Report of Investigations 8506

Measurement of Blast-Induced Ground Vibrations and Seismograph Calibration

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UNITED STATES DEPARTMENT OF THE INTERIOR
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BUREAU OF MINES
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This publication has been cataloged as follows:

Stagg, Mark S

Measurement of blast-induced ground vibrations and seismograph calibration.

(Report of investigations - Bureau of Mines ; 8506)
Bibliography: p. 25-27.
Supt. of Docs. no.: I 28.23:8506.

1. Seismic prospecting. 2. Blast effect. 3. Seismometers—Calibration. 4. Seismometry. I. Engler, Alvin J., joint author. II. Title. III. Series: United States. Bureau of Mines. Report of investigations ; 8506.

TN23.U43 [TN269] 622s [622'.159] 80-607894

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MEASUREMENT OF BLAST-INDUCED GROUND VIBRATIONS AND SEISMOGRAPH CALIBRATION

by

Mark S. Stagg[1] and Alvin J. Engler[2]

ABSTRACT

Blast-induced ground vibrations from surface coal mine, quarry, and construction blasting were measured and analyzed for frequency content and duration characteristics. Eighteen commercially available ground vibration measurement systems were evaluated in the field and laboratory for linearity, accuracy, and crosstalk. Buried, surface, and sandbagged transducer placement methods were compared, along with peak and vector-sum measurements.

The recommended minimum frequency ranges for ground vibration instrumentation are 2 to 150 Hz for coal mine and quarry blasting, and 5 to 200 Hz for construction and excavation blasting. When higher or lower frequency vibrations are possible, as in construction blasting or for a quarry shot close to a residence, care should be taken to insure proper choices of instrumentation and vibration criteria.

Several instruments operating in these ranges are available, and all but one of the seismographs tested fell within ±3-dB accuracy limits (+41 pct, -29 pct).

Waveform recordings of all three ground vibration components are recommended as the peak amplitude and frequency may vary among the three. Peak or vector-sum readings are adequate if only amplitude levels are desired. The soil density matched box should be anchored or buried, particularly for high-frequency, high-amplitude construction blasting.

INTRODUCTION

Effects of ground vibrations generated from surface blasting have been of increasing public concern. The growing number of surface coal mines and quarries operating in populated areas has caused considerable consternation

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for mine operators and for people who live nearby. The Bureau of Mines has responded by conducting research on measurement and analysis of ground vibrations, and their effects on structures and people.

Displacement seismographs and falling-pin gages were commonly the first instruments used to measure the effects of ground vibrations (21).[3] Displacement seismographs and calibration tables were designed by the Bureau as part of an extensive research program conducted from 1930 to 1940 to study the effects of ground vibrations from quarry blasting (25). This study proposed that acceleration, calculated from displacement measurements, was the criterion most closely associated with damage. Later studies proposed a criterion based on particle velocity (2, 7, 13) calculated from displacement and acceleration measurements. Transducers were then developed to measure acceleration, displacement, or velocity directly. Because the velocity criterion was based on converted acceleration or displacement readings, two studies (8, 19) took direct measurements of acceleration, displacement, and particle velocity. Peak particle velocity remained the recommended damage criterion. Earlier studies measured the vibration at various locations: ceiling panels, foundation walls, and at the surface of the soil near the structure. Additional data were collected, using the peak particle velocity determined from the vector addition of all three ground vibration components (26). The Bureau reexamined the problem and reported results on seismograph calibration (9, 17), instrumentation design requirements (4-5), soil coupling of gages (11), and damage criteria based on velocity (6). In 1971, the results of these studies were published (18), and the industry has incorporated the information into the design and production of velocity seismographs. However, questions still remained on the effects of surface placement of transducers (1, 10, 27), the frequency range that should be measured, velocity seismograph calibration, and velocity measurement methodology. Recent publications give an overview of instrumentation and damage criteria (24), list frequency and scaled-distance ranges for coal, quarry, and construction vibrations (14), and demonstrate new measurement analysis techniques of velocity exposure level (12) and response spectra (3, 16). The results of analysis using these techniques have recently been published (23) by the Bureau.

Investigation results differed depending upon the instrumentation and measurement method used. Frequency response characteristics, system resonances, transducer mounting, and other factors can alter the measured amplitude from one seismograph to another. The present study provides the results of calibration tests performed on commonly utilized seismographs from various manufacturers. Their advantages and disadvantages are discussed, and minimum operating parameters are recommended.

[3]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

ACKNOWLEDGMENTS

The authors thank Joseph L. Condon, research supervisor, Denver (Colo.) Research Center, and David E. Siskind of Twin Cities (Minn.) Research Center, Bureau of Mines, for their assistance in planning and data analysis.

The authors are especially indebted to James A. Gould of Philip R. Burger & Associates, Thomas W. Novotny of Vibra-Tech Engineers, Inc., Ray Callicoatte of Dallas Instruments, Inc., and Spence Lucole of VME-Nitro Consult, Inc., who assisted or provided their companies' vibration instrumentation for calibration.

INSTRUMENTATION

Ground vibration waves from a blast emanate in every direction. Of principle importance for instrumentation monitoring these vibration waves are their frequency (f), amplitude range, and duration. As seen in figure 1, the wave has a peak particle velocity of 0.45 in/sec and a duration of 1 sec, and is composed of complex frequencies, one being 28 Hz $\left(\frac{1}{\text{period}} = f\right)$. The frequency spectrum of the shot is shown to the right in the figure. The spectrum is a histogram of the frequencies present in the vibration, with the relative amplitudes given in decibels. A seismograph is an instrument that records ground motions and is usually a package of three mutually orthogonal ground vibration transducers, signal conditioners, and a recording mechanism, such as a light-beam oscillograph or magnetic tape. Some seismographs do not produce a permanent record but display only the peak value of one or more of the orthogonal components on a meter or digital display.

Most velocity transducers (geophones) can be modeled by a mass suspended on a spring from a support. If the mass is displaced and then released, it will oscillate at its natural or undamped frequency and will eventually return

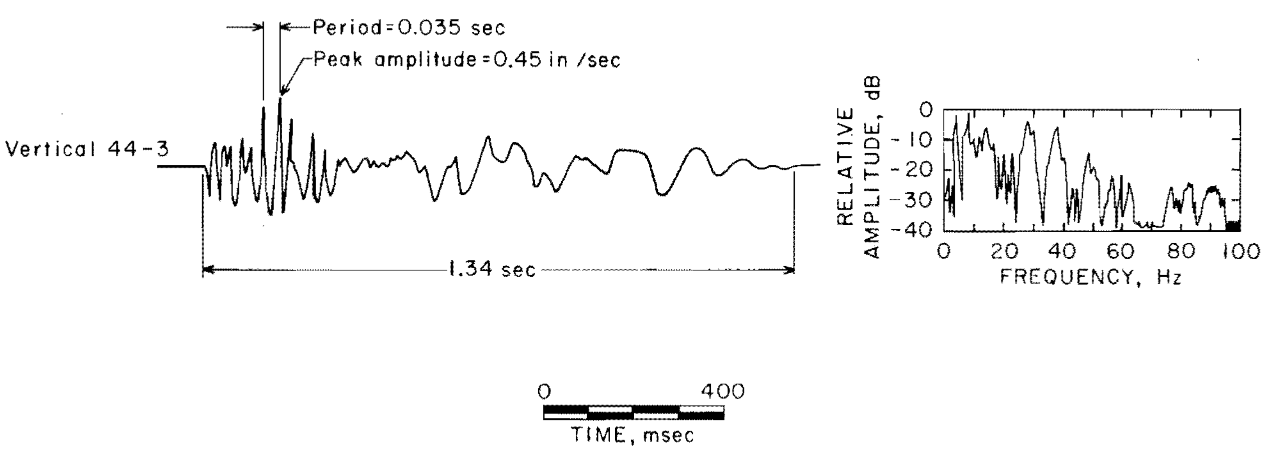

FIGURE 1. - Typical ground vibration.

to its original position. This frequency, f_0, is determined by the ratio of total mass to the system's spring constant. A voltage output is obtained by making the mass a magnet, which oscillates inside a wire coil.[4]

To obtain an accurate waveform, a velocity gage must be damped; it cannot be allowed to resonate at its natural frequency. If the coil in which the magnetic mass oscillates is shunted by a resistor, the resistor produces a current in the coil and a magnetic field force that opposes the motion of the mass. When properly adjusted, the gage can be critically damped; that is, the mass has no overswing or oscillation (15, 18). Many transducers, however, are not critically damped, but underdamped, to produce a higher output voltage.

Frequency Ranges

The frequency characteristics of the transducers used in a seismograph are critical to the accuracy of the system. Most velocity transducers are calibrated in terms of voltage output; for example, a certain amount of volts out for every inch/second of excitation force. This relationship is constant over a range, called the useful frequency range. Transducers are limited on the low end by f_0, their resonant frequency. The useful frequency range of an instrument is usually defined as the span between the -3-dB points on both the high- and low-frequency ends. The -3-dB point is defined as the point at which the frequency response amplitude is down by 3 dB from the nominal sensitivity (fig. 2), or, more specifically, when $20 \log \frac{\text{amplitude}}{\text{nominal amplitude}} = -3$. Outside this range, amplitude and phase distortion are above accepted limits.

Low-Frequency Amplifiers

The useful range of a velocity transducer can be extended below the resonant frequency by introducing a low-frequency amplifier into the signal-conditioning electronics of the seismograph. This system selectively amplifies the transducer signal (fig. 2) and must be matched closely with the transducer to provide correct compensation in the desired frequency range.

Accelerometers

The Bureau researchers used piezoelectric accelerometers along with velocity gages to measure ground vibration and structure motion. The output of the accelerometer was fed into a charge amplifier, where the signal is amplified and integrated electronically to produce a velocity or displacement output. The output is linear over a frequency range determined by the integrator and the natural frequency of the accelerometer.

[4] In reality, most geophones have a stationary mass and an oscillating coil. The voltage produced is proportional to the velocity experienced by the gage.

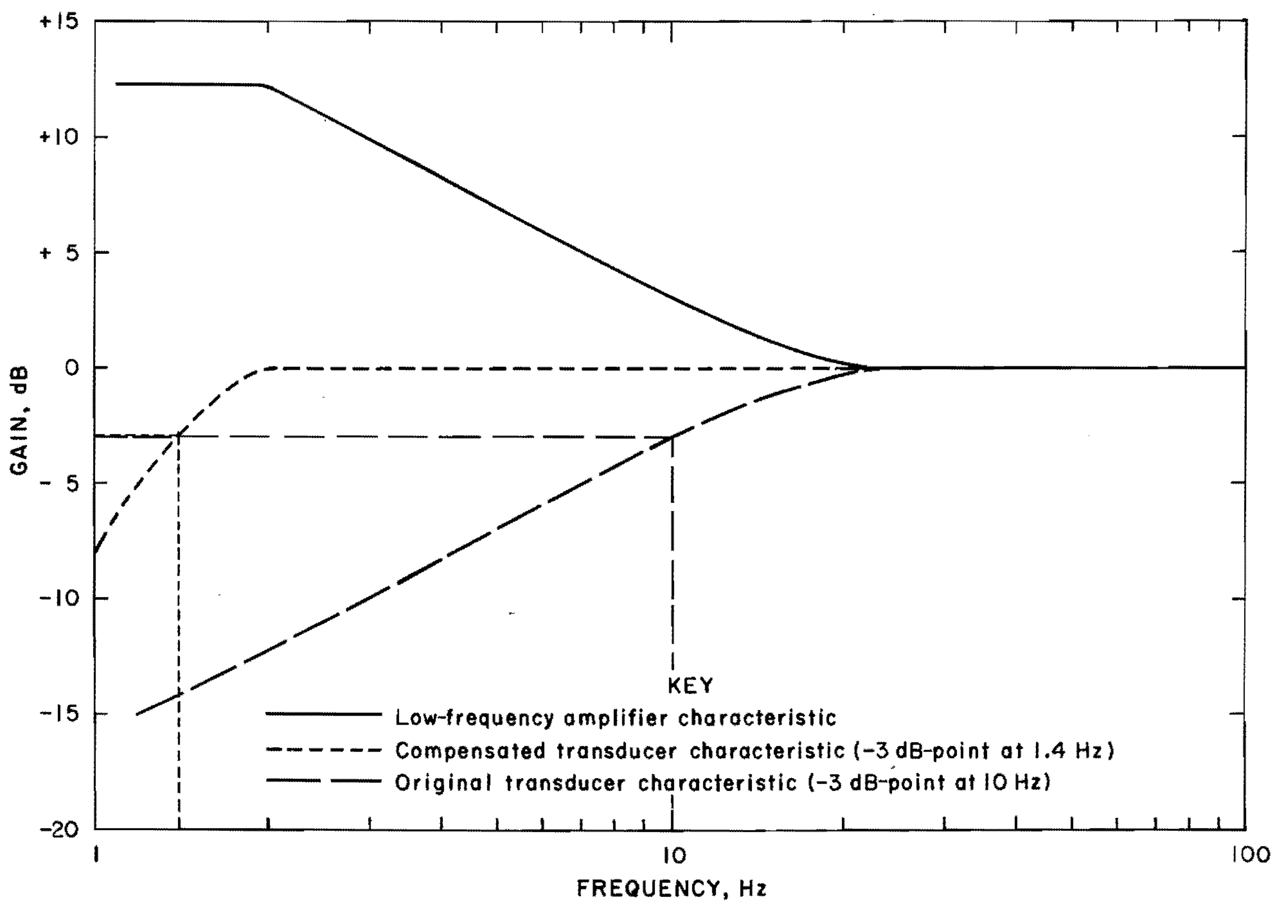

FIGURE 2. - Transducer low-frequency compensation.

Three-Component Boxes

For use in a seismograph, the transducers measure three orthogonal components, one vertical (V) and two horizontal, radial (R), and transverse (T). These are mounted in a box made of nonferrous metal, such as aluminum, and weatherproofed to allow burial of the package. The box's density should be designed to be about 100 to 150 lb/cu ft to match the density of the soil and to provide good coupling.

Vector Summing

Some seismographs record their output as a vector sum of the three orthogonal ground vibration components. A true vector sum is defined as

$$\text{vector sum} = \left[H_1^2(t_1) + H_2^2(t_1) + V^2(t_1) \right]^{1/2} \qquad (1)$$

where H_1 and H_2 are the horizontal components, V is the vertical component of the ground vibration, and t_1 is an instant of time. Seismographs of this type vector sums the components during the full duration of the incident and then record the highest value. This is not to be confused with the pseudo vector sum, which is defined as

$$\text{pseudo vector sum} = \left[H_1^2(\text{peak}) + H_2^2(\text{peak}) + V^2(\text{peak}) \right]^{1/2} \qquad (2)$$

The pseudo sum is calculated the same way as the true sum, except that it sums only the absolute peaks of the ground vibrations, regardless of when they occur. This will naturally give a higher reading than the true vector sum, unless the peak values occur simultaneously. All the vector sum instruments tested measure the true vector sum. When comparing peak-reading instruments against the vector sum types, the pseudo vector sum is often used, which is incorrect. To find a true vector sum, the values that are summed must be taken at the same instant of time.

CALIBRATION PROCEDURES

Commercial seismographs that had not been studied in the field by Bureau researchers were borrowed or rented to run calibration tests. Seismographs used in the field were also calibrated, along with the individual velocity transducers and triaxial transducer packages. The seismographs and seismometers listed in table 1 are only a sampling of commercially available instruments, but they are a good cross section of instrument modes of operation and recording or display formats.[5] The instruments calibrated and their transducer packages are shown in figures A-1 through A-31.

[5]Reference to specific equipment, trade names, or manufacturers does not imply endorsement by the Bureau of Mines.

TABLE 1. - Specifications of commercial seismographs and seismometers tested

Company and model	Amplitude ranges, in/sec	Frequency range, Hz	Recording format	Recording duration	Power requirements	Weight, lb	Size, inches	Temperature range, ° F	Internal calibration system	Airblast monitor capability
Dallas Instruments, Inc.: VS-3 blast monitor.	0-2	1-200	Peak vector sum, bar graph chart recorder.	Internal power--5 to 7 days. External power--1 month (chart paper duration).	Internal--3 6-v lantern batteries. External--12-v car battery.	25	14.5 by 10 by 7 4 diam by 2.2 transducer package.	0-140	Yes	No.
Dallas Instruments, Inc.: 3B-2 blast monitor.	0-2, 0-10	10-100[1]	Peak velocity meter readings of all 3 components.	Event..............	2 9-v batteries....	15	14.5 by 10 by 7 4 diam by 2.2 transducer package.	0-140	Yes	No.
Dallas Instruments, Inc.: ST-4 seismic triggered.	0-1 or 0-4 (8 maximum). (Maximum 137 dB tape).	1-200 5-200 air	Waveform record,[a] cassette magnetic tape, analog form, and digital display (peak).	Internal power--3 days/75 events. External power--30 days/150 events.	Internal--12-v, rechargeable. External--12-v car battery.	30	20.5 by 10 by 7 4 diam by 2.2 transducer package.	32-120 Tape recorder.	Yes	Provided.
SINCO Slope Indicator Co.: S-4 peak vibration monitor.	0.05 multirange 0-20	6-150	Digital printout peak vector sum.	AC paper duration... External 80 or 400 hr	30 w, 115 v/230 v, 50/60 Hz. 12-v dc power pack--rechargeable or 12-v dc car battery.	33	16 by 8.5 by 6 8.75 by 3.75 by 3.25 transducer package.	NA	No	No.
Vibra-Tech Engineers, Inc.: Vibra-Tape 1000 Series.	0-1, 0-4 (Maximum 137 dB tape limit).	1-200 5-500 air	Waveform record, cassette[a] magnetic tape, analog form and meter display (peak).	Event--30 min continuous.	3 6-v batteries....	26	15 by 13 by 7.5 4 diam by 2.2 transducer package.	NA	Yes	Provided.
Vibra-Tech Engineers, Inc.: Vibra-Tape 2000 Series.	0-1, 0-4 (Maximum 140 dB tape limit).	1-200 4-500 air	Waveform record, cassette[a] magnetic tape, analog form and meter display (peak).	.....do............	2 6-v batteries....	28	17 by 13.75 by 7.25 4 diam by 2.2 transducer package.	NA	Yes	Do.
VME-Nitro Consult Inc.: Model F.	0-0.25, 0-1, 0-4 (Maximum 140 dB	5-200 5-200 air	Waveform on 70 mm direct-print paper.	Event..............	12-v dc rechargeable	40	19.4 by 9.75 by 9 5.75 by 5.75 by 4.75 transducer package.	NA (paper limit).	Yes	Do.
Phillip R. Burger & Associates, Inc.: Seismic Safeguard Unit II.	0-2 (Maximum 145 dB)	5-200	Waveform on 70 mm direct-print paper and digital display (peak).	.....do............	.....do...........	26	18 by 14 by 6 5 by 5 by 3 transducer package.	NA (paper limit).	Yes	Do.
W. F. Sprengnether Instrument Co., Inc.: VS-1100.	0-0.05, 0-2, 0-1, 0-5.	2-200	Waveform on 70 mm direct-write-print paper.	.....do............	.....do...........	52.5	13.75 by 11.5 by 10 7 by 7 by 7 transducer package.	NA (paper limit).	Yes	Yes, auxiliary item.

NA Not available.
[1]Wider frequency response available of down to 1 Hz or as high as 1,000 Hz.
[a]Auxiliary equipment needed for playback (direct-print paper trace, standard).

The instrument calibration was done on two shaker systems, one operated by the Twin Cities Research Center, and the other by the U.S. Naval Research Laboratory, Washington, D.C. The Bureau of Mines shaker system is an Unholtz-Dickie Model CV608R-12A (fig. 3). The transducer packages were excited in both the horizontal and vertical directions. Horizontal excitation was accomplished by coupling the shaker head to an aluminum plate sliding on an oil-bearing surface, which was mounted on a block of granite. Transducers were tested at 2, 2.5, 3.0, 3.5, 4.0, 4.5, 5, 6, 7, 10, 15, 25, 35, 50, 100, 200, and 250 Hz at 1-in/sec peak particle velocity, and the tests were repeated over the same frequency range at other velocities ranging from 0.25 to 4 in/sec. For seismographs and seismometers, the instrument response to shaker response ratio (normalized response) was found for all three components and plotted versus frequency. The individual gages were also tested over the same frequency range, and the sensitivity was found by measuring the gage voltage output divided by a shaker velocity as determined by a B & K model 4370 accelerometer traceable to the National Bureau of Standards (NBS). Excitation was provided to the shaker from an Exact Waveform Generator model 7030.

The U.S. Naval Research Laboratory shaker system was a Ling model B-335 (fig. 4) with excitation provided by a Hewlett Packard model 200 CD audio sweep oscillator, and table motion monitored by an Endevco model 2270 standard accelerometer. Tests were performed on all three-component transducer

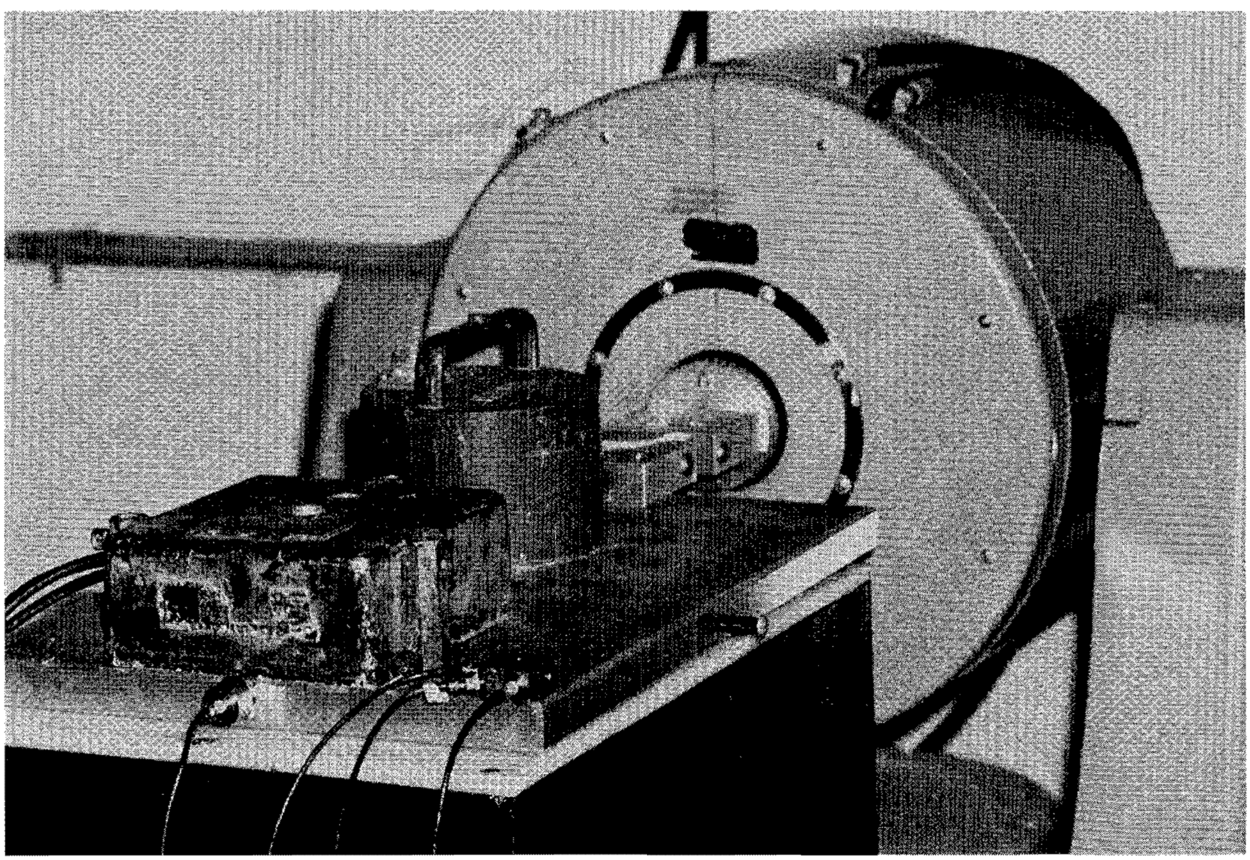

FIGURE 3. - Bureau of Mines shaker system.

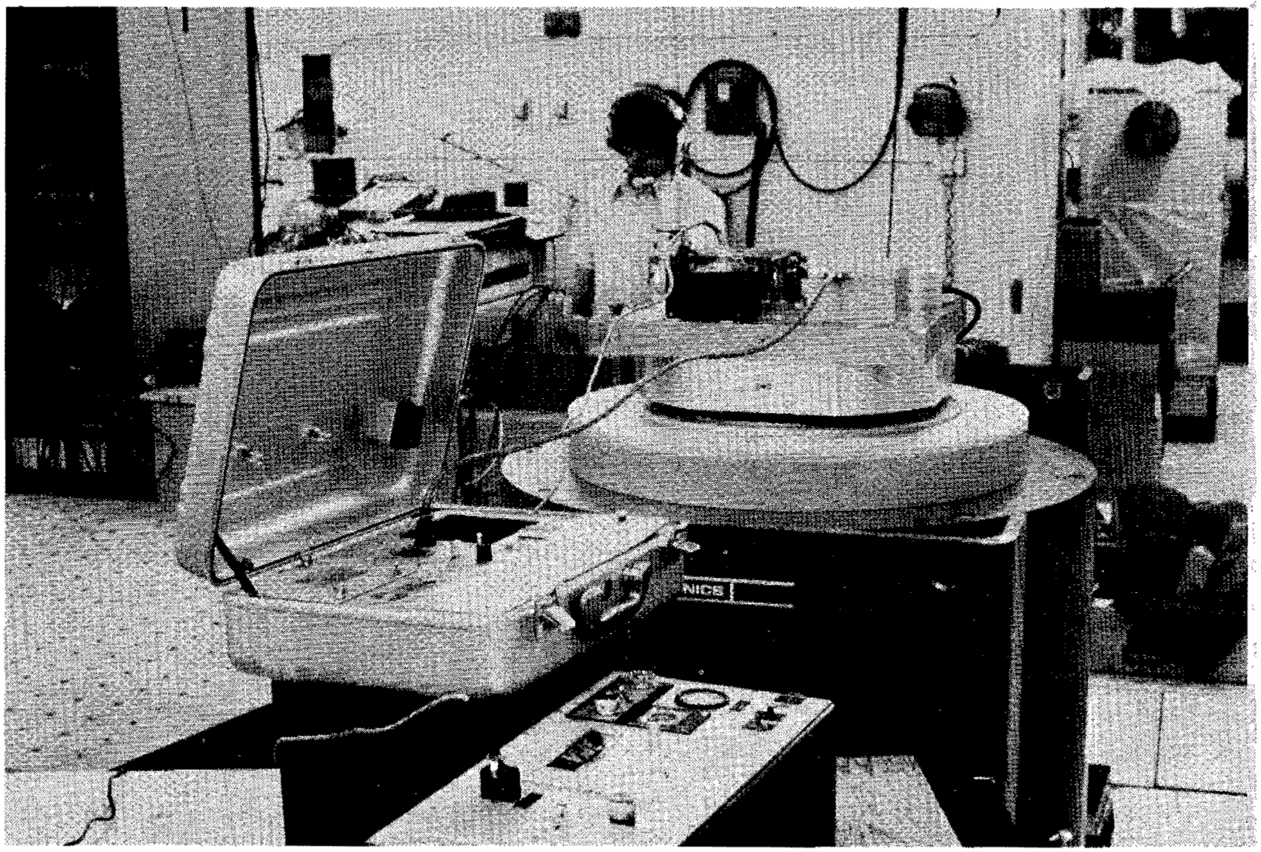

FIGURE 4. - U.S. Naval Research Laboratory shaker system.

packages in the same manner as the Bureau of Mines system, and over the same frequency ranges, except 100 Hz was used as the upper frequency limit, compared with 250 Hz on the Bureau of Mines system. The commercial seismographs were also tested in the same manner.

