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Tests of a hole-to-hole acoustic pulse measurement system

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ABSTRACT

The U.S. Geological Survey recently tested a downhole sparker source and hydrophone cable that were developed for research of hole-to-hole acoustic pulse measurement techniques. This research is directed toward detecting faults and fracture zones in rock between boreholes. The tests were made at the Lake Travis Transducer Calibration Facility (University of Texas). Results indicated that the repeatability of the sparker source is good under varying conditions of operation, that sparker electrode wear rate is very low, and that the frequency response of the receivers is well matched to the output of the source. The frequency of the sparker-source pulse varies slightly with voltage, showing a shift to higher frequency at the maximum discharge voltage tested, 4600 v.

Introduction

As part of a program of borehole-geophysical research, the U.S. Geological Survey is developing equipment and techniques for making hole-to-hole acoustic-pulse measurements for examining the integrity of rock between boreholes. The equipment consists of a sparker source that can be lowered into a borehole and fired repeatedly at various depths of interest, and a string of 6 hydrophones that can be lowered into another borehole to receive the waveforms generated by the source and propagated through the rock. The objective of the measurements is to detect acoustic velocity and attenuation anomalies associated with subsurface discontinuities such as faults and fracture zones. Such discontinuities are commonly associated with hardrock mineral deposits where they may provide structural control for deposition of ore and are, therefore, of interest in mineral exploration and evaluation. Acoustic anomalies are also important in the evaluation of tentative sites for the underground storage of radioactive waste materials where fracture zones must be avoided because they constitute potential pathways for the leakage of wastes.

A hole-to-hole acoustic-measurement system was designed and developed to meet USGS specifications by the Simplec Manufacturing Company, Inc. The system was completed and delivered in December 1979 and was tested in May 1980 at the Lake Travis Transducer Calibration facility operated by the Applied Research Laboratories of the University of Texas at Austin. The hole-to-hole measurement system and the Lake Travis test procedures and results are described in this report.

System Specifications

The mechanical and electrical characteristics of the borehole sparker-source probe and hydrophone cable are outlined below.

Sparker source:

Outside diameter	8.89 cm (3.5 in)
Length	3.35 m (11 ft)
Fluid pressure range	0-422 kg/cm^2 (0-6000 psi)
Temperature range	0°-60°C (32°-140°F)
Discharged electrical energy	1000 joules

Hydrophones:

Outside diameter	8.57 cm (3.375 in)
Length (each)	1 m (3 ft)
Spacing (center-to-center)	7.62 m (25 ft)
Total length (6 hydrophones)	39 m (128 ft)
Fluid pressure range	0-422 kg/cm^2 (0-6000 psi)
Temperature range	0^{o}-60^{o}C (32^{o}-150^{o}F)

Test Facilities

The Lake Travis Test Station is operated by the Applied Research Laboratories of the University of Texas and is available for use by government agencies by special arrangement with the Director of the Applied Research Laboratories. The transducer-calibration facility at the Lake Travis Test Station includes calibrated underwater acoustic transmitters and receivers and test shafts for attaching, orienting, and submersing transducers to depths of 6 m or more below the surface of the lake. The spacing between the test shafts to which the transducers are attached is 11.7 m. The frequency response of the Test Station's calibrated receivers ranges from 100 Hz to 1.5 MHz, and the frequency output of the calibrated transmitters ranges from 100 Hz to 100 KHz. The calibration facility is located on a barge that is permanently moored about 30 m from shore in water that is more than 20 m deep. The water depth and the distance from shore are large enough to delay the arrival of bottom and shoreline reflections so that they can be excluded from waveform analysis.

Sparker Source Tests

Waveforms from the Simplec sparker source were received with a hydrophone having a flat response from 100 to 10,000 Hz provided by the Lake Travis Test Station. The waveforms were digitized and recorded for the source conditions listed below:

1. no variation of sparker parameters (repeatability),
2. variation of resistivity of water surrounding sparker electrodes,
3. variation of sparker discharge voltage,
4. variation of sparker electrode gap,
5. variation of orientation of sparker probe.

The sparker pulse-repeatability tests were made by firing the sparker 20 times without changing any of the following parameters:

1.	electrical resistivity of water surrounding electrodes	31 ohm-m
2.	capacitor voltage prior to sparker discharge	4200 v
3.	sparker electrode gap width	0.15 cm
	orientation of probe	vertical

Additional sparker tests were made by varying each of the above parameters, one at a time, while holding the others constant. The electrical resistivity of water surrounding the electrodes was varied by filling a large plastic bag with saline water and fastening it around the probe above the electrodes so that the electrodes were immersed in the saline water. Three levels of resistivity were used in these tests: 0.09 ohm-m (80,000 ppm NaCl), 3.5 ohm-m (16,000 ppm NaCl), and 31 ohm-m (lake water). Comparisons of waveforms obtained with and without the plastic bag fastened over the electrodes indicated that the bag had no significant effect on the amplitude or frequency of the sparker pulse.

The discharge voltage tests were made by varying the capacitor charging voltage from 4000 to 4600 v in steps of 200 v by adjusting the voltage control on the Simplec surface-control module.

The sparker electrode-gap tests were made by adjusting the gap width from 0.05 cm to 0.25 cm in steps of 0.05 cm and making repeat waveform measurements at each gap setting.

The probe orientation tests were made by positioning the probe at angles of $\pm 22.5^{\circ}$ and $\pm 45^{\circ}$ from the vertical with the sparker electrodes pointing toward ($+22.5^{\circ}$ and $+45^{\circ}$) and away from (-22.5° and -45°) the hydrophone. The waveforms obtained with these angular probe orientations were compared with waveforms obtained with the probe oriented vertically.

