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Model-Scale Sound Propagation Experiment

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PROPAGATION EXPERIMENT (NASA) 32 pCSCL 20A

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ABSTRACT

The purpose of this paper is to report the results of a scale model propagation experiment to investigate grazing propagation above a finite impedance boundary. In the experiment, a 20x25 ft ground plane was installed in an anechoic chamber. Propagation tests were performed over the plywood surface of the ground plane and with the ground plane covered with felt, styrofoam, and fiberboard. Tests were performed with discrete tones in the frequency range of 10 to 15 kHz. The acoustic source and microphones varied in height above the test surface from flush to 6 in. Microphones were located in a linear array up to 18 ft from the source. A preliminary experiment using the same ground plane, but only testing the plywood and felt surfaces was performed. The results of this first experiment were encouraging, but data variability and repeatability were poor, particularly for the felt surface, making comparisons with theoretical predictions difficult. In the main experiment the sound source, microphones, microphone positioning, data acquisition, quality of the anechoic chamber, and environmental control of the anechoic chamber were improved. High-quality, repeatable acoustic data were measured in the main experiment for all four test surfaces. Comparisons with predictions are good, but limited by uncertainties of the impedance values of the test surfaces.

INTRODUCTION

Acoustic propagation above a finite impedance boundary is a subject which has received much attention, particularly in the last decade when accurate and sophisticated propagation models have been required. Grazing propagation above a boundary has been of particular interest. The propagation models developed to predict this situation have typically been validated with outdoor measurements. As propagation distances of interest have increased, changing the focus to low frequency propagation, the difficulty of obtaining quality outdoor measurements have increased due to the increased influence of propagation anomalies such as wind and temperature gradients, turbulent scattering, and topology. Propagation models which include these effects are becoming more numerous and practical. Experimental verification of these models will rely more heavily on scale model experiments due to the control and idealization this class of experiments allow. A foundation for performing more complicated scale model propagation experiments is the ability to perform and understand a scale model propagation experiment of a point source above a flat, finite impedance boundary.

Theoretical models for sound propagation above a finite impedance boundary are well developed and understood. A good review of the theoretical developments is given by Parrott et al (ref. 1) and Pao et al (ref. 2). Model scale experiments have been used in noise control applications, as well as in propagation research, and are reviewed by Anderson (ref. 3).

The purpose of this paper is to report the results of a scale model propagation experiment to investigate grazing propagation above a finite impedance boundary. The experiment used the same ground plane and was performed in the same anechoic chamber as the model scale propagation experiment described in reference 1. The first experiment was primarily a feasibility experiment. For that experiment, a 20x25 ft model ground plane was constructed. Propagation tests were performed over the plywood ground plane surface and over a layer of felt placed over the plywood. Tests were performed with discrete tones in the frequency range of 10 to 15 kHz. The acoustic source and microphones varied in height above the test surface from flush to 4 in. Microphones were located in a linear array up to 18 feet from the source. The preliminary experiment was encouraging, but

data variability and repeatability were poor, particularly for the felt surface, making comparisons with theoretical predictions difficult. In the main experiment the sound source, microphones, microphone positioning, data acquisition, quality of the anechoic chamber, and environmental control of the anechoic chamber were improved. The second experiment covered the same frequency range and repeated the propagation test over plywood and felt. Two additional surfaces, styrofoam and fiberboard, were also tested. A second part of the experiment, not reported here, involved propagation over an idealized but finite impedance hill. High-quality, repeatable acoustic data were measured in the second experiment for all four test surfaces. Comparisons with predictions are good, but limited by uncertainties of the impedance values of the test surfaces.

EXPERIMENTAL APPARATUS AND PROCEDURE

Anechoic Chamber

The experimental apparatus and check-out are given in great detail in reference 4 which is a master thesis concerned with most of the flat ground plane portions of this experiment. Additional information about the ground plane model may be found in reference 1. The experiment was performed in the anechoic chamber in Building 1218 at NASA Langley Research Center in Hampton, Virginia. The dimensions of the anechoic chamber are (wedge tip to wedge tip) 27 by 25 by 27.5 ft high. The acoustic wedges in the chamber are fiberglass and covered with wire. The chamber has the capability of flow and has a large collector in the ceiling. The acoustic performance of the basic chamber at the test frequencies, 10 to 15 kHz, was tested and judged not to be acceptable. A perimeter of acoustic foam wedges was positioned around the ground plane model and as many as practicle light fixtures, receptacles, and other metal objects were covered with foam. The environmental control of the chamber was also judto be insufficient. The chamber has no active heating or cooling system. It is open to the outside by the collector exit, the end of a trench, and a vent in the old compressor mechanical room. These openings were closed or plugged.

Ground Plane Model

The ground plane model was the one constructed for the experiment reported in reference 1. The ground plane model was re-installed in the anechoic chamber for the present test. The model is comprised of 15 modules each consisting of a 4 by 8 ft sheet of $3/4$ in marine plywood on a wooden frame. Figure 1 shows a diagram of the model ground plane. The modules go together to form a ground plane of dimensions 20 by 25 ft. The perimeter of the ground plane was fitted with a shroud to minimize edge diffraction. The shroud consisted of one quarter of a circular cross section, heavy plastic pipe with a diameter of 16 in. Four test surfaces were investigated with the model ground plane: the plywood surface of the model ground plane, and the plywood surface covered with layers of $1/8$ in thick felt, 1 in thick styrofoam, and $1/4$ in fiberboard. The felt was made of wool, the top surface of the styrofoam was lightly sanded, and the fiberboard had a smooth finish. All three layers were secured to the ground plane with double backed tape. Figure 2 shows a photograph of the styrofoam test surface installed on the model ground plane.

Acoustic Source

The acoustic source was a tube connected to a 100 watt mid-range driver with approximately 3 ft of heavy rubber tubing. The tube consisted of a heavy brass pipe of $1/2$ in inside diameter. The tube was terminated with a solid metal plug. The plug was disk shaped and had the same outside dimensions as the tube. A $.2$ in hole was drilled just beneath the plug through the tube. On top of the plug was a 7.5 in long tube of the same outside dimension as the tube. This second tube terminated in a gradual cone. The tube assembly was designed to simulate an infinite cylinder with an acoustic point source on its surface. The rubber tube connecting the tube to the drive was wrapped with mass-loaded foam. The acoustic driver was wrapped with multiple layers of mass-loaded foam and placed in a heavy wood box which was suspended with elastic cord underneath the model ground plane. With this set-up the tube would stick up through the ground plane. The position of the tube would be adjusted until the source hole would be at the desired height above the ground plane surface. The point source tube was used at the following four heights: flush with the test surface, 1.5, 3.0, and 6.0 in above the test surface. The tube was manually adjusted to the desired height. Directivity patterns for the source tube

used may be found in reference 4. The source tube was acceptably omnidirectional in the direction of the microphone array, but did not radiate as much in the direction of the large collector in the ceiling of the anechoic chamber. The source tube was used to generate continuous discrete frequency signals.

Probe Microphones

The primary receivers in the experiment were seven probe microphones located in a linear array extending roughly from 6 in to 18 ft from the source tube. The location of the source and receivers is illustrated in figure 1. The solid triangle symbol in the figure is the source location which was located one foot from the ground plane edge. The seven microphone locations are illustrated in the figure. The horizontal distances from the closest edge of the source tube to the center of the probe microphones is found in table 1. The microphones were not positioned on a radial line from the source tube. Instead, they were randomly positioned within a 10 deg. cone such that no microphone would 'block' one behind it. The probe microphones consisted of 10.0 in long, 0.1 in outside diameter probe tubes connected to 1/2 in condenser microphones. The probe microphones were used so that the active portion of the microphone could be positioned beneath the ground plane with only the probe tube sticking through the ground plane and test surface. Also, advantage was taken of the fact that the probe tubes have a resonant frequency response. The frequency response of three probe tubes is illustrated in figure 2. The test frequencies were selected to be the peak probe tube response frequencies which were 9945., 10644., 11298., 12673., and 14025. Hz. The probe microphones were calibrated at least twice a day. The calibration procedure included mounting the probe microphone such that the end of the probe was flush to the inside surface of a circular cross section plane wave tube. Opposite the probe tube was a 1/4 in condenser type microphone which was also flush mounted without a grid cap to the inside surface of the plane wave tube. The condenser microphone was calibrated according to standard laboratory practice. The calibration of the probe microphones was a relative calibration referenced to the condenser microphone. A high frequency tweeter was mounted on the end of the plane wave tube and controlled by a computer to generate the discrete test frequencies. A thermocouple was placed on the probe tube during calibration and data taking to monitor the temperature of the probe.

Figure 3 is a photograph of the probe microphone calibration apparatus located in the trench beneath the ground plane model. A probe microphone may be seen installed in the calibration device.

Four of the probe microphones, 3 through 6(see Figure 1), were mounted on computer controlled traverses; the remaining three probe microphones were manually set to be flush with the test surface. The traverses allowed for easy and quick changes in height of the four probe microphones from flush to the test surface to 6 in above the test surface. The flush positions of the traverse microphones were defined as the position at which a digital ohm meter registered a resistance when the end of the probe microphone approached a metal mounument positioned on top of the test surface. The probe tube and metal monument were connected to the two leads of the ohm meter. This procedure was found to be more accurate and repeatable than mauually defining the flush position. For the felt surface, the monument was position on top of the plywood ground surface. The data analysis software take this exception into account. The accuracy and backlash of the four traverse systems were checked three times with a laser interferometer system. With backlash correction the accuracy of the traversing systems was typically .004 in.

