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Report 1980

PROPAGATION OF HIGH-INTENSITY, LOW-FREQUENCY SOUND WITHOUT LOSS

by

Kenneth J. Oscar and Terence T. Bordelon

April 1970

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U. S. ARMY MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT CENTER
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Report 1980

PROPAGATION OF HIGH-INTENSITY, LOW-FREQUENCY SOUND WITHOUT LOSS

Project 1T061101A91A

April 1970

Distributed by

The Commanding Officer
U. S. Army Mobility Equipment Research and Development Center

Prepared by

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Combat Concepts and Technical Analysis Branch
Barrier and Countersurveillance Division
Military Technology Laboratory

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SUMMARY

This report describes a research program on sound propagation conducted under the In-House Laboratory Independent Research (ILIR) program. The objective of this work was to develop a concept for transmitting high-intensity, low-frequency sound over a distance without large losses of sound-pressure level. A hyperbolic lens and hemispherical reflector were developed and tested for directivity improvement.

This report concludes that:

a. The goal of a sonic transmission loss of only 3 decibels for every doubling of distance from the source has been achieved for the distances recorded.

b. The average intensity loss with the hyperbolic lens, in going from 10 to 100 feet over a frequency range of 50 to 230 hertz, was 9.5 decibels. This is less than half the loss of a source following the inverse square propagation law.

c. The initial intensity loss in going from 0 to 10 feet can be reduced by enclosing the open space between the lens and the acoustic source.

FOREWORD

The investigation covered in this report was conducted under the authority of U. S. Army Materiel Command Project 1T061101A91A.

Tests were performed at the Experimental Proving Ground, Fort Belvoir, Va, from 10 November 1969 to 11 December 1969.

The investigation was made by Kenneth J. Oscar and Terence T. Bordelon, Barrier and Countersurveillance Division, Military Technology Laboratory. Assisting were technicians George M. D'Orazio, Joseph E. Smith, and Peter C. Weinhold. David Lyons, Mathematician, Computation and Analysis Division, developed the computer program for the design of the hyperbolic lens. The photographer was Harold Mohaupt, RD&E Pictorial Support Division.

This project was under the general supervision of William Taylor, Technical Director of MERDC, and under the direct supervision of James A. Dennis, Chief, Combat Concepts and Technical Analysis Branch.

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PROPAGATION OF HIGH-INTENSITY,

LOW-FREQUENCY SOUND WITHOUT LOSS

I. INTRODUCTION

1. **Subject.** This report describes the first phase of a research program whose objective is to demonstrate the feasibility of utilizing low-frequency, high-intensity sound in barrier applications. The first phase of this program covers the experimental effort to transmit low-frequency sound over large distances without great losses of sound-pressure level. To accomplish this goal, reflectors and lenses were studied and tested as methods of focusing or collimating the generated sound.

2. **Background.** Previous investigations have shown that the low end of the acoustic frequency spectrum, or infrasonics, offers the most potential for barrier applications (1).* The benefits of such low-frequency sound are its low atmospheric absorption loss, harmful effects, inaudibility, and ease of enemy barrier penetration. The disadvantages arise from the natural dispersion of sound and the large sizes of devices needed to focus or collimate sound. The natural spreading of sound is constant at all frequencies and follows the inverse square law. The size of focusing devices is on the order of the wavelength of the sound used and therefore can be quite large for low-frequency sound. Past studies have shown that the one remaining problem area left to solve is not the generation of a more intense sound wave, but the propagation of such sound by a device of reasonable size without the normal high loss of sound-pressure level. It is now possible to generate more than 185 decibels of sound by reasonably sized devices, but the intensity losses due to dispersion are 60 decibels for 1000 feet.

There are two methods of overcoming this natural spreading of sound. The first is to actually create or generate sound in phase across a plane front. This development of a plane wave acoustic source is presently being performed by contract and will be reported at a later date. The approach is the utilization of a large-area-type source that will produce the sound using a totally new electromagnetic concept. The second method is to use an external mechanism in conjunction with a spherical-type acoustic source to convert or refract the spreading sound wave to that of a plane wave. The reason for wanting a plane wave is that its directivity is many times better than other wave forms (2,3). Jet engines and detonation tubes, for example, propagate sound like a quadrupole with the majority of the energy concentrated in lobes 30 to 40 degrees from the main axis (4).

*Numbers in parentheses refer to entries in *Literature Cited*, p.29.

The material covered in this report is the first phase of the in-house effort to change the character of generated sound to that of a plane wave by the use of external devices. Normally, the size of focusing devices must be, as a minimum, on the order of the size of the wavelength of the sound to be focused. As an example, for 10-cycle sound, the device must be on the order of 100 feet in effective length. There are three possible ways to shorten this length. First, at Marshall Space Flight Center, sound has been appreciably focused by horns smaller than the wavelength generated due to resonances. Second, it may be possible to focus low-frequency modulated sound by using a higher frequency carrier wave. Modulated sound usually propagates and focuses in the same way as the carrier frequency. Third, even though perfect focusing is not achieved, the results may be sufficient for barrier applications. No matter which approach is finally taken, each requires the same initial experimental testing. This first phase is to determine the amount of focusing or collimation that can be achieved by various devices for a range of frequencies. Once this amount of focusing is determined, the correct approach can be chosen. These experiments may show that the amount of focusing is sufficient or may indicate that a modulation method is necessary to reach the goals in the low-frequency region.

II. INVESTIGATION

3. **Approach.** The approach that was taken in this report was to change the character of the generated sound wave, by focusing or collimating techniques, to that of a wave in phase across a plane front. To achieve this improved directivity, a hyperbolic lens and a hemispherical reflector were used separately in conjunction with a normally diverging acoustic source to focus or collimate the sound.

Three major experiments were involved. The first was to determine the directivity of a standard acoustical source. The second experiment was to determine the directivity of the same source with the lens. The third experiment was to determine the directivity of the source with the reflector.

After all three directivities were determined, the last two were compared with the first to show how the lens and the reflector affected the directivity of the source.

An achievement of 160 decibels at 300 feet will be used as an arbitrary goal based on the latest effects data (5). There is about a 50-decibel loss due to natural spreading of sound traveling 300 feet from the source. At that rate of dispersion, a source would have to produce around 210 decibels to achieve our goal. This level is quite unreasonable. If the loss could be reduced to 25 decibels over the same 300 feet, a source would have to produce only 185 decibels. This output is within the present

range of many reasonably sized commercial acoustic sources. Obtaining a loss of 25 decibels over 300 feet means that a loss of only 3 decibels would occur for every doubling of distance instead of the normal 6-decibel loss predicted by the inverse square law. Therefore, this 3-decibel loss for every doubling of distance will be used as the goal.

Each of the experiments conducted contained four major stages (Fig. 1). The first stage was the production of the sound. The same setup and source were used for all three experiments. The second stage of experiments 2 and 3 was the refraction of the sound. The level of directivity established in experiment 1 was used as a standard to gage the amount of directivity gains in the other two. Experiment 2 used a hyperbolic lens for the refractor, and experiment 3 used a hemispherical reflector. The third stage of each experiment was the recording stage. The equipment used in this stage was the same for all three experiments, but the way in which it was used varied. In the fourth stage—analyzing—the same equipment and methods of analyzing were used for all three experiments. A list of all the equipment used can be found in Appendix A.

Before any of the above experiments were conducted, extensive preliminary runs were made to familiarize personnel with the equipment and procedures.

All equipment was calibrated before and after each run. The procedure used was as follows:

a. Set up the recording stage as desired.

b. Record a known decibel sound level through the entire system by attaching a sound-level calibrator to each of the microphones placed in their proper positions in the field.

c. On analyzing each track, calibrate the analyzer to the known reading in the beginning of each track. Then, all future readings recorded from that track will have absolute decibel values.

4. **Experiment 1: Sound Source.** The main objective of this experiment was to determine the directivity of the sound generated by the acoustic source. The results of all the experiments conducted will be given in Section III.

a. **Production Stage.** The equipment was set up as shown in Fig. 1. Referring to Figs. 2 and 3, the production stage can be seen. Figure 2 shows the acoustical source. The source includes an electropneumatic transducer and an exponential horn. The horn was used to couple the sound to the air. This, in itself, increases the directivity of the transducer, as will be seen in the results of experiment 1. The acoustic source was placed on an adjustable stand. Attached to the rear of the transducer was a manifold.

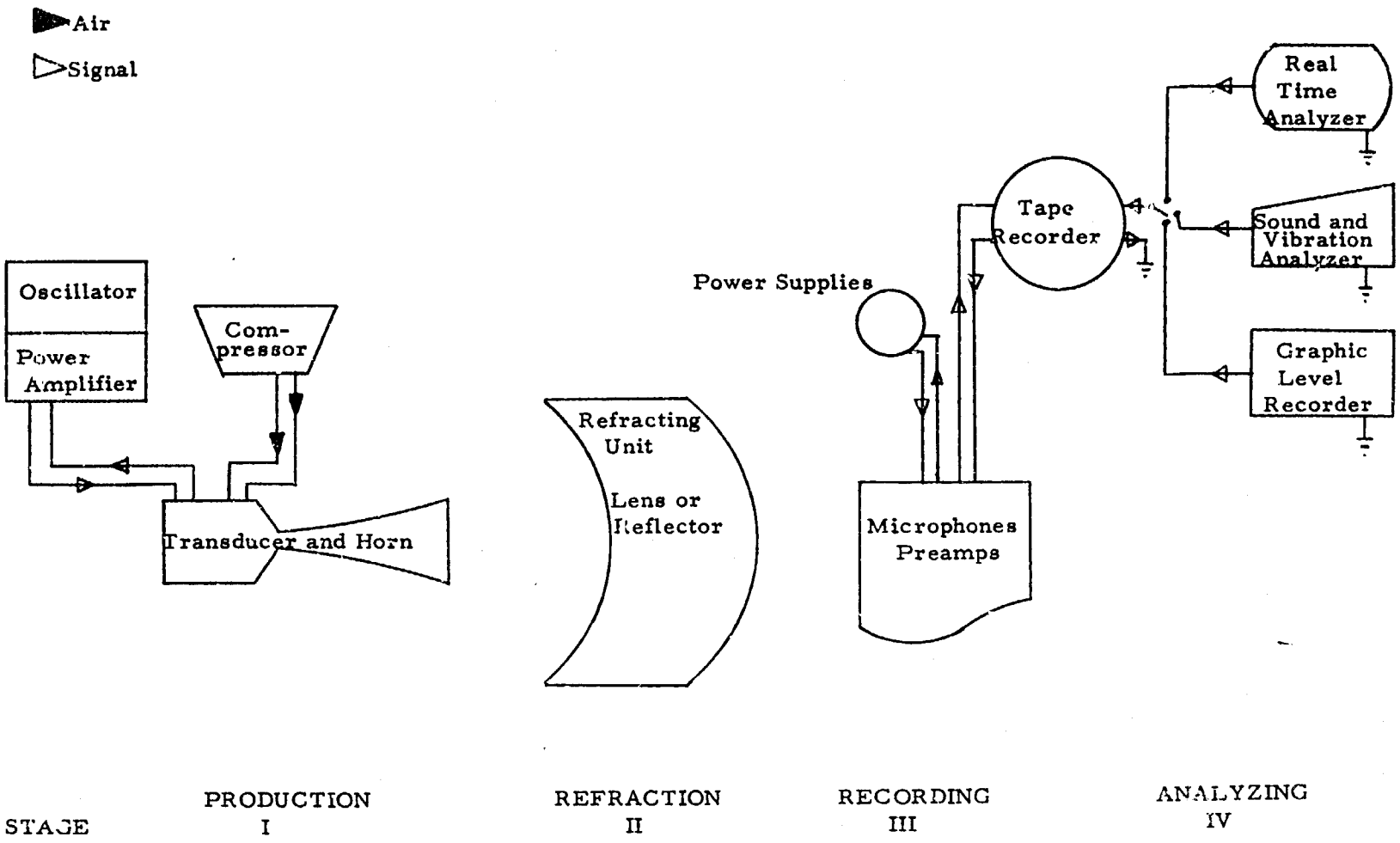

Fig. 1. Flow diagram of test setup and procedure.

