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A METHOD FOR REDUCING GROUND REFLECTION EFFECTS FROM ACOUSTIC MEASUREMENTS

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16. Abstract

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SUMMARY

The method involved placing foam blocks on the ground between sound source and receiver in an approximation of the wedges in an anechoic chamber. The tests were performed out-of-doors as a function of the receiver height and source-receiver separation distance. The spacing between blocks and the extent of ground covered were varied to estimate the optimum placement and minimum amount of foam treatment needed. Base-line tests without foam were also performed. It was found that the foam treatment reduced the amplitude of the peaks and valleys in the sound pressure spectra substantially. The foam was least effective at low frequency, especially for the low receiver height and for large source-receiver distances. Results from the base-line tests were compared with theoretically predicted results. These base-line test results were in reasonable agreement with those from theory.

INTRODUCTION

The measurement of far-field noise from outdoor test rigs can be complicated by several factors, one being ground reflection. With ground-reflection measured spectra show a series of maxima and minima at those frequencies where the reflected wave reinforces or cancels the direct wave, respectively. This phenomenon has been studied rather extensively in the past, for example, in references 1 to 3. For a point sound source and a hard reflecting surface the methods of ray acoustics predict these interference patterns adequately and enable correction of the measured spectra.

For other conditions such as a distributed sound source, the prediction becomes more difficult, and thus the correction of the data also. Atmospheric conditions, particularly thermal and air velocity variations, can lead to errors in accounting for ground reflections. Often the reflecting surface is partially absorbing and in this case, the practice is generally to perform a site calibration to determine the interference patterns (refs. 2 and 4).

An alternate and more direct approach to the ground reflection problem is to try to eliminate the effect. The present paper describes the results of an attempt to eliminate ground reflections through the use of absorbing surfaces placed to intercept and absorb the sound that would otherwise be reflected. The technique consisted of placing rectangular blocks of polyurethane ether foam on the ground surface between the sound source and receiver in an approximation to the wedges of an anechoic chamber. A similar concurrent experiment that used this approach has recently been reported in reference 5.

The polyurethane ether foam has been effectively used for sound absorption previously (refs. 4, 6, and 7). The transverse and longitudinal ground coverage and the spacing between the blocks were varied. The sound source, an electro-pneumatic driver and exponential horn, generated a broadband noise sound field. This source was placed at a fixed height above the ground. Its sound field was surveyed at three microphone heights as a function of distance from the source.

Experiments without the foam provided base-line data to demonstrate the effect of the foam. Data from the base-line tests are compared with theoretically predicted ground reflection effects calculated from the relations in reference 2. A series of experiments were also performed to determine the minimum area of ground treatment required to attenuate the reflected wave and eliminate ground reflection.

SYMBOLS

A_e	excess attenuation of sound diffracted around a barrier
C	speed of sound
f_c	frequency of wave cancellation
h_F	height of foam
h_R	height of receiver
h_S	height of source
L	horizontal source-receiver separation distance
n	integer
Q	fraction of foam barrier height exposed to direct noise from source (see eq. (10))
r	direct-wave path length from source to receiver
r_R	reflected-wave path length from source to receiver
Δr	difference in path length between direct and reflected waves

X axial coordinate between source and receiver

X_n distance from source to n^{th} row of foam panels

X_R distance from source to point of reflection

Y transverse coordinate of foam panels

θ turning angle around foam barrier required for diffracted sound to reach microphone

λ wavelength of sound

APPARATUS AND PROCEDURE

In order to study the ground reflection phenomena, the behavior of the sound spectra must be examined as a function of the distance separating source and receiver and as a function of the heights of the source and receiver. The tests described in this report were performed out-of-doors over a flat concrete surface that was highly reflective. The noise source was an electropneumatic driver producing high intensity broad-band sound.

Test Site

A plan view of the test site (fig. 1) shows the noise source and the locus of microphone positions studied. These positions are tabulated in table I as a function of distance from the mast supporting the source. The microphone positions are logarithmically spaced to give a 1-decibel decrement between successive positions for a spherically spreading sound wave.

The noise source was mounted on a platform at an elevation of 4.95 meters above the ground surface (fig. 2). The microphone survey line was located at an azimuthal angle of 45° from the axis of the source horn. Geometric considerations show the choice of 45° reduces the initial difference in sound intensity between the direct wave and the wave that reflects due to the source directivity pattern.

The microphones were mounted on a movable mast (fig. 3). Three fixed microphones heights were used to permit simultaneous measurements for three acoustic path lengths. The microphone heights were 4.95, 3.30, and 1.65 meters. A fourth microphone shown in figure 1 was located at a fixed position and was used to monitor the noise output of the source and to permit repetition of a given source output.

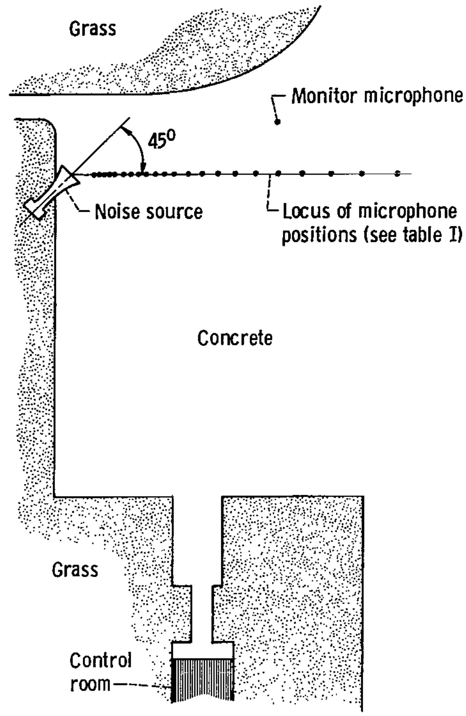


Figure 1. - Plan view of test site.

TABLE I. - MICROPHONE LOCATIONS

Microphone position number	Source-receiver separation distance, L m	Microphone position number	Source-receiver separation distance, L m
1	48.31	14	10.81
2	43.05	15	9.64
3	38.37	16	8.59
4	34.20	17	7.66
5	30.48	18	6.82
6	27.16	19	6.08
7	24.21	20	5.42
8	21.58	21	4.83
9	19.23	22	4.31
10	17.14	23	3.84
		24	3.42
11	15.28	25	3.05
12	13.61		
13	12.13		

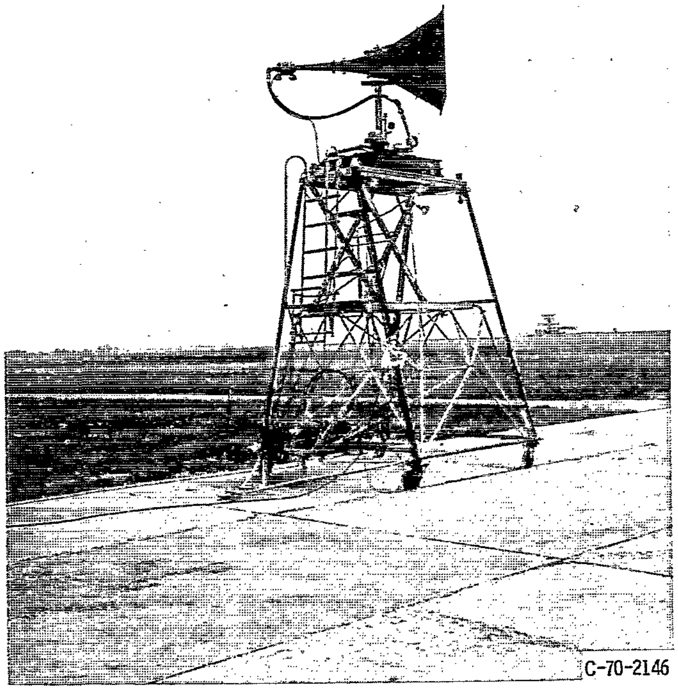


Figure 2. - Noise source mounted on platform.

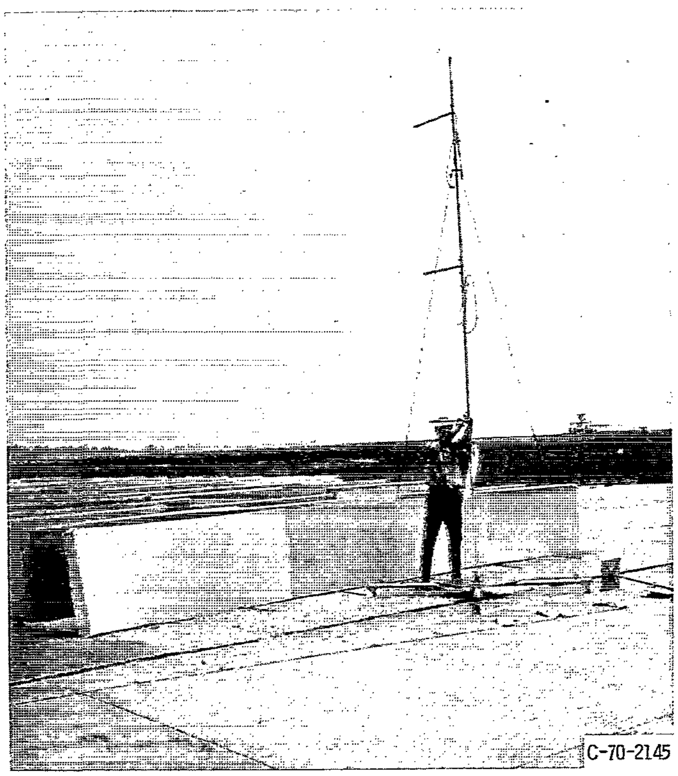


Figure 3. - Microphones mounted on movable mast.

Noise Source

The noise source used was an electropneumatic driver coupled to an exponential horn 1.83 meters long terminating in a square cross section of one meter on a side. The unit had a low-frequency cutoff of 100 hertz and was capable of generating 4000 watts of acoustic power. Band-limited white noise was applied to the driver for the ground-reflection studies. Preliminary testing indicated that this input signal would produce sufficient acoustic output above the background to 10 000 hertz.

Some measurements of the source directivity were performed using the test setup described in reference 4. The microphones were on a 30.5-meter radius and were located every 10°. The source and receiver heights were 5.8 meters. Figure 4 shows results for the overall sound pressure level and for several one-third octave band center frequencies. The data are normalized by the values measured on the source axis. It can be seen that the levels diminish away from the source axis and that the amount of the decrease increases with increasing frequency.

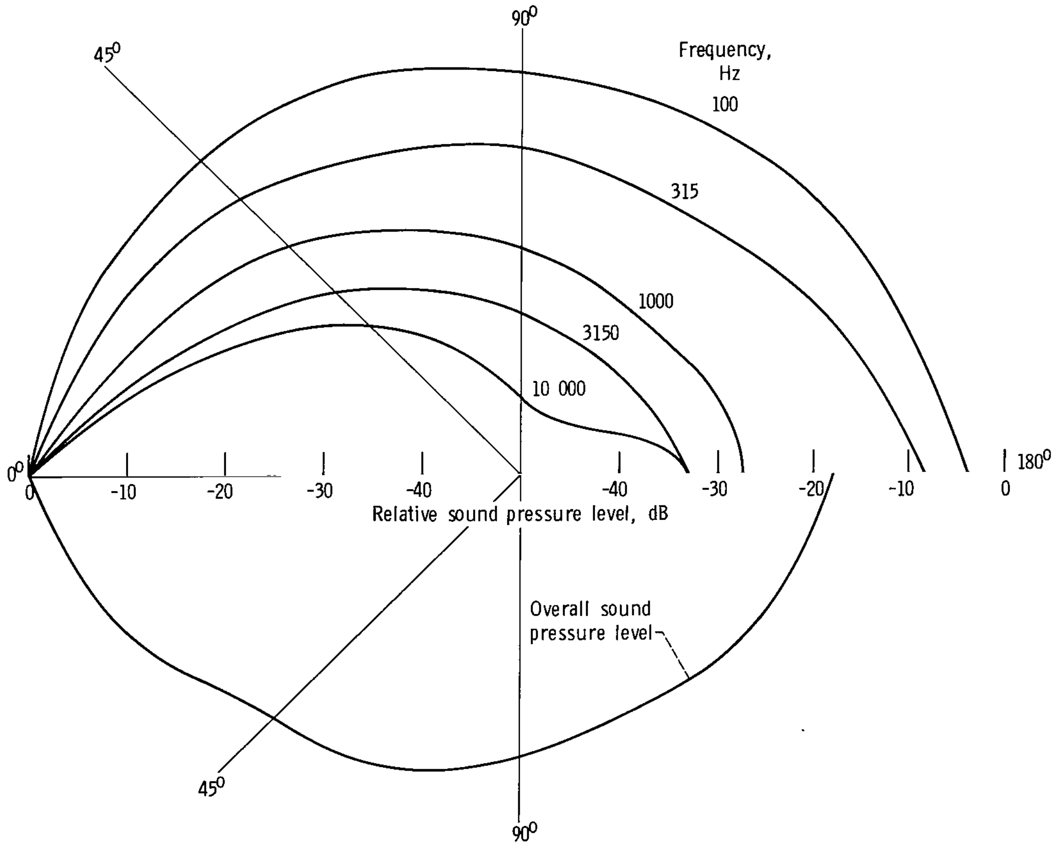


Figure 4. - Source directivity.

Anechoic Ground Treatment

The main objective of this study was to evaluate a method of eliminating ground reflections. The method consisted of placing "fences" of sound absorbing material in a manner to intercept and absorb sound radiation that otherwise would reflect from the hard ground plane. The absorbing material used was open cell polyurethane ether foam. Blocks of this foam were placed between the sound source and receiver as shown in figure 5. The blocks were 0.91 meter high and 0.15 meter thick and 2.44 meters long.

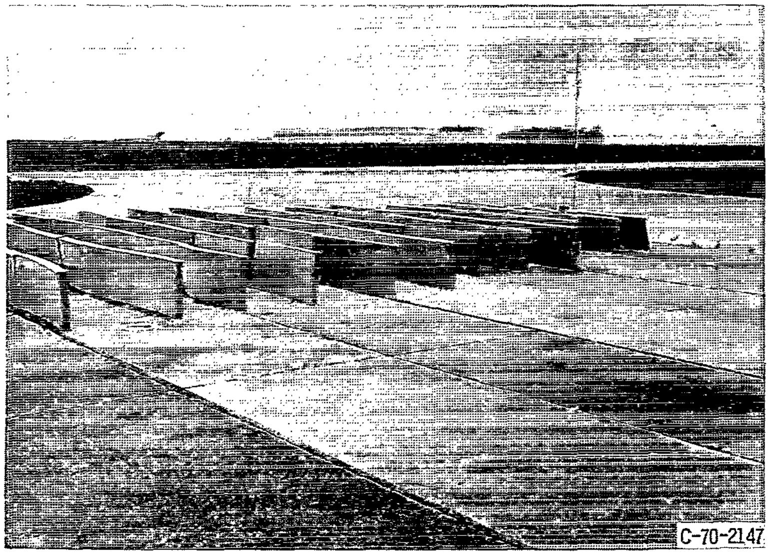
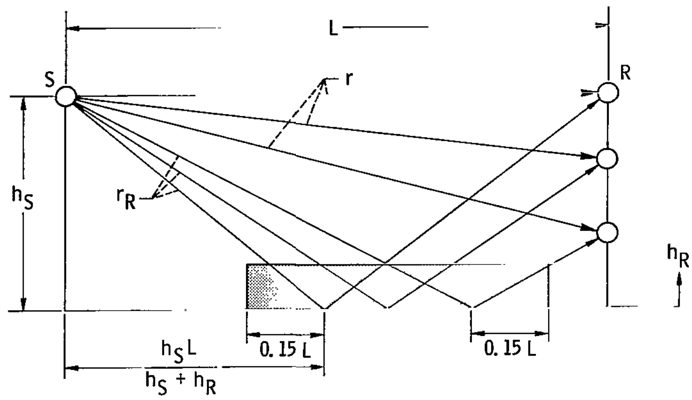


Figure 5. - Blocks of foam placed between sound source and receiver.

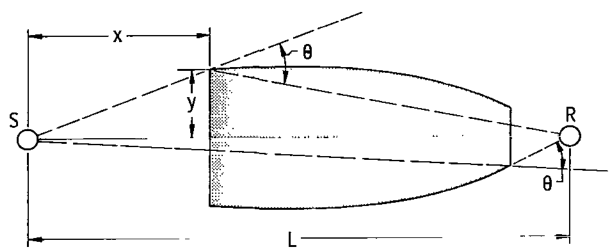
Some criterion had to be used to define the area of the ground plane requiring treatment. This was established basically by a ray acoustic approach. From ray acoustics, the theoretical point of reflection occurs at a distance from the source given by

$$X_R = \frac{h_S L}{h_S + h_R} \qquad (1)$$

Since ray acoustics only approximately applies in the actual case (there are extended wave fronts and the reflector has some diffuse properties), it was decided to cover an extended axial distance about the theoretical point of reflection X_R. This arrangement is shown in figure 6(a). It is seen that the axial coverage toward the source is determined by the highest microphone position and that toward the receiver by the lowest microphone position.



(a) Elevation.



(b) Plan view.

Figure 6. - Typical area coverage for ground treatment.

Some lateral coverage is also required because of the ability of sound to diffract around obstacles. This coverage is assumed to eliminate the effects of the diffuse properties of the ground reflection. Data presented in reference 8 show the amount of excess attenuation of sound diffracted around a barrier as a function of the sound wavelength, the barrier height, and the distance of the barrier from the source. The excess attenuation can be approximated by

$$A_e = 10 \log \frac{Y^2}{\lambda X} + 10 \tag{2}$$

The geometry applicable to equation (2) is shown in figure 6(b). The distance Y must be sufficient to reduce the sound diffracting around the barrier and reaching the receiver.

The lateral distance to be treated with foam was determined by

$$Y = \frac{-L}{2 \tan \theta} + \left[\left(\frac{L}{2 \tan \theta}\right)^2 + X(L - X)\right]^{1/2} \tag{3}$$

A constant turning angle ($\theta = 30^{\circ}$) around the edge of the foam was used for all values of X. If the excess attenuation is 5 decibels or more the diffracted sound will add only 1.2 decibels to the signal of the direct wave. For X = 15.24 meters, L = 30.5 meters, and a turning angle $\theta = 30^{\circ}$, equation (2) yields 5 decibels at 100 hertz. The attenuation would be greater for higher frequencies.

The present experiment is not an exact duplicate of the experiments that led to equation (2); however, equation (2) gave the best estimate available of the required lateral coverage.

It should be noted that the lateral coverage indicated by equation (3) was only roughly followed. Blocks of foam 2.44 meters long were added when necessary to eliminate the need for cutting the foam. The lateral half-width Y was, therefore, matched within ±0.61 meter.

Two spacing distances between successive rows of foam were tested in these experiments. These spacings were 1.52 and 0.91 meter. The spacing and the height of the foam are perhaps related to the low-frequency effectiveness of the treatment. In the usual anechoic chamber, wedges of 0.91-meter height would provide a lower cutoff frequency of about 100 hertz (ref. 9). The present configuration is not an accurate replica of the closely spaced wedges in an anechoic chamber; however, 100 hertz can be assumed to be a rough estimate of the lower cutoff frequency of the treatment.

Acoustic Measurements

The microphones were omnidirectional and had a normal incidence free-field frequency response that was flat to within 1 decibel over the frequency range 20 hertz to 20 kilohertz. For calibration, a 124-decibel 250-hertz pistonphone was used.

All microphone signals were recorded onto a FM magnetic tape recorder at 152 centimeter per second (60 in./sec) tape speed. A 1-minute sample of data was recorded at each testing condition.

The magnetic tape was played back through a narrow-band spectrum analyzer with a dynamic range of 50 decibels. Two frequency analysis ranges - 0 to 1 kilohertz and 0 to 5 kilohertz - were used in the analysis. One-hundred-twenty-eight samples were taken on the lower frequency range; 256 samples were taken on the upper range. The noise bandwidth of the analyzer was constant over each of the analysis ranges, with a value of 3.2 hertz on the 0 - 1000-hertz range and 16 hertz on the 0 to 5000-hertz range.

A one-third octave band analysis of the data was also obtained. Three samples were obtained from each microphone. The averaging time for each sample was approximately 1 second. Mean sound pressure level spectra were established by averaging the three recorded samples for each microphone at each position. Atmospheric absorption was computed from the meteorological conditions on the test day, following the procedures given in reference 10. The data were then corrected to standard day conditions (15° C, 70 percent relative humidity). A correction for source directivity was also applied as discussed in the following section.

Correction of One-Third Octave Spectra for Source Directivity

The horizontal horn axis was oriented at an azimuth angle of 45° relative to the microphone survey line. The only sound radiated at an angle of 45° to the horn axis and along the microphone survey line is that sound propagating directly to the microphone positioned at an elevation equal to that of the horn. The reflected wave will always be radiated at an angle relative to the horn axis that is greater than 45°, even when the source and receiver are at the same elevation. At small source-receiver distances, the difference between the two angles of direct and reflected waves can be quite large. For example, at a separation of 3.05 meters and equal source and receiver heights of 4.95 meters, the angle of the direct radiation is 45°, and the angle of the reflected radiation is 78°. At receiver heights less than the source height, both waves are radiated at angles greater than 45°. For example, at a separation of 3.05 meters, a source height of 4.95 meters, and a receiver height of 3.30 meters, the direct wave is radiated at an angle of 52° to the horn axis, and the reflected wave is radiated at an angle of 76°. At large source-receiver distances, both the direct and reflected wave are radiated at an angle that approaches 45° for all receiver heights used.

The source directivity was shown in figure 4. It can be seen from this figure that even small changes in the angle of radiation above 45° will make a significant difference in the signal strength, particularly at higher frequencies. All practical sources would have some degree of assymmetry as in the present case.

To account for the reduction in sound pressure level produced by radiation at angles exceeding 45° the one-third octave data can be corrected to an angle of 45°. This correction was based on the angle of the direct wave only. Thus, the data at the highest receiver height need no correction, and the correction was applied only to data for the lower two receiver heights. The maximum correction amounted to 4.3 decibel. This correction does not affect the comparison of the foam tests to the base-line tests since only relative effects are examined.

RESULTS AND DISCUSSION

The discussion of results is organized to show (1) the results of base-line tests without foam treatment and their comparison with simple theory, (2) the results with foam treatment and their comparison with base-line results, and (3) a comparison of the base-line results with the theory of reference 2. Because of the amount of data obtained, most of the data are presented in figures 15 to 22 bound at the back of the report.