To calibrate a three-component transducer package, the package was first attached to the shaker by a fast-setting epoxy, as were a standard accelerometer (B & K 4370) and a triaxial accelerometer which measured the crosstalk in the shaker and the horizontal table. The outputs of the transducers and the accelerometers were recorded on a light-beam oscillograph. The signal generator supplied the excitation at the desired frequencies, and the output was recorded at each frequency. The table vibration level was set on an oscilloscope, with the standard accelerometer as a reference. A calibration signal was fed into each output channel immediately after each calibration run, and the output was recorded on the oscillograph. The AC-RMS voltage of the calibration signal was measured to four decimal places with an accurate digital volt-ohm meter, traceable to NBS. The table velocity could be calculated from these values, as could the sensitivity and velocity of the transducer being calibrated. If the tested package was part of a commercial seismograph unit, the output of the whole system was used. Calibration and measurement at low-frequency vibrations required lowering the peak particle velocity below 1 in/sec when the calibration frequency used was below the stated -3-dB frequency of the geophone used. This was done to stay within the peak-to-peak (p-p) displacement limits of the transducers.

When calibrating commercial seismographs or seismometers, care also had to be taken that the steady-state response of the signal-conditioning electronics did not produce an erroneous output. For instance, the Sinco S-4, which has a digital vector sum signal-conditioning process, produces inaccurate results if subjected to steady-state vibrations for over 1 or 2 sec. A short burst of the desired frequency had to be fed into the shaker excitation system to produce accurate results.

FIELD PROCEDURES

The data used for this study were taken from over 200 sets of blast-induced ground and structure vibrations recorded at 20 surface coal mines, 9 quarries, and 3 construction sites. The coal mines are in Ohio, Virginia, Illinois, Indiana, and Kentucky; the quarries are in Alabama, Illinois, Texas, Wisconsin, and Minnesota, and the construction sites are in Washington. These sites represent various geological and topographic conditions with a variety of blasting techniques and thus provide a cross section of vibration characteristics. Most of the data (appendix B) were collected in cooperation with Bureau of Mines studies of the effects of ground vibration and airblast on structures.

Two portable Lockheed 7 channel FM tape recorders with built-in amplifiers were used with the Bureau recording system developed in 1970 (22). Frequency spectra of ground vibration signals were obtained by playing back the recorded signals through a Nicollet Scientific model UA-500A Spectrum Analyzer.

The ground vibration transducers tested by the Bureau are presented in table 2. Mark Products and Geo Space transducers are common in commercial seismographs, whereas the MB-120, MB-124, and accelerometer velocity systems are used for more specialized applications, such as low-frequency studies or machinery noise analysis. An MB-120 transducer with a commercially sealed triaxial box is shown in figure A-19. Similar boxes were buried for nearly every shot monitored. Figure A-22 shows Geo Space model HS-1 with transducers mounted in an aluminum box and in a tree arrangement, along with the triaxial VLF-LP-3D. The VLF was used when low-frequency and low-amplitude vibrations were expected. Figure A-25 shows Mark Products models L-1B and L-15B transducers, with 3 L-15B gages mounted in an aluminum box.

TABLE 2. - Specifications of commercial velocity transducers tested

Transducer company and model	Transducer natural frequency, Hz	Damping, percent	Coil resistance, ohms	Maximum excursion P-P, in	Sensitivity, volt/in/sec, peak	System frequency range, Hz	Weight, oz	Size, in
Mark Products, Inc.:								
L-15B.	4.5	60	24	0.08	0.24	4.5- 150	5.3	1.25 diam, 1.28 high.
L-1B.	4.5	40	125	.0625	.75	4.5- 150	13.25	2.38 diam, 1.5 high.
Geo Space Corp.:								
VLF-LP-3D.	8.0	100	4,000	.10	4.5	0.8- 400	78	5.25 diam, 5.0 high.
HS-1.	4.5	27	215	.07	.35	4.5- 500	9.3	1.63 diam, 1.82 high.
Vibra-Metrics, Inc.:								
MB-124.	4.75	65	650	.350	.0963	8.0-2,000	10.3	2.16 by 1.59 by 1.44
MB-120.	2.50	65	650	.350	.0963	4.0- 500	10.3	2.16 by 1.59 by 1.44
Unholtz-Dickie Corp.:								
1000PA accelerometer.[1]	>10,000	NA	NA	NA	Variable .01 v/in sec-100 v/in sec	0.5-1,000[3]	3.8	2.25 by 1.0 by 1.0
Brüel and Kjær:								
4370 accelerometer.[2]	18,000	NA	NA	NA	Variable .254 mv/in sec-2.54 v/ips	1.0-1,000[3]	1.9	.8 diam, .85 high.
4321 triaxial accelerometer.[2]	40,000	NA	NA	NA	.254 mv/in sec-2.54 v/in sec[1]	1.0-1,000[3]	1.9	1.05 by 1.05, .67 high.

NA Not applicable.
[1]Velocity output with 2216II signal conditioner.
[2]Velocity output with 2635 charge amplifier.
[3]Variable high-frequency cutoff.

Accelerometer velocity-measurement systems primarily recorded structure vibrations but were periodically mounted in an aluminum box and buried as a comparison with conventional ground vibration transducers. None of the commercial systems tested use accelerometers as transducers. Figure A-28 shows the Unholtz-Dickie and Brüel and Kjær accelerometer integrator systems.

The instrumentation set up for a production shot was almost always near residential structures that were relatively close to the blasting operation. To instrument a measurement site, the following procedures were usually followed:

1. A triaxial box containing three velocity gages was buried near the corner of the structure. The axes of the box and structure were alined in most cases. The aluminum box was designed to match the density of soil, to insure good coupling with the ground.

2. Another triaxial box was set on the surface, with axes alined the same way as the axes of the buried box. Tests were run with the surface box on concrete, sandbagged on concrete, directly on and sandbagged on the soil surface, and spiked or anchored to manufacturers' recommendations. These comparisons determined the effects of transducer placement on the measured ground vibration waveforms. Buried tests were also performed for comparisons among all types of transducers. The direct-readout seismometers, both peak and vector sum display models, were tested in both surface and buried conditions and correlated with the individual ground vibration component measurements. This was accomplished for the vector-sum units by electronically summing the individual vibration components from the FM recorder.

RESULTS

Calibration Results

The linear range of the transducers defined by ±3-dB-frequency points corresponds to frequencies where the sensitivity drops to 0.707 of the average value. The average value of transducers is difficult to determine as no standard procedure has been developed. If we follow accelerometer calibration techniques, a straight-line fit to the data is applied over a frequency range when the data are minus rolloff or resonant effects. The value determined at a specific frequency, that is, 100 Hz, is the average sensitivity. Following this approach, the average value of the transducers at 20 Hz was chosen; results are listed in table 3, and data are listed in table B-2. The results show the error of the calibration and experimental procedure as being within ±1.5 dB with a 95-pct confidence level. Steady-state sensitivities for 5 Hz and 90 Hz agree, within 10 pct, to transient shot response with the same predominant frequencies, as shown in table 3. The transducer responses to these shots with representative spectra are shown in figures 5 and 6, with corresponding amplitudes based on nominal sensitivities. Although the waveform and spectrum measured by different transducers are virtually identical, the peak values can differ by over 20 pct owing to the rolloff characteristics of the transducer when frequencies are present at or near the -3-dB point.

TABLE 3. - Transducer-calibrated sensitivities

(Sensitivity, v/in/sec)

Transducer	Nominal	Direction	Calibrated value at 20 Hz	5 Hz		≈ 100 Hz	
				Steady-state	transient	Steady-state	transient
MB-120	0.0963	H	0.0998	0.097	0.099	0.102	0.100
		V	.0948	.095	.105	.105	.098
MB-124	.0963	H	.0980	.077	.079	.095	.096
		V	.0962	.073	.076	.099	.092
Geo Space HS-1	.350	H	.344	.286	.312	.359	.371
		V	.373	.273	.251	.373	.369
Geo Space VLF-LP-3D	4.5	H_1	4.43	4.39	4.23	4.60	4.61
		H_2	4.19	4.32	4.31	4.31	4.27
		V	4.35	4.33	4.28	4.42	4.57
Mark Products L-15B	.240	H	.228	.215	.222	.233	.238
		V	.227	.236	.228	.208	.215
Mark L-1B	.750	H	.768	.85	.91	.75	.78
		V	.794	.87	.90	.80	.84
Unholtz-Dickie 1000PA	1.00	H	1.06	.99	.97	[1].110	[1].114
		V	1.03	1.02	1.03	[1].350	[1].350

H Sensitivity of horizontal transducers.
V Sensitivity of vertical transducers.
[1]Instrument sensitivity changed to 0.100 and 0.333, respectively.

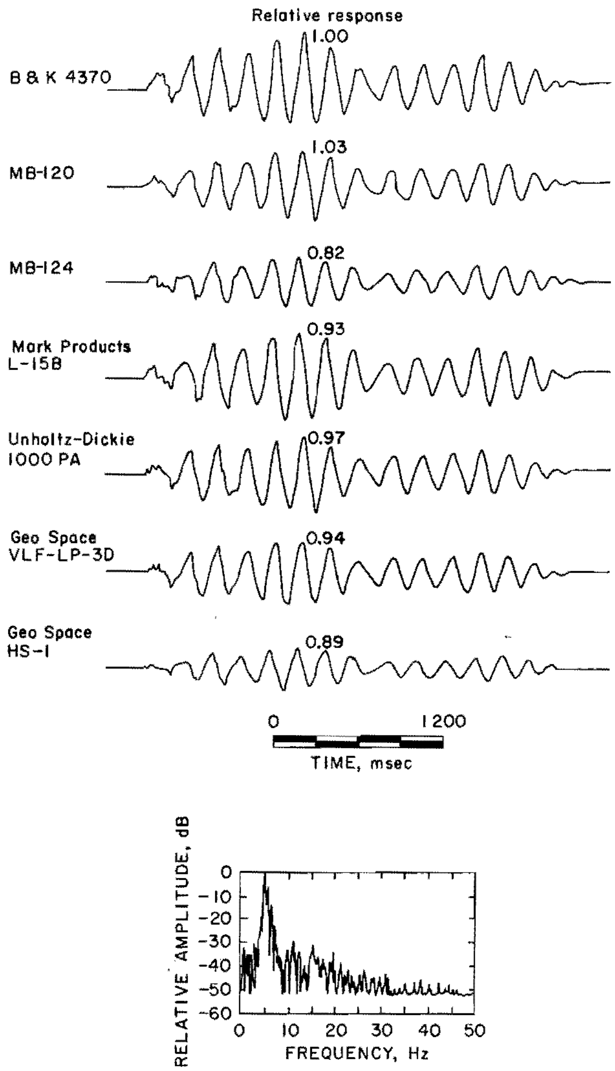

FIGURE 5. - Transient 5-Hz transducer response.

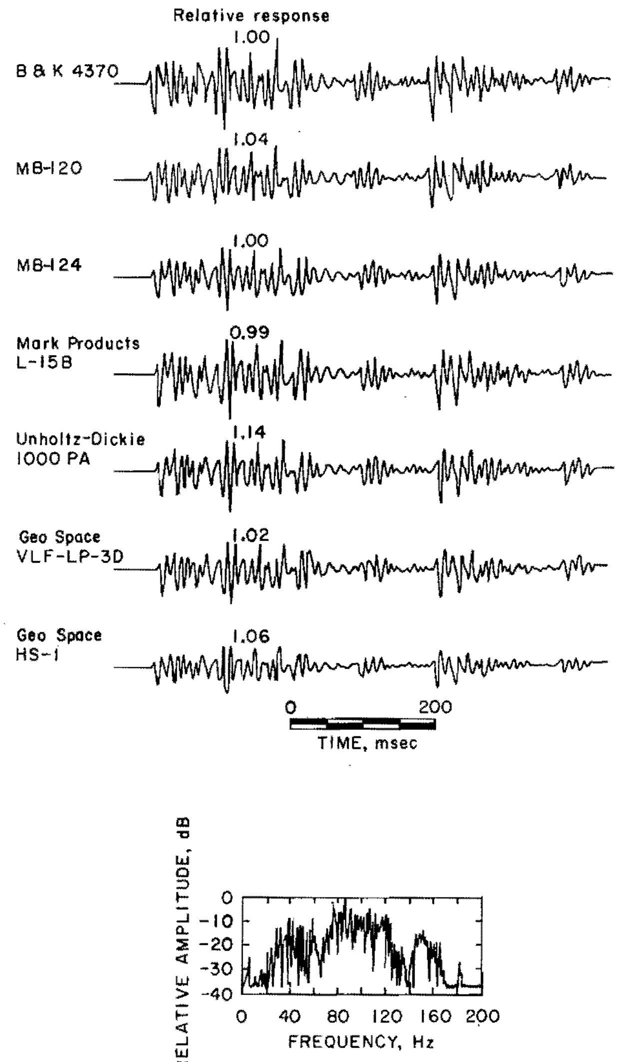

FIGURE 6. - Transient 90-Hz transducer response.

Commercial systems ±3-dB frequencies can be read directly off the curves at frequencies where the normalized response (instrument response divided by shake table input) is down to 0.707, or above 1.414. A straight-line fit of the data above the influence of rolloff characteristics displays a precision of ±1.5 dB about the average normalized response. Except for the Sprengnether VS-1100, seismograph responses are all within the manufacturers ±3-dB limits with less than 5-pct crosstalk. The horizontal components exhibited a resonant frequency at 50 Hz, resulting in crosstalk of up to 100 pct.

Ground Vibration Characterization

Generally, coal mine blasts were characterized by large blasthole diameters (8 to 15 inches) with relatively thick overburden. Quarry blasts generally had smaller blasthole diameters (3 to 6 inches) and smaller charge weights. Shot durations for both coal and quarry blasts ranged from 0.5 sec to about 3 sec, with the majority of shots in the 0.5- to 1 sec range.

Construction blasting was usually characterized by small-diameter holes (1 to 3 inches) and very small charge weights. The distances to structures were also much shorter, down to 5 ft in one case. This accounts for the higher frequency content of construction blasting because at longer distances the lower frequencies are predominant. Shot duration for construction blasts was nearly always less than 1 sec.

Figures 7, 8, and 9 are typical three-component, ground vibration recordings, and their frequency spectra from surface coal mine, quarry, and construction blasts, respectively. All three sets of recordings were taken from a buried MB-120 triaxial box. Of principal importance are the frequency ranges and durations of each of the three types of blast. Frequency histograms, combining the triaxial readings of all the recorded quarry and construction shots and a representative sample of the coal shots, are presented in figures 10 and 11. The predominant frequencies and the range of frequencies (table B-1) 20 dB down (1/10) from the predominant frequency spectral amplitudes

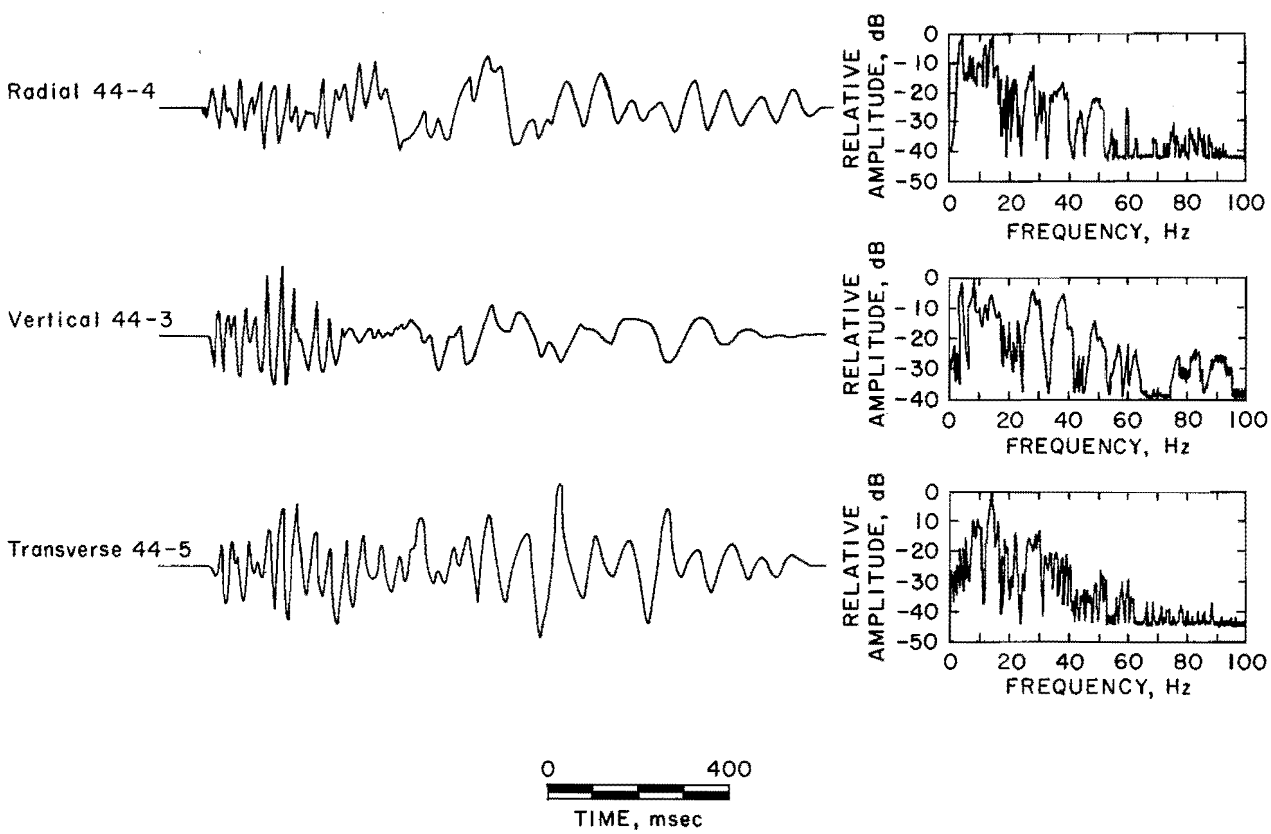

FIGURE 7. - Typical coal mine blast vibration time histories.

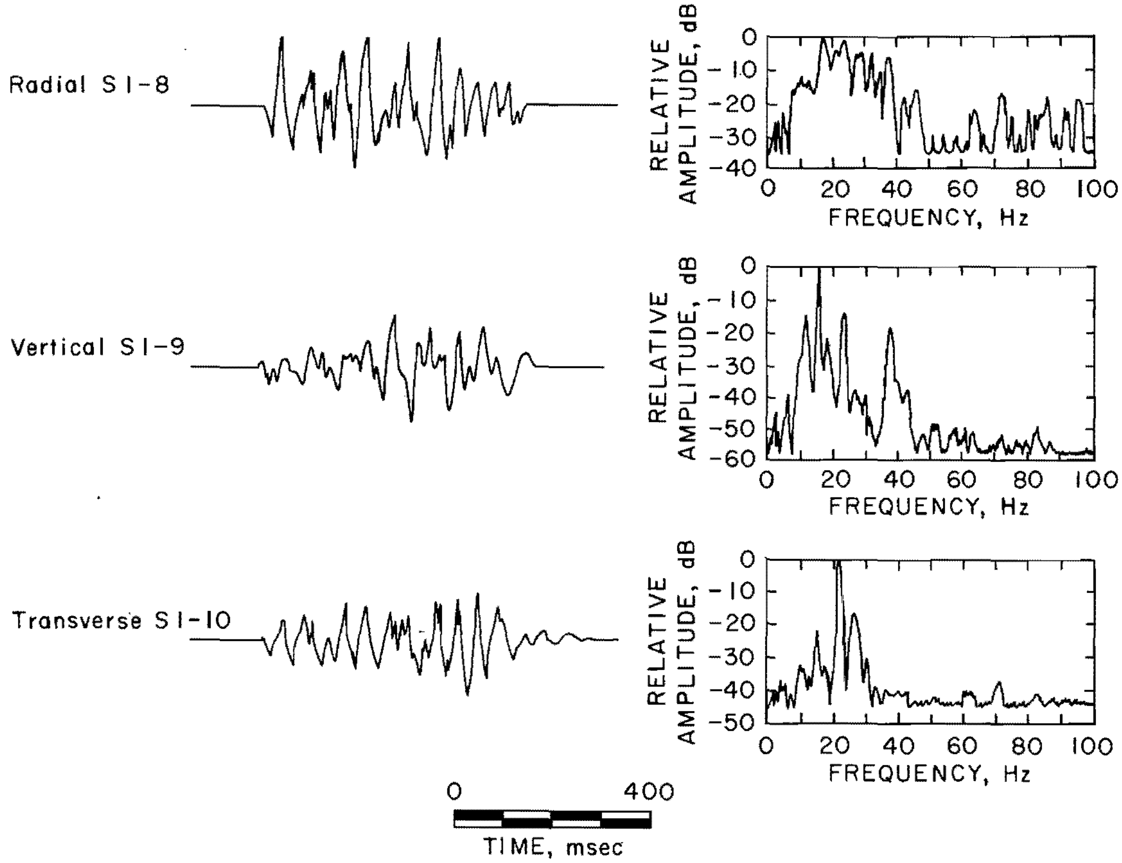

FIGURE 8. - Typical quarry blast vibration time histories.

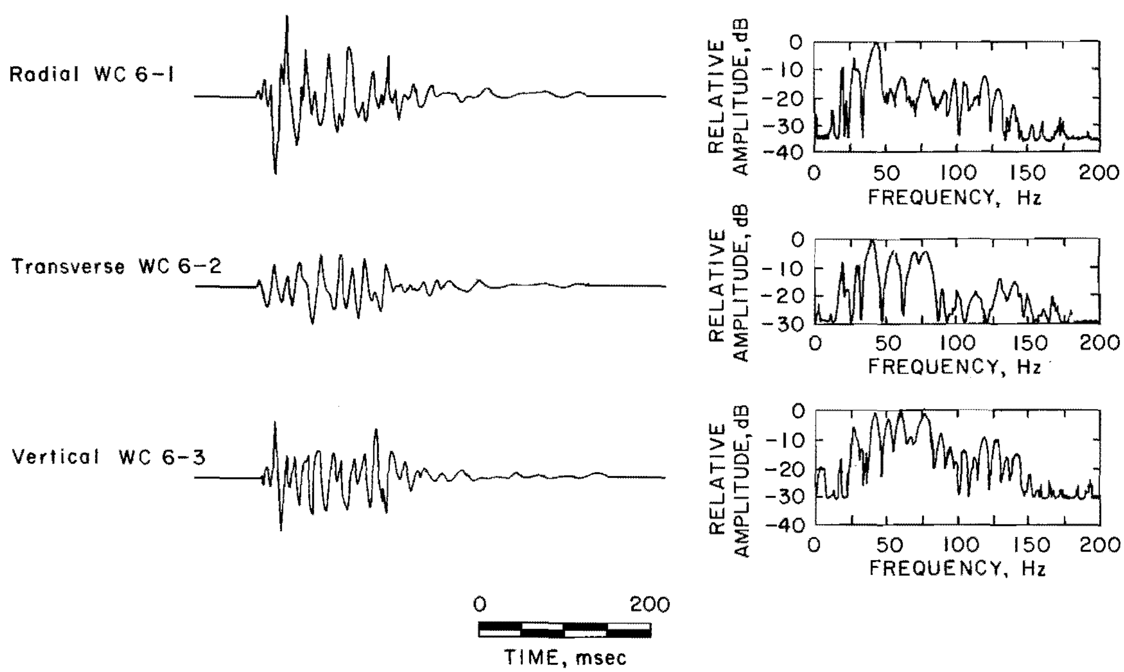

FIGURE 9. - Typical construction blast vibration time histories.

