WASHINGTON STATE HIGHWAY DEPARTMENT RESEARCH PROGRAM REPORT **24.1**

NOISE BARRIER SCREEN MEASUREMENTS

SINGLE BARRIERS

RESEARCH PROJECT

Y-1663

JUNE 1975

PREPARED FOR
WASHINGTON STATE
HIGHWAY COMMISSION

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
NOISE BARRIER SCREEN MEASUREMENTS, Single Barriers	June 1975
	6. Performing Organization Code
7. Author(s) Rene N. Foss	8. Performing Organization Report No. APL-UW 7509
9. Performing Organization Name and Address Applied Physics Laboratory University of Washington 1013 N.E. 40th Street Seattle, Washington 98195	10. Work Unit No. 11. Contract or Grant No. Y-1663
12. Sponsoring Agency Name and Address Washington State Highway Commission Department of Highways Highway Administration Building Olympia, Washington 98504	13. Type of Report and Period Covered Interim 14. Sponsoring Agency Code

15. Supplementary Notes

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

This Laboratory has undertaken an extensive series of experimental measurements to determine the effect of barrier screens on the transmission of sound from a point source. By exercising great care in the experimental procedures, the data spread was kept within a narrow band about 1 dB wide. The results of these experiments indicate that the correct attenuation curve (in decibels vs Fresnel number "N") for a point source is given by Fresnel's equations. This is an important determination because computer programs based on the widely used National Cooperative Research Program Report 117 use a curve suggested by the work of Maekawa that is lower than Fresnel's curve.

The results of calculations that convert this point source curve to the incoherent line source (and line source segment) case are also given.

The measurements were conducted at two frequencies, 5.19 and 10.019 kHz, and employed a variety of source-to-wall and wall-to-microphone spacings. They were carried out indoors using pulse techniques to eliminate unwanted bounces and reflections.

17. Key Words	18. Distribution Statement
Noise suppression Noise barriers Noise screens Highway acoustics Fresnel diffraction	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	71	

Form DOT F 1700.7 (8-69)
HWY FORM 341-004 6/72

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ABSTRACT

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The results of calculations that convert this point source curve to the incoherent line source (and line source segment) case are also given.

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INTRODUCTION

The amount of sound that will be diffracted over the top of a wall depends on several geometric parameters as well as the frequency of the sound source. All else being equal, the higher the wall, the more effective it is in blocking sound. A given height of wall will, in general, be more effective if the source is close to the wall; i.e., if the angle between the source and the top of the wall is as great as possible.† For a fixed geometry, the amount of sound that will be diffracted over the top of the wall will depend on the frequency of the source; in general, the lower the frequency the more easily it will be diffracted over the top of the wall. Conversely, higher frequencies will be less readily diffracted; i.e., walls are much more effective at blocking higher frequency sounds.

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*Maekawa, Applied Acoustics, 1:157-173 (1968).

†In most cases, the increased angle reduces the sound faster than is compensated for by the reduced distance (not counting inverse square spreading).

If we measure the various geometric distances in units of wavelengths,* however, it is no longer necessary to concern ourselves directly with frequency and distance because the units are now a function of both the frequency and the distance. According to the laws of physics, the distances in wavelengths are thus all that are needed to calculate the effect of the barrier screen. For example, if the path from the source to the top of the wall and then to the microphone is, say, exactly one wavelength longer than the direct path would be without the wall, then the signal will be 19 dB less than it would be if the wall were absent. This would be true whether the one wavelength difference reflected a low frequency (long wavelength) and a relatively high wall, or a higher frequency (shorter wavelength) and a relatively low wall. The dependence of attenuation on wavelength difference only is very advantageous because it allows experiments to be conducted at higher frequencies with complete confidence that the results will be fully applicable at lower frequencies, if the results are expressed in terms of wavelengths. Thus, we could conduct the experiments in a carefully controlled interior environment and still use wavelength separations very similar to those that would be encountered in normal community noise problems. (A source-to-microphone spacing of 4 meters at a frequency of 5 kHz, typical of some of the measurements described in this report, would be equivalent to a source-to-microphone spacing of 40 meters at 500 Hz; at 10 kHz, a 4-meter spacing would correspond to 80 meters, or 262 ft, at 500 Hz.)

If the wall <u>blocks</u> the line of sight between the noise source and the microphone (listener), see Figure 1, less noise will reach the listener than if the source and the listener were in free space. In this report, the attenuation resulting from this configuration is called <u>positive</u> attenuation and N values for this case are also, by convention, considered to be positive. Figure 2 depicts the case in which the wall is <u>below</u> the line of sight and there is a direct path between the source and the microphone. In this case, the path length difference reflects the first bounce of a ray down to the top of the wall and back up to the microphone. In this report, N values resulting from this configuration are considered to be <u>negative</u>. A negative configuration may or may not produce attenuation, depending on the value of N.

*A unit wavelength is the speed of sound divided by the frequency, $\lambda = c/f$.

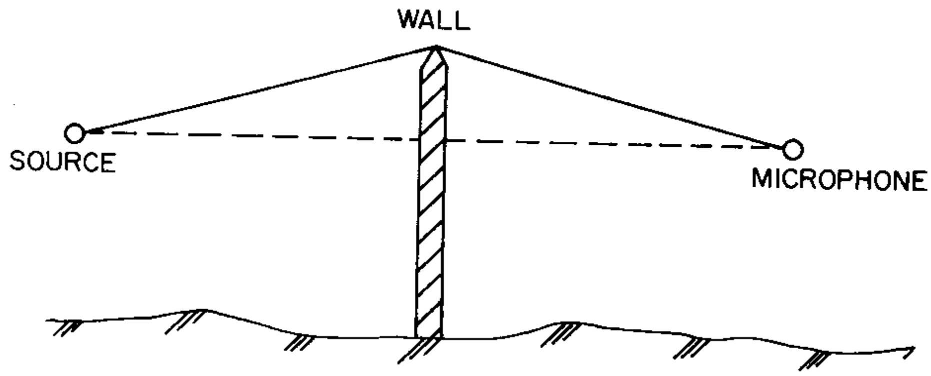


Figure 1. Positive N configuration.

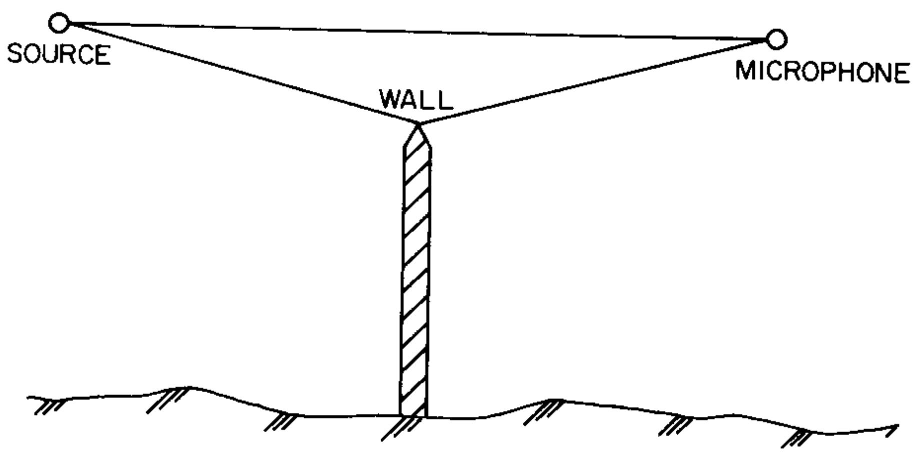


Figure 2. Negative N configuration.

In this report, attenuation is usually plotted in decibels vs Fresnel number, N. N is a geometrically derived number defined as

$$N = \frac{2\delta}{\lambda} ,$$

where

δ = the difference between the geometrical distance from source to microphone and the shortest path from the source to the top of the wall and then to the microphone. Referring to Figures

1 and 2, δ = (line segment source-to-wall) + (line segment wall-to-microphone) - (line segment source-to-microphone).

λ = the wavelength of the sound in the medium of propagation (air in this case) for the frequency used. λ = c/f, where c is the sound velocity (about 343 meters per second for air at ordinary temperatures) and f is the frequency of the sound in cycles per second (Hz).

The curves presented in this report reflect only the attenuation caused by the wall itself; dissipative atmospheric absorption and inverse square spreading due to the changes in distance would produce additional effects.

DISCUSSION OF THE DATA

Figure 3 is a plot of our experimental data (data points) and the curve predicted by classical Fresnel diffraction (solid line) for negative values of N. The experimental data points taken at 5.19 kHz are shown as dots and those at 10 kHz as triangles. As can be seen, in some regions (for example, at N = -1), the signal received at the microphone is actually greater than it would be if the wall were not there at all.

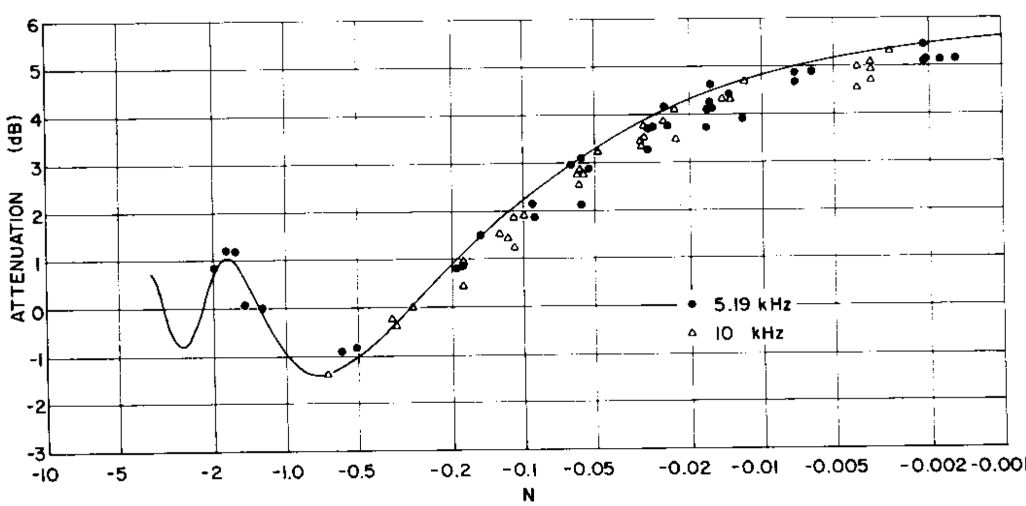


Figure 3. Comparison of data with Fresnel's curve for negative values of N.

Figure 4 is a plot of the experimental data (shown as points) and the curve predicted by Fresnel diffraction (shown as a solid line) for positive values of N. Once again, the data points fall close to the Fresnel diffraction curve, with the Fresnel curve tending to form an upper bound to the experimental data. Figures 3 and 4 are semi-log plots which do not allow presentation of the data at N = 0, i.e., where a direct line betweeen the microphone and the noise source just grazes the top of the wall; the value for Fresnel diffraction at N = 0 is 6 dB. Figure 5 is a plot of Fresnel diffraction on a linear scale. As can be clearly seen on this plot, the most rapid rate of attenuation change occurs at N = 0. This is the region that produces the "most for the money"--the largest increase in attenuation for a given increase in wall height. It is interesting to note that at N = 0 the barrier is equally effective (6 dB) at all frequencies. For this reason, it is particularly important that predictive methods include this region in their calculations and use the proper values for it.

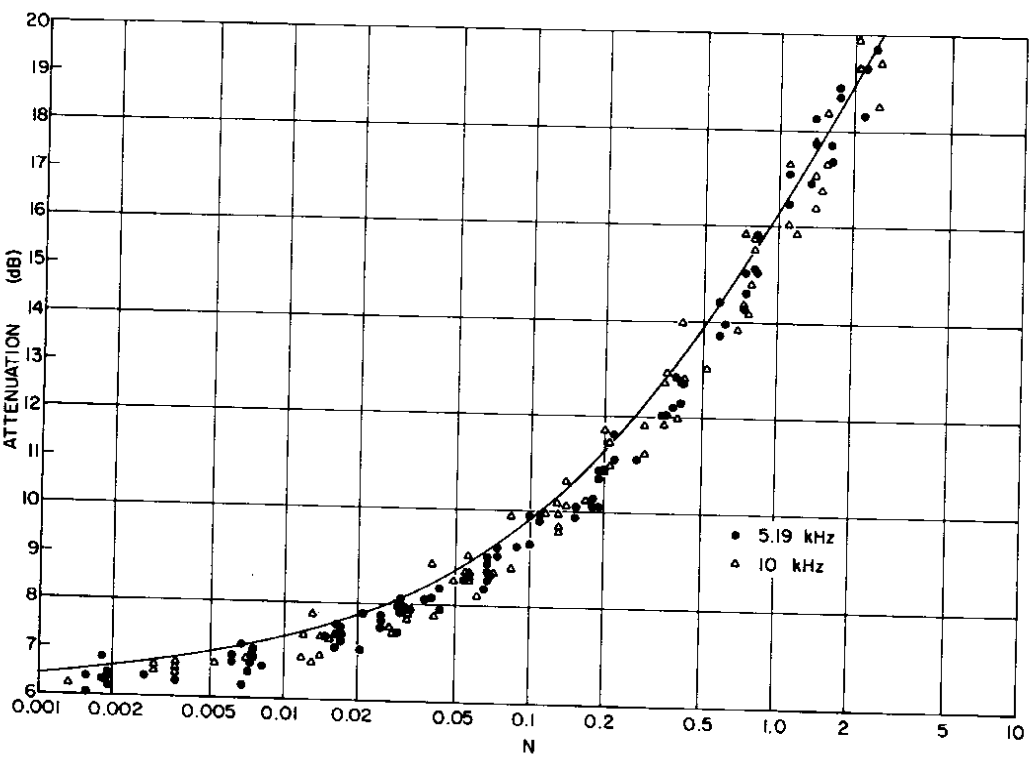


Figure 4. Comparison of data with Fresnel's curve for positive values of N.

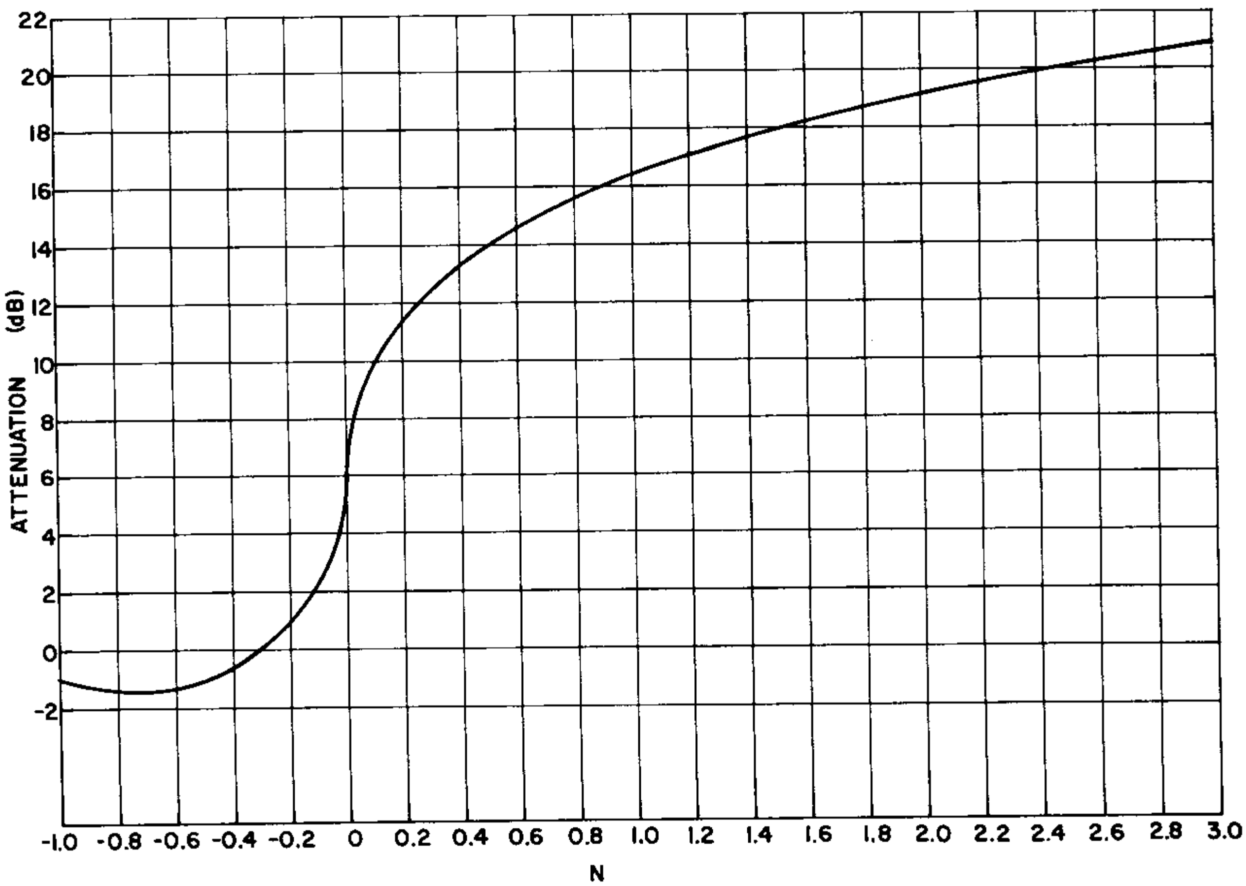


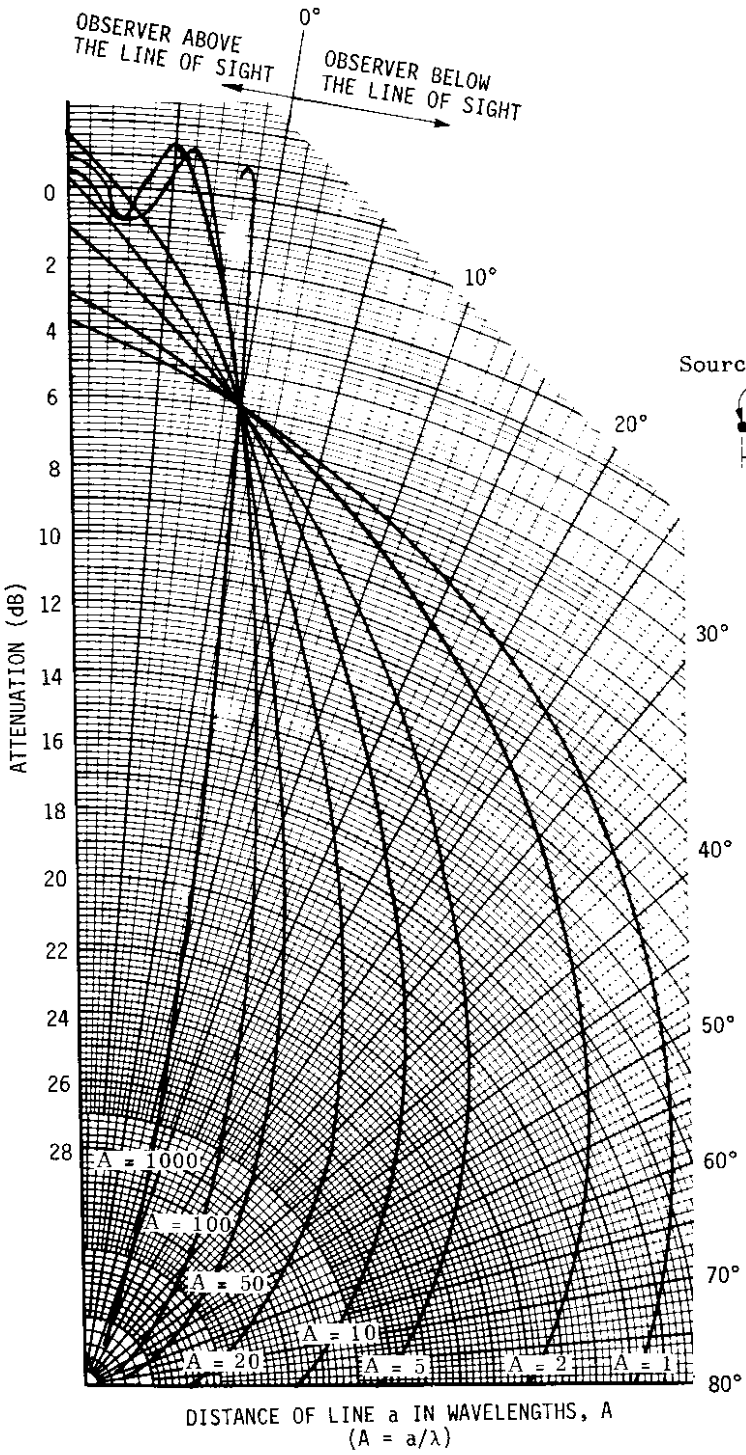
Figure 5. Plot of Fresnel diffraction on a linear scale of N.

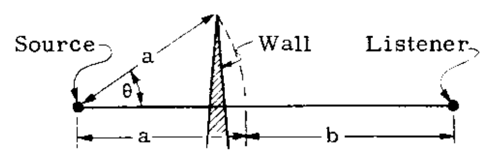
Table I shows the values for the Fresnel diffraction curve in decibels vs V, R and N, where V is the geometric function used classically to describe Fresnel diffraction (see p. 31), R is a parameter used when Fresnel diffraction is obtained from a Cornu spiral, and N represents the Fresnel number as used in this report and in the 117 Program. In this table, N is taken to equal $V^2/2$; this is essentially correct over all ranges of values of likely interest for roadside barrier construction. Values of N greater than 2 are not included in this table; however, the attenuation would be equal to 16 + 10 log N.

If the wall or screen is near the edge of a road and the listener is a considerable distance behind the wall (and if the road is considered to be a point noise source), then Fresnel diffraction can be described in terms of the angle between the source and the top of the wall (θ) and the distance in wavelengths between the source and the top of the wall. This information has been charted in Figure 6, which presents a handy reference for quick in-the-field estimates of the relative effectiveness of a given wall when the effective frequency and the geometric positions are known. For example, with a distance of 10 wavelengths between the source and the top of the barrier and an angle of 15° to the top of the barrier, Figure 6 shows that a listener would receive 15 dB less sound with the wall present than he would if the wall were absent. If the angle remained at 15° but the frequency were lower, so that it was only one wavelength to the top of the wall, he would receive 9.2 dB less. The fact that the effect of all the parameters is 6 dB for a grazing line of sight is clearly demonstrated in this chart: at zero angle of incidence, the other parameters are immaterial.

Table I. Fresnel diffraction, $N = (V^2/2)$.

R	V	dB	N	R	V	dB	N	
0.707	0	-6.0	0	0.815	-0.14	-4.79	-0.01	
0.782	-0.1	-5.15	-0.005	0.782	-0.10	-5.15	-0.005	
0.863	-0.2	-4.29	-0.02	0.75	-0.06	-5.51	-0.0018	
0.955	-0.3	-3.41	-0.045	0.736	-0.04	-5.67	-0.0008	Above line of sight
1.045	-0.4	-2.63	-0.08	0.707	0	-6.0	0	
1.14	-0.5	-1.87	-0.125	0.68	+0.04	-6.36	+0.0008	Below line of sight
1.24	-0.6	-1.14	-0.18	0.666	+0.06	-6.54	+0.0018	
1.34	-0.7	-0.47	-0.245	0.64	+0.10	-6.89	+0.005	
1.41	-0.77	0	-0.296	0.614	+0.14	-7.25	+0.01	
1.433	-0.8	+0.11	-0.32	0.58	+0.2	-7.74	+0.02	
1.52	-0.9	+0.63	-0.405	0.526	+0.3	-8.59	+0.045	
1.588	-1.0	+1.01	-0.50	0.478	+0.4	-9.42	+0.08	
1.635	-1.1	+1.26	-0.605	0.436	+0.5	-10.22	+0.125	
1.665	-1.2	+1.42(P)	-0.72	0.40	+0.6	-10.97	+0.18	
1.645	-1.3	+1.31	-0.845	0.366	+0.7	-11.74	+0.245	
1.60	-1.4	+1.07	-0.98	0.336	+0.8	-12.48	+0.32	
1.525	-1.5	+0.66	-1.125	0.308	+0.9	-13.24	+0.405	
1.430	-1.6	+0.10	-1.28	0.285	+1.0	-13.91	+0.50	
1.41	-1.62	0	-1.312	0.265	+1.1	-14.55	+0.605	
1.335	-1.7	-0.50	-1.445	0.248	+1.2	-15.12	+0.72	
1.265	-1.8	-0.97	-1.62	0.230	+1.3	-15.78	+0.845	
1.250	-1.88	-1.07(B)	-1.767	0.218	+1.4	-16.24	+0.98	
1.30	-2.0	-0.73	-2.0	0.206	+1.5	-16.73	+1.125	
1.41	-2.12	0	-2.247	0.193	+1.6	-17.30	+1.28	
1.485	-2.2	+0.42	-2.42	0.183	+1.7	-17.76	+1.445	
1.55	-2.33	+0.80(P)	-2.714	0.175	+1.8	-18.15	+1.62	
1.54	-2.4	+0.74	-2.88	0.168	+1.9	-18.50	+1.805	
1.475	-2.5	+0.37	-3.125	0.158	+2.0	-19.04	+2.0	
1.41	-2.56	0	-3.277	For N above 2, use				
1.30	-2.7	-0.73	-3.645	dB = -(16 + 10 log N).				





Distance b is assumed to be much larger than distance a. If not, the attenuation will be greater than that predicted. The following table indicates the increase for various ratios of b/a.

b/a	Max. Increase, dB (occurs at higher decibels)	Approx. Increase at 11 dB	Increase at 6 dB (θ = 0)
1	3.00	1.5	0
2	1.76	0.9	0
3	1.25	0.6	0
4	0.97	0.5	0
5	0.79	0.4	0
10	0.414	0.2	0

Figure 6. Chart for calculating attenuation (diffraction only) caused by walls or barriers.

COMPARISON WITH MAEKAWA'S DATA

As can be seen in Figures 3 and 4, Fresnel diffraction tends to represent an upper bound to the experimentally measured results. Fresnel diffraction also forms an approximate upper bound to the published results of Maekawa's experimental work.* Maekawa's data, however, have sufficient spread (a band several decibels wide would be needed to encompass most of the data points) to becloud the issue, and he chose to represent his data by a line drawn more toward the middle to bottom of this data.

Figures 7 and 8 are a repetition of Figures 3 and 4 with the addition of Maekawa's curves for comparison. The experimental data fall much nearer Fresnel's curve than Maekawa's curve. Clearly, Fresnel's curve seems to be the better representation of the experimental data, especially when we consider that those acoustic phenomena that tend to produce "jitter" in the measurement all tend to lower the apparent attenuation for a given N. (These phenomena are discussed more extensively later in this report.) This evidence leads to the conclusion that <u>Fresnel diffraction</u> is the <u>correct</u> representation for the effect of <u>barrier screens</u> on sound propagation from <u>point</u> sources.

GEOMETRIC MEASUREMENT ACCURACY

One important requirement for keeping the data scatter small is to measure the positions of the microphone, the source, and the wall with sufficient accuracy that this is not a major source of error. The question then arises, How accurately do these measurements need to be performed? Too little accuracy would result in data with more scatter than necessary, whereas too great an accuracy would merely result in wasted time and effort. This question can be broken down into two parts:

(1) How accurate do the horizontal measurements of the distance from the microphone to the wall and from the source to wall need to be?

(2) How accurately does the height of the wall need to be measured relative to a straight line connecting the microphone and the source?

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*Maekawa, Applied Acoustics, 1:157-173 (1968).