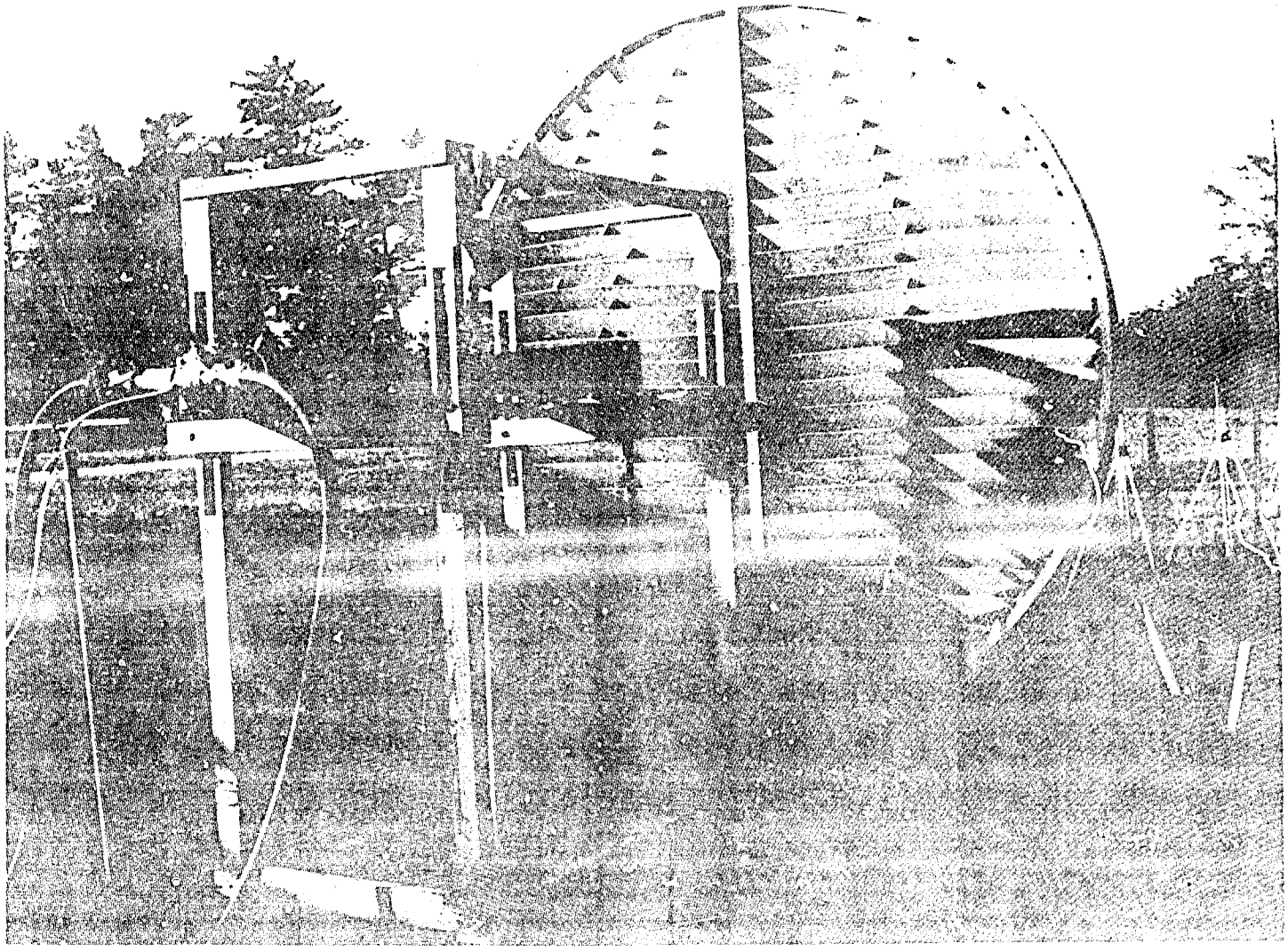

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Fig. 2. Acoustic source and hyperbolic lens. Note microphones on tripods at right in picture.

Fig. 3. Test instrumentation.

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This was used so that two air hoses could be engaged in the transducer simultaneously. Two hoses were needed to achieve the airflow necessary to operate the transducer. The transducer could be operated only when the air pressure was above a certain minimum. This criterion was automatically measured by an interlock system that was incorporated into the amplifier. This minimum flow was needed to keep the coils in the transducer from overheating. Within the system was a pressure gage that measured the instantaneous inlet pressure. The maximum safe pressure and airflow was 40 pounds per square inch and 450 cubic feet per minute. To drive the coils at the desired frequency, an oscillator and power amplifier were used (Fig. 3). The amplifier was needed to boost the output current of the oscillator. The compressor used to supply the airflow was of a rotary type with diesel drive. Its maximum output was 600 cubic feet per minute at 100 pounds per square inch. For testing, this compressor was stationed at such a distance that the noise created by its motor did not affect the experiments. Throughout the experiments, only about 70 percent of the acoustic source's output was used. Since the main objective of these experiments was to determine whether or not the directivity could be increased, full output was not needed.

b. **Recording Stage.** To record the data that would determine the directivity of the source, seven microphones, preamplifiers, and tripods were used in conjunction with a seven-track tape recorder/reproducer. The microphones were lined up in a straight line, with the microphones at the same height as the center of the exponential horn. This line was referred to as the zero-degree line. The microphones, numbered one through seven, were spaced at intervals, as shown in Fig. 4. The acoustic source was then directed toward the array of microphones. The preamplifiers were powered by individual power supplies (Fig. 3). These were connected to the microphones by 100-foot cables. The preamplifiers were needed to adjust for signal loss in the cables. From the power supplies, the signal was fed into the tape recorder. Each track on the tape recorder had its own attenuator, which allowed each input to be modified for the proper range and elimination of distortion.

To begin the experiment, the calibration of each microphone was recorded on its track of the tape. The oscillator was set on 50 hertz, and the current of the amplifier was brought to 5 amperes. The sound field was then recorded long enough so that the signal could be analyzed easily. The pressure and tape recorder reel rotation units were then recorded in the field data book. Next, a blank space was put on the tape to facilitate identification of data when analyzing, and the entire procedure was repeated for the next frequency. This process continued, in steps of 10 hertz, until the region from 50 to 230 hertz was covered. Throughout the experiments, the current was held constant.

The horn and transducer were then turned 10 degrees, with respect to the zero line. The entire process was repeated for intervals of 10 degrees until

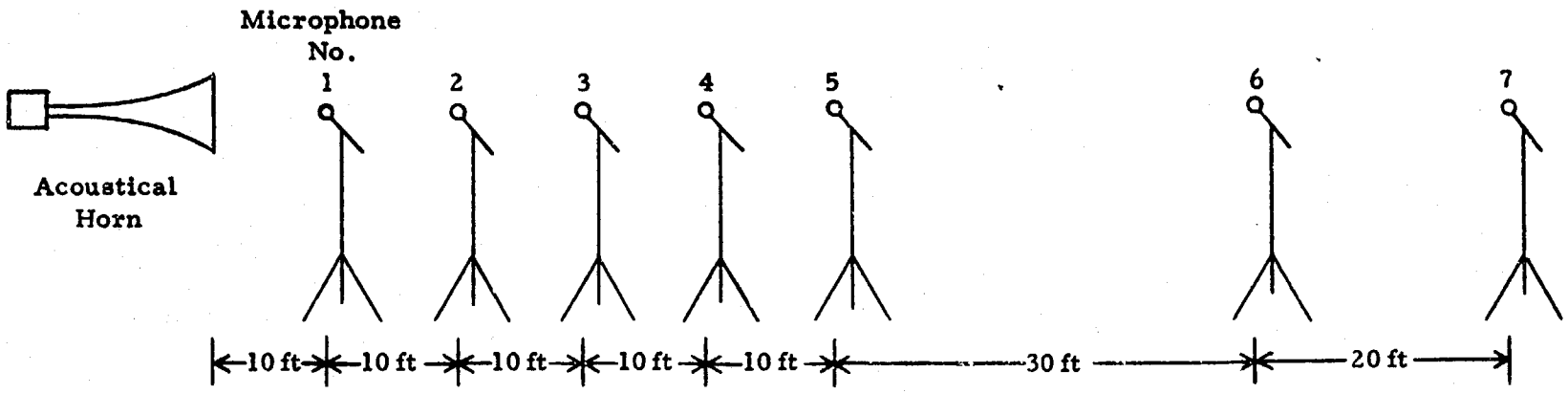

Fig. 4. Field setup for experiment 1.

90 degrees were reached and recorded. Rather than rotating the large and heavy devices for the lens and reflector experiments, the microphones were moved. Aluminum poles were used to permanently mark the height and position of each microphone, as indicated in Fig. 5. The temperature, atmospheric pressure, wind speed, and humidity for every hour of the experiments were also recorded. The experiments were run on days offering similar weather conditions.

c. **Analyzing.** A one-tenth and one-third octave sound and vibration analyzer was used to analyze the signals on the tape recorder. Figure 6 shows a sample form used to record the data. On this form, "No." refers to the reel rotation numbers of the tape recorder and "α" means the degrees of rotation of the source with respect to the zero-degree line. The data for the frequency spectrum were recorded on strip chart paper of a graphic level recorder. This data was used to check the frequency output for changes and possible higher harmonics due to the refracting stage.

5. **Experiment 2: Lens.** The objectives of this experiment were to determine the directivity of the sound produced by directing the sound generated by the acoustic source through a hyperbolic lens and to determine the amount of sound-pressure loss in propagating this sound over a distance.

Refracting Stage: A hyperbolic lens was used as the refracting unit in this stage (Figs. 2, 7, and 8). The equation used to describe the surface of the lens can be developed as follows.

The only requirement of the lens is to refract the incoming spherically spreading sound wave so that the outgoing wave will be in phase across a plane front. A plano-convex lens can give us this result. Fig. 9 has the general description of the lens.

To obtain a plane wave at the planosurface, the time required for a wave to travel distance B must be equal to the time required to travel the distance A.

That is $t_B = t_A$. The time is equal to the distance traveled in a medium divided by the velocity in that medium.

Therefore

$$t_B = \frac{B}{V_{air}} \quad \text{and} \quad t_A = \frac{f}{V_{air}} + \frac{x}{V_{med}}$$

Equating and dividing by V_{air} gives

$$B = f + x\,\frac{V_{air}}{V_{med}}$$

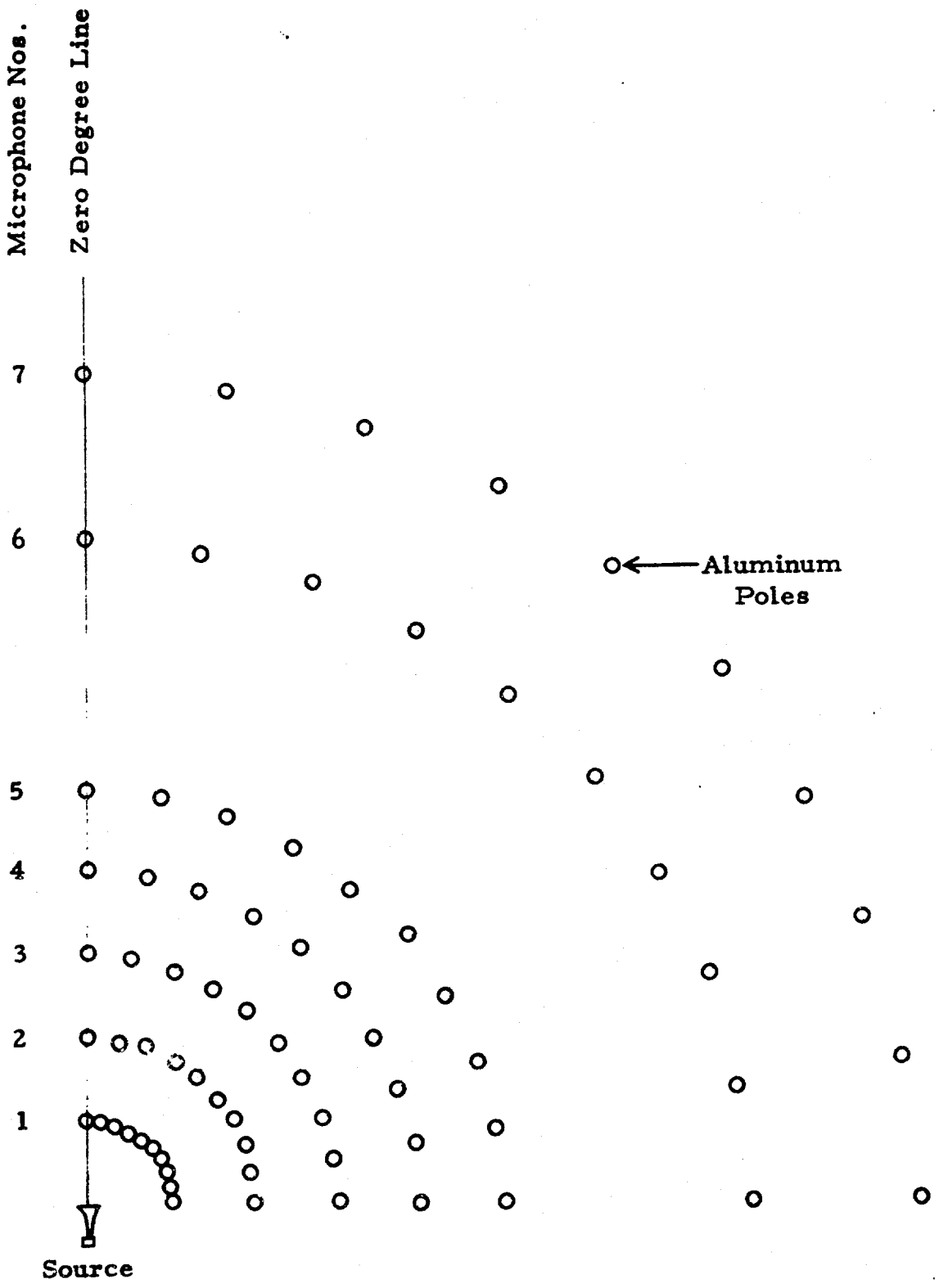

Fig. 5. Microphone layout. Circles indicate aluminum poles used to permanently mark the location of the microphones.

TEST NO. ____ DATE _____ RUN TIME:

CHANNEL NO. ____ START ___ FINNISH ___

α	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	
NO.											HZ
1											50
2											60
3											70
4											80
5											90
6											100
7											110
8											120
9											130
10											140
11											150
12											160
13											170
14											180
15											190
16											200
17											210
18											220
19											230

Fig. 6. Test data form.