All of the sparker tests were made with the sparker electrodes positioned at depths of 6 to 7 m below the surface at distances of 10 to 13 m from the calibrated hydrophone, which was positioned at a depth of 6 m.

Received waveforms were digitized by use of a Nicolet oscilloscope (model 2090-3C) at an interval of 5 microseconds and a sweep time of 20 milliseconds after a delay of 5 milliseconds following sparker discharge. The digitized waveforms were recorded on magnetic tape after transfer of the 12-bit digital data from the Nicolet oscilloscope to a Hewlett-Packard 9825 desktop computer. Later the waveform data were played back, smoothed, and plotted. The wavelets arriving ahead of interference from surface reflections were analyzed for frequency content (power density spectrum) by use of the desktop computer. Waveform smoothing was accomplished by use of a 0.25 millisecond-wide hamming-window smoothing filter (Blackman and Tukey, 1958) which attenuated noise at frequencies above 3 KHz and to some extent simulated the filtering effect of rock between boreholes.

Results of the sparker source tests indicated that repeatability was extremely good when no probe parameters were varied (fig. 1). These waveforms are very similar in character to farfield pressure signatures recorded from a marine seismic sparker source (Kramer and others, 1968). Figure 2 shows that power-density spectra computed for the three waveforms of figure 1 are nearly identical. Peak amplitude occurs at a frequency of 200 Hz in all three.

Results of sparker source tests made by varying the electrical resistivity of saline water surrounding the electrodes indicated that sparker output is practically independent of any such variation. Waveforms obtained with the sparker electrodes immersed in 0.09, 3.5, and 31 ohm-m water are shown in figure 3 with corresponding power-density spectra given in figure 4.

Results of tests involving varying the voltage level to which capacitors are charged just prior to spark discharge indicated that the output waveform is essentially the same for 4000-4400 v (figs. 5a, b). However, at 4600 v (fig. 5c) the power-density spectrum (fig. 6c) indicates a general shift to higher frequencies.

Results of tests involving variation of sparker electrode gap indicated that no significant differences in sparker output occur for a relatively large variation in gap width from 0.05 cm to 0.25 cm. Tests of electrode wear were made by firing the sparker 20 times in lake water with the gap set initially at 0.15 cm. After 20 spark discharges, the electrodes were slightly eroded

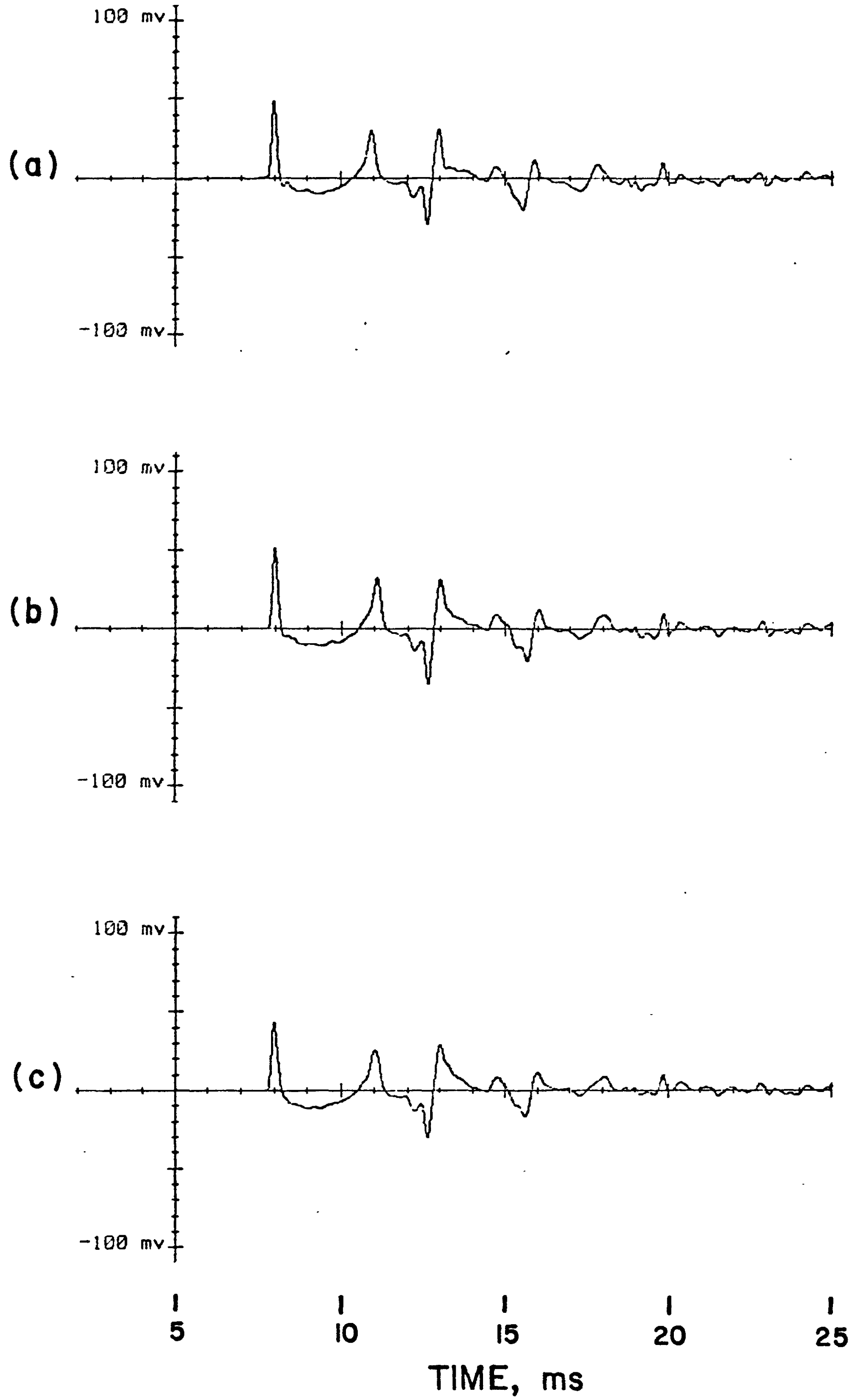

Figure 1.--Waveforms showing repeatability of sparker source output when no parameters are varied: (a) Run 1, (b) Run 4, (c) Run 6.