Base Line Tests

The signal produced by the source may be approximated by data obtained by the highest microphone at the shortest source-receiver distance. At this location, the reflected wave travels the longest distance relative to the direct wave and is thus attenuated the greatest amount (7.6 dB more than the direct wave) due to spherical spreading. Figure 7 shows a narrow-band (3.2-Hz bandwidth) spectrum at this location. The fall-off in

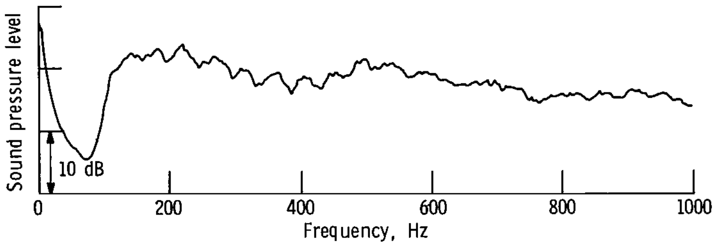


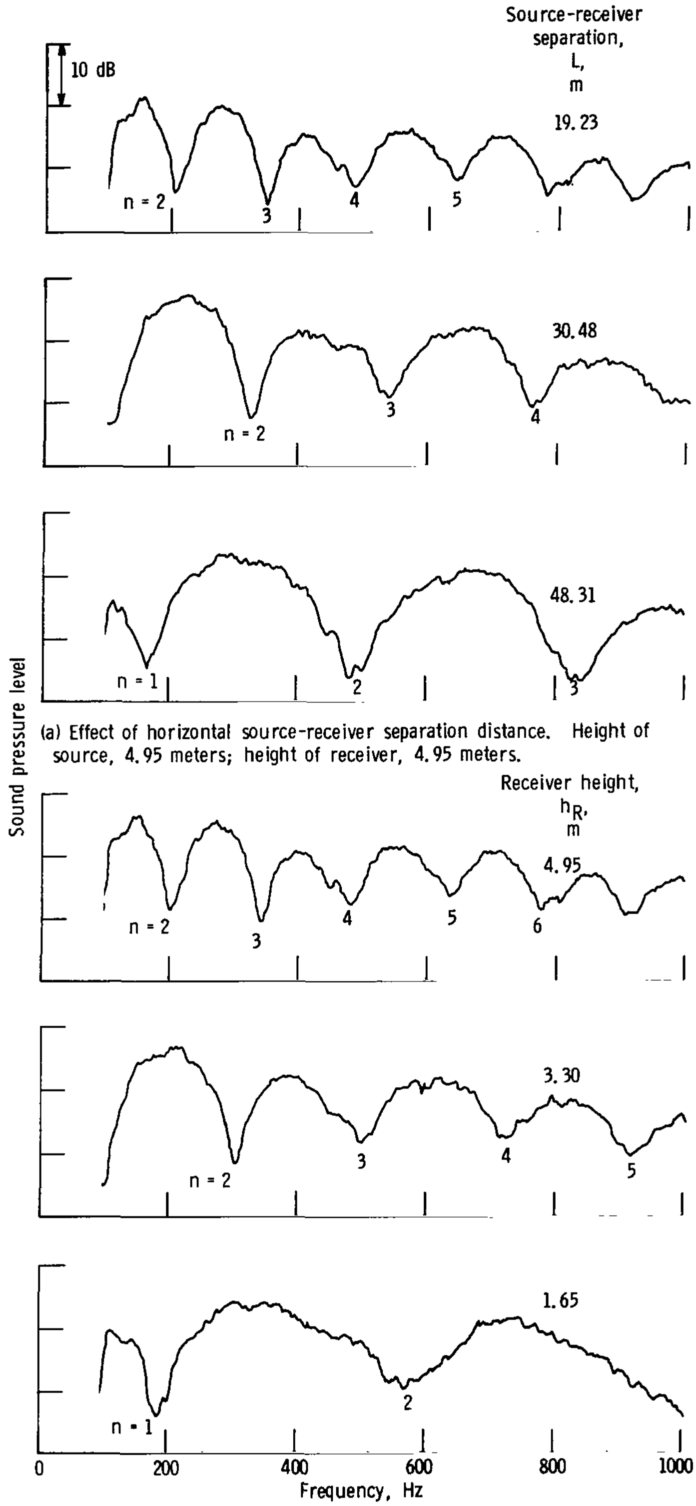
Figure 7. - Narrow-band spectra at closest source-receiver separation. Bandwidth, 3.2 hertz; height of source, 4.95 meters; height of receiver, 4.95 meters; horizontal source-receiver separation distance, 3.05 meters.

the spectrum near 100 hertz is caused by the low-frequency cutoff of the horn. All the plots are therefore terminated at 100 hertz. Some evidence of ground reflection is seen in figure 7 where small peaks and valleys are observed below about 500 hertz.

Strong ground reflection is seen in figure 8 where narrow-band (3.2-Hz bandwidth) spectra are shown at much larger source-receiver separations. Peak to valley fluctuations of over 20 decibels are observed in these data. The spectra in figure 8(a) are shown as a function of source-receiver separation for equal source and receiver heights. Those in figure 8(b) are shown as a function of receiver height for constant source height and source-receiver separation. These results can be interpreted through reference to relationships derived from ray acoustics that predict the frequencies at which the direct and reflected waves will reinforce or cancel each other.

The difference in path length between the direct and reflected waves is

$$\Delta r = r_R - r = \left[(h_S + h_R)^2 + L^2\right]^{1/2} - \left[(h_S - h_R)^2 + L^2\right]^{1/2} \tag{4}$$



(a) Effect of horizontal source-receiver separation distance. Height of source, 4.95 meters; height of receiver, 4.95 meters.

(b) Effect of receiver height. Height of source, 4.95 meters; source-receiver separation, 19.23 meters.

Figure 8. - Narrow-horizontal band spectra for base-line tests. Bandwidth, 3.2 hertz.

where the geometry is as shown in figure 6(a). When L is much greater than h_S and h_R, equation (4) may be approximated by

$$\Delta r \approx \frac{2h_S h_R}{L} \tag{5}$$

Reinforcement will occur when

$$\Delta r = n\lambda \qquad n = 1, 2, \ldots \tag{6}$$

and cancellation will occur when

$$\Delta r = \left(n - \frac{1}{2}\right)\lambda \quad n = 1, 2, \ldots \tag{7}$$

From equations (5) and (7) the frequencies of cancellation can be shown to be

$$f_C \approx \frac{(2n - 1)LC}{4h_S h_R} \tag{8}$$

Similarly, the frequencies of reinforcement can be obtained from equations (5) and (6).

An approximation to the differences in sound pressure level between the peaks and valleys can be obtained assuming that both the direct and reflected pure tone waves diminish in amplitude as the square of distance from the source. Subject to the same restrictions as in equation (5) ($L >> h_S$ and h_R), this difference can be approximated as

$$\Delta dB \approx 20 \log \left(\frac{L^2}{2h_S h_R}\right) \approx 20 \log \left(\frac{L}{\Delta r}\right) \tag{9}$$

Referring to figure 8, the cancellation frequencies have been labeled with the appropriate value of n that would appear in equation (8). In figure 8(a), where only the source-receiver separation L was varied, the frequencies of the minima increase linearly with L in quantitative agreement with equation (8). Also, the differences in sound pressure level between the maxima and minima increase with increasing L, in qualitative agreement with equation (9).

In figure 8(b), only the receiver height h_R is varied. The frequencies of the minima increase with decreasing h_R again in quantitative agreement with equation (8). Similarly, the differences in sound pressure level between the maxima and minima increase with decreasing h_R also in qualitative agreement with equation (9).

The complete data for the base-line tests are presented in figures 15 to 17 where the 3.2- and 16-hertz bandwidth spectra and the one-third octave spectra are presented. The one-third octave data have been corrected to standard day conditions, and the correction for source directivity previously discussed has been applied.

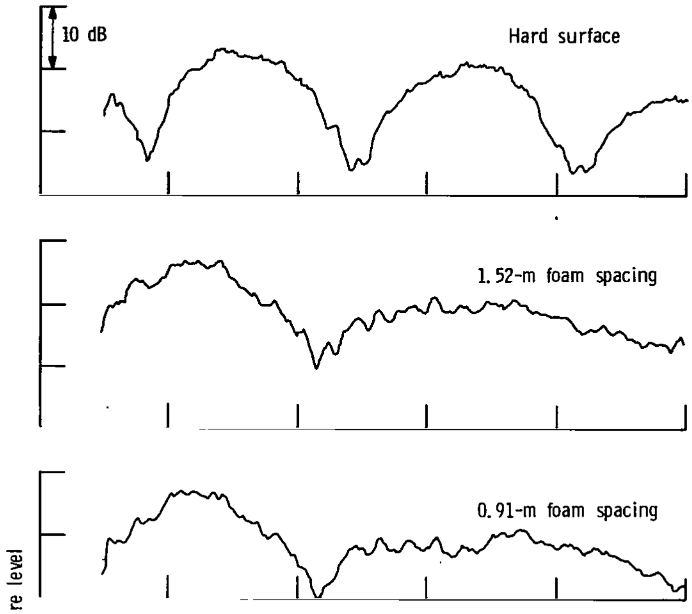
Foam Treatment Tests

In figure 9 results from foam treatment tests are compared with those for the hard surface. The spectra shown have a 3.2-hertz bandwidth. Both spacing distances of the foam blocks are shown. Several source-receiver distances and receiver heights are shown. It can be seen that the large peaks and valleys observed in the hard surface data were significantly reduced and, in fact, essentially disappeared at high frequency for the foam treated case. Also, the frequencies of the minima have shifted between the data for the hard and treated surfaces. This is probably due to the finite impedance of the surface with foam treatment. Apparently, the foam introduces a reactive component into the impedance of the surface. Similar behavior has been reported previously in references 11 and 12 for grassy surfaces.

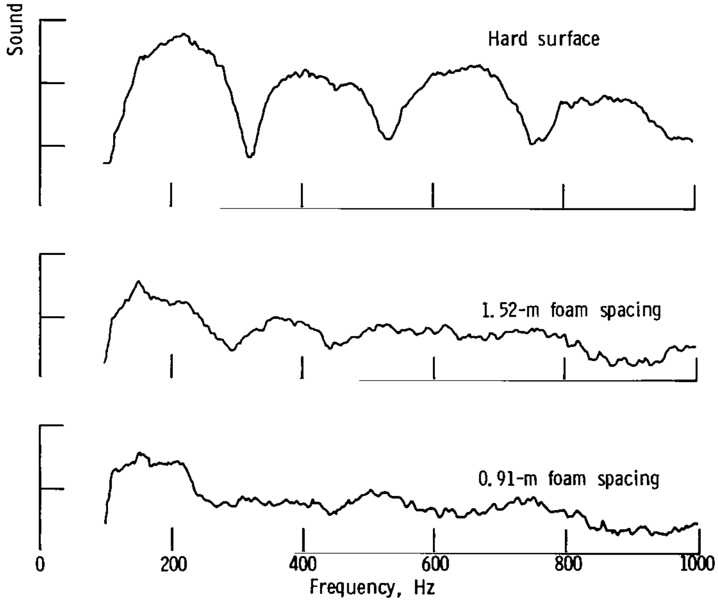
A one-third octave analysis of the same data as in figure 9(b) is shown in figure 10. These data have been corrected for atmospheric absorption to standard day conditions and for source directivity as previously described. The cancellations and the reinforcements that were observed with hard ground surface do not appear nearly as strong with the foam treatment. At higher frequencies a one-third octave analysis does not reveal the ground reflection effect because of the increasing bandwidth of the filter as frequency is increased. Several peaks and valleys may occur within a single filter bandwidth.

Figures 9 and 10 show results for both the 1.52- and 0.91-meter foam spacings. It can be seen that at least above 300 hertz there is very little difference between the results for these spacings. It appears, therefore, that the larger spacing was sufficiently small that the desired effect of eliminating the ground reflection was achieved, for practical purposes.

For a white noise spectrum, if all of the acoustic power incident on the foam were absorbed, the overall sound pressure level would be reduced by up to 3 decibels at a particular microphone location. This would be true if the source directivity were not changed by the foam and if $\Delta r/r$ were small. The overall sound pressure level was observed to drop about 1.4 decibel with the foam present indicating an absorption of more than half of the reflected acoustic power. It should be noted that for any microphone location the overall sound pressure level can be influenced by the reinforcements and cancellations if they occur near the peak of the noise spectrum. This effect has been min-

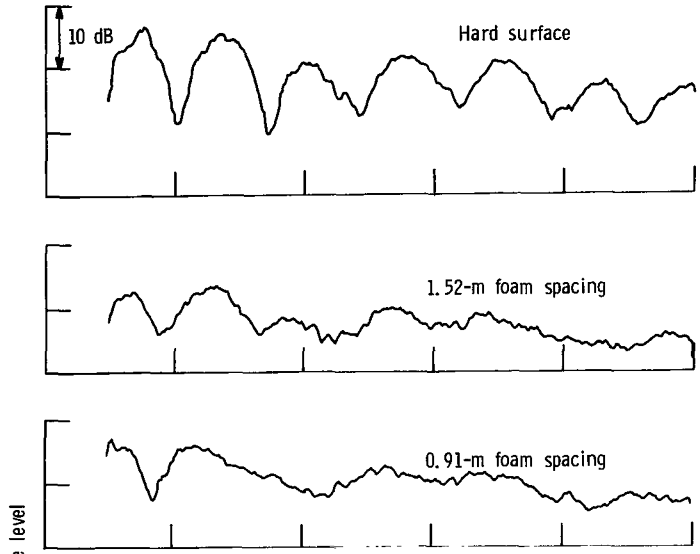


(a) Source-receiver separation, 48.31 meters; height of source, 4.95 meters; height of receiver, 4.95 meters.

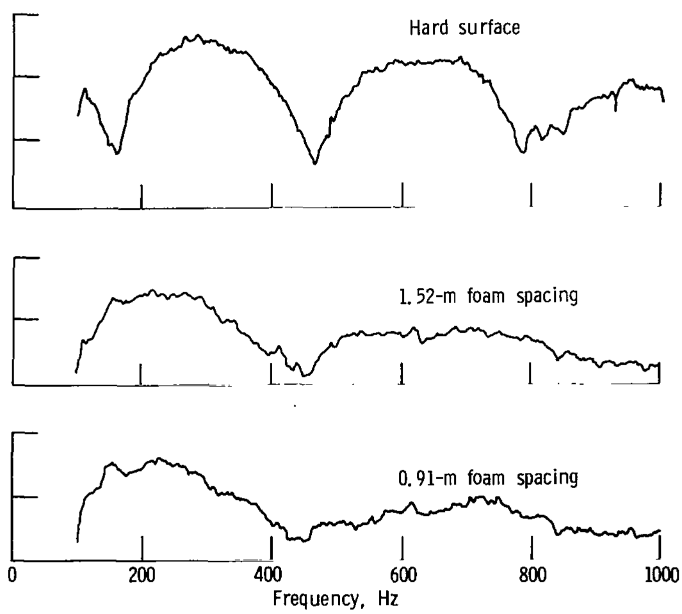


(b) Source-receiver separation, 30.48 meters; height of source, 4.95 meters; height of receiver, 4.95 meters.

Figure 9. - Comparison of narrow-band spectra with and without foam treatment. Bandwidth, 3.2 hertz.

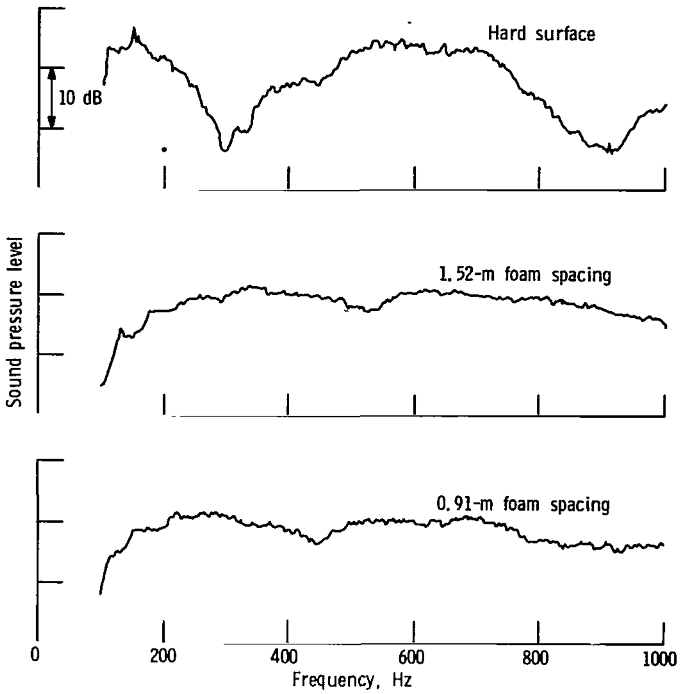


(c) Source-receiver separation, 19.23 meters; height of source, 4.95 meters; height of receiver, 4.95 meters.



(d) Source-receiver separation, 30.48 meters; height of source, 4.95 meters; height of receiver, 3.30 meters.

Figure 9. - Continued.



(e) Source-receiver separation, 30.48 meters; height of source, 4.95 meters; height of receiver, 1.65 meters.

Figure 9. - Concluded.

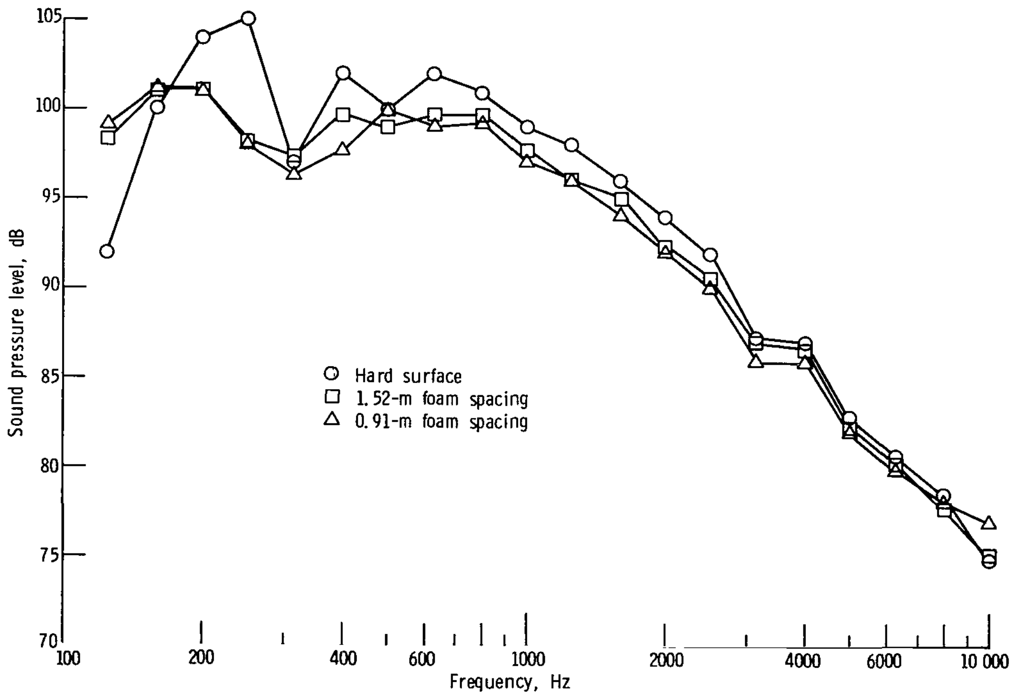


Figure 10. - Comparison of one-third octave spectra with and without foam treatment. Source-receiver separation, 30.48 meters; height of receiver, 4.95 meters; height of source, 4.95 meters.

imized by averaging over several microphone positions which distributes the peaks and valleys throughout the spectra.

Complete data for the foam treatment tests are shown in figures 18 to 21. Narrow-band data (3.2-Hz bandwidth) are shown in figures 18 and 19 for the 1.52- and 0.91-meter foam spacings, respectively. Figures 20 and 21 show one-third octave spectra for the 1.52- and 0.91-meter foam spacings, respectively.

Optimum Area Coverage

The preceding ground treatment tests have been primarily concerned with demonstrating the feasibility of this method reducing the ground reflection pattern. The delineation of the area to be covered by the sound absorbing foam was described earlier. An effort was made to provide more than the minimum area coverage needed to eliminate the effects of ground reflection. In an attempt to determine the optimum area coverage required, an additional test was run. The optimum foam distribution is here defined as the minimum amount of foam required to produce the desired reduction in the ground reflection pattern.

In this test, a single microphone was placed at the source elevation with a fixed source-receiver separation of 30.5 meters. An additional microphone was positioned as in previous tests to provide a check on the repeatability of the operating point of the source. Area coverage was as shown by the plan views shown with each curve in figure 11. From the plan views it can be seen that the area covered by foam approximated an ellipse whose size was progressively diminished. Each row of foam was made up of one, two, or three blocks of foam that were 2.44 meters (8 ft) long. A spacing of 0.91 meter was used between successive rows of foam. The results of this series of tests are shown in the narrow-band traces of figure 11.

As the amount of coverage was decreased (fig. 11) the ground reflection became more prominent as evidenced by the peaks or valleys in the spectra. A low-frequency cancellation (240 Hz) first appeared in the third plot and coverage diagram of figure 11. This grew in strength as the amount of coverage was reduced, and its frequency increased as coverage was reduced (as noted previously in the discussion of fig. 9) so that in the eighth plot of figure 11 it appeared at about 330 hertz. Because the change in cancellation was first noticed between the second and third plots (fig. 11), one might conclude that at least as much coverage was needed as was present in the data for the second plot (fig. 11). In the first three plots, only the axial coverage was changed. When the lateral coverage was also reduced the ground effects were even more prominent as seen in the fourth to the seventh plots. A lateral coverage of at least ±12 percent of the source-receiver separation is thus required.