The model ground plane, point source tube, and probe microphones in the anechoic chamber together made a very good experimental apparatus. A key to the suitability of the set-up was use of the trench indicated in Figure 1 with the dashed lines. All of the experimental hardware was mounted underneath the model ground plane. Access to the hardware was made through the trench. Only the point source tube and the probe microphones when they were in elavated positions protruded into the acoustic propagation field. The test apparatus was checked for source induced vibration contamination of the probe microphone signals. Fourteen accelerometers and a ten-pound shaker were used in the check. Little source tube induced vibration was measured, and it was concluded that source induced vibration did not effect the measurements made with the probe microphones. The model ground plane was equipped with two thermocouple profile instruments which measured the temperature in the plywood surface, at the surface, 2 in, and 6 in above the surface. The profilers were located one foot away on either side of the point source tube, perpendicular to the microphone array. The relative humidity and atmospheric pressure

were measured each test day.

Test Conditions & Procedures

The test matrix is illustrated in Figure 5. Each block in the test matrix represents a run. The three letter abbreviations in the test matrix block represent runs for the four test surfaces. Data were measured for four source heights and five frequencies. The source heights were flush, 1.5, 3.0, and 6.0 in above the test surface. The five test frequencies were 9945, 10644, 11298, 12673, and 14025 Hz. Data were not taken for each combination of source height, frequency, and test surface. Typically one but as many as five repeat runs were taken for the conditions shown.

A run was defined as measuring data for all the probe microphone heights for a particular source height and test frequency. A run consisted of data taken at 35 microphone heights. The data acquisition was automated and once initiated proceeded under computer control. At the beginning of a run all the microphones were flush with the surface. The first measurements made in a run were the background noise at the seven probe microphones with the point source turned off. The point source then was turned on and the source amplitude was adjusted so that microphone 7, the microphone the greatest distance away from the source, had a signal-to-noise ratio of 10 dB. The highest source level at microphone 1 required was 82 dB. After the amplitude of the point source was set, data were measured with all seven probe microphones. The probe microphone and profiler thermocouples were read. The traverse microphones, microphones 3 through 6, were then moved up .1 in. Acoustic data were measured from the traverse microphones and microphone number 1, the closest flush mounted microphone. The traverse microphones were raised another .1 in and data measured from the same five microphones. This process was repeated four times. After the data were taken at the fifth microphone height, the microphone probe and profiler thermocouples were read. Data were then taken five times from the traverse microphones and microphone 1, incrementing the heights of the moving microphones by .1 in between data samples. Again the thermocouples were read and the cycle continued until the traverse microphone heights were 2.9 in. The microphones were then moved to 3.0, 4.0, 5.0, and 6.0 in. Data were taken with the five microphone group at each position. The microphones were moved to the flush position, and data taken with all seven microphones,

as well as with all the thermocouples. The source was turned off and a second set of ambient levels was taken for all seven microphones. A run took approximately 1.75 hours to complete.

Data Acquisition and Reduction

The data acquisition and reduction hardware are illustrated in figure 6. The frequency and amplitude of the output of the point source was computer controlled. The probe microphone signals were reduced one at a time through the use of a mutiplexer. The selected probe microphone signal was high-passed filtered at 5 kHz, amplified, and digitized at 50000 points per second. A software based 4096 point Fast Fourier Tranform (FFT) was performed which had a bandwidth of 12.5 Hz. The result of the FFT at the test frequency was corrected for principle error (ref. 5). Knowledge of the test frequency allows for correction of power leakage from the discrete frequency signal to near-by frequency bands. The results of ten FFTs were averaged for microphones 1 to 4; 25 results were averaged for microphones 5 to 7. The 90 percent confidence interval for microphone numbers 5 to 7, assuming a chi-square distributed random varaible, was -1.3 to 1.6 dB. This measurement uncertainty interval is a upper bound on the actual mesurement uncertainty since the nature of the measured signal was periodic rather than random.

PROPAGATION THEORY

Mathematical Model

The theoretical model used to make predictions to compare with the measured results is the model of a point source above a finite impedance plane boundary (refs. 2 and 5) as shown in Figure 7. The model is used to predict what will be defined as ground effect (GE). Ground effect is the influence expressed in decibels of the ground surface on the propagation of an acoustic signal. Ground effect is the decibels of the level of difference in a received signal which has propagated over a ground surface and the level which would have been received if no ground surface were present (the free-field level). The ground effect prediction equation is

$$GE = 20 \log_{10} \left[1 + \frac{r_1}{r_2} Q e^{ik(r_1 - r_2)} \right] \quad (1)$$

where r_1 and r_2 are, respectively, the direct and reflected path lengths, k is the wavenumber in air, and Q is given by

$$Q = R_p + F(w)(1 - R_p) \quad (2)$$

where R_p is the plane wave reflection coefficient for a locally reacting surface, F is the so-called boundary loss factor, and w is the numerical distance for a locally reacting surface given by

$$w = \frac{1}{2} ikr_2 \frac{(\sin\phi + \beta)^2}{1 + \beta\sin\phi} \quad (3)$$

where ϕ is the grazing angle of the reflected path, and β is the normalized admittance. The effective image source strength, Q , is a function of ground impedance because the plane wave reflection coefficient and the numerical distance depend on ground impedance.

Impedance Estimation

In order to make ground effect predictions, the acoustic impedance of the test surfaces at the test frequencies is required. Unfortunately, it was not possible to directly measure the impedance of the test surfaces at the test frequencies. The impedances of the test surfaces were measured in a normal incidence impedance tube for the frequency range of 500 to 3000 Hz. The measured impedance results were then extrapolated to the test frequency range of 10 to 15 kHz. The extrapolation was performed by fitting the measured values of impedance with an empirical impedance model and then using the model to predict the values of impedance at the test frequencies. Two empirical impedance models were used. The single parameter model of Delany and Bazley (ref. 6) was used with the plywood, fiberboard, and styrofoam impedance data. The four parameter model of Attenborough (ref. 7) was used with the felt impedance data. The imaginary part of the measured impedance for plywood, fiberboard, and styrofoam were, in general, larger than real part. The impedance model of Delany and Bazley predicted the imaginary part to be larger than the real part of the impedance. The Attenborough model predicted the real part to be larger than the imaginary part which was closer to the felt measured results. The extrapolation of the plywood measured impedance data was accomplished on the bases of

the magnitude of the plane wave reflection coefficient (see refs. 1 and 4). The fiberboard and styrofoam results were based on best fits to the measured real and imaginary parts of the impedance. The normal incidence impedance tube measured styrofoam impedance values were supplemented by impedance values for similar styrofoam measured at higher frequencies (16, 37, and 103 kHz) by Jones et al (ref. 8). The result of the best fit of the Delany and Bazley empirical model to the measured styrofoam impedance data is shown in figure 8. The values selected for the four parameter Attenborough impedance model were suggested by Dr. Richard Raspet and his student, Mr. B. Bobak. The values of extrapolated values of impedance used for the four test surfaces and the best fit parameters of the empirical models used are given in table 2.

RESULTS AND DISCUSSION

Data Repeatability

A goal in any experiment is good data repeatability. Data repeatability was a problem in the preliminary experiment for the felt test surface. Repeatability was not easily obtained in the main experiment. After much effort in improving the environmental control of the anechoic chamber, the anechoic qualities of the chamber, developing the directional point source tube, and monitoring the temperature changes of the probe microphones excellent data repeatability was achieved. An example of the data repeatability for the felt surface is given in Figure 9. The data given in the figure are for a frequency of 14025 Hz, and a source height of 6 in. The data represent two repeat runs made on different days and have been corrected for slightly different source levels. Data are given for the four traverse microphones. Probe microphone height is plotted versus measured sound pressure level (SPL). Notice that, since the flush or zero position of the traverse was referenced to the top of the plywood model ground plane surface, the first points plotted are actually associated with negative probe microphone heights. The fine microphone height spacing below 3 in is readily apparent in the figure. As are the one inch steps above this height to a microphone height of 6 in.

Acoustic Spreading

In noise propagation studies noise level is often plotted versus distance or the loga-

rithm of distance to investigate the dependence of sound level on propagation distance. In the absence of the ground, the sound from a point source spreads spherically, which is characterized by a 6 decibel (dB) decrease in level with every doubling of propagation distance. Three decibels for every doubling of distance is characteristic of a line source and is referred to as cylindrical spreading. Propagation above a finite impedance boundary may exhibit cylindrical spreading. When this occurs a surface wave is said to exist. If a twelve decibel decrease for every doubling of distance is observed above a boundary a ground wave is said to exist. Ground or surface waves do not always exist, and in fact the spreading observed above a finite impedance surface may be spherical or something else. Mathematically, for a given geometry and frequency, the value of impedance determines the existence of a ground wave or a surface wave through the dependence of the boundary loss factor on numerical distance. Data is plotted in Figure 10 to illustrate the measured spreading for grazing propagation over three of the four surfaces tested. In the figure, data are given for propagation over plywood, felt, and styrofoam for a frequency of 9945 Hz with the source and the microphones flush with the surfaces. The plywood and styrofoam results exhibit spherical spreading while the felt results follow a 12 dB characteristic which is characteristic of a ground wave.