(a)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE (0 10 20 30 40 50 60 70 80 90 100)

Freq, Hz	Amplitude
0	37
100	240
200	570
300	500
400	284
500	170
600	165
700	207
800	239
900	235
1000	254
1100	234
1200	245
1300	193
1400	189
1500	155
1600	156
1700	132
1800	136
1900	80
2000	83
2100	45
2200	43
2300	23
2400	25
2500	16

(b)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE (0 10 20 30 40 50 60 70 80 90 100)

Freq, Hz	Amplitude
0	60
100	341
200	679
300	493
400	227
500	162
600	176
700	243
800	241
900	210
1000	225
1100	230
1200	210
1300	199
1400	179
1500	167
1600	162
1700	155
1800	110
1900	99
2000	50
2100	45
2200	33
2300	29
2400	17
2500	17

(c)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE (0 10 20 30 40 50 60 70 80 90 100)

Freq, Hz	Amplitude
0	80
100	431
200	833
300	557
400	227
500	191
600	190
700	255
800	253
900	220
1000	229
1100	246
1200	220
1300	180
1400	164
1500	143
1600	120
1700	102
1800	74
1900	55
2000	30
2100	20
2200	23
2300	19
2400	13
2500	11

Figure 2.--Power-density spectra for waveforms of figure 1 showing repeatability of spectral characteristics when no probe parameters are varied: (a) Run 1, (b) Run 2, (c) Run 6.

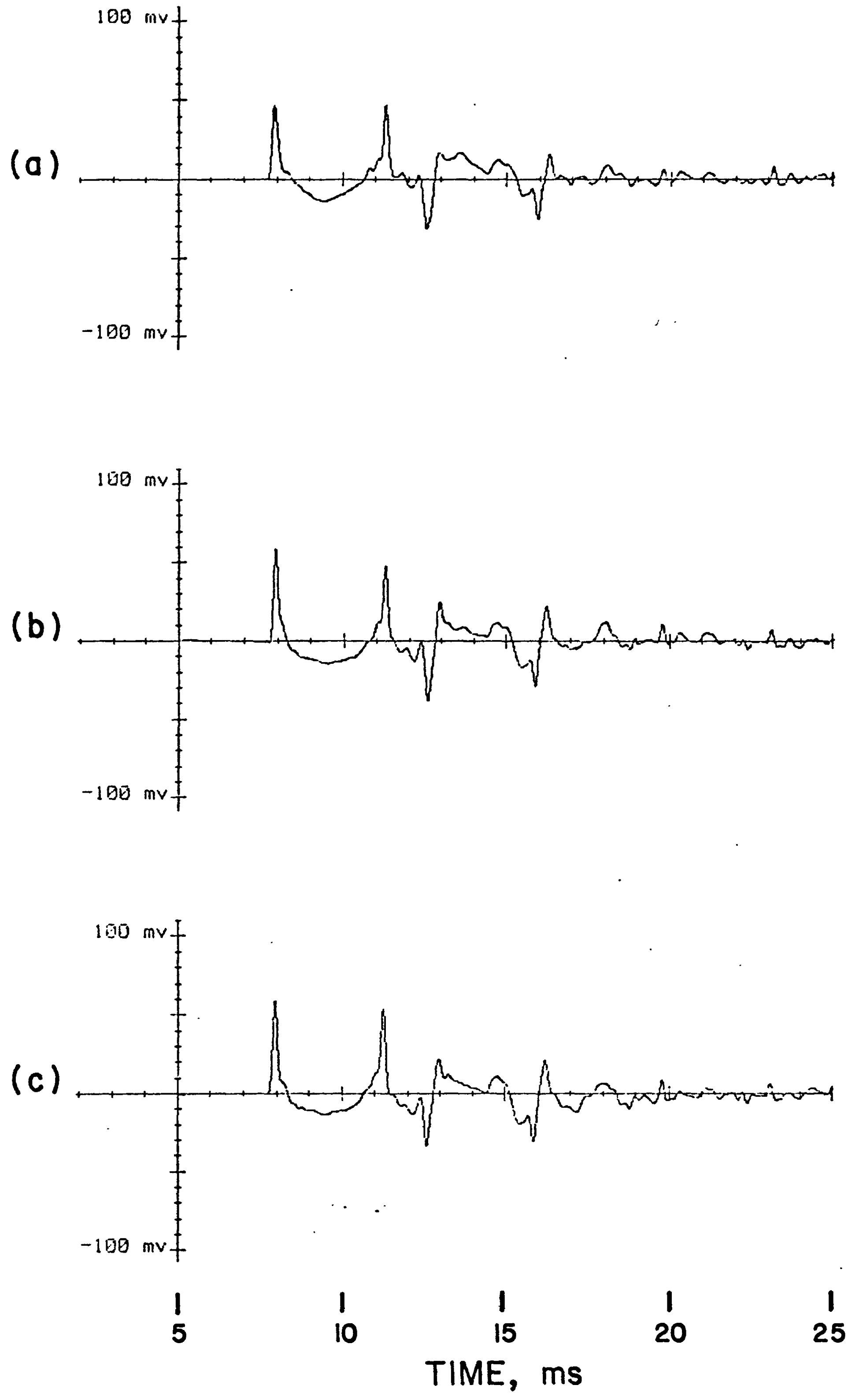

Figure 3.--Waveforms showing similarity of sparker source output for variations of the resistivity of water surrounding the sparker electrodes: (a) resistivity 0.09 ohm-m, (b) resistivity 3.5 ohm-m, (c) resistivity 31 ohm-m (lake water).