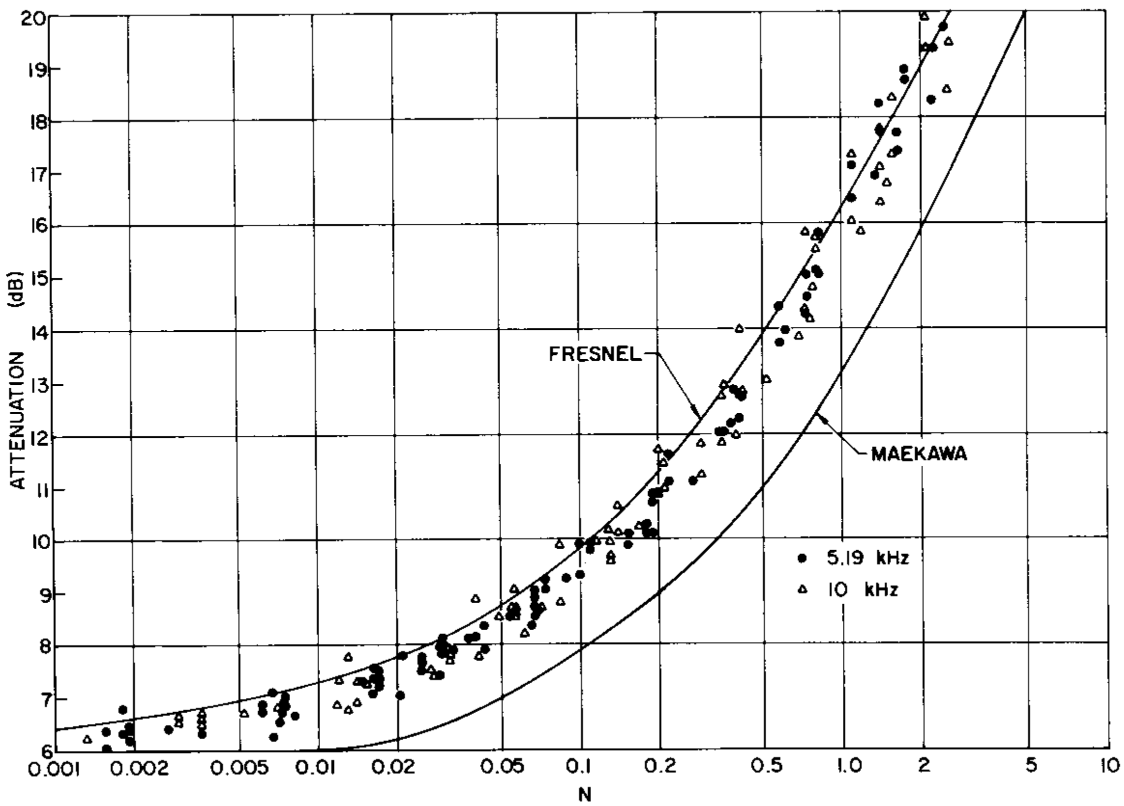


Figure 7. Comparison of data with Fresnel's curve and with Maekawa's curve for positive values of N.

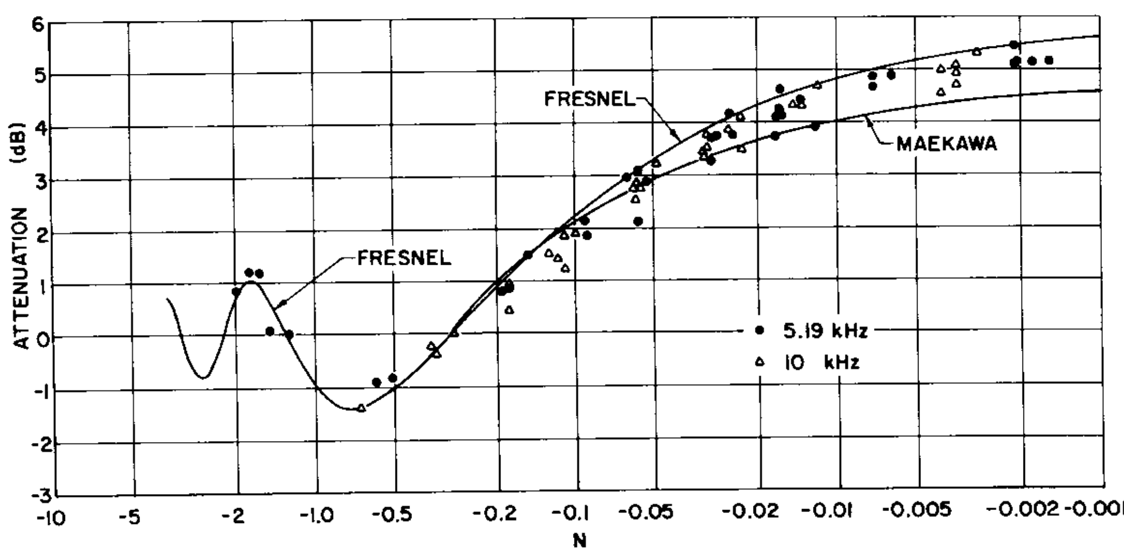


Figure 8. Comparison of data with Fresnel's curve and with Maekawa's curve for negative values of N.

Consider Figure 9, in which there is a straight line between the noise source and the microphone. The portion of this line between the source and the wall is labeled A, the wall extends above this line by a height labeled H, and the angle between the line connecting the source and the microphone and a line from the source to the top of the wall is called θ. For simplicity, we will consider only the geometry for the left half of the figure, involving the distance from the source to the wall and the wall height. However, keep in mind that, if the distances from the microphone to the wall and from the source to the wall were comparable, the effect on N of an error in the wall height measurement would be twice as great because the wall height measurement affects the calculations for both sides of the wall. We now derive the effect on N of an error in measurement of either A or H as follows:

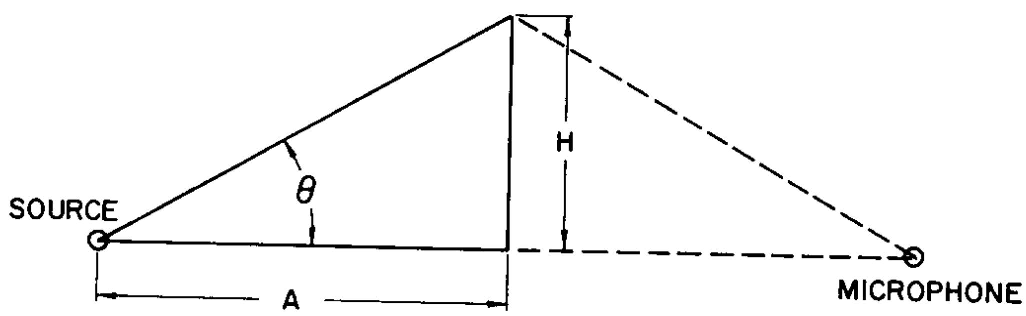


Figure 9. Sketch for calculating measurement accuracy requirements.

$$\delta = \sqrt{A^2+H^2} - A = \text{path length difference}$$

$$N = \frac{2\delta}{\lambda}$$

$\lambda = \frac{c}{f}$ where c is the sound velocity and f is the frequency

$$N = \frac{2f\delta}{c} = \frac{2f}{c}\left[\sqrt{A^2+H^2} - A\right]$$

$$\frac{\partial N}{\partial A} = \frac{2f}{c}\left[\frac{2A}{2\sqrt{A^2+H^2}} - 1\right]$$

$$\frac{\partial N}{\partial H} = \frac{2f}{c}\left[\frac{2H}{2\sqrt{A^2+H^2}}\right]$$

$$H = A \tan \theta$$

$$\frac{\partial N}{\partial A} = \frac{2f}{c}\left[\frac{A}{\sqrt{A^2+A^2 \tan \theta}} - 1\right] = \frac{2f}{c}\left[\frac{1}{\sqrt{1+\tan^2 \theta}} - 1\right] \qquad (1)$$

$$\frac{\partial N}{\partial H} = \frac{2f}{c}\left[\frac{A \tan \theta}{\sqrt{A^2+A^2 \tan^2 \theta}}\right] = \frac{2f}{c}\left[\frac{\tan \theta}{\sqrt{1 + \tan^2 \theta}}\right] \qquad (2)$$

Equation 1 gives the change in N that would occur for a change in A as a function of the frequency and the angle θ. Equation 2 gives the change in N that would occur for a change in H, again as a function of the frequency and the angle θ.

In Table II, the columns labeled dN/dA and dN/dH give the values of these parameters as a function of the angle θ (in degrees) for a frequency of 10 kHz. The higher (10-kHz) frequency was used for these calculations because, as can be seen, the measurement accuracy requirement increases with frequency. The last column in Table II gives the ratio of these two parameters. This ratio is independent of frequency (the frequency term cancels out) and thus is generally indicative of the relative precision to which height measurements need to be performed compared to horizontal distance measurements. For very small angles, the height measurement is considerably more important than the horizontal distance measurements; e.g., at 1° it is 114 times more important, at 5° it is almost 23 times more important, and for very large angles (45°) it is only slightly under 2-1/2 times more important. It is obvious from Table II that considerably greater care must be taken in the height measurements than in the horizontal distance measurements; however, neither must be allowed to stray outside an acceptable range.

In general, when plotting the curves, a percentage accuracy may be a more important criterion than a fixed accuracy. In this case, the acceptable value, dN, would be a function of N. For example, if the value for N is to be accurate to within 5%, then

$$dN = 0.05\ N\ .$$

Therefore,

$$dA = \frac{0.05\ N}{(dN/dA)} \quad . \qquad (3)$$

At an angle of 5°, dN/dA = 0.0022. Therefore,

$$dA = \frac{0.05\ N}{0.0022} = 22.7\ N \quad .$$

If, for example, we choose to examine dA at N=0.1, then dA = 2.27 cm. That is, for these values, the horizontal measurement would have to be accurate to 2.27 cm to hold N within 5% of its true value; the measurement of H is 22.9 times more sensitive, so it would have to be within 1 mm to hold the accuracy to 5%. These conditions (N=0.1, θ=5°, f=10 kHz), imply that A = 45 cm and H = 3.9 cm.

Table II. Measurement sensitivity at 10 kHz, $\frac{2f}{c} = \frac{(2)(10,000)}{(1125)(12)(2.59)}$ *= 0.58 cycle/cm.*

θ (deg)	dN/dA $0.58\left[\frac{1}{\sqrt{1+\tan^2\theta}} - 1\right]$	dN/dH $0.58\left[\frac{\tan\theta}{\sqrt{1+\tan^2\theta}}\right]$	$\frac{(dN/dH)}{(dN/dA)}$ $\frac{\tan\theta}{1-\sqrt{1+\tan^2\theta}}$
0	0	0	-
1			-114.6
5	-0.0022	0.0506	- 22.9
10	-0.0088	0.1007	- 11.43
15	-0.020	0.150	- 7.596
20	-0.035	0.198	- 5.67
25	-0.054	0.245	- 4.511
30	-0.078	0.290	- 3.73
35	-0.105	0.333	- 3.172
40	-0.136	0.373	- 2.747
45	-0.1699	0.410	- 2.414

As can be seen from Table II, the measurements are most critical when the angles are small; also, the ratio of the criticality of the vertical measurement to the horizontal one becomes very large at small angles. The geometric accuracies are also important at small values of N; however, on a semi-log plot, in which a fixed distance on the horizontal axis represents a given percentage, the curves tend to become horizontal for the lower values of N, and thus the accuracy in evaluating N (a horizontal displacement) may not be so critical. On the other hand, it can be seen from Eq. 3 that the allowable value of dA increases as N becomes large; thus it is easier to hold a given percentage accuracy at the larger values of N--precisely where the curve is no longer so horizontal and a greater percentage accuracy is needed.

In general, at 10 kHz it is desirable to hold the measurements, particularly the height measurement, to within 1 mm. This is not an easy task, and I do not claim that it was always accomplished. However, by exerting great care, we did manage to come fairly close to this degree of accuracy.

The wall was removed and the free field amplitude was rechecked between every measurement point taken with the wall in place. This greatly increased the problem of geometric measurement accuracy, since the plasterboard wall had to be removed and replaced many, many times for any one curve, each time to within 1 mm of its original height. To accomplish this, we constructed the angle-iron structure shown in the photographs of Figures 10 and 11. When the wall was folded down, it was only a few centimeters from the floor, which was low enough that measurements on the main pulse could be taken under free field conditions. The wall was then pivoted into a vertical position and clamped to vertical side arms as shown in the photographs. The wall could thus be repositioned quite accurately. The height of the wall itself was not changed during the course of the measurements. To change its "effective" height, the heights of the source or the microphone, or both, were varied. This was accomplished using a rack and pinion adjustment, as can be seen in the photographs.

The floor of the building in which the measurements were taken was much too uneven to use directly as a height reference. It would, in fact, be rare to find any floor that was flat to within 1 mm over a range of 4 or 5 m. To overcome this problem, a reference level planar to within 1 mm or better was glued to the floor. This reference level consisted of two separate, kiln-dried wooden parts, each 1 m in length, separated by a gap of precisely 2 m. Each part had a meter stick fastened to its surface. These parts were initially aligned by tightly stretching a very strong, light nylon string across the two references and adjusting them until they were parallel to this string to within 1 mm or better. The references were then held fast in this position by gluing them to the concrete floor with epoxy glue.

The horizontal positions of the microphone and source were measured by dropping a plumb bob from a particular spot on the source or microphone to the permanently affixed meter sticks and reading the scale. The reference sites on the source and microphone were easily identifiable dots near the equivalent center of radiation.

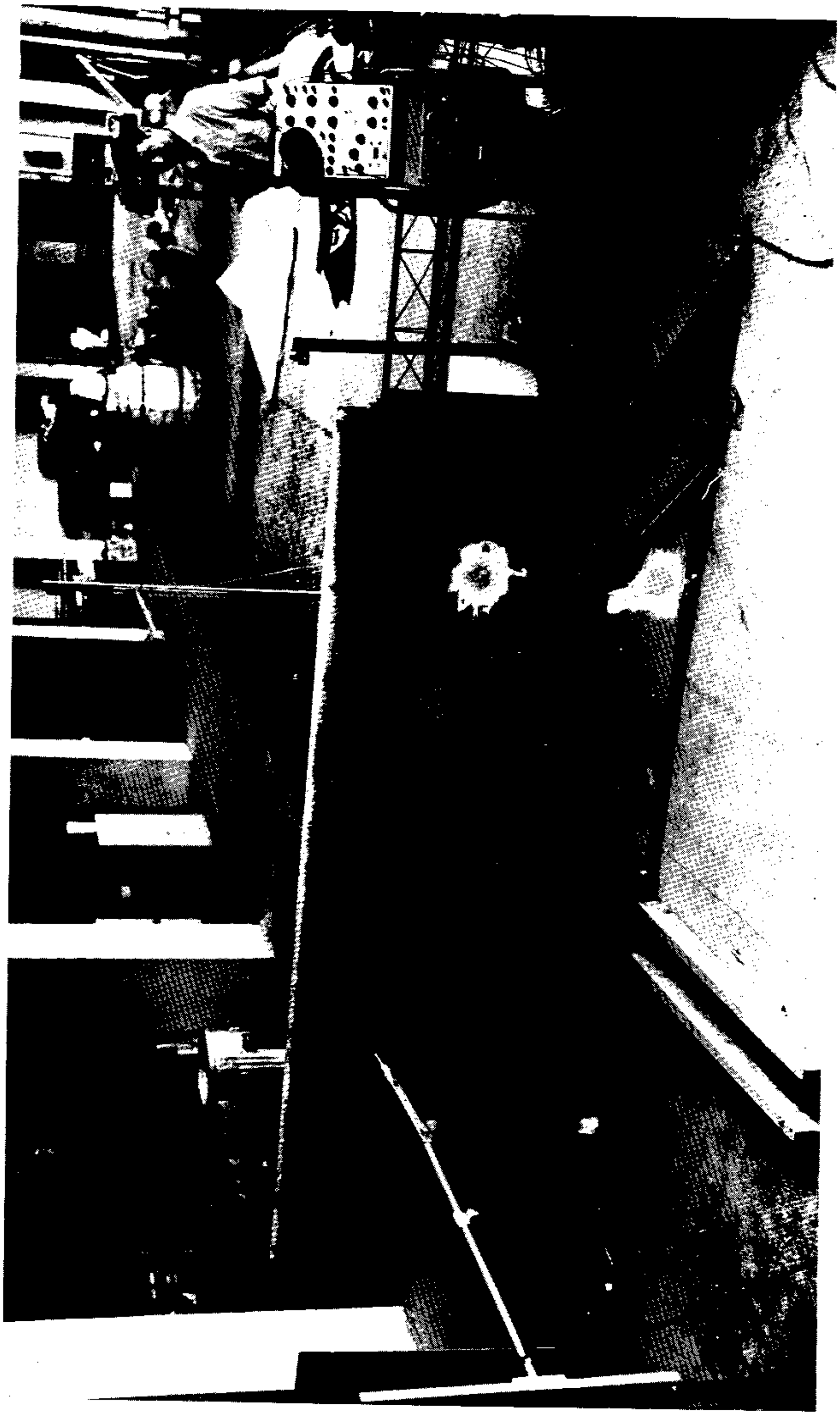


Figure 10. Photograph of measurement setup with wall up.

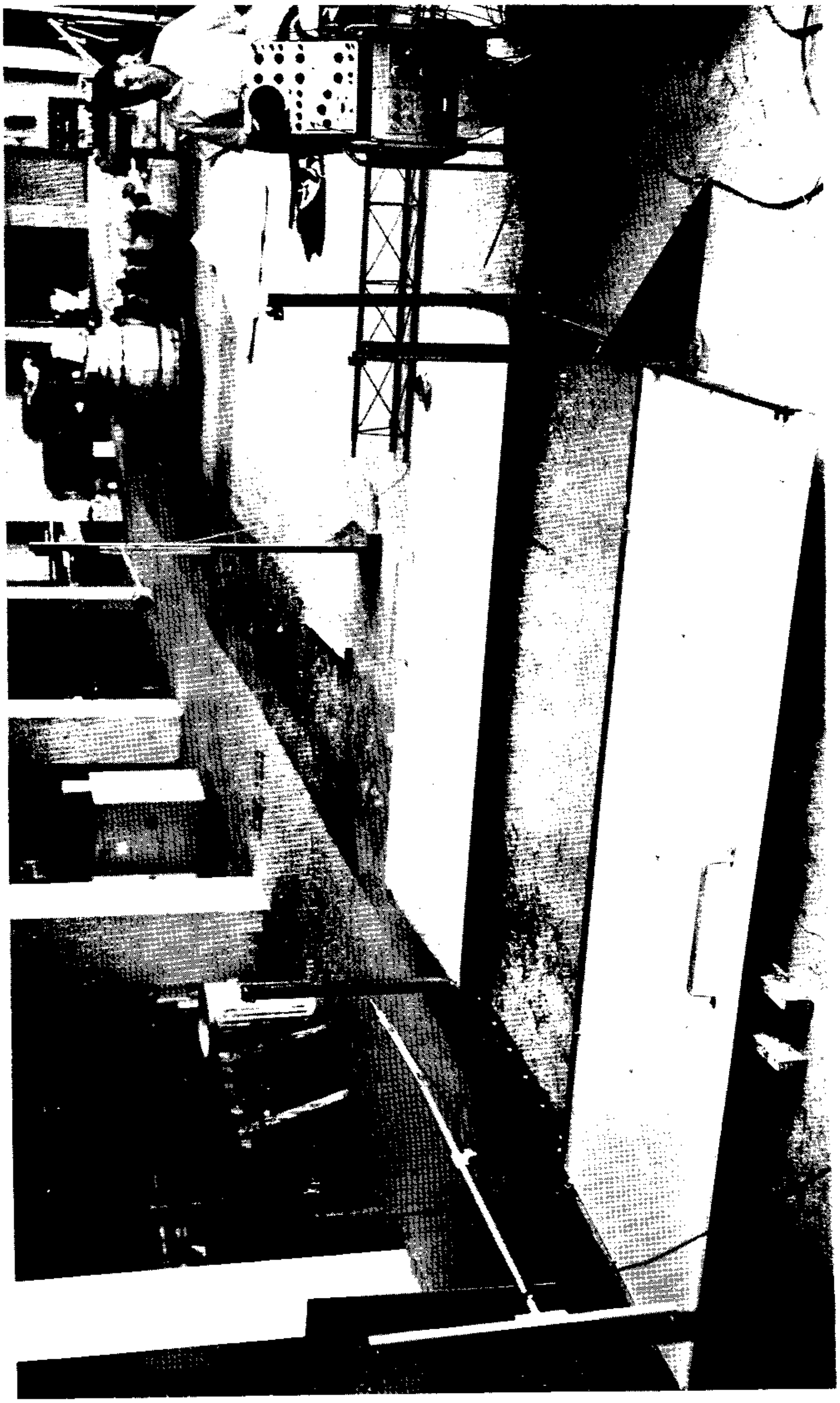


Figure 11. Photograph of measurement setup with wall down.

Both the microphone and the source were cylindrically symmetrical about the horizontal axis. It was quite reasonable, then, to assume the center of radiation was located on this axis. The effective height of the center of radiation could thus be measured unequivocally. This is fortunate, since the vertical measurements are the more critical. The horizontal center of radiation was more difficult to establish absolutely; therefore, the best estimate of its position was used in the measurements. As previously shown, however, the horizontal distance measurements are intrinsically less critical.

The basic heights were measured using a 2-m wooden rod graduated in millimeters. The reference height was the top surface of the horizontal meter sticks glued to the floor. To measure the height of the source or the microphone, this rod was used directly to read the distance to a spot on the microphone or source located on the cylindrical axis. To measure wall height, we constructed two jigs of identical length (there was considerably less than 1 mm difference) which were affixed perpendicular to the horizontal meter sticks on either side of the wall to establish the points that were at exactly the same height. A rigid, and essentially nondeflecting, aluminum angle was then placed above the wall between the two jigs (the height of the jigs was such that this reference beam was higher than the wall). The difference between the top of the wall and the bottom of the aluminum angle was then measured and used together with the known jig height to compute the effective wall height.

As mentioned previously, the horizontal distances for the source and the microphone were measured by dropping a plumb bob to the horizontal reference scale. The horizontal position of the wall was ascertained by dropping a vertical line from a scribed position on the aluminum angle described above to the top of the wall. A plumb bob was then dropped from another scribed position a precisely measured distance along the angle to the horizontal meter sticks on the floor. These data were then used to define the horizontal position of the wall.

One of the cardinal positions in the measurement set is zero, or the position where a ray joining the precise centers of radiation of the source and the microphone would just graze the top of the wall. To cross check the geometric measurements mentioned above, the zero height point was checked visually. The procedure that seemed to work best, and to be, indeed, accurate, was as follows.

One observer would put his head immediately beside the source and attempt to align his eye at exactly the same height as the center of the source. At the same time, another observer would put his head beside the microphone and attempt to align his eye at precisely the same height as the center of the microphone. The relative heights of the source and the microphone were than adjusted until, to both observers, the center of the other instrument and the pupils of the other's eyes simultaneously appeared to precisely intersect the top of the wall. This method cross checked accurately with the measurements made geometrically, giving confidence to both measurements.

When the zero position was established by the cross-check method described above, the acoustic attenuation was always close to 6 dB compared to the 5 dB in the 117 Report. The actual measured values tended to scatter slightly, ranging from 5.8 to 6.1 dB. When the height of the microphone was adjusted until 6 dB was obtained, the line of sight was usually extremely close to a grazing angle, the microphone typically being low by perhaps a millimeter.

THE ACOUSTIC MEASUREMENTS

Instrumentation

Figure 12 is a schematic drawing of the acoustic measurement setup and Figure 13 is a block diagram of the instrumentation used. Basically, an acoustic pulse was transmitted by the source, and the level received at the microphone was measured with the wall present and with the wall absent; the difference between these two levels (in decibels) was then the measured attenuation. The source and microphone were both located on booms oriented perpendicular to the wall so that they presented minimum acoustic interference.

The experiments were conducted at two frequencies, 5.193 kHz and 10.019 kHz, supplied from a continuously running oscillator that could be switched from one frequency to the other. This signal was appropriately gated to provide the desired tone burst. A free-running multivibrator was used to establish the pulse repetition rate. The period was adjustable over a wide range, but, in practice, the repetition rate was set so that the reverberation from the preceeding pulse would die out before the next pulse originated. In the large concrete warehouse in which the experiments took place, this rate was approximately once every 3/4 second. In this time, the sound from the previous pulse would have traveled about 800 feet and, at the frequencies used, was highly attenuated because of absorption in the air even though the walls were fairly reflective.

The oscillator fed a synchronizing signal to the repetition generator so that the pulse would always commence on the same part of the waveform and the tone burst would appear as a completely stationary figure on the oscilloscope. The repetition rate generator also triggered

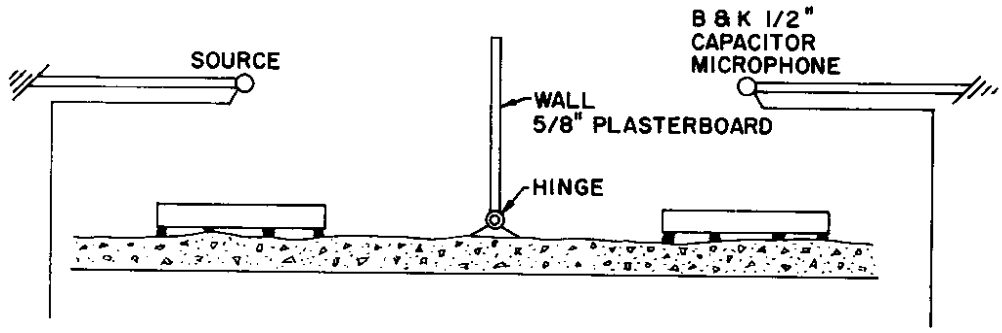


Figure 12. Sketch of measurement setup.

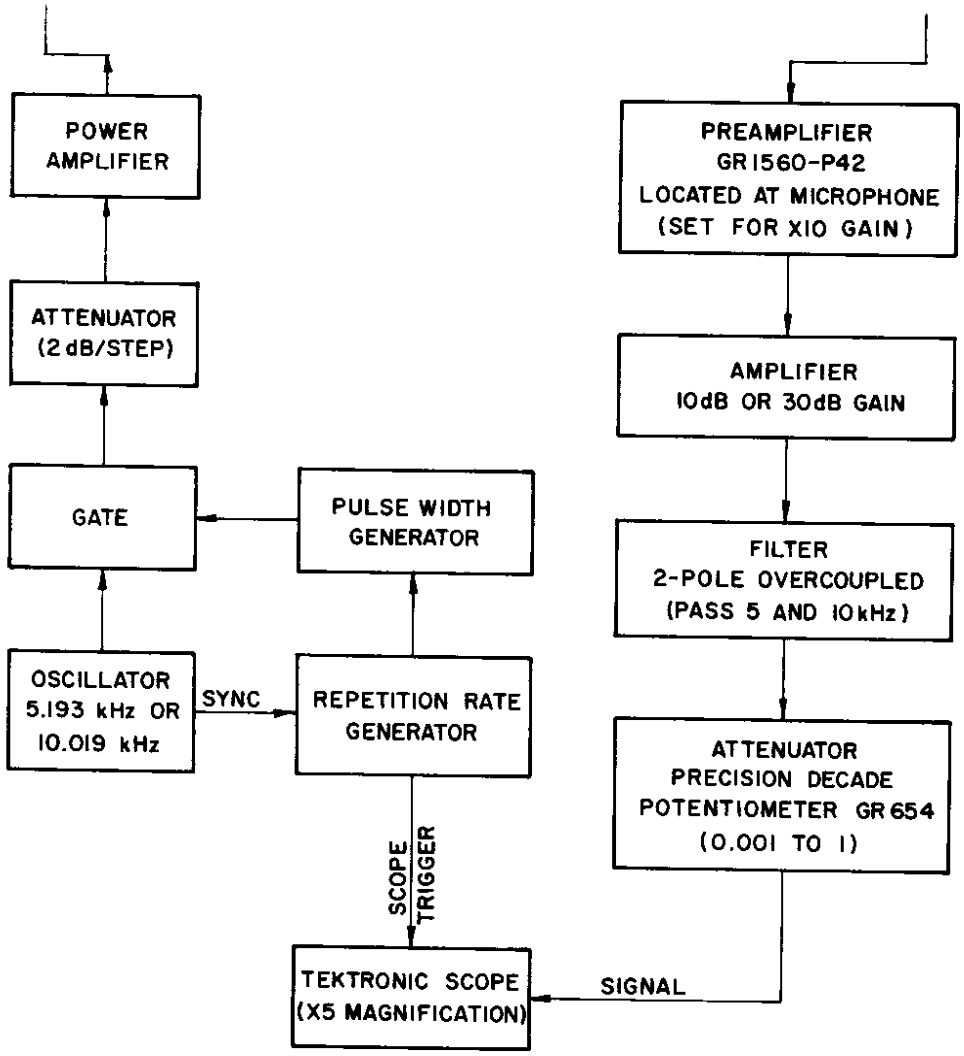


Figure 13. Block diagram of measurement apparatus.

the oscilloscope. The Univibrator pulse width generator was also adjustable through a wide range; in practice, it was set to give the widest acoustic pulse that would permit the tone pulse on the oscilloscope display to end cleanly before the first reverberation arrived. The pulse width varied depending on the geometry of the particular experiment but was typically about 1 or 2 msec. The accuracy of the measurements did not depend on the calibration of the 2 dB-per-step attenuator, which was normally set so that the signal was approximately 97 dB 1 m from the source. For some measurements where the microphone was near the source, the attenuator was turned down to prevent saturation of the microphone amplifiers; however, this was done prior to the particular experiment and the setting left that way throughout.