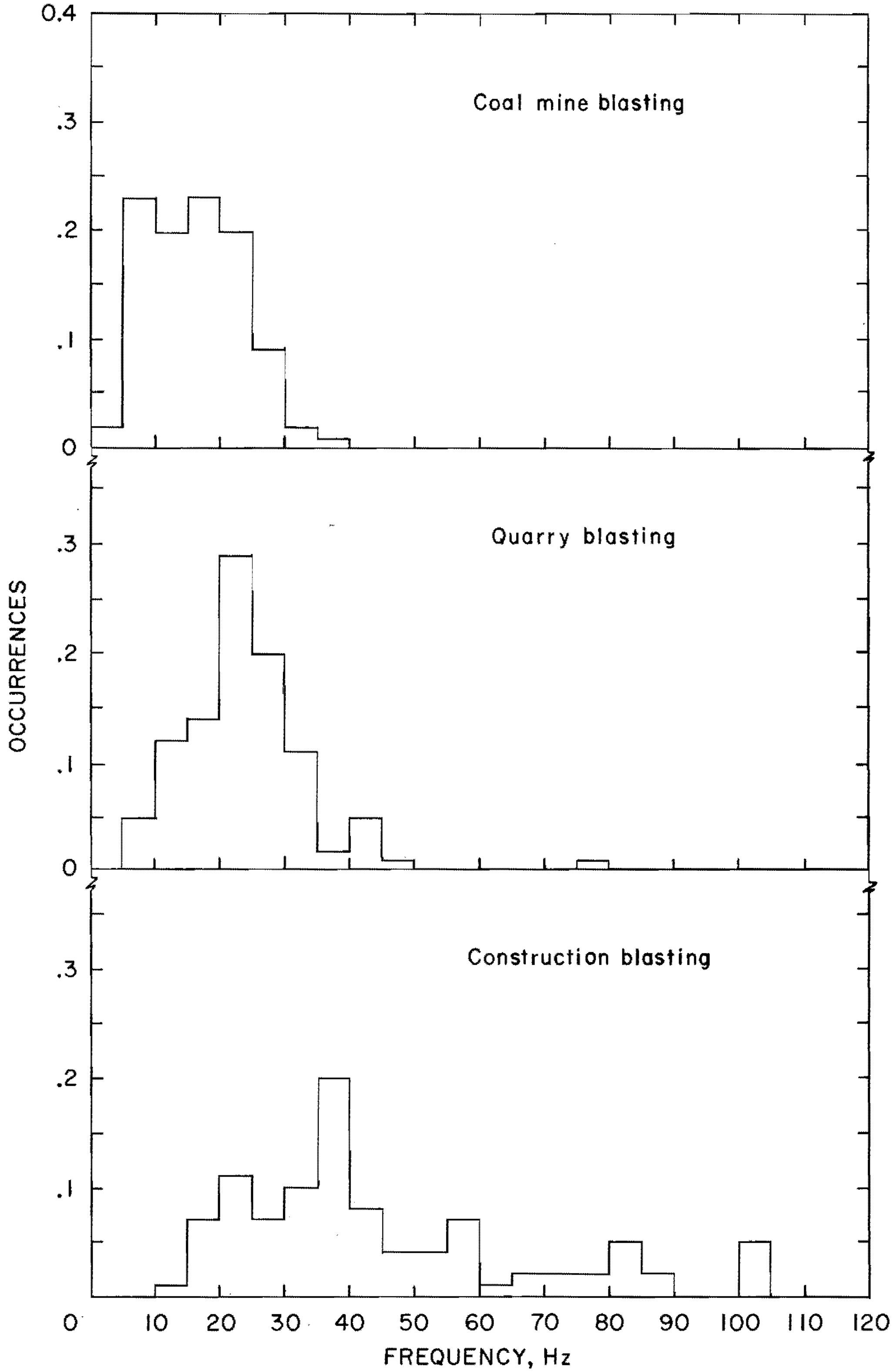

FIGURE 10. - Predominant frequency histogram of coal quarry and construction blasts.

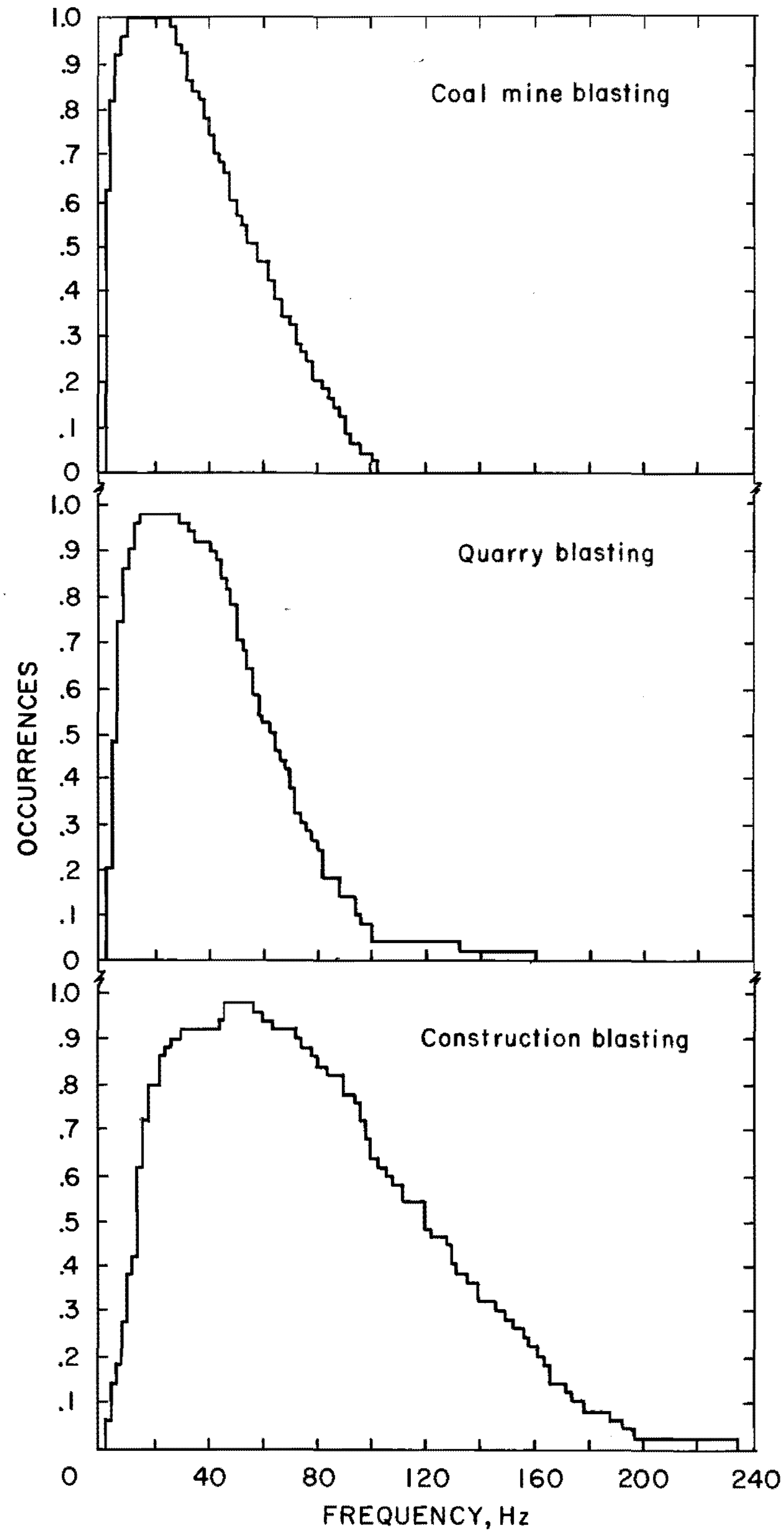

FIGURE 11. - Minus 20-dB-range histogram of coal quarry and construction blasts.

are displayed for each shot type, with the mean and standard deviation values listed in table 4 for normal and log normal distributions.

TABLE 4. - Coal, quarry, and construction predominant frequency normal and log normal distribution points

	Normal distribution, Hz		Log normal distribution, Hz	
	Mean	Standard deviation	Mean	Standard deviation points
Coal................	16.2	±9.2	14.2	8.3, 24.3
Quarry..............	24.0	±19.6	22.0	14.3, 33.9
Construction........	44.8	±26.3	39.5	24.0, 65.3

These shots show the frequencies with measurable energy content range from less than 2 to 105 Hz for coal, 160 Hz for quarry, and 235 Hz for construction blasting. The values that occurred below 2 Hz could not be quantified because of instrument limitations, but they were present nonetheless. Frequency values below 2 Hz occurred for shots that were measured at a long distance and had thick overburden. Additional research is needed to quantify this low-frequency energy and to determine its effects.

Instrumentation capable of accurately measuring signals over the entire frequency range of the incident vibration is desirable for research and analytical purposes. For measurement of peak particle velocities only, at least the frequency range at which significant spectral energy is present should fall within the linear frequency range of the instrumentation used. Predominant frequencies ranged from 2 to 35 Hz for coal, 5 to 80 Hz for quarry, and 5 to 235 Hz for construction. The construction data are from only three varying geological formations. From past reports (13, 18, 20), construction blasting frequencies above 200 Hz have been recorded, but they are not typical of the majority of construction blasts. In addition, a recently completed study (14) analyzed many records of coal, quarry, and construction blasts. The duration of the vibrations was less than 2 sec for coal and quarry blasts and 1 sec for construction blasts. The distribution of the frequency of the radial component's peak amplitude using 4.5 Hz natural frequency transducers was from 3 to 110 Hz for coal, 5 to 130 Hz for quarry, and 5 to 200 Hz for construction.

The peak particle velocity often occurs at a frequency different from the predominant frequency as is shown in figure 7, where the peak frequency is ≈9 Hz. This difference between the predominant frequency and that of the peak amplitude occurs often because the peak amplitude frequency is a combination of many frequencies, and interpretation leads to varying results.

The results of these studies indicate that the recommended linear frequency ranges should extend from 2 to 150 Hz for coal and quarry, and from 5 to 200 Hz for construction.

Instruments with a -3-dB frequency above 2 Hz such as 5 Hz, should be utilized only for events for which past measurements have shown a negligible

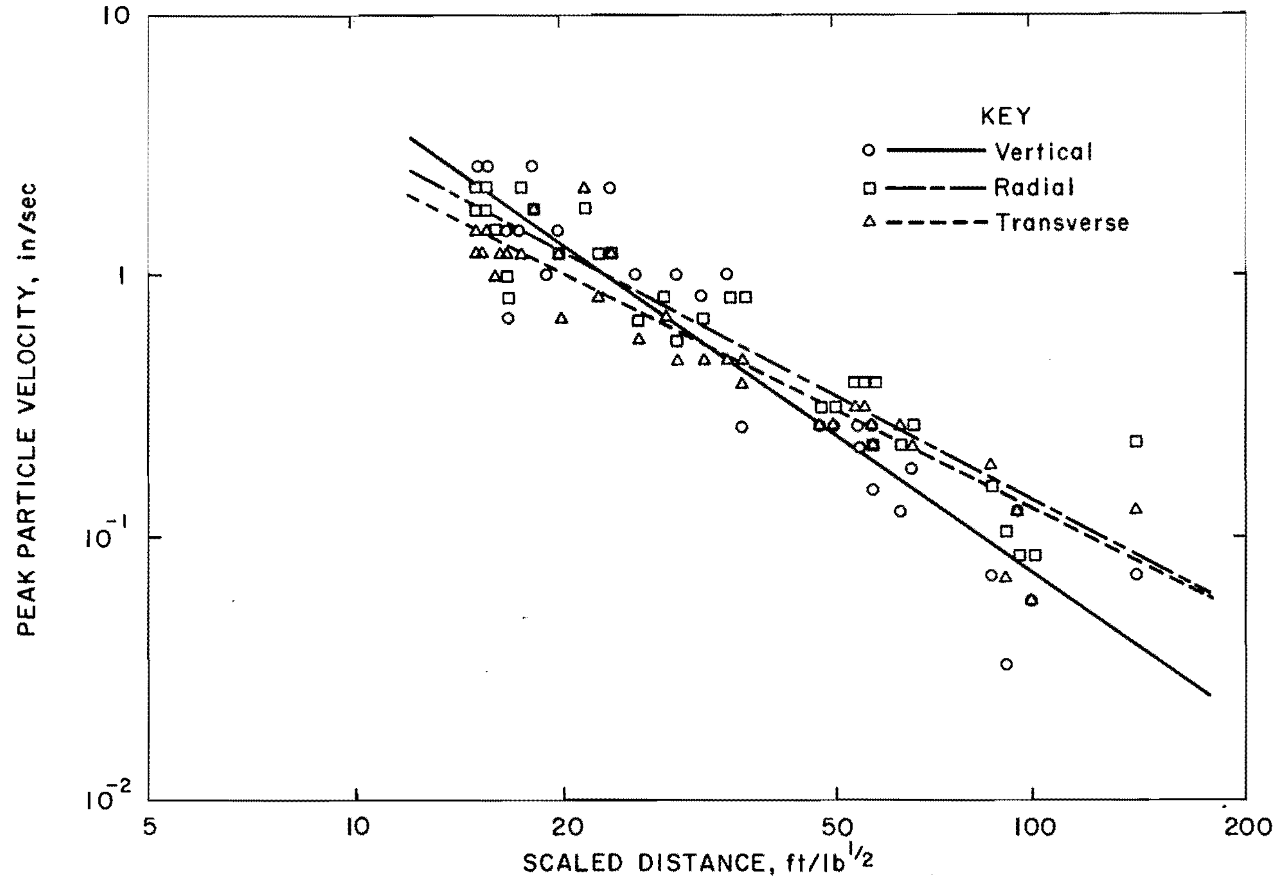

FIGURE 12. - Radial, transverse, and vertical particle velocity versus square root scaled distance.

amount of spectral energy below this value, such as <5 Hz. Measurements made at or below -3-dB cutoff frequency will be attenuated 30 to 100 pct according to the rolloff characteristics of the transducer. Care should be taken to insure proper selection of instrumentation frequency range according to blast design parameters instead of blast classification, as for example, construction blasting using large-diameter blastholes and large charge weights.

Field Comparison Results

Typical plots of radial, transverse, and vertical peak particle velocity versus square root scaled distance (SRSD) for a single mine are presented in figure 12, where $\text{SRSD} = \frac{\text{distance to monitor}}{\sqrt{\text{maximum pounds to explosive/delay}}}$. Although the axes of the monitor were alined with the structure axes, data were taken from records where true radial and transverse conditions existed (table 5). It is noteworthy that no one component dominates; thus the peak value can occur in any one of the three. Further analysis of particle velocity versus scaled distance have been published (14, 28).

TABLE 5. - Particle velocity-scaled distance data, in/sec

Vertical	Radial	Transverse	True vector sum	Pseudo vector sum	Square root scaled distance
0.120	0.25	0.23	0.27	0.36	64.3
.150	.28	.20	.14	.38	58.4
.260	.30	.39	.41	.56	56.3
.280	.21	.36	.40	.50	57.5
.200	.33	.41	.44	.56	55.3
.034	.07	.10	.11	.13	91.1
.240	.26	.29	.30	.46	49.7
.250	.24	.33	.37	.48	50.7
.880	.49	.82	1.13	1.30	37.9
.930	.44	.90	1.10	1.37	35.1
.064	.12	.20	.21	.24	138.5
.850	.51	.62	1.00	1.17	32.7
1.060	.45	.59	1.09	1.29	30.4
.780	.66	.81	1.02	1.30	28.6
.940	.53	.70	1.28	1.29	25.9
.070	.19	.16	.24	.26	85.7
.170	.21	.28	.31	.39	67.1
2.240	1.24	1.24	2.40	2.84	24.4
1.230	.75	1.12	1.78	1.82	22.6
.120	.08	.12	.19	.19	92.6
1.580	.68	1.14	1.73	2.06	20.2
2.570	1.77	1.77	3.25	3.59	18.2
.700	1.14	1.03	1.44	1.69	16.7
.240	.35	.45	.56	.62	36.8
1.65	1.98	1.85	2.77	3.17	22.1
1.48	1.37	1.05	1.69	2.27	16.1
1.91	1.97	1.27	2.12	3.02	15.6
2.21	1.89	1.23	2.21	3.15	15.3
.06	.08	.05	.09	.11	98.4
2.51	1.68	1.53	3.06	3.39	15.4
2.45	1.99	1.60	3.04	3.54	15.7
1.41	.79	1.25	1.71	2.04	17.1
1.35	2.08	1.14	2.27	2.72	17.9
.99	1.22	1.18	1.66	1.96	19.3

Single-component peak particle velocity, true vector sum (TVS), and pseudo vector sum (PVS) values are given in table 5 where TVS, PVS, and peak values were obtained from analysis of the data in figure 12. True vector sum values exceeded the peak value of the three components from 0 to 58 pct. In field use, true vector sum values below a peak criterion level will be in compliance. But compliance will be indeterminate for true vector sum values at or slightly above the peak criterion.

When measuring vibrations from blasting, the triaxial transducer is usually buried, placed on the surface, spiked, or sandbagged. However, previous Bureau studies (5, 9) have shown that for accelerations of 1 g (32.2 ft/sec^2) or greater, ground vibration from blasting cannot be accurately measured by a gage that is loosely placed on the surface, stood or knelt upon, or sandbagged. Burying the density-matched transducer box in soil or bolting it to rock provides a satisfactory gage mount. The field tests confirmed that slippage or rotation of nonanchored, surface-placed transducers occurs at levels as low as 0.2 g, but spiking the gage will preclude slippage up to higher g levels, depending on the coefficient of friction and instrument geometry. Improper coupling of the transducer distorts the waveform, as shown in figure 13, with peak amplitudes often occurring at different times within the event. The resulting peak value varies by up to ±60 pct. The probability of slippage increased with frequency and amplitude; for example, a 1-in/sec blast at 12.3 Hz is 0.2 g, and at 61.5 Hz it is 1.0 g. Surface placement techniques are adequate for low-frequency, low-amplitude levels (less than 1 in/sec at less than 20 Hz). With the higher frequency character of construction blasts, special care should be taken to assure good coupling of the transducer to soil or rock.

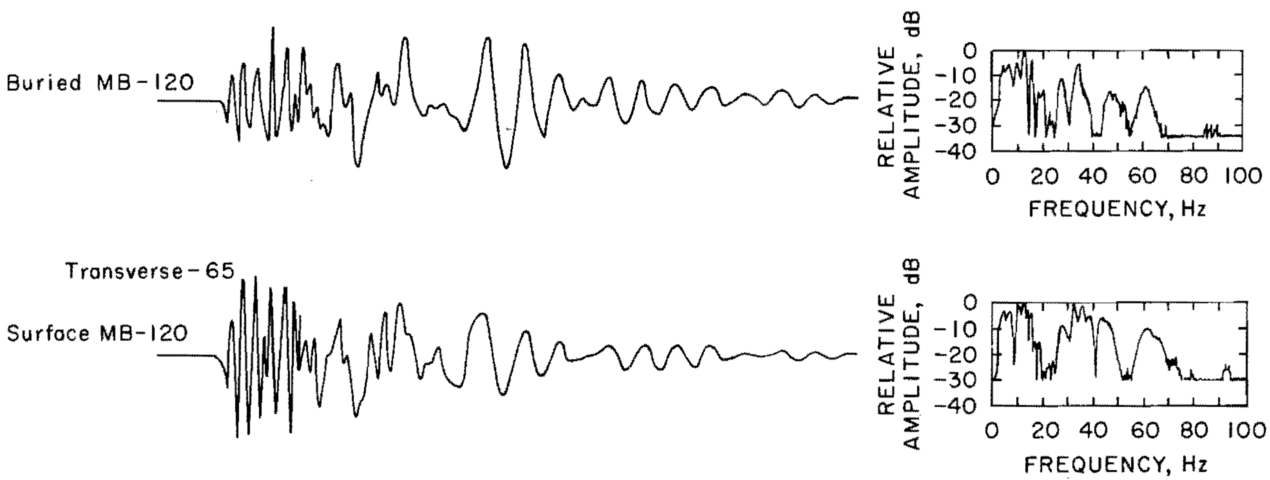

FIGURE 13. - Comparison of buried versus surface-placed transducer time histories.

SELECTION OF A MEASUREMENT SYSTEM

The wide range of instrumentation and support services available offers many choices to an operator choosing a monitoring program. To obtain the desired outcome of the program, however, several factors must be evaluated. For selecting instrumentation, decisions must be made as to the method of data collection and the type of information desired from these data. Vibration data can be collected by recording peak readings or by capturing the entire waveform. Shots can be monitored manually by an operator, or a seismograph can be installed which automatically records all shots that it senses.

For both types of instruments, the working condition of the seismograph can be checked if an internal calibration system is provided. For a quick check in the field to see if the instrument is operating properly, internal calibration is useful, but to determine sensitivity, a shake-table calibration should be performed.

Peak-reading or recording instruments provide only a peak amplitude or peak vector-sum value and contain no information about duration or frequency. When only the peak amplitude levels are of interest, peak-reading instruments provide a quick, easy check of vibration levels with a minimum amount of man-power, because no time is needed to analyze waveforms. Yet for peak-recording instruments that are used as long-term monitors, identification of the peak value may be difficult when outside factors (radio interference, nonblast events) occur within a few minutes of the blast. Timing inaccuracies between blast logs and instrument records complicate, or make impossible, identification of the peak associated with the blast when multiple events are recorded near the time of the blast. Examination of the waveform would determine, in most cases, if outside interference did occur.

In addition, recording the entire waveform is by far the more versatile method because information pertaining to frequency, duration, and amplitude can be obtained. The waveform-recording equipment, however, is more expensive than the peak-recording equipment; and the waveforms must be analyzed either by the operator or by professional services.

CONCLUSIONS

The frequency ranges of the vibrations were found to extend from below 2 Hz to 150 Hz for coal mine and quarry blasting, and from below 5 Hz to above 200 Hz for construction blasting. Blast vibration energy below 2 Hz were present, but amount and significance were indeterminate because of limitations in measurement and analysis systems. The spectral amount of energy measured above 200 Hz was negligible, but special cases have been reported of higher frequency blasts (13, 20). A velocity instrument encompassing a frequency range of from 1 Hz or below to 500 Hz would cover the frequency range of vibrations generated from surface blasting. Instrumentation frequency ranges of 2 to 150 Hz for coal mine and quarry blasting and 5 to 200 Hz for construction and excavation blasting would be adequate for the majority of blasts monitored. Special cases may require extending the frequency range to cover nontypical events such as a large construction shot of a road cut in an area with nearby homes resting on soil overburden.

All the instruments tested except one fell within the manufacturers' stated accuracy limits of ±3 dB (+41 pct, -29 pct). Only one instrument of each type was tested, limiting the conclusions that could be drawn about specific models. Instruments that have a -3-dB frequency above 2 Hz should be utilized only for events for which past measurements have shown a negligible amount of spectral energy at or below the -3-dB point of the instrument. An instrument with a -3-dB frequency at 5 Hz would be adequate to monitor vibrations from a particular site that had demonstrated negligible spectral energy below 5 Hz. Measurements made of events with frequencies at or below the -3-dB point of the instruments would cause attenuation of these frequency components from 30 to 100 pct according to the rolloff characteristics of the instruments.

Waveform recordings of all three ground vibration components are recommended as the peak amplitude and frequency may vary among the three. Peak or vector sum readings are adequate if only amplitude levels are desired. Vector sum values exceeded the peak value of the three components from zero to 60 pct, confirming compliance at levels below a peak criterion. Compliance would be indeterminate from vector sum values equal to or slightly above the peak criterion.

Loose surface placement of transducer packages should be avoided if acceleration levels of over 0.2 g are expected. Slippage can occur at this level, and the transducer package should be anchored. Ground spikes can be effective at higher g levels, but above 1 g, the transducer package should be buried with the soil compacted around it, or if burial is not possible, it should be very firmly anchored, such as by gluing or bolting. To insure proper coupling when buried, the density of transducer packages should be close to the average density of soil, about 100 to 150 lb/cu ft.

REFERENCES

1. Bycroft, G. N. The Magnification Caused by Partial Resonance of the Foundation of a Ground Vibration Detector. Trans. Am. Geophys. Union, v. 38, No. 6, December 1957, pp. 928-931.

2. Crandell, F. J. Ground Vibration Due to Blasting and Its Effect Upon Structures. J. Boston Soc. Civil Eng., April 1949, pp. 222-245.

3. Dowding, C. H. Response of Buildings to Ground Vibrations Resulting From Construction Blasting. Ph.D. Thesis, Univ. Ill., Urbana, Ill., 1971, 204 pp.

4. Duvall, W. I. Design Criteria for Portable Seismographs. BuMines RI 5708, 1961, 6 pp.

5. _____. Design Requirements for Instrumentation To Record Vibrations Produced by Blasting. BuMines RI 6487, 1964, 7 pp.

6. Duvall, W. I., and D. E. Fogelson. Review of Criteria for Estimating Damage to Residences From Blasting Vibrations. BuMines RI 5968, 1962, 19 pp.

7. Dvorak, A. Seismic Effects of Blasting on Brick Houses. Prace geofyrikeniha ustance Ceskoslovenski Akademie Ved. No. 169. Geofys. Sb. (Prague), 1962, pp. 189-202.

8. Edwards, A. T., and T. D. Northwood. Experimental Studies of the Effects of Blasting on Structures. Engineer, v. 210, Sept. 30, 1960, pp. 538-546.

9. Fogelson, D. E., and C. F. Johnson. Calibration Studies of Three Portable Seismographs. BuMines RI 6009, 1962, 21 pp.

10. Gutowski, T. G., L. E. Witting, and C. L. Dym. Some Aspects of the Ground Vibration Problem. Noise Control Eng., v. 10, No. 3, May-June 1978, pp. 94-100.

11. Johnson, C. F. Coupling Small Vibration Gages to Soil. Earthquake Notes, v. 33, September 1962, pp. 40-47.

12. Kamperman, G. W., and M. A. Nicholson. The Transfer Function of Quarry Blast Noise and Vibration Into Typical Residential Structures. Kamperman Associates, Inc., Final Report EPA 550/9-77-351, February 1977, 43 pp.

13. Langefors, U., B. Kihlstrom, and H. Westerberg. Ground Vibrations in Blasting. Water Power, February 1958, pp. 335-338, 390-395, 421-424.

14. Lucole, S. W., and C. H. Dowding. Statistical Analysis of Blast Emission Records From Quarrying, Mining and Construction Operations in the State of Illinois. Report to Illinois Institute of Natural Resources, Document No. 79/02, Project 30.0113, January 1979, 200 pp.

15. Mark Products, Inc. Geophone General Information. Mark Products, Inc., Houston, Tex.

16. Mederis, K. The Development of Rational Damage Criteria for Low-Rise Structures Subjected to Blasting Vibrations. Kenneth Mederis Associates, Final Report prepared under contract to National Crushed Stone Association, Washington, D.C., August 1976, 93 pp.