(a)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE (0 10 20 30 40 50 60 70 80 90 100)

Freq, Hz	Amplitude
0	58
100	340
200	744
300	786
400	526
500	313
600	261
700	197
800	179
900	170
1000	180
1100	176
1200	143
1300	136
1400	121
1500	110
1600	102
1700	85
1800	75
1900	56
2000	48
2100	38
2200	28
2300	21
2400	16
2500	12

(b)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE (0 10 20 30 40 50 60 70 80 90 100)

Freq, Hz	Amplitude
0	110
100	475
200	823
300	566
400	287
500	165
600	234
700	242
800	208
900	224
1000	224
1100	201
1200	172
1300	141
1400	137
1500	121
1600	111
1700	94
1800	84
1900	71
2000	50
2100	43
2200	40
2300	26
2400	23
2500	17

(c)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE (0 10 20 30 40 50 60 70 80 90 100)

Freq, Hz	Amplitude
0	61
100	353
200	721
300	612
400	346
500	187
600	243
700	274
800	232
900	210
1000	241
1100	219
1200	146
1300	132
1400	117
1500	107
1600	98
1700	86
1800	76
1900	55
2000	52
2100	49
2200	40
2300	34
2400	27
2500	21

Figure 4.--Power-density spectra for waveforms of figure 3 showing similarity of output for water of different resistivities surrounding the sparker electrodes: (a) resistivity 0.09 ohm-m, (b) resistivity 3.5 ohm-m, (c) resistivity 31 ohm-m.

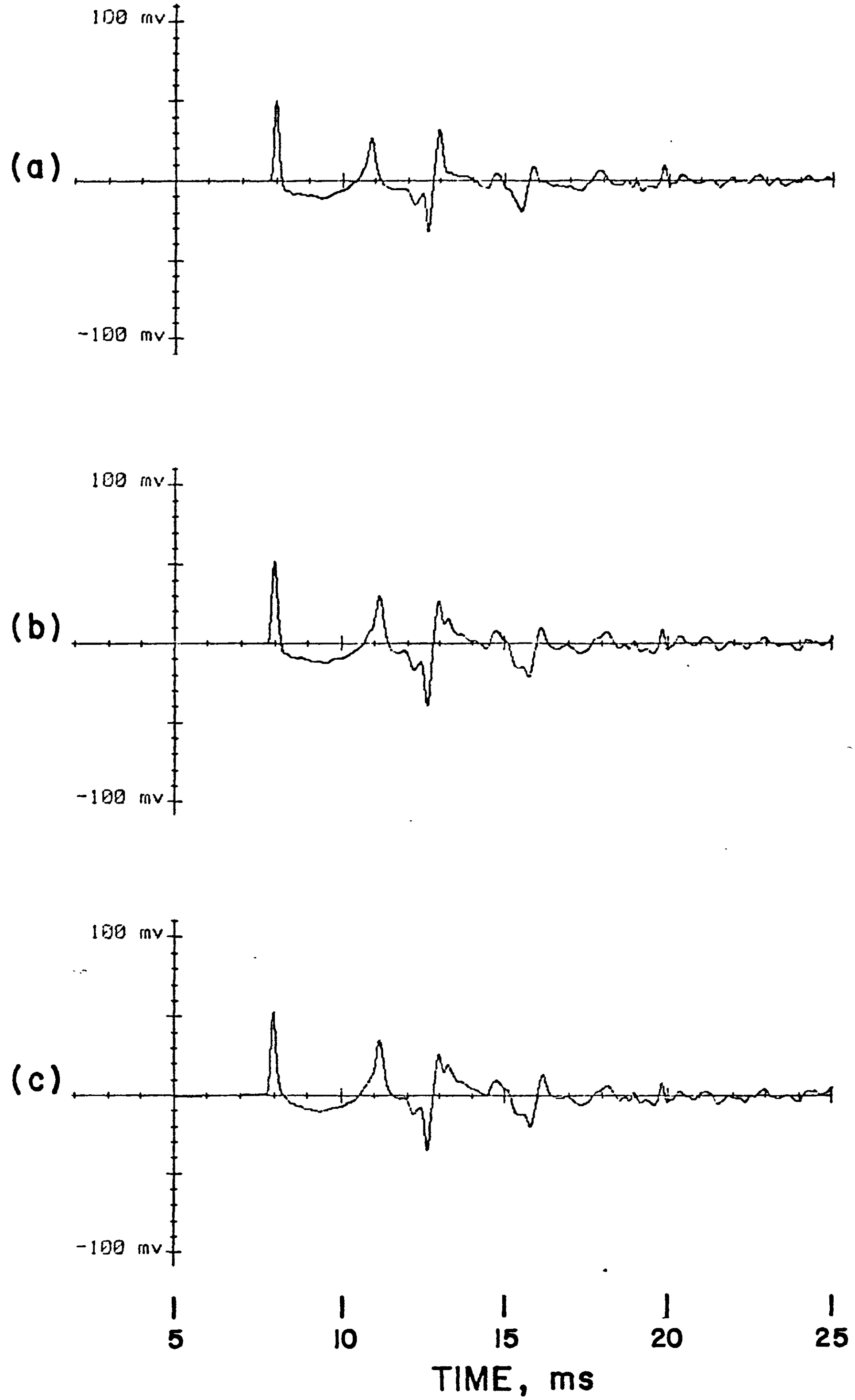

Figure 5.--Waveforms showing similarity of sparker source output for capacitor charging voltages of (a) 4000 v, (b) 4400 v, (c) 4600 v.