The source transducer itself was a dynamic "tweeter" element, the housing and mounting of which were extensively modified to make it closely approximate a point source while still transmitting a desirable tone burst envelope shape.

The receiving system consisted of a 1/2-in. B&K capacitor microphone coupled to a General Radio P-42 preamplifier set to a X10 gain position. This in turn was coupled to an amplifier as shown in Figure 13. A two-pole overcoupled filter with one peak at 5 kHz and another at 10 kHz produced strong signal rejection above and below these bands. The General Radio 654 precision decade potentiometer, the standard to which the precision of the measurements was directly related, was accurate to 0.05%. The oscilloscope readout was used for several purposes, but during data taking it was primarily used as a "null meter," and the actual data readings were taken from the potentiometer.

Measurement Procedure

When a series of measurements was to be performed, the oscilloscope and other electronics were warmed up well before hand to ensure they had stabilized. The acoustic pulse was then turned on and the oscilloscope adjusted to monitor the microphone from the time the pulse left the source until well after the main pulse had passed. The gain was set very high to examine the trace before the arrival of the first tone burst to ensure that traces of reverberation from previous pulses were not still occurring, and the repetition rate was adjusted accordingly. The gain was then reduced and reverberation subsequent to the main pulse was examined to see if it seemed reasonable in light of the geometries involved. The pulse width was checked both with the wall down and with the wall up to assure that the pulse was as long as possible but was still completely terminated before the arrival of any reverberation from the floor, ceiling, etc.

The sweep on the oscilloscope was switched to X5 magnification and a region in the center of the tone burst where it had leveled off in a "steady state" was centered on the screen. The particular positive-going cycle of the pulse chosen for the actual measurement was then carefully identified by counting the cycles from both ends of the tone burst. The base line of the waveform was then suppressed well below the bottom of the oscilloscope screen and the gain of the oscilloscope was turned up so the tone burst tops were displayed on the scope. This allowed small changes in the amplitude of the waveform to be detected. With the wall removed, the precision decade attenuator was then set and the oscilloscope adjusted so that the peak of the chosen cycle was exactly on one of the horizontal graticule lines of the oscilloscope screen, usually the next to the top line. The wall was then erected and the setting on the decade potentiometer increased (less attenuation) until the selected part of the waveform was again on the reference graticule of the oscilloscope. The difference in the two readings on the precision decade potentiometer was then used to compute the attenuation caused by the presence of the wall. The equation used was 20 log (A1/A2).

As can be seen, we did not depend on the oscilloscope as a calibrated reading instrument; this function was transferred to the highly accurate precision potentiometer. The oscilloscope does not even have to be linear; it does , however, have to remain stable for the period between the two measurements. Our oscilloscope easily met this requirement. When reading the waveform after the wall had been erected, we had to be careful to pick the same part of the tone pulse used for the first measurement, since the pulse was delayed slightly because of the wall. We do not believe we introduced any error in the data from this particular source.

The base line on the oscilloscope was usually sufficiently suppressed and the gain sufficiently high that a 1-dB change (the system was actually linear, not in decibels) in the amplitude of the waveform corresponded to 1 or 2 cm on the face of the oscilloscope. At this resolution, the signal varied slightly from pulse to pulse in a somewhat random manner, with small changes in amplitude occurring over a period of perhaps 1 second and longer-term changes with periods of 5-10 seconds. We verified that these were acoustic (not electronic) phenomena by placing the microphone close to the source while it was transmitting at a fairly high level, in which case the received waveform is quite steady. If the drift had been in the electronics, or transducers, it should have showed up in this experiment, as well as in the actual measurements. The base line of the waveform was also checked by displaying it on the oscilloscope screen during conditions when the peaks of the waveform were observed to vary considerably. The base line was relatively steady, indicating that components of the received tone burst amplitude were being modulated rather than an additional signal being applied. As discussed later, the amount of this variability depended on the specific measurement conditions. This variability meant that some operator judgment was required when "nulling" the oscilloscope for an attenuation measurement.

The method used to establish the setting on the precision decade potentiometer was essentially that of "eye averaging." The operator would make a tentative setting and observe the waveform for 20 or 30 seconds to see if the setting was a reasonable value; if not, he would move the potentiometer to a new setting and repeat the observation. This process was continued until the signal appeared to spend as much time above the reference gradicule as it did below it. It would certainly be possible to refine this procedure with more extensive processing; however, the scope of the program was too small to include such refinement at the time.

SIGNAL VARIABILITY

Much of the time when data were being taken, the received signal varied by a few tenths of a decibel. At other times the variability would be as great as 1 or 2 dB (data were not taken under these conditions). The results of the checks discussed in the previous section demonstrated that this variability was an acoustic phenomenon and was not caused by drifts or jitter in the associated equipment.

We also believe that, under most circumstances, the phenomenon was not caused by an overly high ambient (background) noise level. Data were normally taken only when the doors to the building were closed and when there were no extraneous disturbances, such as especially loud trucks passing on nearby roadways. The typical noise level in the room ranged between 45 and 50 dBA; on a C scale, the value would be about 60 dBC. The source level, measured at 1 meter on a sound level meter with the tone momentarily switched to emit steady sound, was approximately 95 to 97 dB, depending on the frequency. This would indicate a signal-to-noise ratio of 45 to 50 dB at 1 m. In actual practice, of course, a more effective filter than A-weighting (for this application) was used to screen out background noise. After passing through the filter, the ambient noise during quiet periods was approximately 54 dB below the amplitude of the tone bursts when measured at a source-to-microphone spacing of 4 m. This would equal a signal-to-noise ratio of 66 dB at 1 meter.

Figure 14 is a plot of the error that would occur in measuring the level of a signal as a function of the signal-to-noise ratio. This curve assumes that the signal and noise are uncorrelated so that the power of the signals is additive (and that, of course, both the signal and the noise are within the bandpass of the system under consideration).

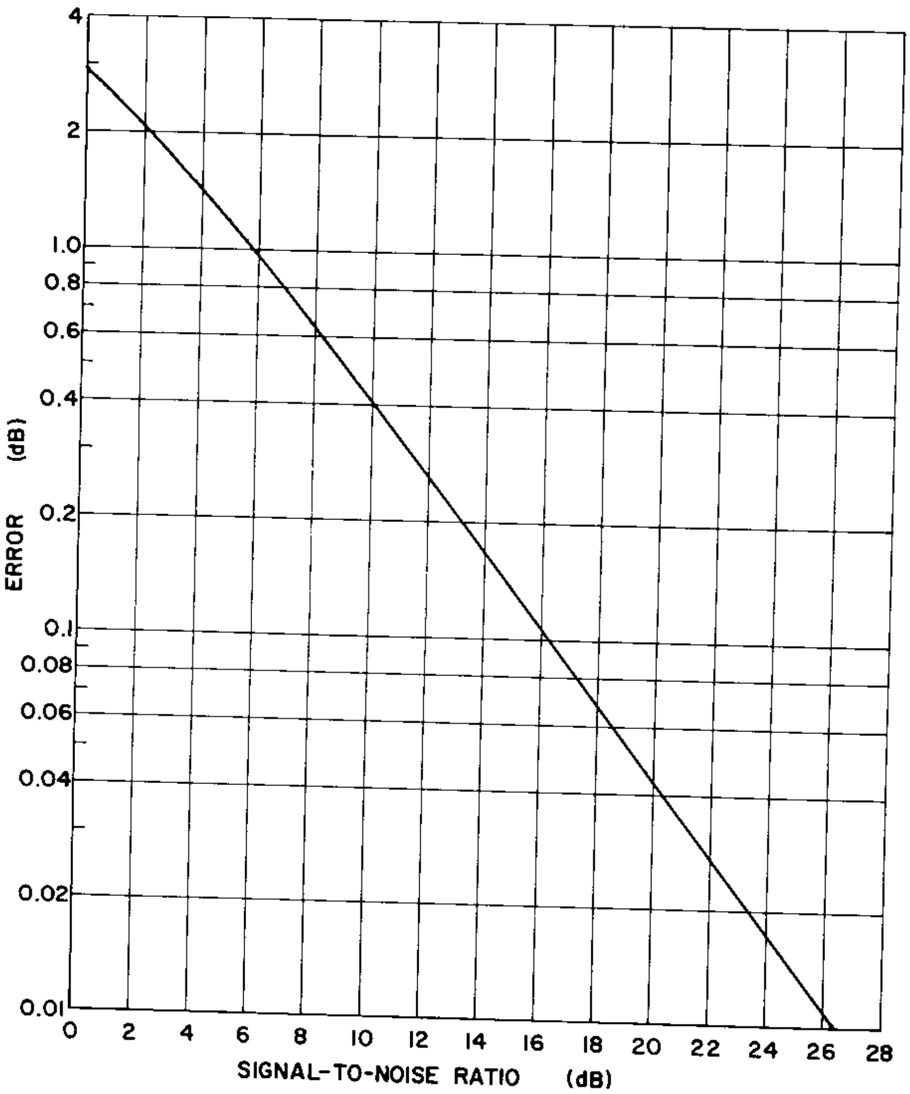


Figure 14. Measurement error as a function of the signal-to-noise ratio, assuming power is additive.

As can be seen from this curve, the adage that if one signal is 10 dB higher than another the contribution of the lower signal is negligible is substantially correct--but not entirely; the curve indicates this difference would still yield an error of approximately 0.4 dB. To reduce the error to 0.1 dB would require a signal-to-noise ratio between 16 and 17 dB, whereas a signal-to-noise ratio of 20 dB would be required to reduce the error to 0.04 dB. A difference of 0.4 dB is probably undetectable for most listeners; certainly, lesser values would never be discriminated.

With instruments, however, smaller variations can be detected, and, when establishing principles, can sometimes be important. For the purposes of the program described here, it seems reasonable to assume that a signal-to-noise ratio of 20 dB would be more than adequate to eliminate any measurement error from this source. By this criterion, if the source-to-microphone spacing were 4 m, the attenuation caused by the wall would have to be in excess of 34 dB before it could be reasonably assumed that the effect was being influenced by ambient noise. Furthermore, the measured "noise" appears to be mostly modulating the amplitude of the received tone burst, whereas an additive signal would primarily displace the base line. This modulation effect was most noticeable when the attenuation was high (the signal levels were low) because of the presence of the wall.

To the extent that this error mechanism is effective, it will produce curves that are lower than the true attenuation value; our values are, on the average, slightly lower than would be predicted by Fresnel diffraction.

The most likely cause of the disturbance is slight wind currents in the room. When the wind stream from an electric fan was directed into the sound path between the source and the microphone, the jitter was greatly increased. This was, of course, not a very "clean" experiment since the fan also made considerable noise, thus somewhat raising the ambient sound level. A more convincing experiment was to stand well to one side of the sound path and quietly wave a large sheet of cardboard or plywood to create a wind without adding noise. This procedure also greatly increased the pulse modulation. It took 30 seconds to 1 minute or more for the effect to subside; when one of the experimenters walked between the source and the microphone, it could take 10 or 20 seconds for the resulting disturbance to die down.

We examined the sound path with smoke plumes and found no evidence of any unusual stratification or turbulence in the air. The natural ventilation of the room did produce a small but steady air current which usually flowed from the microphone toward the source. This current was undetectable without the smoke.

The scope of the contract and the resources available did not allow us to pursue this particular phenomenon further. The effect of wind and turbulence on acoustics would obviously be much more severe in an open environment and it represents an area that needs further study.

TRANSMISSION THROUGH THE TEST WALL

If there were direct transmission through the test wall, it could, in principle, make the measured attenuation somewhat less than the true value. This does not, however, seem to be the case. Tests at both 5 kHz and 10 kHz did not detect any signals passing through the wall. These tests were conducted by setting the source and the microphone at half the height of the wall, fixing the returned waveform in the center of the oscilloscope screen (using a rather narrow pulse width), then erecting the wall and noting the signal that remained at that center position (the signal diffracted around the top of the wall will arrive later). We found that at both frequencies the signal did not differ from the background noise level. The signal-to-noise ratio was at least 55 dB, effectively eliminating this source of possible error.

THE POINT SOURCE

The experiments described in this report were conducted using "point" sources (and receivers), as opposed to lines or arrays. This was done not because sources that act as though they are radiating from an area of greater dimension are of little interest both practically and theoretically, but rather because we did not wish to introduce any unnecessary variables into the experimental program; furthermore, we felt the program should thoroughly examine point sources before proceeding to more complex emitters.

This section considers just how "pointed" the source used in this experimental investigation was. Obviously, we could not have, in practice, an actual point source, since, in addition to all its other contradictions, such a source would be incapable of radiating any power. We were seeking a source that radiated a reasonably spherical pattern (at least in the direction in which the propagation was to take place) with essentially spherical radiation up to as near the source transducer as any of the parameters of the study would be likely to be measured. One way to achieve spherical radiation would be to use a pulsating sphere for the source; however, such a device was not feasible for these experiments. A more practical approach is to make the radiating dimensions of the transducer very small; unfortunately, this approach conflicts with our desire for a transducer capable of producing a reasonably high source level, and sometimes conflicts with the desire for the low electroacoustic "Q" that is needed for the pulse work involved. Initially we attempted to use commercial "tweeter" units; their patterns, however, were not sufficiently spherical.

Considerable effort was directed toward obtaining a suitable source. The final result utilized the driving element from an electromagnetic tweeter, the housing of which was extensively modified. Ultimately, the whole device except the radiating surface was cocooned in several layers of foam and lead foil to prevent radiation from any part except the desired radiation surface.

Two methods were used to experimentally determine the degree of "pointiness" of the candidate sources: (1) beam patterns, and (2) plots of attenuation vs distance. First, we took patterns in the far field to determine if a given transducer (or modification of a transducer) would be a good candidate for the source. Figure 15 shows the 5-kHz beam pattern of the transducer ultimately selected. Figure 16 shows the beam pattern at 10 kHz. The pattern departs from sphericity by less than 1 dB over a total beam width of approximately 50°. This is slightly more marginal than we would have liked; however, since we also needed a transducer capable of a high source level (a conflicting requirement), it was deemed an appropriate compromise.

Figures 17 and 18 are experimentally measured beam patterns at 5 and 10 kHz, respectively, for the 1/2-in. B&K capacitor microphone (mounted in a General Radio preamplifier) used as the sound pickup device. As can be seen, even at 10 kHz the pattern departs from sphericity by less than 1 dB over a total beam width of 80°, whereas at 5 kHz it is very flat, departing from sphericity by less than 1 dB over about 150°.

The other important test criterion was the shape of the attenuation vs distance curve. A point noise source will exhibit inverse square spreading if:

(1) It is measured in free space.

(2) There is no other attenuation mechanism, such as atmospheric absorption.

(3) Most important to this discussion, it really is acting as a point source.

If the source is not quite small compared to the distance at which the closest measurement is made, the attenuation vs distance function will fall off <u>less</u> steeply than for inverse square spreading. For example, the intensity of a line source (which would exhibit cylindrical spreading) would fall off as the first power of the distance rather than as the square of the distance. Sufficiently near a very large broadside array consisting of incoherent sources, there would be no fall-off at all with distance. As long as the subtended angle between the microphone and the edge of the array approached 90°, the received signal would remain the same.

The test, then, consisted of measuring the received amplitude vs distance to ascertain whether it fell off at least as steeply as inverse

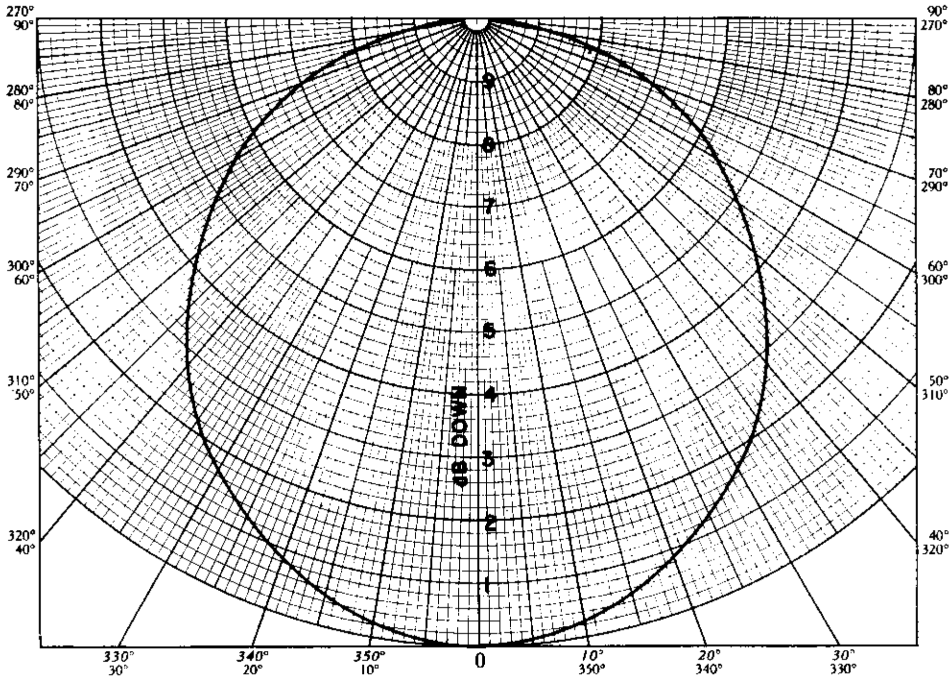


Figure 15. Source beam pattern, 5 kHz.

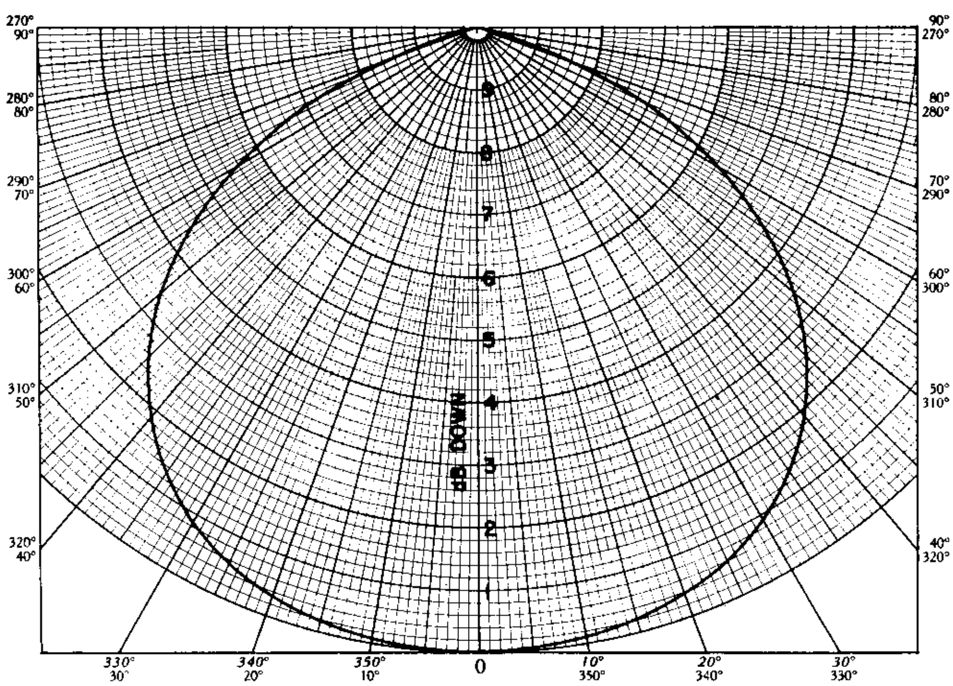


Figure 16. Source beam pattern, 10 kHz.

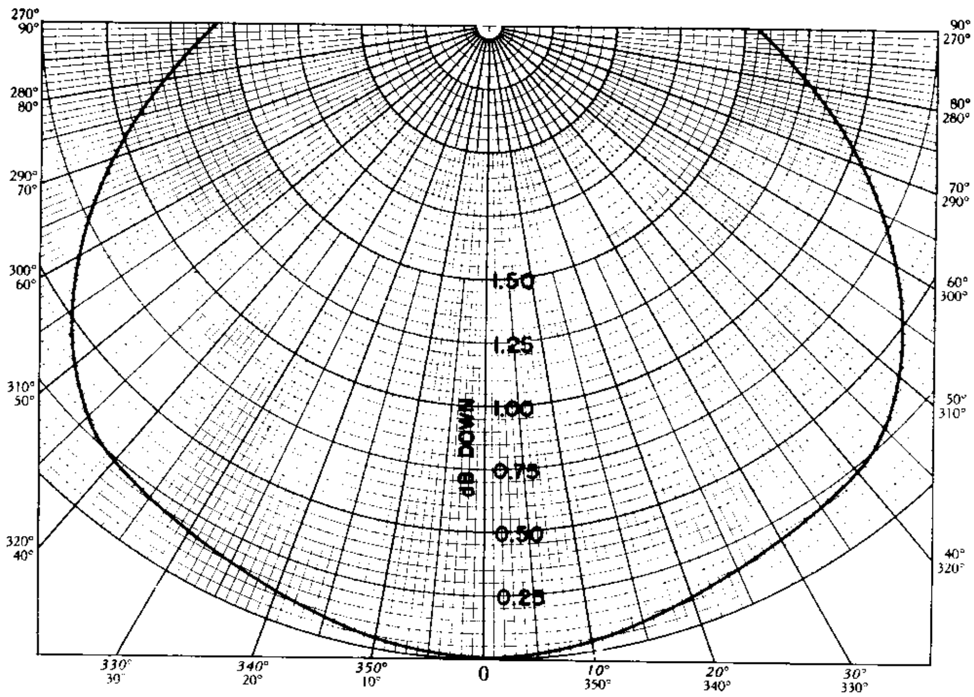


Figure 17. Microphone beam pattern, 5 kHz.

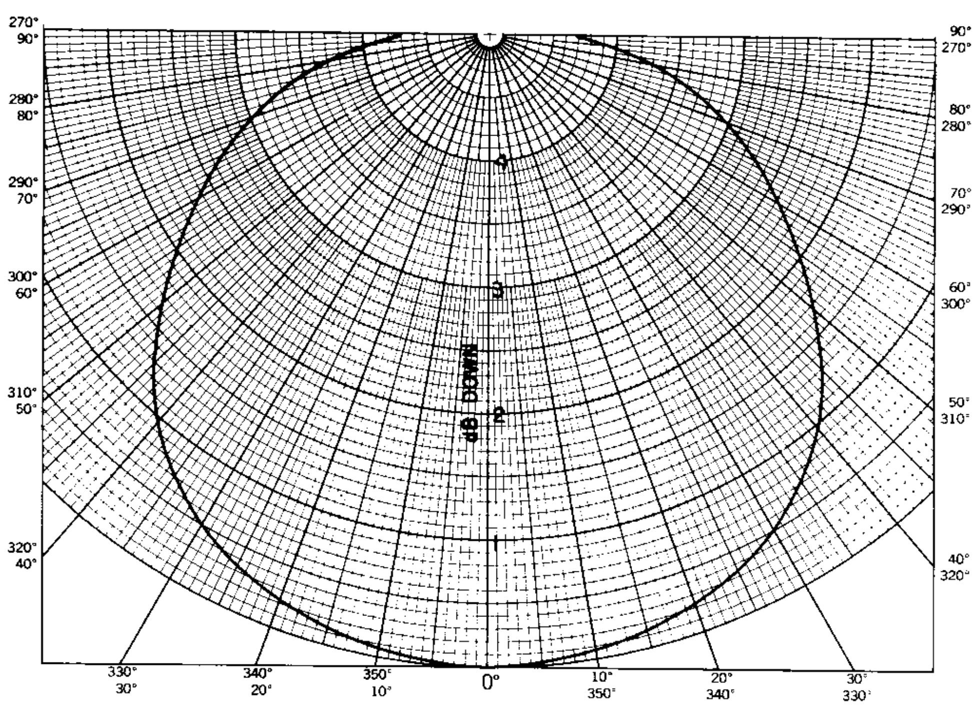
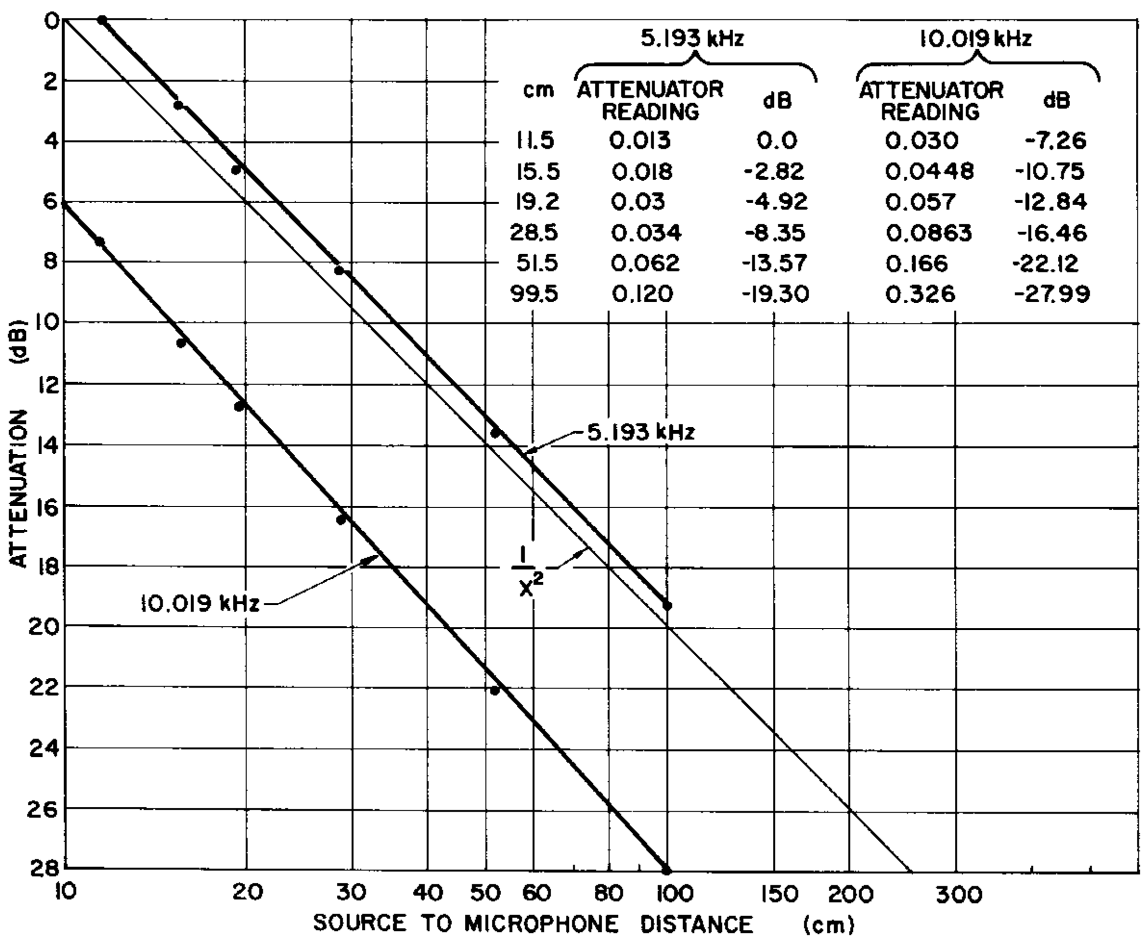


Figure 18. Microphone beam pattern, 10 kHz.

square spreading through a range of distances down to and including those much closer than would ever be used in the experiment. Figure 19 is a plot of the level vs distance for the source transducer ultimately used. The light line is a reference line showing the slope of inverse square spreading. The 10-kHz plot was not normalized with the 5-kHz plot when making the figure, so the actual level difference between these two frequencies shows on the curve. As can be seen, both the 5-kHz curve and the 10-kHz curve are very straight down to 10 cm, which is much closer than any of the distance parameters used in the actual testing. The 5-kHz curve almost parallels the inverse square reference line, indicating the unit is a very good point source at this frequency as well as the absence of any noticeable atmospheric absorption within the 2.5-m span. The 10-kHz plot is also very straight, but shows a slightly greater



cm	5.193 kHz ATTENUATOR READING	5.193 kHz dB	10.019 kHz ATTENUATOR READING	10.019 kHz dB
11.5	0.013	0.0	0.030	-7.26
15.5	0.018	-2.82	0.0448	-10.75
19.2	0.03	-4.92	0.057	-12.84
28.5	0.034	-8.35	0.0863	-16.46
51.5	0.062	-13.57	0.166	-22.12
99.5	0.120	-19.30	0.326	-27.99

Figure 19. Plot of distance vs signal for the experiment source.

slope than the inverse square reference line. This is probably due to the fact that atmospheric absorption can produce a slight but measurable effect at this frequency, even within the relatively short distances involved. The temperature at the time of the measurements was 62°F and the relative humidity was 43.5%.