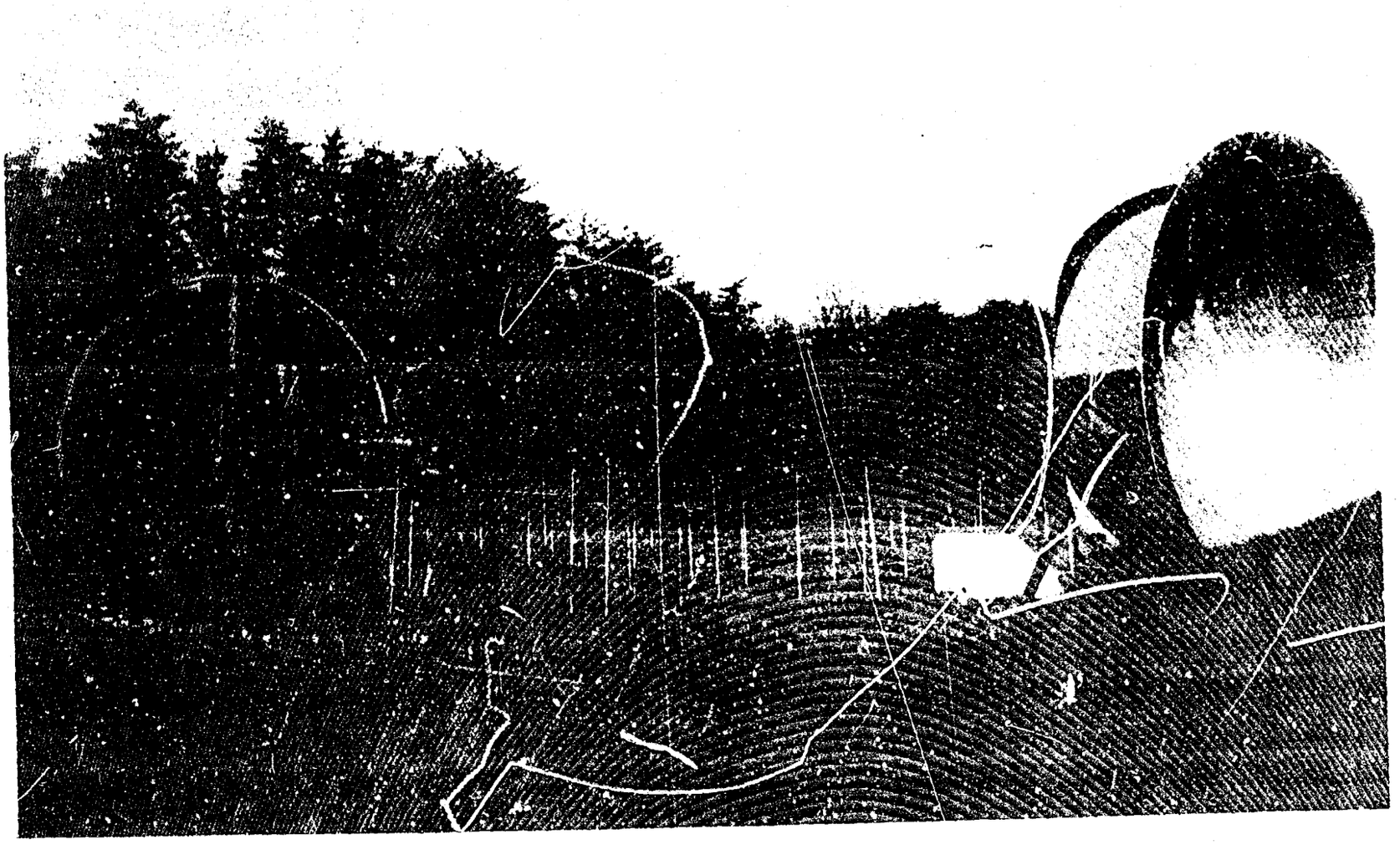

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Fig. 7. Hyperbolic lens and hemispherical reflector.

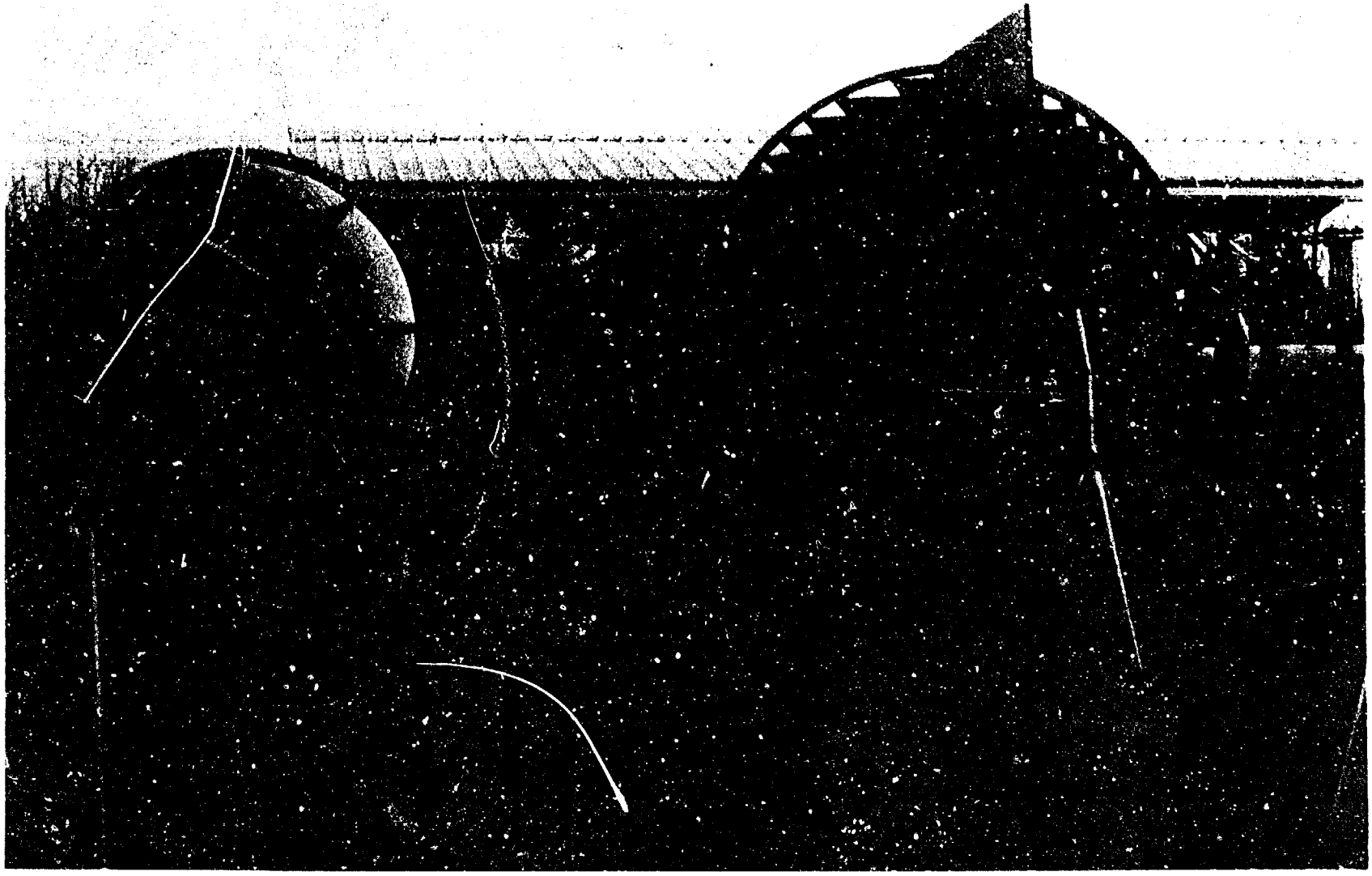

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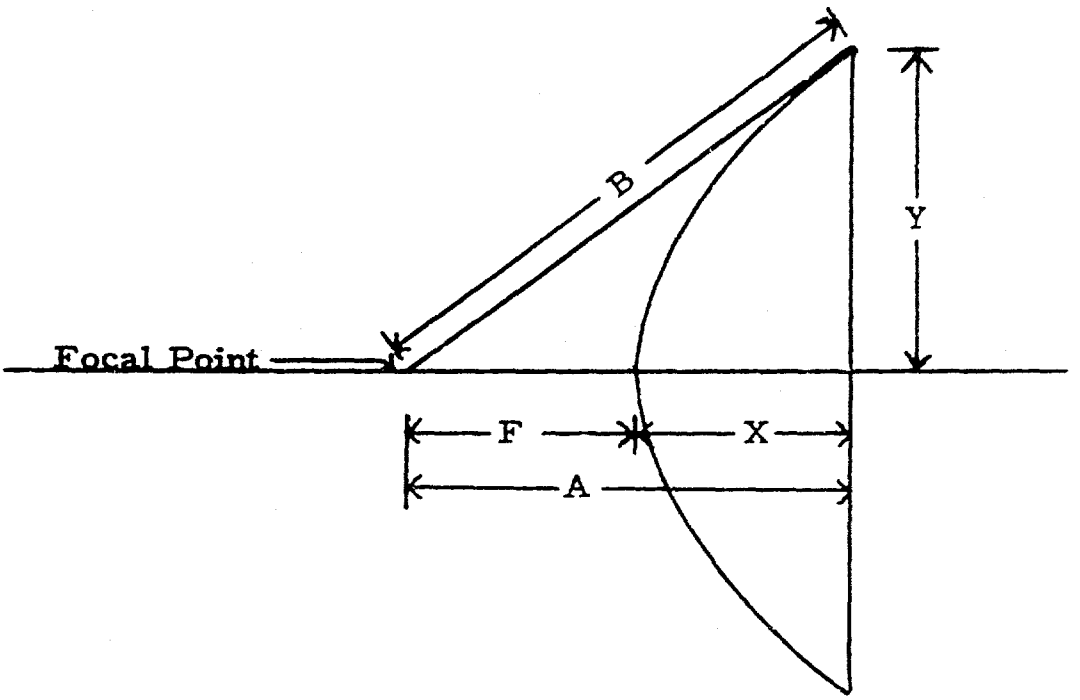
Fig. 8. Back view of reflector and lens.



B = Distance from focal point to outer edge of lens
F = Focal distance of lens
X = Thickness of lens
A = X+F
Y = Radius of lens

Fig. 9. Hyperbolic lens parameters.

From Fig. 9, it can be seen that

$$B = \sqrt{(f+x)^2 + y^2}$$

Therefore

$$\sqrt{(f+x)^2 + y^2} = f + Kx$$

$$\text{where } K = \frac{V_{air}}{V_{med}}$$

This equation may be written:

$$x^2 (1 - K^2) + 2 f x (1 - K) + y^2 = 0$$

Or

$$x^2 + \frac{2 f x}{K + 1} - \frac{y^2}{(K^2 - 1)} = 0$$

Completing the square yields

$$\frac{\left[x + \frac{f}{(K+1)} \right]^2}{\left[\frac{f}{(K+1)} \right]^2} - \frac{y^2}{[f(K-1)]^2} = 1$$

This is the equation of a hyperbola with the axis shifted. To determine K, recall that the velocity in a medium is just equal to the index of refraction in air over the index of refraction in a medium. So

$$K = \frac{N_{air}}{N_{med}} = \frac{1}{N}$$

where $N_{air} = 1$ and $N_{med} = N$

To determine the index of refraction of the lens, we have

$$K = \frac{\dfrac{\text{Sonic Path Distance in Air (SPDA)}}{T_{air}}}{\dfrac{\text{Sonic Path Distance in Medium (SPDM)}}{T_{med}}}$$

but

$$T_{air} = T_{med}, \text{ so } K = \frac{SPDA}{SPDM} = \frac{1}{N}$$

Therefore

$$N = \frac{SPDM}{SPDA}$$

Requiring $N \geqslant 1$, yields SPDA $\leqslant$ SPDM. One way to accomplish this is to place guides in the form of slats in the path of the sonic waves (Fig. 10). With the slats tilted at an angle θ with respect to the incoming wave, the equation defining the index of refraction is

$$\cos\theta = \frac{\text{SPDA}}{\text{SPDM}} = \frac{1}{N}$$

Therefore, the greater the angle θ, the higher the index of refraction. Choosing the index of refraction to be 1.5 gives

$$\theta = 48^\circ\ 11' \doteq 48.2^\circ$$

Therefore, if the slats are set at an angle of 42.2 degrees with respect to the incoming waves of sound, an index of refraction of 1.5 will be obtained within the medium or

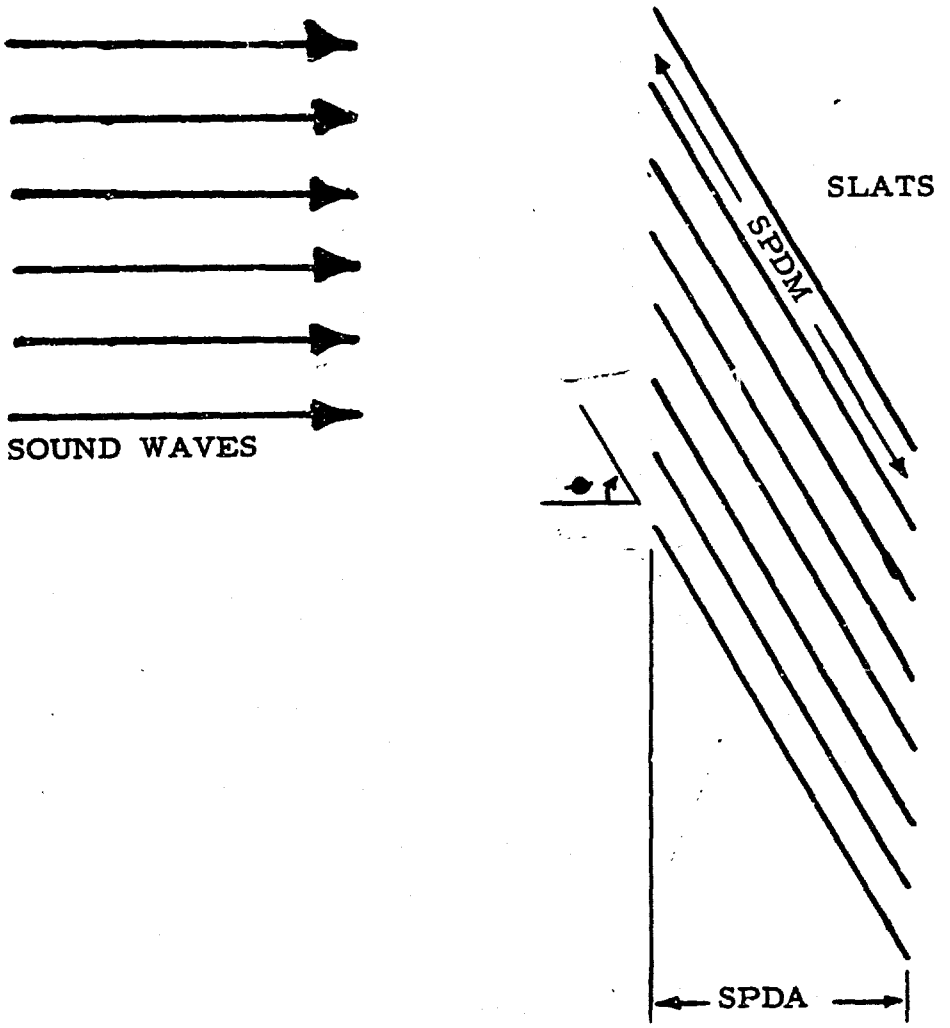


Fig. 10. Lens refraction.

lens. Using these equations, a computer program was written and used to determine the profile of the lens and the shape of the slats. The overall diameter of the lens was chosen to be 9 feet, so that the lens would function in the low-frequency region.