(a)

POWER DENSITY SPECTRUM		PERCENT OF MAXIMUM AMPLITUDE
Freq, Hz	Amplitude	0 10 20 30 40 50 60 70 80 90 100
0	78	.XXXXX
100	379	.XXXXXXXXXXXXXXXXXXXXXXXXX
200	746	.XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX.
300	496	.XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
400	184	.XXXXXXXXXXXX
500	125	.XXXXXXXX
600	118	.XXXXXXX
700	166	.XXXXXXXXXXX
800	183	.XXXXXXXXXXXX
900	205	.XXXXXXXXXXXXX
1000	219	.XXXXXXXXXXXXXX.
1100	244	.XXXXXXXXXXXXXXXX
1200	249	.XXXXXXXXXXXXXXXX
1300	197	.XXXXXXXXXXXXX
1400	186	.XXXXXXXXXXXX
1500	172	.XXXXXXXXXXX
1600	168	.XXXXXXXXXXX
1700	134	.XXXXXXXX
1800	124	.XXXXXXXX
1900	81	.XXXXX
2000	75	.XXXXX
2100	50	.XXX
2200	49	.XXX
2300	27	.X
2400	30	.X
2500	16	.X

(b)

POWER DENSITY SPECTRUM		PERCENT OF MAXIMUM AMPLITUDE
Freq, Hz	Amplitude	0 10 20 30 40 50 60 70 60 96 100
0	72	.XXXX.
100	405	.XXXXXXXXXXXXXXXXXXXXXXXXXX
200	764	.XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
300	491	.XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
400	221	.XXXXXXXXXXXXXX.
500	140	.XXXXXXXXX.
600	183	.XXXXXXXXXXX
700	202	.XXXXXXXXXXXXX
800	222	.XXXXXXXXXXXXXX.
900	227	.XXXXXXXXXXXXXX.
1000	260	.XXXXXXXXXXXXXXXXX
1100	261	.XXXXXXXXXXXXXXXXX
1200	230	.XXXXXXXXXXXXXXX
1300	215	.XXXXXXXXXXXXXX.
1400	188	.XXXXXXXXXXXX
1500	166	.XXXXXXXXXXX
1600	147	.XXXXXXXXX.
1700	118	.XXXXXXX
1800	99	.XXXXXX
1900	67	.XXXX.
2000	58	.XXX
2100	49	.XXX
2200	30	.XX
2300	25	.X
2400	19	.X
2500	12	.

(c)

POWER DENSITY SPECTRUM		PERCENT OF MAXIMUM AMPLITUDE
Freq, Hz	Amplitude	0 10 20 30 40 50 60 70 80 90 100
0	41	.XXX
100	240	.XXXXXXXXXXXXXXXXXXXXXX
200	527	.XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX.
300	525	.XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX.
400	349	.XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
500	260	.XXXXXXXXXXXXXXXXXXXXXXXXX
600	284	.XXXXXXXXXXXXXXXXXXXXXXXXXX
700	308	.XXXXXXXXXXXXXXXXXXXXXXXXXXXXX.
800	298	.XXXXXXXXXXXXXXXXXXXXXXXXXXXX
900	273	.XXXXXXXXXXXXXXXXXXXXXXXXX
1000	275	.XXXXXXXXXXXXXXXXXXXXXXXXXX
1100	264	.XXXXXXXXXXXXXXXXXXXXXXXXX
1200	204	.XXXXXXXXXXXXXXXXXXX.
1300	170	.XXXXXXXXXXXXXXXX
1400	132	.XXXXXXXXXXXX
1500	110	.XXXXXXXXXX
1600	78	.XXXXXXX
1700	63	.XXXXX
1800	45	.XXXX.
1900	35	.XXX
2000	21	.XX
2100	21	.X
2200	20	.X
2300	26	.XX
2400	24	.XX
2500	31	.XX

Figure 6.--Power-density spectra for waveforms of figure 5 showing variation of sparker output for capacitor charging voltages of (a) 4000 v, (b) 4400 v, and (c) 4600 v.

but the gap had increased only to 0.16 cm. The insignificance of this change indicated that the sparker probe could be fired between 100 and 200 times in a borehole before the probe would have to be withdrawn to reset the electrode gap.

Results of the sparker probe orientation tests indicated that the amplitude and frequency characteristics of the pressure waveform do not vary significantly with direction of propagation in the vertical plane. Waveforms for angles of $\pm 45^{\circ}$ and $\pm 22.5^{\circ}$ are shown in figure 7 with corresponding spectra in figure 8.

Hydrophone Tests

The Simplec hydrophones were tested by use of a calibrated underwater acoustic projector provided by the Lake Travis Test Station. The projector was swept over a frequency range of 100 to 5000 Hz and the amplitudes of the signals from the Simplec master hydrophone and one of the slave hydrophones were recorded as a function of projector frequency. Hydrophone outputs were processed in real-time by a tracking filter with a bandwidth of 30 Hz. Results indicate that the response of the hydrophone is reasonably flat from 200 to 3000 Hz (fig. 9). Minor variations in amplitude are probably caused by surface reflections (Bobber, 1970) and/or wave noise because they correlate with variations picked up by a standard hydrophone used for control.