Comparison of Data and Predictions

The next four figures are examples of comparisons between measurements and ground effect predictions, one for each surface tested. The ground effect predictions were made with the mathematical model described earlier. Input to the prediction model was the test frequency, source and probe microphone geometry, temperature, and ground impedance. The values of ground impedance used in the model were discussed earlier and are listed in table 2. In order to cast the measured sound pressure level of the probe microphones into a measure of ground effect, an estimate of the free-field sound pressure level for each probe microphone position is required. An estimate of the free-field level of the source was obtained for each run by selecting a source level which made the computed ground effect match the predicted ground effect for the 6 in high position of microphone number 3, the probe microphone closest to the source. In other words, the calculated ground effect was made to agree with the predicted ground effect at this one point out of the total 140 points

per run. For example, say for a particular source height and surface, the predicted ground effect was 3 dB for the 6 in position of microphone number 3. This means that the presence of the ground surface made the sound level at this position 3 dB louder than if the ground surface were not present. In this case then the source free-field level was taken to be 3 dB less than the measured SPL at this position. This free-field level is associated with the direct path distance between the source and the 6 in microphone number 3 position. Spherical spreading corrections are then applied to this free-field estimate to calculate ground effect at other microphone positions and their corresponding direct path distances. If, for some reason, the 6 in microphone number 3 SPL is wrong or the prediction for this position is wrong, a bias is introduced into the measurement/prediction comparison. Evidence of a bias would be the predicted ground effect curve to be offset a constant amount with respect to the calculated ground effect results.

The comparison of calculated and predicted ground effect for the plywood surface for a frequency of 9945 Hz and the source flush is given in Figure 11. The agreement between measurement and theory is judged to be good. The largest disagreement between the two occurs for microphone number 6 at microphone heights less than an inch. Here the maximum difference is less than 3 dB. As illustrated in the spreading results, and supported with this data presentation for plywood at grazing incidence, the sound propagates with spherical spreading and with twice the amplitude of a similar signal propagating in free space.

Results are given in Figure 12 for a frequency of 14025 Hz with the source 6 in above the fiberboard test surface. The location and magnitude of the interference minima and maxima are closely predicted for microphone number 3. A curious underprediction of the magnitude of the minima occurs in the microphone number 4 results. This fact would seem to indicate that the predicted magnitude of the spherical reflection coefficient (the second term in the ground effect prediction equation) was too small. The agreement between the calculated and predicted ground effect for microphone numbers 5 and 6 is best close to the surface. Further above the surface for these two microphones an interference minima is measured but the predicted minima is off in location and in magnitude.

Results for styrofoam are given in Figure 13 for a frequency of 14025 Hz and a flush

source. These results show the worst agreement between calculated and predicted ground effect. The agreement is judged to be fair for microphone numbers 3 and 4. However, the apparent interference observed in the measured results for microphone numbers 5 and 6 above 3 inches is not predicted, as in the previous results.

Calculated and predicted ground effect results are compared in Figure 14 for the felt test surface for a frequency of 11298 Hz and a source height of 1.5 in. This agreement between theory and measurement is judged to be excellent, which indicates that the extrapolated impedance values are correct and that the local reaction assumption inherent in the ground effect mathematical model appears, somewhat surprisingly, to be valid for the felt surface.

CONCLUDING REMARKS

A successful scale-model sound propagation experiment was performed to investigate grazing propagation over a finite impedance ground plane. Excellent data repeatability was achieved. The experiment apparatus, as a whole, was adequate and should have application to more complicated scale model propagation experiments. The comparison of predicted and measured ground effect was generally good. A noteworthy discrepancy is that, with the source elevated for the hard surfaces the measured and predicted interference maxima and minima for the closest traversing microphone were good; however, the predicted amplitude of the first minima for the next probe microphone was too small. The location of the minima was correct. Uncertainties in the values of the test surface ground impedance may have been the cause of this theory/measurement disagreement. An improvement in this experiment and in future experiments would be the ability to directly measure the impedance of the test surfaces at the test frequencies.

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TABLE I.- MICROPHONE LOCATION

<u>MIC. NO.</u>	<u>HORIZONTAL DISTANCE FROM SOURCE, IN.</u>
1	6.46
2	13.27
3	26.66
4	53.66
5	107.62
6	161.56
7	215.58

TABLE II.- EXTRAPOLATED IMPEDANCE VALUES

DELANEY & BAZLEY MODEL

<u>SURFACE</u>	<u>BEST FIT GROUND FLOW RESISTANCE MKS UNITS</u>	<u>FREQUENCY, HZ</u>	<u>RE(Z)</u>	<u>IM(Z)</u>
STYROFOAM	24,285,386	9945	18.5	22.6
		11298	16.9	20.6
		14025	14.5	17.6
FIBERBOARD	34,348,036	9945	23.7	29.1
		11298	21.7	26.5
		14025	18.6	22.7
PLYWOOD	48,000,000	9945	30.2	37.2
		11298	27.6	33.9
		14025	23.6	28.9

ATTENBOROUGH MODEL

SURFACE: FELT
 GROUND FLOW RESISTANCE
 VOLUME POROSITY
 GRAIN SHAPE FACTOR
 PORE SHAPE FACTOR

50,000 MKS UNITS
 1.
 .5
 1.

<u>FREQUENCY. HZ</u>	<u>RE(Z)</u>	<u>IM(Z)</u>
9945	1.09	.22
11298	1.09	.19
14025	1.08	.16

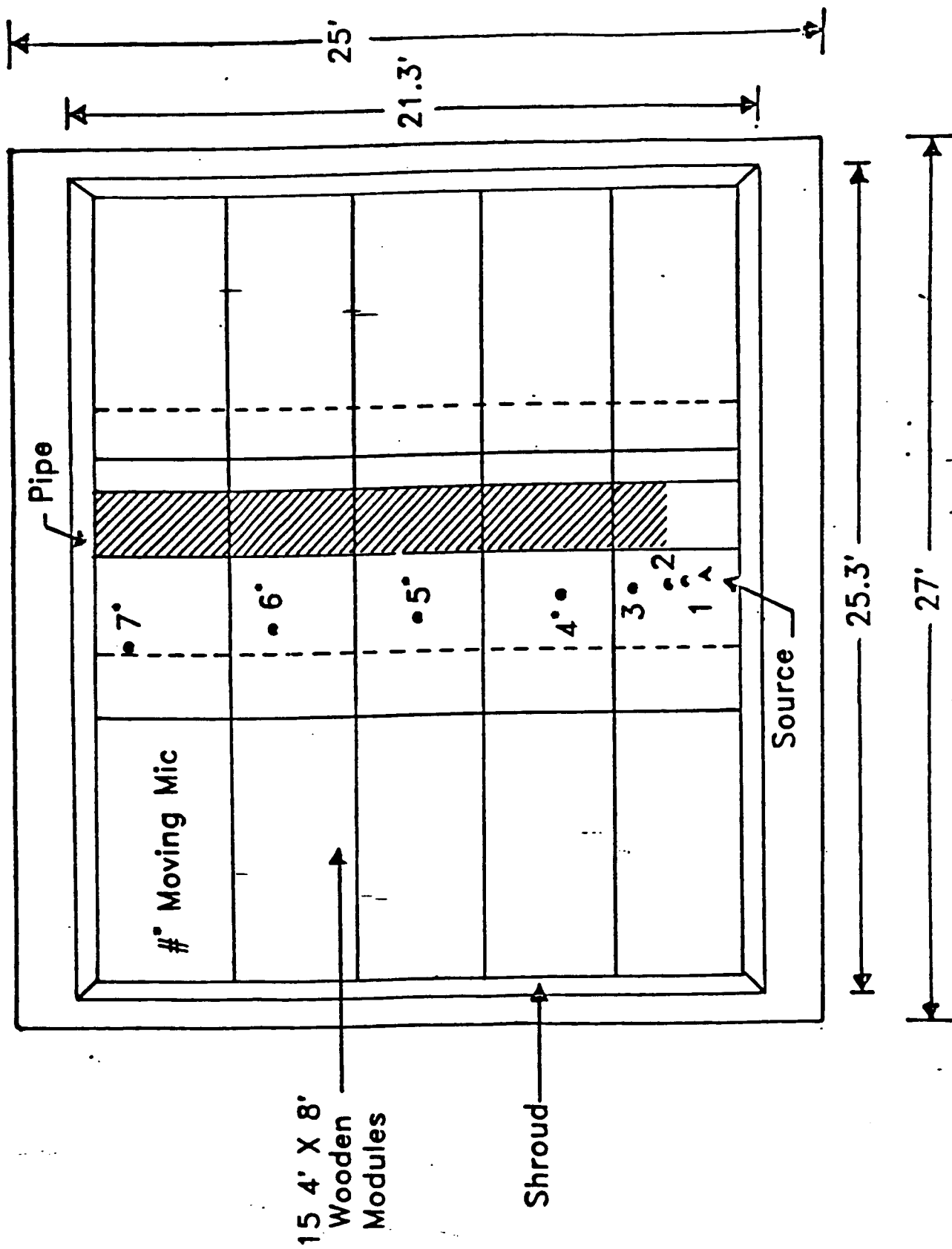


Figure 1.- Diagram of model ground plane illustrating microphone and source placement.