17. Meyer, A. V. C., and W. I. Duvall. Calibration Study of a Peak-Reading Accelerograph. BuMines RI 6026, 1962, 6 pp.

18. Nichols, H. R., C. F. Johnson, and W. I. Duvall. Blasting Vibrations and Their Effects on Structures. BuMines Bull. 656, 1971, 106 pp.

19. Northwood, T. D., R. Crawford, and A. T. Edwards. Blasting Vibrations and Building Damage. Engineer, v. 215, May 31, 1963, pp. 973-978.

20. Olson, J. J., R. A. Dick, D. E. Fogelson, and L. R. Fletcher. Mine Roof Vibrations From Production Blasts, Shullsburg Mine, Shullsburg, Wis. BuMines RI 7462, 1970, 35 pp.

21. Rockwell, E. H. Vibrations Caused by Quarry Blasting and Their Effect on Structures. Rock Prod., v. 30, 1928, pp. 58-61.

22. Siskind, D. E., and V. J. Stachura. Recording System for Blast Noise Measurement. Sound and Vibration, v. 11, No. 6, June 1977, pp. 20-23.

23. Siskind, D. E., M. S. Stagg, J. W. Kopp, and C. H. Dowding. Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting. BuMines RI 8507 (in press).

24. Skipp, B. O. Ground Vibration Instrumentation--A General View. Instrumentation for Ground Vibration and Earthquakes. Proc. Conf. for Earthquake & Civil Eng. Dynamics, Keele University, Staffordshite, England, Paper 2, July 4, 1977, pp. 11-34.

25. Theonen, J. R., and S. L. Windes. Seismic Effects of Quarry Blasting. BuMines Bull. 442, 1942, 83 pp.

26. Wall, J. F., Jr. Seismic-Induced Architectural Damage to Masonry Structures at Mercury, Nevada. Bull. Seismolog. Soc. America, v. 57, No. 5, October 1967, pp. 991-1007.

27. Washburn, H., and H. Wiley. The Effect of the Placement of a Seismometer of Its Response Characteristics. Geophysics, v. 6, 1941, pp. 116-131.

28. Wiss, J. F., and P. W. Linehan. Control of Vibration and Blast Noise From Surface Coal Mining. May 1978, vols. 1-3. BuMines Open File Rept. 103(1)-(4)-79(set), December 1978, 1119 pp.; Contract No. J0255022; available for consultation at Bureau of Mines facilities in Denver, Colo., Twin Cities, Minn., Pittsburgh, Pa., and Spokane, Wash.; U.S. Department of Energy facilities in Carbondale, Ill., and Morgantown, W. Va.; National Mine Health and Safety Academy, Beckley, W. Va.; and the National Library of Natural Resources, U.S. Department of the Interior, Washington, D.C.; and from National Technical Information Service, Springfield, Va., PB 299 886/AS (set).

APPENDIX A.--INSTRUMENTATION AND RESPONSE CURVES

FIGURE A-1. - Dallas Instruments, Inc., model VS-3 blast monitor.

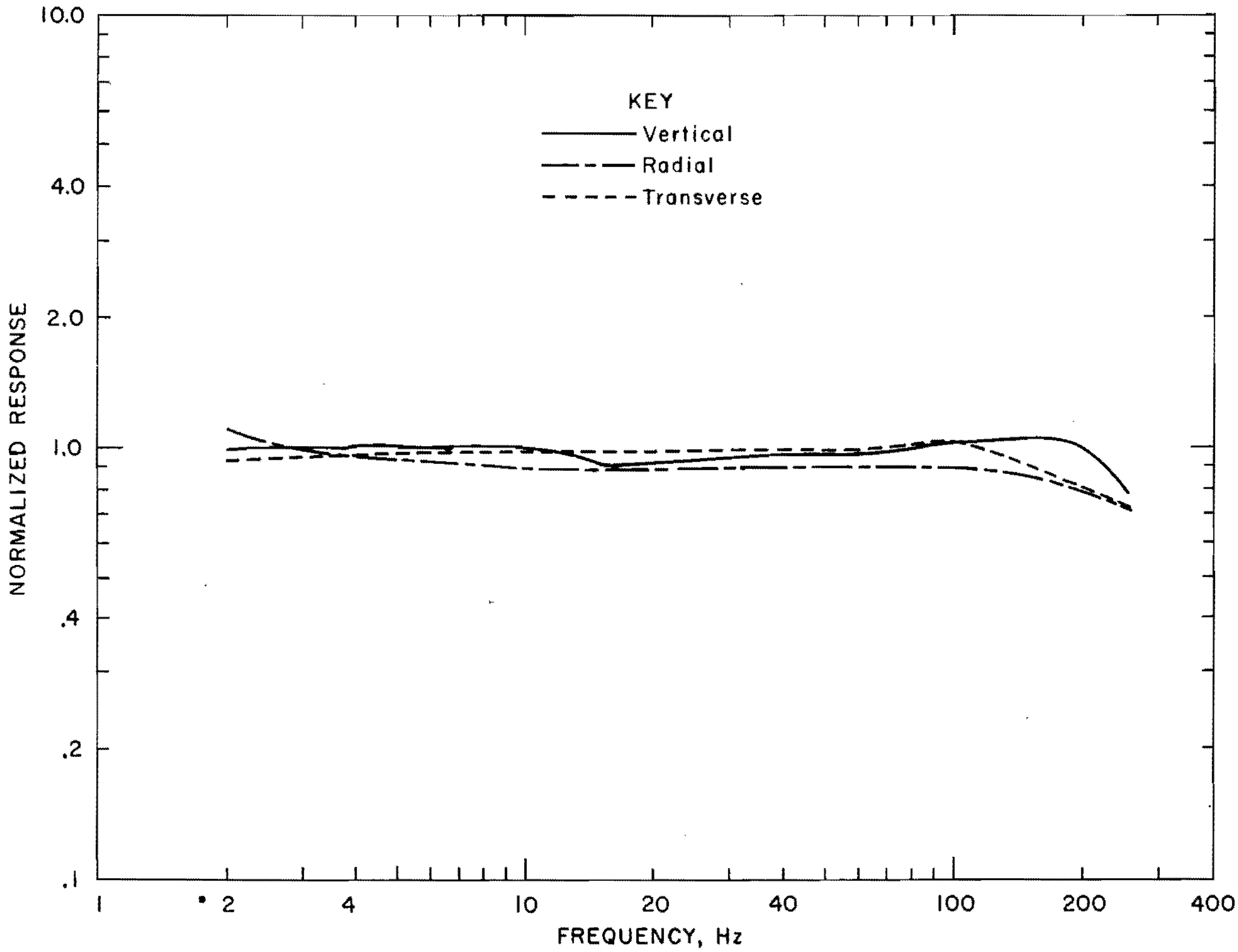

FIGURE A-2. - Dallas Instruments, Inc., model VS-3 normalized response versus frequency.

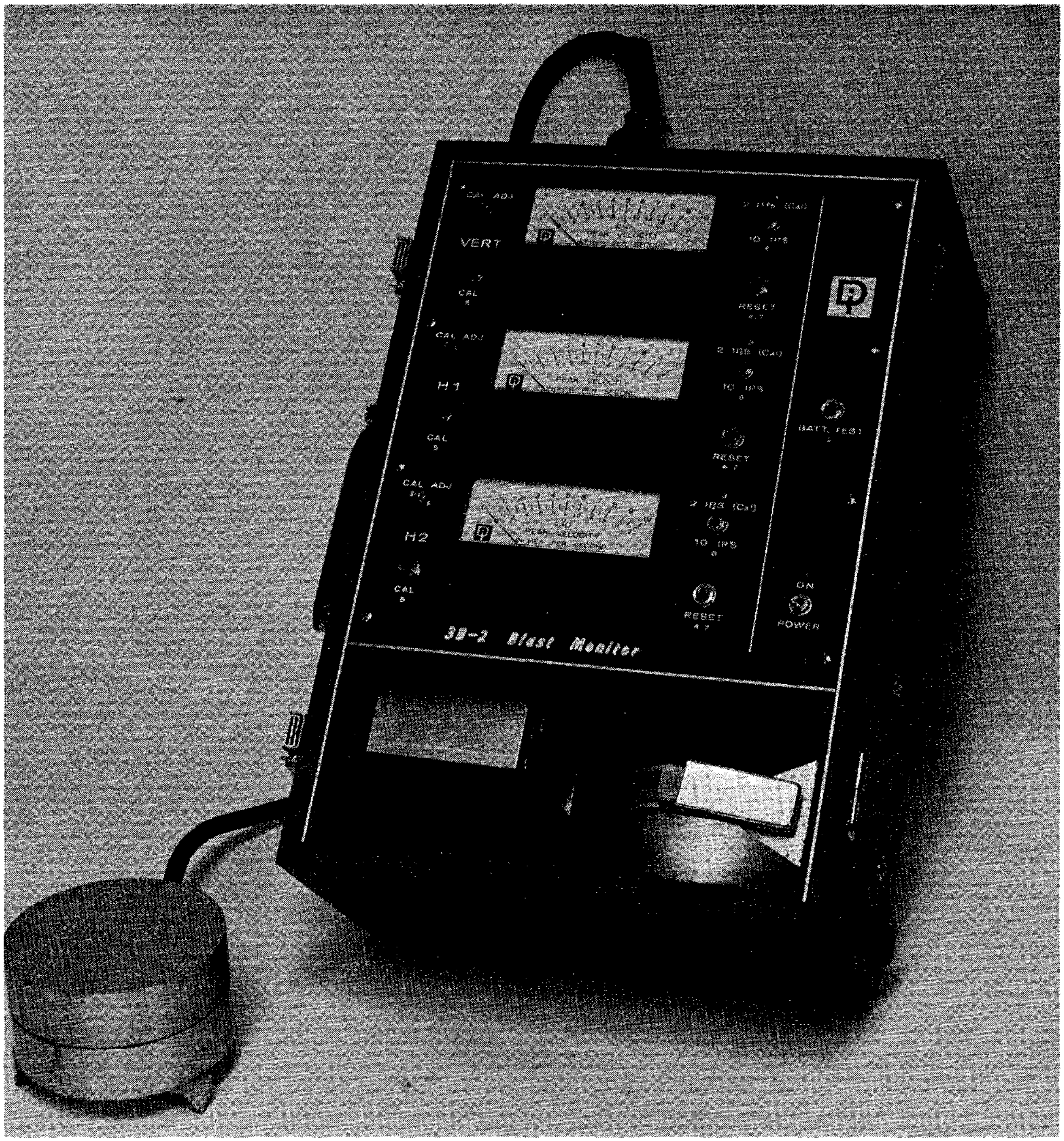

FIGURE A-3. - Dallas Instruments, Inc., model 3B-2 blast monitor.

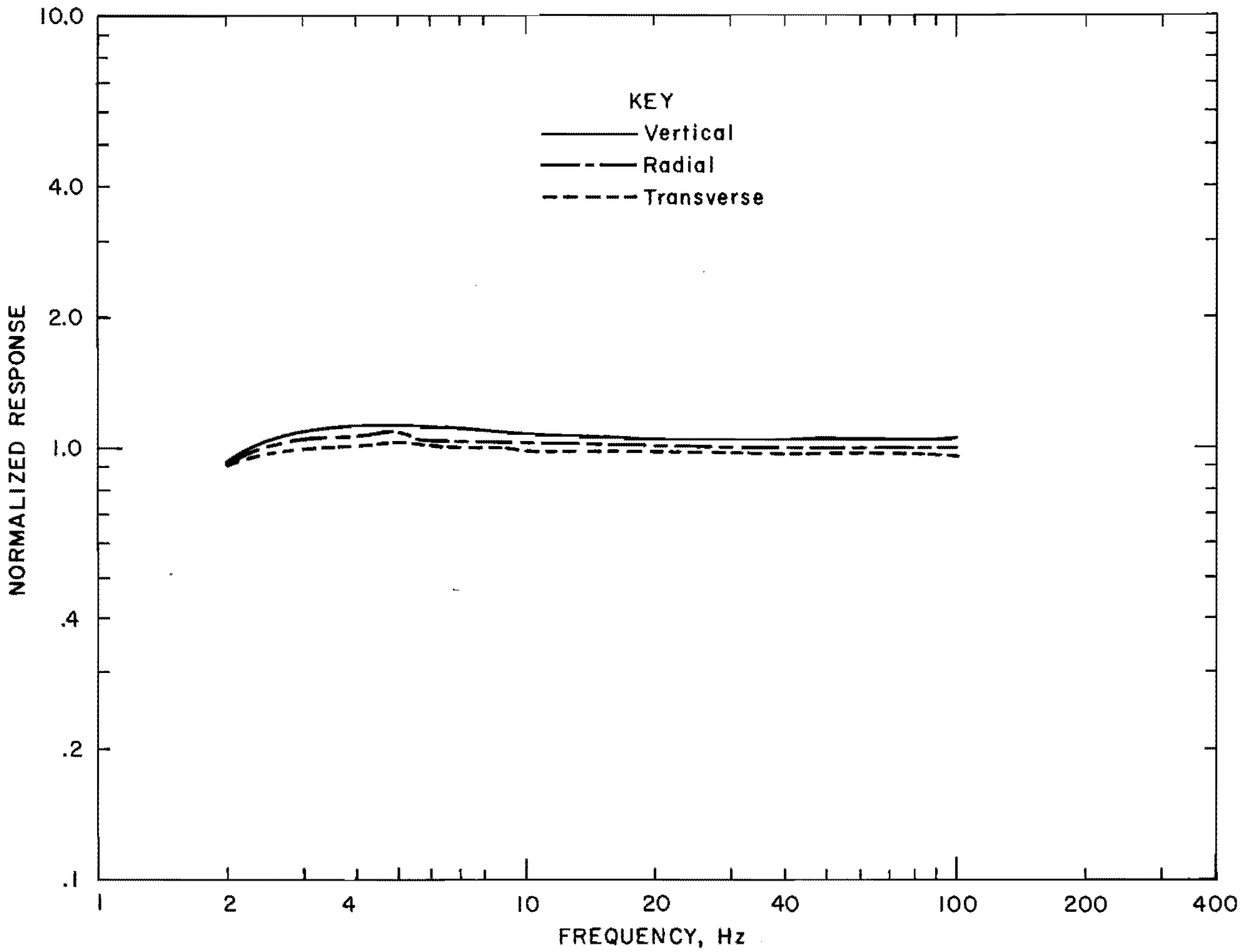

FIGURE A-4. - Dallas Instruments, Inc., model 3B-2 normalized response versus frequency.

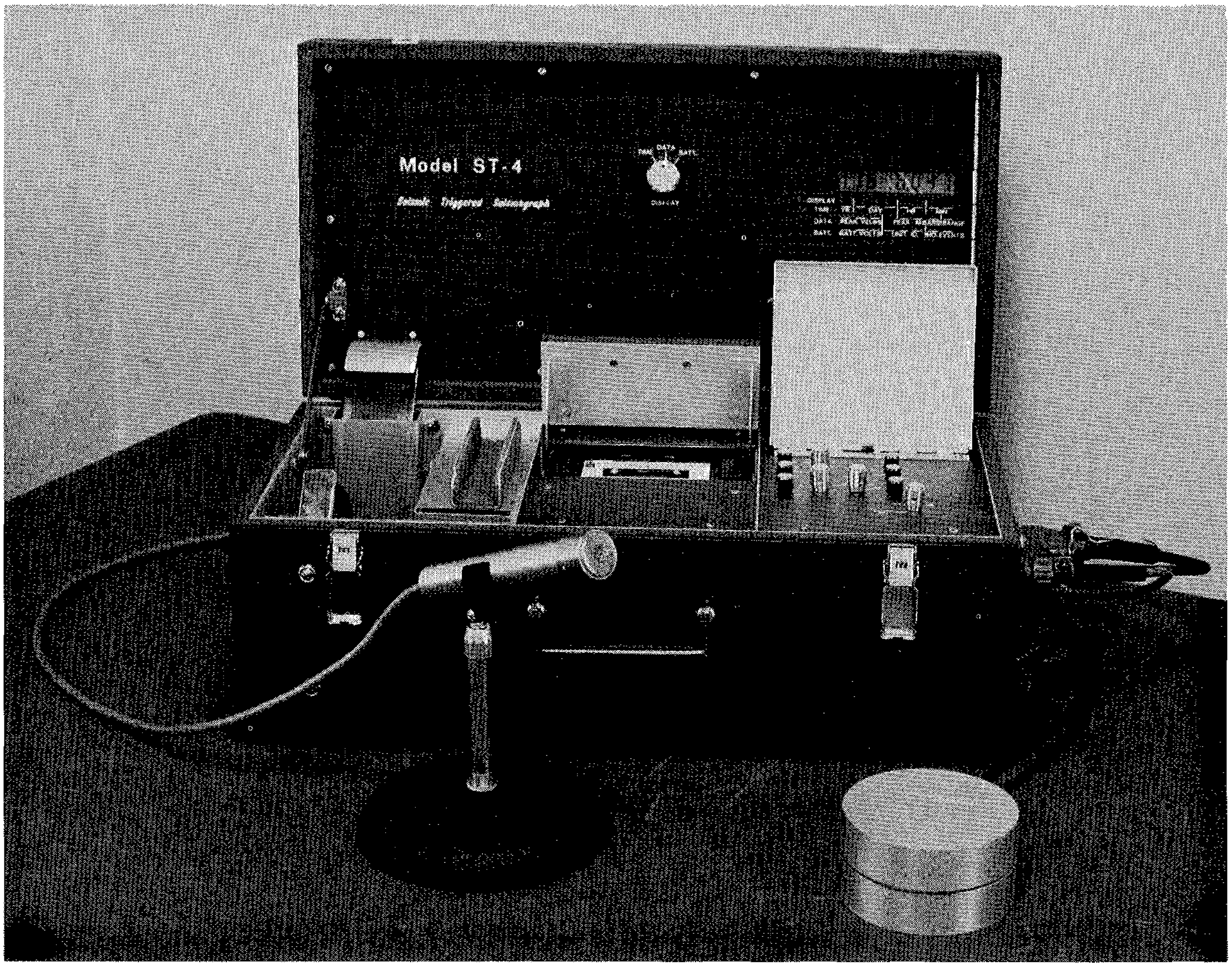

FIGURE A-5. - Dallas Instruments, Inc., model ST-4 seismic-triggered seismograph.

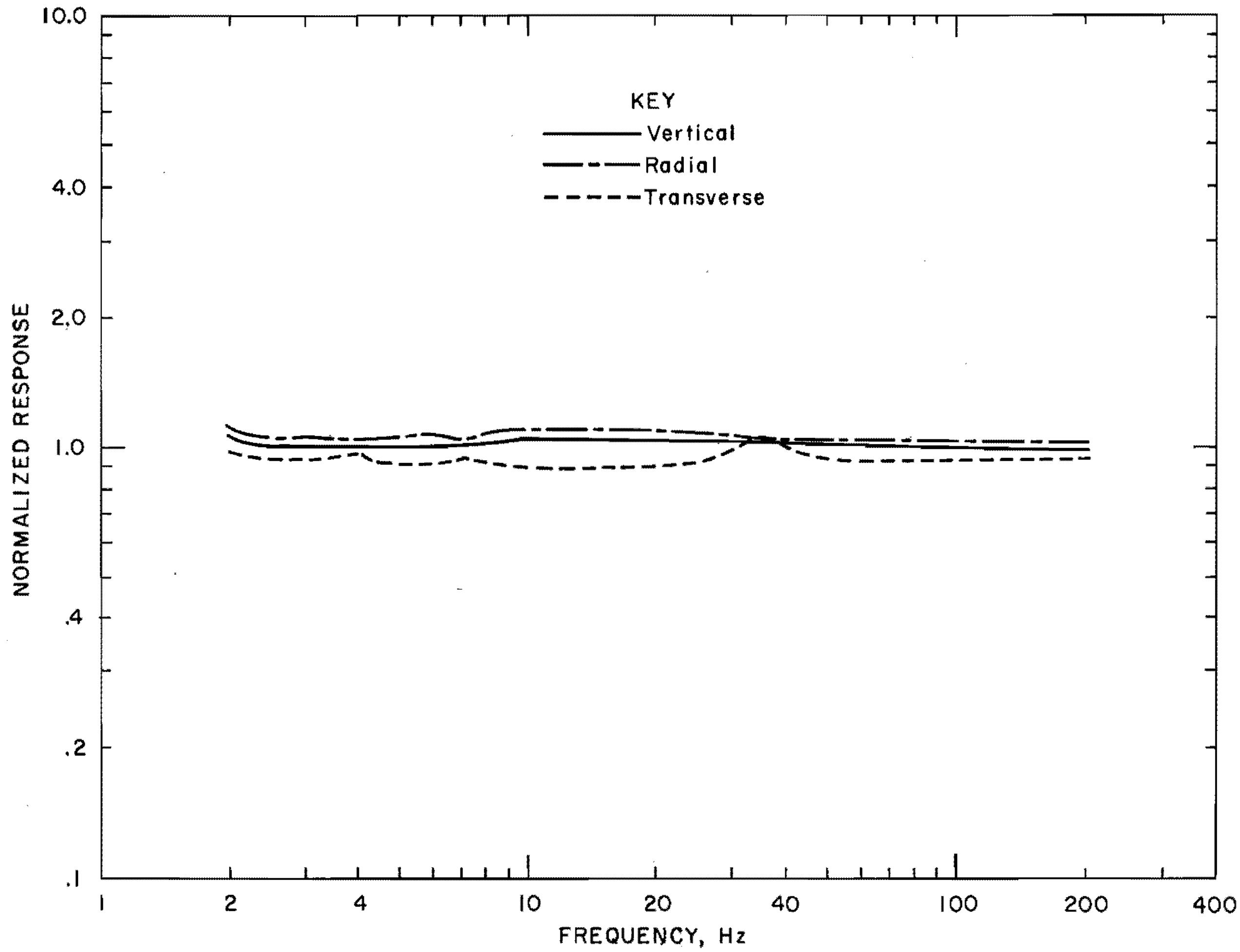

FIGURE A-6. - Dallas Instruments, Inc., model ST-4 normalized response versus frequency.

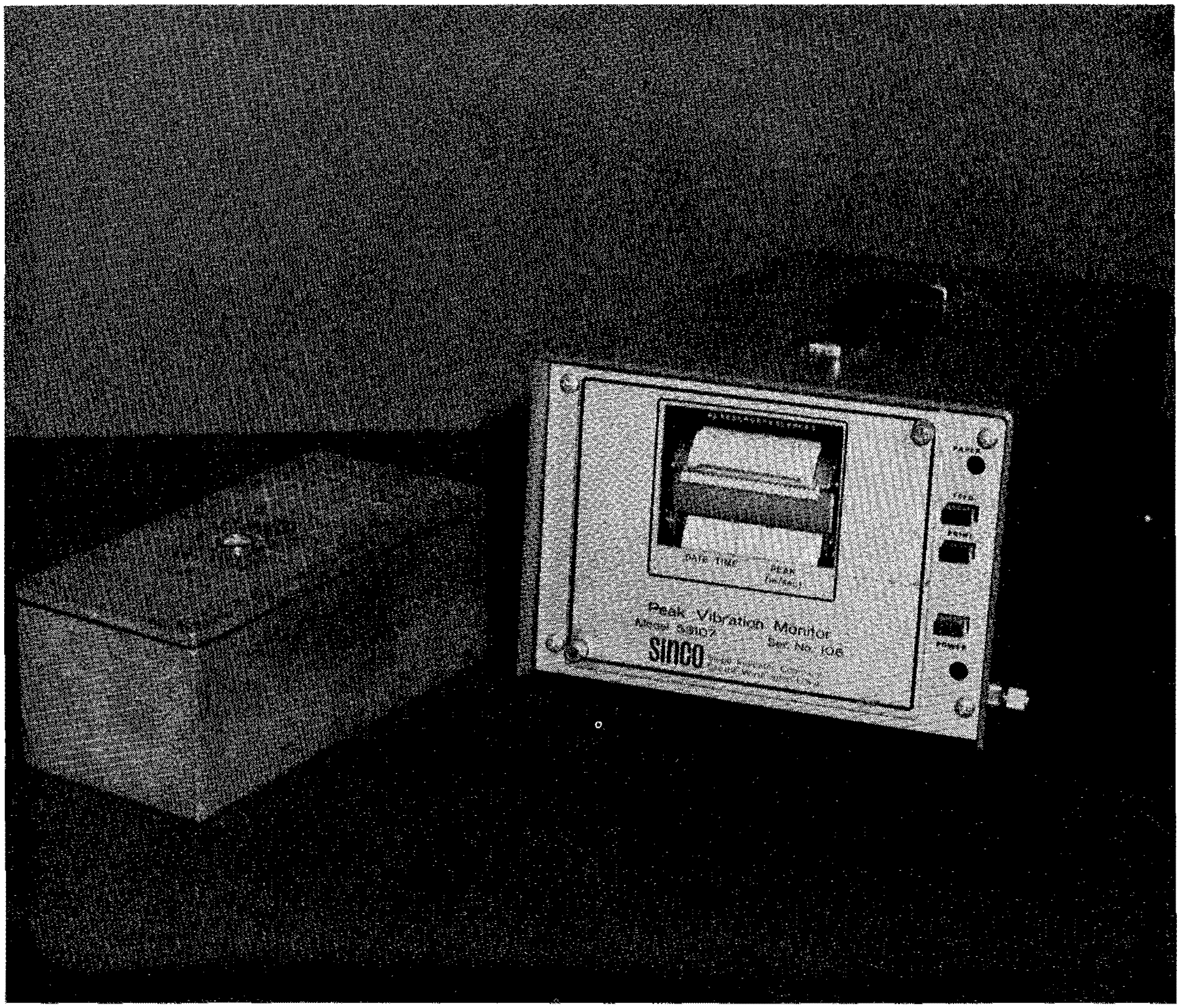

FIGURE A-7. - SINCO Slope Indicator Co., model S-4 peak vibration monitor.