The mouth of the exponential horn was placed at the focal point of the lens, which was calculated to be 3 feet. This calculation was for a point source which is an idealized case. For this reason, the optimum position of the horn was found experimentally by moving the horn back and forth until the maximum reading was realized. This optimum distance was found to be 5 feet behind the lens.

6. **Experiment 3: Reflector.** The main objective of this experiment was to determine the directivity of the sound produced by directing the sound generated by the acoustic source into a hemispherical reflector and to determine the amount of sound-pressure loss in propagating this sound over a distance.

Refracting Stage: A hemispherical reflector was used as the refracting unit in this stage (Figs. 7 and 8). The reflector was made of fiberglass and had a diameter of 10 feet. Its focal point was calculated to be 1½ feet.

To set up this stage (Fig. 11), the source was turned 180 degrees about a vertical axis passing through the center point of the mouth of the horn. The reflector was then placed at such a position that the center point of the horn coincided with the focal point of the reflector.

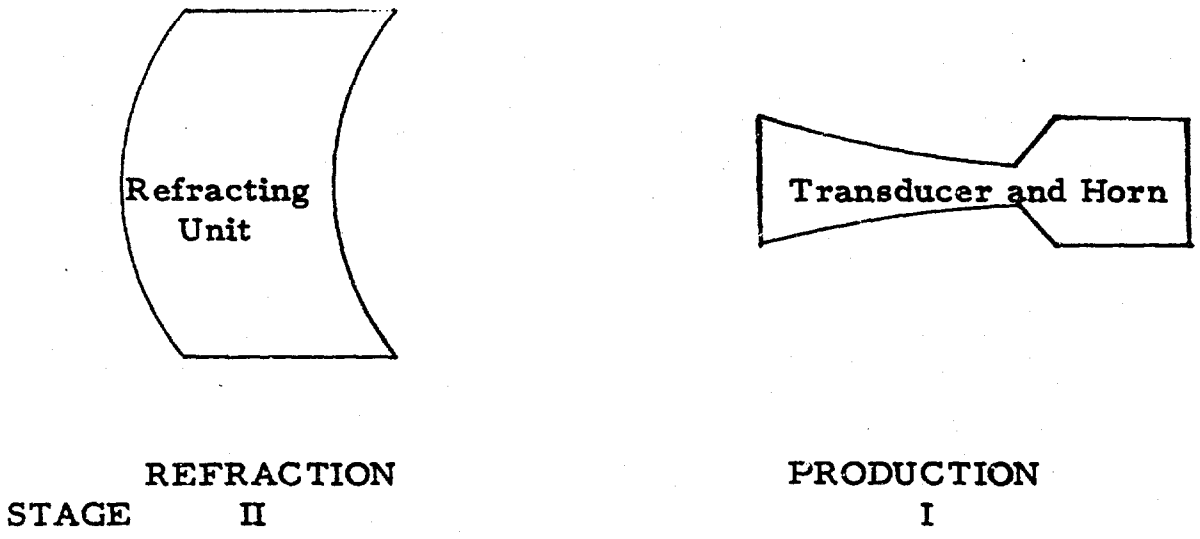


Fig. 11. Reflector setup.

The experiments on the reflector could not be completed under this In-house Laboratory Independent Research (ILIR) project and will not be included in this report. The reflector experiments, along with other concepts, will be conducted and continued under Project 1J662708462, *Barrier-Counterbarrier Research.*

III. TEST RESULTS AND DISCUSSION

7. **Source and Lens Test Results.** Several types of graphs were made for each experiment in order to achieve a complete understanding of the phenomena taking place. In the first type of graph, intensity in decibels is plotted as a function of distance from the source with frequency and angular distance about the source held constant. Four of the 19 frequencies tested are plotted here as being representative of the wide range of frequencies tested. The graphs of Figs. 12 and 13 show the intensity at distances up to 100 feet from the source for 50, 110, 170, and 230 hertz. These graphs compare the intensity with and without the lens. The inverse square loss for an idealized spherical source is also included for comparison. It can be seen from the graphs that the source with exponential horn has less loss than predicted by the inverse square law, as the frequency increases. This is due to the increase in atmospheric absorption loss as a function of increasing frequency. The graphs also demonstrate that the source with the lens undergoes less intensity loss than either the inverse square law or the source alone at every frequency. The lens also shows an almost constant intensity loss at all frequencies. This implies that a slightly better focusing is being achieved as the frequency increases, because the increasing absorption loss with rising frequency has been overcome. It must be noted that the experiments were not all performed at the same initial intensity level at the source, because certain other parameters such as current, flow, and pressure were far easier to keep experimentally constant. The initial intensity was always within 10 decibels and does not interfere with test results, as will be shown later.

The second type of graphs are directivity patterns, sometimes called iso-intensity graphs. These graphs demonstrate the directivity of a sound source. They plot angle around the source as a function of distance from the source with frequency and intensity held constant. The directivity pattern of an idealized spherical source would be represented on this type of graph by a circle with the source at the center. On all of these graphs, the source is at the center of the graph facing in the zero-degree direction. The source, with the lens and without the lens, is graphed for comparison at 50, 110, 170, and 230 hertz. From the graphs of Figs. 14 through 17, it can be seen that the directivity pattern of the source and attached exponential horn are basically spherical, with a sphere having a slightly larger radius than the sphere in front of the source in the back. As the frequency increases, the front half of the circle tends to get larger and the back half of the circle smaller, demonstrating some limited front-to-back

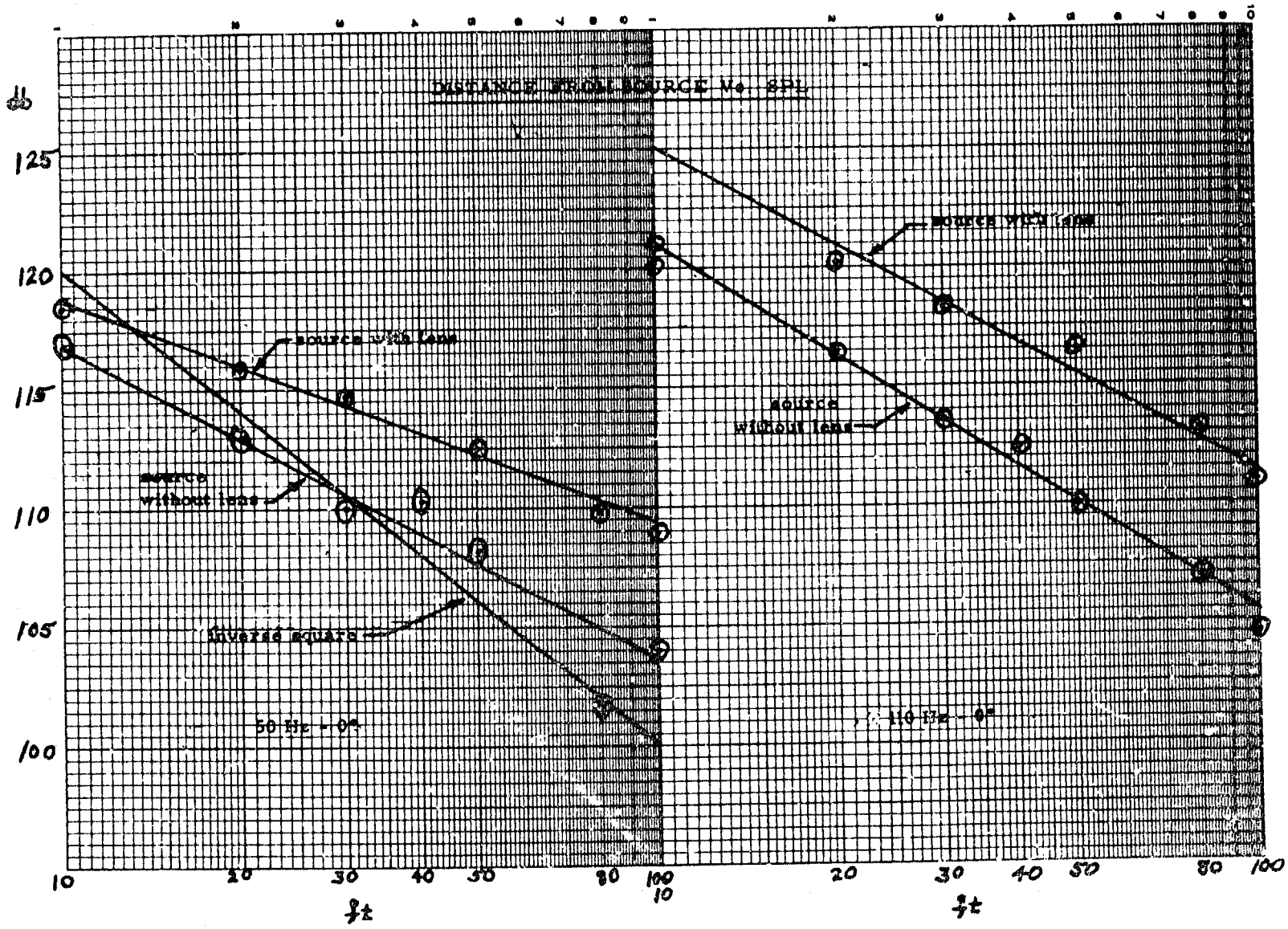


Fig. 12. Graph of sound-pressure level versus distance from source for 50 and 110 hertz, with and without lens.

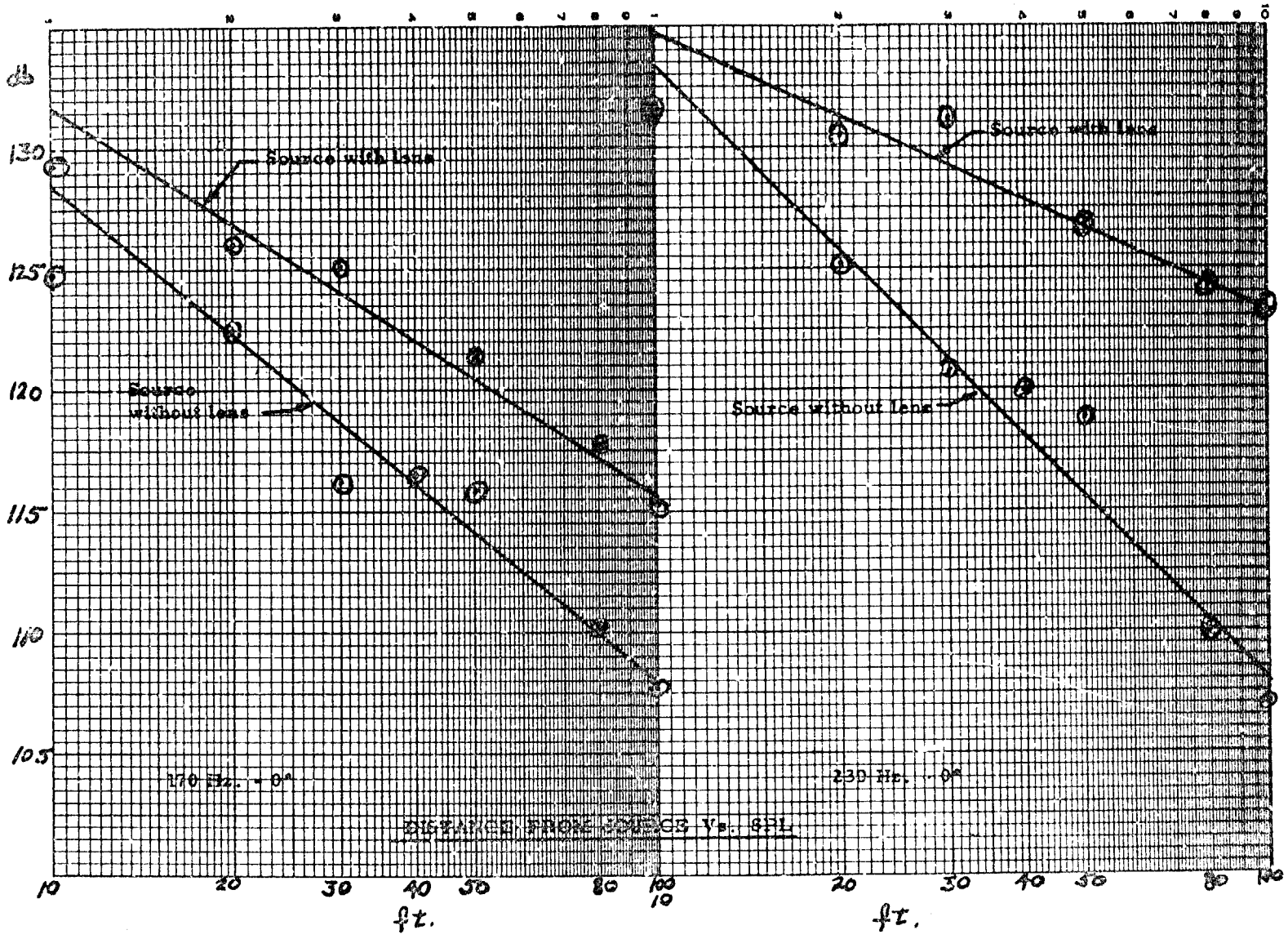


Fig. 13. Graph of sound-pressure level versus distance from source for 170 and 230 hertz, both with and without lens.