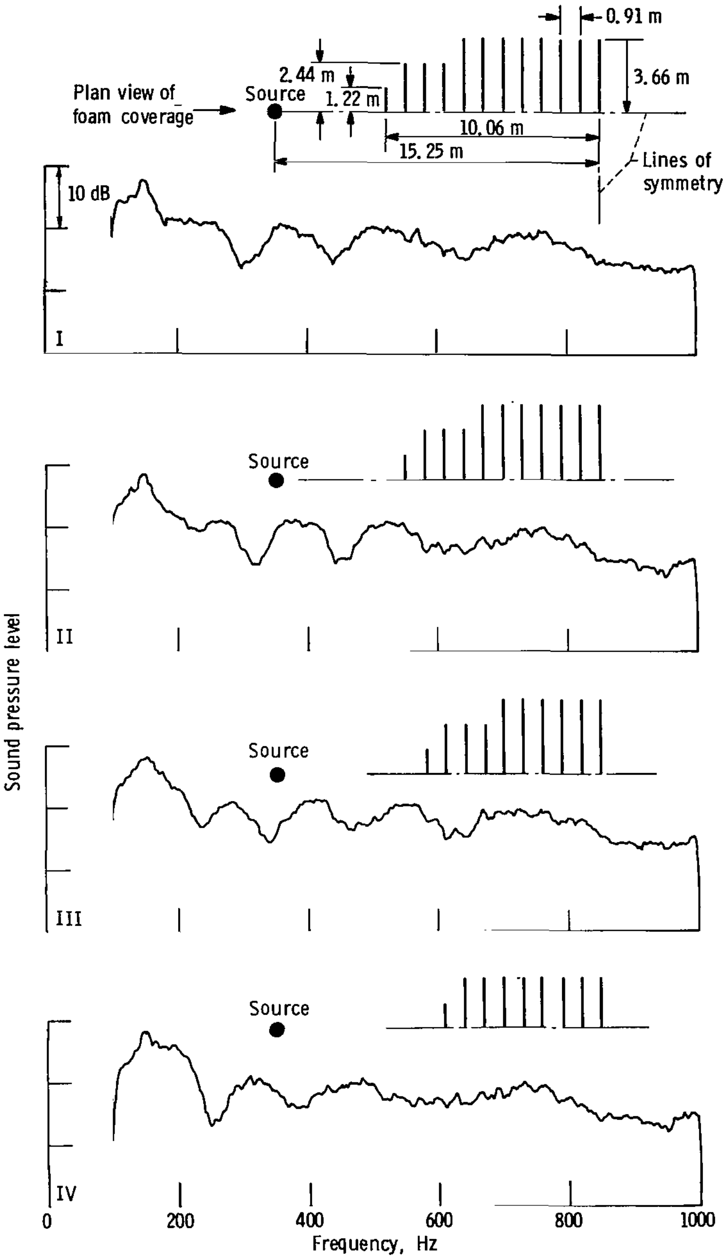


Figure 11. - Effect of area coverage by foam. Source-receiver separation, 30.48 meters; height of source, 4.95 meters; height of receiver, 4.95 meters.

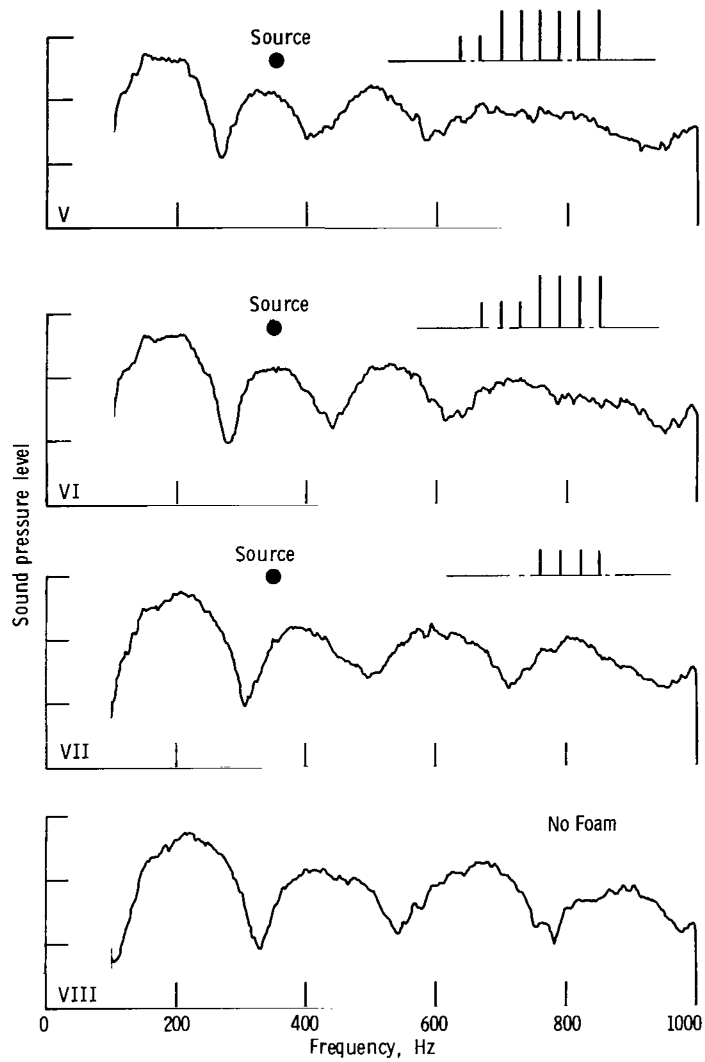


Figure 11. - Concluded.

The minimum width of coverage required to eliminate effectively the effects of ground reflection is of importance primarily for single microphone measurements. The more usual situation is to have a circular array of microphones on a fixed radius. Foam panels, supported between the source and the receivers, should thus be laid out in a patterm of concentric circular rings.

Using the same microphone configuration as in the last series of tests, foam panels were set up in rows 9.75 meters wide. For a foam panel spacing of 1.52 meters, a depth of ±0.15 L was found to be only minimally effective with ±0.17 or ±0.20 L a more optimum depth. With a depth of ±0.20 L, the spacing between successive rows was then increased in increments of 30.5 centimeters from a 1.83- to a 3.05-meter spacing. The maximum spacing which still produced good absorption of the sound wave incident on the ground was found to be 2.44 meters for this geometric configuration. A larger source-receiver separation would permit increased spacing between successive rows while a shorter separation would require decreased spacing. The decreased effectiveness of the larger spacing between rows of foam panels is due to increasing amounts of the incident sound being reflected off the hard surface before it can be absorbed by the foam. The most effective spacings, 0.91 meter and 1.52 meter, for example, allow none of the sound to be directly incident on the ground (assuming ray propagation). Further decreases in spacing do not yield any increased absorption as evidenced by the similarity between the 0.91- and 1.52-meter foam spacing data. For a fixed source-receiver separation and foam spacing, increasing the height of the source increases the amount of sound which can be reflected directly off the ground, thus decreasing the effectiveness of the foam.

With a fixed spacing between successive rows of foam, the foam farthest from the source is partially shielded from incident sound by the foam at shorter radial distances. Thus, less of its total surface area is effective in absorbing sound. To better optimize the foam distribution, a spacing which increases with increasing distance from the source may be used. Such a spacing could be designed to minimize the effects of shielding by providing a constant surface area to incident rays in each row of foam panels as shown in figure 12. For example, requiring an incident ray to strike the upper fraction (Q) of the foam panel produces the following relationship between the distance X_n to the n^{th} row of foam panels:

$$X_n = X_1 \left(1 + \frac{Qh_F}{h_S - h_F}\right)^{n-1} \tag{10}$$

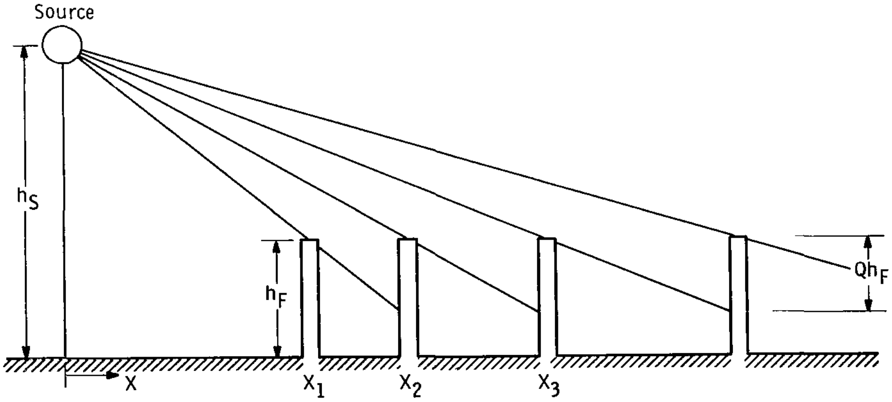


Figure 12. - Variable spacing of foam panels to minimize shielding between successive rows.

where h_F is the foam height, h_S is the source height, and Q is the fraction of the foam panel height exposed to direct noise radiation. Thus if $Q = 2/3$, seven rows are required to cover the distance 9 to 21 meters for a source height of 4.95 meters and a foam height of 0.91 meter. Spacing varies from 1.37 to 2.77 meters. Similarly, six rows are needed with spacing varying from 1.66 to 3.27 meters to cover the same distance if the incident ray is allowed to strike the upper 80 percent of the foam panel. Thus, while total area coverage remains proportional to the source-receiver separation, the spacing between successive rows is now dependent on the height of the source.

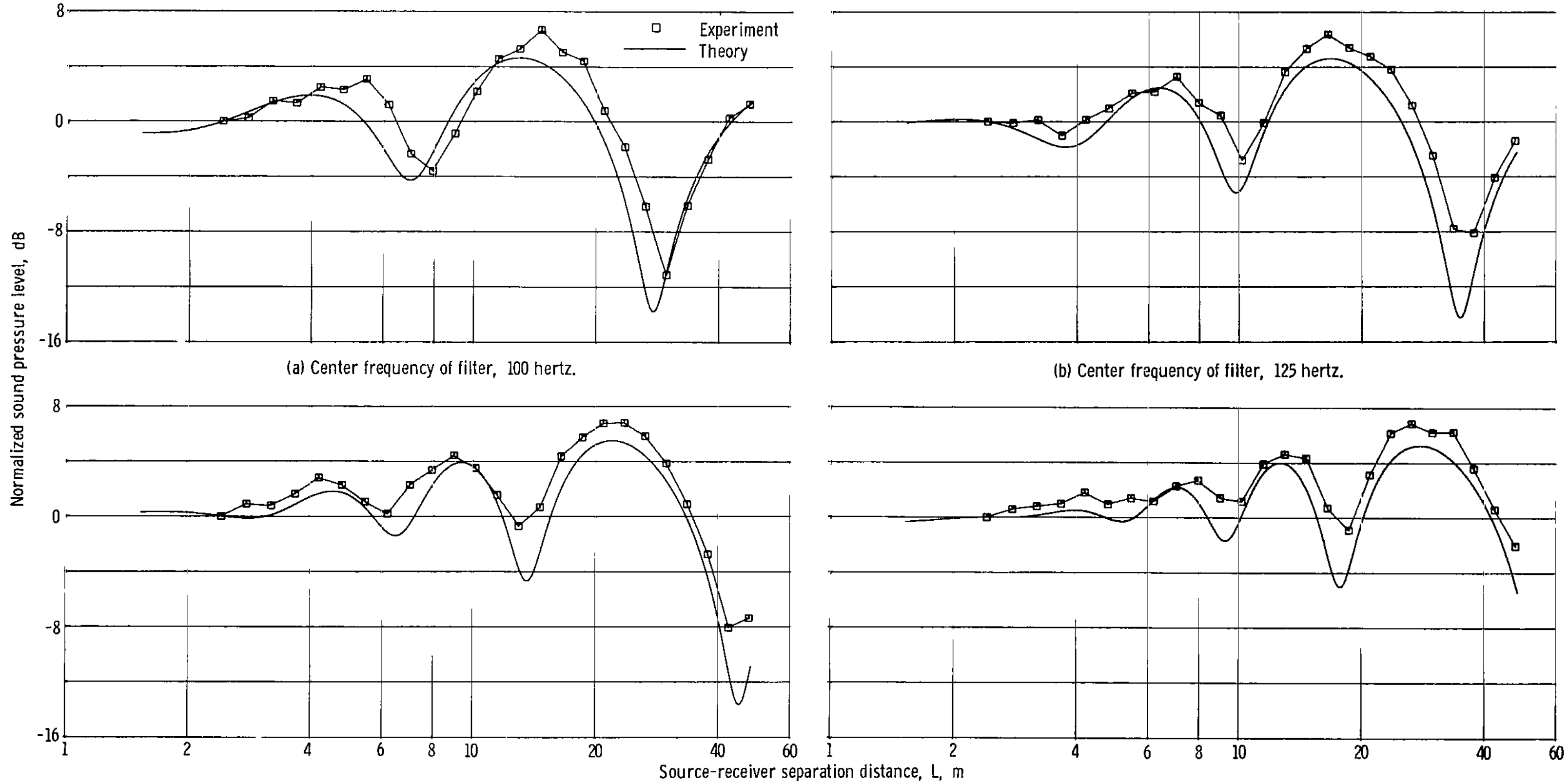
Comparison of Theoretical Ground Reflection Prediction with Base Line Data

Several authors have investigated the problem of ground reflection theoretically (refs. 1, 2, 3, and 13 to 15). These formulations vary in complexity from consideration of a single point source to a uniform plane distribution of sound sources. Receiver band width may be limited to a pure tone or can extend to any bandwidth. The effects of spectrum shape and a ground plane of arbitrary impedance have also been treated.

For the present experiments the sound source can be approximated by a point source and the concrete surface is close to a perfect reflector. In addition, the sound spectra are taken to be band-limited white noise within each third-octave band. For these conditions, the analysis of Howes (ref. 2) was used to generate theoretical curves for the ground reflection effect.

In reference 2, the effect of the ground plane is expressed as the ratio of the sound pressure level in the presence of a ground plane to that in the absence of a ground plane (free field). Since free-field data cannot be measured in the present experiments, it is convenient to eliminate the need for them in the following manner. Measured sound pressure levels are corrected for source directivity as previously described and atmospheric attenuation is added. The noise data are then adjusted to the distance of the microphone nearest to the source (position 25) by the inverse square law (amounting to 20 dB/decade of distance). The data are normalized by the data at position 25 by taking the difference between the sound pressure level for any microphone location and the value measured at position 25. The results from the theory can be expressed in an analogous form for direct comparison with the experimental results.

This comparison is shown in figure 13, where the sound pressure levels normalized as described are plotted as a function of source-receiver separation distance for several one-third octave bands. It can be seen that the maxima and minima are reasonably well predicted with regard to both frequency and level. Similar data for the three receiver heights are shown in figure 22. As seen in figure 22, the agreement becomes poor at higher frequencies and lower microphone heights. This behavior is discussed in the following section.



(a) Center frequency of filter, 100 hertz.

(b) Center frequency of filter, 125 hertz.

(c) Center frequency of filter, 160 hertz.

(d) Center frequency of filter, 200 hertz.

Figure 13. - Comparison of base-line results with theory. Height of source, 4.95 meters; height of receiver, 4.95 meters.

In a careful evaluation of the data as required to obtain figure 13, it was found that the apparent source location was not precisely as previously described and presented in table I. An effective value of the source-receiver separation L was calculated using equations (4) and (7) with the experimentally observed cancellation frequencies of figures 15 and 16. This was done for the first six frequencies at each value of L, and the results were averaged for each microphone height. The resulting average reduction in L was 0.64, 0.79, and 1.74 meters for the top, middle, and bottom microphones, respectively. It is not surprising that the arbitrary selection of the horn support mast as the source location was incorrect; however, the reason for the dependence on microphone height is not apparent.

Sound Attenuation with Distance

In figure 14 the attenuation of overall sound pressure level and the sound pressure level of the one-third-octave band centered at 4000 hertz (high-frequency example) is shown as a function of source-receiver separation. Data for each of the microphone heights are presented for the base-line case. For reference, a curve of the inverse square law attenuation of 20 decibels per decade of distance is also shown.

At sufficiently large distances all the data appear to follow the inverse square law; however, for shorter distances, depending on frequency and microphone height, the sound

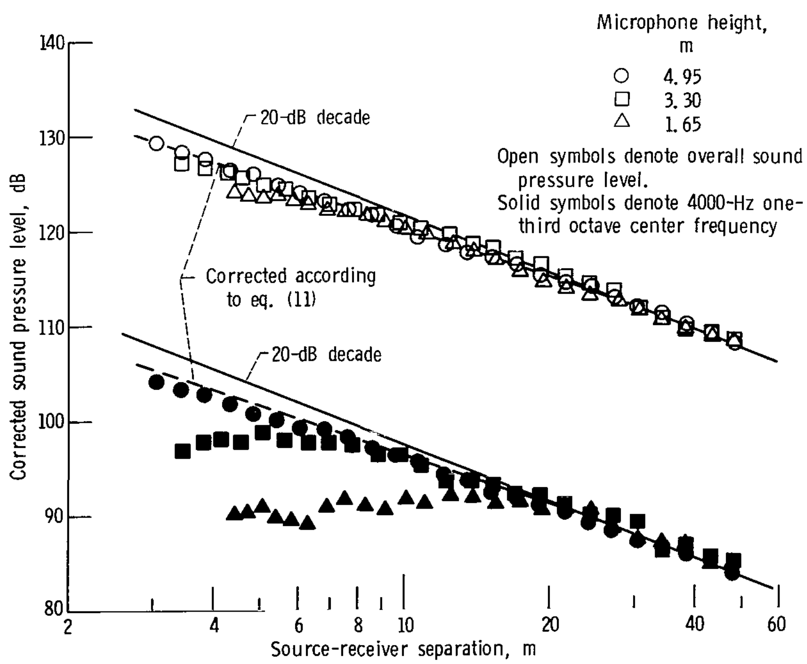


Figure 14. - Attenuation of sound pressure level with distance.

does not appear to attenuate with distance at all. This is particularly noticeable at high frequencies as illustrated by the 4000-hertz data obtained at the lowest microphone height where the sound pressure level remains almost constant to a distance of about 25 meters from the source. The effect is less noticeable in the overall sound pressure level which is controlled by frequencies less than 1000 hertz. However, at distances less than 10 meters, the decay rate is less than the inverse square law rate. Part of the falloff at short distances can be accounted for (up to 3 dB). At large distances the reflected and direct wave travel about the same distance and about 3 decibels is added due to the sum of the two waves. At short distances, the reflected wave travels much further and thus is attenuated more than the direct wave and as a consequence adds almost nothing to the total sound pressure level. Behavior similar to that found for the overall sound pressure level was observed in reference 2. The sound source described in reference 2 was an air jet exhaust and the effect was suggested to be caused by the extended distance covered by the source. It is difficult to conceive that the driver-horn combination used in these experiments produces an extended source such as might be formed by a jet.

The deviation from the attenuation line of 20 decibels per decade for the high microphone (4.95 m) data in figure 14 can be explained. The deviation from this line can be expressed as

$$\Delta \mathrm{dB} = 10 \log \left[1 + \frac{1}{\left(1 + \frac{\Delta r}{r}\right)^2} \right] - 3 \qquad (11)$$

This expression accounts for the fact that the reflected wave travels further than the direct wave to reach the microphone. For large values of r, $\Delta r/r \approx 0$ and $\Delta \mathrm{dB} \approx 0$. The total sound pressure level is made up of almost equal contributions from the direct and the reflected wave. However, for small r (less than h_S and h_R), $\Delta r/r$ is very large, and $\Delta \mathrm{dB} \approx -3$. The reflected wave contributes little to the total sound pressure level which is thus 3 decibels below the line extrapolated from the data for large r.

In figure 14 the correction of equation (11) has been applied to the 20-decibel-per-decade attenuation lines. It is seen that the curvature of the data at low values of r has been accounted for in the high microphone (4.95 m) data. The additional falloff of the data for the middle (3.3 m) and low (1.65 m) microphones cannot be explained by the corrections from equation (11). It is possible that the source directivity patterns, especially at high frequencies, are much more directional than that shown in figure 4. This could explain the unexpected behavior of the data since (as previously discussed) the lower microphones at short distances receive radiation from the source at very large angles from the source axis. For large distances that angle is nearly 45° for all of the microphones, and there the data are well behaved.

SUMMARY OF RESULTS

An experiment to evaluate the effectiveness of a method for eliminating ground reflection effects from acoustic measurements has been performed. The method involved placing blocks of an absorbing foam on the ground between the sound source and receiver in an approximation of the wedges of an anechoic chamber. The tests were performed out-of-doors with data taken as a function of source-receiver separation distance and receiver height. The spacing distance between foam blocks and the extent of ground covered were varied to estimate the optimum placement and minimum amount of foam treatment needed. Base-line tests without foam were performed to show the improvement provided by the foam. Results from these base-line tests were compared with the theoretical model obtained by Howes. The results of the study may be summarized as follows:

1. Foam treatment was effective in reducing ground reflection as evidenced by the reduction in amplitude of the peaks and valleys in the sound spectra. The foam was least effective at low frequencies where residual evidence of ground reflection was observed. This was most apparent at the lowest microphone height and at the largest source-receiver separation distances.

2. The optimum placement of the foam for these experiments was judged to be a spacing between foam blocks of 2.4 meters. With this spacing it was estimated that the minimum area of the ground treated should be ±12 percent of the source-receiver separation distance in the lateral or transverse direction and ±20 percent of the source-receiver separation distance in the axial direction. The lateral coverage is centered on the source-receiver axis and the axial coverage is centered on the theoretical point of ground reflection.

3. At low frequencies, the theory of Howes predicted the features of the experimental data without foam treatment fairly well. These included the frequencies as well as the amplitudes of reinforcement and cancellation.