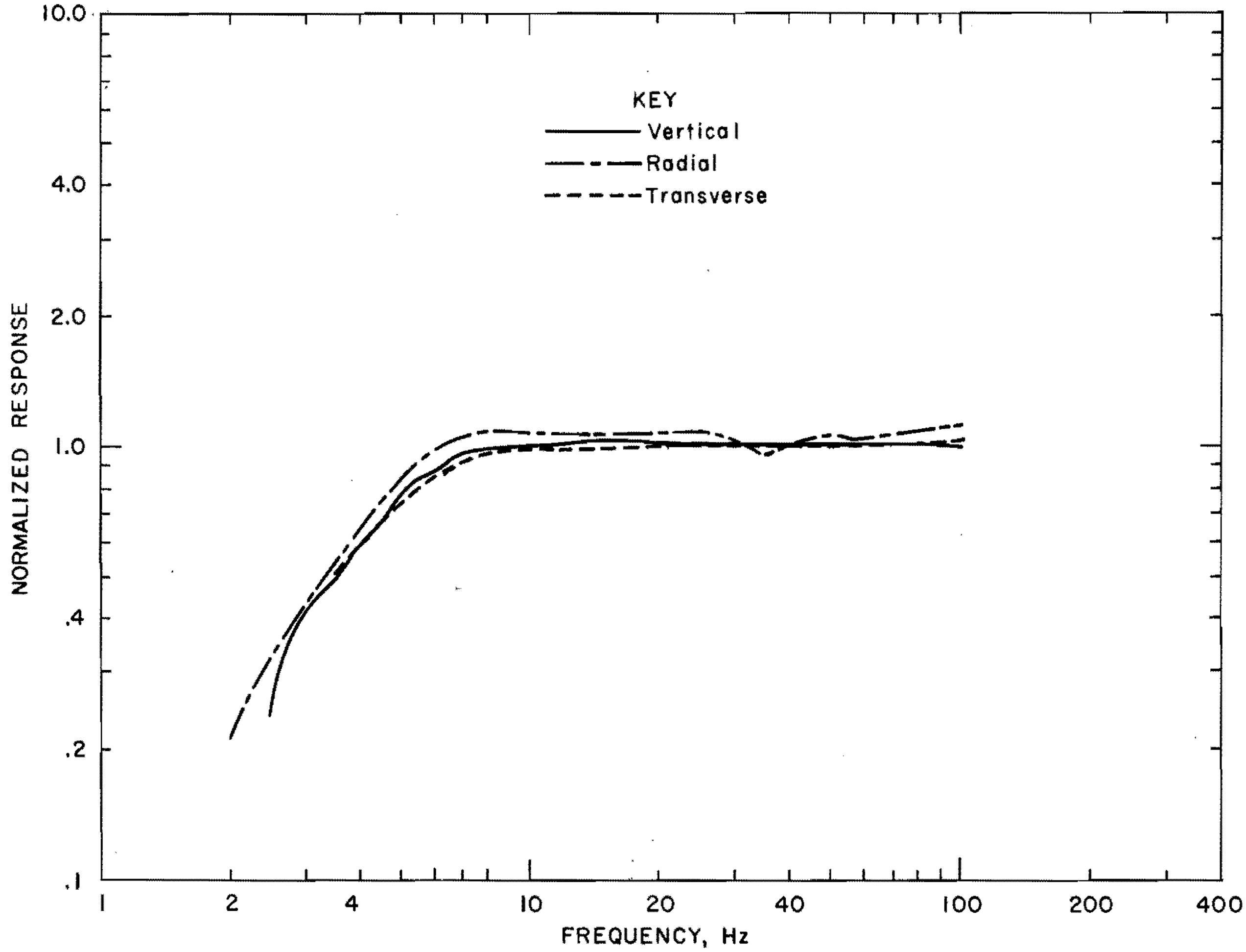

FIGURE A-8. - SINCO Slope Indicator Co., model S-4 normalized response versus frequency.

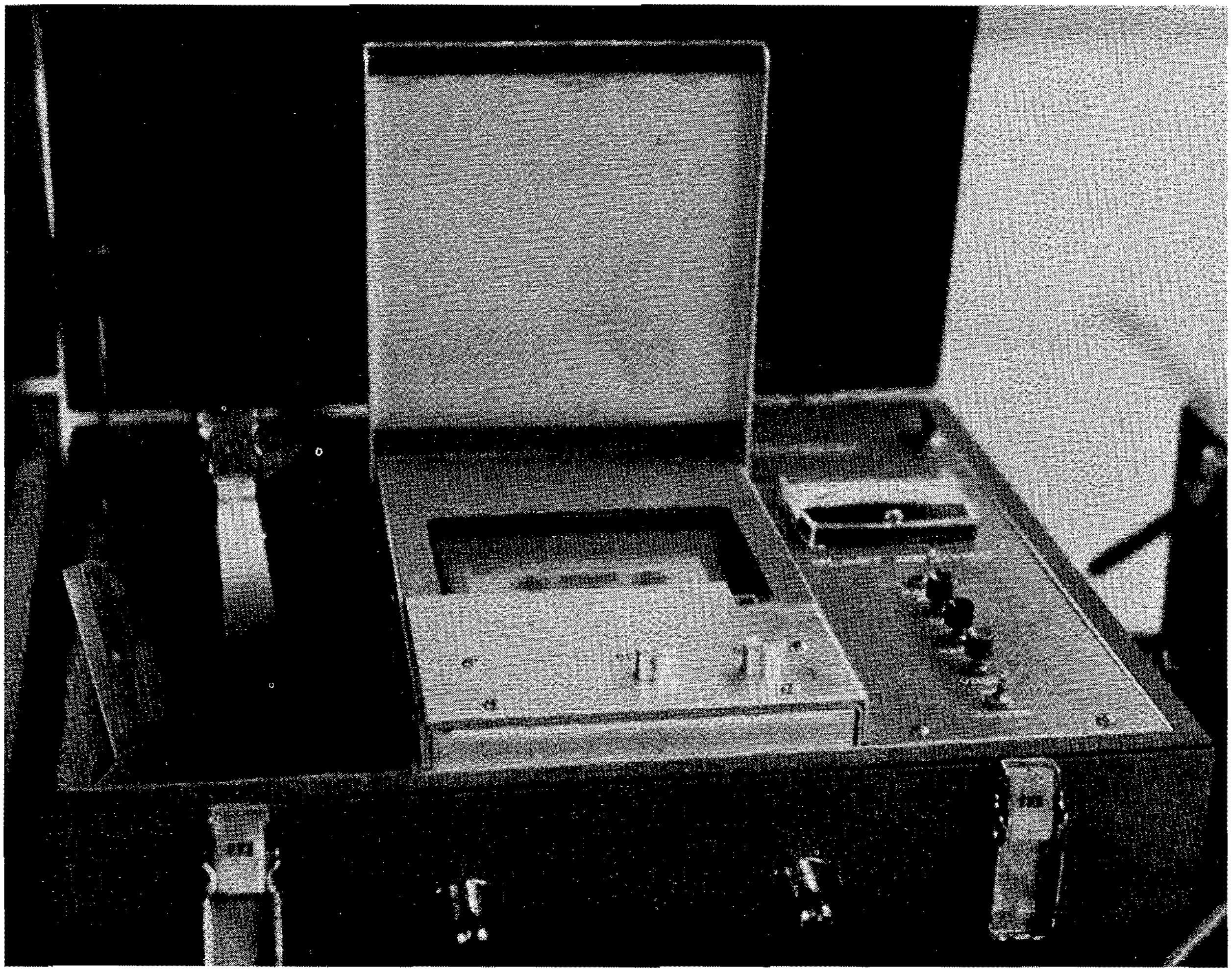

FIGURE A-9. - Vibra-Tech Engineers, Inc., model Vibra-Tape 1000 Series.

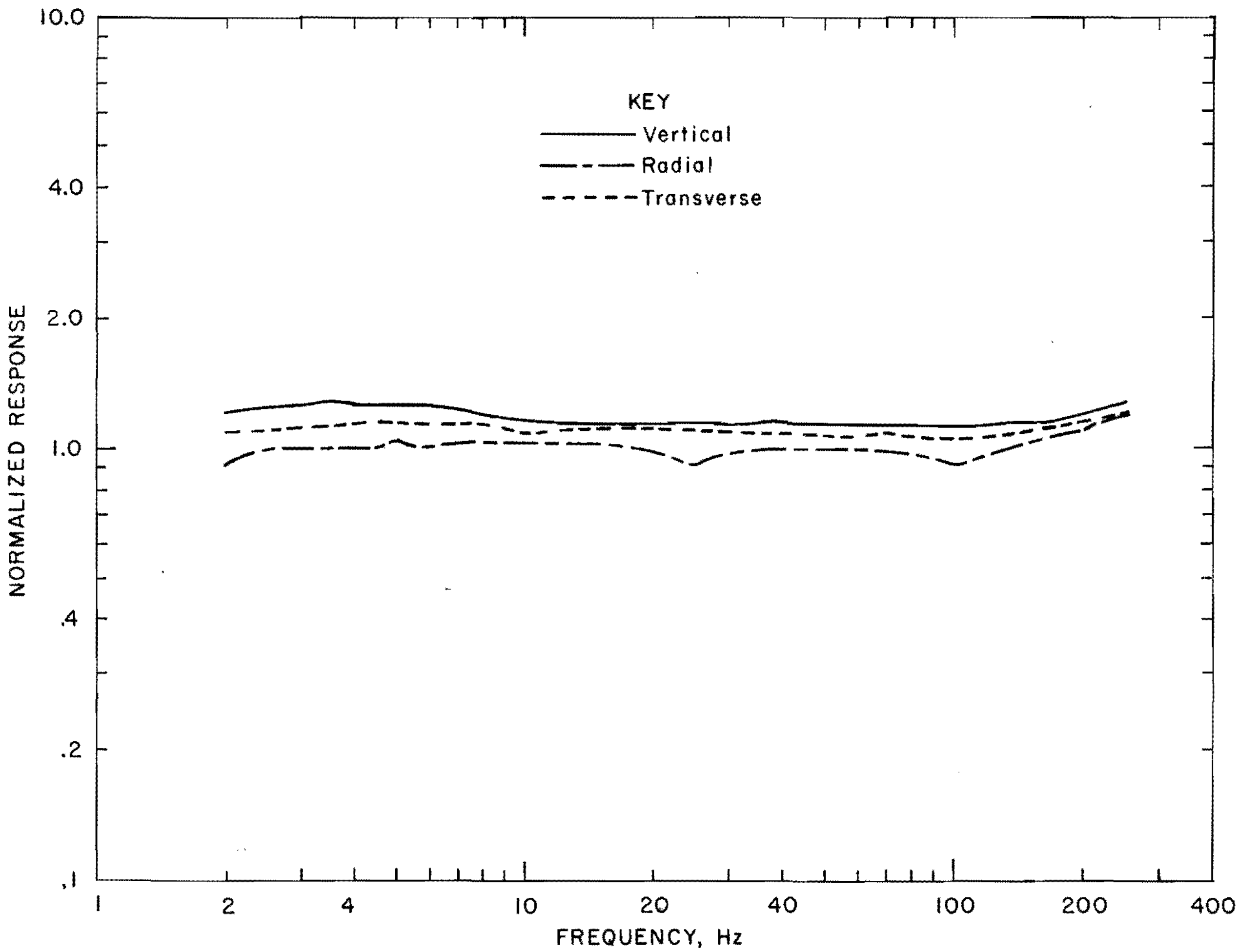

FIGURE A-10. - Vibra-Tech Engineers, Inc., model Vibra-Tape 1000 Series normalized response versus frequency.

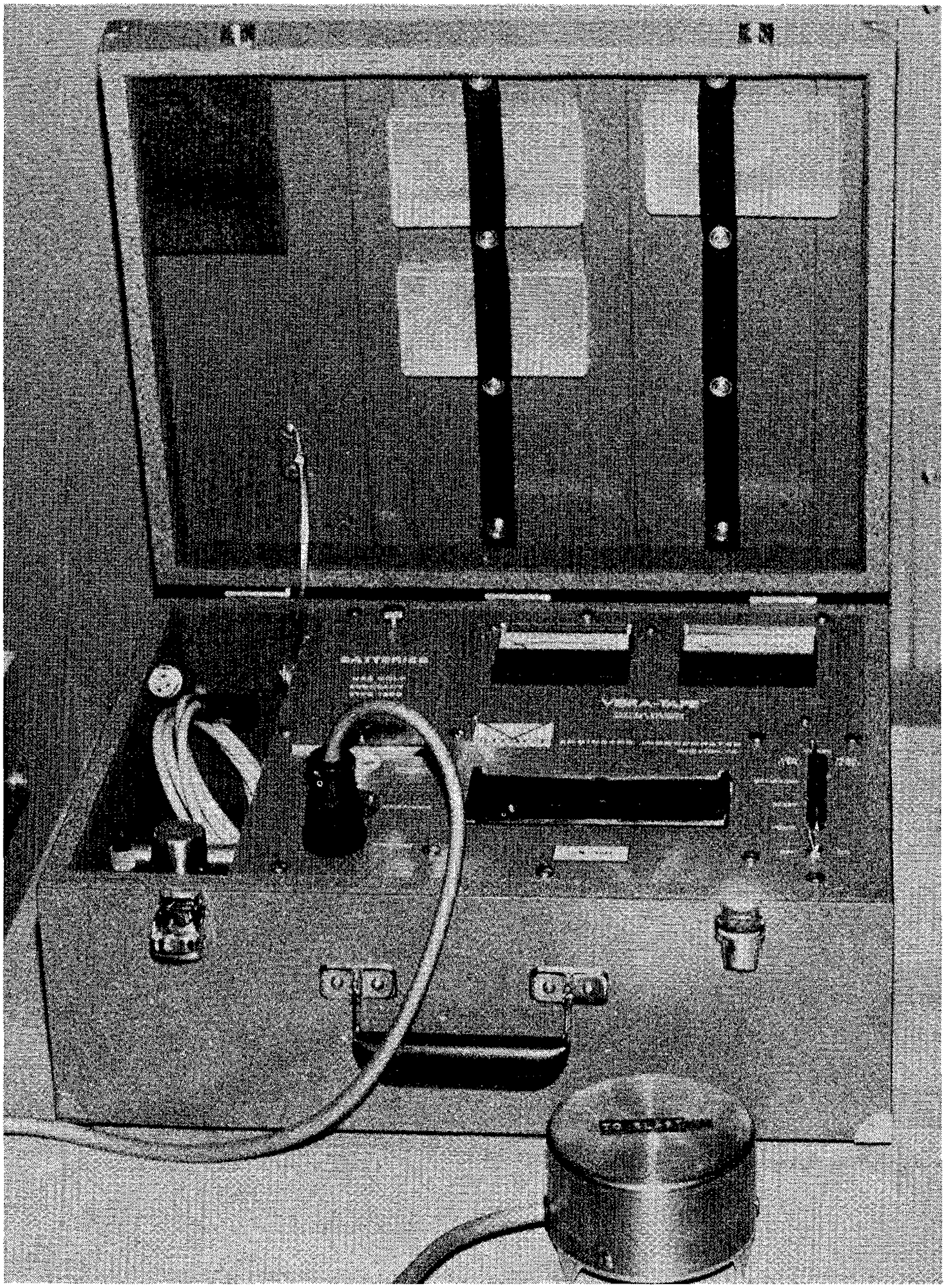

FIGURE A-11. - Vibra-Tech Engineers, Inc., model Vibra-Tape 2000 Series.

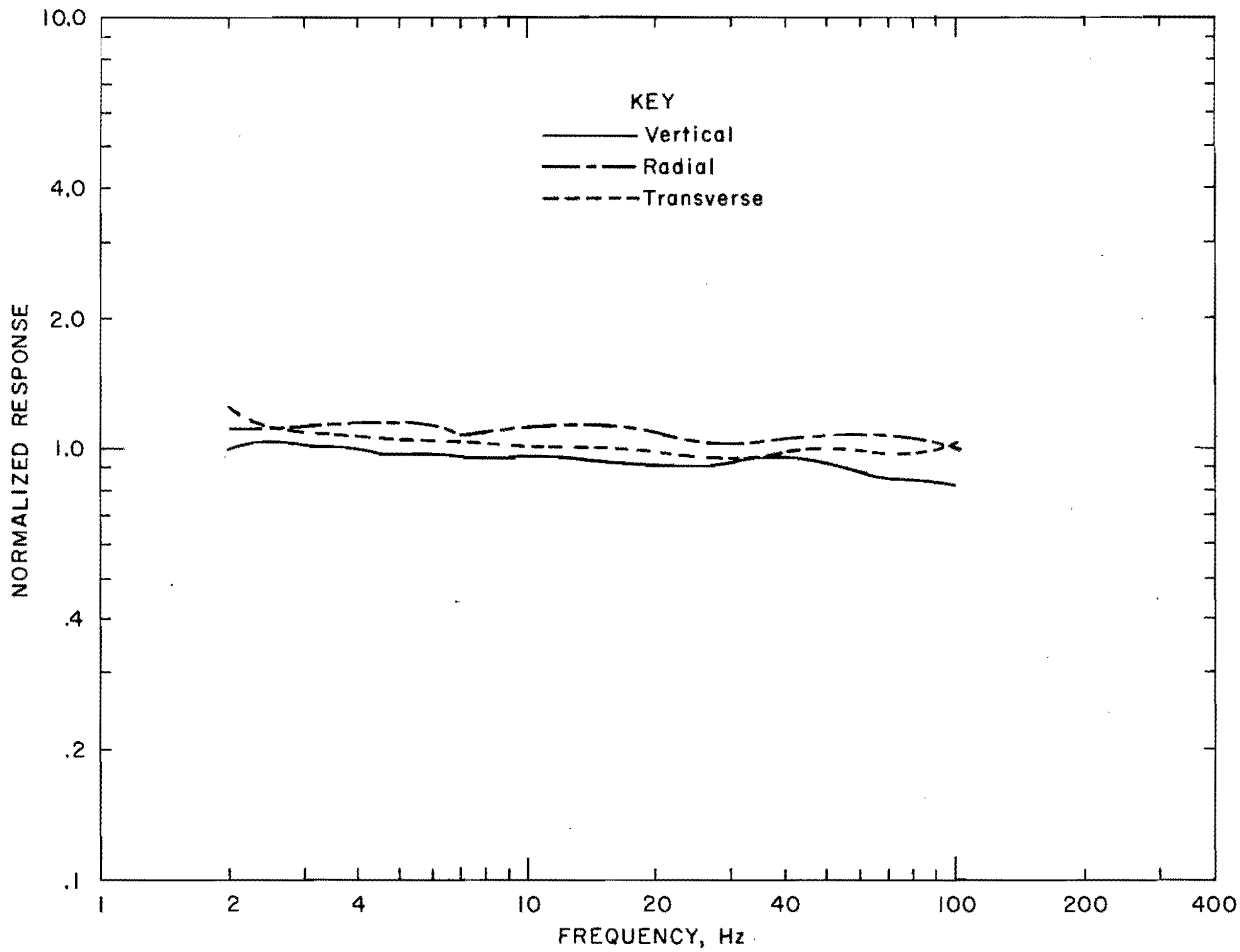

FIGURE A-12. - Vibra-Tech Engineers, Inc., model Vibra-Tape 2000 Series normalized response versus frequency.

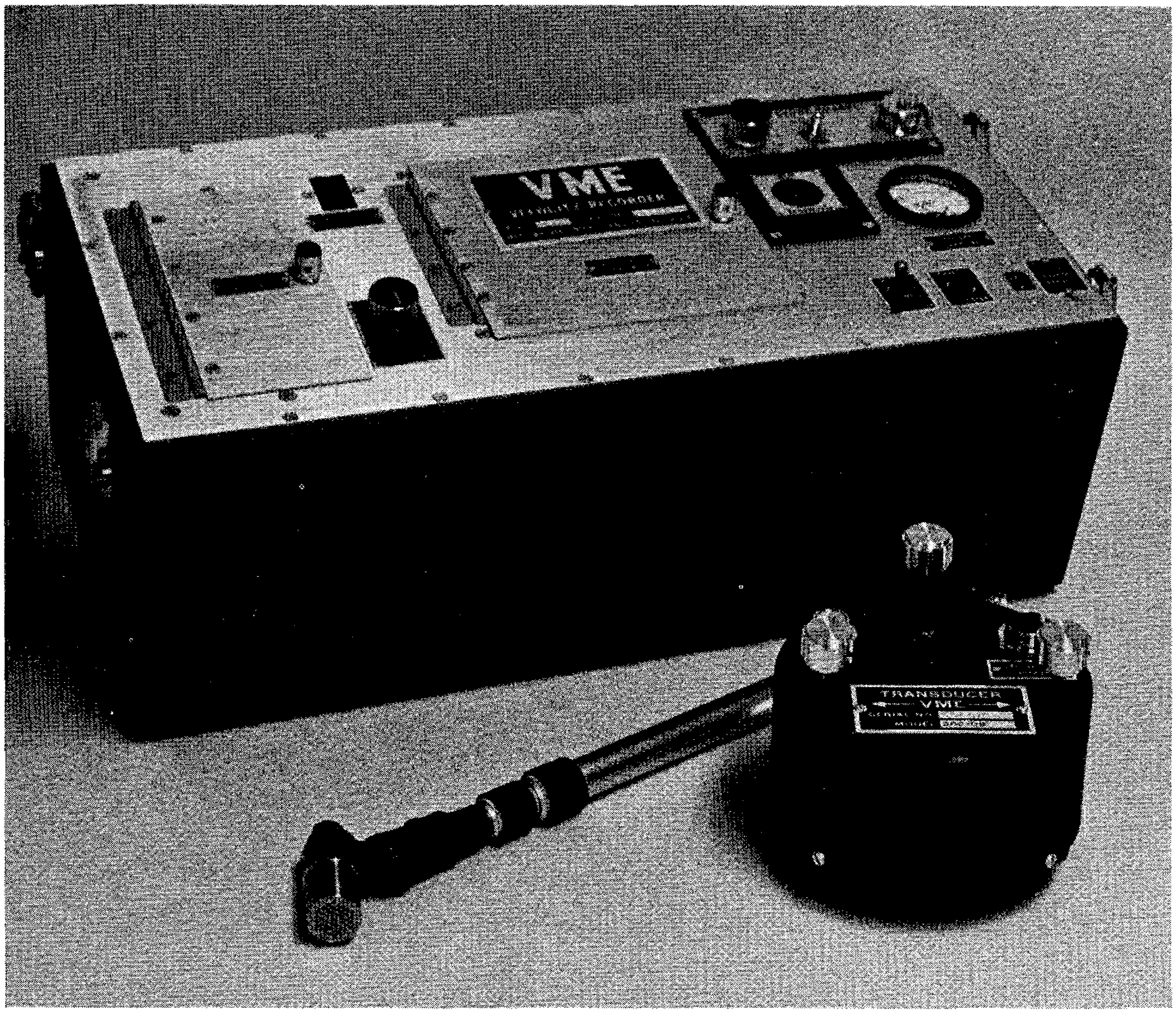

FIGURE A-13. - VME-Nitro Consult, Inc., model F.

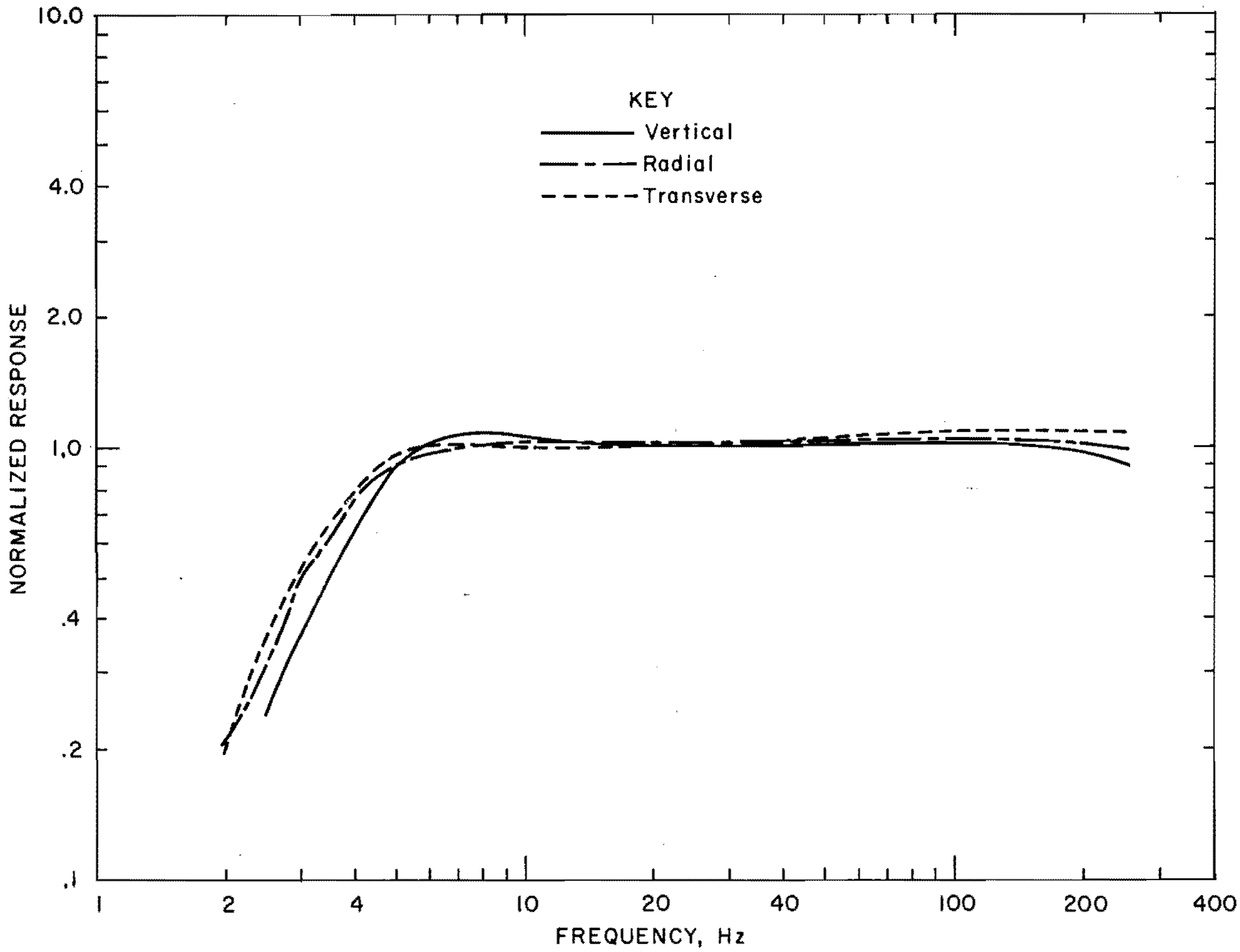

FIGURE A-14. - VME-Nitro Consult, Inc., model F normalized response versus frequency.