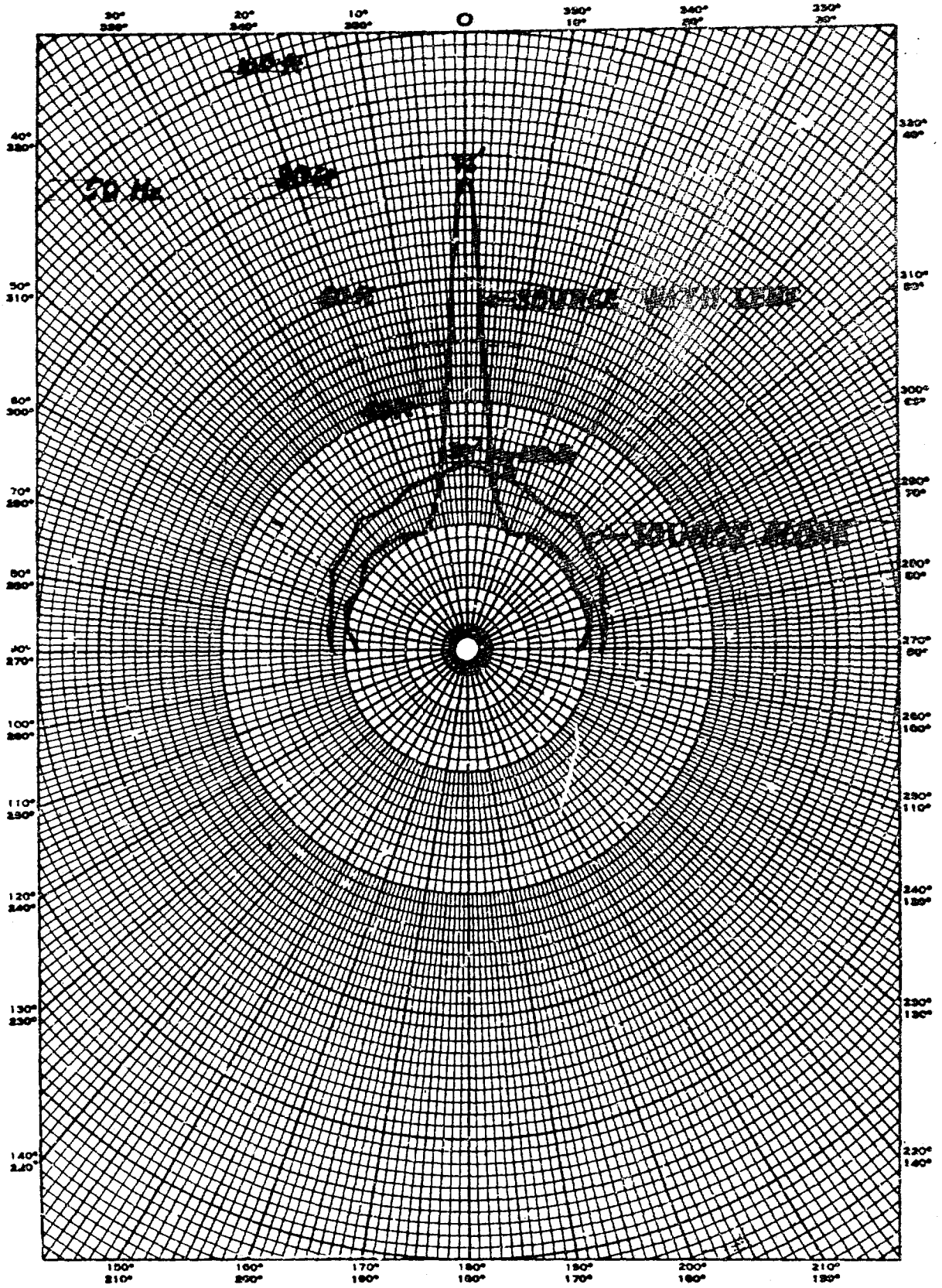


Fig. 14. Directivity pattern for 50 hertz, with and without lens.

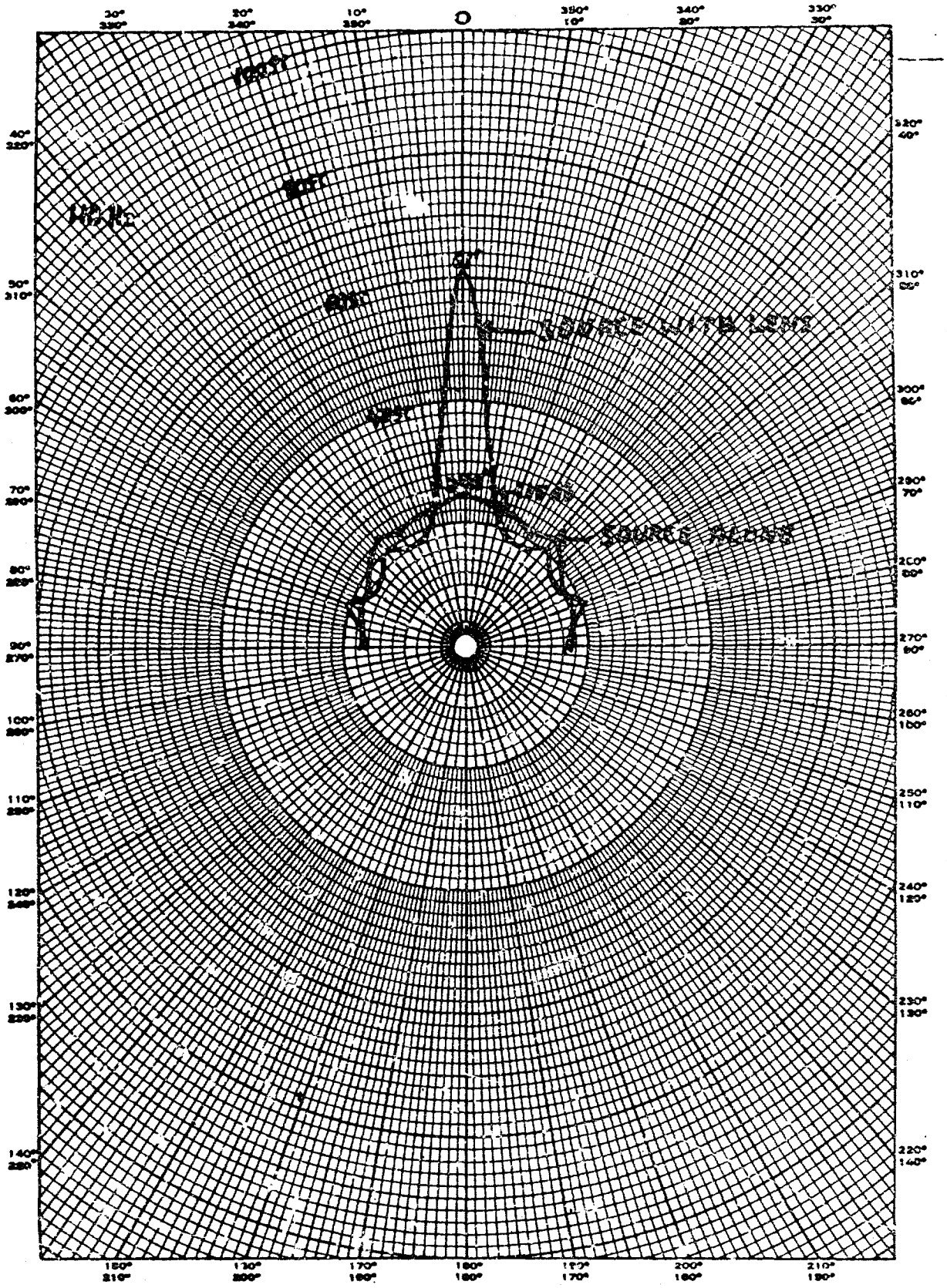


Fig. 15. Directivity pattern for 110 hertz, with and without lens.

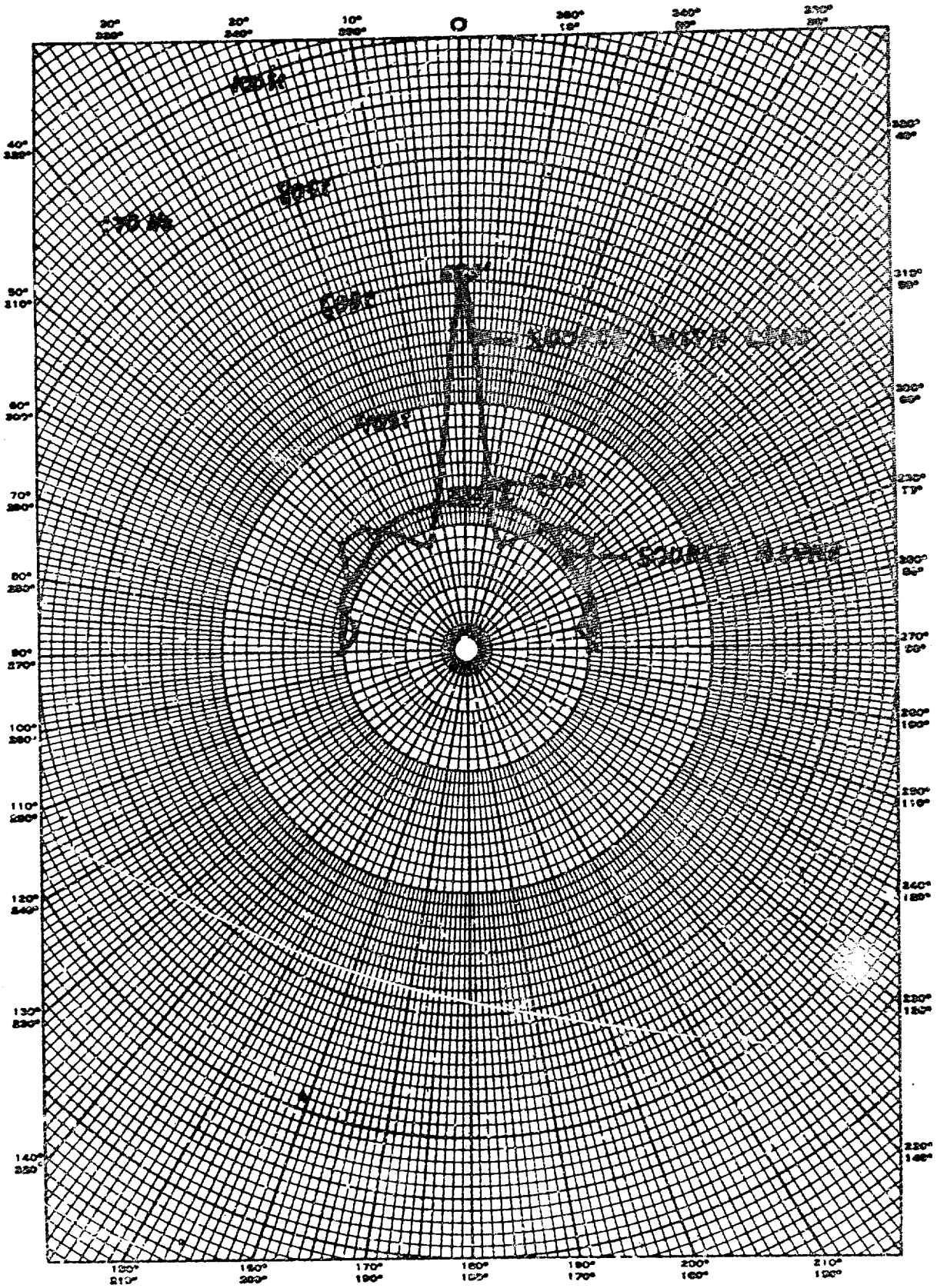


Fig. 16. Directivity pattern for 170 hertz, with and without lens.