4. Some of the data did not follow the inverse square law of attenuation with distance. This effect was particularly pronounced at high frequencies and low receiver heights. At sufficiently large distances all of the data followed the inverse square law of attenuation with distance.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 29, 1971,
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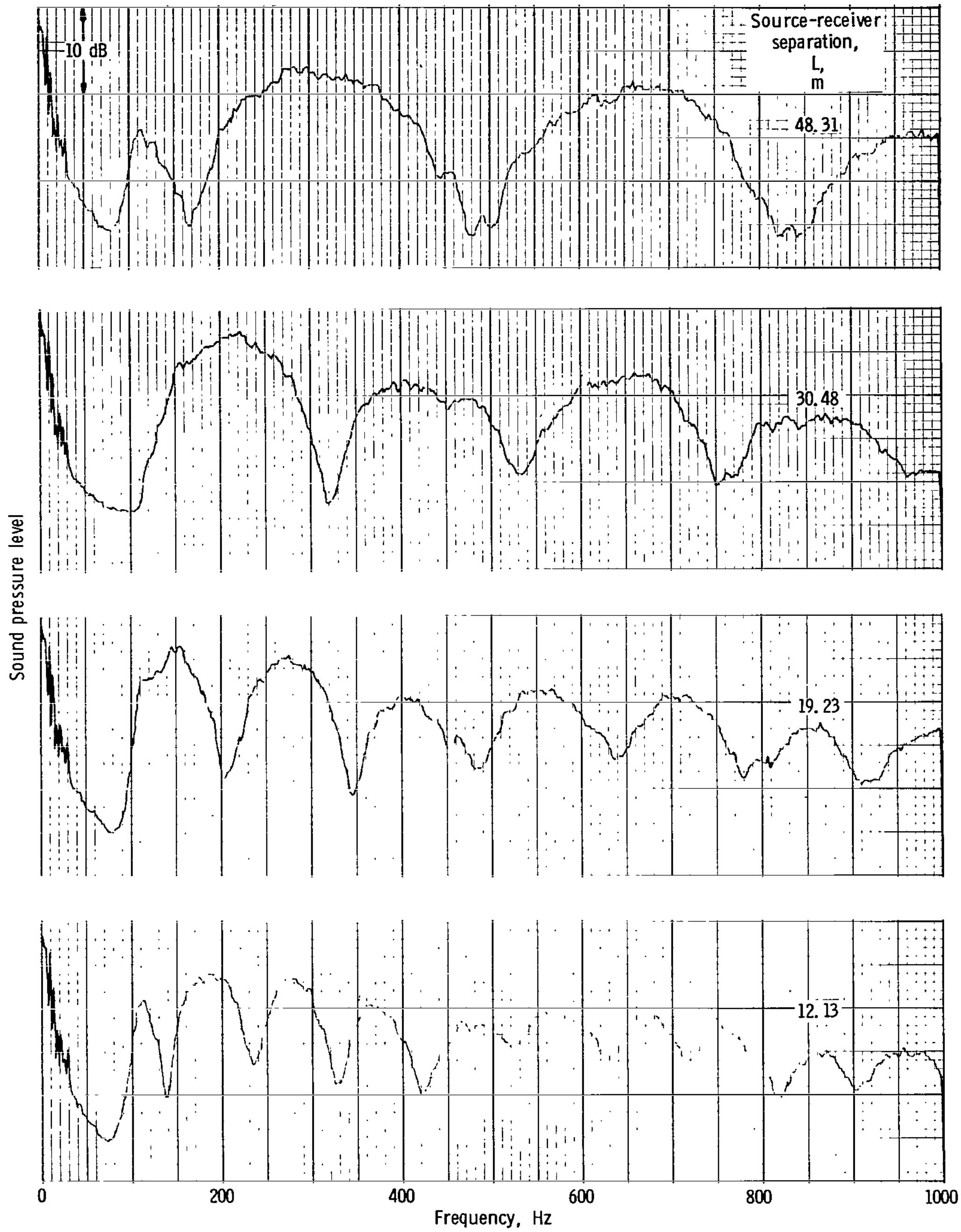
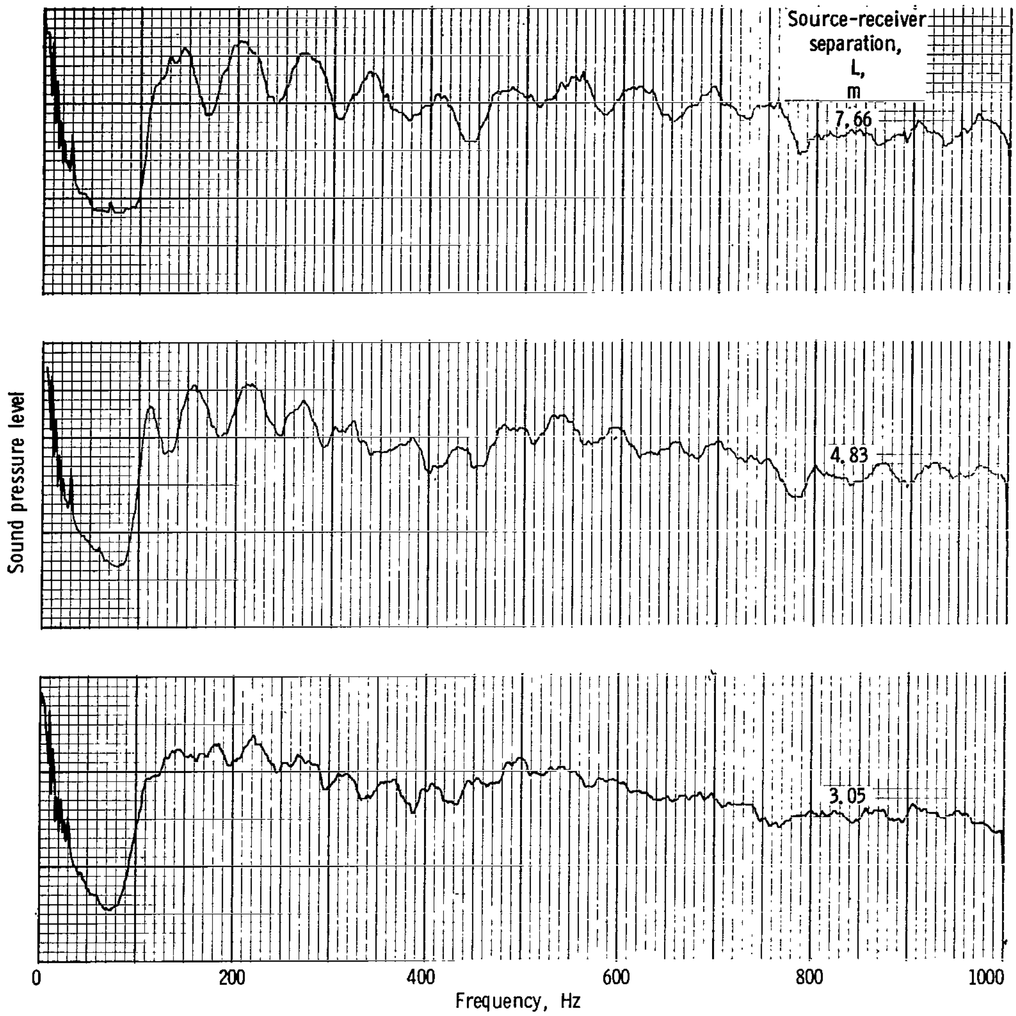


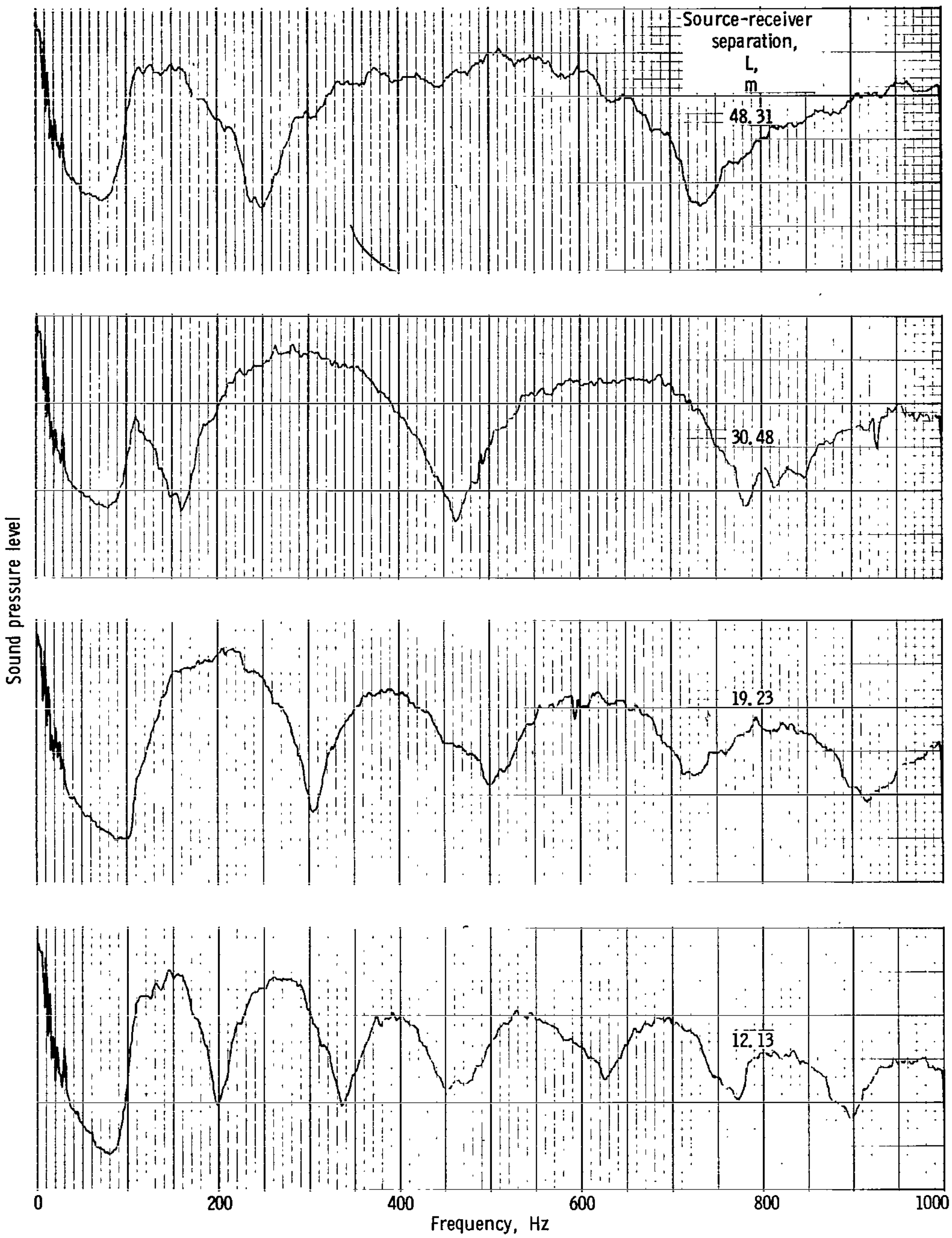
(a) Height of receiver, 4.95 meters.

Figure 15. - Narrow-band spectra of base-line tests. Bandwidth, 3.2 hertz.



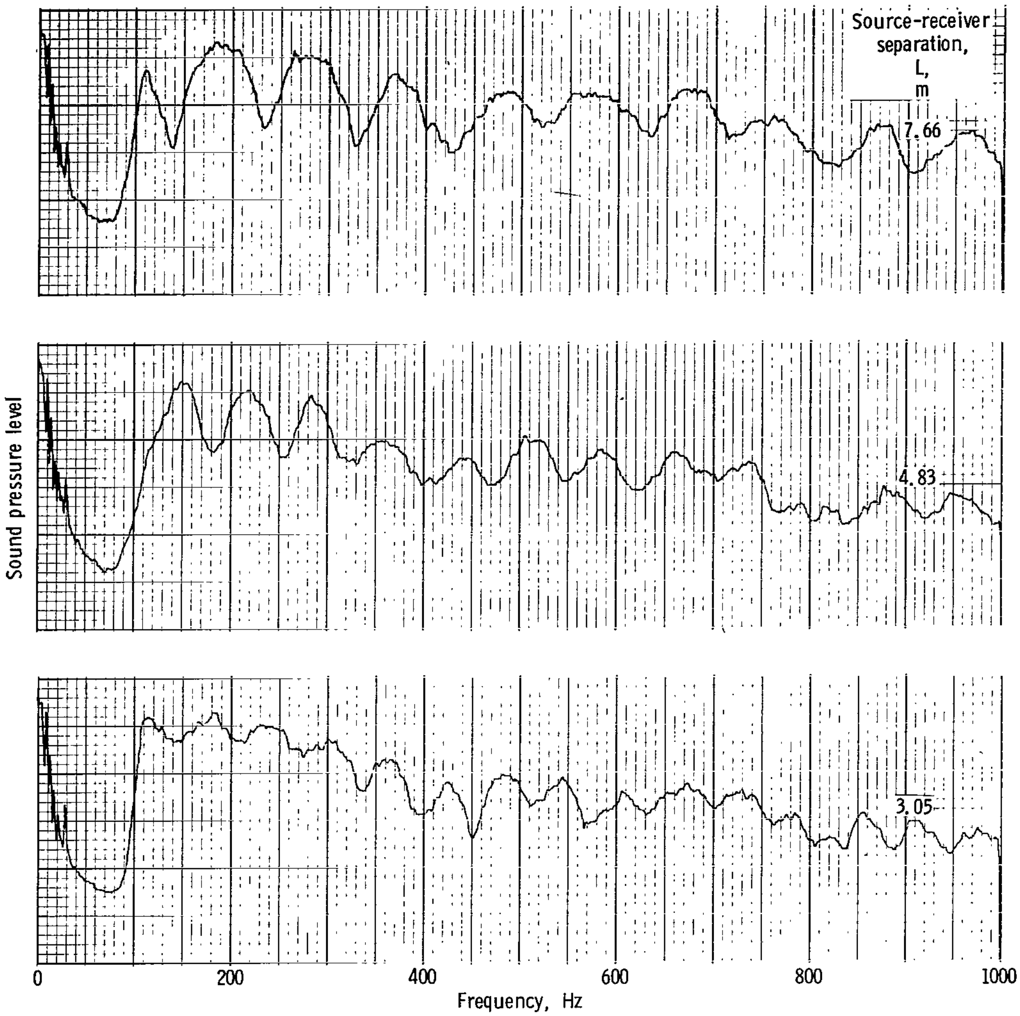
(a) Concluded.

Figure 15. - Continued.



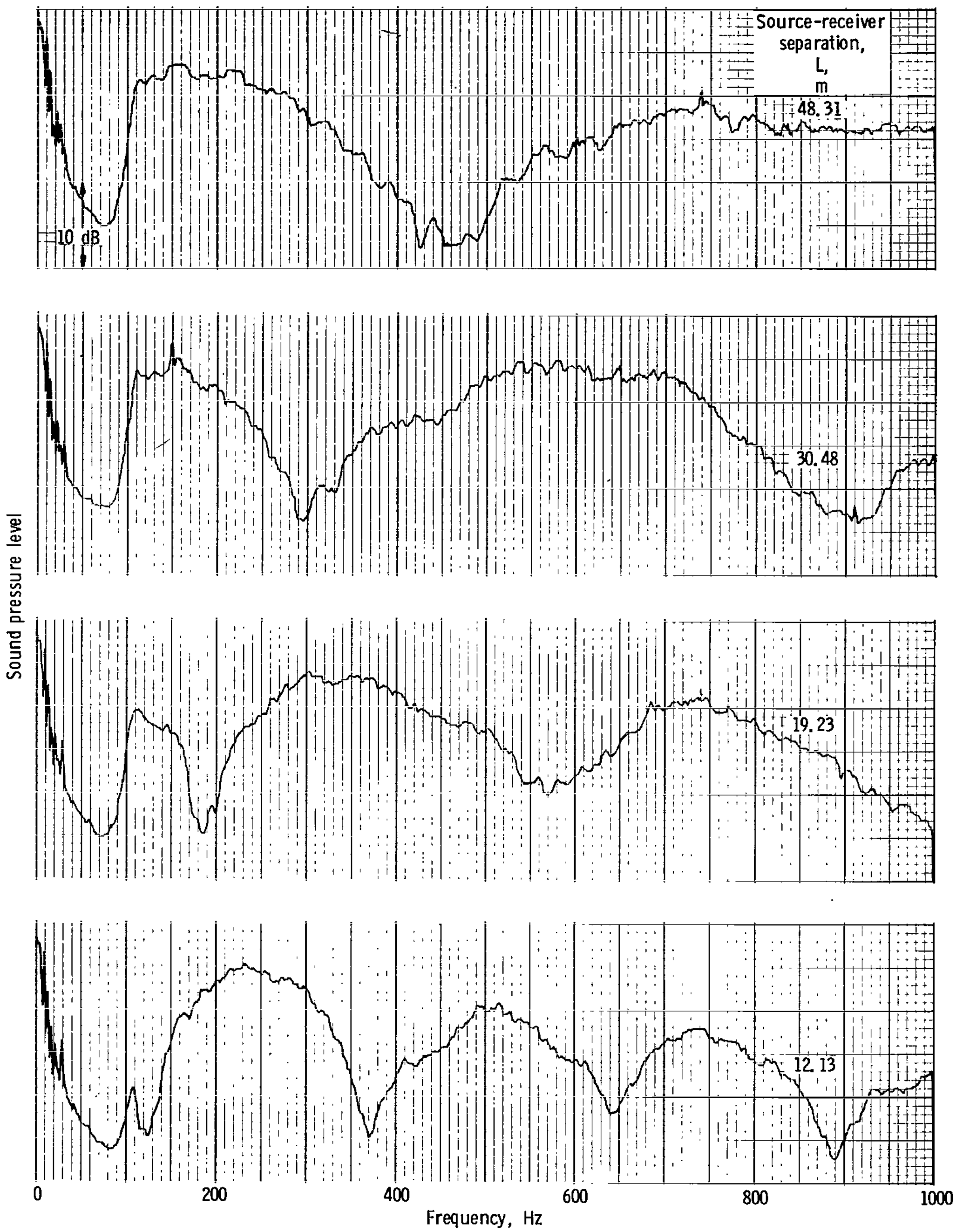
(b) Height of receiver, 3.30 meters.

Figure 15. - Continued.



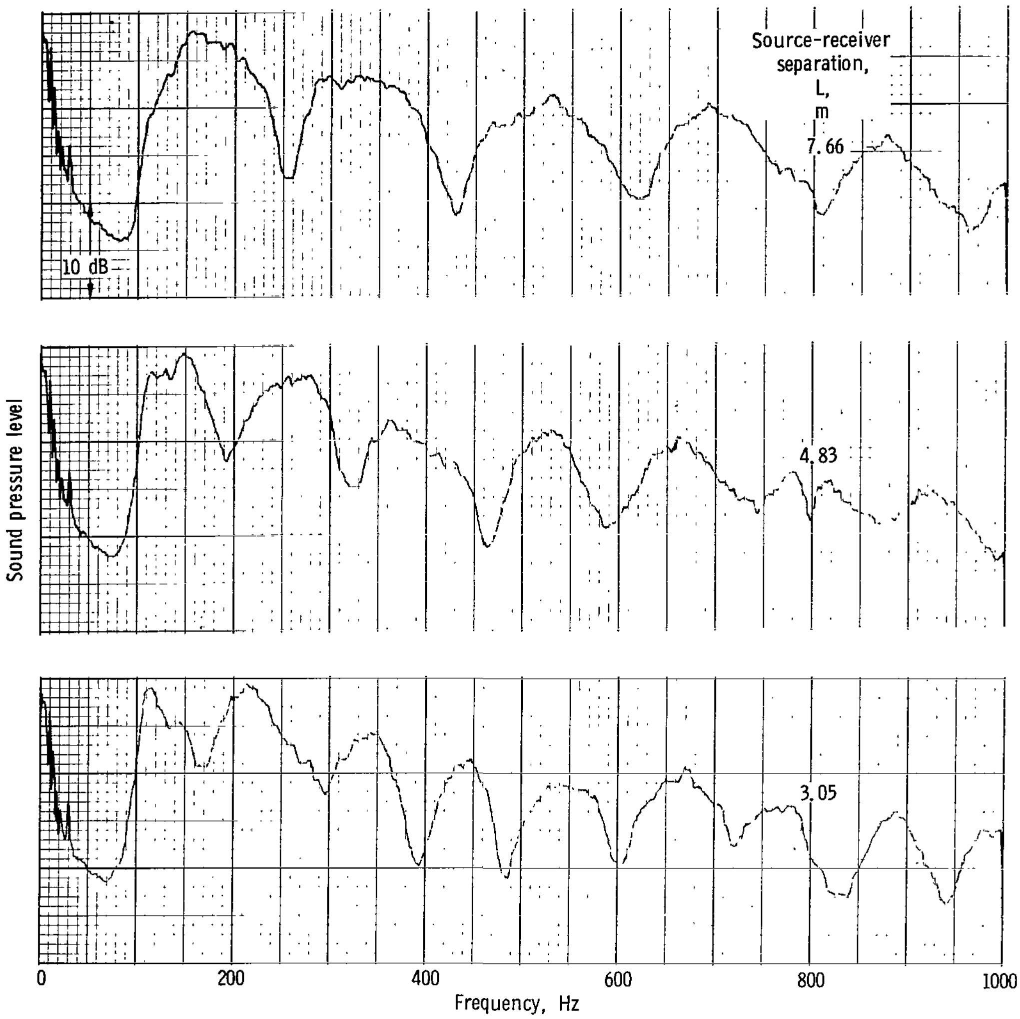
(b) Concluded.

Figure 15. - Continued.



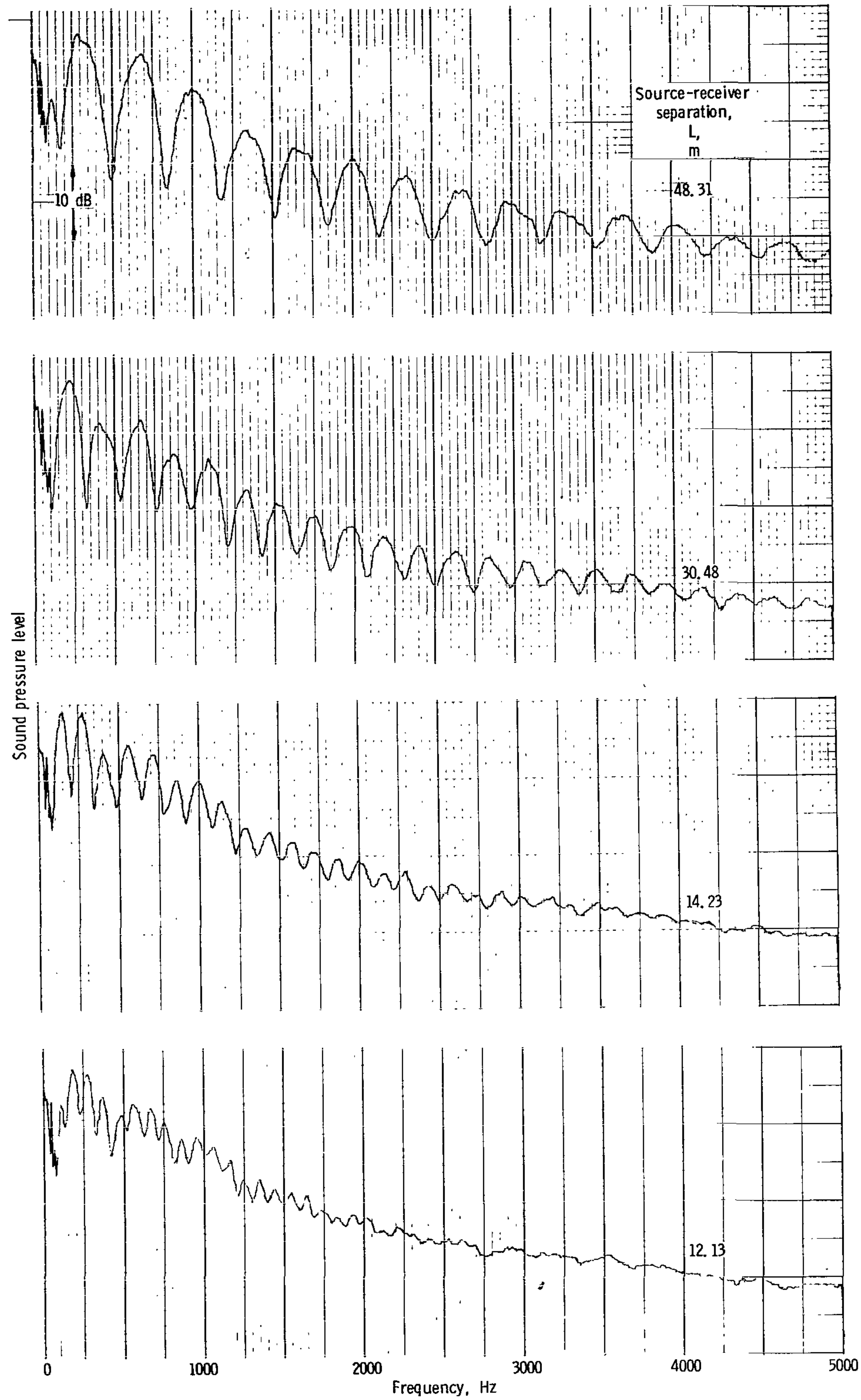
(c) Height of receiver, 1.65 meters.