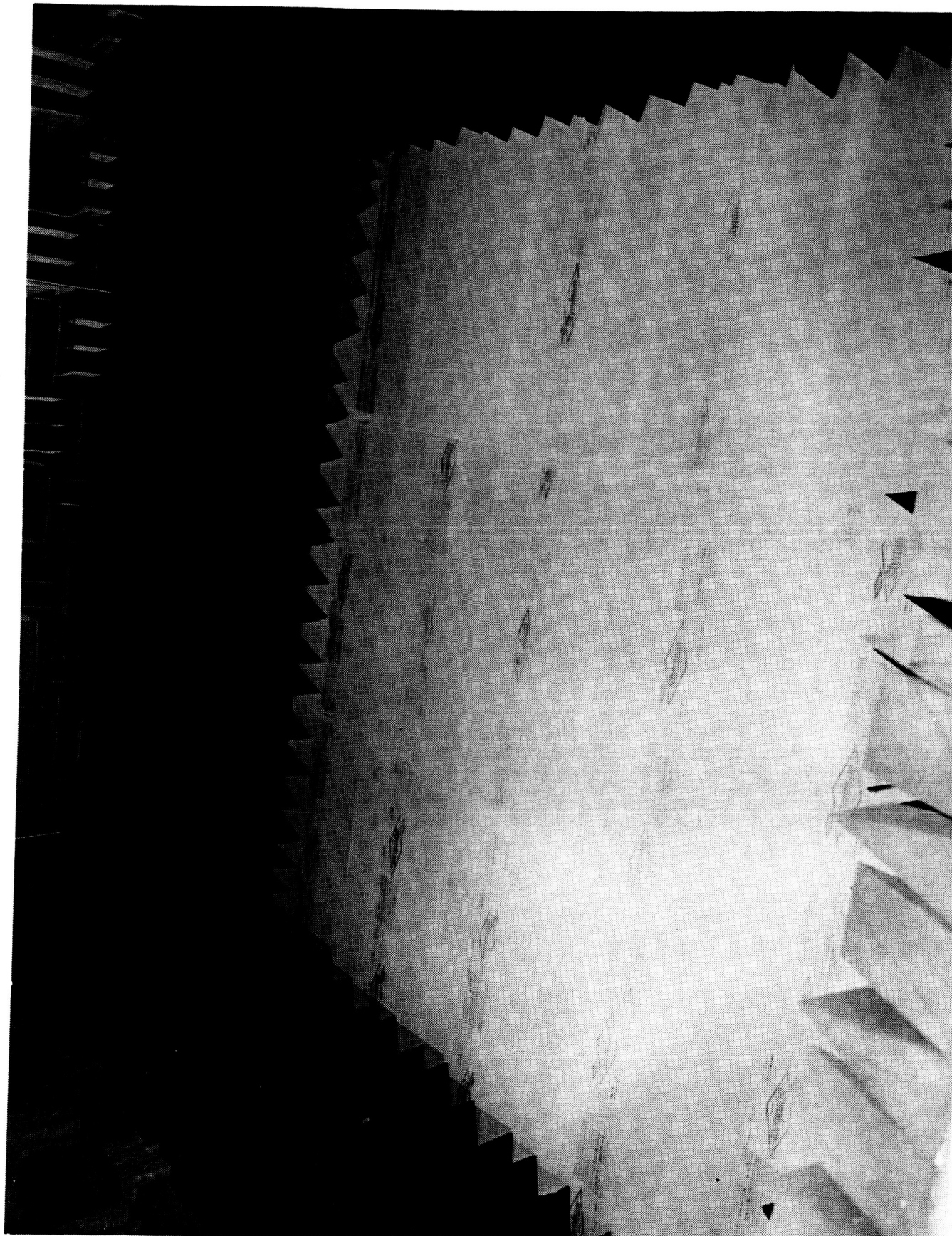


Figure 2. Photograph of styrofoam test surface installed on ground plane model.

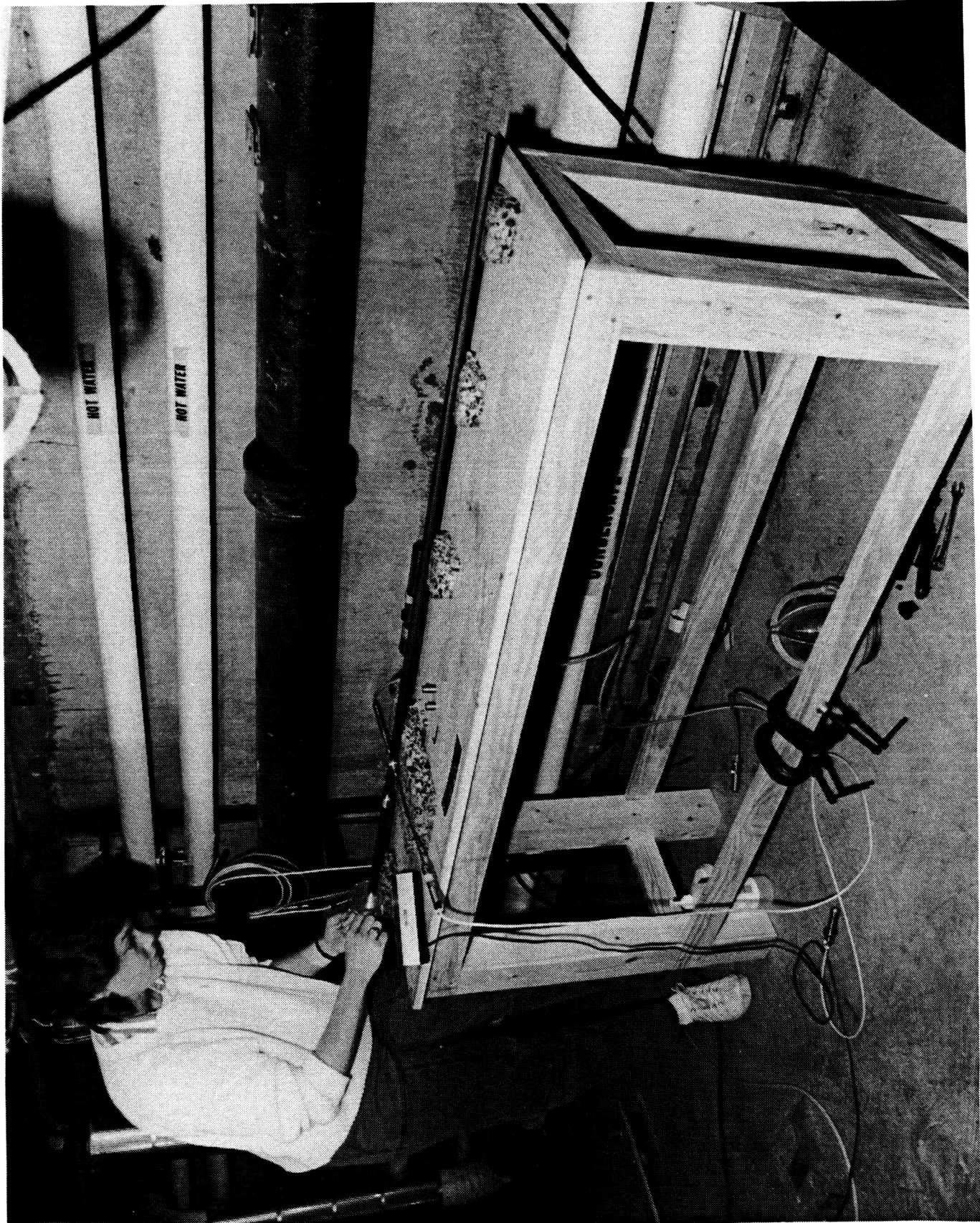


Figure 3. Photograph of probe microphone calibration apparatus.

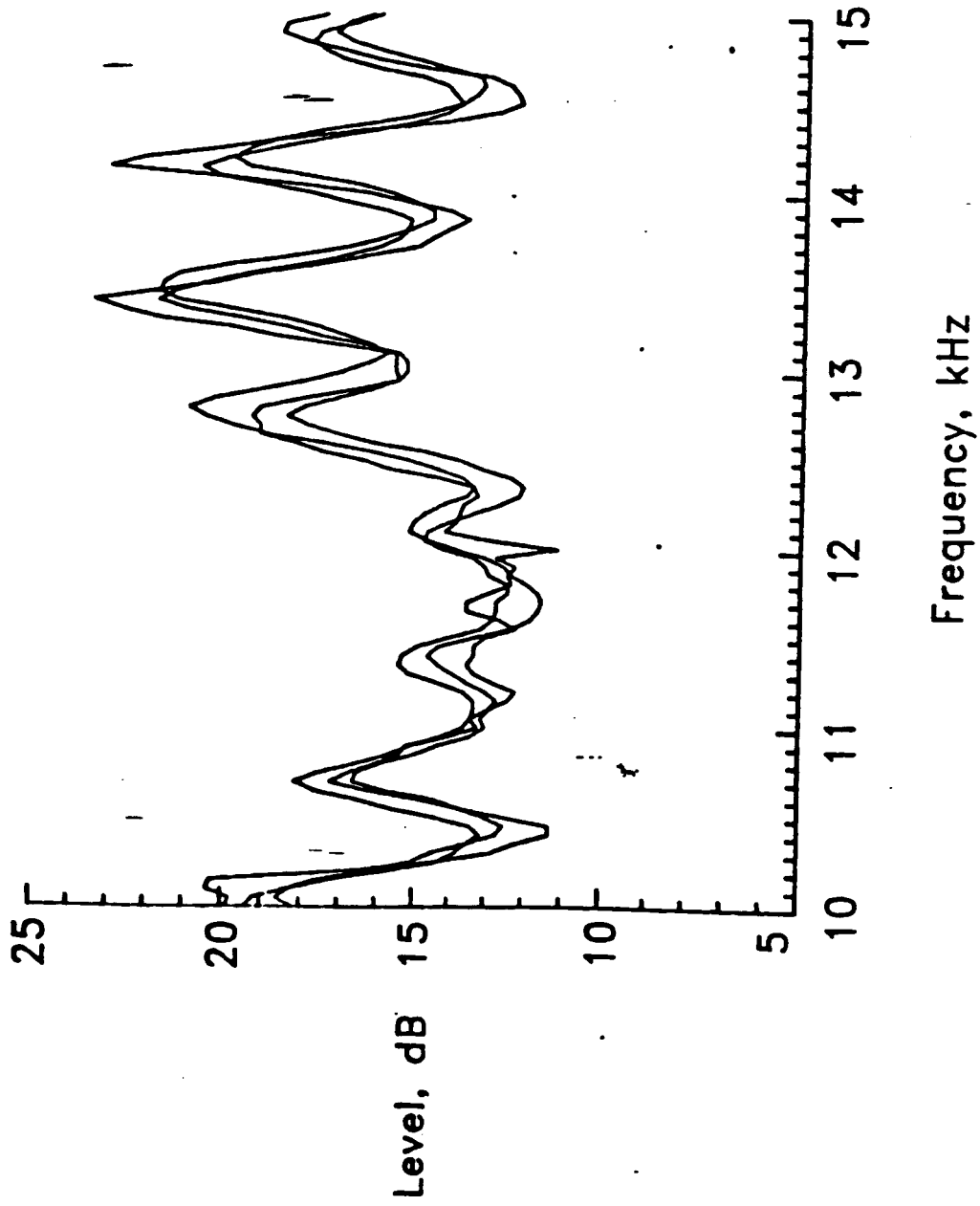


Figure 4.- Probe microphone frequency response curves.