The Simplec hydrophones were further tested by recording waveforms generated by the Simplec sparker source. The waveforms were recorded with two hydrophones at depths of 6 and 8 m and with the sparker electrodes at a depth of 6 m (fig. 10). Frequency spectra for these waveforms are shown in figure

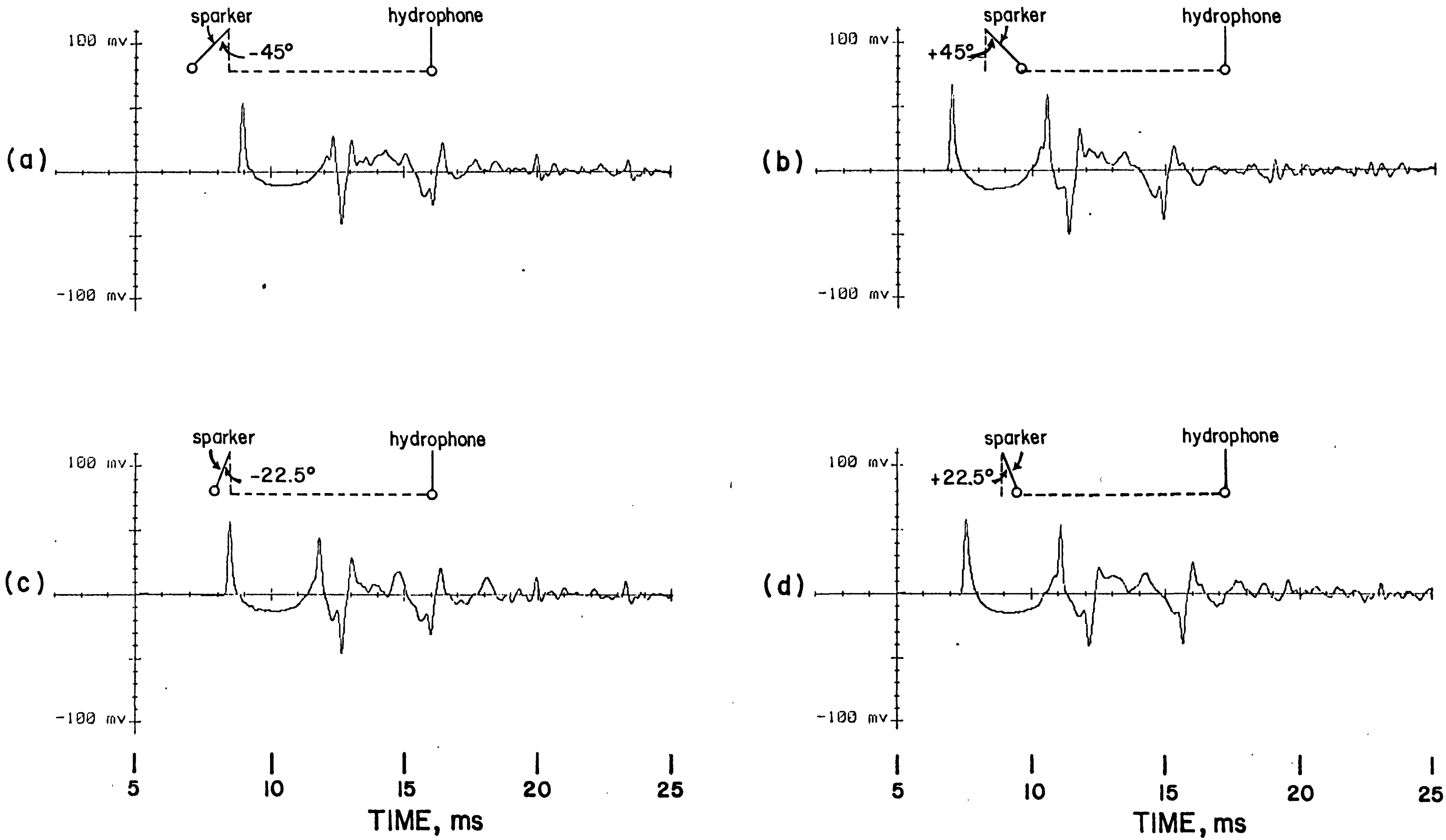

Figure 7.--Waveforms showing the effects of vertical angle of propagation: (a) 45° above sparker electrodes, (b) 45° below electrodes, (c) 22.5° above electrodes, and (d) 22.5° below electrodes.

(a)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE

Freq, Hz	Amplitude
0	75
100	363
200	678
300	510
400	279
500	175
600	255
700	264
800	199
900	198
1000	209
1100	197
1200	174
1300	174
1400	167
1500	139
1600	132
1700	115
1800	101
1900	88
2000	74
2100	63
2200	50
2300	40
2400	35
2500	25

(b)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE

Freq, Hz	Amplitude
0	115
100	425
200	731
300	554
400	311
500	190
600	266
700	256
800	170
900	190
1000	195
1100	176
1200	175
1300	162
1400	152
1500	131
1600	118
1700	110
1800	94
1900	80
2000	66
2100	47
2200	40
2300	30
2400	24
2500	19

(c)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE

Freq, Hz	Amplitude
0	134
100	491
200	790
300	509
400	251
500	156
600	238
700	244
800	192
900	208
1000	201
1100	177
1200	173
1300	157
1400	158
1500	140
1600	120
1700	108
1800	93
1900	79
2000	69
2100	54
2200	49
2300	37
2400	31
2500	24

(d)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE

Freq, Hz	Amplitude
0	134
100	472
200	791
300	586
400	323
500	208
600	338
700	336
800	223
900	245
1000	238
1100	169
1200	156
1300	147
1400	119
1500	92
1600	83
1700	71
1800	51
1900	41
2000	36
2100	24
2200	21
2300	16
2400	12
2500	9

Figure 8.--Power-density spectra for waveforms of figure 7 at various vertical angles of propagation: (a) 45° above electrodes, (5) 45° below electrodes, (c) 22.5° above electrodes, and (d) 22.5° below electrodes.