Figure 15. - Continued.



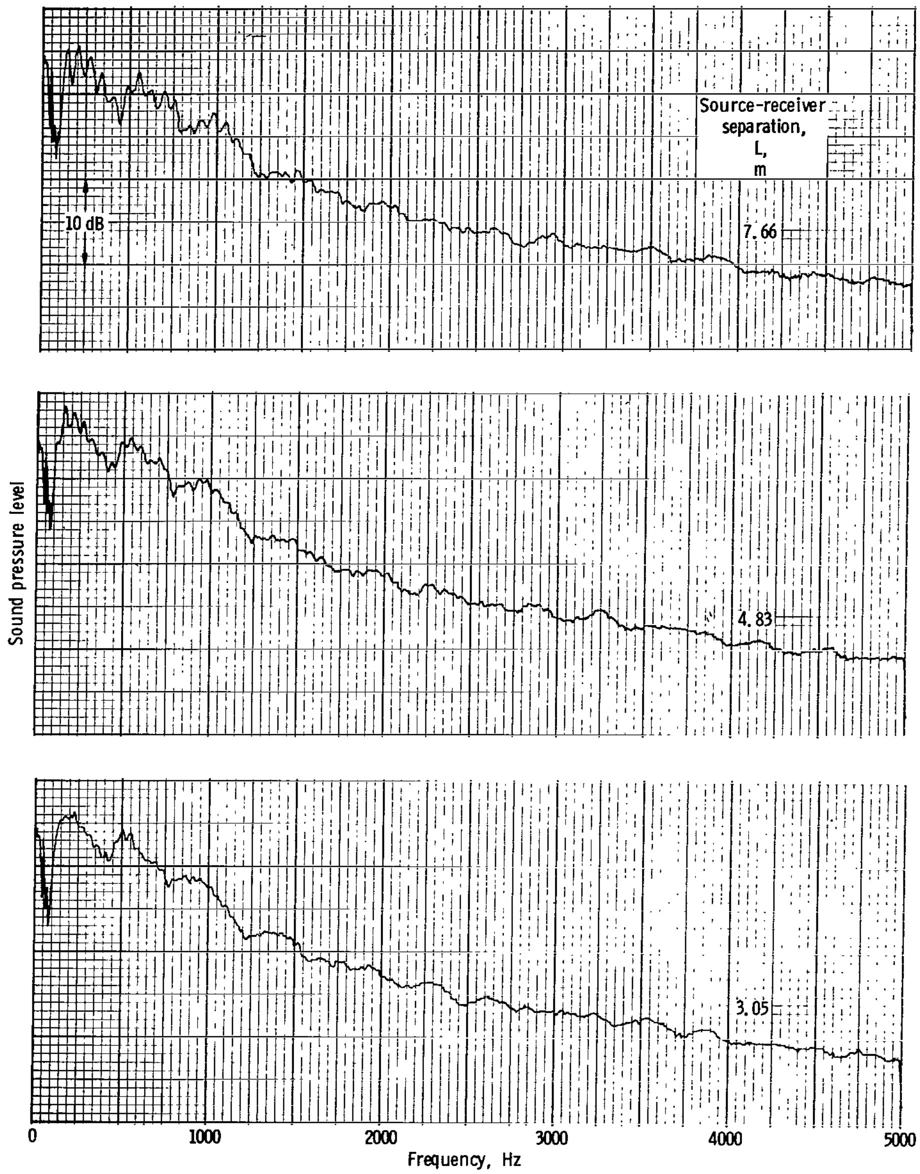
(c) Concluded.

Figure 15. - Concluded.



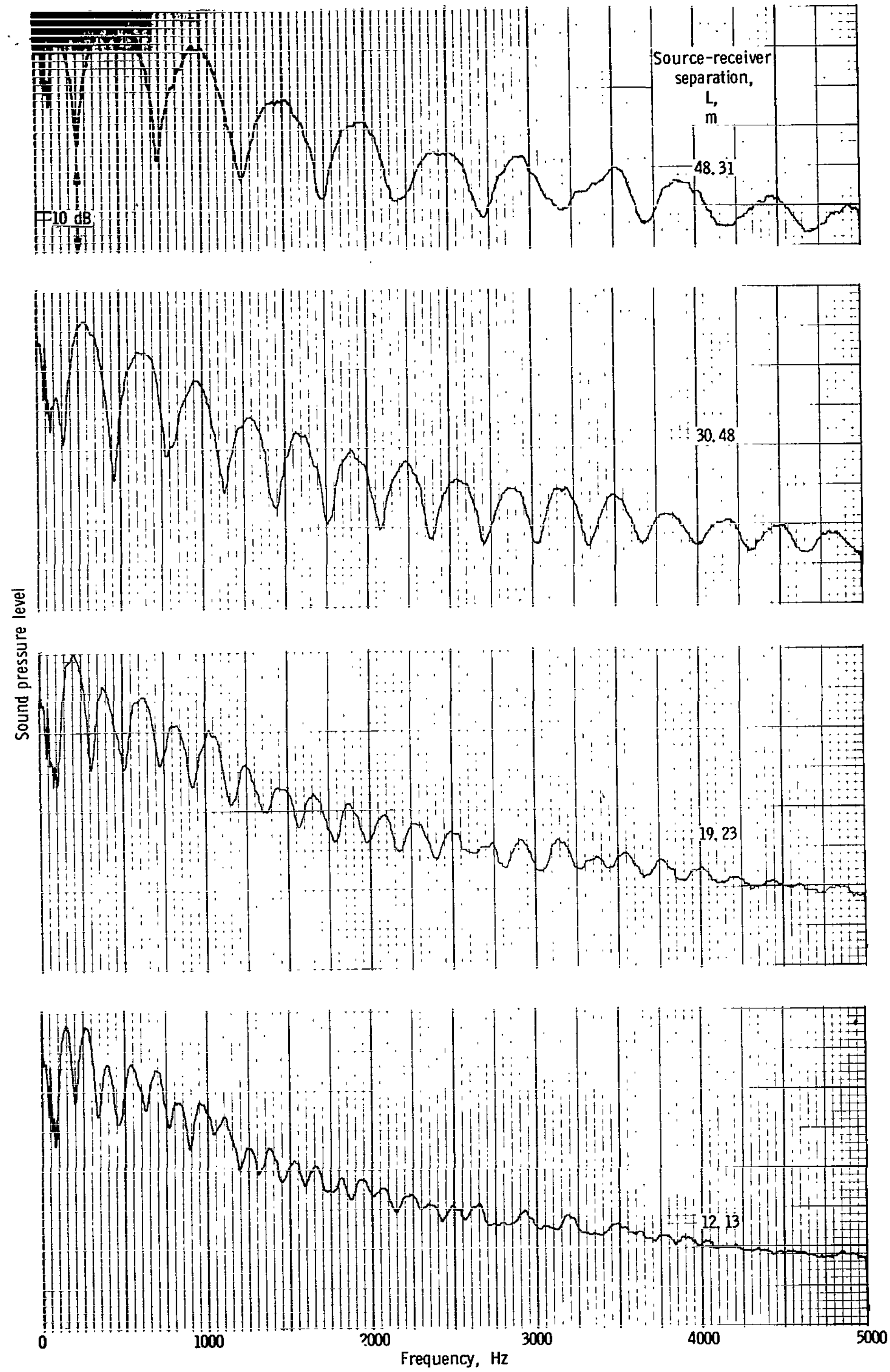
(a) Height of receiver, 4.95 meters.

Figure 16. - Narrow-band spectra of base line tests. Bandwidth, 16 hertz.



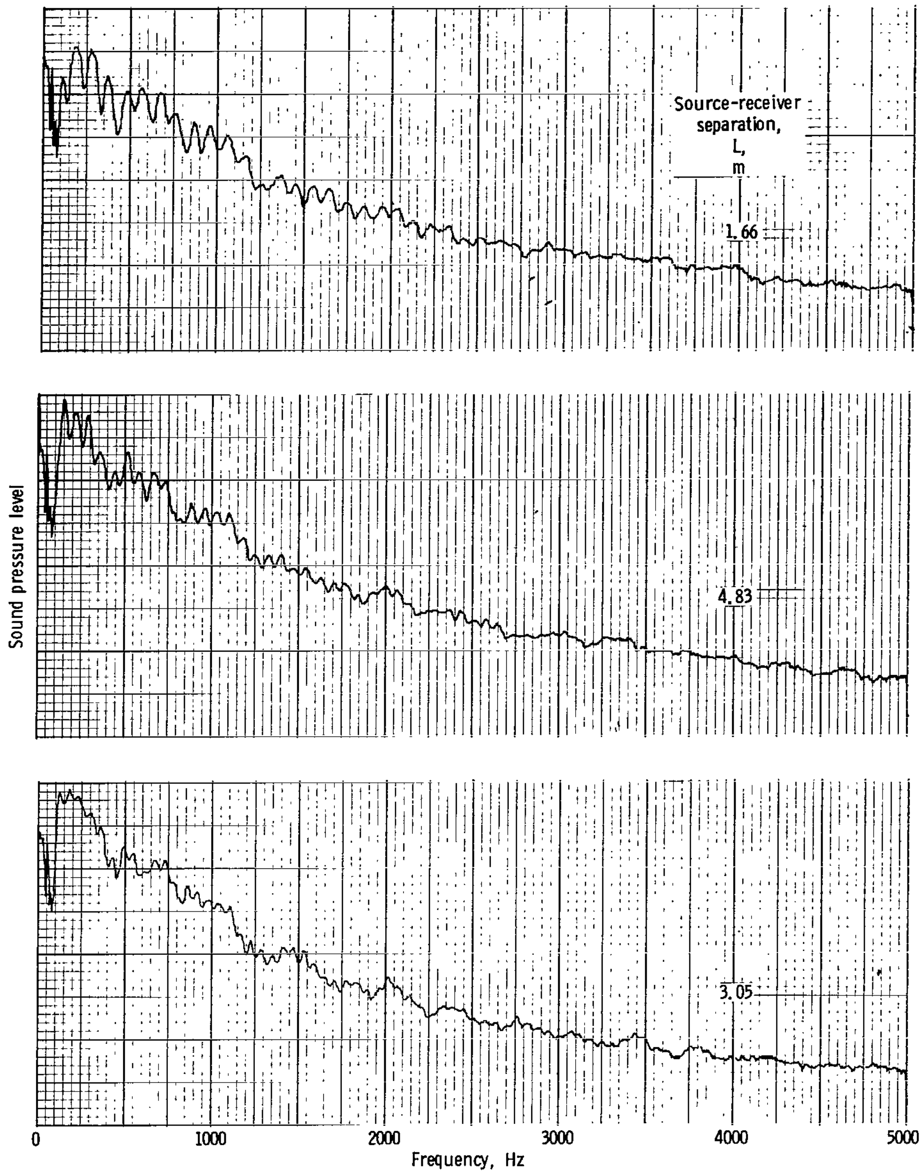
(a) Concluded.

Figure 16. - Continued.



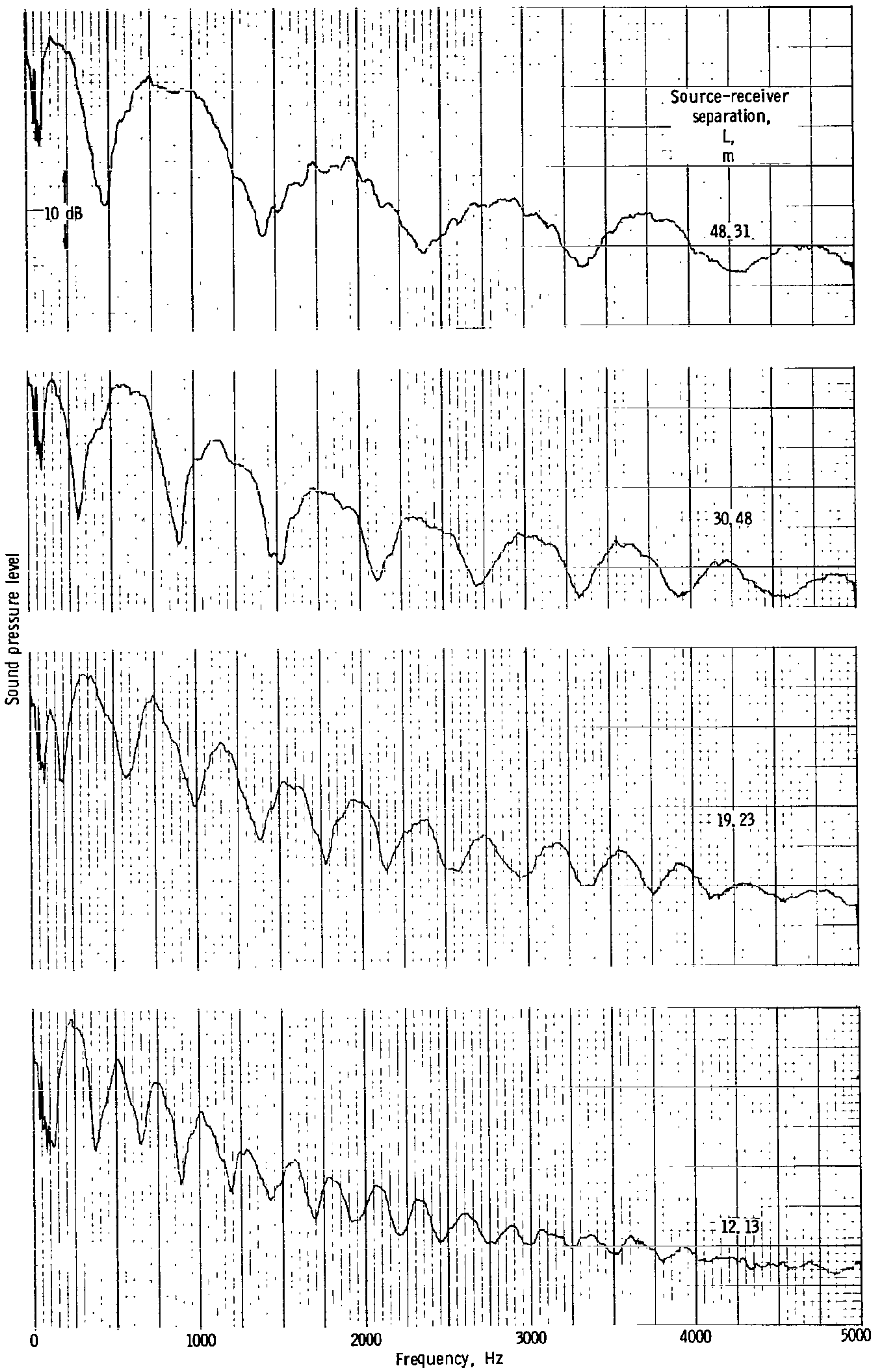
(b) Height of receiver, 3.30 meters.

Figure 16. - Continued.



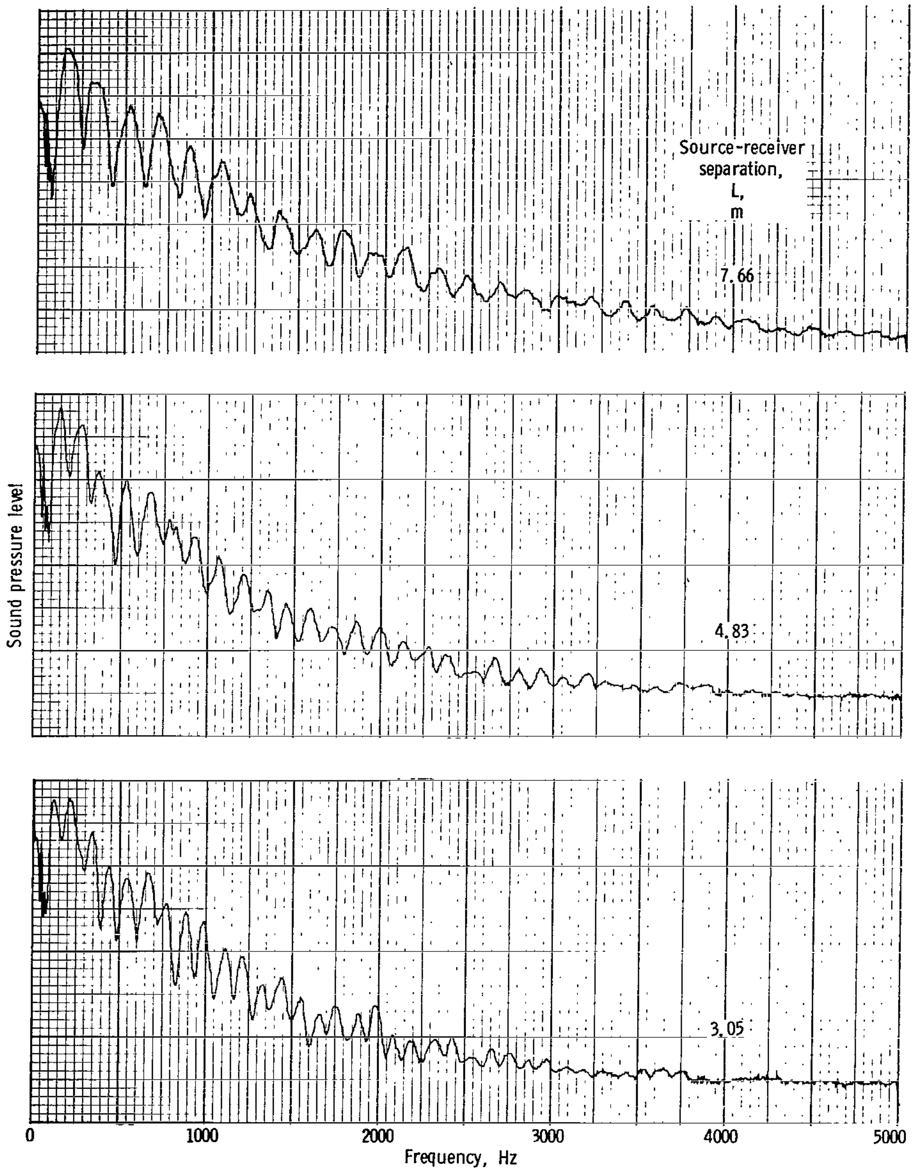
(b) Concluded.

Figure 16. - Continued.



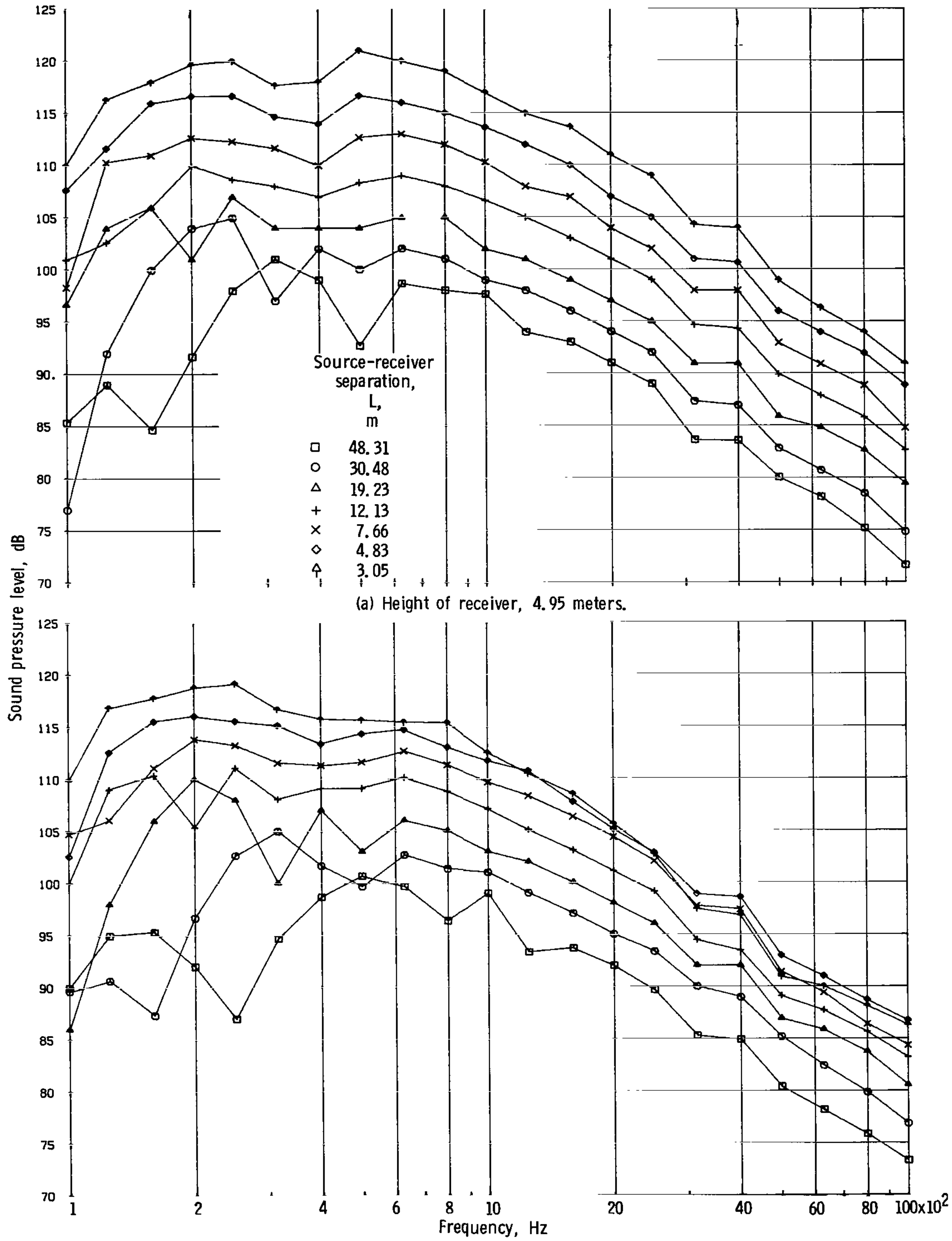
(c) Height of receiver, 1.65 meters.