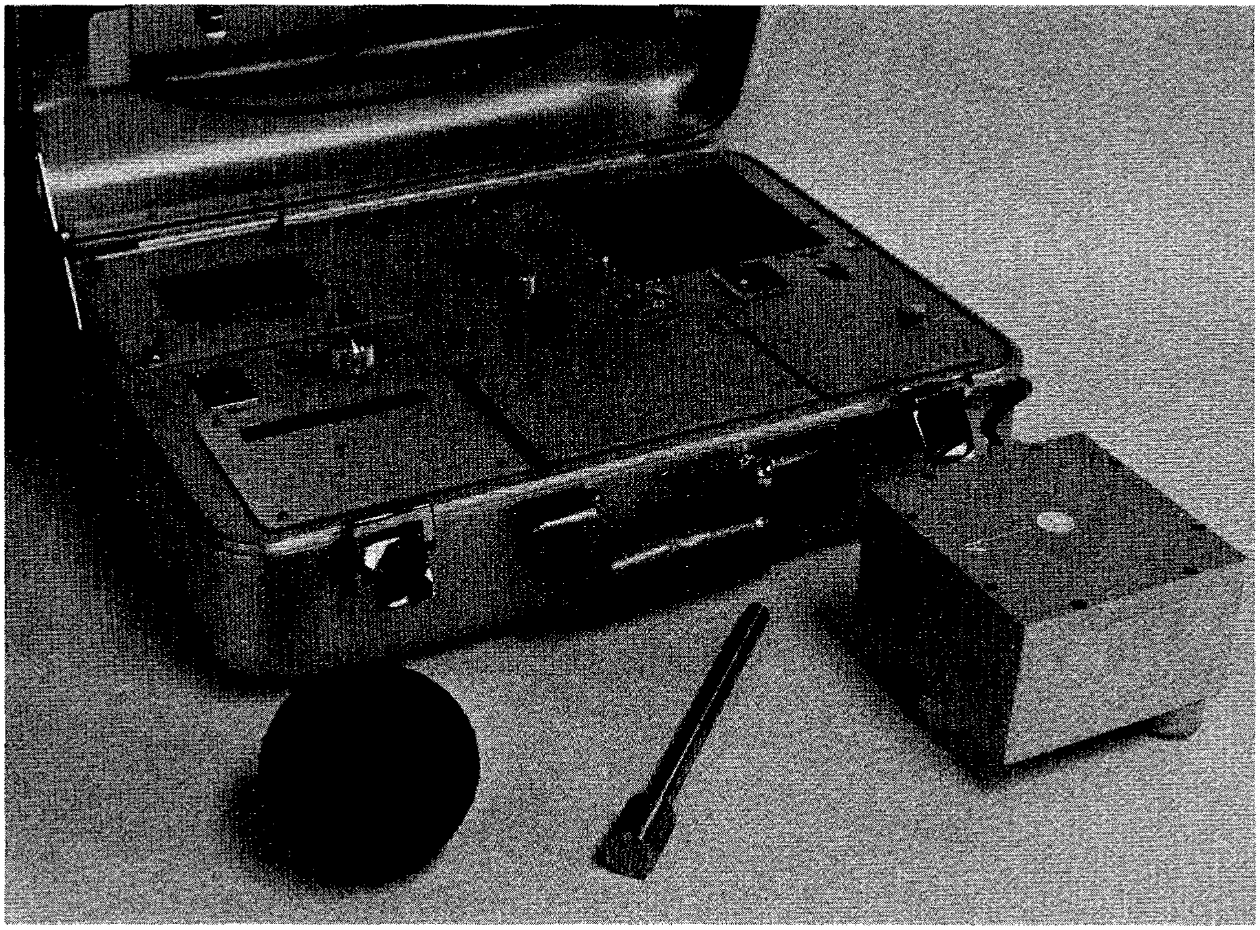

FIGURE A-15. - Philip R. Burger & Associates, Inc., model Seismic Safeguard Unit II.

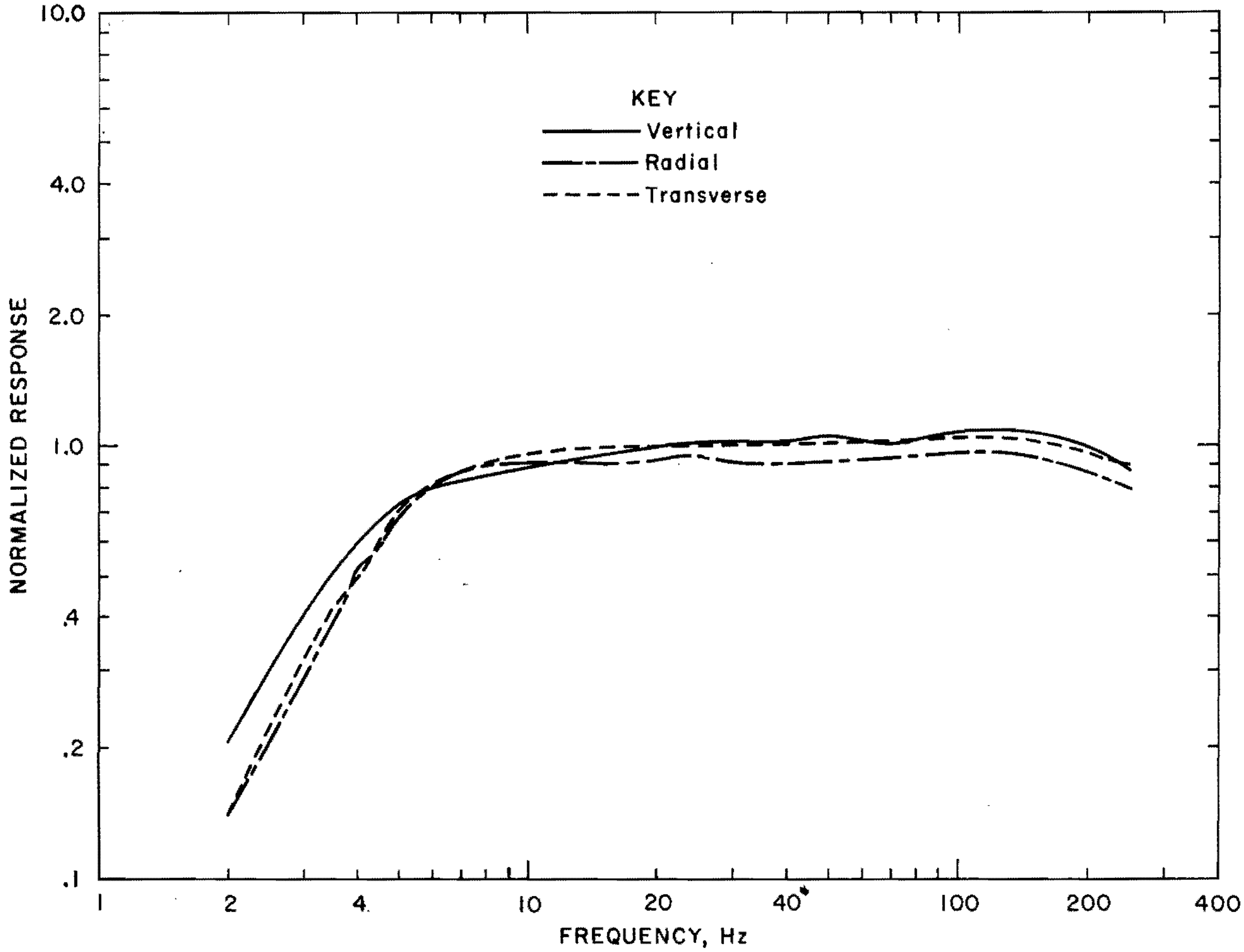

FIGURE A-16. - Philip R. Burger & Associates, Inc., model Seismic Safeguard Unit II normalized response versus frequency.

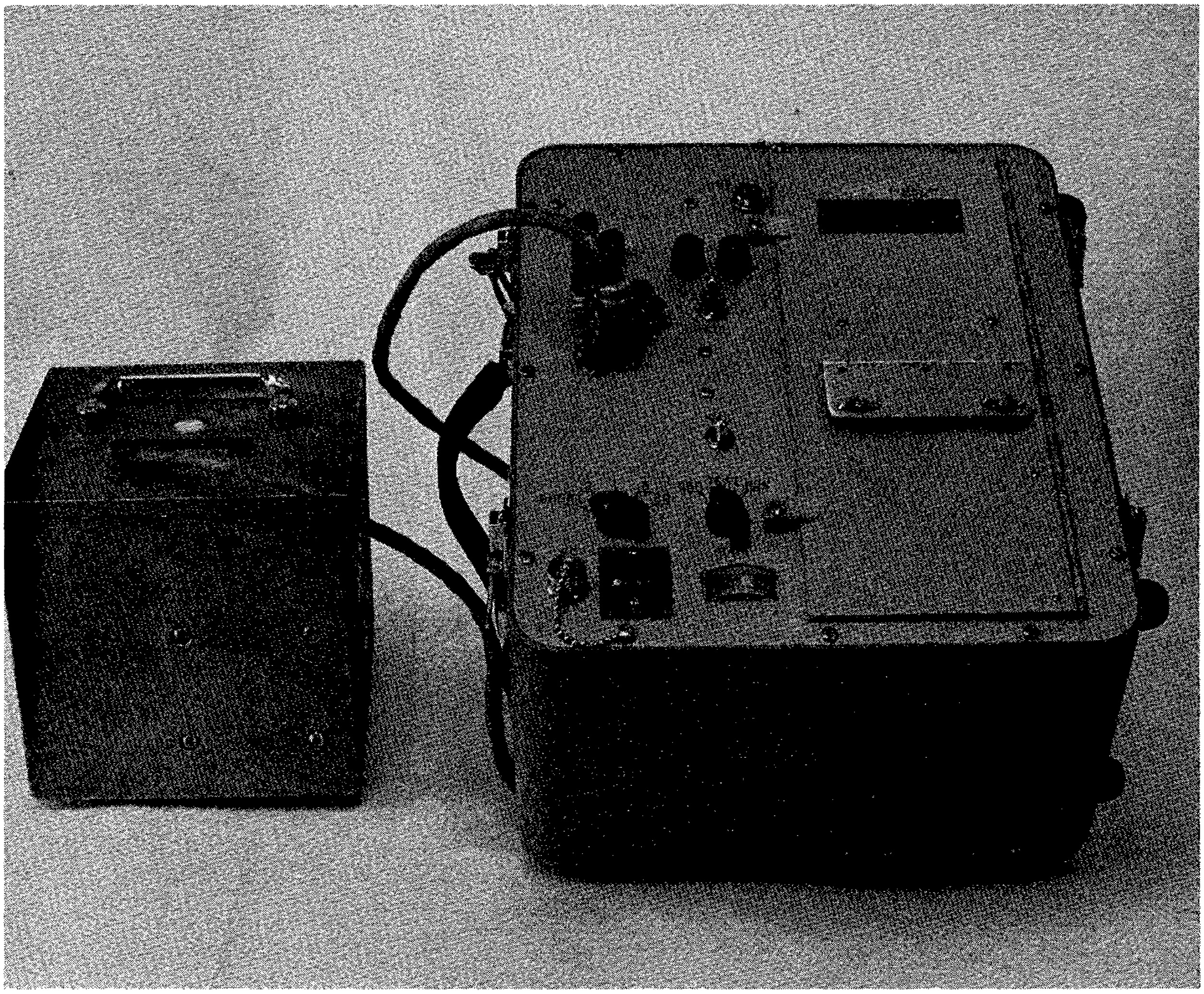

FIGURE A-17. - W. F. Sprengnether Instrument Co., Inc., model VS-1100.

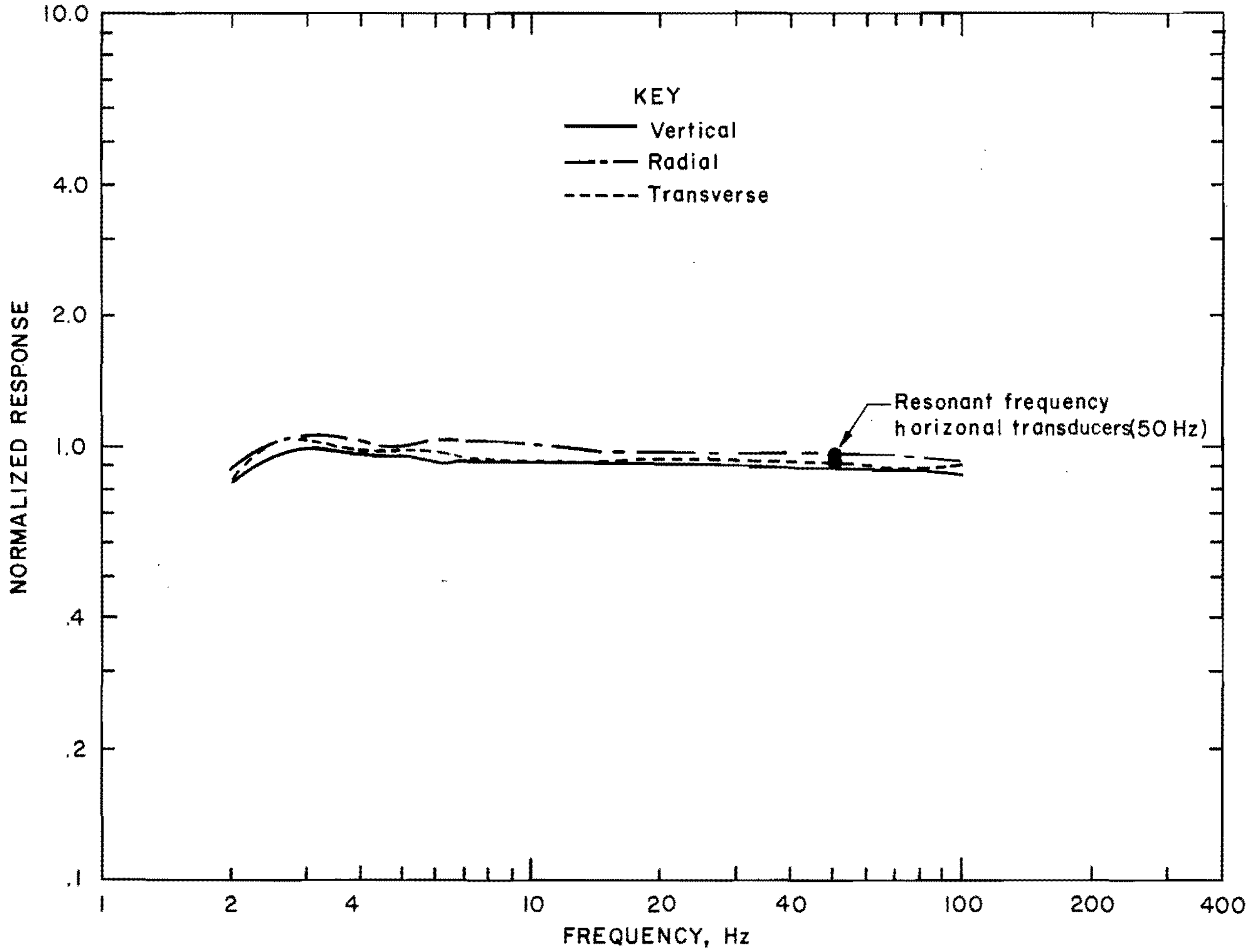

FIGURE A-18. - W. F. Sprengnether Instrument Co., Inc., model VS-1100 normalized response versus frequency.

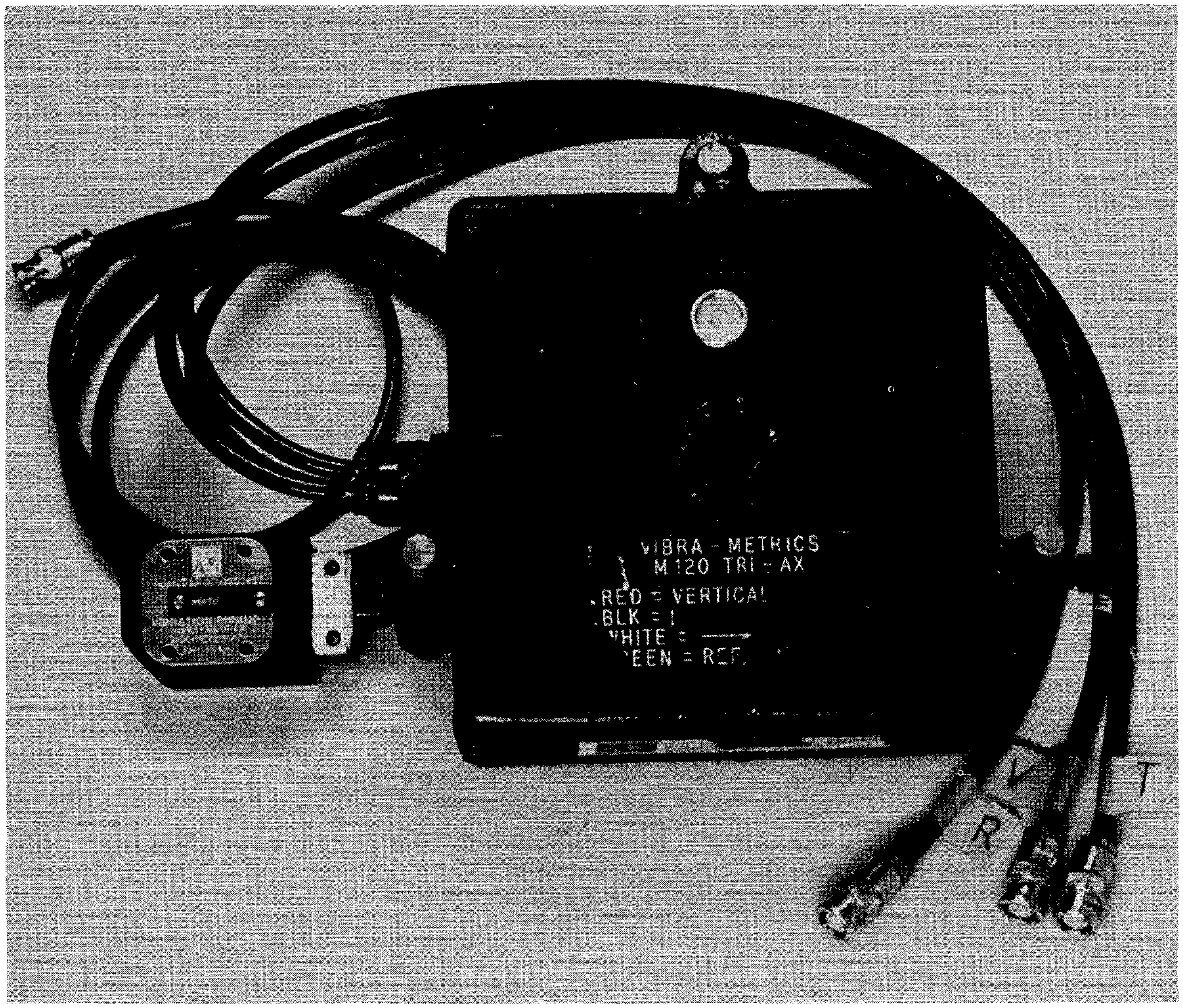

FIGURE A-19. - Vibra-Metrics model MB-120 transducer and triaxial box.

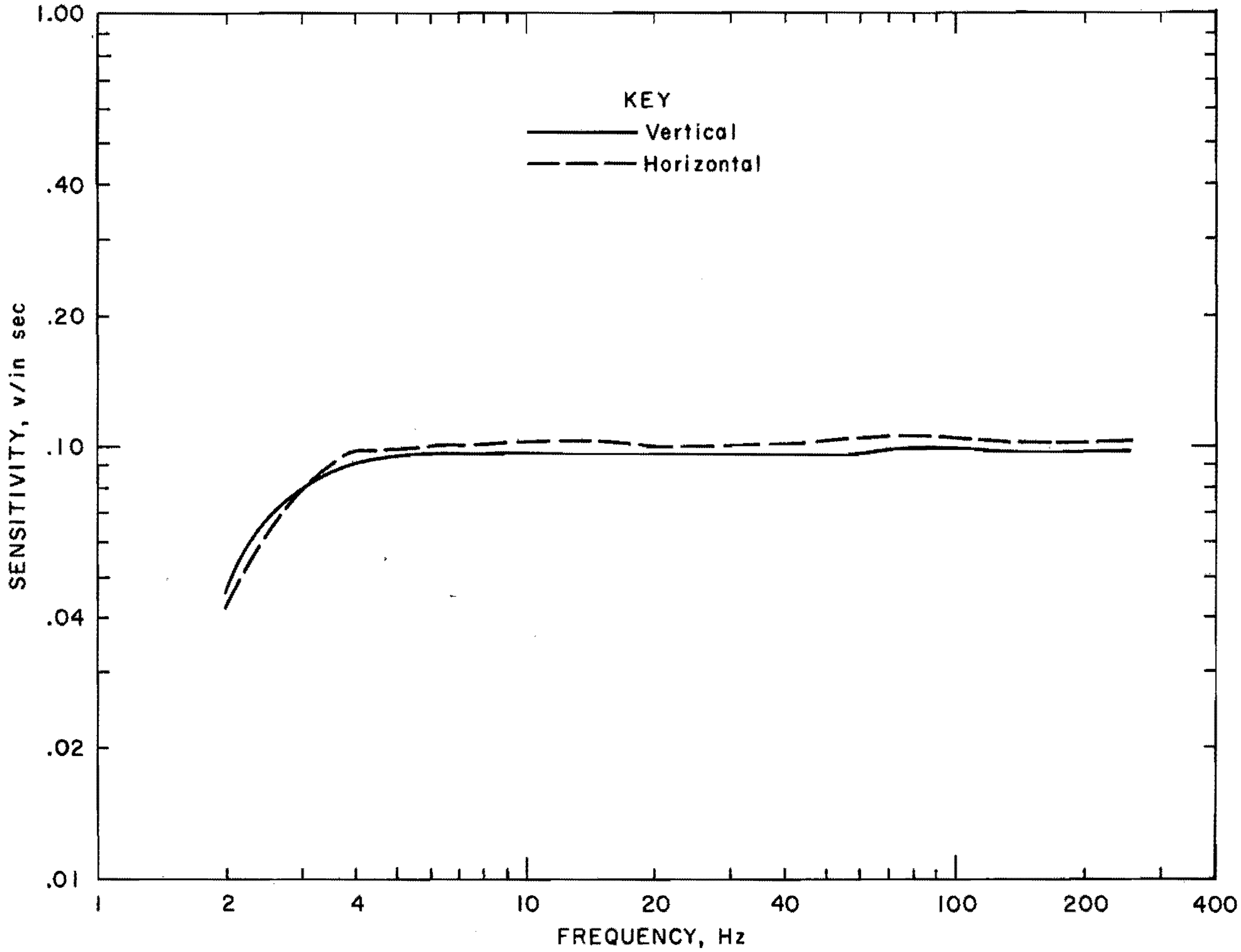

FIGURE A-20. - Vibra-Metrics model MB-120 sensitivity versus frequency.

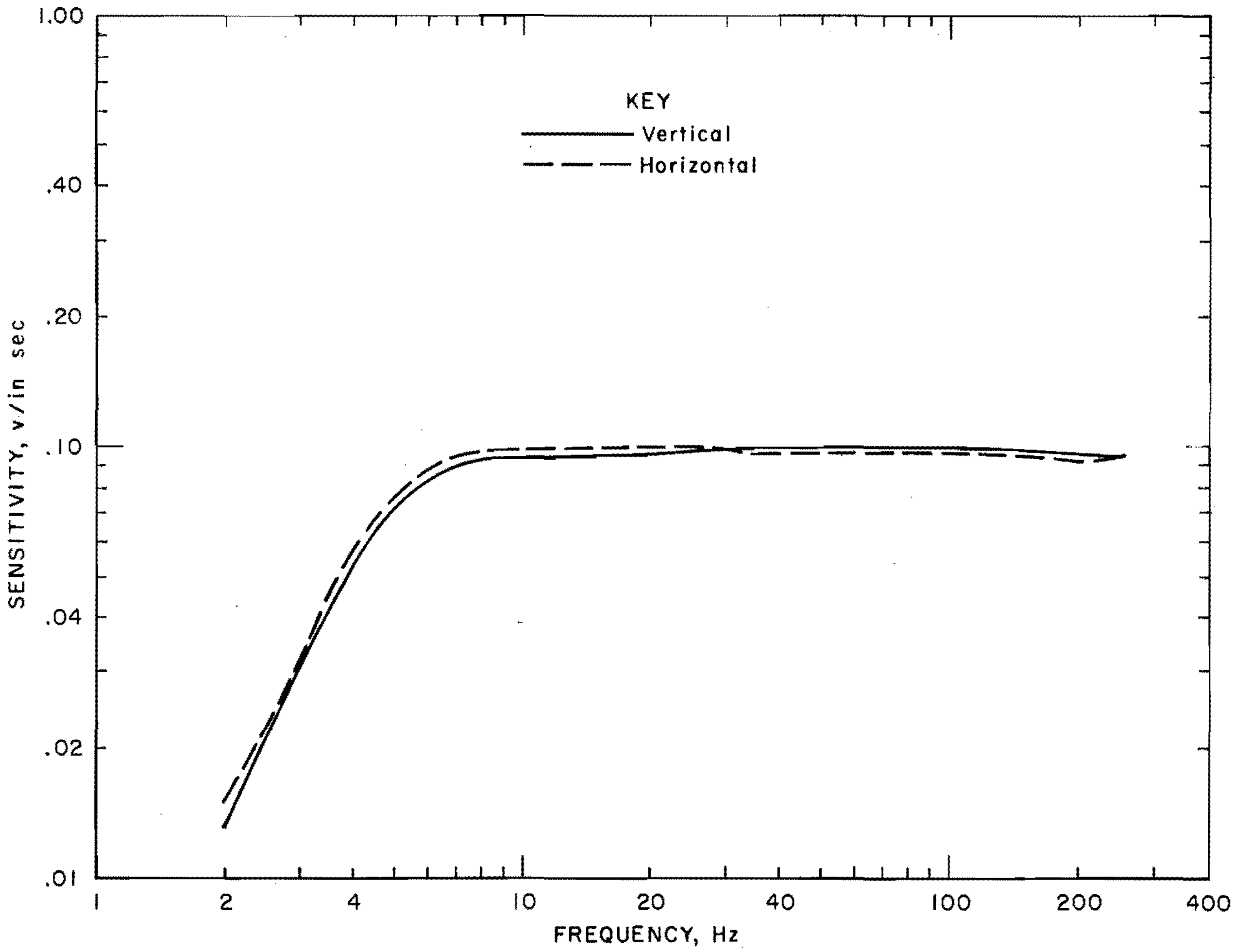

FIGURE A-21. - Vibra-Metrics model MB-124 sensitivity versus frequency.