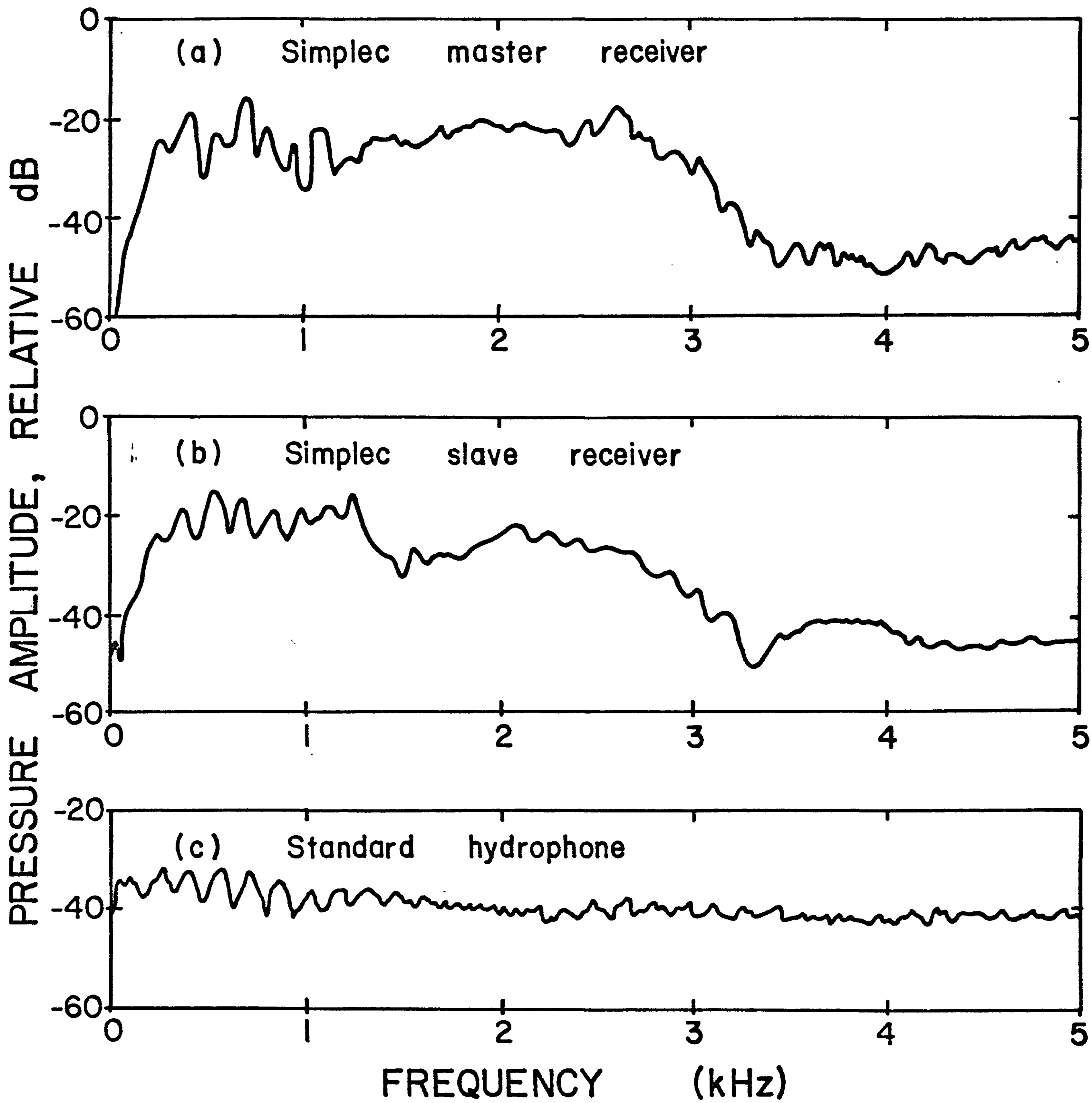

Figure 9.--Hydrophone frequency response: (a) Simplec master hydrophone, (b) Simplec slave hydrophone, (c) standard hydrophone (Lake Travis Test Station).