Figures 15, 16 and 19 indicate that the sound source used in these measurements was a good approximation to a point source. It should be pointed out, however, that a beam pattern that is not completely spherical in the vertical direction will produce data that show less attenuation for a given configuration than would be produced by a true point source.

There are at least two points of view about why a nonspherical pattern would cause such an effect. Consider, for example, if we did not have a point source, but were using a small square array of incoherent sound emitters. If a wall evenly balanced out the effects of the top and bottom transducers of the array, it would make no difference in the measurement whether we used the array or a point source. The Fresnel noise power-vs-wall height curve is not linear, however. In most cases, the extra sound reduction from the bottom of a small array will not compensate completely for the sound increase from the top of the array. Thus the received sound level will be higher than it would be if all the sound power had been concentrated at a point at the center of the array, and the attenuation measurement will be lower than it would have been for a point source.

From another point of view, consider the fact that with the higher walls the more direct rays between the source and the microphone are eliminated and only those rays that proceed at a more upward angle can influence the sound received at the microphone. As can be seen from Figures 15 and 16, the relative amplitude transmitted at these angles is slightly less than on axis, and thus the relative received amplitude would be reduced. This would not be true if the source were truly a point; in that case, it would have a completely omnidirectional beam pattern.

It therefore appears that a substantial amount of the small deviation from Fresnel diffraction experienced in the experimental program can be accounted for by the effects discussed above. If this hypothesis is correct, the experimental data should lie very close to Fresnel diffraction for very small or negative values of N whereas higher values of N, which involve larger angles (as well as higher attenuation) should produce a larger deviation. Examination of Figures 3 and 4 shows this tendency clearly.

THE RELATIONSHIP BETWEEN FRESNEL DIFFRACTION AND FRESNEL NUMBER

Current work in the field of highway noise screens uses the geometric parameter N, referred to as the Fresnel number. This is defined as

$$N = \frac{2\delta}{\lambda} ,$$

where δ is the difference between the shortest direct path if no barrier existed and the shortest path to the top of the barrier and back down to the microphone, and λ is the wavelength of the sound in the medium (in this case, air). This is a very useful number, with a simple geometric relationship, for highway work.

Fresnel diffraction, on the other hand, is classically derived and presented in terms of the geometrically related parameter V. This is defined as

$$V = a\theta\sqrt{\frac{2(a+b)}{a\,b\,\lambda}}$$

where

a = the distance from the source to the top of the wall

θ = the angle (in radians) between a line joining the source and the microphone and a line between the source and the top of the wall

b = Z-a (see Fig. 20). This is close to, but not the same as, the distance from the wall to the microphone.

λ = the wavelength of the sound under consideration.

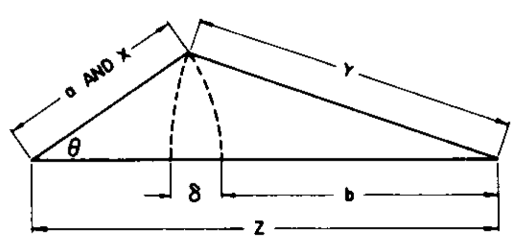


Figure 20.

The question now arises, What is the functional relationship between V and N? As will be shown, for small angles of θ, including most situations of practical interest for highway work,

$$V = \sqrt{2N} \ .$$

We proceed as follows (consider Fig. 20).

First we need the relationship between θ and the other parameters. For small angles, θ = sin θ (θ in radians). One trigonometric identity involving sin θ is

$$\sin \frac{\theta}{2} = \sqrt{\frac{(S-X)(S-Z)}{XZ}}$$

where

$$S = \frac{1}{2}(X+Y+Z) \ .$$

If, for small angles,

$$\frac{\theta}{2} = \sin \frac{\theta}{2} ,$$

then,

$$\theta \simeq 2 \sin \frac{\theta}{2} \ .$$

Table III shows the error in this approximation. As can be seen, the approximation is remarkably good. Even at 50°, it is off only a little over 3%. For all angles likely to be found in highway barrier work, the error from this approximation is so small that it can be neglected.

Table III. Error in the approximation θ ≃ 2 sin(θ/2).

θ (deg)	θ (rad)	2 sin(θ/2)	ratio	Percentage 2 sin(θ/2) is low
5	0.08727	0.08724	1.00032	0.032
10	0.17453	0.17431	1.00127	0.127
20	0.34907	0.34730	1.00510	0.510
30	0.52366	0.51764	1.01152	1.15
40	0.69813	0.68404	1.0206	2.06
50	0.87266	0.84524	1.0325	3.25

Proceeding with the substitution,

$$\theta = 2\sqrt{\frac{(S-X)(S-Z)}{XZ}} \quad .$$

$$X = \delta - Y + Z \quad ,$$

therefore,

$$S-X = \frac{Y+Z-\delta+Y-Z}{2} = \frac{2Y-\delta}{2} \quad .$$

$$Y = b + \delta \quad ,$$

therefore,

$$S-X = \frac{2b+2\delta-\delta}{2} = \frac{2b+\delta}{2} = b + \frac{\delta}{2} \quad .$$

$$S-Z = \frac{X+Y+Z}{2} - Z = \frac{X+Y-Z}{2} = \frac{\delta}{2} \quad .$$

Therefore, the small angle value for θ is

$$\theta = 2\sqrt{\frac{\left(b+\frac{\delta}{2}\right)\left(\frac{\delta}{2}\right)}{a(a+b)}} \quad .$$

Substituting for V,

$$V = 2a\sqrt{\frac{\left(b+\frac{\delta}{2}\right)\left(\frac{\delta}{2}\right)}{a(a+b)}}\sqrt{\frac{2(a+b)}{a\,b\,\lambda}} \quad ,$$

$$V = 2\sqrt{\frac{2}{\lambda}\left(1+\frac{\delta}{2b}\right)\left(\frac{\delta}{2}\right)} = \sqrt{\frac{2\delta}{\lambda}\left(2+\frac{\delta}{b}\right)} \quad .$$

Since

$$N = \frac{2\delta}{\lambda} \quad ,$$

therefore

$$V = \sqrt{N\left(2 + \frac{\delta}{b}\right)} \tag{4}$$

or, since $\delta = Y-b$,

$$V = \sqrt{N\left(2 + \frac{Y-b}{b}\right)} = \sqrt{N\left(1 + \frac{Y}{b}\right)} .$$

Table IV shows the error in ignoring the second term under the square root sign in Eq. 4. The error is 1% when b (in this case, the approximate distance between the wall and the microphone) is 25 times as long as the path length difference. Even when it is only 10 times as long, the error is just 2-1/2%.

Table IV. Error involved in using the simplification $V = \sqrt{2N}$.

b/δ	$\sqrt{1+\delta/20}$	Percentage V is too small
1	1.2247	22.47
2	1.1180	11.80
5	1.0488	4.88
10	1.0247	2.47
20	1.0124	1.24
25	1.0100	1.00
50	1.0050	0.5
100	1.0025	0.25
200	1.0012	0.12

Figure 21 shows a typical high wall configuration used in these experiments. The wall is 280 cm from the source, 120 cm from the microphone, and 40 cm high. In this case, $\delta = 9.33$, $b = 117.16$, and $b/\delta = 12.56$. Therefore, the assumption that $V = \sqrt{2N}$ would result in an error of 1.97%. This means that a data point plotted at, say, N = 1.00 should actually be at N = 0.98; this would hardly show on the plot and can not be considered a significant source of error. To the extent that it did affect the results, however, it would again tend to make the experimental data lower than the Fresnel diffraction curve.

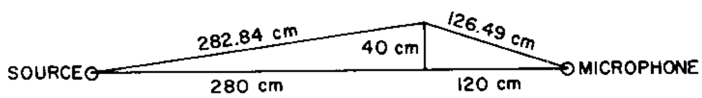


Figure 21. Typical high wall configuration.

COMPUTATION FROM FRESNEL'S CURVE

To compute the attenuation that would result from the installation of a barrier, the following information must be known:

(1) The frequency (or effective frequency) of the source.

(2) Sufficient geometric information so that the path length difference between the direct path and the path from the source to the top of the wall and then to the microphone (or listener) can be computed.

The value of N can then be found using the formula

$$N = \frac{2\delta}{\lambda} \quad .$$

For a single screen, as discussed in this report, the value of N can then be used to determine the added attenuation. The actual evaluation could proceed in a number of ways. For example,

(1) If the computation is being done by hand, the easiest way would be to refer to a graph of Fresnel diffraction such as is shown in Figures 3, 4 or 5.

(2) If the computation is to be run on a computer, one of the choices available would presumably be the direct computer solution to Fresnel's equations for each point. This is, however, not a very productive use of computer time.

(3) Another method to use on the computer would be to store a table of Fresnel diffraction values such as shown in Table I and use an interpolation technique for establishing the intermediate values.

(4) An easier, and more appropriate, course would be to use simpler equations which closely approximate Fresnel diffraction. It is not possible to find a single equation that will cover the entire range through which N might vary; however, by dividing the range into segments and using a different equation for each segment, it is possible to cover the whole range using relatively simple equations. I suggest dividing N into four ranges, using the formulas shown below:

(a) For positive values of N greater than 1.2, use

$$16 + 10 \log N \text{ (dB)} \quad .$$

(b) For positive values of N greater than (but not including) zero and up to (but not including) N = 1.2, use

$$5.8 + 10.4 (N)^{0.41} \text{ (dB)} \quad .$$

(c) For negative values of N from zero (including zero) to -0.22, use

$$6 - 12 \sqrt{|N|} \text{ (dB)} \quad .$$

(d) For negative values of N greater than -0.22, use

$$-1.8\, e^{-0.3N} \sin [180(N-0.3)] \text{ (dB)} \quad .$$

The sin function is used as though the contents of the brackets were in degrees.

Figures 22 and 23 are plots of the Fresnel curve and the curves derived from the preceding equations for positive and negative values, respectively. Note that the results deviate less than 0.2 dB from the Fresnel diffraction curve; in most regions the fit is much closer. The largest deviation occurs at N = -0.22 where, for a very small region, the equations give values that are lower by about 0.4 dB.

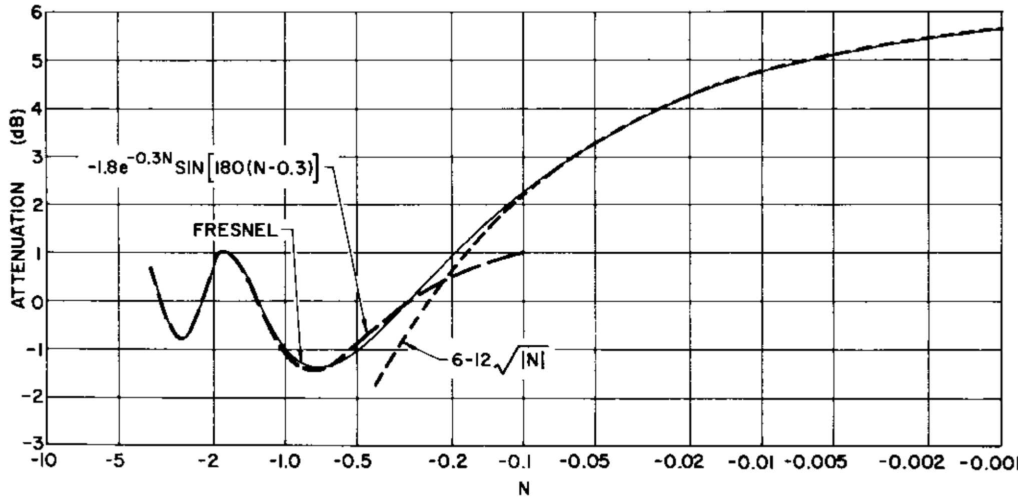


Figure 22. Approximate formula plots for the case where the wall does not block the line of sight.

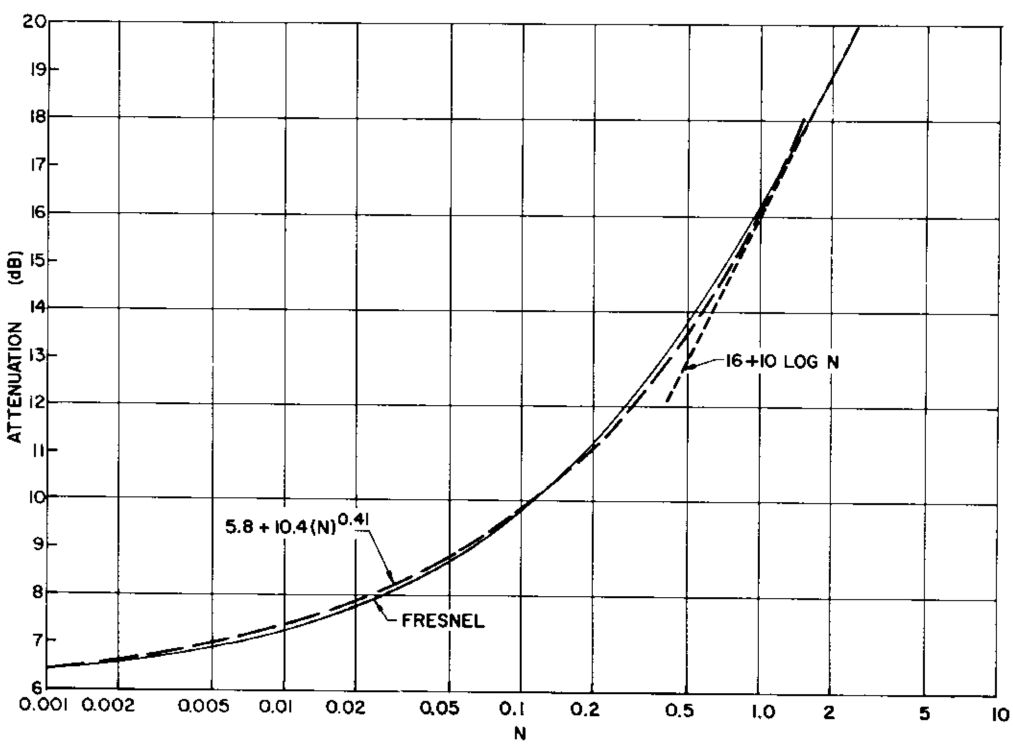


Figure 23. Approximate formula plots for the case where the wall blocks the line of sight.

LINE SOURCES

The experimental work described in this report deals with point sources at a known frequency and a precisely measured geometry. Actual highway acoustic work normally involves many vehicles which, under certain circumstances, act more like an incoherent line source--incoherent since the noise emitted from one vehicle is not correlated with the noise emitted from any other vehicle. It can be assumed that each of these vehicles is merely a source of radiated noise power which each contributes additively to the total reaching the listener.

If Fresnel diffraction is accepted as correct for calculating the effect of walls on sound from a point source, it is then possible to use this curve to calculate what the effect would be if an incoherent line source (or incoherent line segment) were the radiator. It is still necessary, of course, to know the effective radiating frequency and the effective height of the source relative to the top of the wall. These calculations have been performed and the results plotted in Figures 24 and 25 for positive and negative values of N, respectively.

These calculations assume:

(1) That the radiator is a perfectly straight line of densely-packed incoherent sound emitters.

(2) That all of the line is at substantially the same frequency (if it were all at precisely the same frequency it would be a coherent rather than an incoherent line source).

(3) That the top of the wall is perfectly straight and parallel with the line source.

(4) That the line source and its accompanying wall run to infinity in both directions. In the case of line segments, it is assumed that they run to the effective angles indicated and then suddenly and completely cease; this would correspond to a perfectly straight roadway and wall that at each end suddenly disappear into a tunnel or duck behind a hill, or to the case where segmented summation is being used in a computer program.

(5) That the symbol N_0 represents the effective Fresnel number, $N = 2\ (\delta/\lambda)$, calculated on a vertical cut perpendicular to the line source that passes through the measuring microphone (i.e., the shortest distance connecting the line segment with the microphone).

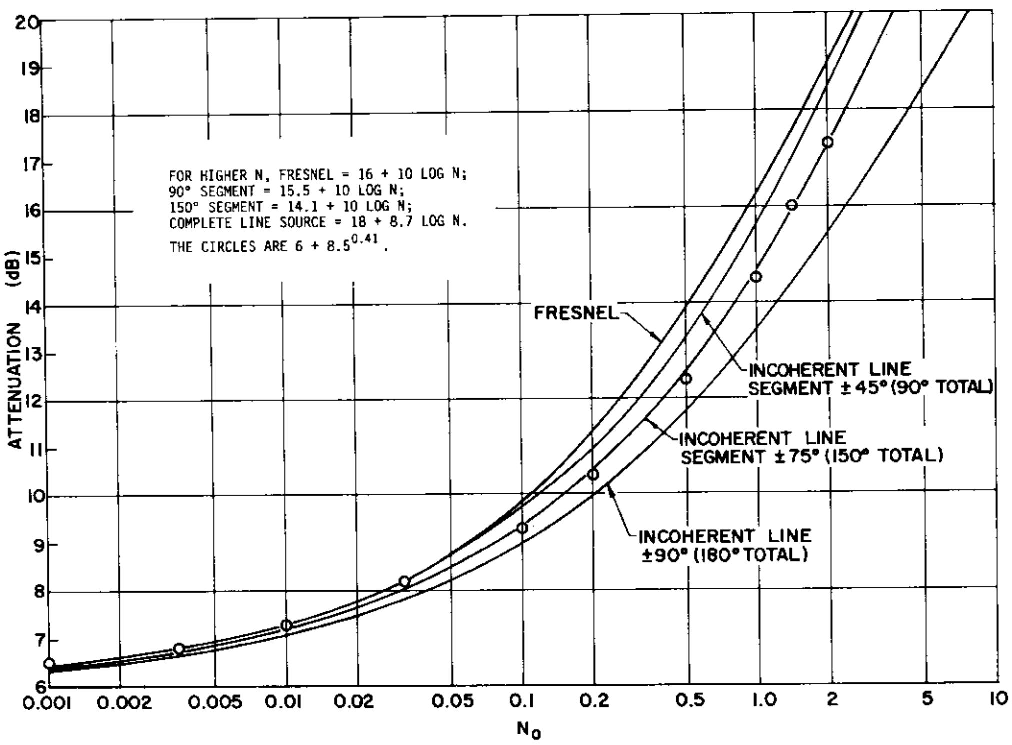


Figure 24. Plot of attenuation calculations for various incoherent line sources and Fresnel diffraction; wall blocking line of sight.

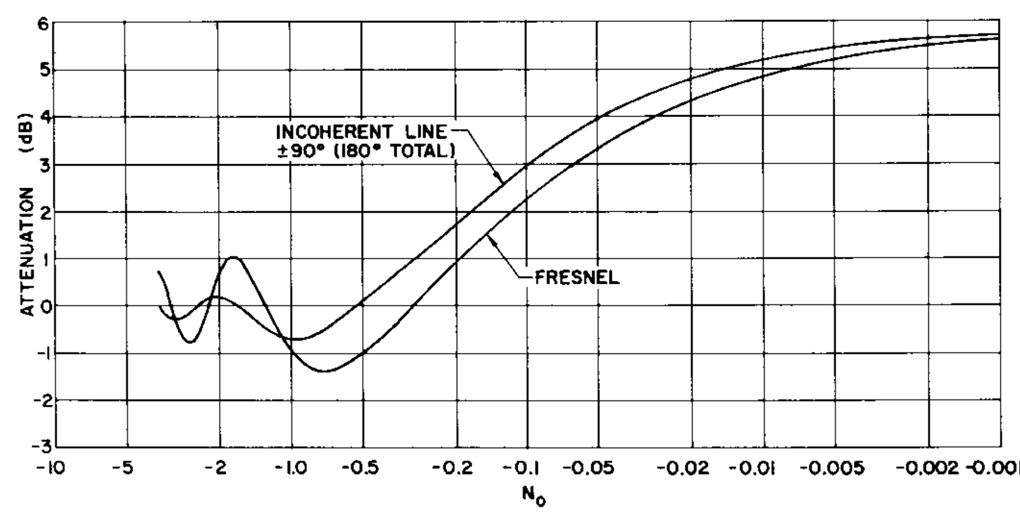


Figure 25. Plot of attenuation for an incoherent line source and Fresnel diffraction; wall not blocking line of sight.

Table V lists the results of these calculations for the case in which the wall blocks the line of sight between the line source and receiver (positive N). Column 1 is the Fresnel number. Columns 2 through 10 give the attenuation in decibels (vis-a-vis free space) that would result from various computations. Column 2 gives the attenuation values for Fresnel diffraction. Column 3 gives the attenuation values that would be computed from the simple formula shown which represents a reasonable approximation to the Fresnel curve for N values from 0.001 to 1.5. Column 4 gives the values obtained from a simple equation for finding Fresnel values for N = 1.5 or greater; as can be seen, this equation gives virtually exact answers for N values greater than 2. Column 6 lists the attenuation that would occur from a straight line segment with an azimuthal angle of 45° on each side of the measuring microphone; i.e., a segment of a line source that subtends a 90° angle from the measurement point. Column 6 is similar to column 5 except that in this case the line segment subtends ±75° from the microphone; i.e., has a total subtended angle of 150°. Column 7 shows the calculations from a simple equation that approximates column 6 for N values from 0 to about 2; column 8 shows an equation closely approximating column 6 for N values of 2 and higher. Column 9 gives the results of the calculation for a line that extends to infinity in each direction; i.e., a total subtended angle of 180°. Column 10 lists the simple equation which is a good approximation to the incoherent line for higher values of N.

Table VI is similar to Table V except in this case the calculations are for the case in which the wall does not block the line of sight between the line source and the receiver (negative N). Column 1 shows the N values. Column 2 gives the attenuation values for Fresnel diffraction. Column 3 shows the attenuation using a simple equation that approximates Fresnel diffraction between N = 0 and -0.22, and column 4 shows the results of an equation that approximates Fresnel diffraction from N = -0.22 on. Column 5 gives the results of the calculation for an incoherent line subtending a total angle of 180° from the microphone.

Since Figures 24 and 25 were plotted on standard logarithmic paper, it is not possible to show N = 0 directly; however, in all cases, zero N would yield 6 dB of attenuation vis-a-vis free space.

As can be seen from Figure 24 and Table V, for positive values of N_0, the effective attenuation from lines and line segments is lower overall than it would be from a point source located at the closest part of the road. At higher values of N_0, the curve for the incoherent line falls quite a bit below that predicted by Fresnel diffraction; at $N_0 = 2$, it is about 3-1/2 dB lower; at $N_0 = 10$, it is a little over 5 dB lower; at $N_0 = 100$, it is about 6-2/3 dB lower; at $N_0 = 1000$, it would be almost 8 dB lower. It never becomes parallel with the Fresnel diffraction curve --the higher the N value, the greater the divergence. On the other hand,

Table V. Noise attenuation calculations for a line source, with wall blocking the line of sight.

1	2	3	4	5	6	7	8	9	10
	Attenuation, dB								
N_0	Fresnel	$5.8 + 10.4N^{0.41}$	$16 + 10 \log N$	±45° Incoherent Line Segment	±75° Incoherent Line Segment	$6 + 8.5 N^{0.41}$	$14.1 + 10 \log N$	Incoherent Line (±90°)	$12 + 8.7 \log N$
0	6.0	5.8		6.0	6.0	6.0		6.0	
0.001	6.4	6.41		6.39	6.33	6.50		6.29	
0.002	6.55	6.61		6.58		6.67		6.45	
0.005	6.89	6.98		6.93		6.97		6.74	
0.01	7.25	7.37		7.31	7.17	7.29		7.05	
0.02	7.74	7.89		7.80		7.71		7.45	
0.025	7.95	8.09			7.79	7.87			
0.05	8.7	8.85		8.71	8.45	8.49		8.19	
0.1	9.8	9.85		9.67	9.31	9.31		8.95	
0.2	11.25	11.18		10.94	10.45	10.39		9.94	
0.35	12.8	12.56		12.27	11.63	11.53		10.93	
0.5	13.91	13.63		13.29	12.53	12.40		11.65	
0.7	15.0	14.79		14.39	13.51	13.34			
1.0	16.3	16.2		15.73	14.67	14.50	14.1	13.40	
1.5	17.85	18.08	17.77	17.31		16.04	15.86		
2.0	19.0	19.62	19.0	18.51	17.27	17.29	17.11	15.45	
3.0	20.77		20.77	20.29	18.94	19.34	18.87		
4.0	22.0		22.0		20.16		20.12		
5.0	23.0		23.0	22.49	21.11		21.09	18.46	18.08
7.0	24.45		24.45				22.55		
10.0	26.0		26.0	25.52	24.13		24.10	20.8	20.70
20.0	29.0		29.0	28.52	27.13		27.11	23.2	23.32
50.0	33.0		33.0		31.12		31.09	26.7	26.78
100.0	36.0		36.0	35.52	34.12		34.10	29.35	29.40
1000.0	46.0		46.0	45.51	44.12		44.10	38.17	38.10

Table VI. Noise attenuation calculations for a line source, with wall not blocking the line of sight.