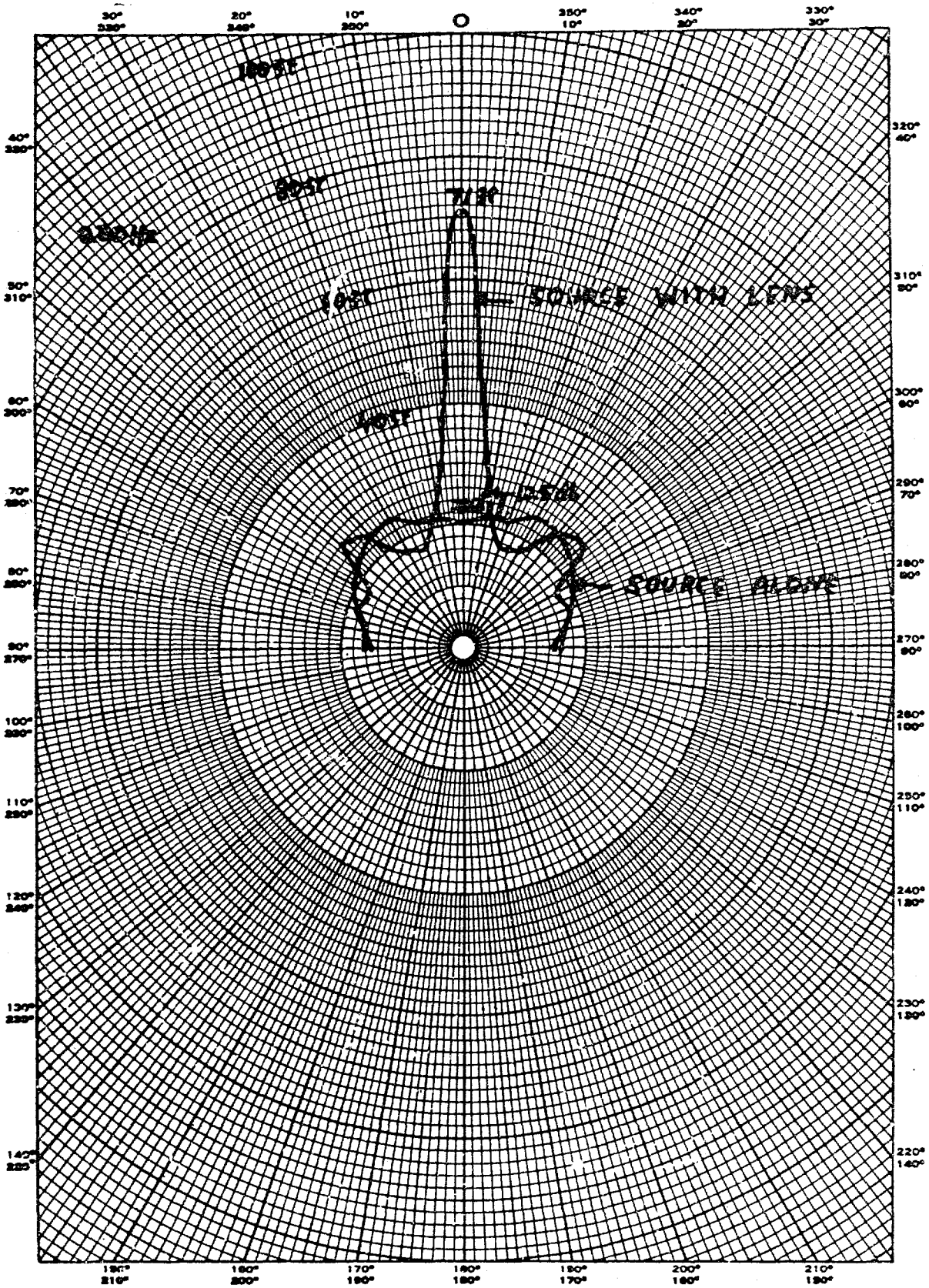


Fig. 17. Directivity pattern for 230 hertz, with and without lens.

directivity. As can be seen from the same graphs, the source with the lens demonstrates appreciable focusing. At all frequencies, there is considerable directivity with most of the energy contained in about a 10-degree cone in the forward direction. As the frequency increases, small side lobes, at around 50 degrees off the main axis, are starting to form. There are no side lobes present at any of the lower frequencies with the lens.

The least type of graph is a plot of decibel loss in going from 10 to 100 feet on the zero-degree line versus frequency. Experiments with and without the lens are plotted on the same graph, for comparison (Fig. 18). Without the lens, the average decibel loss is 18.25, as compared with 20 decibels predicted for the inverse square law. The loss without the lens generally increases with increasing frequency, except for a resonance at 160 decibels. With the lens, the average loss in going from 10 to 100 feet in the forward direction is 9.51 decibels, which is less than half the loss that would be experienced by the inverse square law and which was our original goal. It must be noted that the decibel scale is logarithmic, and a 20-decibel savings represents 100 times more intensity, and 30 decibels represents 1000 times more intensity. As seen by the graph, the decibel loss for the lens is fairly constant at all frequencies. Graphs of percentage of intensity loss as a function of frequency were also plotted. These curves exactly follow those plotted in Fig. 18, indicating that initial intensity had no effect on the results.

This data demonstrates that, with the lens, there is less than a 3-decibel loss for every doubling of distance in going from 10 to 100 feet, which is less than one-half the loss predicted by the inverse square law. Data on directivity for the regions from 0 to 10 feet and beyond 100 feet still need to be accurately recorded. Preliminary data taken at the mouth of the exponential horn seem to indicate about a 25-decibel loss in going from 0 to 10 feet. Zero feet represents the mouth of the exponential horn. The lens was placed 5 feet in front of the horn and was 3 feet in depth. Therefore, none of the spreading sound was affected until it traveled 5 feet, and some of it had to travel 8 feet before coming in contact with the lens.

Some of the early experiments conducted to determine the optimum focal point of the lens indicate that, if the region between the lens and the mouth of the horn were enclosed, considerably better results could be achieved and much of the initial intensity loss prevented. These initial experiments were conducted by sliding the transducer and horn back and forth on a board 2 feet wide. The maximum sound-pressure level was recorded when the horn was 5 feet behind the lens. In this position, the board extended 2 feet in front and under the mouth of the exponential horn. When the system was permanently adjusted for testing and the board brought back from in front of the sound generator, it was found that the sound-intensity level at 100 feet from the source decreased by about 2 decibels. This indicates that the presence of a 2- by 2-foot board under and in front of the mouth of the horn increased the

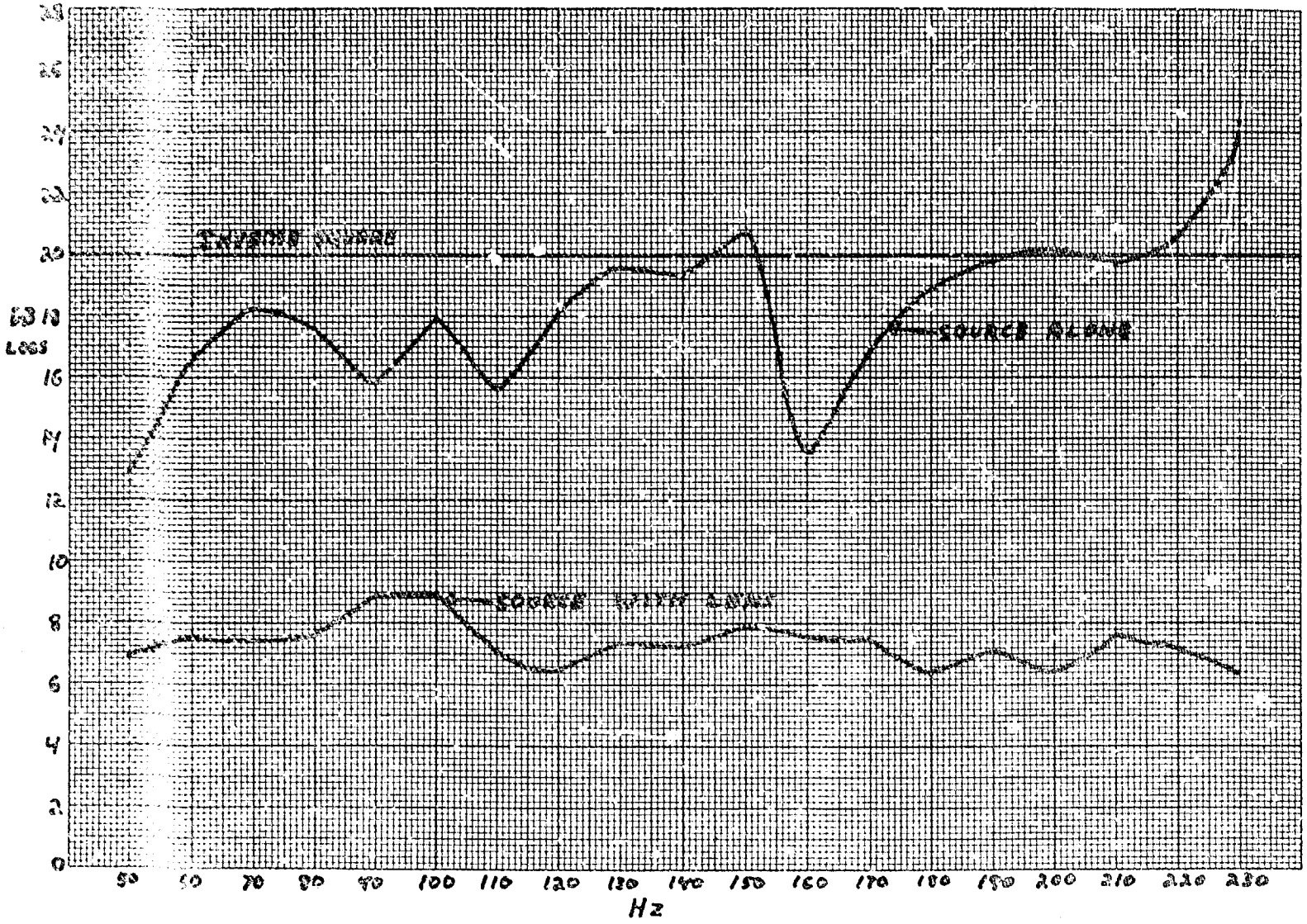


Fig. 18. Decibel loss versus frequency, both with and without lens, for 10 to 100 feet from the source in the zero-degree direction.

intensity level significantly. Using this same principle, if the whole area between the horn and lens were enclosed, it is believed that significantly better results would be achieved and the initial high-intensity loss would be overcome. A possible method to accomplish this end will be tested at a later date by using the lens and horn in conjunction to enclose this open space.

IV. FUTURE WORK

8. **Future Work.** This report terminates this project under the Technical-Director-sponsored ILIR program. The results of these experiments have demonstrated considerable collimation of sound can be accomplished. If such propagation potential can be realized, and since low-frequency sound has incapacitating and possible lethal effects against personnel whether in the open or under cover, its application as a controllable barrier mechanism may negate the current requirement for utilization of a family of weapons in order to immobilize armored and wheeled vehicles as well as personnel.

Based on the experimental results of this effort, this program is being continued under Project 1J662708A462, *Barrier-Counterbarrier Research*. Future work to be accomplished is as follows:

a. Tests on the hemispherical reflector will be completed.

b. The reflector and lens will be examined together in an attempt to overcome the high-intensity loss in going from 0 to 100 feet.

c. Experiments on the multiple source and toroidal or streaming effect will be made, as well as any other new directivity concepts.

d. Complete sound-level patterns from 0 to 1000 feet will be recorded for more complete analysis of experimental results.

e. A target-effects study of sound will be conducted by Edgewood Arsenal to firmly fix the intensity level of sound needed. The effects study conducted at Edgewood Arsenal will be closely monitored, so that future research in low-frequency sound at MERDC can be designed to achieve definitive target levels necessary for barrier application.

V. CONCLUSIONS

9. **Conclusions.** It is concluded that:

a. The goal of a sonic transmission loss of only 3 decibels for every doubling of distance from the source has been achieved for the distances recorded.

b. The average intensity loss with the hyperbolic lens, in going from 10 to 100 feet over a frequency range of 50 to 230 hertz, was 9.5 decibels. This is less than half the loss of a source following the inverse square propagation law.

c. The initial intensity loss in going from 0 to 10 feet can be reduced by enclosing the open space between the lens and the acoustic source.

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APPENDIX A

TEST EQUIPMENT

1. Ten GR 1560-P40 preamplifiers.
2. Ten GR 1560-P5 microphones.
3. Ten GR 1560-P32 tripods.
4. Ten GR 1560-9512 power supplies.
5. Thirty GR 1560-P73B, 100-foot extension cables.
6. One GR 1911-A recording sound-vibration analyzer.
7. One GR 1559-9842 microphone reciprocity calibrator.
8. One GR 1262-9703 power supply.
9. One GR 1551-C sound-level meter.
10. One GR 1921-9705 real-time analyzer, with attenuator.
11. One GR 1562-9701 sound-level calibrator.
12. One Ampex SP-300, FM, 7-channel, 1/2-inch (IRIG) instrumentation recorder.
13. One Ampex III degausser.
14. Four Ampex 748-273119 1/2-inch tape.
15. Two LTV-Ling Model EPT-94B electropneumatic transducers.
16. Two LTV-Ling EC series, exponential connectors.
17. Two LTV-Ling Model TP-100-3 power amplifiers.
18. Two LTV-Ling Model AFO-100 low-distortion audio oscillator.
19. Two Ingersoll-Rand, 600-cfm, 100-psi air compressors with connecting hose and/or pipe.
20. Reflector:

    One 5-foot-radius-of-curvature hemispherical fiberglass reflector 1/8-inch to 1/4-inch raised concentric rings, as needed.
21. Lens:

    One hyperbolic lens with curved slats 3 inches apart:

    $5x^2 + 12x - 4y^2 = 0$ in feet for face

APPENDIX B

SOURCE AND LENS DATA

Test VIa. Without Lens
(All Measurements 10 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	116.9	117.0	116.3	116.4	116.1	115.8	116.1	115.4	115.0	114.6
60	118.5	118.8	118.9	118.9	119.0	119.0	118.6	118.5	117.9	117.5
70	125.1	124.3	123.9	123.9	124.3	124.3	123.8	122.8	122.4	121.7
80	125.9	126.2	126.1	125.7	126.1	126.0	124.9	125.1	124.5	123.8
90	121.7	122.4	123.3	123.1	122.8	122.7	121.4	121.8	121.7	121.3
100	119.8	119.9	120.0	120.0	119.9	119.8	119.7	119.7	119.3	118.9
110	120.1	119.7	119.9	120.2	119.5	119.5	118.8	119.6	119.0	118.5
120	123.6	123.1	122.3	123.2	122.9	122.2	121.9	122.7	122.4	122.0
130	128.3	127.7	126.9	127.4	128.1	127.8	127.5	126.9	126.3	125.7
140	129.6	129.4	126.9	120.9	129.9	129.9	129.4	128.8	128.2	127.4
150	127.4	128.0	129.1	129.2	129.4	129.3	128.3	127.8	127.2	126.4
160	124.0	124.4	125.1	124.5	124.4	124.4	123.6	123.5	123.0	122.0
170	124.6	125.1	125.3	125.5	125.0	124.0	124.1	123.8	123.8	123.3
180	124.9	125.4	125.8	125.5	125.4	125.3	124.8	124.4	124.1	123.6
190	124.3	124.7	125.4	125.0	125.0	125.1	124.5	124.4	123.8	122.9
200	127.8	127.1	127.5	127.2	126.5	126.2	126.6	125.8	125.1	124.4
210	130.2	129.7	122.9	129.4	119.3	129.1	128.8	128.4	127.0	126.5
220	130.5	130.0	126.9	130.7	130.6	130.2	129.8	129.4	128.2	127.4
230	131.4	131.1	129.9	131.0	131.5	131.1	130.8	130.2	129.8	128.4