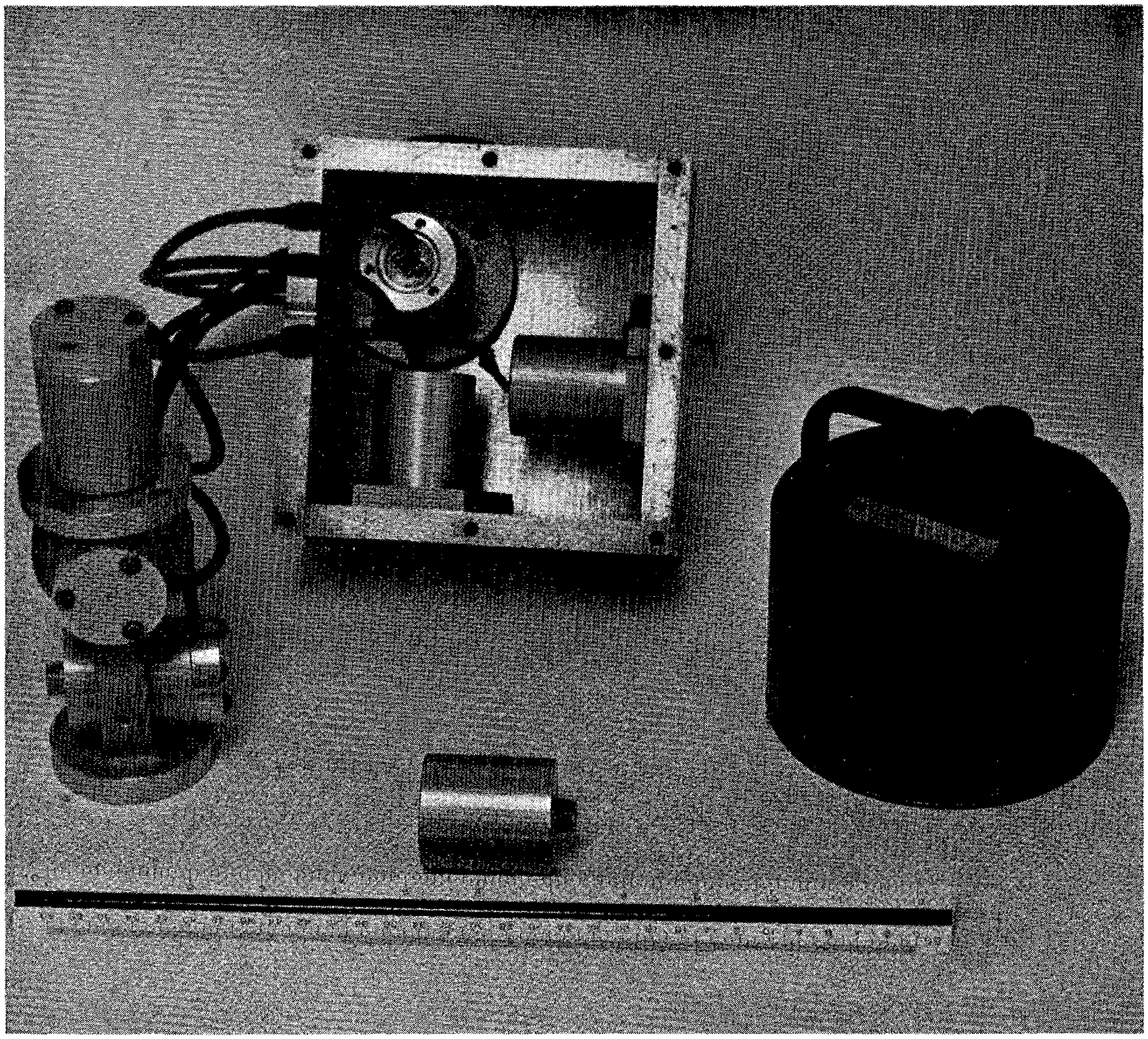

FIGURE A-22. - Geo Space models HS-1 and triaxial VLF-LP-3D velocity transducers.

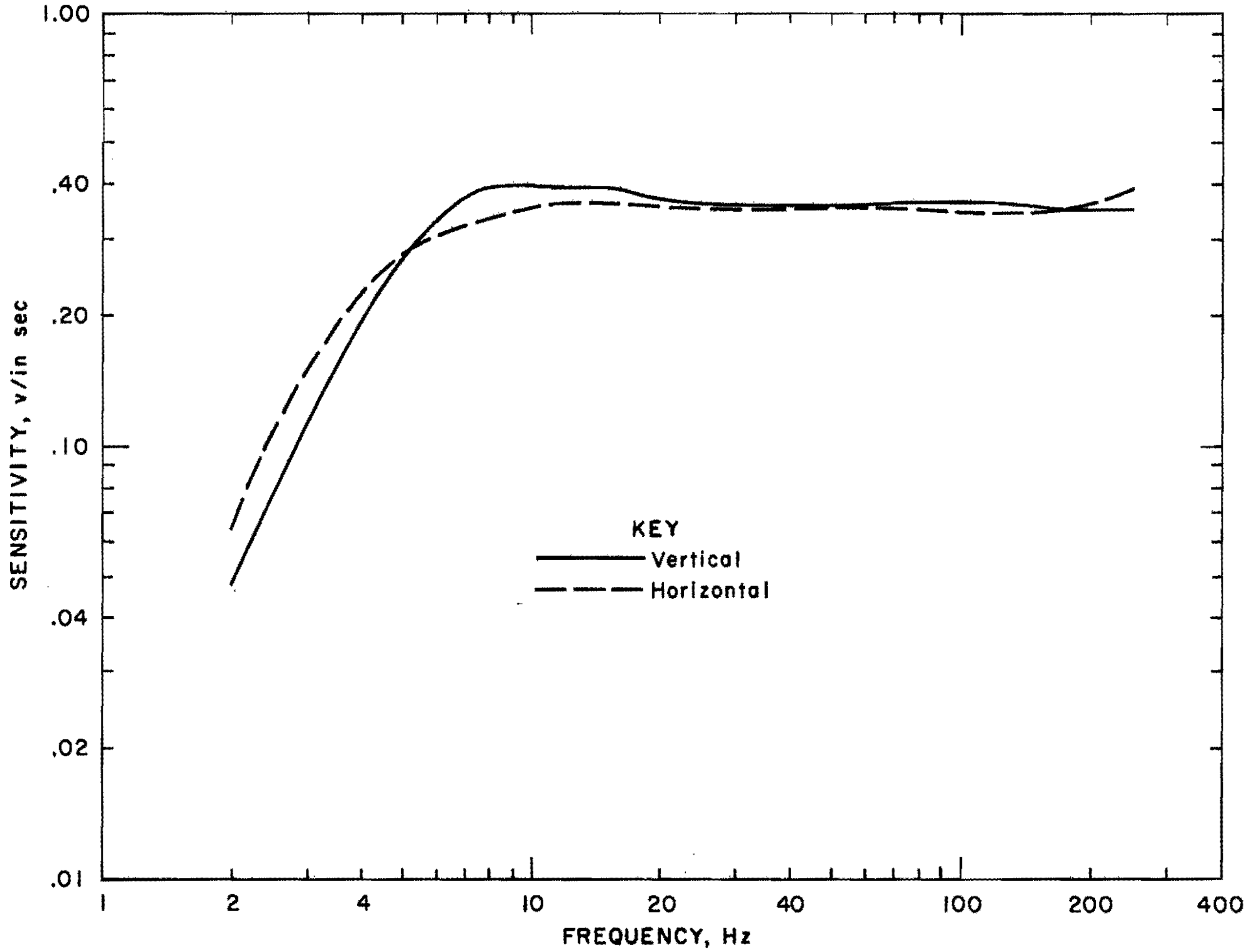

FIGURE A-23. - Geo Space model HS-1 sensitivity versus frequency.

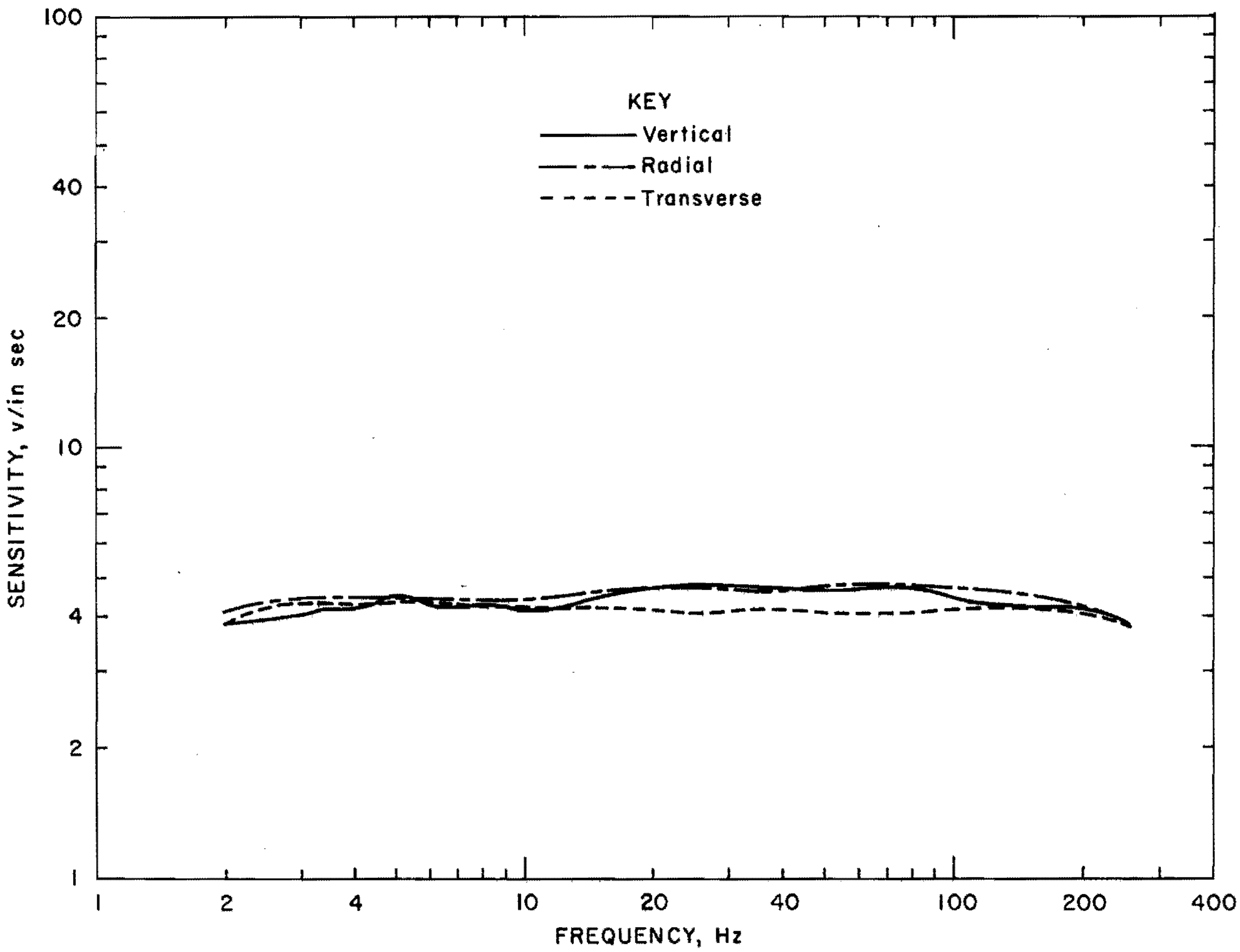

FIGURE A-24. - Geo Space triaxial model VLF-LP-3D sensitivity versus frequency.

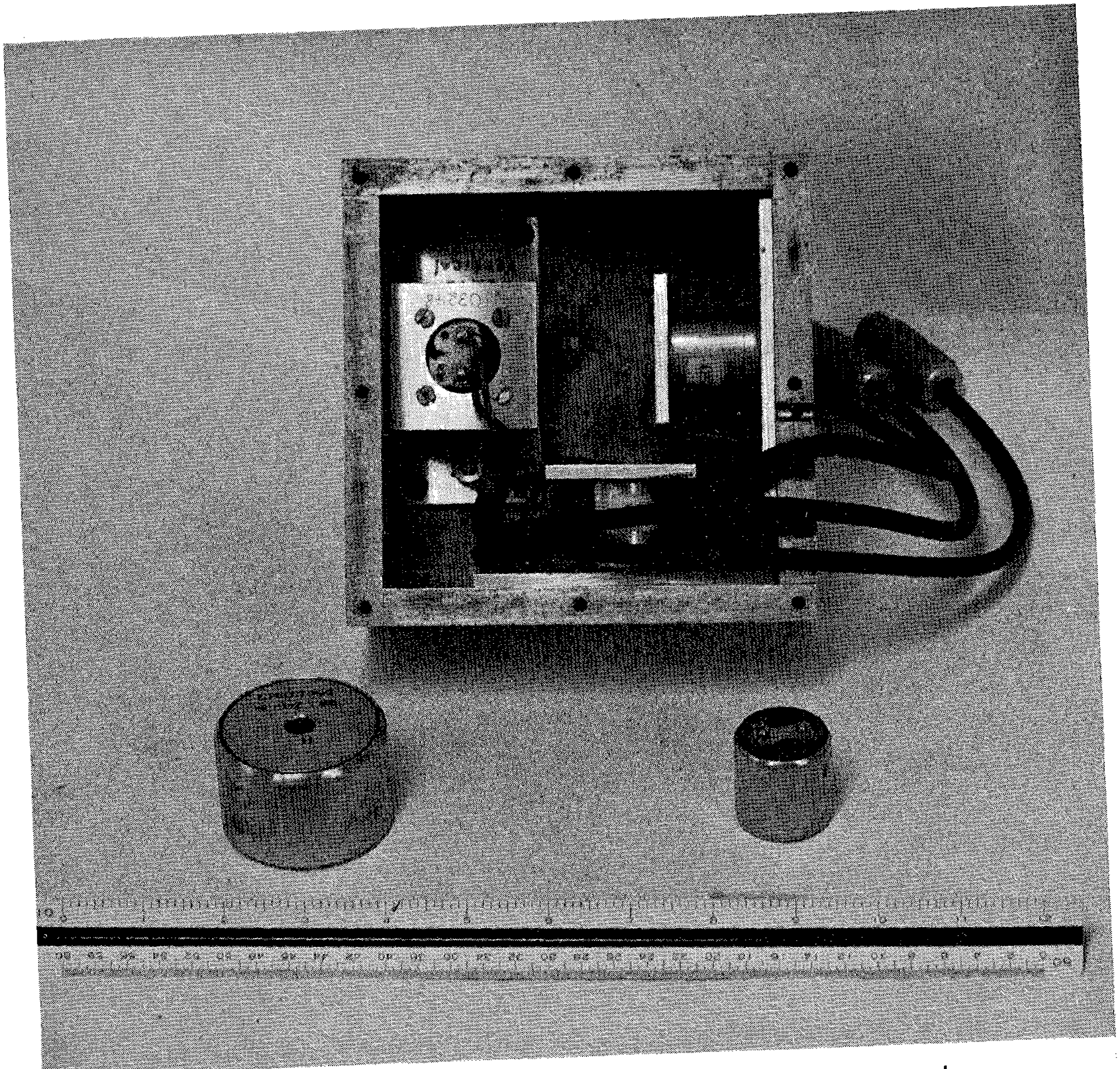

FIGURE A-25. - Mark Products models L-1B and L-15B velocity transducers.

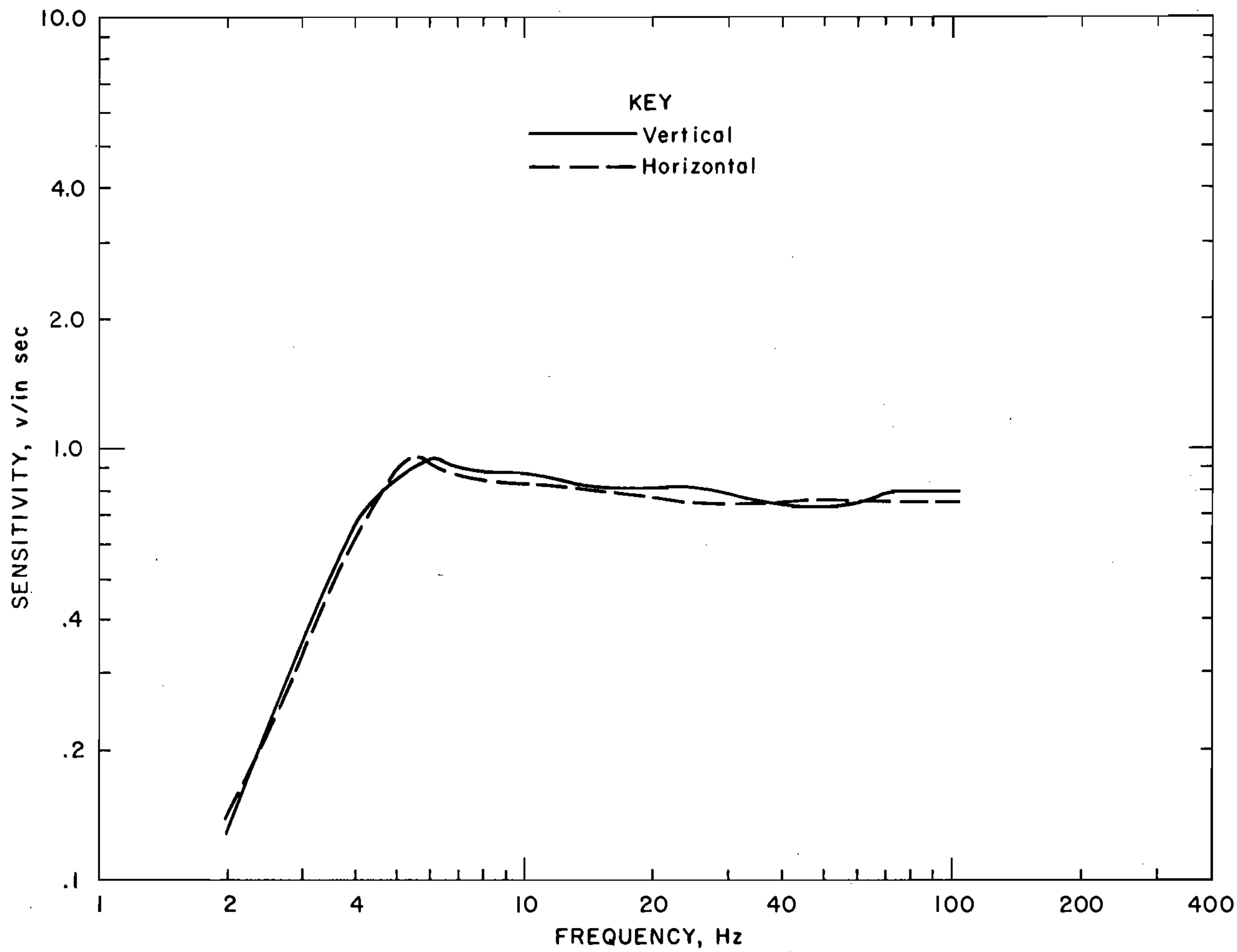

FIGURE A-26. - Mark Products model L-1B sensitivity versus frequency.

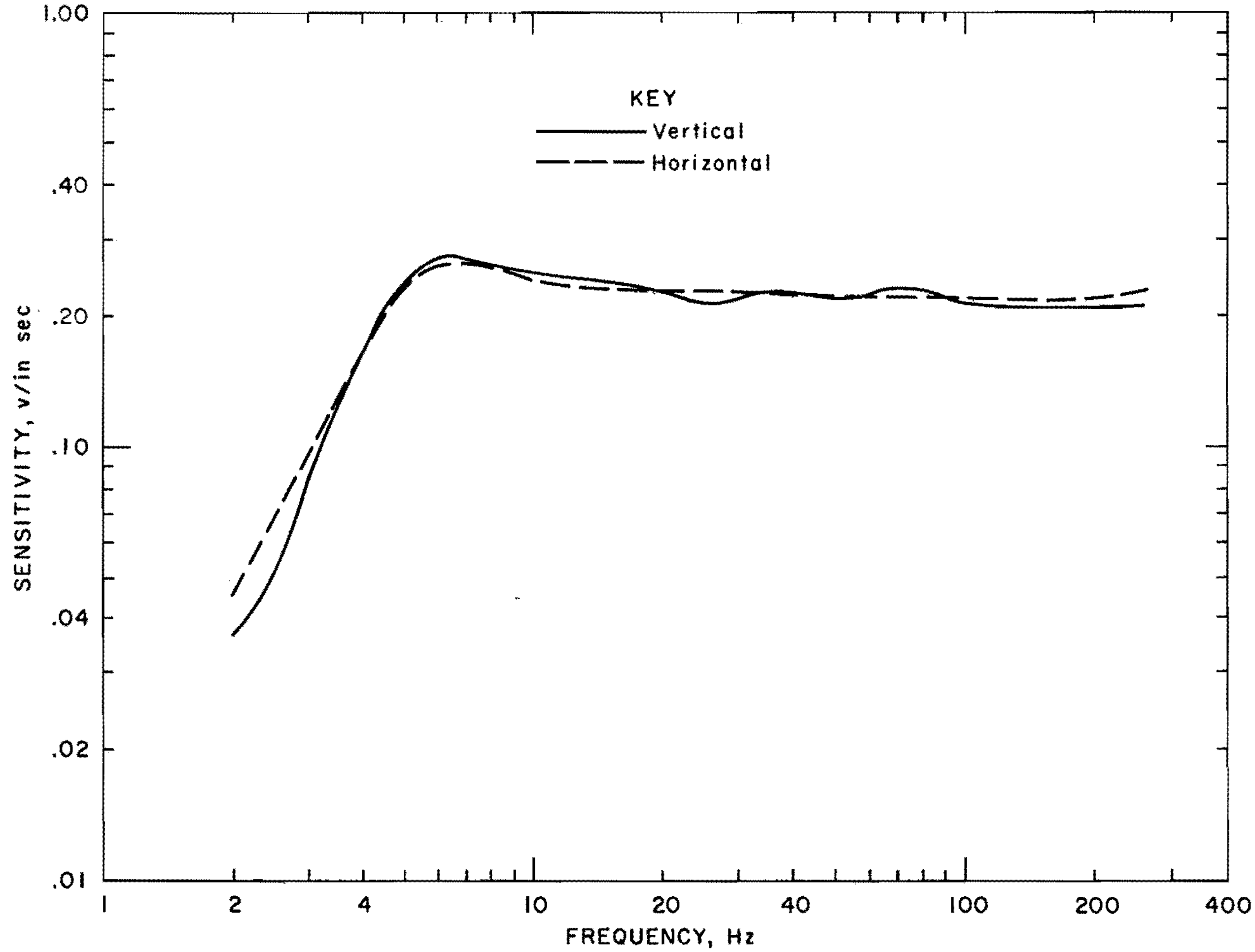

FIGURE A-27. - Mark Products model L-15B sensitivity versus frequency.

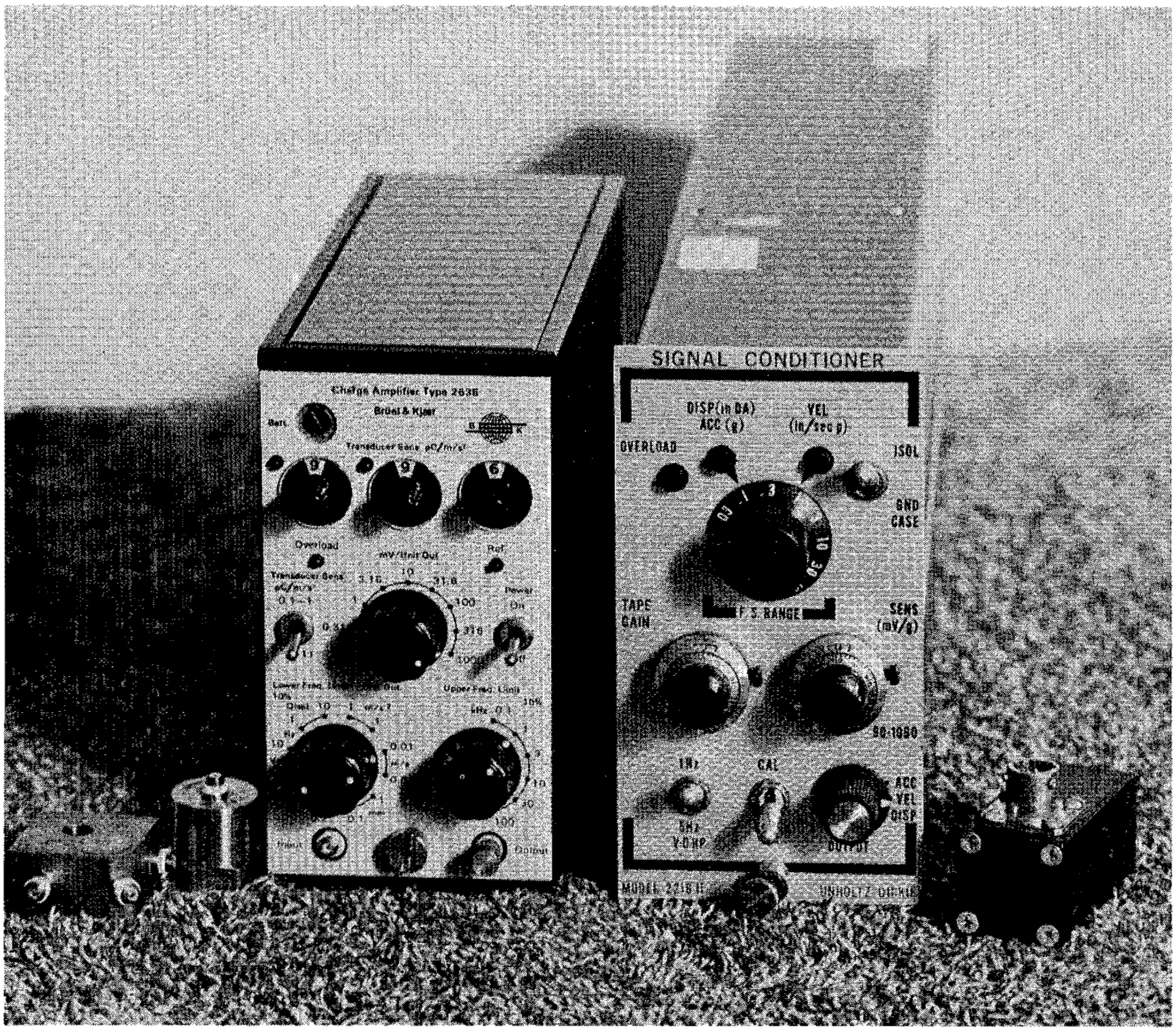

FIGURE A-28. - Unholtz-Dickie model 1000PA accelerometer and 221611 signal conditioner with B & K models 4370 and 4321 accelerometers and 2635 charge amplifier.