1	2	3	4	5
	Attenuation, dB			
N_0	Fresnel	$6 - 12\sqrt{\lvert N\rvert}$	$-1.8\,e^{-0.3N}\sin 180(N-0.3)$	Incoherent Line ±90°
0	+6.0	+6.0		+6.00
-0.001	+5.62	+5.62		+5.71
-0.002	+5.46	+5.46		+5.59
-0.005	+5.15	+5.15		+5.34
-0.01	+4.80	+4.80		+5.07
-0.02	+4.30	+4.30		+4.68
-0.05	+3.3	+3.32		+3.90
-0.1	+2.25	+2.21		+3.0
-0.2	+0.90	+0.63	+0.52	+1.72
-0.22	+0.7	+0.37	+0.42	
-0.3	0		0	+0.76
-0.4	-0.6		-0.49	+0.47
-0.5	-1.01		-0.91	+0.07
-0.7	-1.4		-1.39	-0.50
-0.9	-1.2		-1.31	-0.740
-1.0	-1.0		-1.08	-0.752
-1.1	-0.75		-0.76	-0.705
-1.3	0		0	-0.498
-1.5	+0.70		+0.67	-0.235
-1.7	+1.07		+1.03	
-2.0	+0.73		+0.80	+0.163
-2.25	0		+0.14	
-2.5	-0.6		-0.50	-0.063
-2.7	-0.8		-0.76	
-3.0	-0.6		-0.6	-0.29
-3.3	0		0	
-3.5	+0.4		+0.37	-0.12

the curves for the 90° exposure and the 150° exposure do become parallel with Fresnel diffraction, at least over the range of N values we examined (and N = 1000 is exceedingly high). The 90° segment is about 1/2 dB lower than Fresnel diffraction and the 150° segment is about 1.9 dB lower. This relation is reasonably true at $N_0 = 1$ and above. All of these curves are, of course, close to Fresnel diffraction for low values of N, and all cross through 6 dB at N = 0.

As can be seen from Figure 24, the attenuation curve for a wall that paralleled the road in height as well as direction and subtended a total angle of 90° (±45° each way) from the observer would fall only 1/2 dB or less below that of Fresnel diffraction. A substantial percentage of actual highway walls or barriers should fall in this category, since over much of the country a total exposure greater than 90° is precluded by curves, buildings, hills, the fact that the wall does not run far, etc.

A total angle of 150° (±75°) is probably wider than would actually be encountered in the overwhelming majority of actual highway cases. Since, as can be seen from Figure 24, this curve does not closely approximate the curve for an infinite line, even though the segment is only 15° less on each end, it does not seem reasonable to use the full incoherent line curve in highway barrier calculations.

The Fresnel curve should be used for point sources, for example single cars. For other cases, something falling between the Fresnel curve and the 150° curve would seem appropriate, depending on the circumstances. If a single curve is to be used, I would suggest the curve for the total angle of 150°. To facilitate computation,

$$6 + 8.5\ N^{0.41}\ \text{(dB)}$$

can be used as a reasonable approximation for N between 0 and 2 (see column 7, Table V). Some points calculated from this formula are shown as open circles on Figure 24. For values of N greater than 2,

$$14.1 + 10 \log N\ \text{(dB)}$$

can be conveniently used. These formulas would be most useful in constructing computer programs for calculating diffraction effects; for hand calculation, it might be easier to refer directly to a graph such as Figure 24.

Figure 25 is a plot for negative values of N, i.e., where the wall does not block the line of sight between the source and the receiver. Once again, at N = 0, the attenuation is 6 dB for all cases. At about N = -0.3, Fresnel diffraction drops to 0. Between -0.3 and about -1.3, the signal is actually enhanced and the received signal is more intense than it would be if the wall were not there at all. Attenuation and enhancement continue to alternate in a decaying exponential manner for the rest of the curve. The computations for a full incoherent line source show more average attenuation than for a point source. This is because sounds coming from angles other than normal incidence would have effective N values more toward zero which, in the case of negative N, means they would produce more attenuation than if all the sound were located at a point immediately opposite the observer. As can be seen, the curve for the incoherent line source does not reach zero until $N_0 = -0.5$ and it then goes through oscillations of enhancement and attenuation which are not in phase with those for Fresnel diffraction. The amplitude of these oscillations is small and decays swiftly to zero.

In Figure 25, the curve for the incoherent line source does not differ greatly from that for Fresnel diffraction. That for a line segment would approach the Fresnel curve even more closely. I therefore recommend that Fresnel diffraction be used to calculate negative N values. Again, the curve could be used directly for hand calculations; the approximation equations given in columns 3 and 4 of Table VI would be useful for computer calculations. In practice, the Fresnel approximation shown in column 3 could be used for negative values down to about -0.25, and, since the mixture of frequencies found in actual highway work would probably tend to cancel out the small oscillations produced at more negative values, it might be reasonable to simply assume that they contribute essentially no attenuation.

CONCLUSIONS AND RECOMMENDATIONS

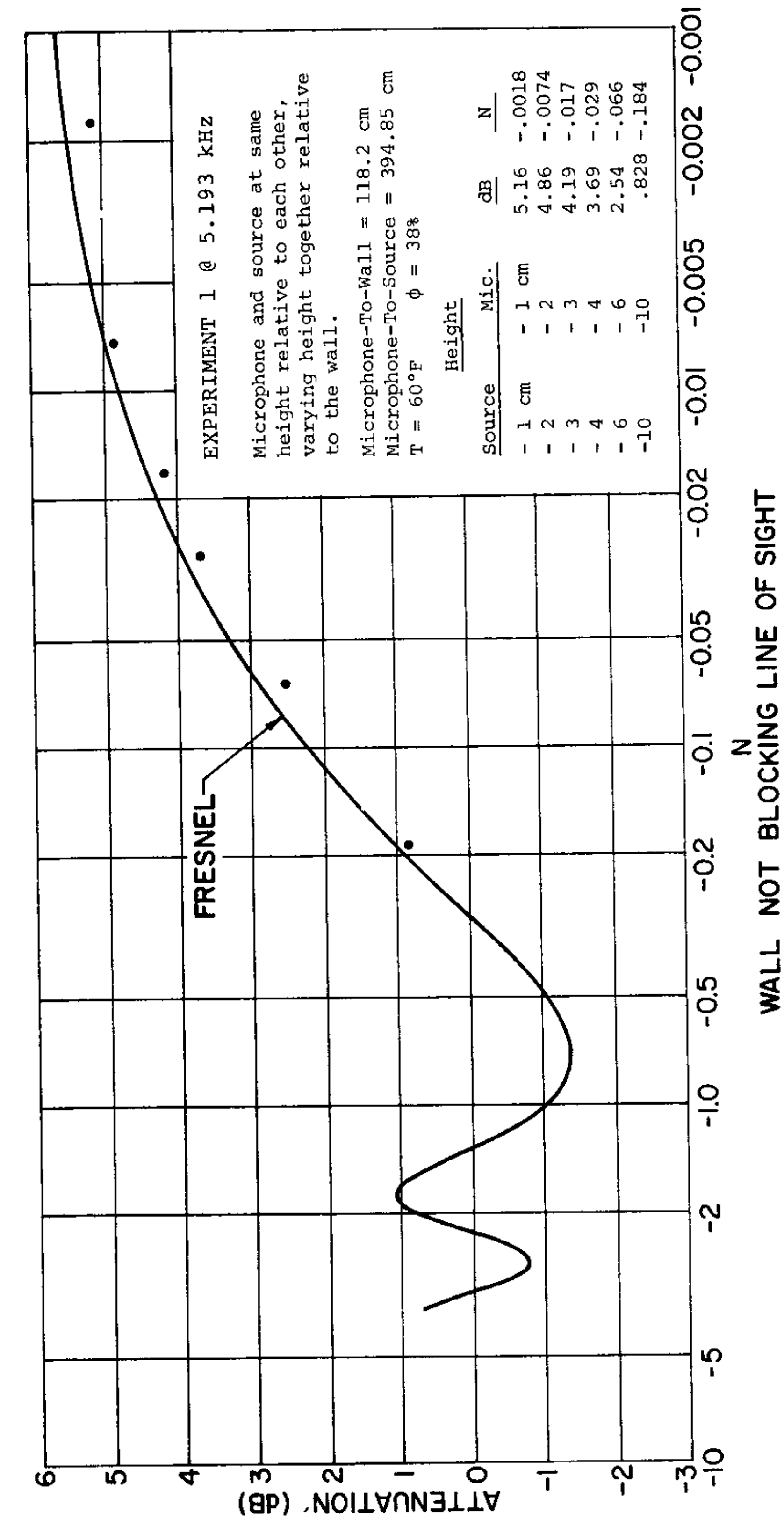
This report has shown that the correct curve for use in computing the effects of walls or screens on the sound transmission from point sources is that of Fresnel diffraction. The 117 Program uses a curve proposed by Maekawa which was also determined experimentally from point sources. However, this curve is too low and does not give a wall full credit for the actual attenuation it would yield. In actual highway work, there are many other variables, of course, such as the effective height and radiating frequency of the vehicles on the road. It might be that using a lower curve would help compensate for some of these unknown factors, but it is my opinion that this is poor practice. The proper course is to use the correct formula for defining the attenuative effects of walls and screens and to investigate the unknown factors until proper predictions of their effects on barriers and screens can also be made. The report suggests some simple formulas that can be used to represent Fresnel diffraction for calculation purposes.

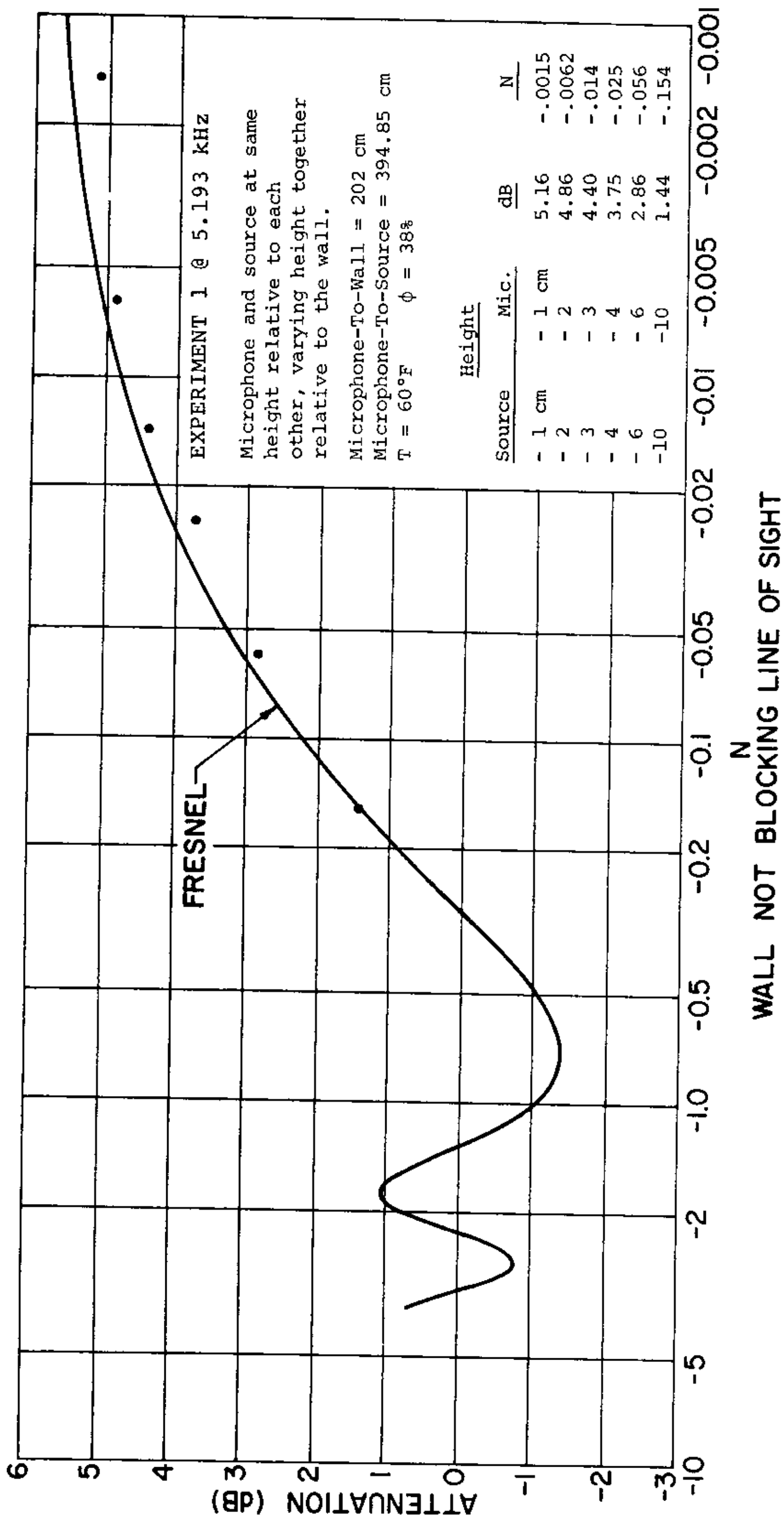
Since highways are often crowded with cars, it is tempting to consider the road as a line source insofar as the effects of barriers are concerned. A curve corresponding to a true incoherent line source has been calculated and is presented in this report. However, circumstances where this particular curve would be appropriate are exceedingly rare, and it would therefore probably not be good practice to build such a curve into a highway noise prediction program.

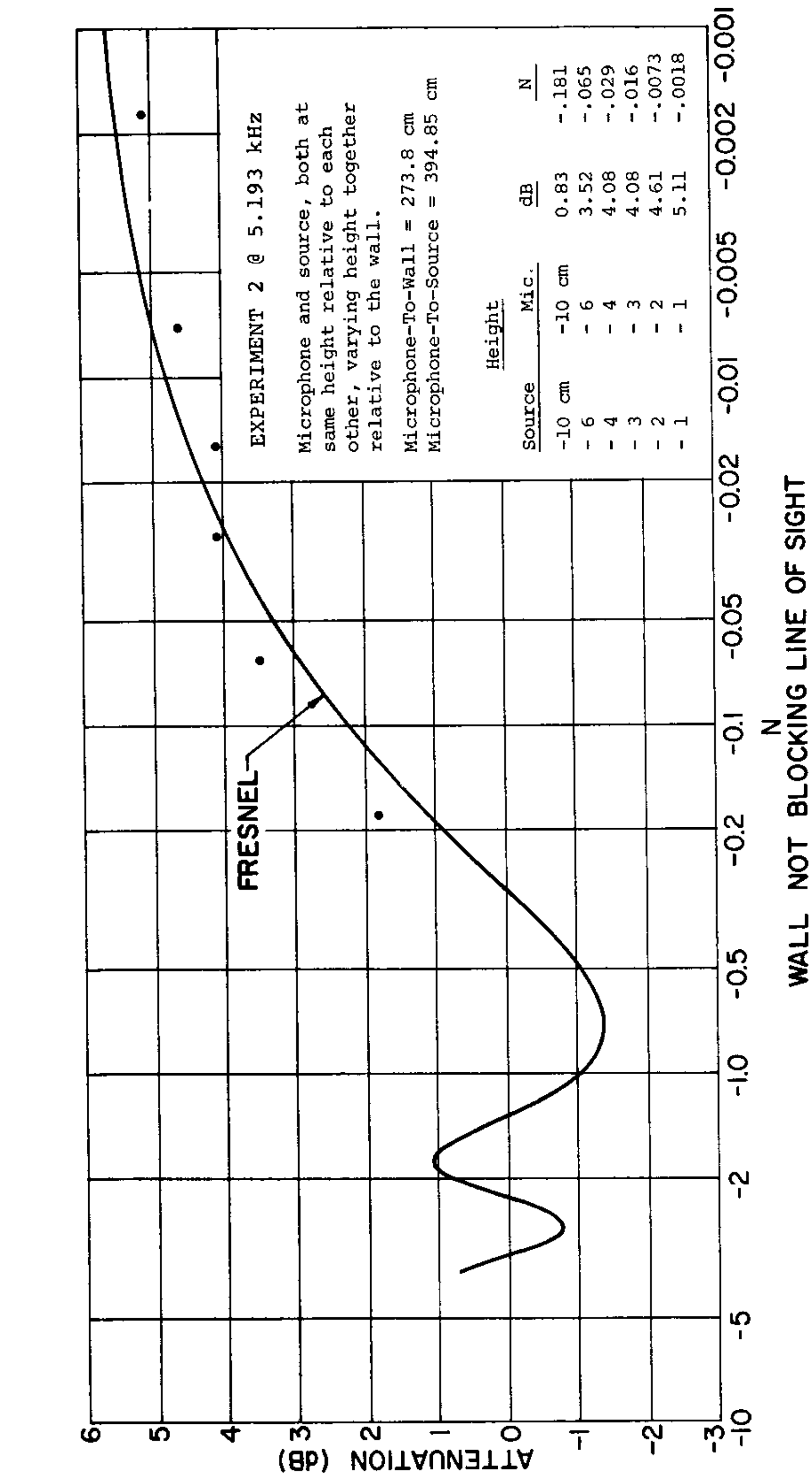
Of more practical interest as noise emitters are incoherent line segments. It is not uncommon that the effective angle of a screened road is less than a full 180°. It is even more common that chance barriers (buildings, natural contours, etc.) cover only a small part of the field of view leaving the rest of the road exposed. The appropriate way of handling these situations is the piecewise addition of the sound energy from each of the sections of the road. For sections that are shielded by walls or barriers, I recommend using the curve for Fresnel diffraction as long as the total subtended angle of the barrier is less than 90°. As shown in this report, a subtended angle of 90° is at most 1/2 dB removed from Fresnel diffraction, and is considerably less than that for the smaller values of N which are more likely to be encountered in actual practice. A straight, shielded roadway of considerable extent could be handled in several ways. One method for computer use would be to arbitrarily divide it into smaller segments, use Fresnel diffraction to compute each segment, and then sum the results. Another method for computer calculations would be to use the simplified formula for a total subtended angle of 150° included in this report.

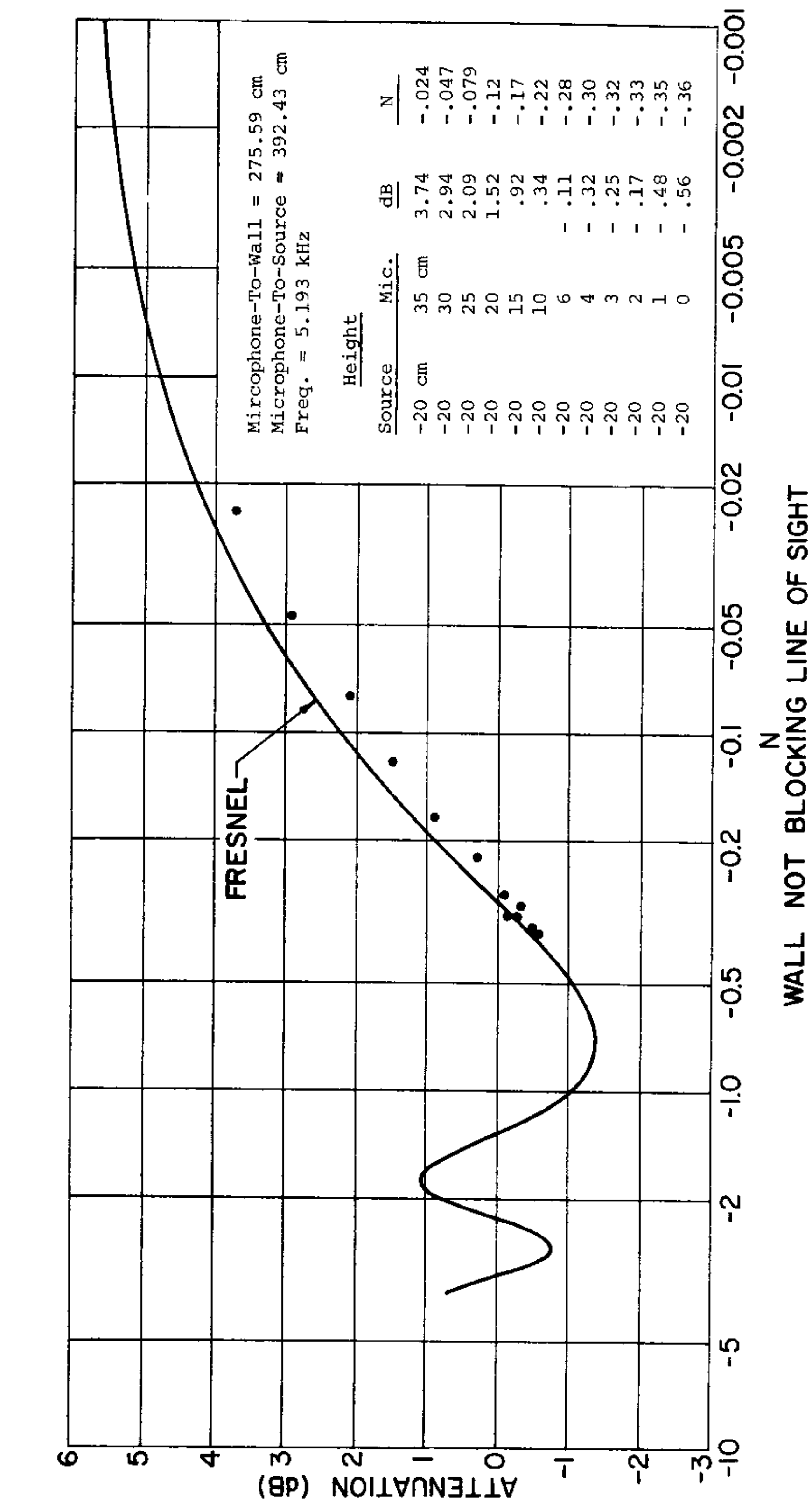
APPENDIX

TEST DATA

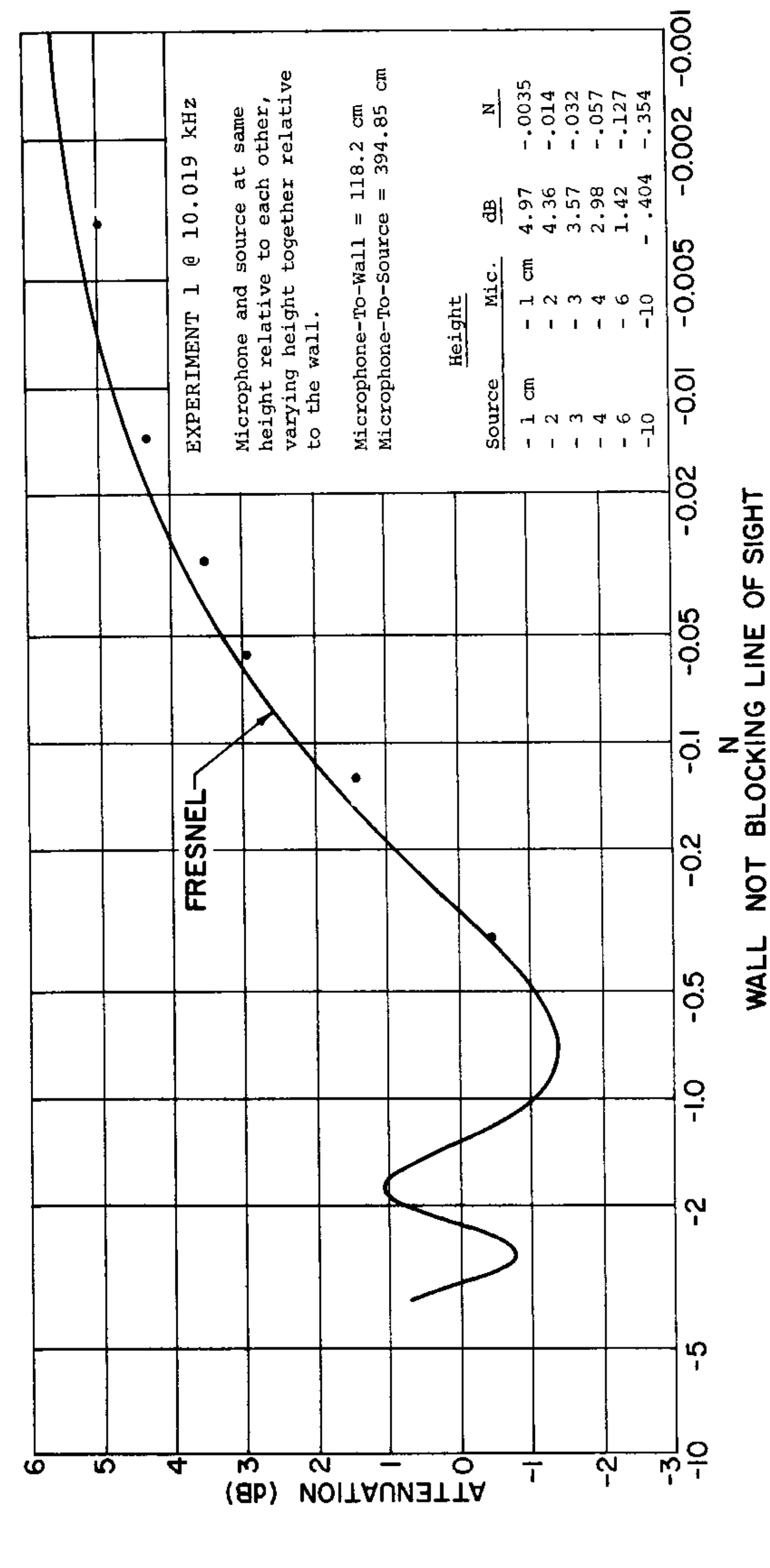

EXPERIMENT 1 @ 5.193 kHz
Microphone and source at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 118.2 cm
Microphone-To-Source = 394.85 cm
T = 60°F φ = 38%
Height
Source Mic. dB N
- 1 cm - 1 cm 5.16 -.0018
- 2 - 2 4.86 -.0074
- 3 - 3 4.19 -.017
- 4 - 4 3.69 -.029
- 6 - 6 2.54 -.066
-10 -10 .828 -.184
FRESNEL
ATTENUATION (dB)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
-2
-1.0
-0.5
-0.2
-0.1
-0.05
-0.02
-0.01
-0.005
-0.002
-0.001
N
WALL NOT BLOCKING LINE OF SIGHT