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test VIb. Without Lens
(All Measurements 20 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	113.0	112.9	112.5	112.7	112.5	112.1	111.8	111.2	111.0	110.7
60	114.6	114.5	114.6	114.6	114.8	114.3	113.7	113.6	113.5	113.1
70	120.9	120.2	119.9	120.1	120.2	119.8	119.4	118.6	118.5	118.2
80	121.3	121.8	121.7	121.5	121.6	121.3	120.2	120.4	119.9	119.6
90	116.2	117.5	117.4	117.2	117.0	116.8	116.0	116.5	116.3	116.0
100	115.8	116.3	116.8	116.6	116.7	116.3	115.3	115.4	115.4	115.3
110	116.5	116.1	115.7	115.3	115.5	115.1	114.6	114.5	114.1	113.9
120	118.3	117.1	117.0	117.0	116.8	116.5	116.9	116.3	115.9	115.9
130	123.6	122.7	122.8	122.9	123.0	122.3	122.0	121.0	120.5	120.2
140	125.3	124.6	124.6	124.7	125.3	124.8	124.7	123.8	123.2	123.0
150	123.5	123.9	124.6	124.4	124.5	123.9	122.4	122.6	121.3	120.6
160	121.5	121.2	121.2	121.3	121.2	121.2	121.0	119.9	119.7	119.2
170	122.5	122.9	122.7	122.6	122.2	121.4	121.3	121.2	120.9	120.3
180	119.9	119.9	119.8	119.8	119.5	119.0	118.8	118.6	118.3	118.0
190	119.7	120.0	120.4	119.6	119.6	119.5	118.4	118.6	117.9	117.9
200	123.1	121.9	122.4	122.3	121.9	120.9	120.8	120.4	119.9	119.6
210	125.8	125.2	125.5	126.1	125.8	124.5	123.9	123.2	122.3	122.1
220	124.9	125.0	125.3	126.4	126.4	125.5	124.3	123.7	122.3	121.9
230	125.2	125.9	125.9	126.7	126.6	126.3	125.3	124.2	123.5	122.7

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test VIc. Without Lens
(All Measurements 30 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	110.0	109.6	109.2	108.7	109.2	108.5	108.5	108.0	107.8	107.7
60	111.4	111.3	111.5	111.6	111.8	111.5	110.9	110.9	110.6	110.1
70	116.3	115.6	115.5	115.8	116.2	115.5	115.3	114.4	114.0	113.7
80	117.9	118.9	119.3	119.4	119.9	119.5	117.9	118.4	117.9	117.4
90	113.0	113.9	114.6	114.4	114.5	114.3	113.1	113.5	113.3	113.0
100	112.9	113.6	113.4	113.2	113.4	113.0	112.5	113.2	113.0	112.7
110	113.6	113.4	113.8	113.7	114.1	113.8	113.5	113.1	113.0	112.9
120	115.4	114.6	114.7	114.8	115.0	114.9	115.4	114.7	114.4	114.2
130	118.8	117.8	118.2	118.6	119.0	118.4	118.3	117.0	116.7	116.2
140	121.2	120.6	120.8	122.1	122.5	122.3	120.9	120.1	119.4	119.1
150	118.9	119.3	121.0	120.3	120.8	120.3	120.0	118.8	118.7	117.7
160	120.0	120.2	120.2	120.4	120.3	120.6	120.1	119.5	119.0	118.8
170	116.2	116.0	116.2	116.4	115.6	114.6	115.2	114.5	114.3	113.4
180	115.5	116.1	116.0	115.9	115.8	114.9	114.3	113.2	112.9	112.6
190	114.1	114.4	114.5	113.6	113.4	113.3	112.4	112.6	111.7	111.9
200	118.5	117.6	118.0	118.2	117.3	116.5	117.1	115.9	115.3	115.4
210	121.2	120.7	120.5	122.2	121.5	120.2	119.1	118.1	117.0	116.4
220	121.7	121.5	122.4	123.9	123.4	123.5	122.8	121.8	121.1	120.8
230	120.8	121.7	121.8	123.6	123.0	122.7	120.7	120.1	118.3	118.2

* All decibel levels are ± 1 decibel reference 0.0002 μ bar.

Test VId. Without Lens
(All Measurements 40 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	110.3	109.0	109.0	108.5	108.6	108.5	109.0	108.2	107.8	107.6
60	110.6	110.6	110.8	110.9	111.1	110.7	110.0	109.8	109.0	108.5
70	115.6	114.9	115.0	115.1	115.1	114.9	114.4	113.7	113.1	112.7
80	116.6	117.7	118.1	118.1	118.4	118.0	116.1	117.1	116.4	115.8
90	114.7	115.8	115.6	115.4	115.5	115.3	114.9	115.5	115.1	115.0
100	112.8	113.5	114.0	113.6	113.5	113.3	111.8	112.5	111.9	111.7
110	112.4	112.5	111.7	112.0	112.0	112.0	112.0	112.4	112.2	112.4
120	115.4	115.1	114.8	115.1	114.9	115.0	114.2	114.6	114.0	113.7
130	118.2	116.6	117.0	117.4	117.7	117.4	117.4	117.1	116.1	115.6
140	120.0	119.2	119.4	119.9	120.5	120.2	119.5	118.6	117.6	117.1
150	119.2	119.0	120.4	120.0	120.2	119.9	119.8	119.4	118.8	118.2
160	118.9	119.3	119.4	119.3	119.3	119.4	118.6	118.8	117.9	117.4
170	116.5	116.6	116.5	116.3	116.4	115.9	115.8	115.6	114.8	114.1
180	115.9	116.5	116.4	116.2	115.4	115.5	114.8	114.8	114.2	113.9
190	113.5	114.0	114.8	113.9	114.1	113.9	113.3	112.8	112.5	112.3
200	117.9	116.1	116.6	116.4	115.8	114.9	115.3	114.8	113.5	113.3
210	121.3	120.8	121.2	121.7	121.5	120.5	120.2	118.8	118.4	118.2
220	120.3	120.9	121.4	122.1	122.0	121.6	121.3	120.4	119.6	119.2
230	121.0	121.0	121.4	122.7	122.7	122.0	121.5	120.5	119.4	119.2

*All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test VIe. Without Lens
(All Measurements 50 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	108.2	107.8	107.8	107.8	107.6	107.3	107.5	106.6	106.4	106.4
60	107.5	107.4	106.9	106.7	106.8	106.5	106.9	106.5	106.1	105.9
70	112.9	112.3	112.2	112.3	112.1	112.0	111.9	111.0	110.3	110.1
80	113.5	114.2	113.9	114.0	114.0	113.7	112.6	112.8	111.9	111.5
90	112.7	113.9	113.8	113.6	113.6	113.5	112.7	113.1	112.7	112.8
100	109.6	110.2	109.6	109.2	109.1	108.8	108.8	108.8	108.3	108.1
110	110.0	109.9	110.5	110.0	109.9	110.0	109.4	108.8	108.3	108.7
120	112.0	111.0	111.3	111.1	111.0	110.9	111.2	110.9	109.9	109.9
130	115.9	115.4	115.5	115.6	115.9	115.7	115.5	115.1	114.4	114.1
140	117.0	115.6	116.0	116.8	117.3	117.0	116.5	115.3	114.5	114.3
150	118.6	119.2	119.7	119.5	119.4	119.6	118.9	118.2	117.6	117.4
160	115.0	114.5	114.7	114.5	114.5	114.6	114.4	114.0	113.1	112.8
170	115.8	116.5	116.0	115.9	115.6	115.5	115.2	114.8	113.6	113.4
180	113.4	113.5	113.3	112.9	112.6	112.5	112.5	112.4	111.7	111.3
190	111.9	111.4	111.9	111.6	112.0	111.8	111.4	110.0	110.0	110.3
200	114.9	113.2	113.7	113.2	112.9	112.1	112.2	111.5	110.5	109.6
210	118.4	118.5	118.5	119.0	118.6	118.1	117.2	116.4	116.0	116.0
220	116.5	117.2	117.7	118.6	118.2	117.0	116.5	115.5	113.9	113.6
230	118.9	119.8	120.0	120.8	120.8	120.2	119.5	119.1	118.1	117.6

*All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test VIf. Without Lens
(All Measurements 80 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	101.8	101.2	101.2	100.7	100.6	100.2	100.8	100.0	99.8	99.4
60	103.5	103.3	103.2	103.5	103.4	103.2	103.3	102.9	102.7	102.4
70	108.3	107.6	107.5	107.7	107.8	107.7	107.9	107.0	106.6	106.5
80	110.4	110.6	110.3	110.3	110.3	110.6	110.3	110.3	109.9	109.8
90	108.7	109.6	109.5	109.5	109.5	109.1	108.6	109.3	109.0	108.8
100	103.8	104.5	104.8	104.5	104.4	104.4	104.0	104.0	103.9	103.9
110	106.9	106.8	106.6	106.5	106.8	106.6	106.7	106.7	106.1	106.5
120	108.8	108.5	108.7	108.8	108.9	109.0	109.0	108.4	108.0	108.2
130	110.9	109.7	109.8	109.8	110.2	110.0	110.1	109.9	109.2	108.9
140	112.4	111.8	111.8	112.1	112.2	112.2	112.1	111.6	111.1	110.9
150	110.6	110.9	111.4	111.3	111.7	111.3	110.5	110.7	109.8	109.1
160	112.0	111.3	111.1	111.5	111.3	111.9	112.3	111.6	111.0	111.1
170	110.2	111.0	110.6	110.6	110.2	110.4	110.1	110.2	109.1	109.1
180	107.9	107.2	107.4	107.0	107.1	106.6	106.5	106.7	105.9	105.4
190	107.0	106.8	107.1	106.5	106.3	106.4	106.0	105.9	105.1	104.2
200	109.8	107.9	108.7	108.6	108.5	107.9	108.5	107.5	107.4	107.2
210	112.1	111.6	111.4	112.0	112.0	111.7	111.5	109.9	109.0	109.2
220	112.7	112.8	113.2	113.7	114.0	114.1	113.6	112.8	112.3	112.1
230	110.0	111.0	111.3	112.2	112.3	112.0	111.2	110.9	109.5	109.0

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test VIg. Without Lens
(All Measurements 100 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	100.0	99.9	99.2	98.4	98.6	98.4	98.8	97.9	97.3	97.4
60	102.0	101.4	101.2	101.5	101.6	101.4	101.9	101.2	100.8	100.6
70	106.9	106.3	106.0	105.9	106.2	106.5	106.8	106.1	105.6	105.5
80	108.3	108.6	108.8	108.8	109.0	109.3	108.6	108.8	107.9	108.0
90	105.9	106.7	106.5	106.4	106.3	106.2	105.6	105.8	105.5	105.8
100	101.9	102.6	102.9	102.7	102.5	102.8	102.4	102.1	101.9	102.5
110	104.5	104.2	104.3	104.6	104.2	104.6	103.9	104.1	103.9	103.9
120	105.4	104.6	104.8	105.0	105.1	105.0	105.8	105.0	104.5	104.5
130	108.6	108.1	108.5	108.5	108.7	109.0	108.3	107.2	106.7	106.6
140	110.1	109.5	109.8	110.0	110.8	111.0	110.8	109.7	109.3	109.3
150	106.5	106.9	107.5	108.3	109.5	108.6	107.8	106.8	105.0	105.5
160	110.9	110.6	110.5	110.3	110.6	111.0	111.0	110.3	110.2	110.1
170	107.7	107.9	107.3	107.6	107.6	107.5	108.0	106.9	106.2	106.4
180	106.0	106.5	106.4	106.2	106.3	105.8	105.6	105.3	104.6	104.5
190	104.5	104.5	104.8	104.2	104.5	104.5	104.1	103.8	102.9	103.0
200	107.5	106.4	106.5	106.6	106.8	106.1	106.1	105.1	104.8	105.1
210	110.4	110.3	110.3	111.0	111.0	110.8	110.1	108.6	108.0	108.1
220	109.8	110.1	110.2	110.5	112.0	111.3	111.1	110.9	110.0	109.8
230	109.0	109.0	109.1	110.6	111.2	109.2	109.1	108.0	106.9	1061.5

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test XIIa. With Lens
(All Measurements 10 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	118.5	116.3	115.3	114.5	116.2	116.6	116.2	115.0	114.6	114.0
60	121.0	120.2	119.9	117.9	120.2	120.3	120.2	119.0	118.0	117.0
70	125.2	125.0	125.0	122.3	124.0	124.3	123.5	122.2	121.3	120.9
80	125.6	126.5	125.9	124.5	126.1	126.6	126.0	125.5	124.1	123.4
90	120.0	120.3	119.8	119.5	120.0	119.8	120.0	119.3	119.0	118.2
100	118.2	117.0	117.5	118.6	120.2	120.0	119.8	118.5	118.0	118.4
110	120.1	116.3	119.9	120.2	121.5	120.1	121.2	120.0	120.2	119.3
120	124.5	123.1	123.7	123.5	125.1	125.4	125.5	125.2	123.8	122.7
130	128.6	127.3	128.3	127.8	128.8	128.8	128.0	127.0	126.7	125.3
140	130.3	130.0	130.1	127.9	129.2	130.5	129.2	128.7	127.1	126.1
150	128.0	129.0	128.5	127.8	130.0	129.5	128.1	127.0	126.3	124.5
160	125.5	125.1	124.0	123.9	126.1	126.5	125.5	124.6	123.7	123.7
170	124.8	123.5	123.9	124.8	127.0	127.4	126.3	125.3	124.8	125.0
180	123.9	123.1	124.5	125.0	125.9	126.1	125.2	124.4	123.7	122.9
190	124.3	124.4	124.7	122.7	125.1	126.4	124.9	122.1	123.2	122.8
200	128.0	128.0	126.1	126.1	127.7	128.6	127.2	125.6	125.3	125.6
210	131.0	130.2	129.9	128.4	131.0	130.9	129.8	129.2	127.7	127.3
220	131.5	130.8	130.8	130.5	131.5	132.2	131.3	129.4	129.8	127.8
230	131.6	129.8	131.0	131.1	131.8	132.2	131.9	130.6	129.9	129.3