Source Height, in.	Frequency, Hz				
	9945	10644	11298	12673	14025
0.	ply, flt sty, brd	sty, brd	ply, flt sty, brd	sty, brd	ply, flt sty, brd
1.5	ply, flt sty, brd	sty, brd	ply, flt sty, brd	sty, brd	ply, flt sty, brd
3.	ply, flt sty, brd	sty, brd	ply, flt sty, brd	sty, brd	ply, flt sty, brd
6.	ply, flt sty, brd	sty, brd	ply, flt sty, brd	sty, brd	ply, flt sty, brd

Figure 5.- Test matrix.

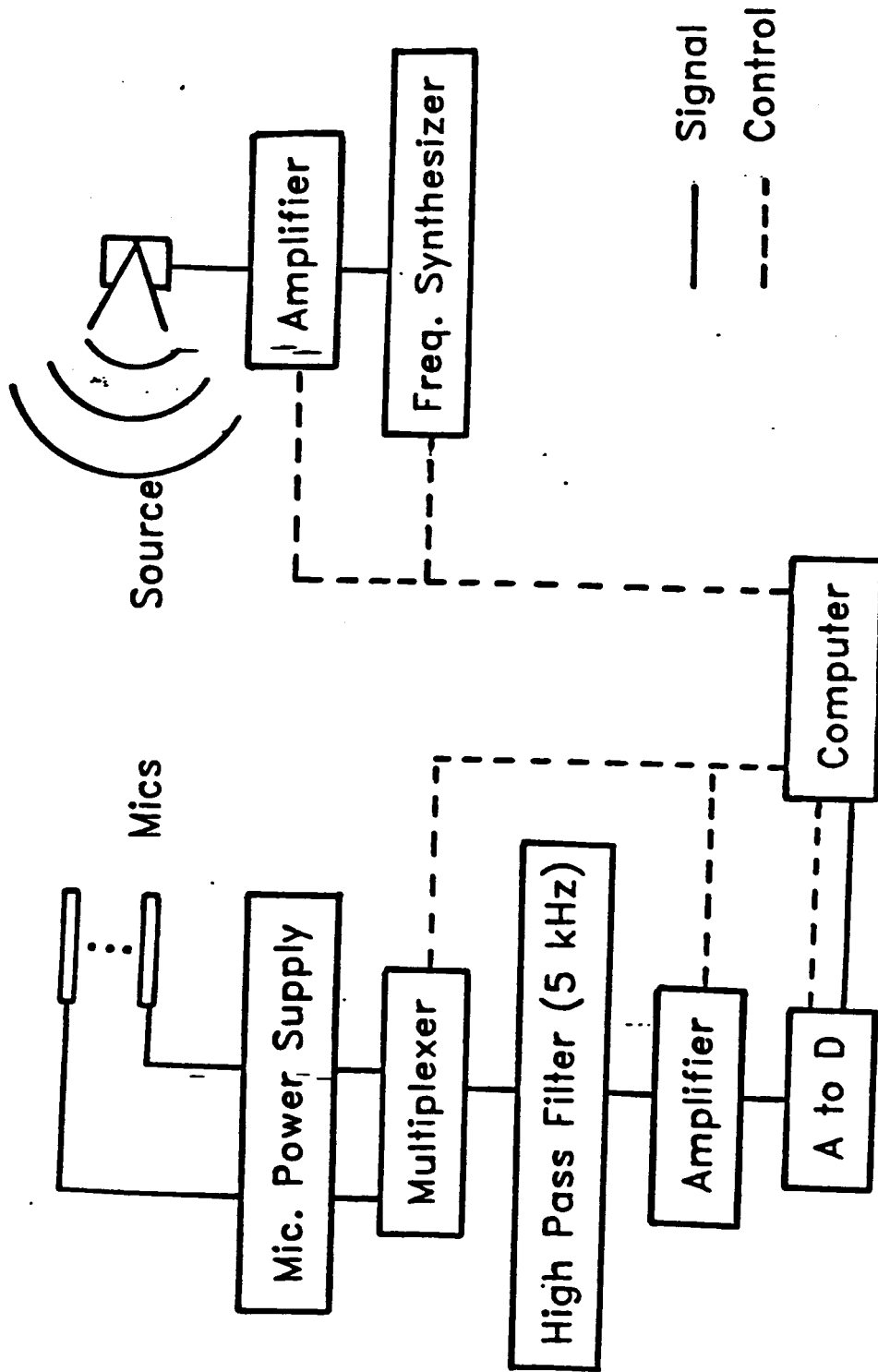


Figure 6.- Schematic of data acquisition system.

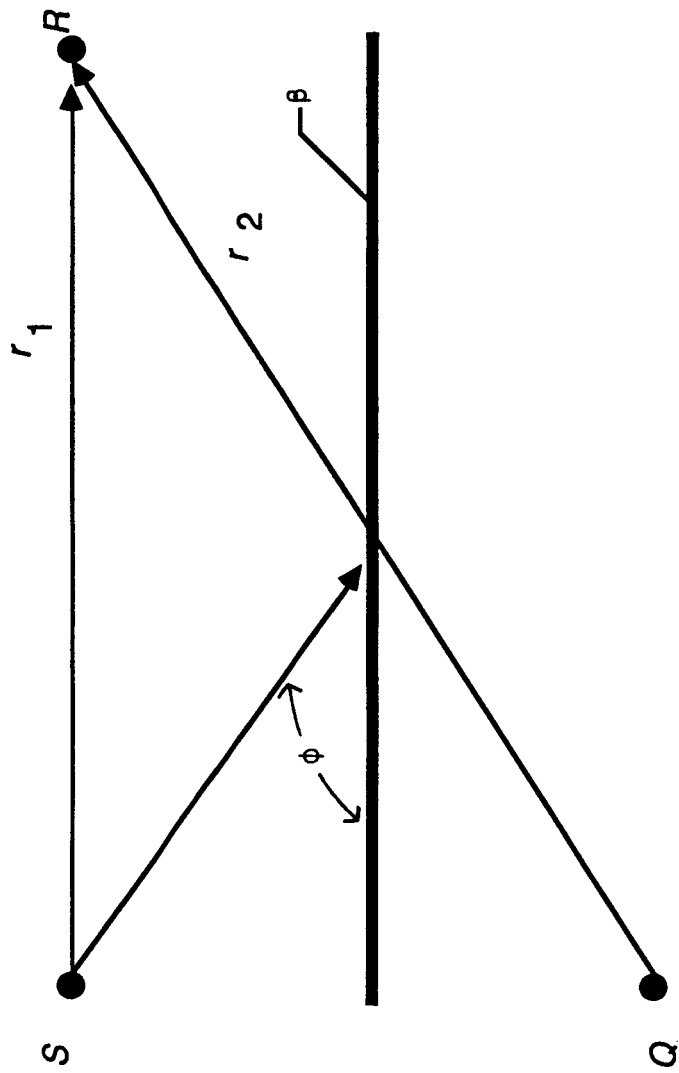


Figure 7.- Sound propagation model.