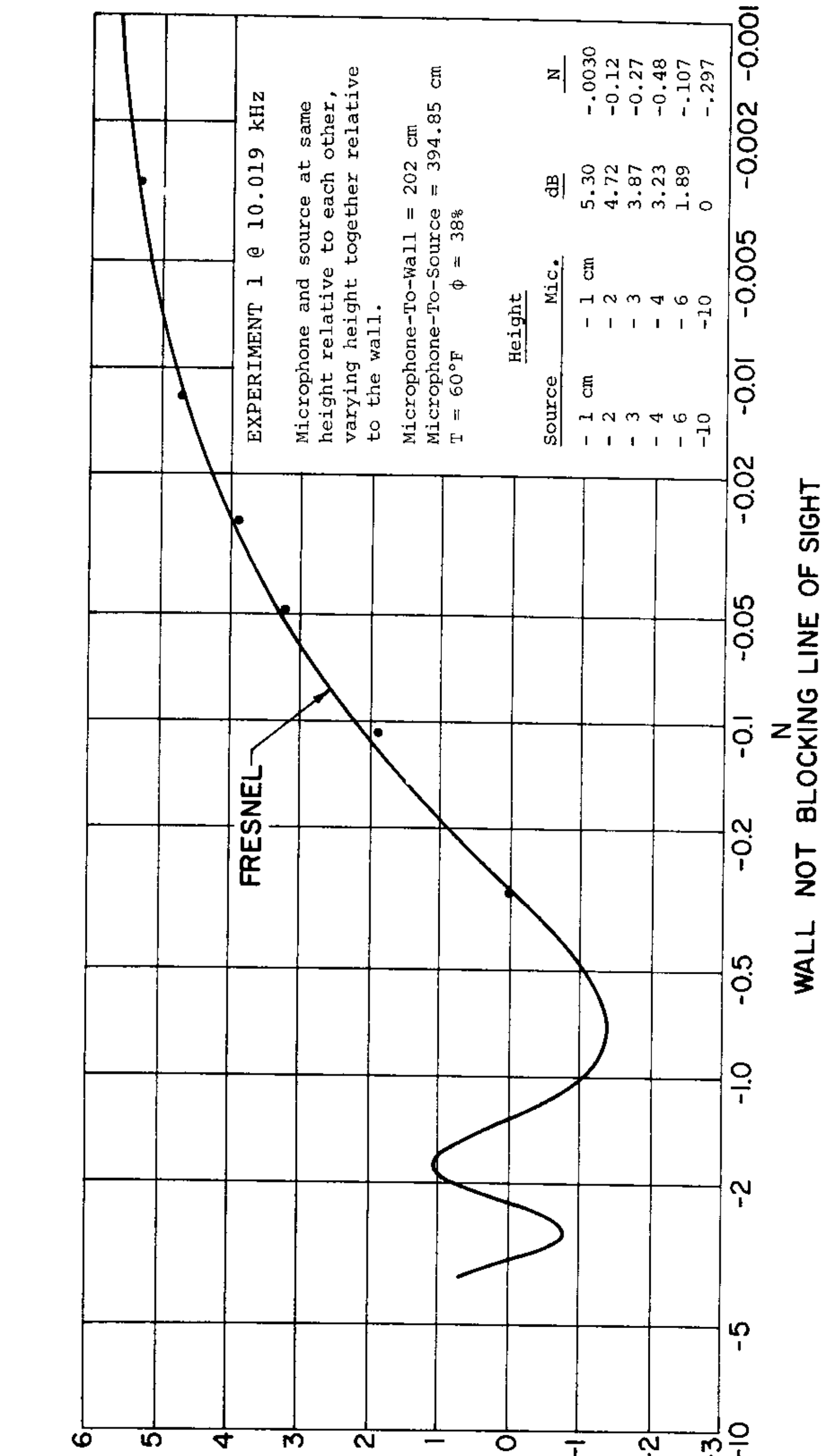

EXPERIMENT 1 @ 5.193 kHz
Microphone and source at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 202 cm
Microphone-To-Source = 394.85 cm
T = 60°F   ϕ = 38%
Height
Source Mic. dB N
- 1 cm - 1 cm 5.16 -.0015
- 2 - 2 4.86 -.0062
- 3 - 3 4.40 -.014
- 4 - 4 3.75 -.025
- 6 - 6 2.86 -.056
-10 -10 1.44 -.154
FRESNEL
ATTENUATION (dB)
N
WALL NOT BLOCKING LINE OF SIGHT


EXPERIMENT 2 @ 5.193 kHz
Microphone and source, both at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 273.8 cm
Microphone-To-Source = 394.85 cm
Height
Source Mic. dB N
-10 cm -10 cm 0.83 -.181
- 6 - 6 3.52 -.065
- 4 - 4 4.08 -.029
- 3 - 3 4.08 -.016
- 2 - 2 4.61 -.0073
- 1 - 1 5.11 -.0018
FRESNEL
ATTENUATION (dB)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
-2
-1.0
-0.5
-0.2
-0.1
-0.05
-0.02
-0.01
-0.005
-0.002
-0.001
N
WALL NOT BLOCKING LINE OF SIGHT

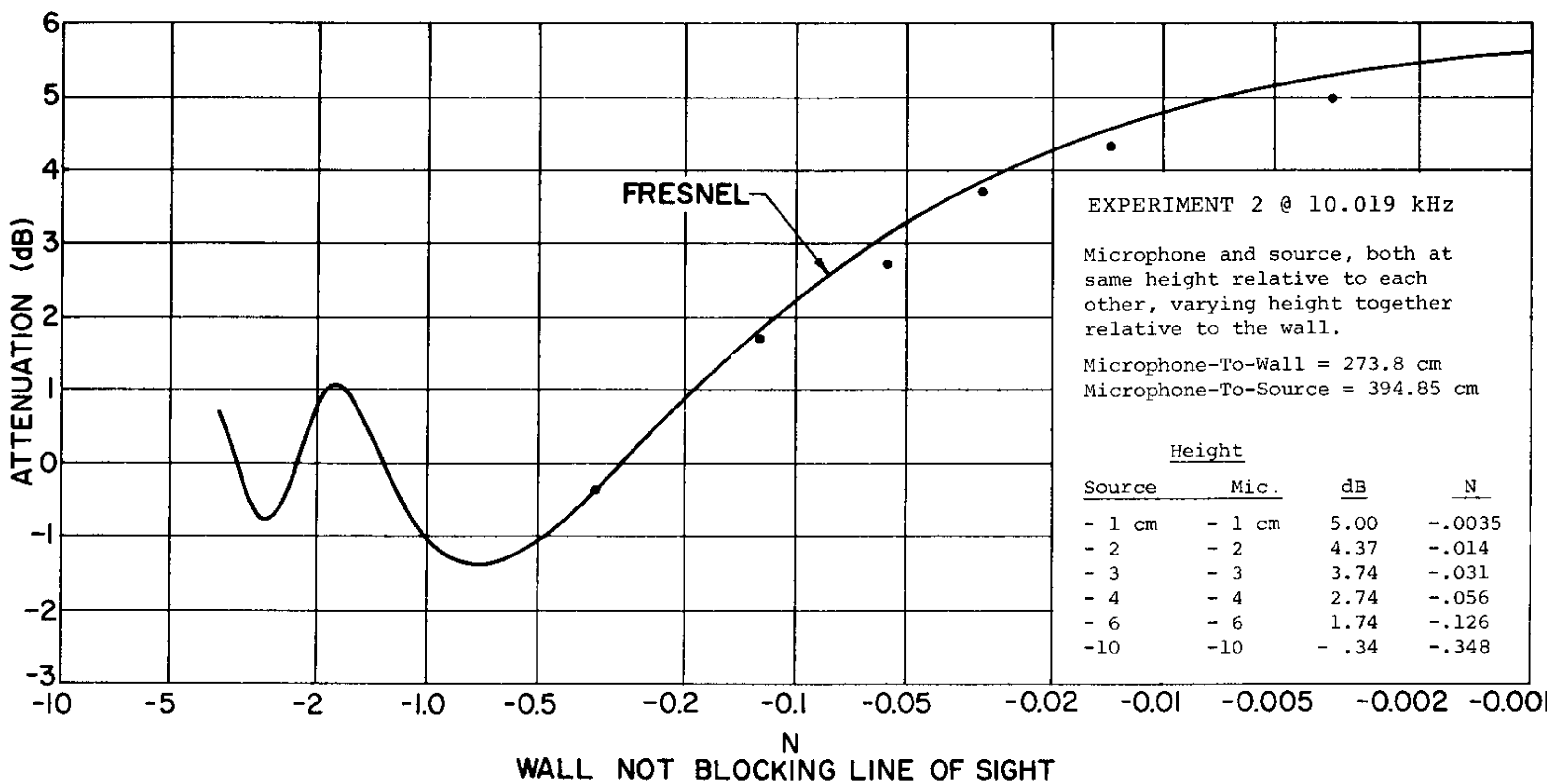


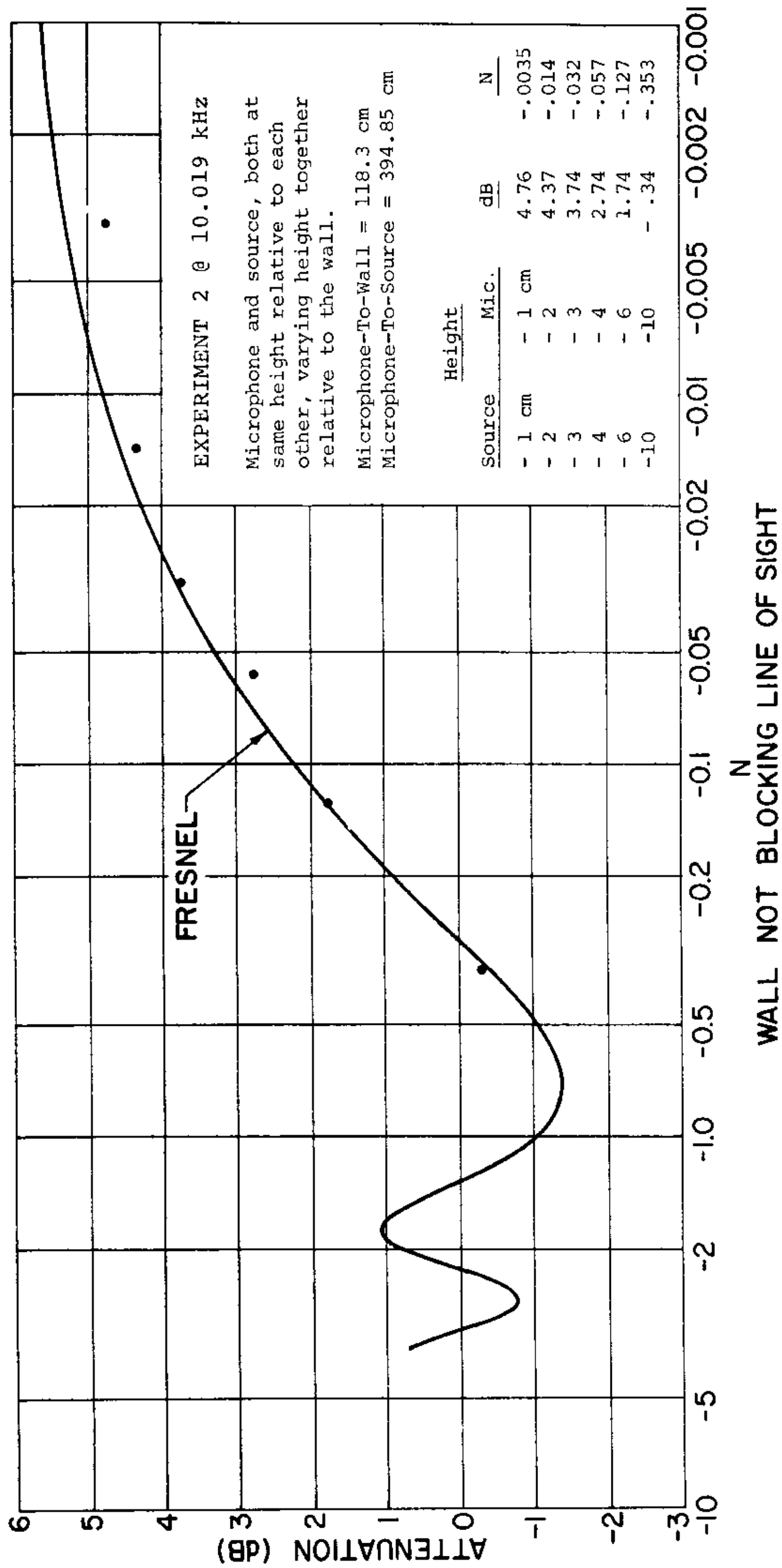
ATTENUATION (dB)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
-2
-1.0
-0.5
-0.2
-0.1
-0.05
-0.02
-0.01
-0.005
-0.002
-0.001
N
WALL NOT BLOCKING LINE OF SIGHT
FRESNEL
Mircophone-To-Wall = 275.59 cm
Microphone-To-Source = 392.43 cm
Freq. = 5.193 kHz
Height
Source
Mic.
dB
N
-20 cm 35 cm 3.74 -.024
-20 30 2.94 -.047
-20 25 2.09 -.079
-20 20 1.52 -.12
-20 15 .92 -.17
-20 10 .34 -.22
-20 6 -.11 -.28
-20 4 -.32 -.30
-20 3 -.25 -.32
-20 2 -.17 -.33
-20 1 -.48 -.35
-20 0 -.56 -.36

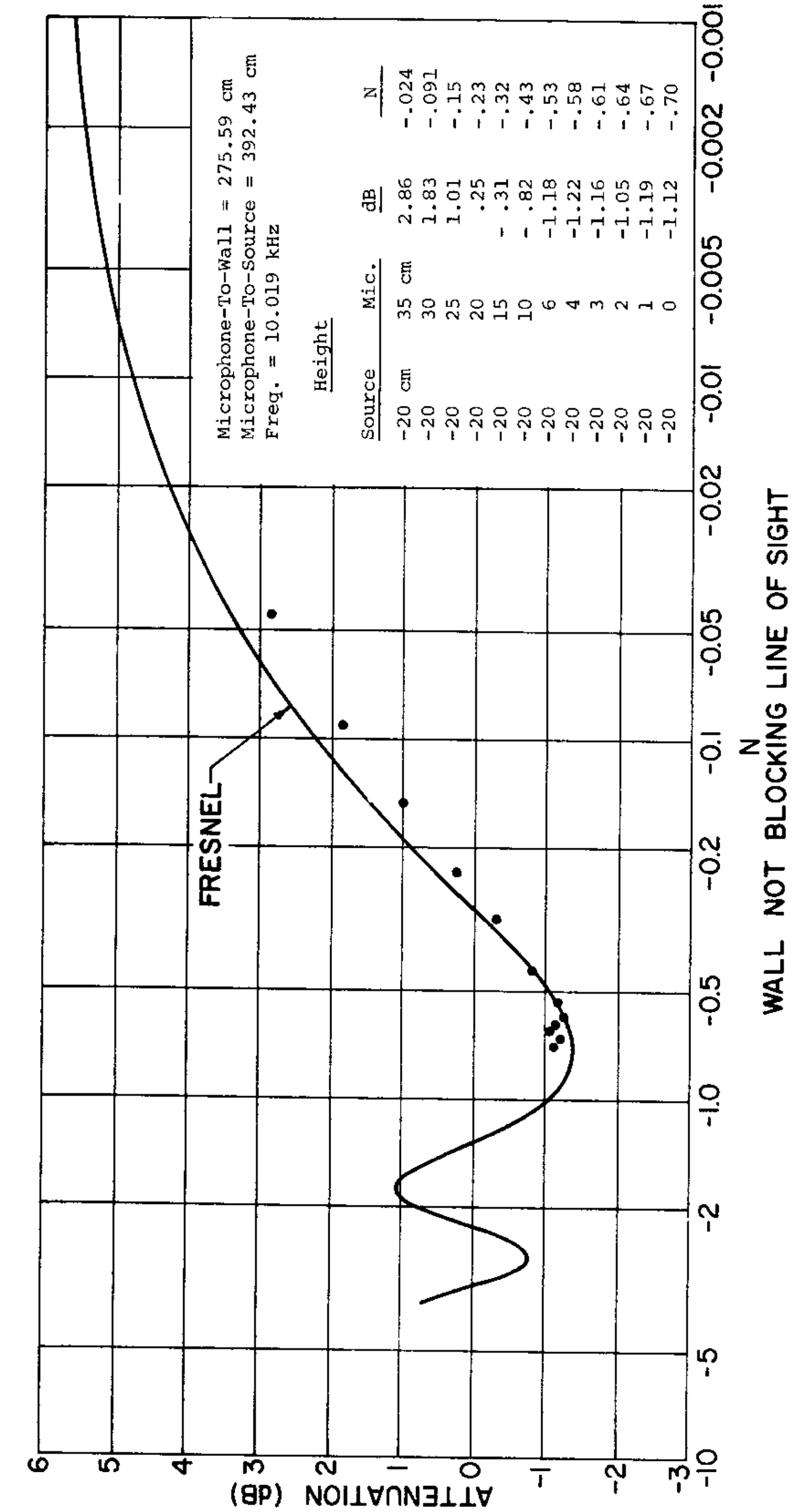

EXPERIMENT 1 @ 10.019 kHz
Microphone and source at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 118.2 cm
Microphone-To-Source = 394.85 cm
Height
Source Mic. dB N
- 1 cm - 1 cm 4.97 -.0035
- 2 - 2 4.36 -.014
- 3 - 3 3.57 -.032
- 4 - 4 2.98 -.057
- 6 - 6 1.42 -.127
-10 -10 - .404 -.354
FRESNEL
ATTENUATION (dB)
N
WALL NOT BLOCKING LINE OF SIGHT
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
-2
-1.0
-0.5
-0.2
-0.1
-0.05
-0.02
-0.01
-0.005
-0.002
-0.001

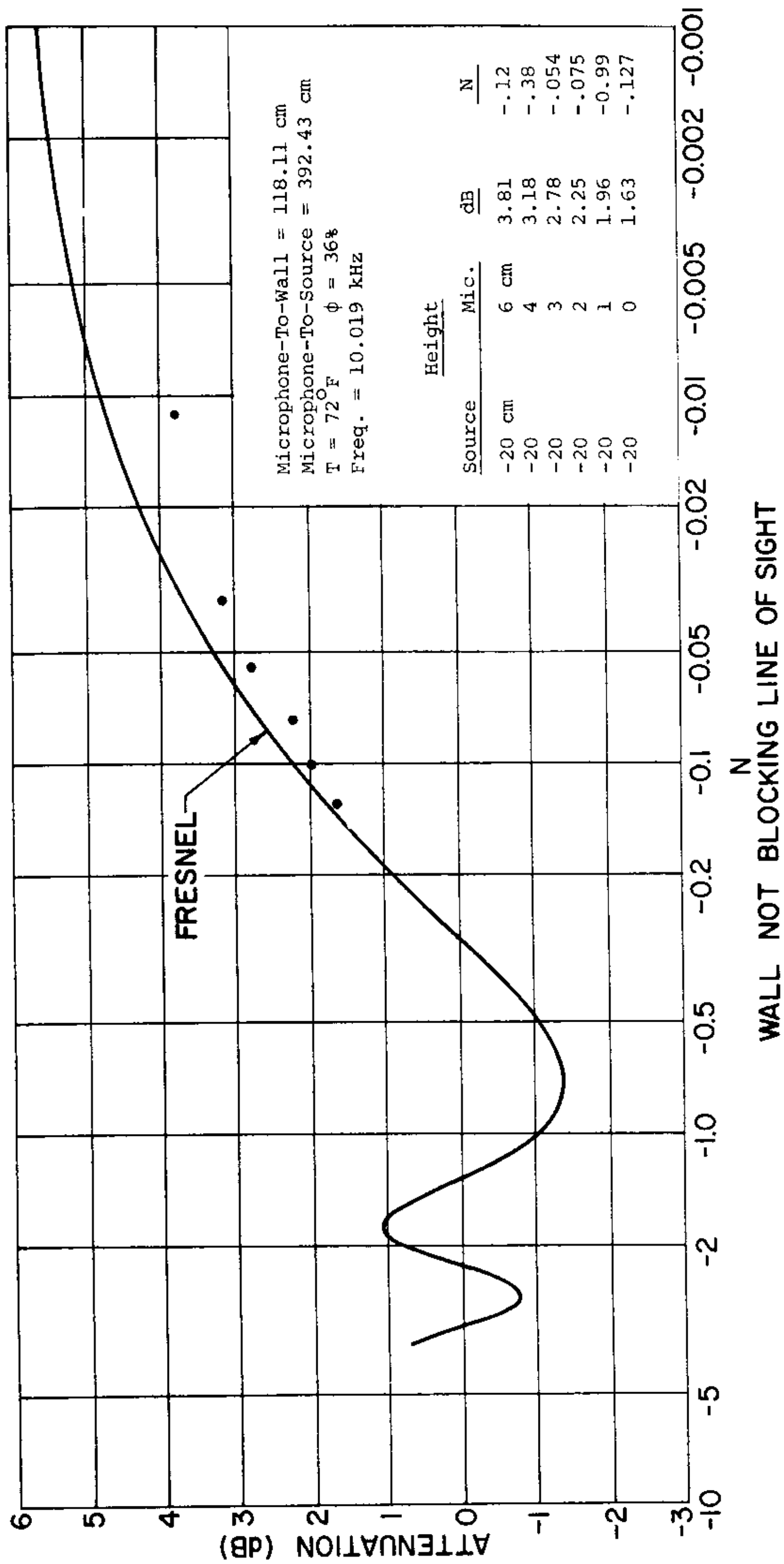


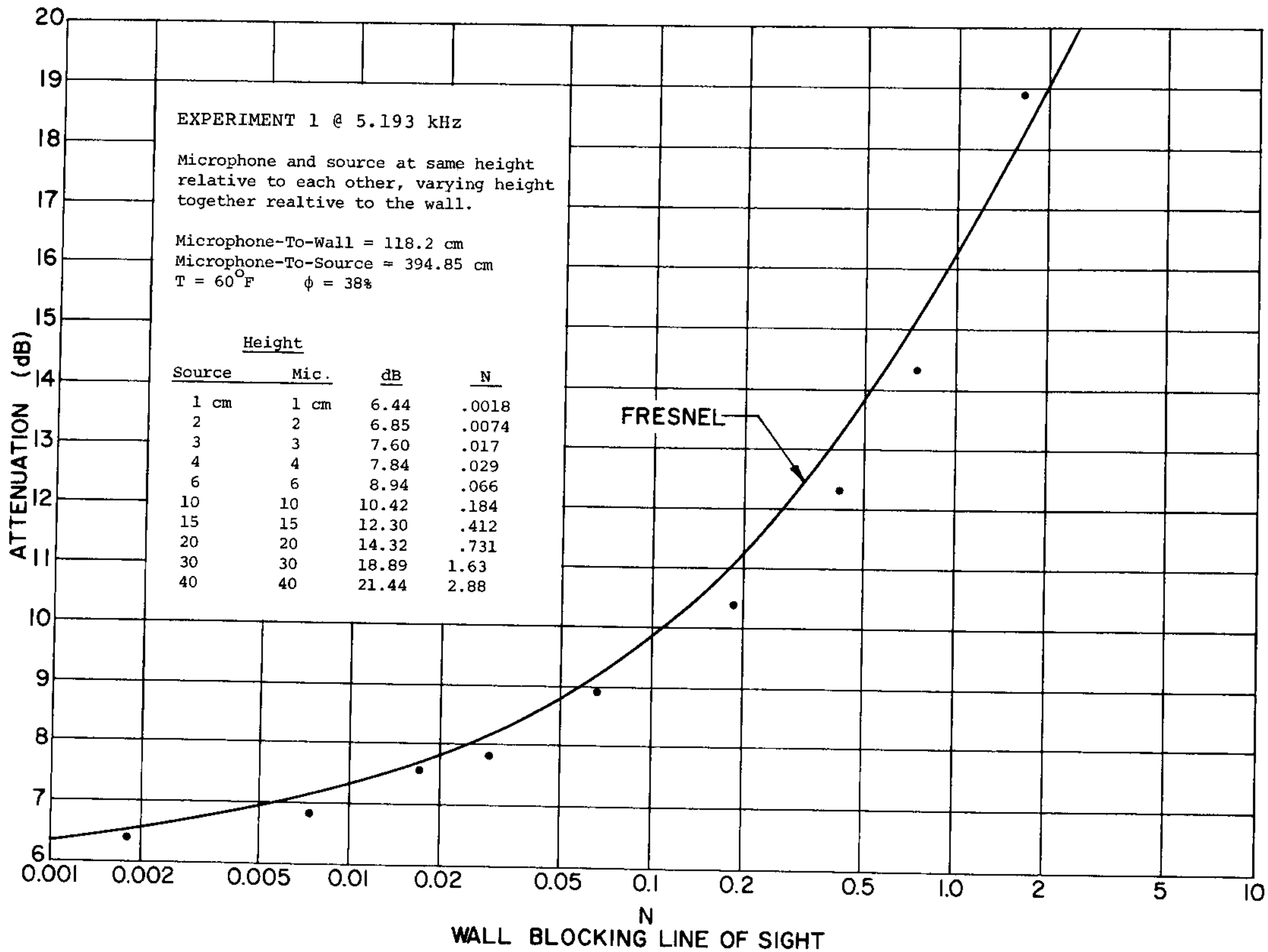
EXPERIMENT 1 @ 10.019 kHz
Microphone and source at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 202 cm
Microphone-To-Source = 394.85 cm
T = 60°F φ = 38%
Height
Source Mic. dB N
- 1 cm - 1 cm 5.30 -.0030
- 2 - 2 4.72 -0.12
- 3 - 3 3.87 -0.27
- 4 - 4 3.23 -0.48
- 6 - 6 1.89 -.107
-10 -10 0 -.297
FRESNEL
ATTENUATION (dB)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
-2
-1.0
-0.5
-0.2
-0.1
-0.05
-0.02
-0.01
-0.005
-0.002
-0.001
N
WALL NOT BLOCKING LINE OF SIGHT


ATTENUATION (dB)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
-2
-1.0
-0.5
-0.2
-0.1
-0.05
-0.02
-0.01
-0.005
-0.002
-0.001
N
WALL NOT BLOCKING LINE OF SIGHT
FRESNEL
EXPERIMENT 2 @ 10.019 kHz
Microphone and source, both at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 273.8 cm
Microphone-To-Source = 394.85 cm
Height
Source Mic. dB N
- 1 cm - 1 cm 5.00 -.0035
- 2 - 2 4.37 -.014
- 3 - 3 3.74 -.031
- 4 - 4 2.74 -.056
- 6 - 6 1.74 -.126
-10 -10 - .34 -.348

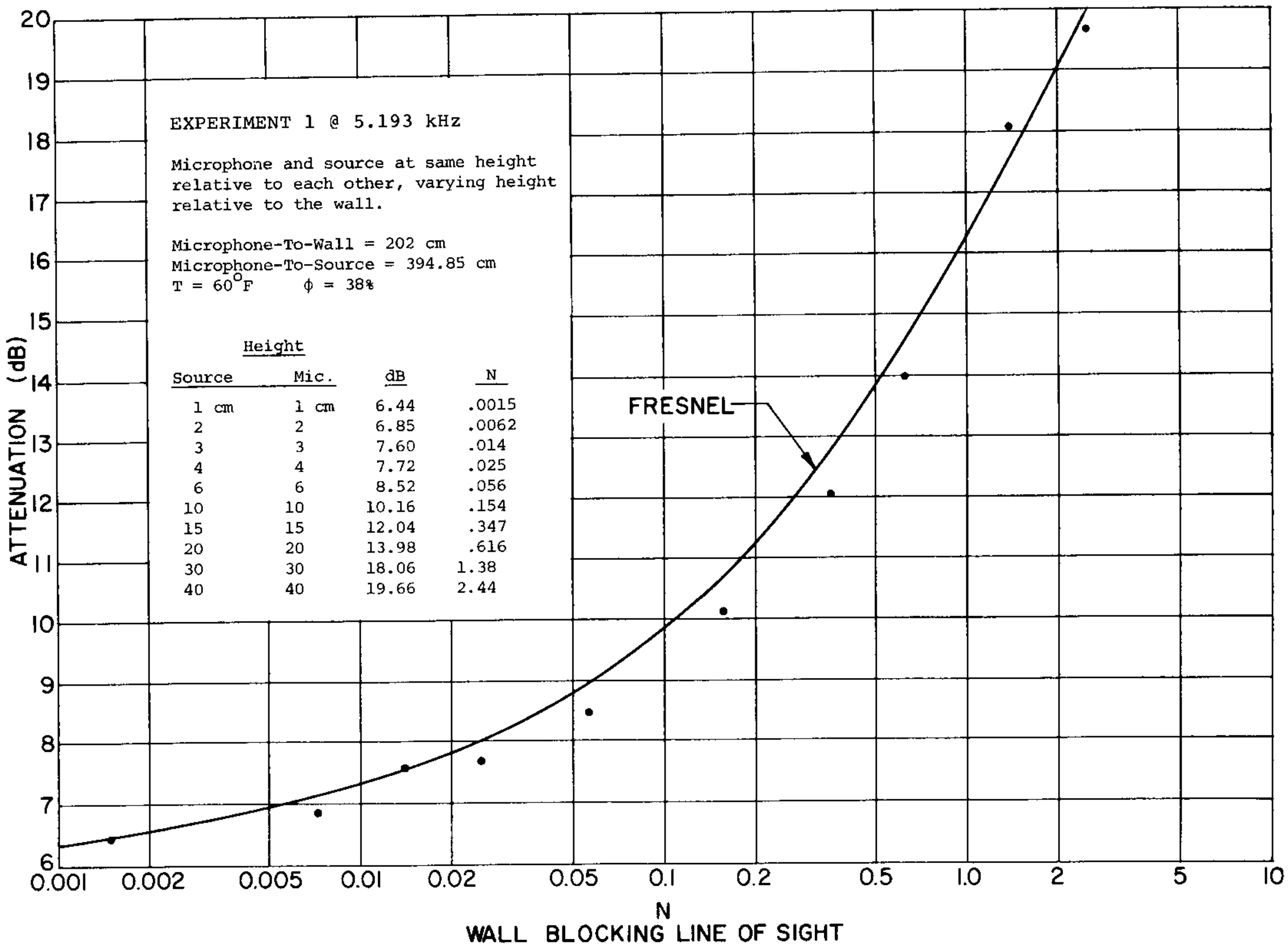

EXPERIMENT 2 @ 10.019 kHz
Microphone and source, both at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 118.3 cm
Microphone-To-Source = 394.85 cm
Height
Source Mic. dB N
- 1 cm - 1 cm 4.76 -.0035
- 2 - 2 4.37 -.014
- 3 - 3 3.74 -.032
- 4 - 4 2.74 -.057
- 6 - 6 1.74 -.127
-10 -10 - .34 -.353
FRESNEL
ATTENUATION (dB)
N
WALL NOT BLOCKING LINE OF SIGHT
-10 -5 -2 -1.0 -0.5 -0.2 -0.1 -0.05 -0.02 -0.01 -0.005 -0.002 -0.001
6 5 4 3 2 1 0 -1 -2 -3