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test XIIb. With Lens
(All Measurements 20 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	115.9	112.0	110.0	110.5	110.9	110.7	110.0	110.5	109.9	109.3
60	118.2	115.0	112.7	113.1	114.0	114.0	113.4	113.8	114.0	112.6
70	123.4	119.9	117.3	118.3	118.6	118.7	118.3	118.2	117.0	117.7
80	124.0	121.5	119.8	120.0	121.9	121.6	121.1	120.4	119.4	119.3
90	118.5	117.4	116.7	116.1	116.5	116.3	116.0	116.8	116.1	115.0
100	117.0	115.1	114.0	114.1	113.6	112.9	112.9	114.4	113.6	112.3
110	120.2	117.2	114.5	114.5	115.1	113.8	113.6	115.9	113.9	113.7
120	123.7	120.2	117.5	116.7	117.5	117.3	116.4	117.6	117.0	114.3
130	126.8	122.7	120.7	121.9	122.6	122.5	122.4	121.5	121.8	121.8
140	128.1	125.0	122.5	124.0	125.0	125.1	124.6	124.3	123.3	124.0
150	128.6	124.5	121.9	123.4	125.3	124.4	123.4	123.8	123.6	122.3
160	125.5	121.8	119.5	119.9	121.6	120.9	120.5	118.8	119.2	117.5
170	126.0	121.3	119.1	121.1	122.2	121.0	120.7	120.6	119.4	120.4
180	125.4	120.8	116.5	118.2	120.8	121.1	120.8	120.3	119.1	118.8
190	125.4	121.1	117.2	118.1	120.6	121.0	120.5	119.2	118.3	119.0
200	128.8	123.5	119.8	121.5	123.5	123.1	122.2	121.6	119.8	121.3
210	129.0	125.8	123.2	124.6	125.6	124.8	124.1	123.8	122.7	123.5
220	129.9	126.8	123.9	124.8	125.8	124.9	123.9	123.8	122.9	122.3
230	130.5	136.9	123.6	124.1	125.9	125.0	123.5	124.2	123.4	123.0

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test XIIc. With Lens
(All Measurements 30 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	114.8	109.2	107.3	107.2	107.4	107.1	108.1	105.9	107.3	105.5
60	118.1	111.8	109.1	109.9	111.3	111.0	110.8	110.2	108.1	108.5
70	123.5	116.8	114.8	114.9	115.8	116.1	116.0	113.8	114.4	112.5
80	123.9	118.9	116.0	116.9	119.1	118.9	117.6	116.3	116.4	115.9
90	116.4	115.0	114.0	114.0	113.9	112.5	113.4	112.2	111.3	114.2
100	114.5	113.2	112.8	112.0	110.2	109.2	110.5	110.8	110.0	109.9
110	118.4	114.1	112.4	112.3	111.8	111.7	112.2	110.4	111.0	111.4
120	123.7	117.1	114.6	114.7	115.7	115.5	114.0	114.3	112.2	112.5
130	127.0	120.9	117.5	117.0	120.0	119.4	118.4	118.3	117.9	116.5
140	128.3	122.1	119.5	120.5	121.6	121.7	121.9	119.7	119.3	117.9
150	128.0	122.0	118.8	120.6	121.9	121.0	121.2	118.3	120.0	117.0
160	125.9	119.1	116.0	117.1	118.2	119.0	117.6	117.5	115.8	114.4
170	125.1	118.1	116.1	115.9	118.6	119.7	118.3	117.9	116.8	117.0
180	124.5	117.1	113.7	114.8	116.7	117.6	116.8	115.4	113.2	113.8
190	123.8	116.6	114.0	114.4	116.2	117.8	117.0	115.0	115.7	113.2
200	128.7	117.8	116.3	117.3	118.3	120.2	117.9	116.6	116.6	114.1
210	130.2	120.2	118.6	121.0	122.2	122.5	121.3	120.2	119.0	118.0
220	131.0	122.0	119.0	121.9	124.3	124.0	122.4	119.8	119.0	117.5
230	131.2	122.8	119.4	121.4	123.9	123.9	122.2	119.6	119.0	120.2

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test XIId. With Lens
(All Measurements 40 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	113.6	108.3	106.5	105.9	106.0	105.9	106.1	105.5	106.2	104.6
60	117.1	110.3	108.2	108.5	109.3	109.1	108.7	108.5	108.3	106.3
70	121.4	115.6	113.3	113.4	114.0	114.2	114.2	112.3	112.8	110.0
80	121.9	118.0	114.9	115.5	117.6	117.3	115.5	114.0	114.2	113.8
90	115.9	113.6	112.5	112.6	112.5	112.2	112.4	110.8	109.6	108.1
100	113.3	112.3	111.8	110.5	109.3	108.2	110.0	110.0	109.2	109.1
110	117.4	113.5	112.1	111.1	110.9	109.8	110.3	109.0	108.6	109.3
120	121.9	116.0	113.3	114.1	113.9	113.8	113.2	113.3	110.8	110.6
130	125.0	119.2	116.5	115.3	118.0	117.4	117.2	117.2	114.9	115.4
140	125.4	120.9	118.5	118.6	119.5	119.6	120.0	118.4	116.1	114.9
150	125.0	121.1	117.6	119.3	120.1	119.0	119.1	117.1	118.1	115.0
160	124.1	118.8	115.9	115.9	116.3	117.1	117.9	116.1	114.2	112.0
170	123.6	117.6	115.8	114.3	115.8	116.8	115.5	114.9	113.8	113.9
180	122.4	116.8	113.6	113.7	114.2	115.3	114.9	113.9	111.9	112.2
190	121.2	116.6	112.8	113.0	114.3	115.4	115.0	114.1	114.3	112.0
200	125.7	117.0	115.8	115.2	116.3	118.1	116.9	114.8	114.5	112.8
210	128.8	119.0	117.0	118.0	118.8	120.1	119.5	118.3	117.5	116.1
220	128.9	121.1	117.5	119.9	122.0	121.9	120.3	117.1	116.3	115.5
230	129.1	120.7	117.9	119.5	121.9	121.8	120.4	118.1	117.5	117.6

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test XIIe. With Lens
(All Measurements 50 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	112.5	107.5	106.0	104.9	104.3	104.7	104.0	104.1	103.4	103.9
60	115.9	109.5	107.1	107.1	107.4	107.6	106.7	106.2	103.8	103.3
70	118.8	114.2	113.3	112.0	112.5	112.9	111.5	111.7	108.1	107.7
80	121.0	117.5	114.7	114.3	116.0	114.6	114.3	113.7	113.1	110.9
90	114.8	112.8	112.6	112.5	110.8	111.9	109.5	108.7	110.0	107.8
100	112.4	111.8	111.7	109.0	108.3	107.1	108.8	107.4	107.8	106.8
110	116.5	112.7	111.2	109.2	110.0	110.2	108.0	107.1	107.2	110.1
120	120.8	115.2	112.7	113.5	112.5	111.6	112.4	111.9	108.2	107.2
130	123.0	118.0	115.4	113.3	116.4	115.2	115.1	113.5	112.6	114.5
140	123.9	119.3	117.4	117.0	117.9	118.3	115.9	116.0	113.4	112.6
150	123.2	119.0	116.5	118.0	118.3	118.3	116.0	116.2	114.7	115.4
160	122.0	118.5	115.8	114.5	116.5	114.6	115.5	114.0	112.7	111.2
170	121.4	117.1	115.6	111.1	114.9	115.2	115.8	113.6	113.0	111.6
180	120.5	115.9	113.5	112.6	112.5	115.1	111.2	111.6	109.1	108.3
190	119.8	116.4	111.7	110.8	113.3	114.5	111.7	111.8	110.6	110.0
200	123.8	116.4	115.3	113.3	115.1	115.0	114.2	113.9	110.0	109.1
210	125.5	118.4	115.1	117.3	118.2	118.6	117.7	115.9	113.4	112.8
220	126.1	120.0	116.1	117.4	120.2	119.6	118.0	116.2	113.9	112.8
230	126.9	118.9	116.7	118.2	120.4	120.3	117.9	117.9	115.2	111.9

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test XIIf. With Lens
(All Measurements 80 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	109.9	105.8	105.4	105.0	103.7	104.7	104.1	104.5	104.0	105.0
60	113.0	107.2	106.6	105.9	105.6	105.9	105.8	106.0	104.7	105.5
70	117.7	111.8	110.1	108.0	108.8	108.3	108.3	109.0	107.5	107.8
80	118.0	115.0	111.5	111.4	112.0	111.4	110.3	111.8	110.5	109.4
90	111.5	110.0	109.8	109.0	109.2	108.0	106.6	108.5	106.5	106.9
100	110.3	109.5	109.2	106.4	106.2	107.5	105.4	106.6	106.5	104.8
110	113.1	110.9	108.8	106.8	107.0	107.9	105.5	107.5	107.2	106.8
120	117.9	112.2	110.9	110.4	109.8	109.5	108.8	109.4	108.6	108.1
130	121.1	115.4	111.7	110.5	111.8	111.3	110.7	110.8	109.9	111.5
140	122.5	116.7	114.2	112.3	114.8	113.9	113.2	113.2	112.4	110.5
150	120.5	115.7	114.0	113.1	113.3	114.5	112.9	112.0	111.9	113.9
160	118.8	115.8	110.9	111.5	112.1	112.4	110.7	111.5	110.5	109.8
170	117.7	114.0	112.6	109.3	111.8	109.8	112.3	110.5	109.7	110.6
180	117.5	112.1	110.5	108.5	110.4	109.3	109.9	109.7	108.1	107.0
190	117.0	113.5	109.1	108.9	107.9	110.2	110.2	109.0	108.4	110.0
200	122.0	114.5	112.5	107.8	111.0	111.9	109.2	110.0	109.3	107.5
210	123.3	115.8	112.6	111.9	114.2	113.2	112.7	112.8	111.1	110.7
220	124.3	118.1	114.0	112.7	114.8	114.9	114.4	114.4	111.5	110.6
230	124.4	117.0	114.3	112.8	116.0	117.0	114.5	115.2	112.4	110.9

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

Test XIIg. With Lens
(All Measurements 100 Feet From Source)*

Hz	Angle in degrees from zero-degree line									
	0	10	20	30	40	50	60	70	80	90
50	106.5	102.5	100.9	99.0	98.1	99.4	97.2	99.1	98.5	99.1
60	111.5	104.5	102.2	100.6	101.0	101.5	101.5	100.0	99.7	99.4
70	115.8	109.5	107.0	103.5	105.5	105.3	106.2	105.0	103.8	103.1
80	116.0	112.3	109.0	108.2	108.8	108.8	107.5	108.7	107.1	106.1
90	109.1	107.6	106.4	105.1	105.8	103.6	103.3	105.5	101.7	102.5
100	107.3	106.2	105.0	102.3	101.2	104.1	100.4	101.9	103.3	101.7
110	111.0	108.1	105.5	103.3	103.3	103.5	102.5	103.3	103.6	103.3
120	116.0	110.0	107.8	106.8	106.8	107.1	105.7	105.2	103.8	104.6
130	119.2	112.8	110.0	108.3	109.2	108.4	107.0	107.8	106.9	106.9
140	121.0	114.8	112.1	108.5	112.1	112.0	111.8	110.5	108.3	108.0
150	118.6	113.5	112.3	110.4	110.0	111.5	109.5	110.2	109.3	110.5
160	111.0	113.3	108.1	109.3	108.3	109.6	108.2	109.0	108.0	105.3
170	115.3	112.2	110.0	104.9	108.5	106.6	108.9	108.2	104.[illegible]	108.1
180	115.5	110.3	107.7	106.3	106.9	105.8	107.8	105.9	104.2	103.3
190	11[illegible].2	110.9	106.0	105.8	102.4	107.1	106.9	106.0	106.3	106.5
200	119.6	112.0	109.6	106.2	107.7	109.0	106.8	106.3	105.5	105.0
210	121.3	113.9	110.5	109.2	111.1	111.7	109.9	110.8	108.8	108.3
220	122.3	115.8	111.7	110.5	112.3	113.4	111.0	111.7	108.7	109.0
230	123.2	115.6	112.3	110.4	112.7	114.1	112.0	112.2	109.1	108.9

* All decibel levels are ±1 decibel reference 0.0002 μ bar.

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13. ABSTRACT

This report describes a research program on sound propagation conducted under the In-house Laboratory Independent Research program. The objective of this work was to develop a concept to transmit high-intensity, low-frequency sound over a distance without large losses of sound-pressure level. An arbitrary goal of reducing the normal inverse square propagation law by 50 percent was chosen and achieved in the regions tested. A hyperbolic lens and hemispherical reflector were developed and tested for directivity improvement.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Sound						
Acoustic						
Sound Propagation						
Sound Transmission						
Low-Frequency Sound						
High-Intensity Sound						
Acoustic Lens						
Acoustic Reflector						