Figure 16. - Continued.



(c) Concluded.

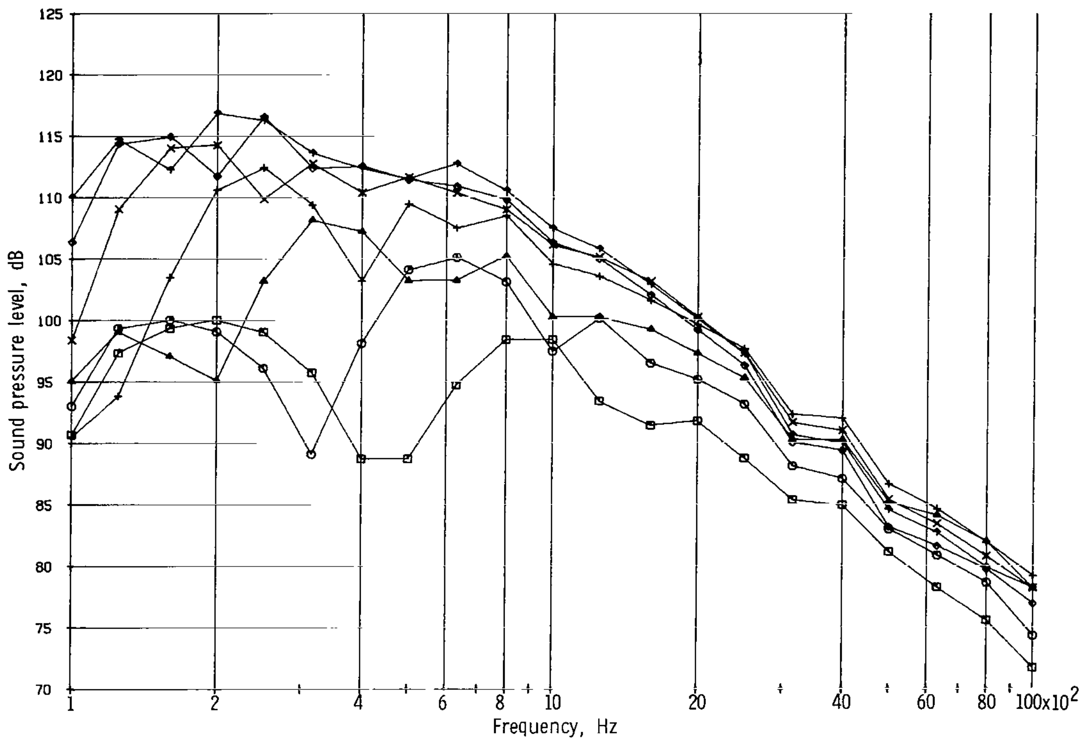
Figure 16. - Concluded.



(a) Height of receiver, 4.95 meters.

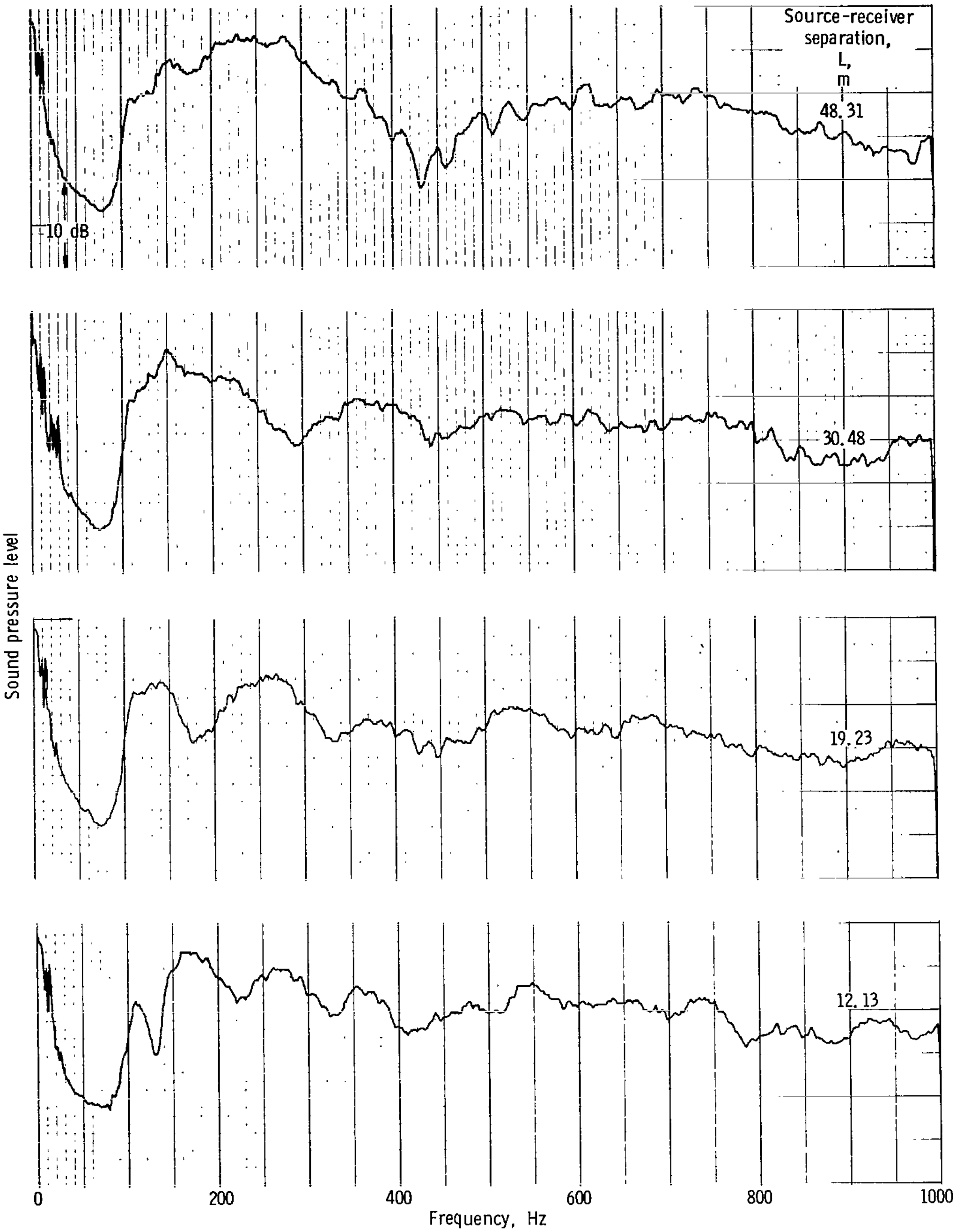
(b) Height of receiver, 3.30 meters.

Figure 17. - One-third octave spectra of base line tests.



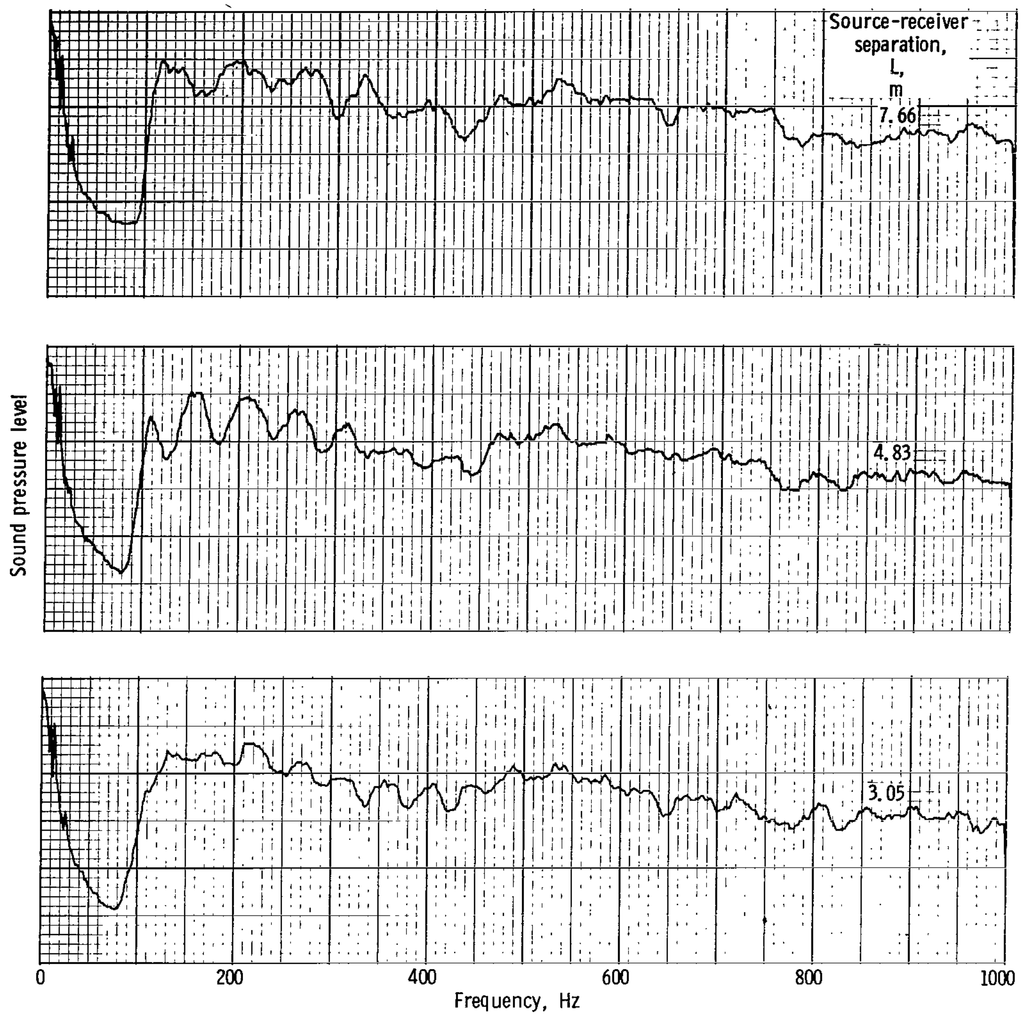
(c) Height of receiver, 1.65 meters.

Figure 17. - Concluded.



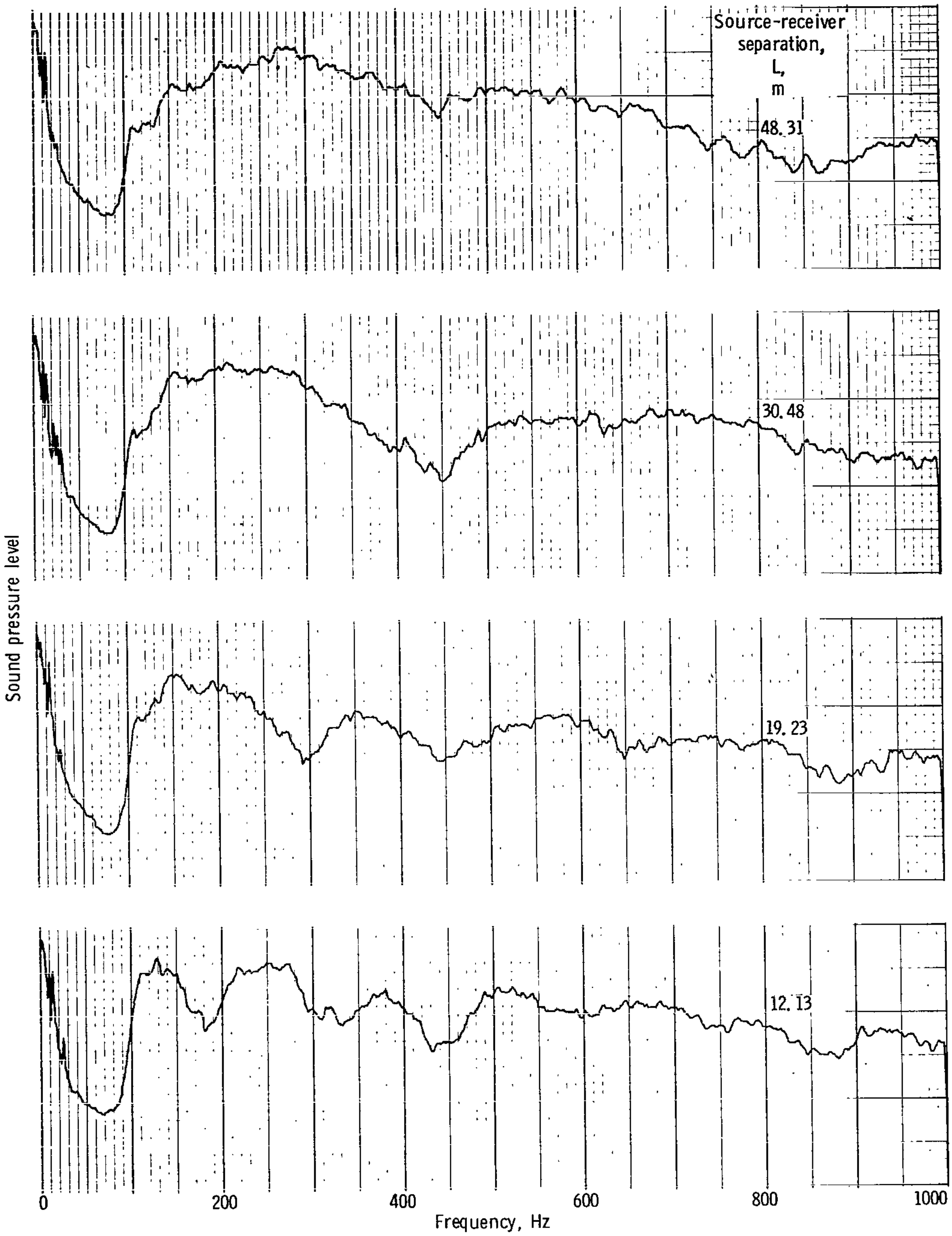
(a) Height of receiver, 4.95 meters.

Figure 18. - Narrow-band spectra for 1.52-meter from spacing. Bandwidth, 3.2 hertz.



(a) Concluded.

Figure 18. - Continued.



(b) Height of receiver, 3.30 meters.

Figure 18. - Continued.

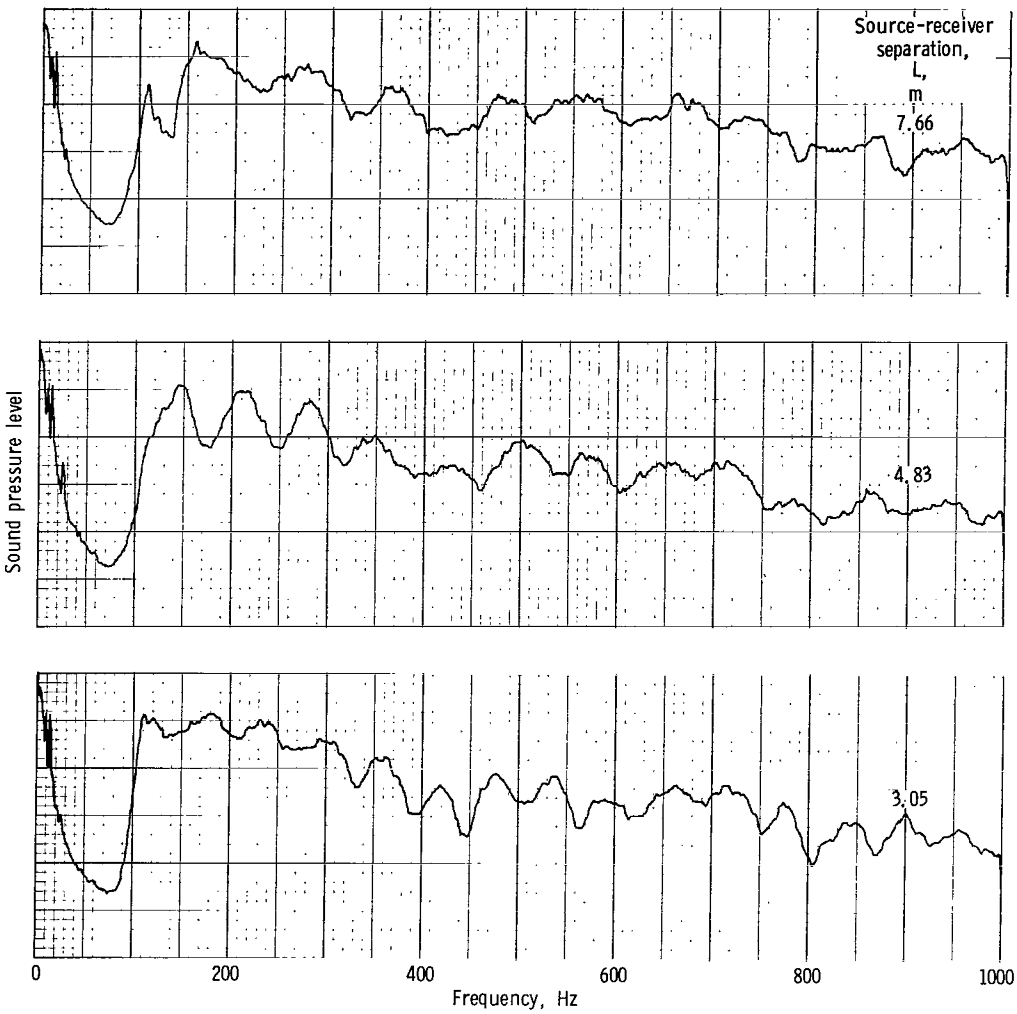


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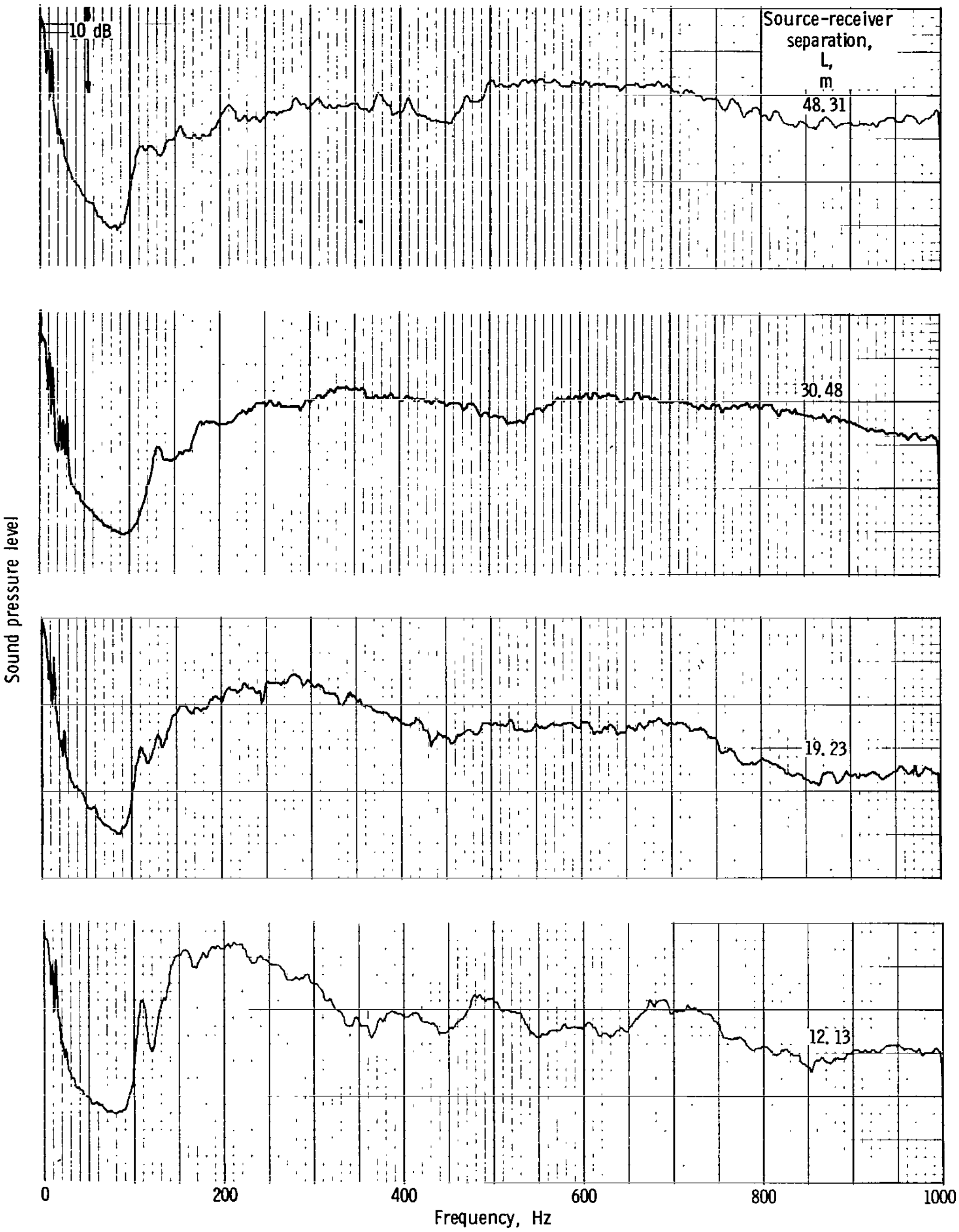
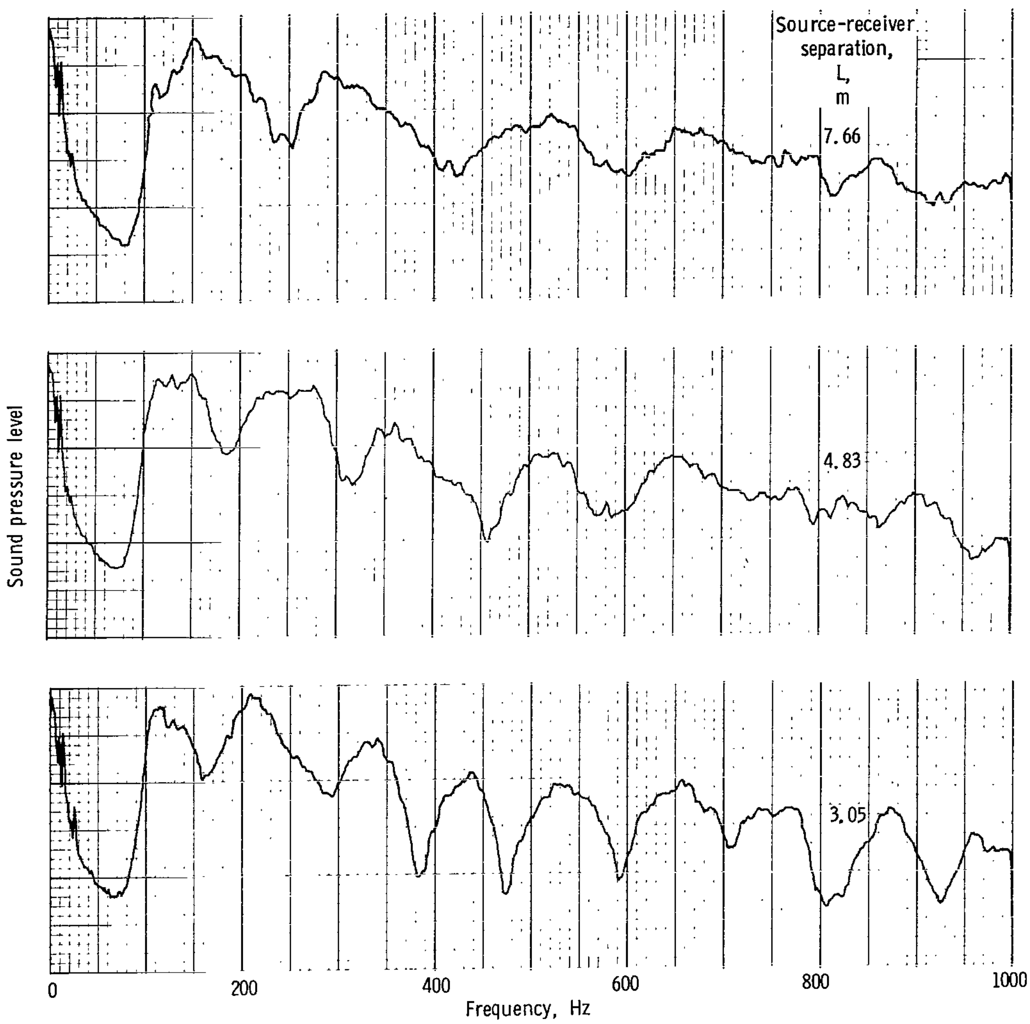
Figure 18. - Continued.