Microphone-To-Wall = 275.59 cm
Microphone-To-Source = 392.43 cm
Freq. = 10.019 kHz
Height
Source Mic. dB N
-20 cm 35 cm 2.86 -.024
-20 30 1.83 -.091
-20 25 1.01 -.15
-20 20 .25 -.23
-20 15 - .31 -.32
-20 10 - .82 -.43
-20 6 -1.18 -.53
-20 4 -1.22 -.58
-20 3 -1.16 -.61
-20 2 -1.05 -.64
-20 1 -1.19 -.67
-20 0 -1.12 -.70
FRESNEL
ATTENUATION (dB)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
-2
-1.0
-0.5
-0.2
-0.1
-0.05
-0.02
-0.01
-0.005
-0.002
-0.001
N
WALL NOT BLOCKING LINE OF SIGHT

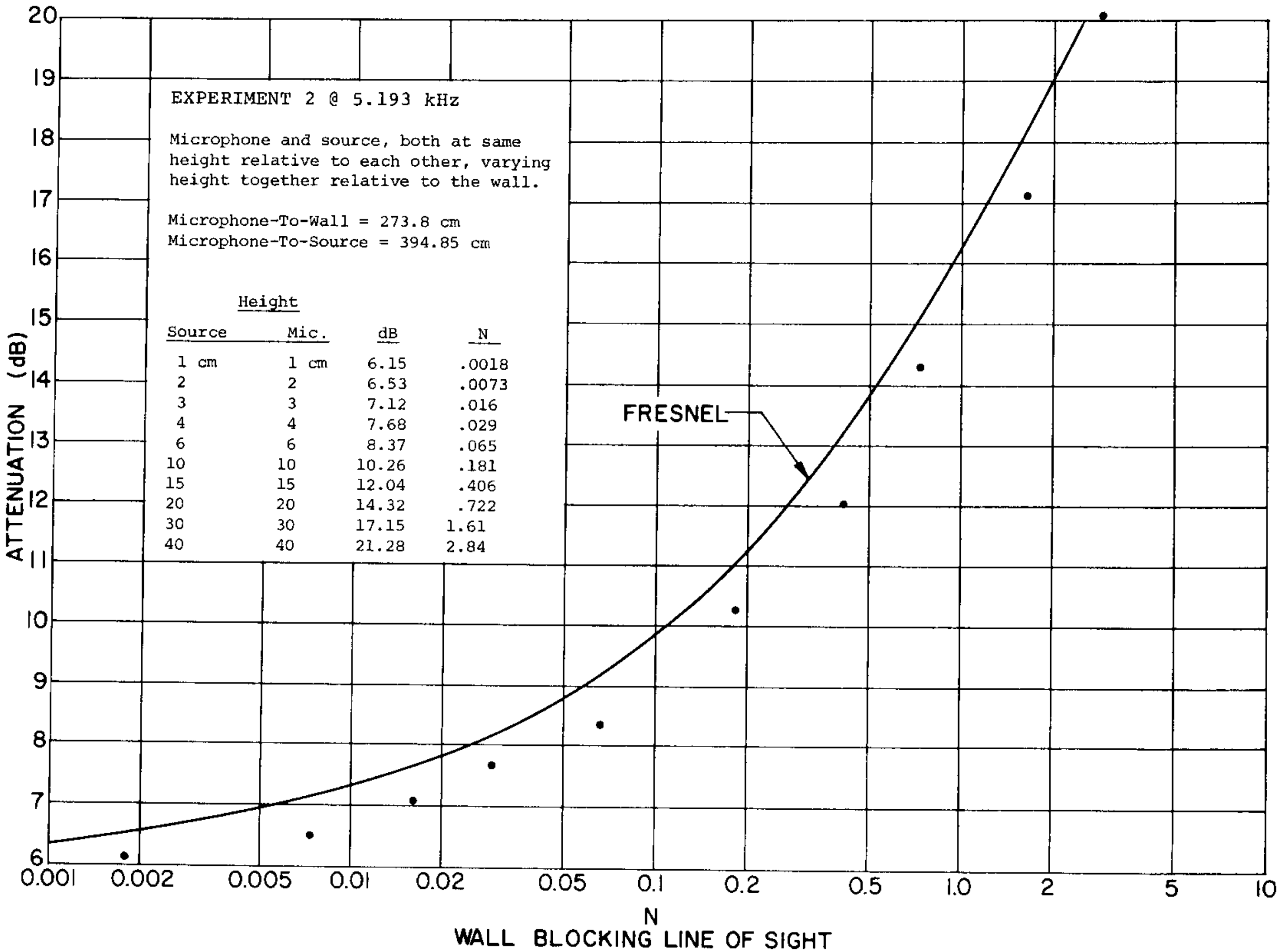

Microphone-To-Wall = 118.11 cm
Microphone-To-Source = 392.43 cm
T = 72°F φ = 36%
Freq. = 10.019 kHz
Height
Source Mic. dB N
-20 cm 6 cm 3.81 -.12
-20 4 3.18 -.38
-20 3 2.78 -.054
-20 2 2.25 -.075
-20 1 1.96 -0.99
-20 0 1.63 -.127
FRESNEL
ATTENUATION (dB)
6
5
4
3
2
1
0
-1
-2
-3
-10
-5
-2
-1.0
-0.5
-0.2
-0.1
-0.05
-0.02
-0.01
-0.005
-0.002
-0.001
N
WALL NOT BLOCKING LINE OF SIGHT



Height Source	Height Mic.	dB	N
1 cm	1 cm	6.44	.0018
2	2	6.85	.0074
3	3	7.60	.017
4	4	7.84	.029
6	6	8.94	.066
10	10	10.42	.184
15	15	12.30	.412
20	20	14.32	.731
30	30	18.89	1.63
40	40	21.44	2.88



Height: Source	Height: Mic.	dB	N
1 cm	1 cm	6.44	.0015
2	2	6.85	.0062
3	3	7.60	.014
4	4	7.72	.025
6	6	8.52	.056
10	10	10.16	.154
15	15	12.04	.347
20	20	13.98	.616
30	30	18.06	1.38
40	40	19.66	2.44

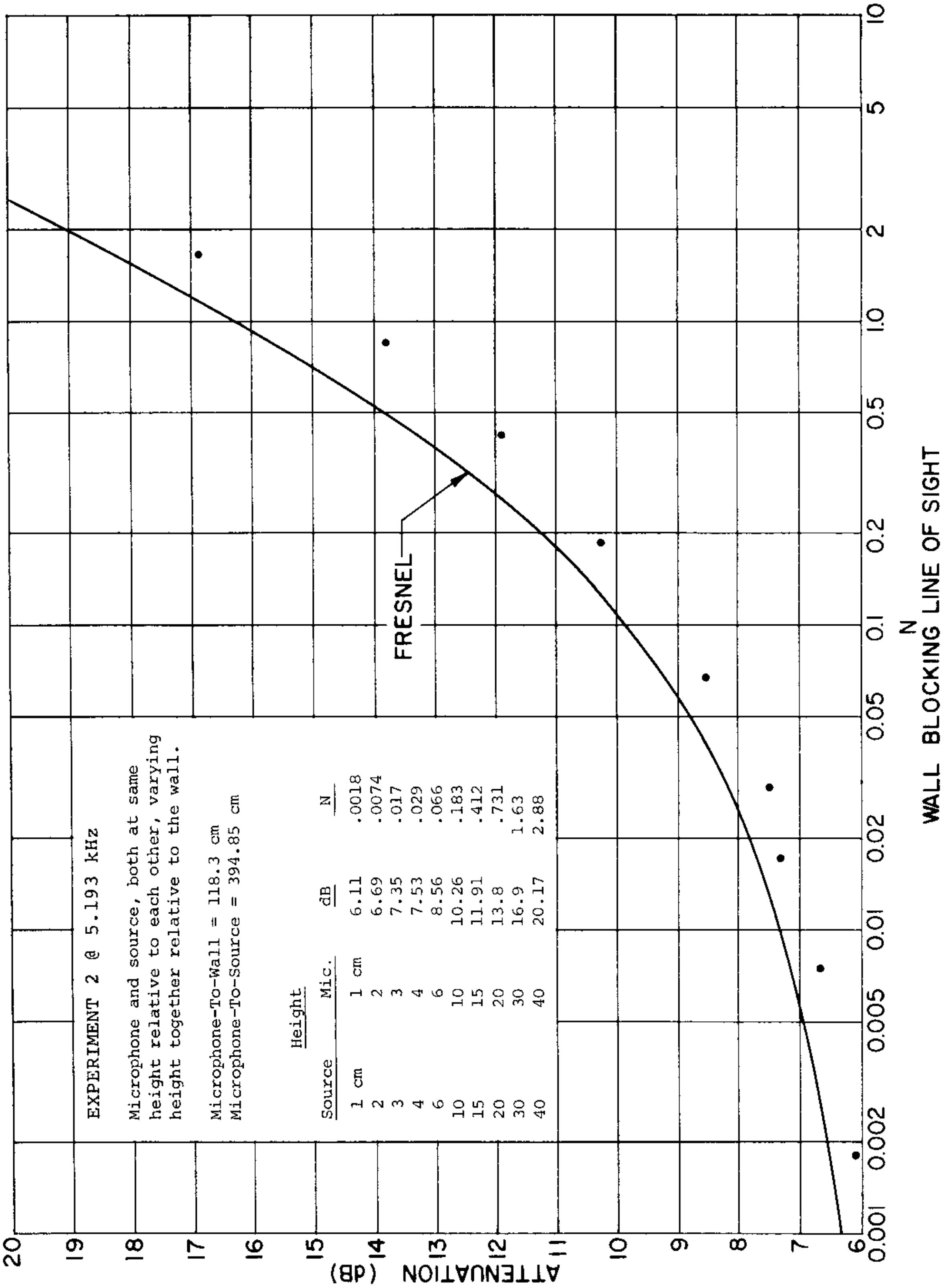


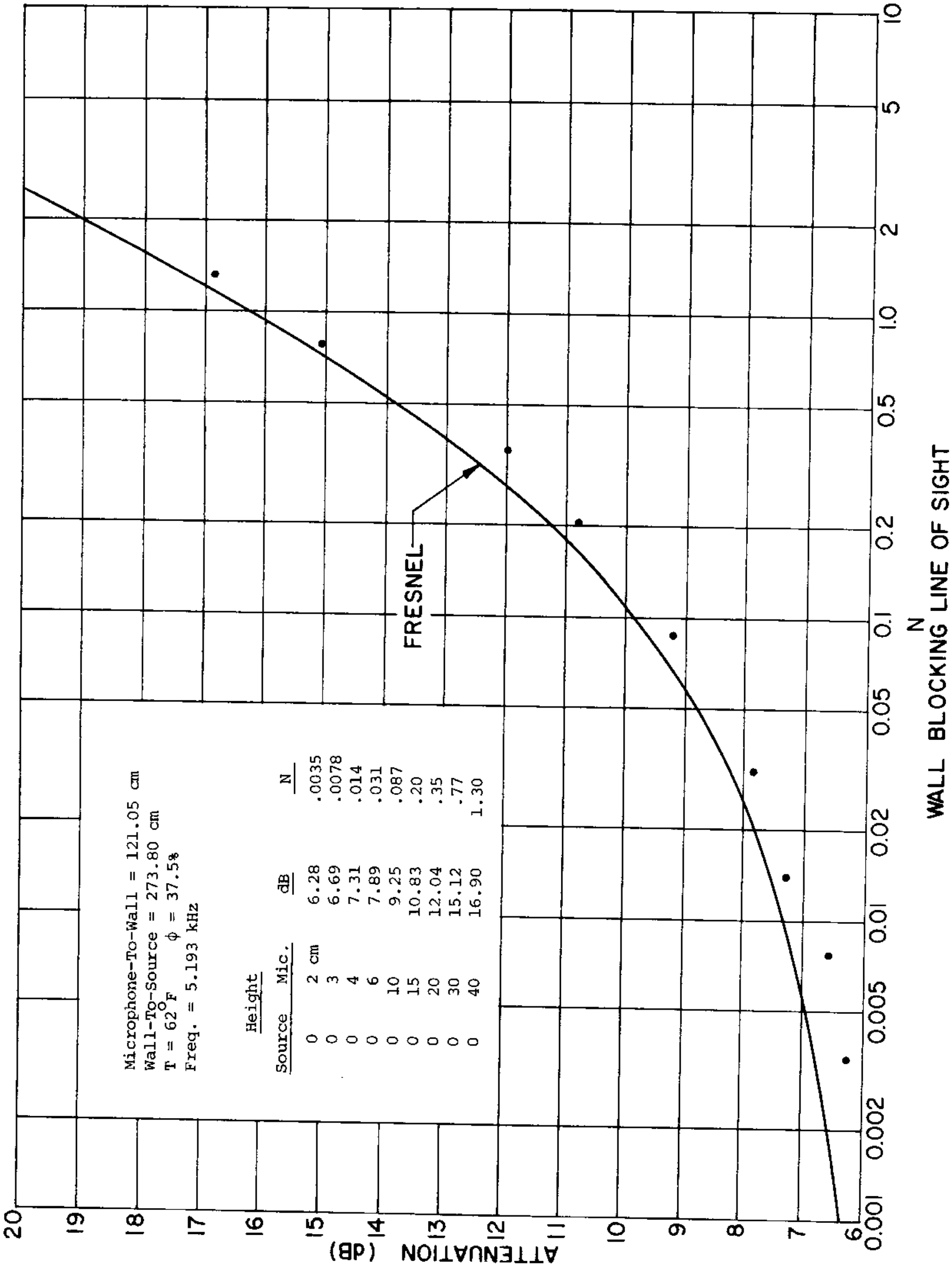
EXPERIMENT 2 @ 5.193 kHz

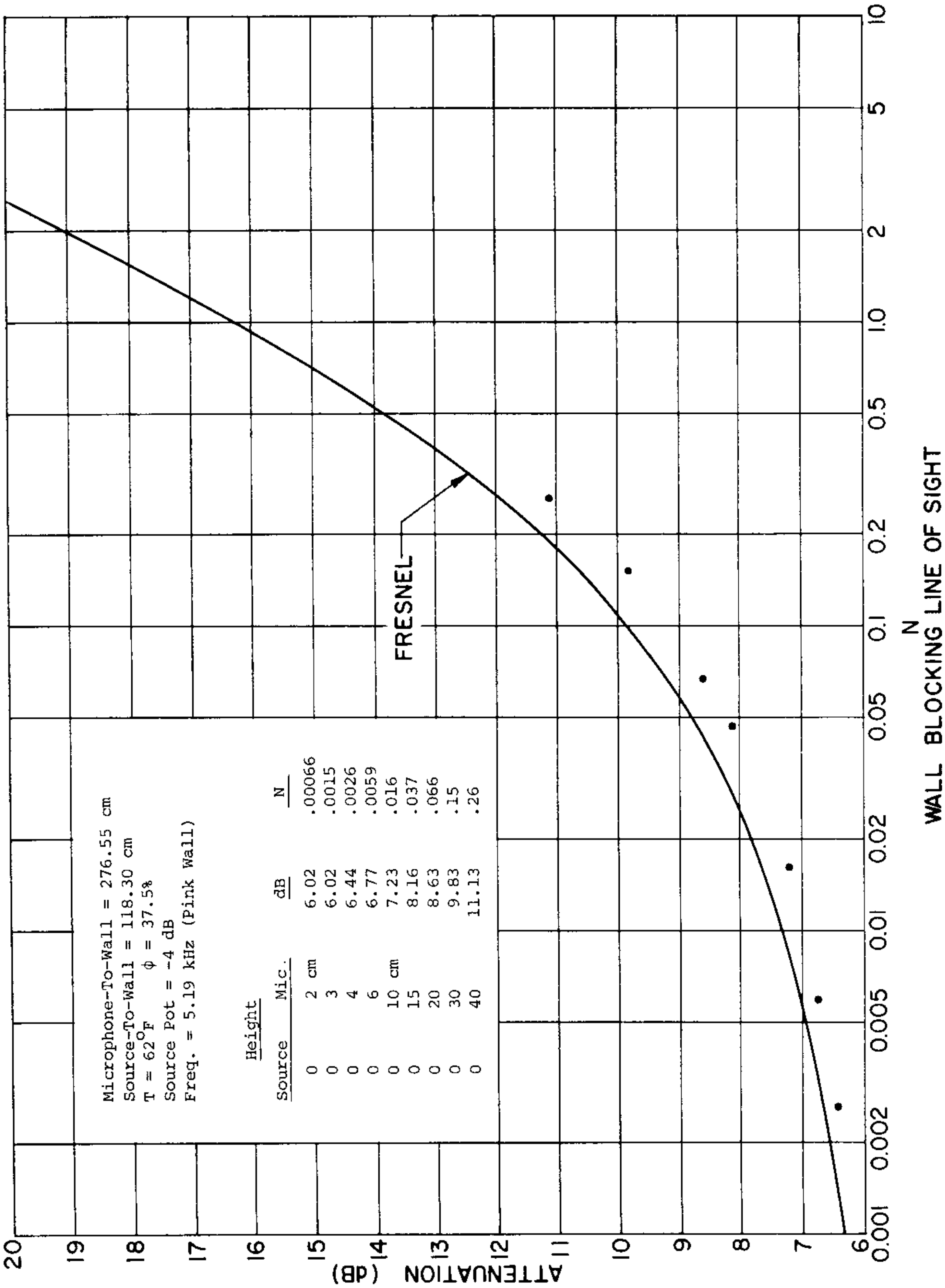
Microphone and source, both at same height relative to each other, varying height together relative to the wall.

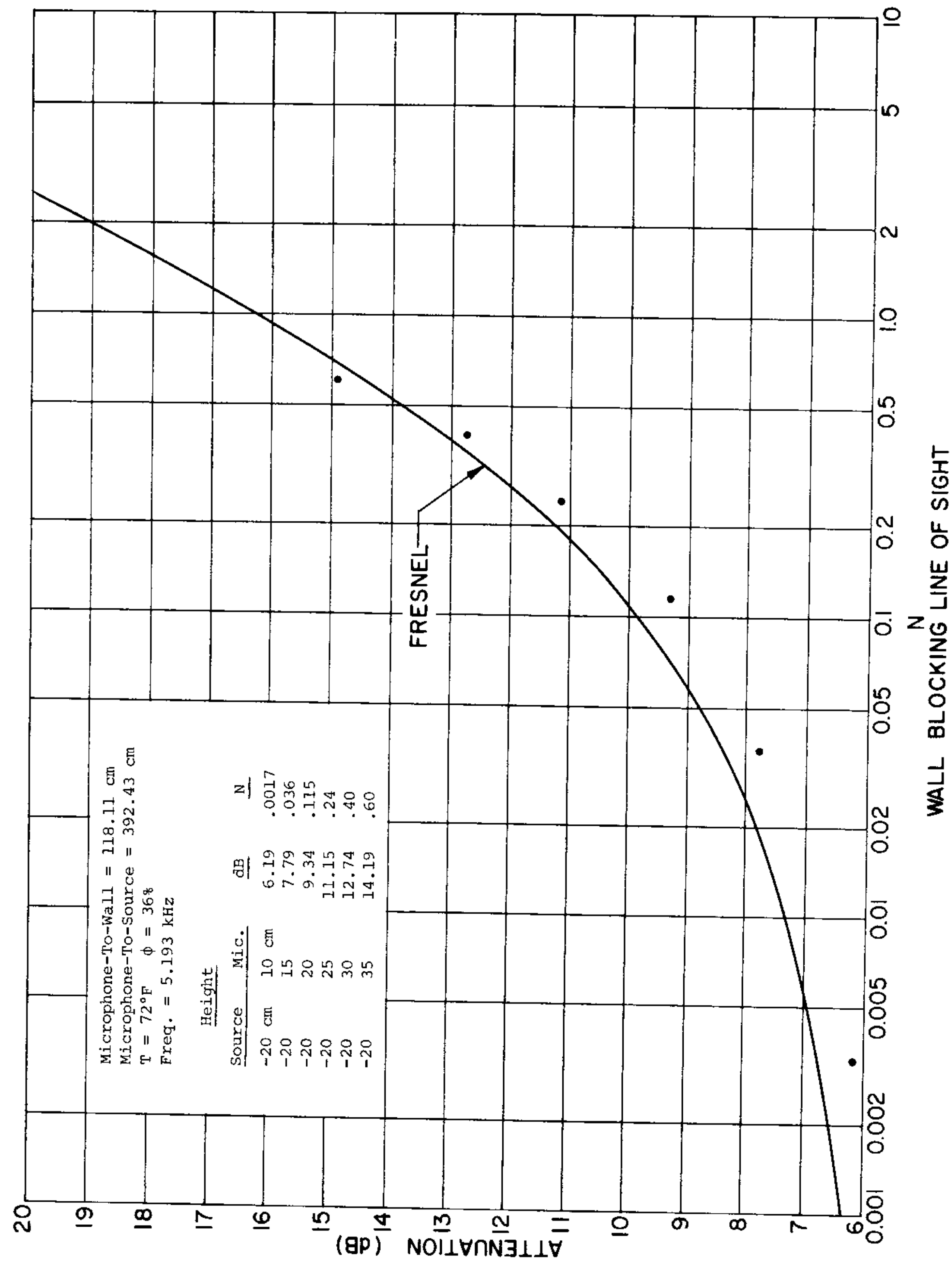
Microphone-To-Wall = 273.8 cm
Microphone-To-Source = 394.85 cm

Height			
Source	Mic.	dB	N
1 cm	1 cm	6.15	.0018
2	2	6.53	.0073
3	3	7.12	.016
4	4	7.68	.029
6	6	8.37	.065
10	10	10.26	.181
15	15	12.04	.406
20	20	14.32	.722
30	30	17.15	1.61
40	40	21.28	2.84

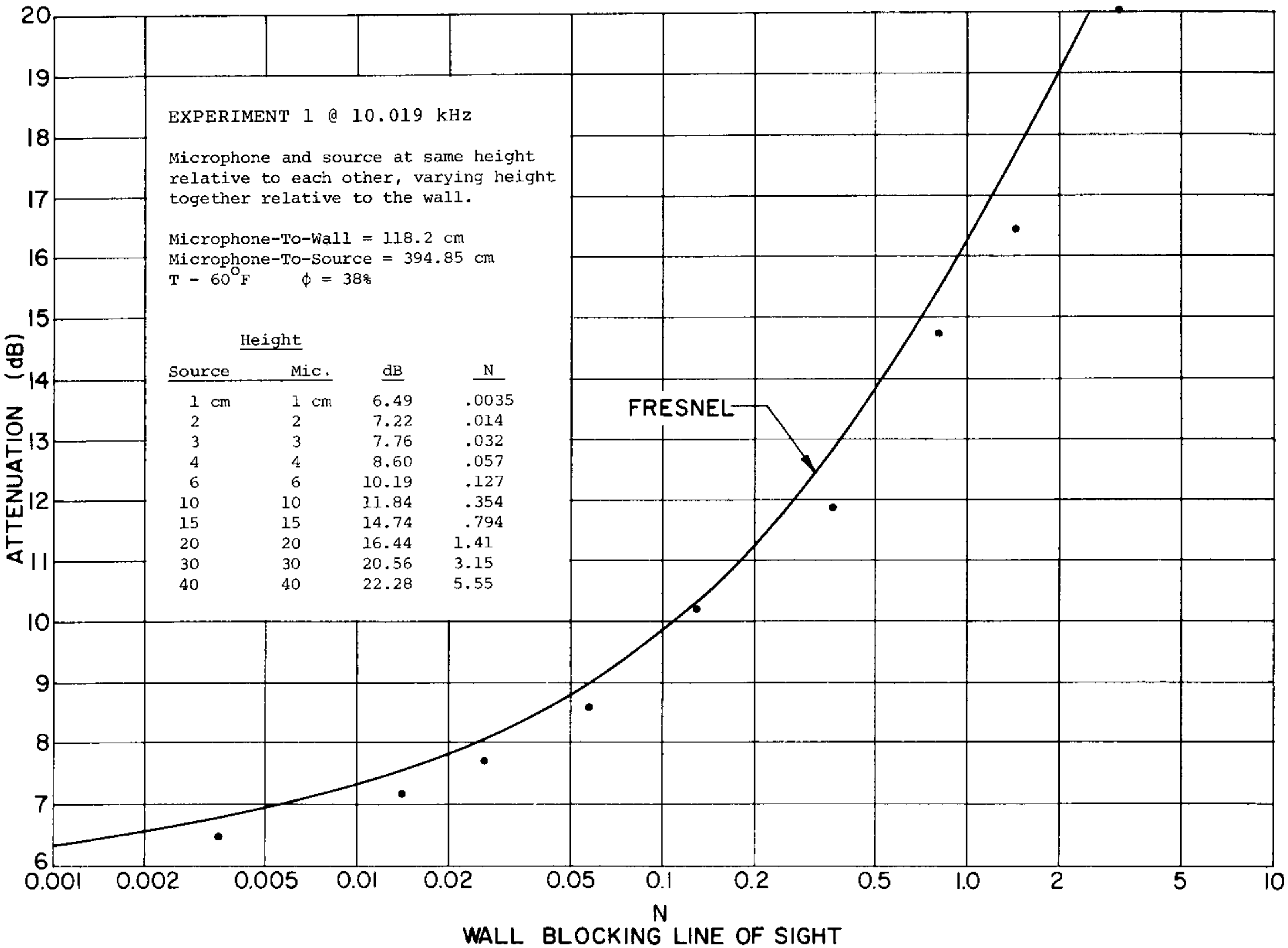

EXPERIMENT 2 @ 5.193 kHz
Microphone and source, both at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 118.3 cm
Microphone-To-Source = 394.85 cm
Height
Source Mic. dB N
1 cm 1 cm 6.11 .0018
2 2 6.69 .0074
3 3 7.35 .017
4 4 7.53 .029
6 6 8.56 .066
10 10 10.26 .183
15 15 11.91 .412
20 20 13.8 .731
30 30 16.9 1.63
40 40 20.17 2.88
FRESNEL
ATTENUATION (dB)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
0.001
0.002
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1.0
2
5
10
N
WALL BLOCKING LINE OF SIGHT