Delany and Bazley Model, best fit $\sigma = 24,285,386$ mks units

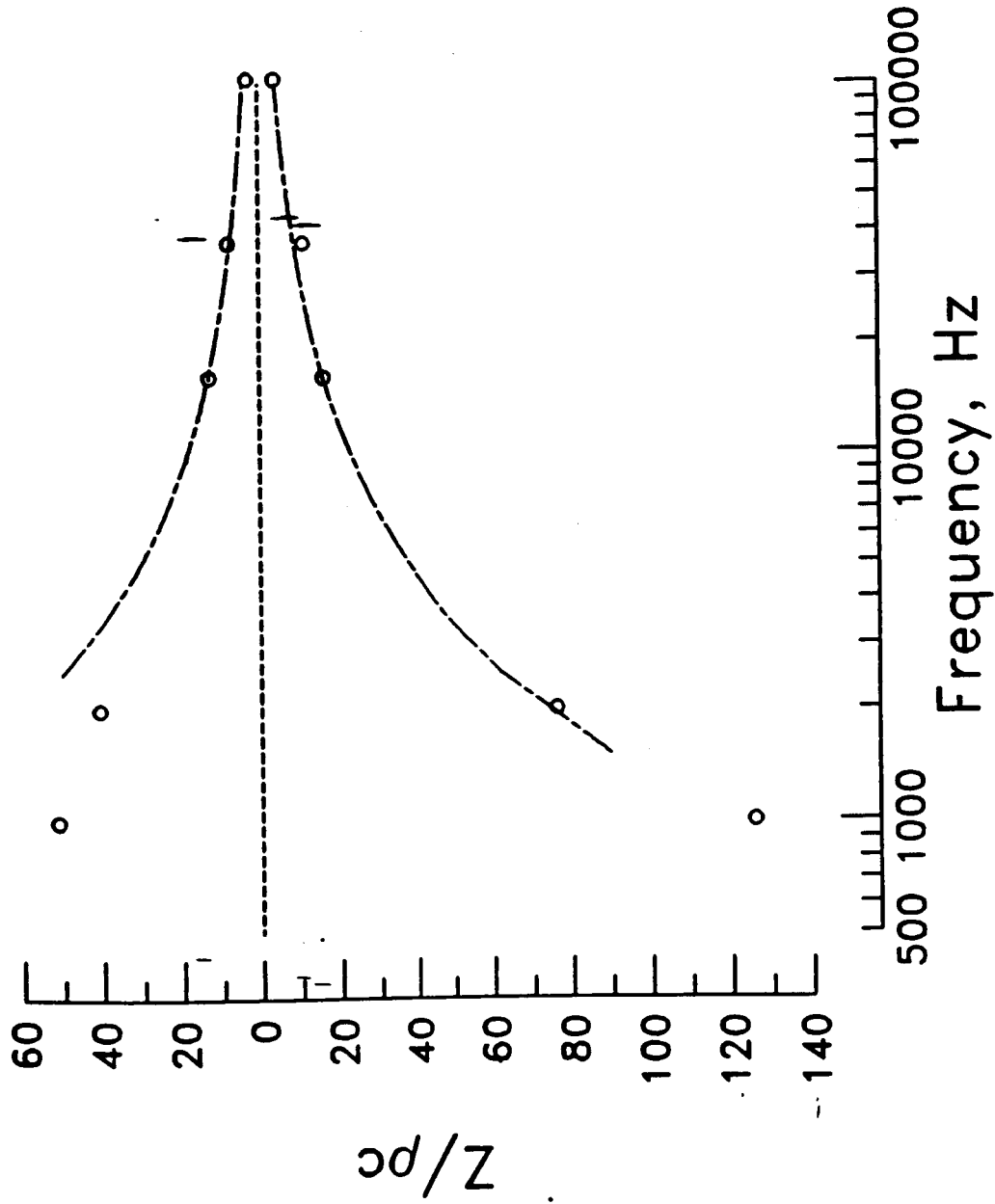


Figure 8.- Impedance estimation for styrofoam using Delaney and Bazley model.

Surface: Felt, Frequency = 14025. Hz, Source Height = 6.00 in. (1,2)

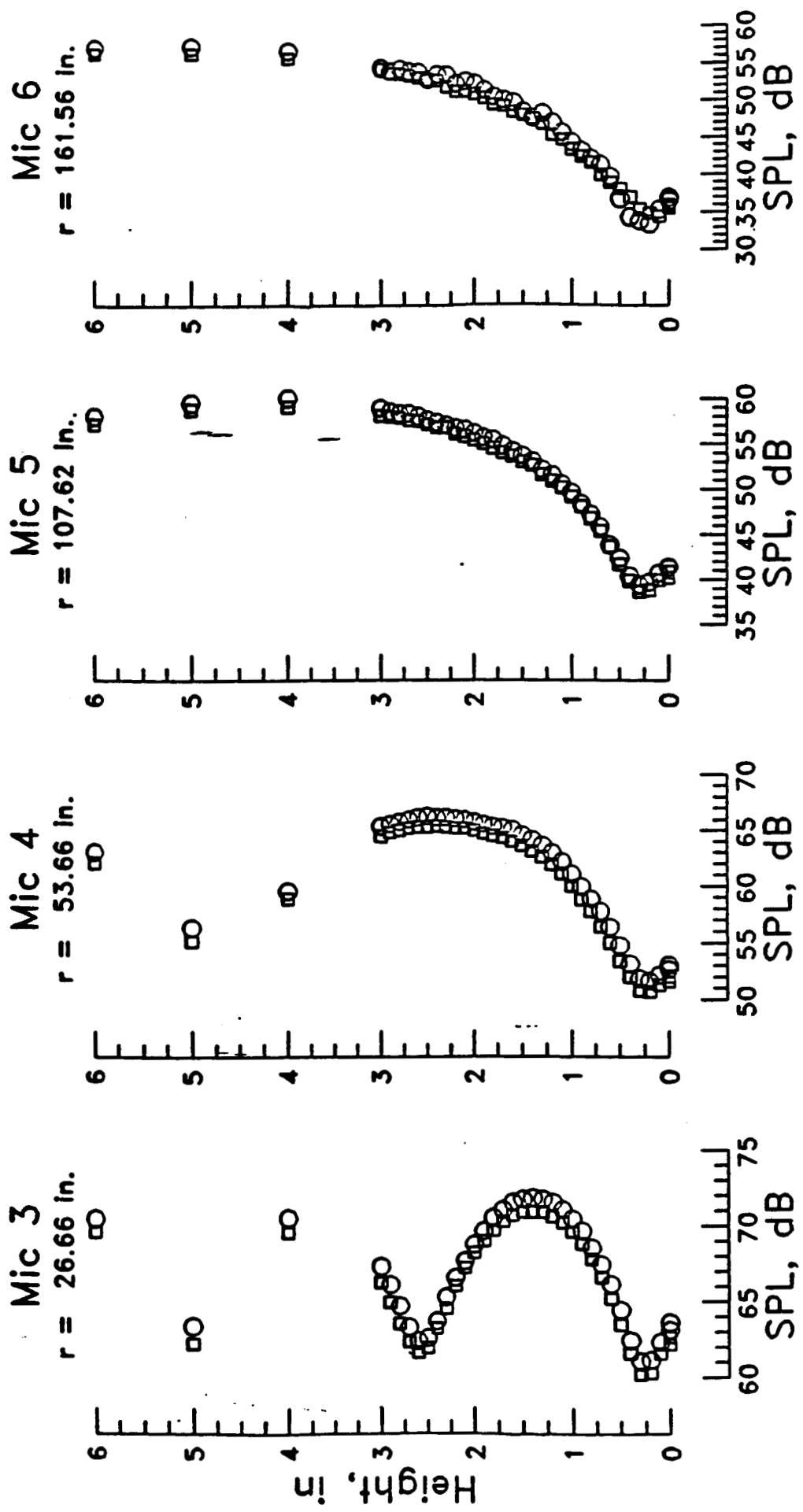


Figure 9.- Data repeatability.

Frequency = 9945. Hz, Source Height = 0.0 in., Receivers Flush

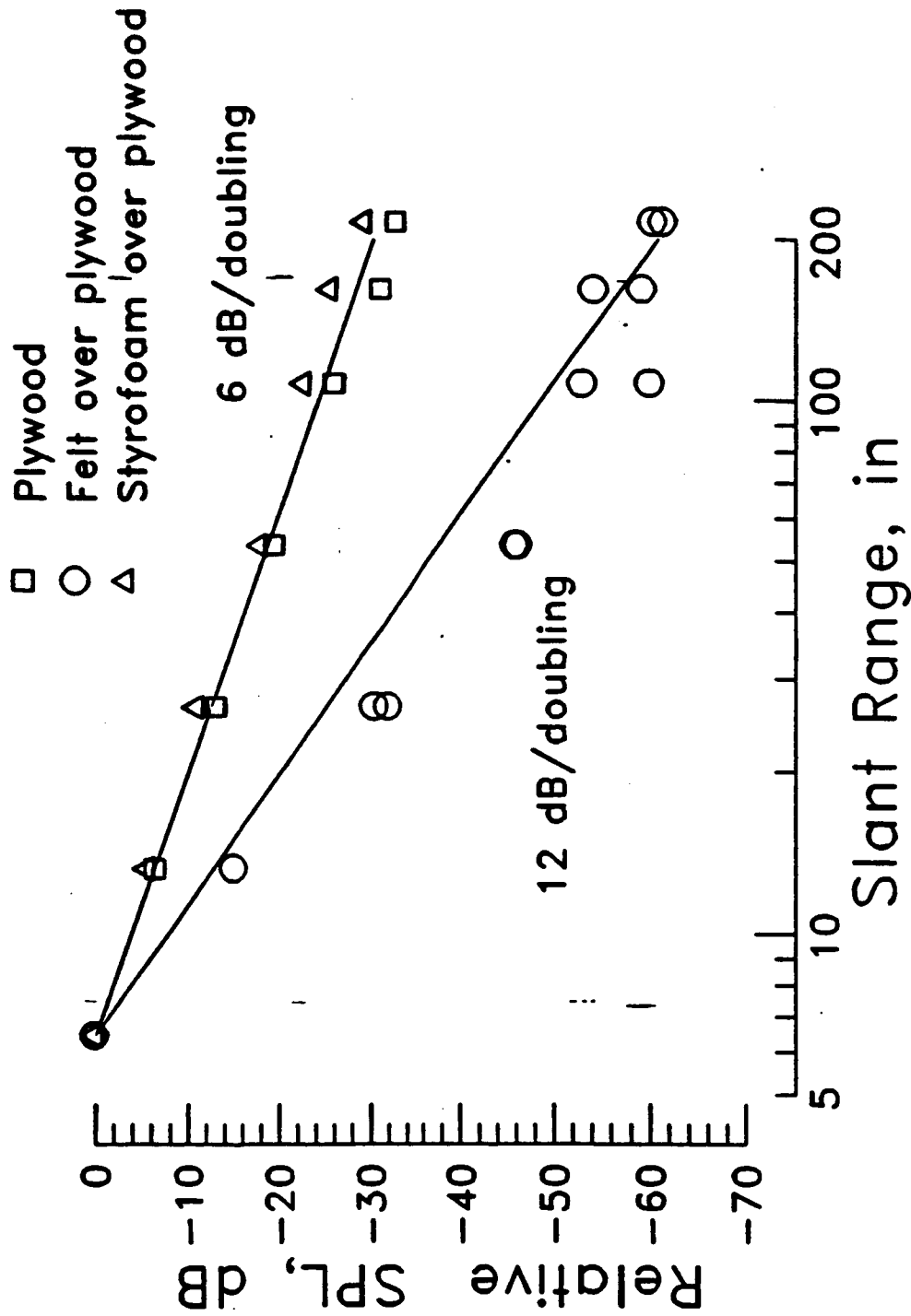


Figure 10.- Acoustic spreading.