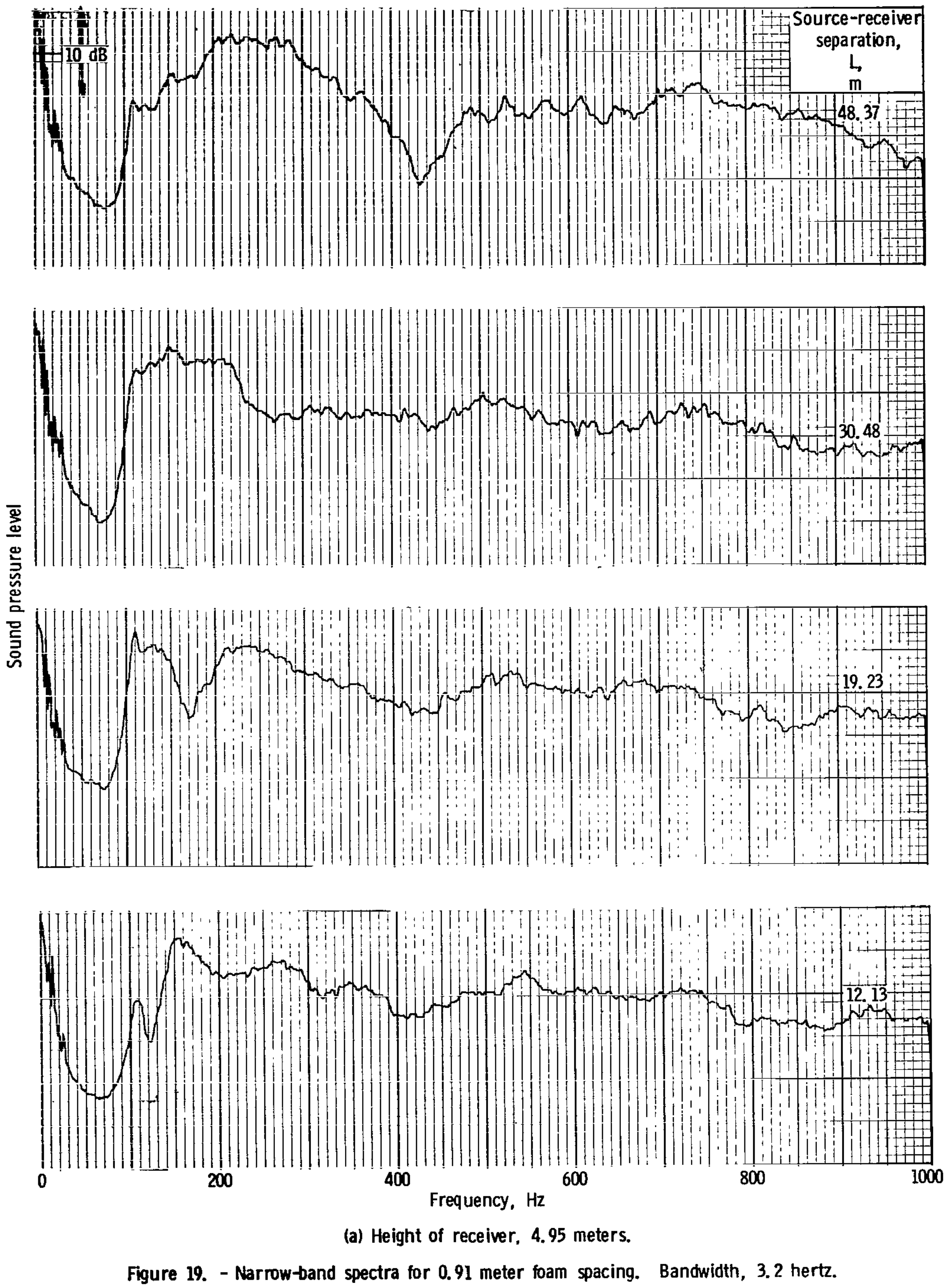
(c) Height of receiver, 1.65 meters.

Figure 18. - Continued.



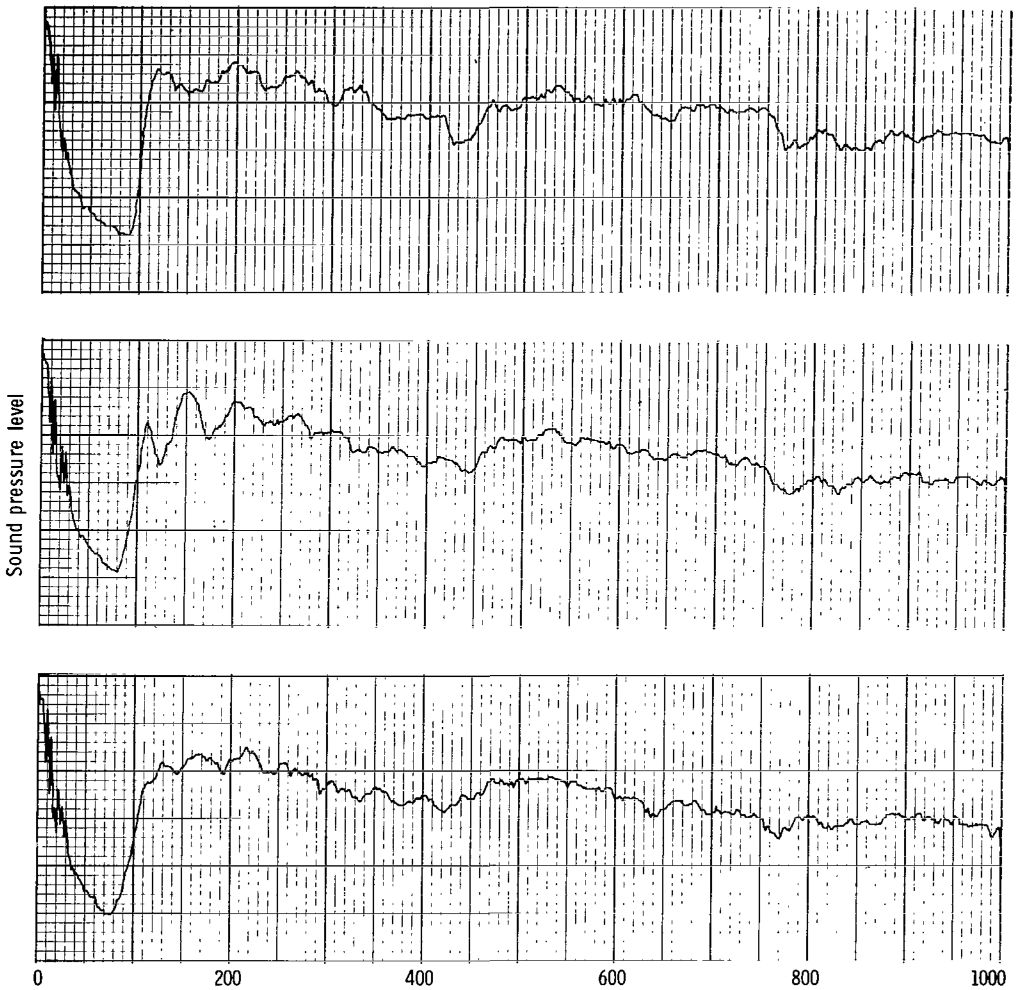
(c) Concluded.

Figure 18. - Concluded.



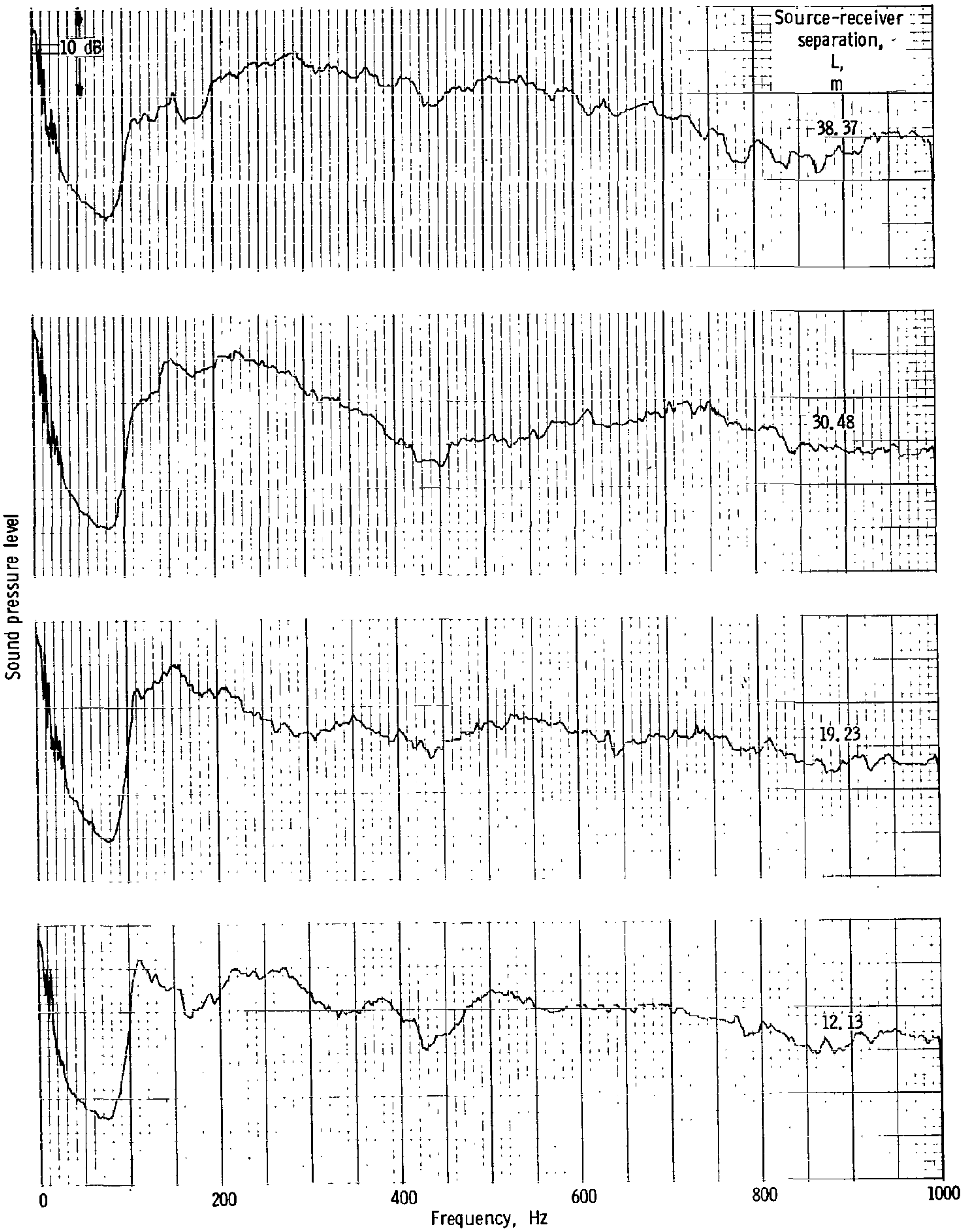
(a) Height of receiver, 4.95 meters.

Figure 19. - Narrow-band spectra for 0.91 meter foam spacing. Bandwidth, 3.2 hertz.



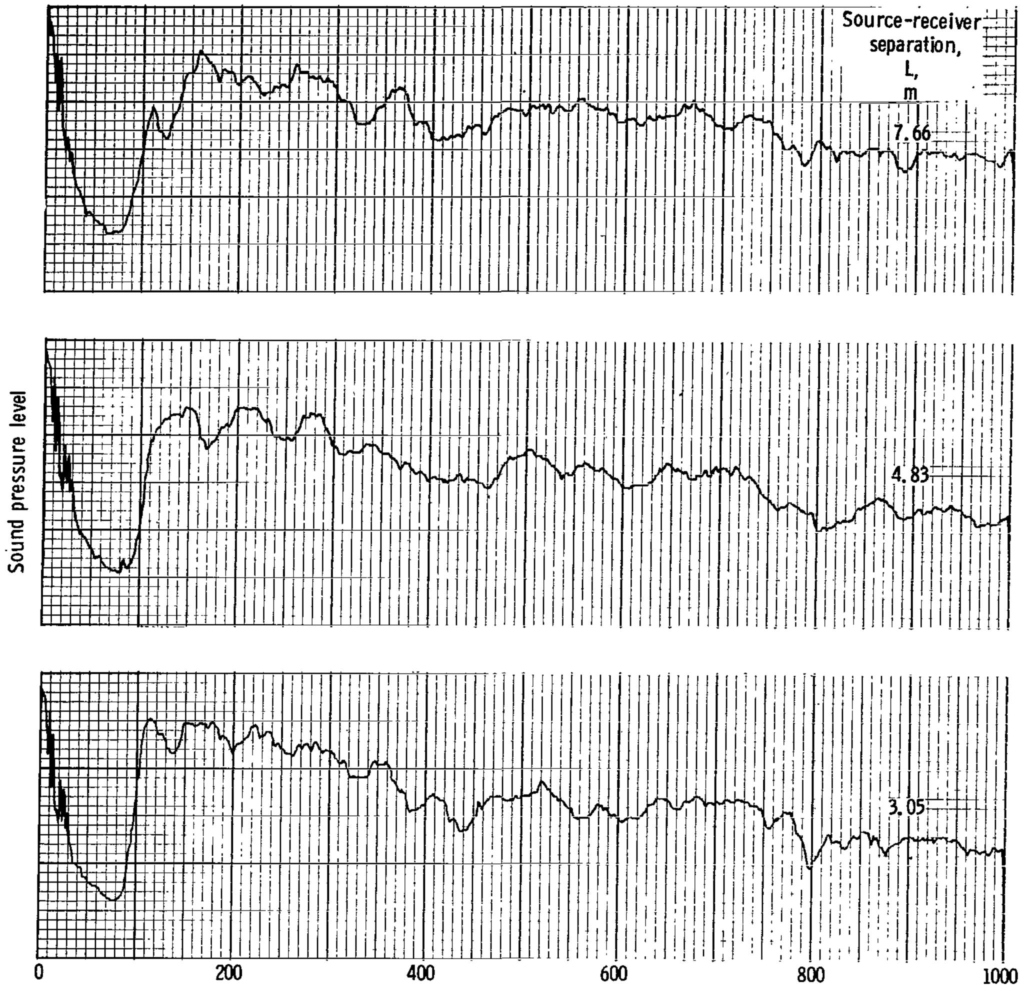
(a) Concluded.

Figure 19. - Continued.



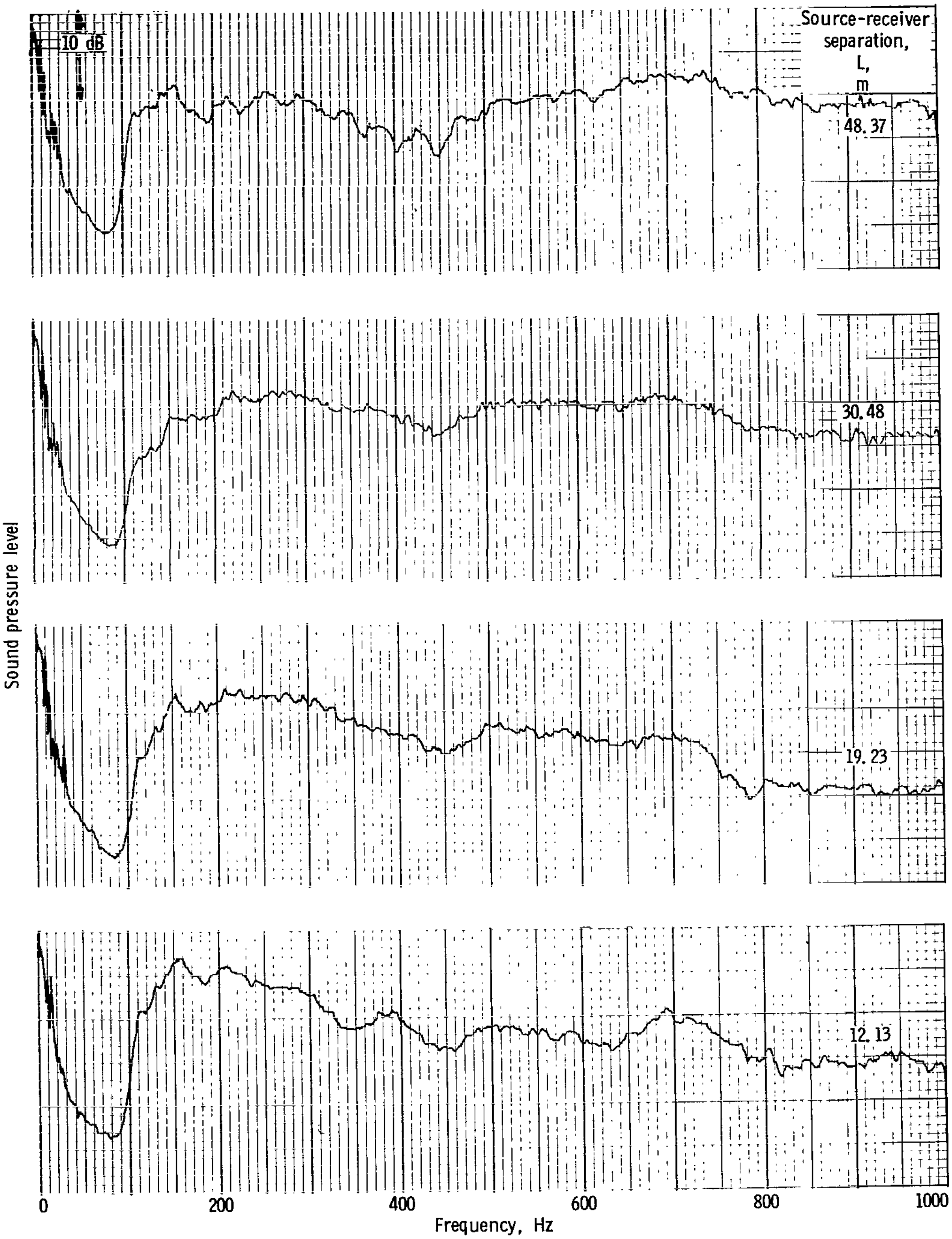
(b) Height receiver, 3.30 meters.

Figure 19. - Continued.



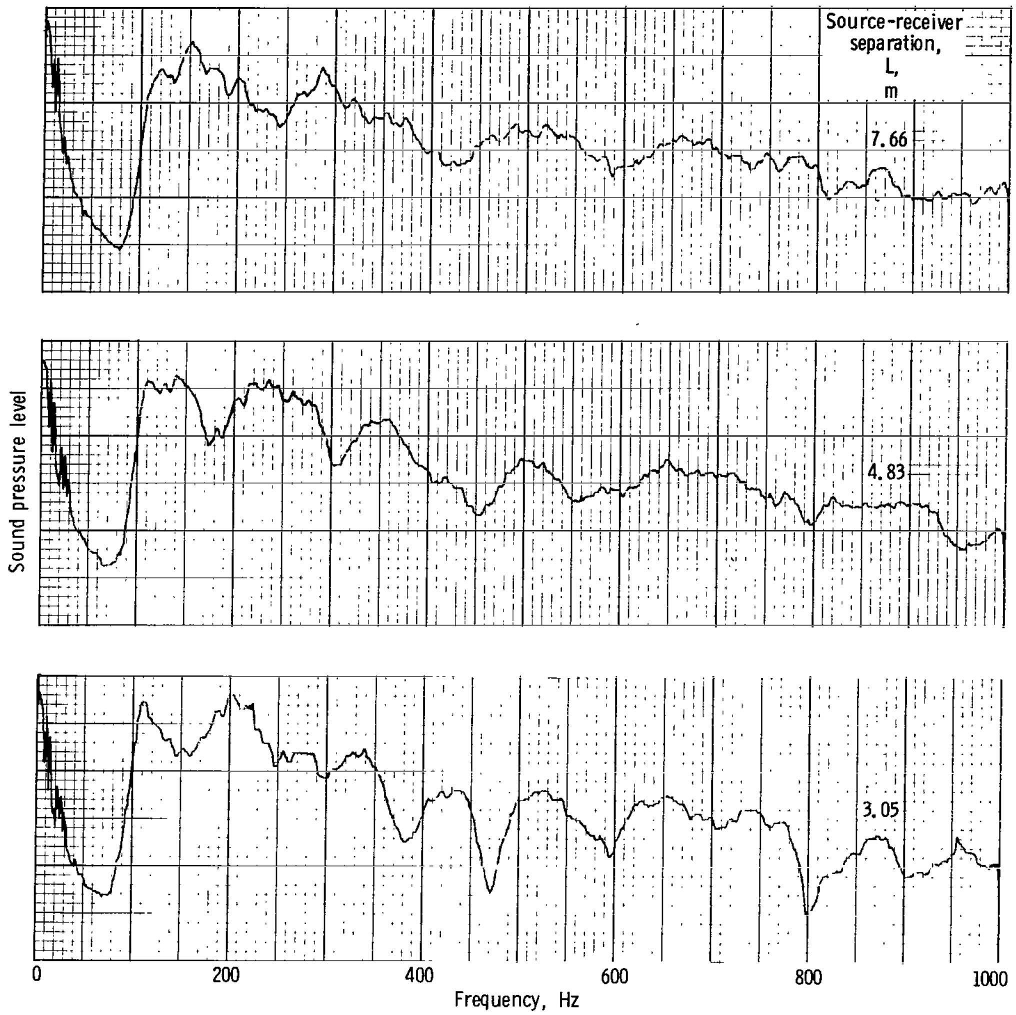
(b) Concluded.