Microphone-To-Wall = 121.05 cm
Wall-To-Source = 273.80 cm
T = 62°F φ = 37.5%
Freq. = 5.193 kHz
Height
Source Mic. dB N
0 2 cm 6.28 .0035
0 3 6.69 .0078
0 4 7.31 .014
0 6 7.89 .031
0 10 9.25 .087
0 15 10.83 .20
0 20 12.04 .35
0 30 15.12 .77
0 40 16.90 1.30
FRESNEL
ATTENUATION (dB)
N
WALL BLOCKING LINE OF SIGHT
0.001
0.002
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1.0
2
5
10
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

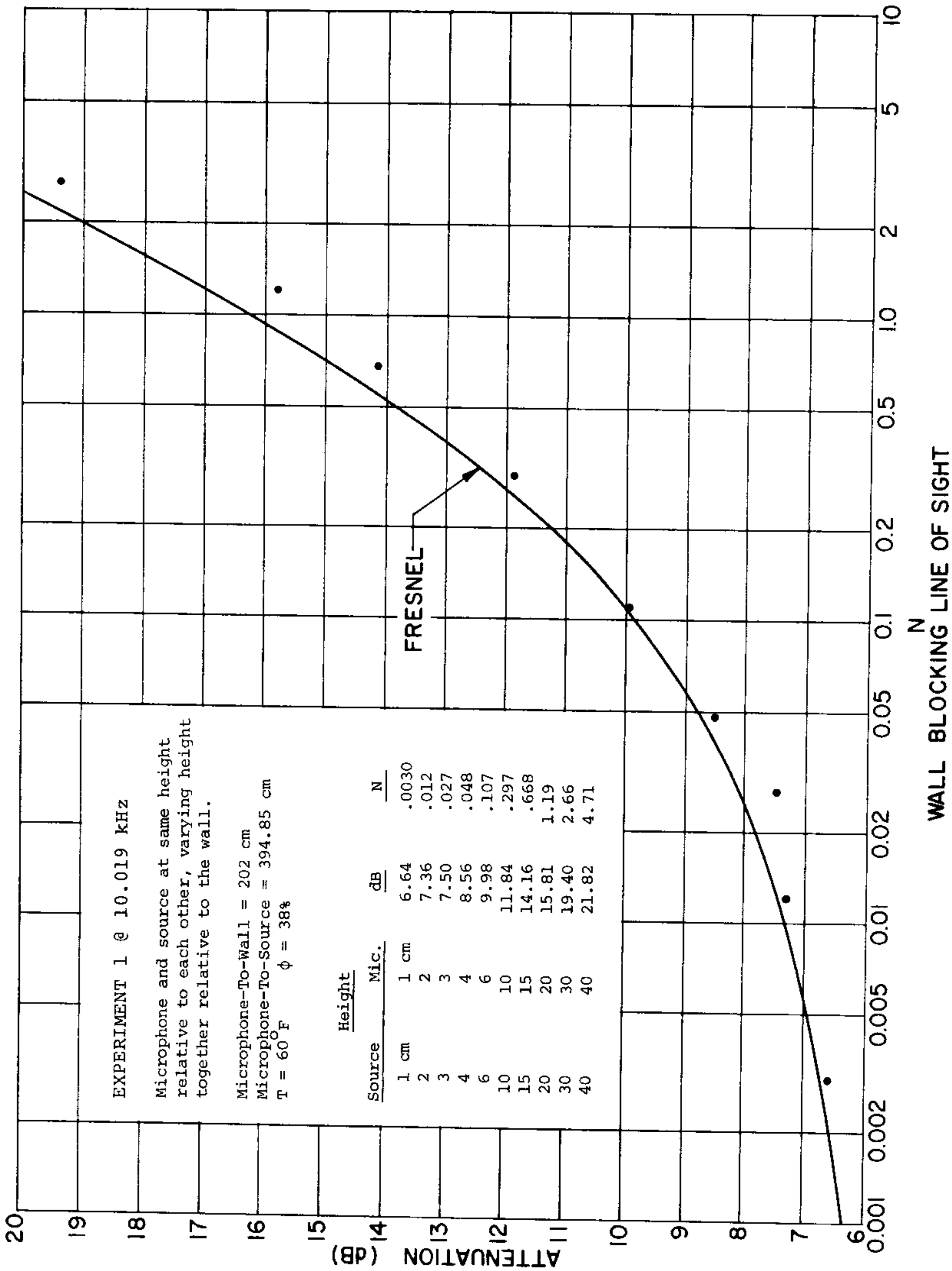

Microphone-To-Wall = 276.55 cm
Source-To-Wall = 118.30 cm
T = 62°F φ = 37.5%
Source Pot = -4 dB
Freq. = 5.19 kHz (Pink Wall)
Height
Source Mic. dB N
0 2 cm 6.02 .00066
0 3 6.02 .0015
0 4 6.44 .0026
0 6 6.77 .0059
0 10 cm 7.23 .016
0 15 8.16 .037
0 20 8.63 .066
0 30 9.83 .15
0 40 11.13 .26
FRESNEL
ATTENUATION (dB)
N
WALL BLOCKING LINE OF SIGHT
0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0 2 5 10
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

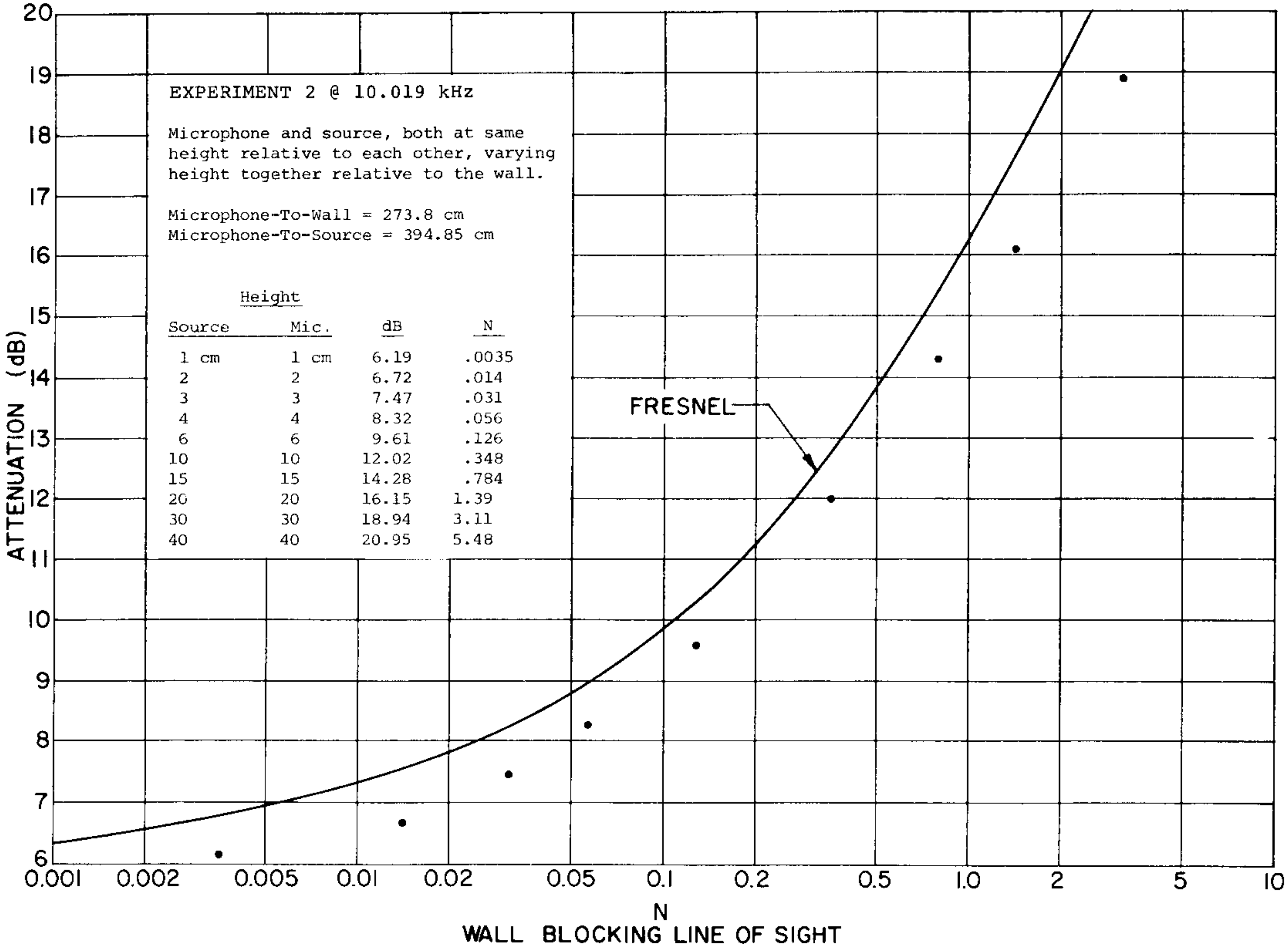


Microphone-To-Wall = 118.11 cm
Microphone-To-Source = 392.43 cm
T = 72°F φ = 36%
Freq. = 5.193 kHz
Height
Source Mic. dB N
-20 cm 10 cm 6.19 .0017
-20 15 7.79 .036
-20 20 9.34 .115
-20 25 11.15 .24
-20 30 12.74 .40
-20 35 14.19 .60
FRESNEL
ATTENUATION (dB)
N
WALL BLOCKING LINE OF SIGHT
20 19 18 17 16 15 14 13 12 11 10 9 8 7 6
0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0 2 5 10



Height: Source	Height: Mic.	dB	N
1 cm	1 cm	6.49	.0035
2	2	7.22	.014
3	3	7.76	.032
4	4	8.60	.057
6	6	10.19	.127
10	10	11.84	.354
15	15	14.74	.794
20	20	16.44	1.41
30	30	20.56	3.15
40	40	22.28	5.55


EXPERIMENT 1 @ 10.019 kHz
Microphone and source at same height relative to each other, varying height together relative to the wall.
Microphone-To-Wall = 202 cm
Microphone-To-Source = 394.85 cm
T = 60°F φ = 38%
Height
Source Mic. dB N
1 cm 1 cm 6.64 .0030
2 2 7.36 .012
3 3 7.50 .027
4 4 8.56 .048
6 6 9.98 .107
10 10 11.84 .297
15 15 14.16 .668
20 20 15.81 1.19
30 30 19.40 2.66
40 40 21.82 4.71
FRESNEL
ATTENUATION (dB)
WALL BLOCKING LINE OF SIGHT
N
0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0 2 5 10
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

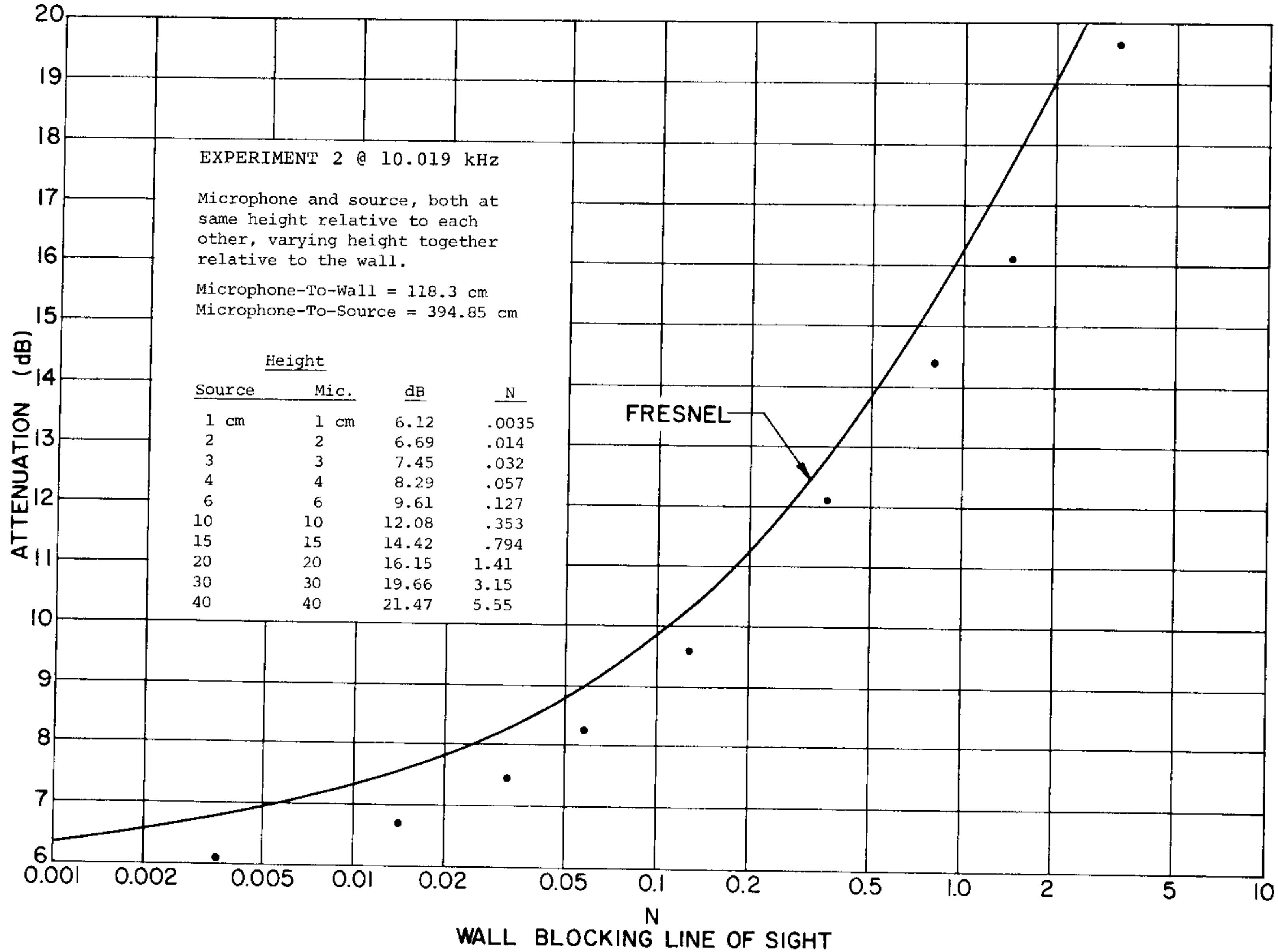


EXPERIMENT 2 @ 10.019 kHz

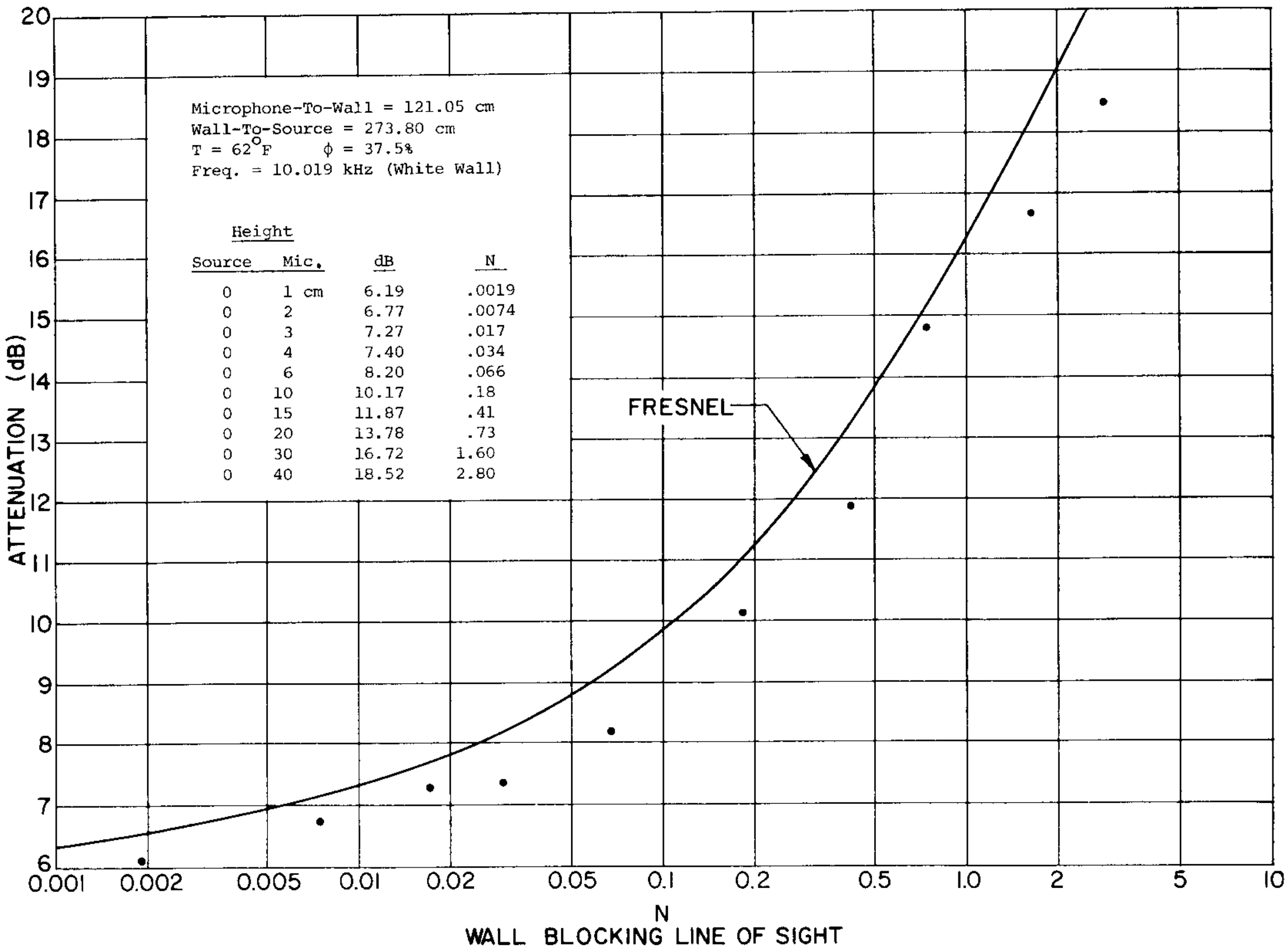
Microphone and source, both at same height relative to each other, varying height together relative to the wall.

Microphone-To-Wall = 273.8 cm
Microphone-To-Source = 394.85 cm

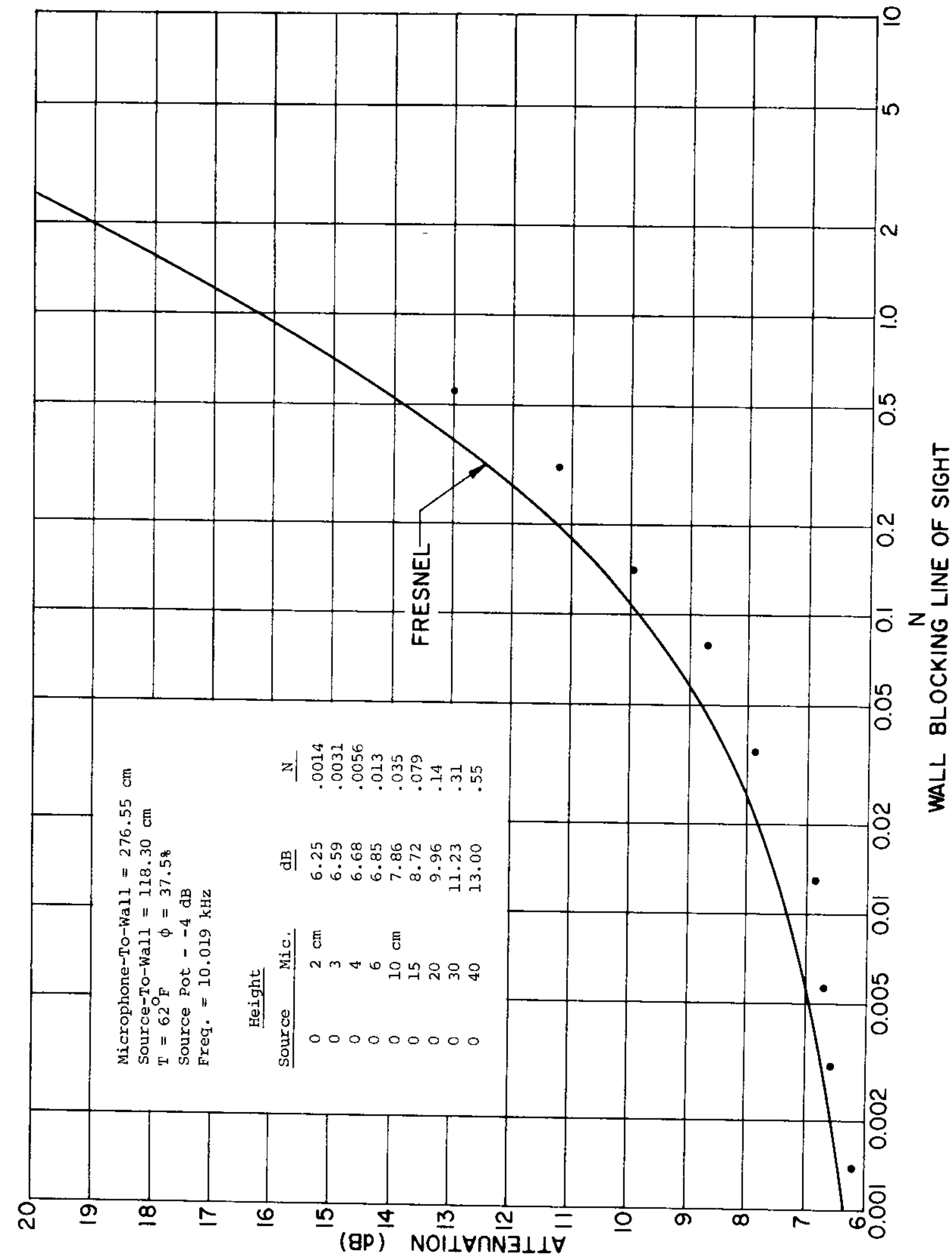
Height			
Source	Mic.	dB	N
1 cm	1 cm	6.19	.0035
2	2	6.72	.014
3	3	7.47	.031
4	4	8.32	.056
6	6	9.61	.126
10	10	12.02	.348
15	15	14.28	.784
20	20	16.15	1.39
30	30	18.94	3.11
40	40	20.95	5.48



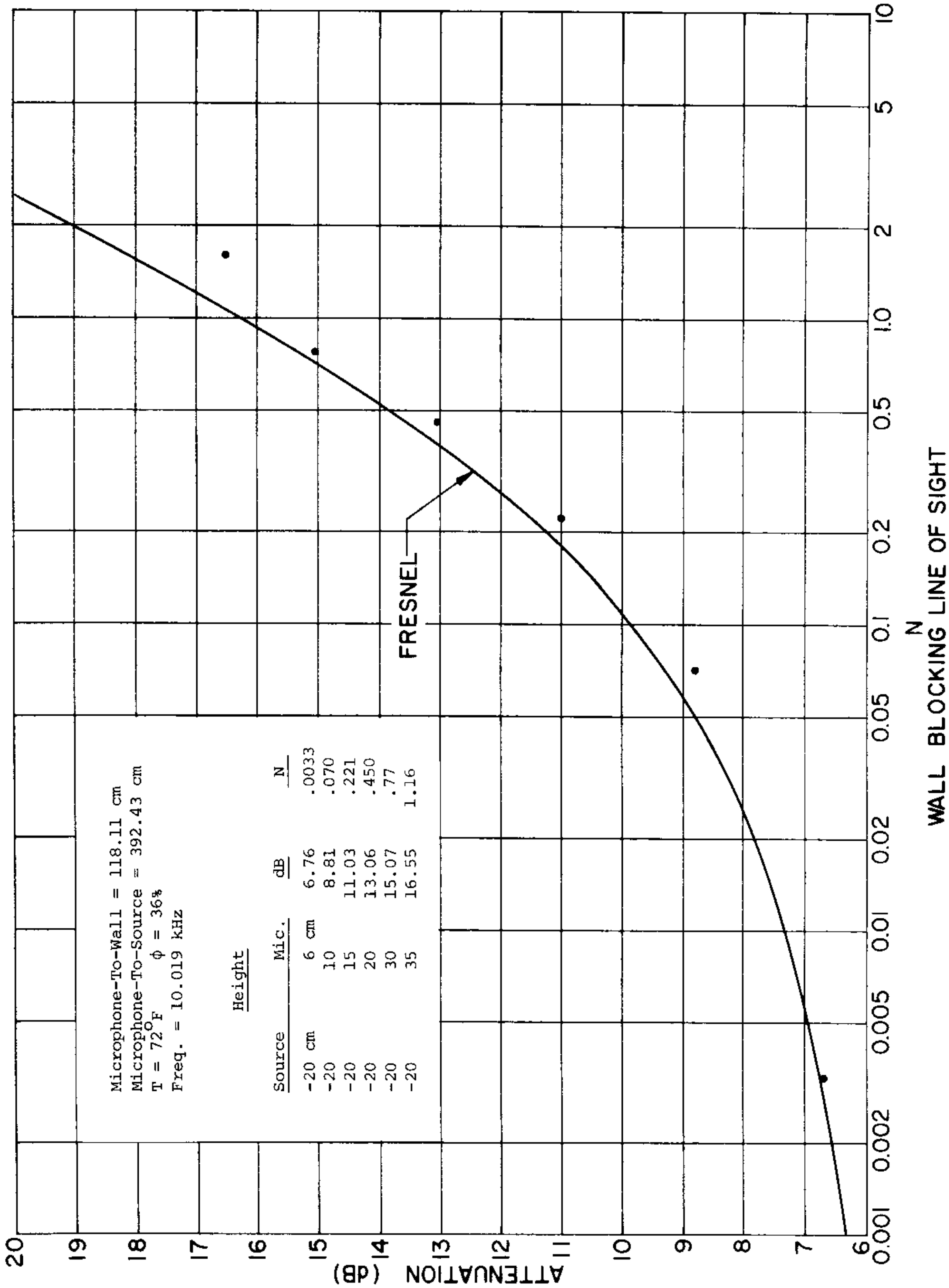
Height: Source	Height: Mic.	dB	N
1 cm	1 cm	6.12	.0035
2	2	6.69	.014
3	3	7.45	.032
4	4	8.29	.057
6	6	9.61	.127
10	10	12.08	.353
15	15	14.42	.794
20	20	16.15	1.41
30	30	19.66	3.15
40	40	21.47	5.55



Height Source	Height Mic.	dB	N
0	1 cm	6.19	.0019
0	2	6.77	.0074
0	3	7.27	.017
0	4	7.40	.034
0	6	8.20	.066
0	10	10.17	.18
0	15	11.87	.41
0	20	13.78	.73
0	30	16.72	1.60
0	40	18.52	2.80



Microphone-To-Wall = 276.55 cm
Source-To-Wall = 118.30 cm
T = 62°F φ = 37.5%
Source Pot - -4 dB
Freq. = 10.019 kHz
Height
Source Mic. dB N
0 2 cm 6.25 .0014
0 3 6.59 .0031
0 4 6.68 .0056
0 6 6.85 .013
0 10 cm 7.86 .035
0 15 8.72 .079
0 20 9.96 .14
0 30 11.23 .31
0 40 13.00 .55
FRESNEL
ATTENUATION (dB)
N
WALL BLOCKING LINE OF SIGHT
0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0 2 5 10
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20


Microphone-To-Wall = 118.11 cm
Microphone-To-Source = 392.43 cm
T = 72°F φ = 36%
Freq. = 10.019 kHz
Height
Source Mic. dB N
-20 cm 6 cm 6.76 .0033
-20 10 8.81 .070
-20 15 11.03 .221
-20 20 13.06 .450
-20 30 15.07 .77
-20 35 16.55 1.16
FRESNEL
ATTENUATION (dB)
N
WALL BLOCKING LINE OF SIGHT
0.001 0.002 0.005 0.01 0.02 0.05 0.1 0.2 0.5 1.0 2 5 10
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20