Surface: Plywood, Frequency = 9945. Hz, Source Height = 0.00 in. (2)
 $Z = 30.8 + 37.8i$

□ Data
 — Theory

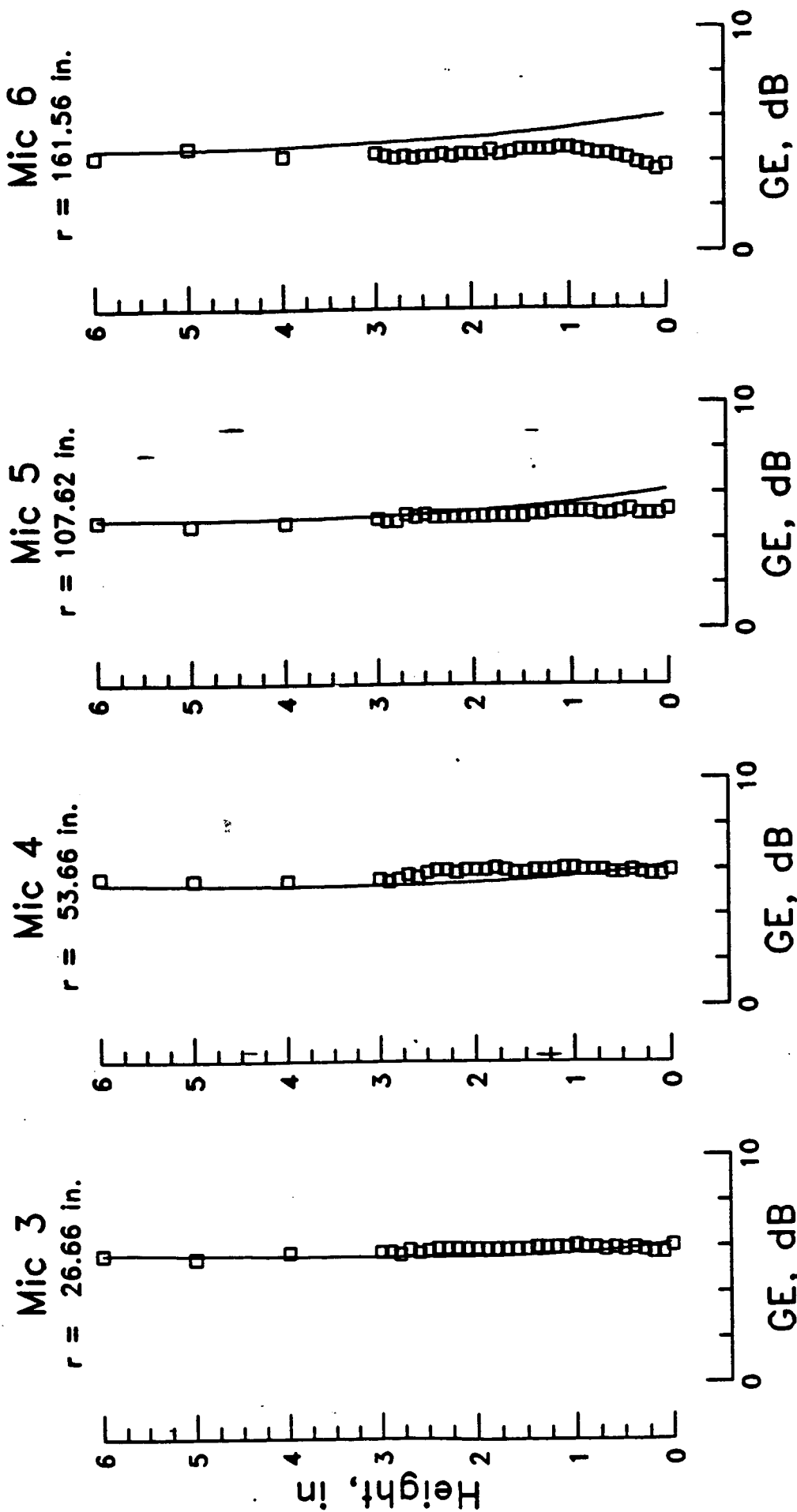


Figure 11.- Ground effect comparison with prediction for plywood test surface.

Surface: Fiberboard Frequency = 14025. Hz, Source Height = 6.00 in. (1)
 $Z = 18.6 + 22.7i$

□ Data
 — Theory

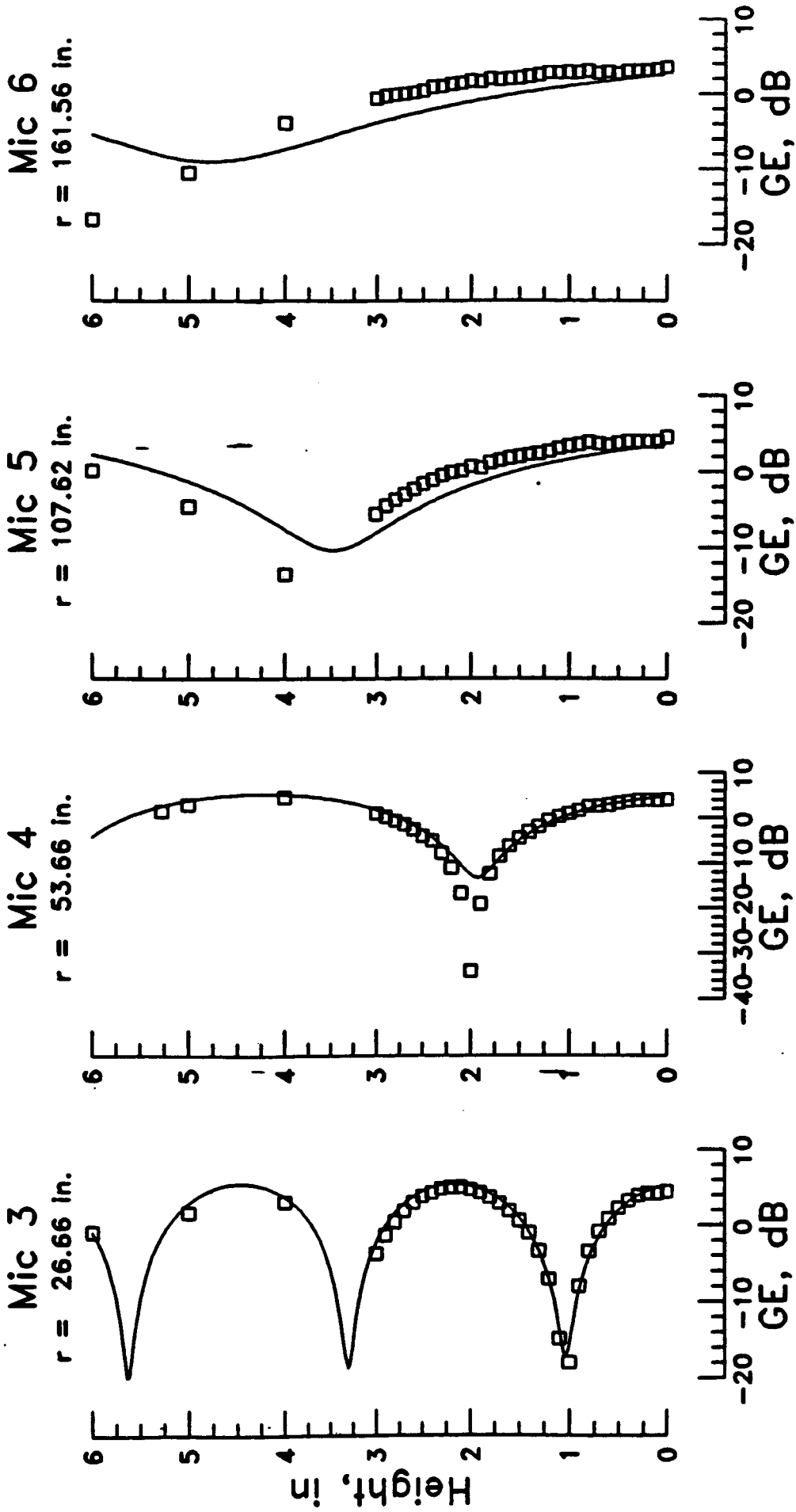


Figure 12.- Ground effect comparison with prediction for fiberboard test surface.

