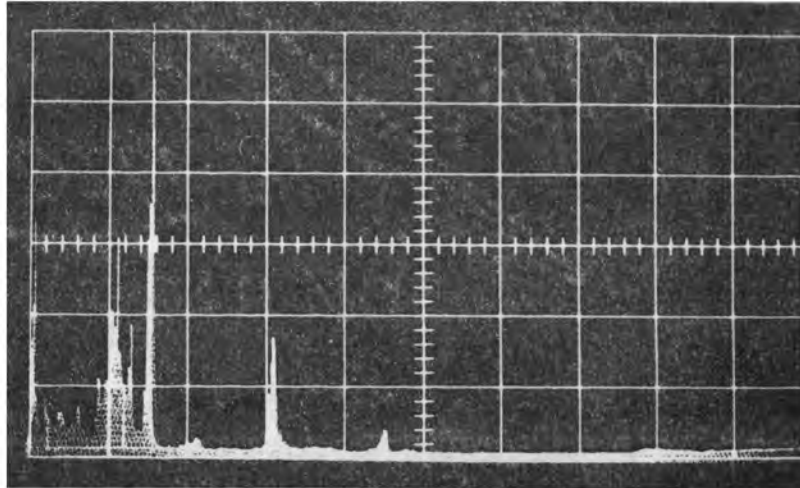
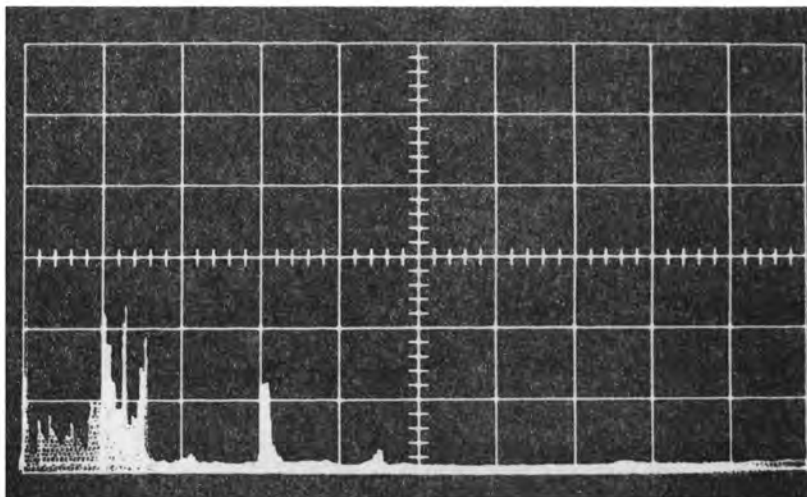


Figure 9. Output Spectra for Specimen No. 1 with 780 kHz Receiver. Center frequency = 500 kHz. Scale - horizontal: 100 kHz/major div. (a) 1.5 MHz transmitter. Scale - vertical: 10 mvrms/major div. (b) 780 kHz transmitter. Scale - vertical: 20 mvrms/major div. (c) 310 kHz transmitter. Scale - vertical: 20 mvrms/major div.



(a)



(b)

Figure 10. Output Spectra for Specimen No. 2. Center frequency = 500 kHz. Scale - horizontal: 100 kHz/major div. (a) Spectrum for initial configuration of transmitter and receiver. Scale - vertical: 50 mvrms/major div. (b) Same configuration as (a) with the role of transmitter and receiver reversed. Scale - vertical: 50 mvrms/major div.