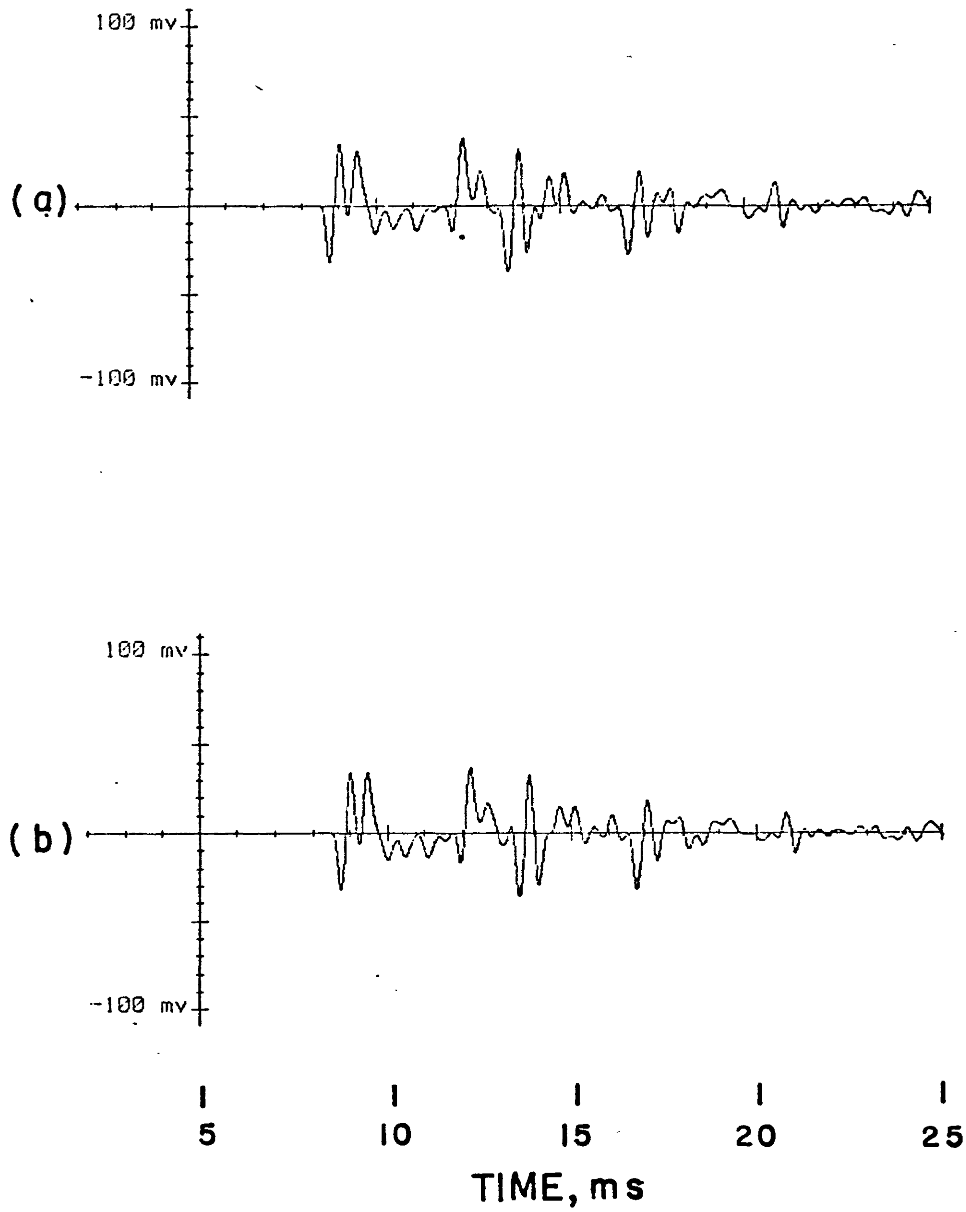

Figure 10.--Hydrophone waveforms from sparker source at a depth of 6 m: (a) Simplec master hydrophone, depth 6 m, (b) Simplec slave hydrophone, depth 8 m.

11. Results indicate that overall system response peaks occur at frequencies of approximately 300 Hz and 1700 Hz with a trough at 1200 Hz, and a pass bandwidth of 100-2700 Hz.

Conclusions

Tests of the hole-to-hole acoustic pulse measurement system at the Lake Travis Transducer Calibration Facility indicated that the Simplec 1000-joule sparker source has the following characteristics:

1. repeatability of pulse amplitude and frequency—excellent,
2. effect of variation of resistivity of water surrounding electrodes—nil (range 0.09-31 ohm),
3. effect of variation of sparker discharge voltage--nil from 4000 to 4400 v; shift to higher frequency at 4600 v,
4. effect of variation of sparker electrode gap--nil (range 0.05-0.25 cm)
5. directional effect: 45° above electrodes to 45° below electrodes—nil,
6. electrode wear with repeated firing--0.01 cm/20 firings.

Tests of the Simplec hydrophones indicated that their frequency response is reasonably flat from 200 to 3000 Hz. This range of frequency covers the output of the sparker source, which peaks at 200 Hz and tails off to insignificant levels above 2500 Hz.

The overall conclusions that can be drawn from the tests are that the Simplec hydrophones are well matched to the sparker source with regard to frequency response, that the repeatability of the sparker source is excellent,

(a)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE (0 10 20 30 40 50 60 70 80 90 100)

Freq, Hz	Amplitude
0	30
100	60
200	268
300	483
400	373
500	200
600	126
700	185
800	266
900	244
1000	85
1100	25
1200	17
1300	32
1400	58
1500	250
1600	521
1700	540
1800	355
1900	147
2000	102
2100	85
2200	69
2300	74
2400	85
2500	106
2600	115
2700	64
2800	16
2900	6
3000	2

(b)

POWER DENSITY SPECTRUM — PERCENT OF MAXIMUM AMPLITUDE (0 10 20 30 40 50 60 70 80 90 100)

Freq, Hz	Amplitude
0	10
100	41
200	206
300	533
400	410
500	193
600	116
700	220
800	308
900	212
1000	80
1100	24
1200	12
1300	23
1400	49
1500	209
1600	411
1700	555
1800	394
1900	157
2000	134
2100	122
2200	78
2300	84
2400	104
2500	120
2600	97
2700	56
2800	10
2900	4
3000	3

Figure 11.--Power-density spectra for waveforms of figure 10: (a) Simplec master hydrophone, depth 6 m, (b) Simplec slave hydrophone, depth 8 m.

and that the sparker pulse output is not significantly affected by any of the variable parameters of operation.

Acknowledgments

Robert Wilson of the Simplec Manufacturing Company, Inc., provided valuable assistance and electronic expertise in planning, setting up the equipment, and running the tests. Bill Purdy of the Applied Research Laboratory Lake Travis Calibration Facility provided technical guidance in coordinating the tests with the facility's test equipment. James E. Stockton and W. G. Foreman of the Applied Research Laboratory (University of Texas) made the necessary administrative arrangements for scheduling and implementing the tests, and C. M. McKinney, Director of the Applied Research Laboratory, approved the arrangements.

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