Surface: Styrofoam, Frequency = 14025. Hz, Source Height = 0.00 in. (3)

$$Z = 14.5 + 17.6i$$

□ Data
 — Theory

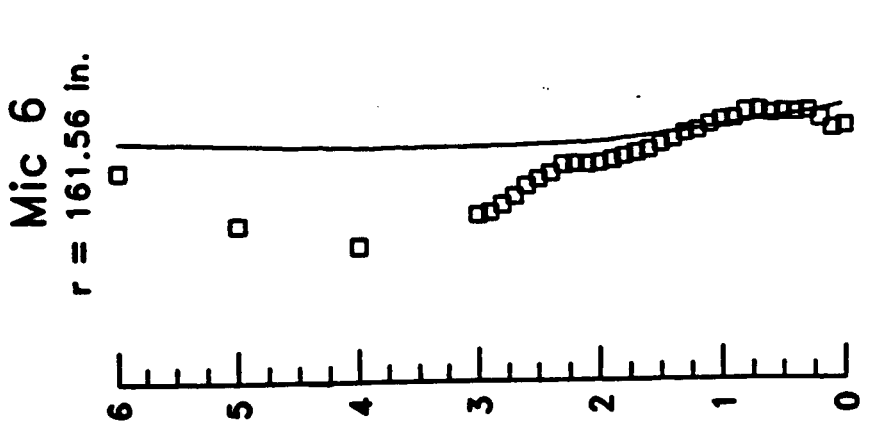
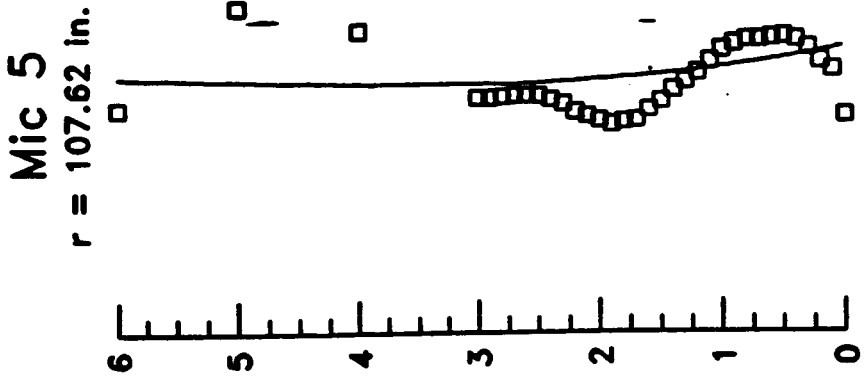
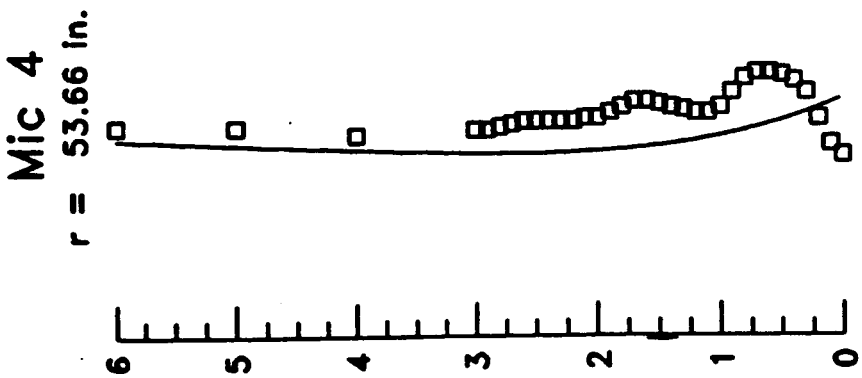
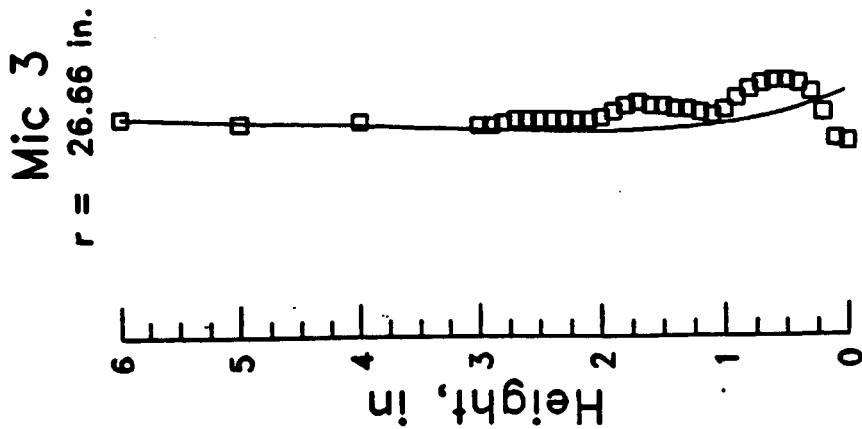


Figure 13.- Ground effect comparison with prediction for styrofoam test surface.

Surface: Felt, Frequency = 11298. Hz, Source Height = 1.50 in. (2)

$$Z = 1.1 + 0.3i$$

□ Data
 — Theory

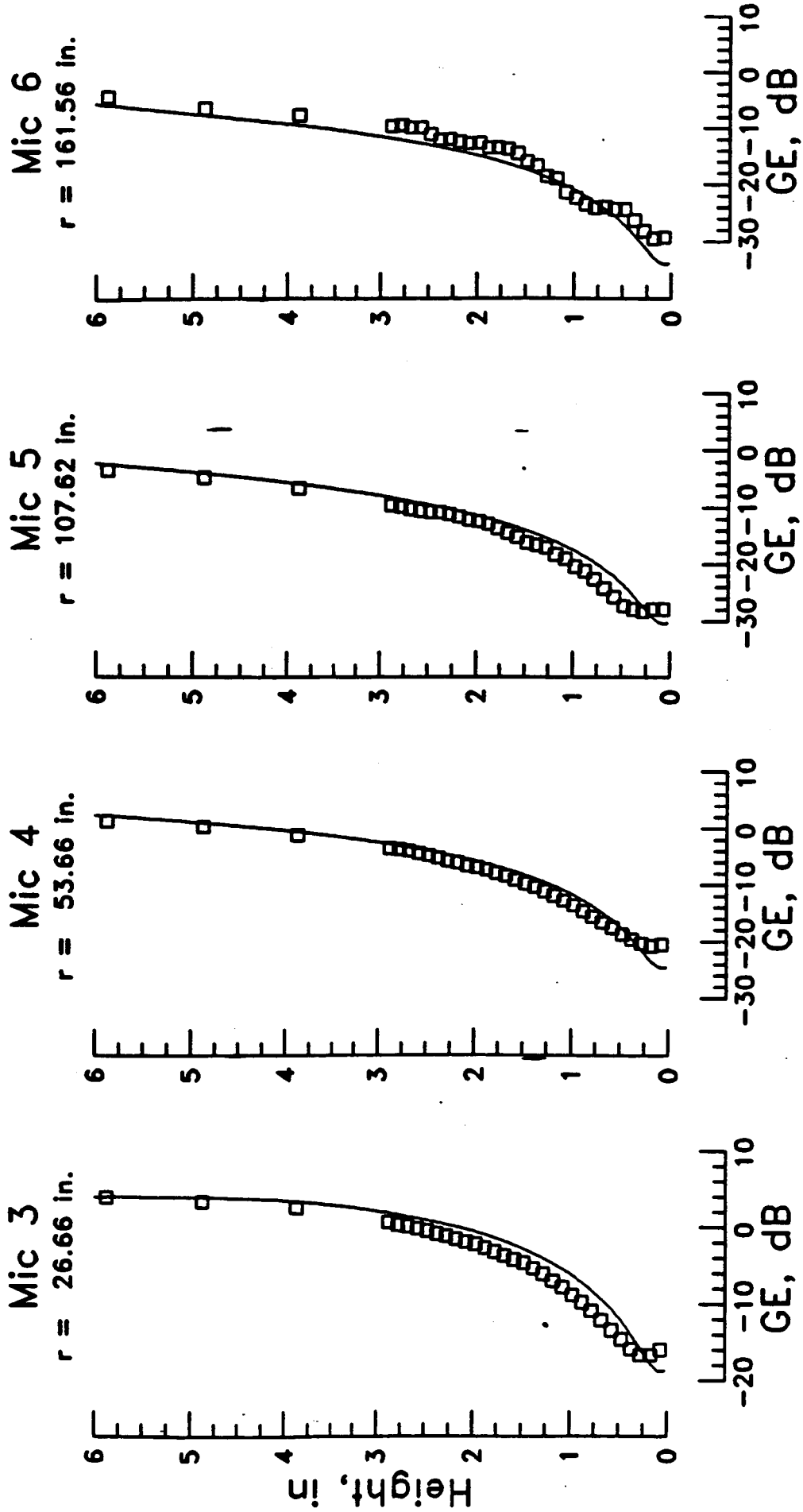


Figure 14.- Ground effect comparison with prediction for felt test surface.



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16. Abstract The purpose of this paper is to report the results of a scale model propagation experiment to investigate grazing propagation above a finite impedance boundary. In the experiment, a 20x25 ft. ground plane was installed in an anechoic chamber. Propagation tests were performed over the plywood surface of the ground plane and with the ground plane covered with felt, styrofoam, and fiberboard. Tests were performed with discrete tones in the frequency range of 10 to 15 kHz. The acoustic source and microphones varied in height above the test surface from flush to 6 in. Microphones were located in a linear array up to 18 ft. from the source. A preliminary experiment using the same ground plane, but only testing the plywood and felt surfaces was performed. The results of this first experiment were encouraging, but data variability and repeatability were poor, particularly for the felt surface, making comparisons with theoretical predictions difficult. In the main experiment the sound source, microphones, microphone positioning, data acquisition, quality of the anechoic chamber, and environmental control of the anechoic chamber were improved. High-quality, repeatable acoustic data were measured in the main experiment for all four test surfaces. Comparisons with predictions are good, but limited by uncertainties of the impedance values of the test surfaces.			
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