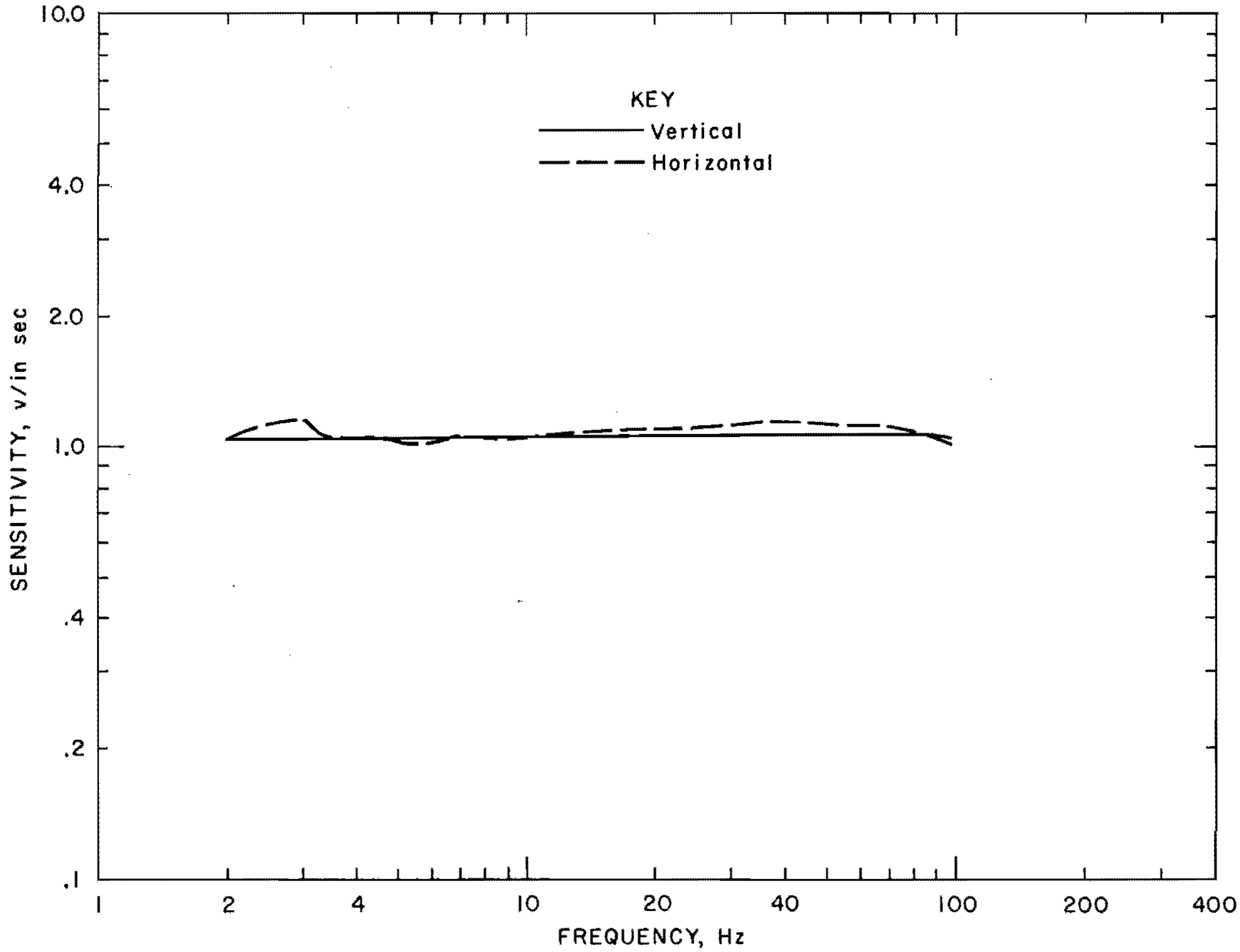

FIGURE A-29. - Unholtz-Dickie model 1000PA sensitivity versus frequency.

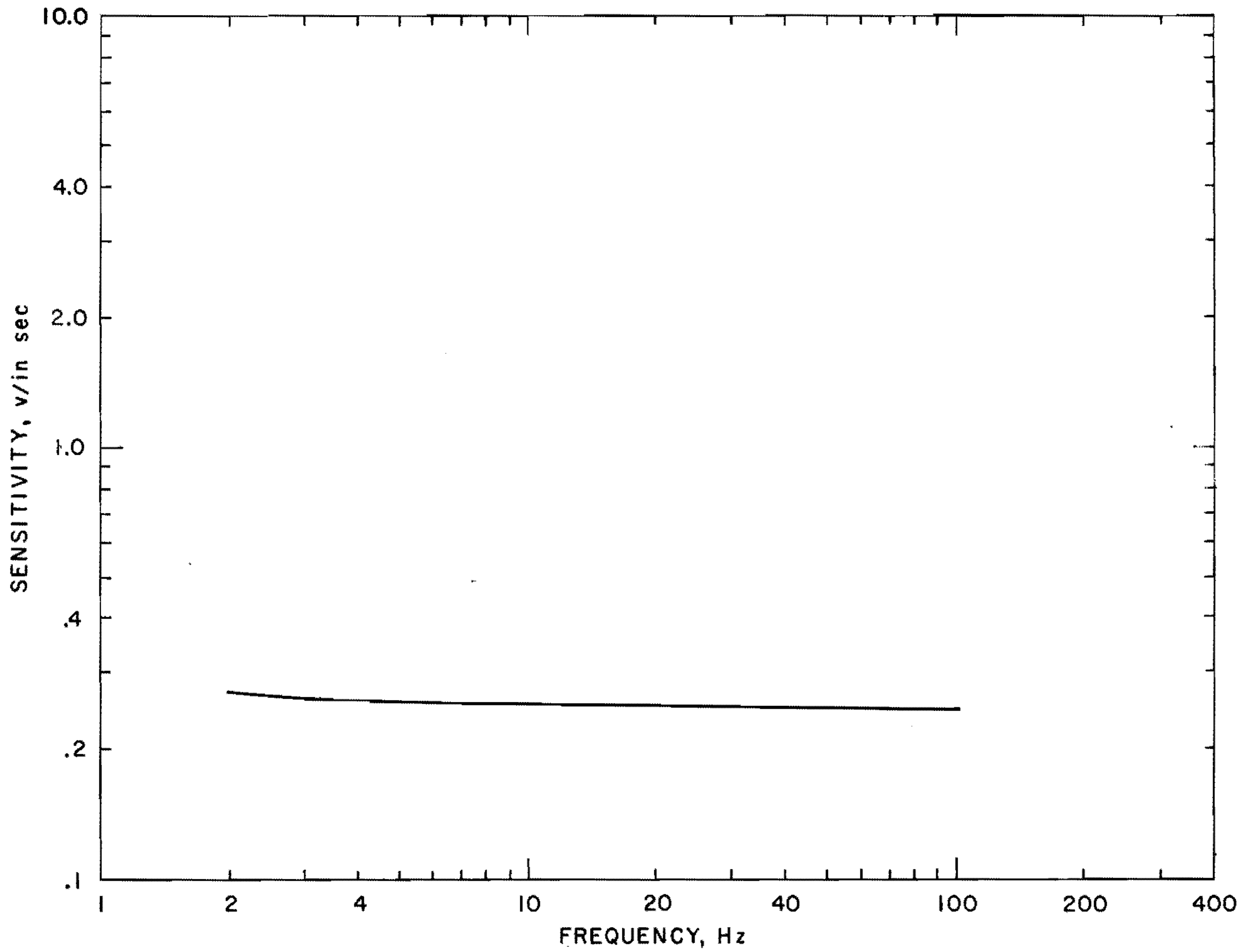

FIGURE A-30. - B & K model 4370 sensitivity versus frequency.

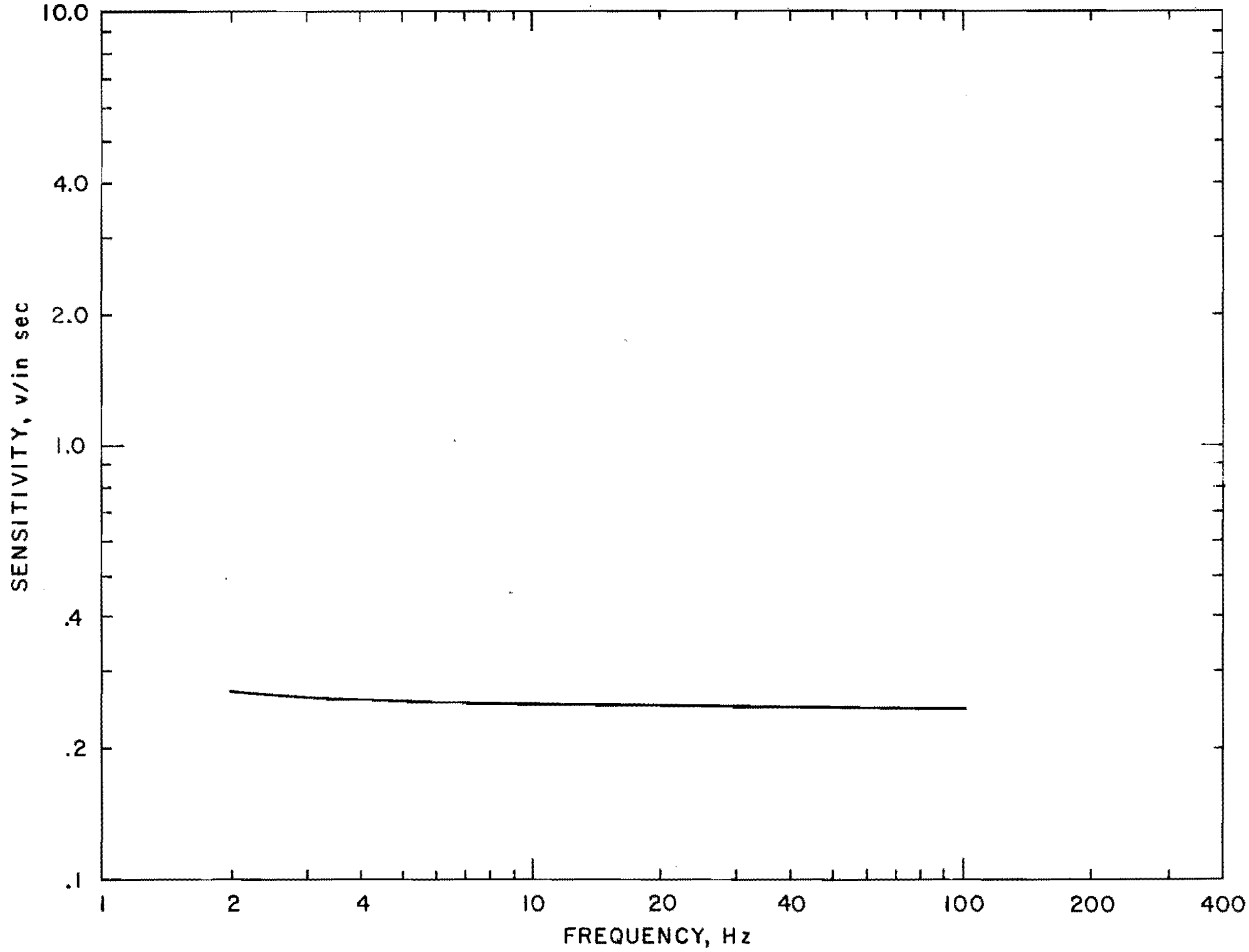

FIGURE A-31. - B & K model 4321 sensitivity versus frequency.

APPENDIX B.--FREQUENCY AND TRANSDUCER CALIBRATION DATA

TABLE B-1. - Peak and -20-dB-range frequency data

Radial		Vertical		Transverse	
Peak	-20-dB range	Peak	-20-dB range	Peak	-20-dB range
COAL MINE SHOTS, Hz					
5.6	2 - 29	11.8	2 - 37	12.8	5 - 24
5.4	3 - 38	23.2	3 - 38	5.2	3 - 62
19.0	NA NA	NA	NA NA	NA	NA NA
9.2	3 - 62	NA	NA NA	NA	NA NA
18.8	2.5- 43	22.6	2 - 36	16.0	2 - 31
5.6	3 - 27	6.4	3 - 38	8.4	2 - 30
3.8	3 - 35	5.6	4 - 37	5.4	3 - 31
7.6	2 - 22	NA	NA NA	15.8	2 - 85
11.2	3 - 27	7.6	3 - 44	11.2	3 - 25
5.8	4 -100	21.8	2 - 80	15.8	1 -100
24.4	3 - 41	NA	NA NA	6.4	2 - 40
15.4	3 - 61	NA	NA NA	27.6	5 - 53
20.4	4 - 46	4.6	2 - 76	5.6	2 - 99
8.0	4 - 52	28.4	4 - 78	13.6	4 - 49
8.5	2 - 90	8.0	3 - 96	8.2	2 - 69
13.8	NA NA	NA	NA NA	NA	NA NA
29.0	6 - 83	28.2	8 - 88	13.4	2 - 75
12.0	3 - 31	15.2	3 - 65	15.4	3 - 35
23.0	8.5- 41	28.6	9 - 71	18.0	11.5- 43
12.0	3 - 31.5	10.8	3 - 38	10.2	3 - 30.5
12.4	2 - 63	33.8	3 - 63	34.4	3 - 65
11.6	4 - 56	29.8	3 - 96	29.2	5 - 36
11.2	5 - 31.5	24.2	2 - 53.2	12.2	9 - 29.5
12.2	1 - 50	9.4	2 - 81	11.2	3 - 36
21.6	2 - 47	21.2	2 - 84	13.4	2 - 32
12.8	2 - 42	16.1	2 - 57	6.8	5 - 57.5
NA	NA NA	23.2	7 - 91	20.2	5.5- 75
19.8	6.5- 46	NA	NA NA	19.0	5.5- 45.5
25.6	4.8- 34	25.8	4.5- 61	6.2	4.5- 29.5
17.2	7 - 27	14.8	9 - 57	14.8	6 - 32.5
12.2	10 - 39	27.4	10.5- 48	27.8	3 - 62
30.4	3 - 59	7.8	3 - 64	38.0	2 - 86
7.6	2 - 85	5.0	2 - 76	4.6	2 - 70
7.0	3 - 40	7.0	3 - 49	18.0	3 - 49
18.2	3 - 41	15.0	3 - 47	20.6	3 - 47
NA	NA NA	20.4	3 - 47	NA	NA NA
9.4	3 - 49	18.6	4.5- 27	18.6	3 - 39
23.4	4 - 69	11.4	3 - 94	20.4	2 - 59
23.4	2 - 52	6.4	3 -105	24.0	1 - 78
18.8	6 - 76	17.4	6 - 86	17.8	1 - 71
17.4	5 - 61	14.2	5 - 92	17.4	1 - 65
26.8	2 - 69	14.6	6 - 82	21.0	1 - 71
19.0	6 - 88	16.4	4 - 88	17.4	1 - 65

NA Not available.

TABLE B-1. - Peak and -20-dB-range frequency data--Continued

Radial		Vertical		Transverse	
Peak	-20-dB range	Peak	-20-dB range	Peak	-20-dB range
COAL MINE SHOTS, Hz--Continued					
24.2	1 - 72	24.0	1 - 75	24.2	4 - 73
17.2	7.5- 52	7.4	4 - 88	17.8	9 - 44
21.8	3 - 72	7.6	5 - 88	19.8	6 - 51
20.8	7.5- 73	21.4	4 - 49	20.2	13 - 61
QUARRY SHOTS, Hz					
15.4	7 - 46	14.6	3 - 83	22.2	2 - 71
NA	NA NA	26.6	7 - 73	NA	NA NA
NA	NA NA	26.2	7 - 56	NA	NA NA
26.2	6 - 74	26.2	5 - 91	NA	NA NA
NA	NA NA	10.2	5 - 82	NA	NA NA
NA	NA NA	16.3	4 - 93	NA	NA NA
20.8	7 - 65	26.2	6 - 48	20.8	7 - 60
NA	NA NA	24.3	10 - 57	NA	NA NA
22.1	14.5- 30	31.0	6 - 49	22.6	8 - 43
23.8	8 - 74	42.8	13 -158	NA	NA NA
32.4	7 - 63	31.8	9 - 49	12.0	7 - 48
19.2	3 - 42	36.4	NA NA	24.4	19 - 47
11.8	7 - 34	33.4	2 - 69	12.6	9 - 15
18.8	8 - 98	41.2	3 - 98	18.2	7 - 43
33.8	12 - 68	33.6	2 -132	22.6	5 - 70
5.8	4 - 50	28.8	2 - 94	27.6	4 - 62
24.8	5 - 57	30.0	3 - 58	NA	NA NA
27.0	4 - 76	47.2	3 - 86	NA	NA NA
25.2	6 - 77	79.0	9 - 49	NA	NA NA
23.0	7 - 52	22.6	15 - 52	NA	NA NA
28.0	1 - 80	32.6	1 - 79	NA	NA NA
28.8	3 - 72	16.2	5 - 53	NA	NA NA
28.2	3 - 68	25.0	4 - 94	NA	NA NA
41.6	5 -130	42.0	8 -115	NA	NA NA
17.0	6 - 55	32.0	4 - 58	NA	NA NA
26.8	5 - 68	19.2	5 - 80	26.8	6 - 71
10.8	4 - 92	NA	NA NA	NA	NA NA
16.3	4 - 54	16.6	5 - 70	16.3	3 - 46
20.5	11 - 55	21.8	11 - 79	22.4	2 - 83
28.2	5 - 32	14.7	8 - 55	20.2	7 - 63
NA	NA NA	26.9	NA NA	NA	NA NA
14.4	12 - 41	37.1	11 - 58	NA	NA NA
14.4	5 - 54	21.4	8 - 62	NA	NA NA
22.1	8 - 66	NA	NA NA	NA	NA NA
22.7	6 - 44	22.1	13 - 49	NA	NA NA
22.1	5 - 87	NA	NA NA	NA	NA NA
22.7	5 - 92	22.1	14 - 48	NA	NA NA
22.4	4 - 38	NA	NA NA	NA	NA NA
NA	NA NA	NA	NA NA	24.2	2 - 40
6.6	5 - 25	14.2	7 - 44	6.8	5 - 27
NA	NA NA	NA	NA NA	15.8	NA NA

NA Not available.

TABLE B-1. - Peak and -20-dB-range frequency data--Continued

Radial		Vertical		Transverse	
Peak	-20-dB range	Peak	-20-dB range	Peak	-20-dB range
CONSTRUCTION SHOTS, Hz					
83.6	45.2-121.2	84.0	23.6-187.2	84.4	23.2-162.8
22.0	3.2-134.0	33.6	8.4-172.8	22.8	8.4- 98.8
41.6	15.6-139.2	59.2	16.4-153.2	39.2	14.8-172.8
16.4	10.4- 62.8	38.4	10.4- 94.0	16.4	8.4- 55.6
37.2	10.8- 78.0	16.8	10.8- 88.4	36.4	9.6- 63.6
17.6	12.0- 98.0	20.4	9.6-149.6	21.6	18.8-191.2
40.0	17.6-100.4	68.4	17.6-111.2	37.6	18.4-109.6
39.2	14.4- 92.4	55.6	15.2-129.2	25.2	18.0- 98.4
34.0	4.0-151.0	72.4	14.0-129.6	34.0	13.6- 82.8
36.0	10.4-128.0	40.4	23.6-119.6	38.8	8.8-118.8
34.0	7.2-155.6	40.0	14.4-145.6	33.2	7.6-130.0
NA	NA NA	34.0	3.6- 77.6	36.4	23.6-110.4
9.2	1.2- 73.6	6.8	4.4- 53.2	NA	NA NA
100.0	47.0-195.0	100.0	59.0-162.0	104.0	50.0-161.0
86.0	31.0-171.0	87.0	47.0-164.0	77.0	46.0-165.0
38.4	15.6- 95.2	38.4	18.8-150.0	46.4	24.0-164.0
74.0	11.2-116.0	104.0	16.0-177.2	51.6	9.6-138.8
60.4	4.0-120.0	59.2	25.2-118.0	83.6	18.4-192.0
NA	NA NA	NA	NA NA	41.6	NA NA
12.0	2.8- 50.0	18.4	4.4- 88.0	20.0	5.2- 71.6
20.4	4.4-104.0	69.2	30.8-195.6	34.4	5.6- 94.0
37.6	14.4- 64.8	50.0	22.0-140.8	37.6	16.0- 83.6
27.6	10.8- 58.4	37.6	15.6-139.6	28.0	16.0- 77.2
32.0	14.8- 56.8	45.0	26.0-178.0	38.4	14.8- 87.6
38.4	14.0- 72.4	26.8	14.8-158.0	26.8	8.8- 94.8
40.4	3.2- 99.2	22.0	16.0-157.6	21.6	3.2- 96.0
36.4	13.2-126.0	27.2	4.4-126.0	20.4	13.2- 88.0
17.6	15.2-133.6	55.6	16.4-119.2	55.6	16.0-107.6
53.6	18.4- 96.4	76.0	14.0-232.0	56.0	11.6-104.4
NA	NA NA	NA	NA NA	46.0	NA NA
NA	NA NA	NA	NA NA	44.8	NA NA

NA Not available.

TABLE B-2. - Transducer calibration data

(Transducer sensitivity, v/in/sec)

Frequency, Hz	Geo Space HS-1		Mark Products L-1B		Unholtz-Dickie 1000PA		Geo Space VLF			Mark Products L-15B		Vibra-Metrics MB-120		Vibra-Metrics MB-124	
	V	H	V	H	V	H	V	H_1	H_2	V	H	V	H	V	H
					↓	↓	↓	↓	↓						
2	0.049	0.066	0.128	0.140	1.03	1.06	3.83	4.03	3.87	0.036	0.046	0.0486	0.042	0.015	0.015
2.5	.077	.115	.227	.221	1.01	1.09	3.91	4.09	4.24	.050	.066	.0671	.062	.022	.023
3	.115	.148	.354	.338	1.01	1.15	4.07	4.33	4.26	.086	.095	.0793	.077	.033	.033
3.5	.145	.188	.490	.486	1.01	1.03	4.20	4.40	4.31	.123	.122	.0884	.089	.043	.046
												↓	↓		
4	.192	.235	.648	.628	1.02	1.02	4.22	4.30	4.22	.162	.160	.0921	.096	.054	.050
4.5	.230	.250	.789	.750	1.03	1.03	4.47	4.27	4.32	.210	.200	.0921	.097	.063	.067
5	.275	.290	.874	.853	1.02	.99	4.33	4.45	4.32	.236	.230	.0921	.098	.073	.076
6	.330	.325	.964	.925	1.03	1.00	4.37	4.51	4.22	.274	.262	.0933	.100	.084	.039
														↓	↓
7	.385	.340	.910	.866	1.05	1.05	4.35	4.29	4.22	.268	.265	.0956	.100	.091	.095
10	.410	.360	.878	.828	1.02	1.04	4.38	4.46	4.15	.250	.245	.0964	.101	.093	.098
			↓	↓						↓	↓				
15	.400	.365	.824	.794	1.08	1.09	4.54	4.60	4.15	.233	.230	.0929	.102	.094	.099
	↓	↓													
25	.360	.340	.820	.751	1.03	1.09	4.54	4.73	4.05	.214	.225	.0920	.098	.097	.100
35	.365	.350	.760	.746	1.04	1.12	4.75	4.78	4.23	.228	.228	.0974	.101	.098	.094
50	.365	.355	.739	.762	1.01	1.11	4.65	4.66	4.05	.219	.225	.0963	.103	.100	.097
70	.375	.355	.787	.750	1.01	1.10	4.77	4.60	4.05	.233	.220	.0995	.105	.099	.096
100	.370	.355	.803	.750	1.05	.99	4.42	4.60	4.31	.208	.220	.1049	.103	.099	.095
			↑	↑	↑	↑				↑	↑				
200	.340	.375			.69	.61	4.23	4.20	4.03	.214	.225	.0968		.093	.092
250	.350	.390			.52	.50	3.92	3.90	3.83	.214	.235	.0964		.094	.093
Regression	↑	↑					↑	↑	↑			↑	↑	↑	↑
line y=mx+b															
m-slope	.0001	.0002	-.0002	-.0003	.0001	.0005	-.0005	-.0011	-.0012	-.0002	-.0001	.00002	.00006	.00004	.00002
b-intercept	.371	.340	.798	.773	1.03	1.06	4.35	4.45	4.21	.230	.230	.0944	.0986	.0961	.0976
Standard deviation	.009	.004	.037	.017	.020	.051	.282	.240	.126	.010	.002	.003	.002	.003	.002

↓ ↑ Frequency range of sensitivities in least-squares line fit.
V Sensitivity of vertical transducer.
H Sensitivity of horizontal transducer.

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