Figure 19. - Continued.



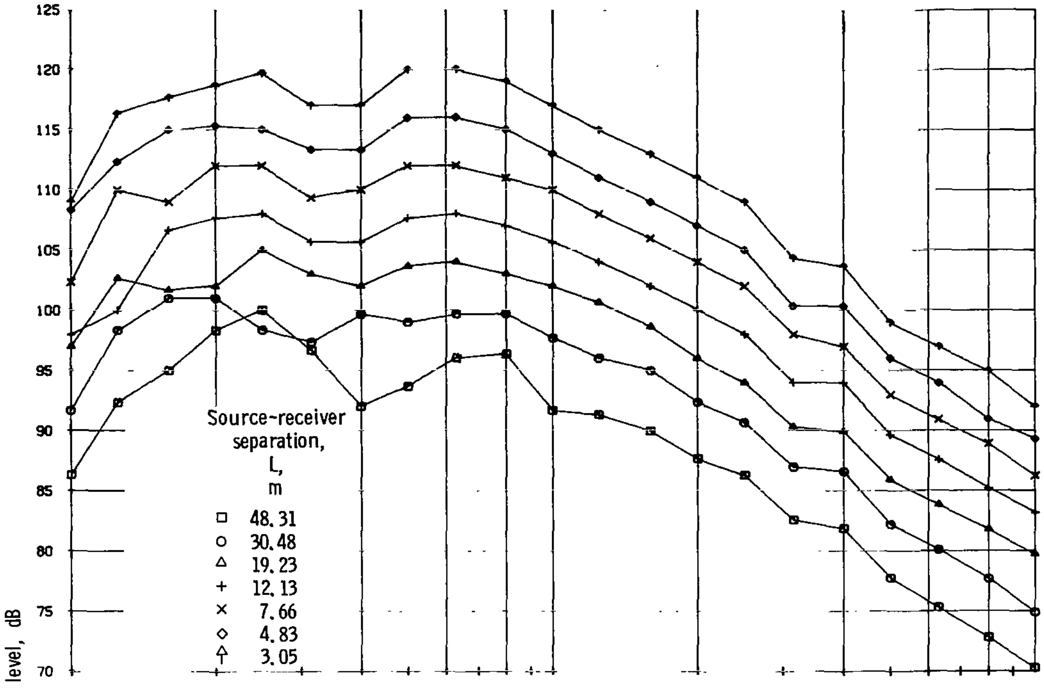
(c) Height of receiver, 1.65 meters.

Figure 19. - Continued.

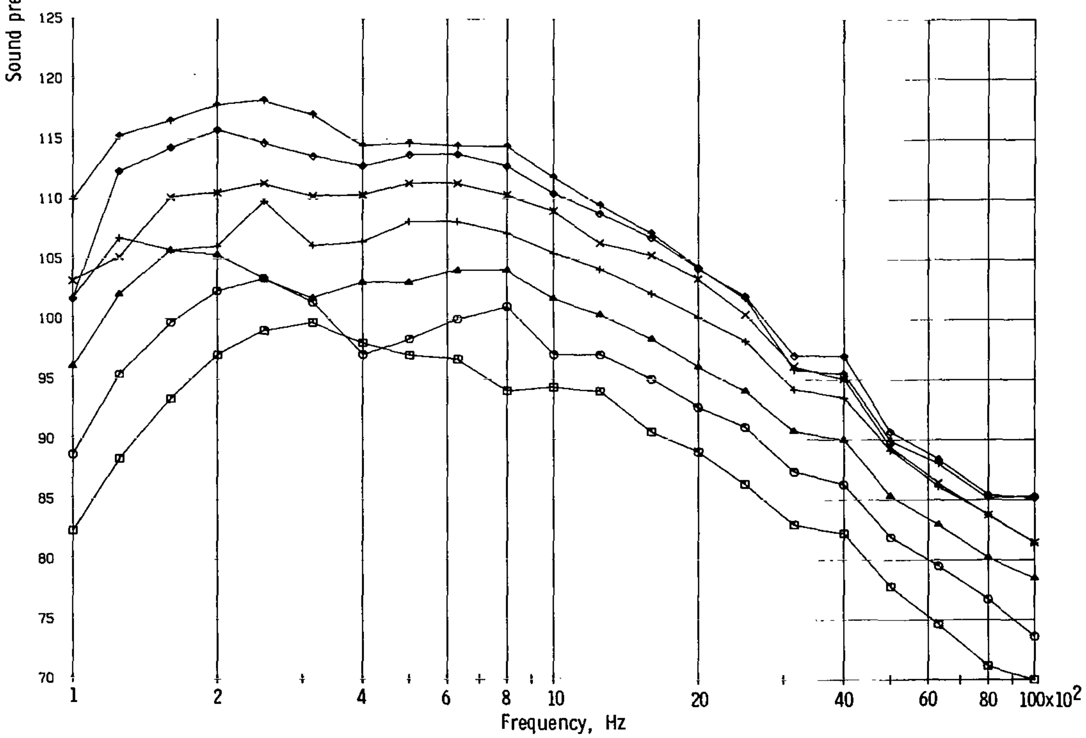


(c) Concluded.

Figure 19. - Concluded.

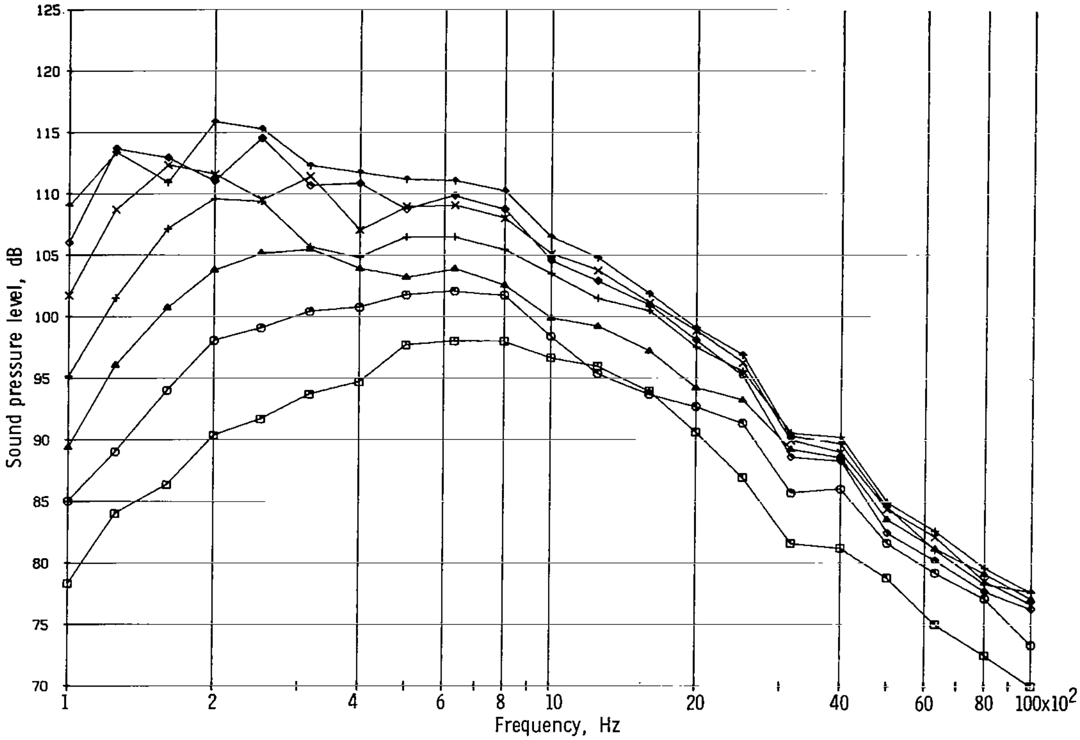


(a) Height of receiver, 4.95 meters.



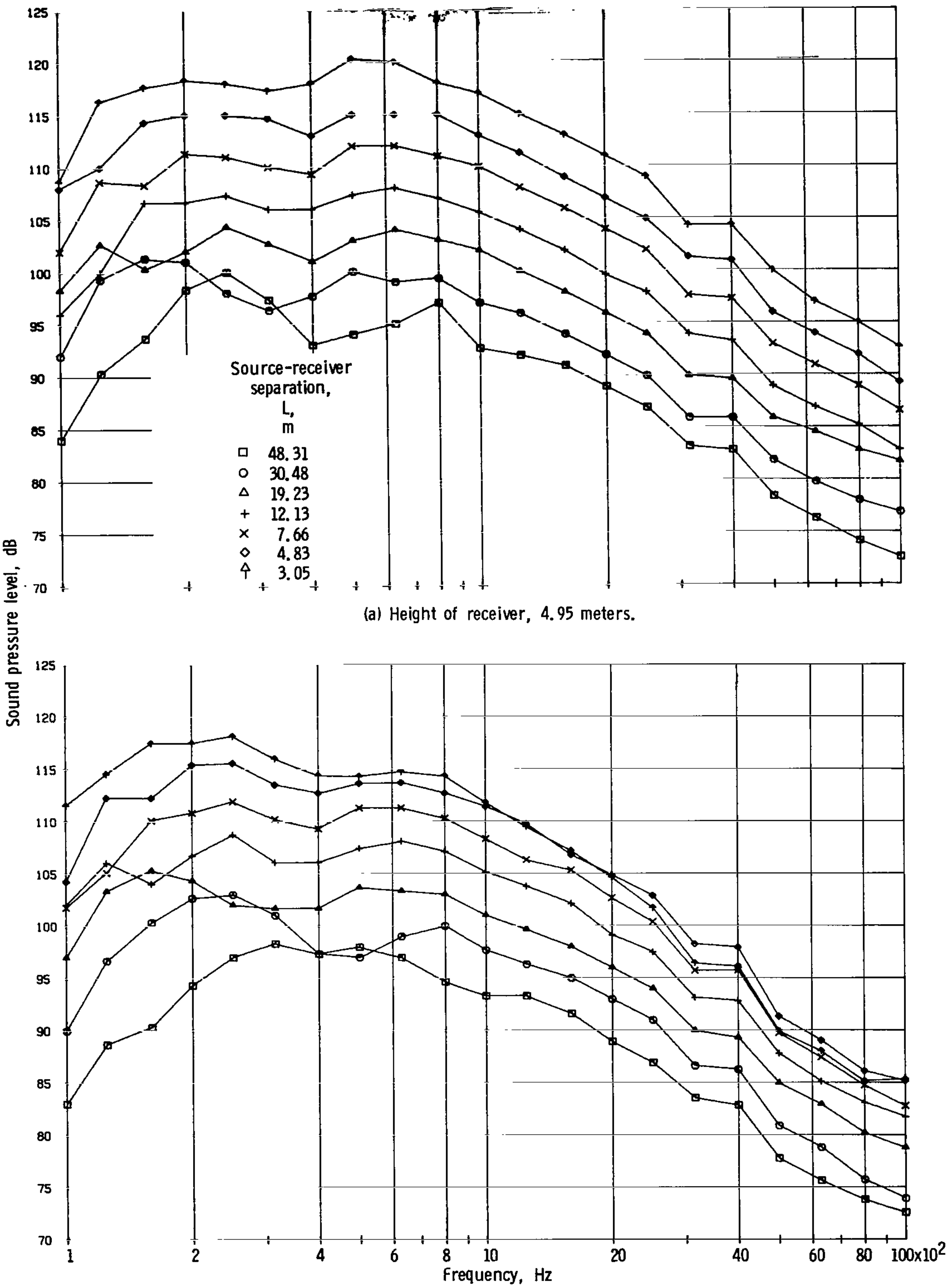
(b) Height of receiver, 3.30 meters.

Figure 20. - One-third octave spectra for 1.52 meter foam spacing.



(c) Height of receiver, 1.65 meters.

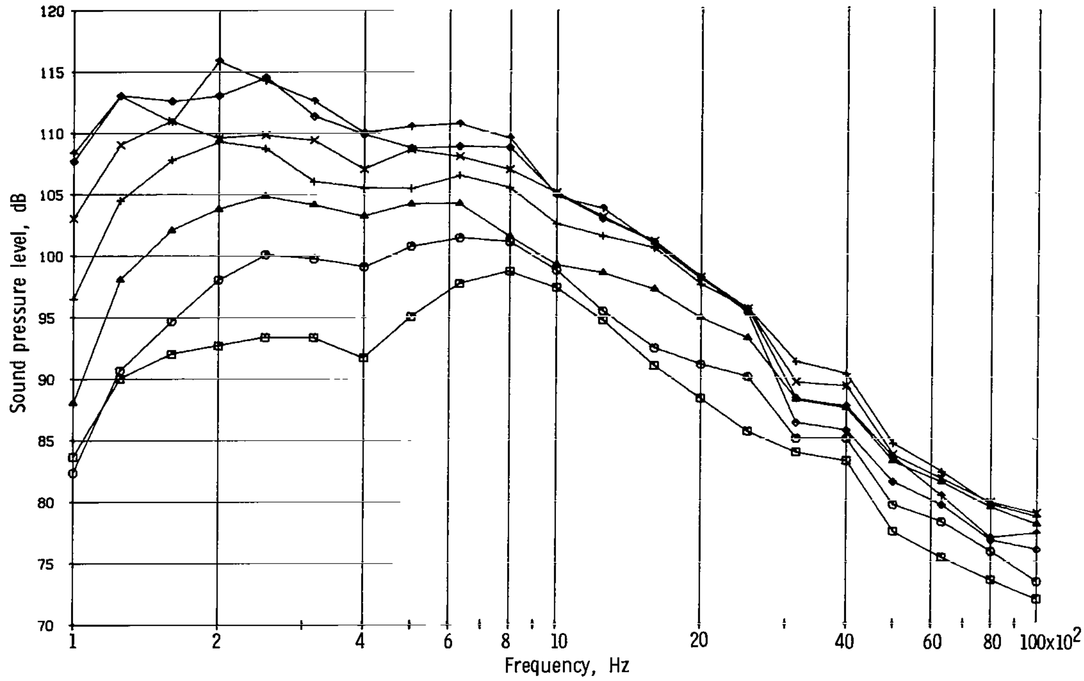
Figure 20. - Concluded.



(a) Height of receiver, 4.95 meters.

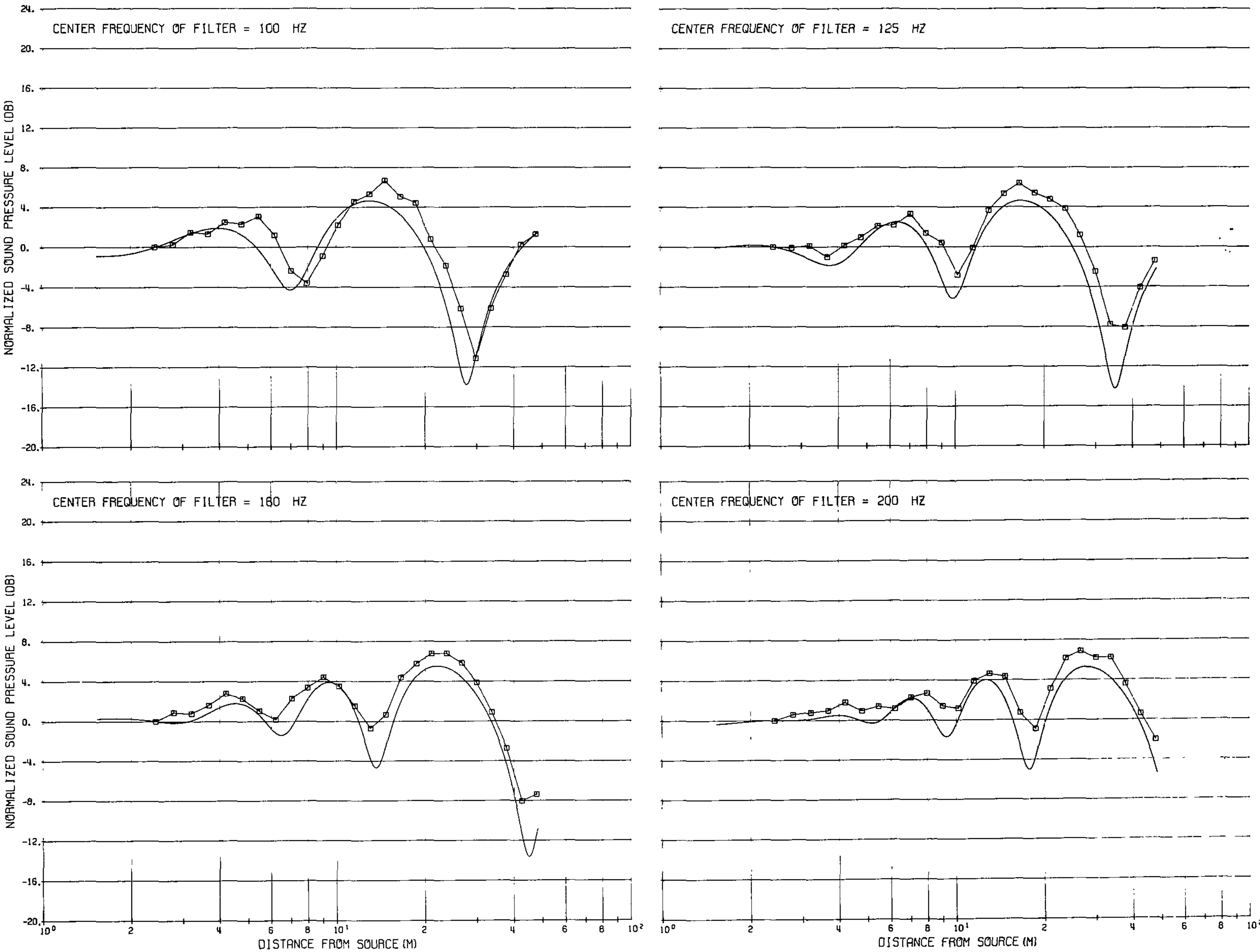
(b) Height of receiver, 3.30 meters.

Figure 21. - One-third octave spectra for 0.91-meter foam spacing.



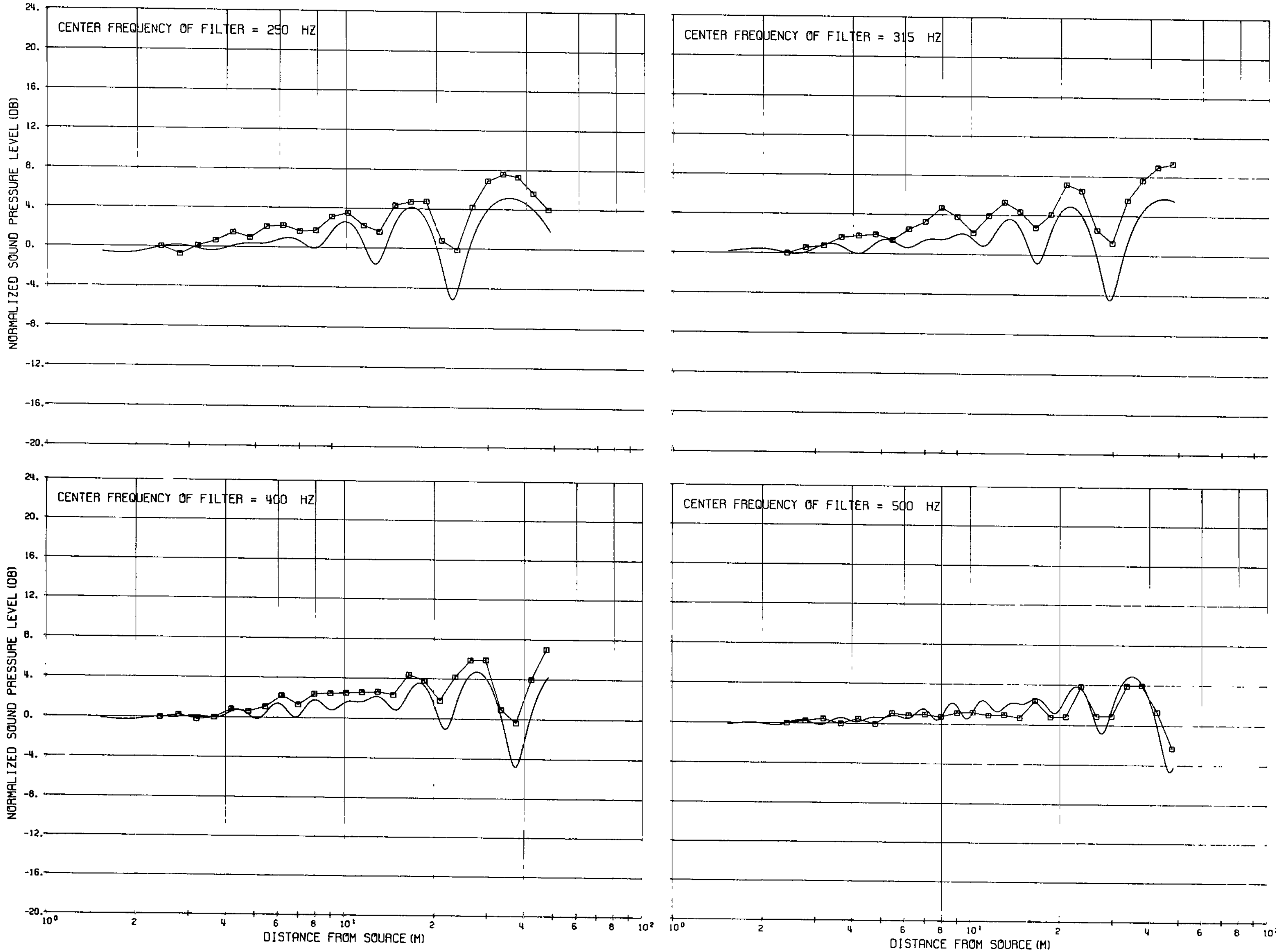
(c) Height of receiver, 1.65 meters.

Figure 21. - Concluded.



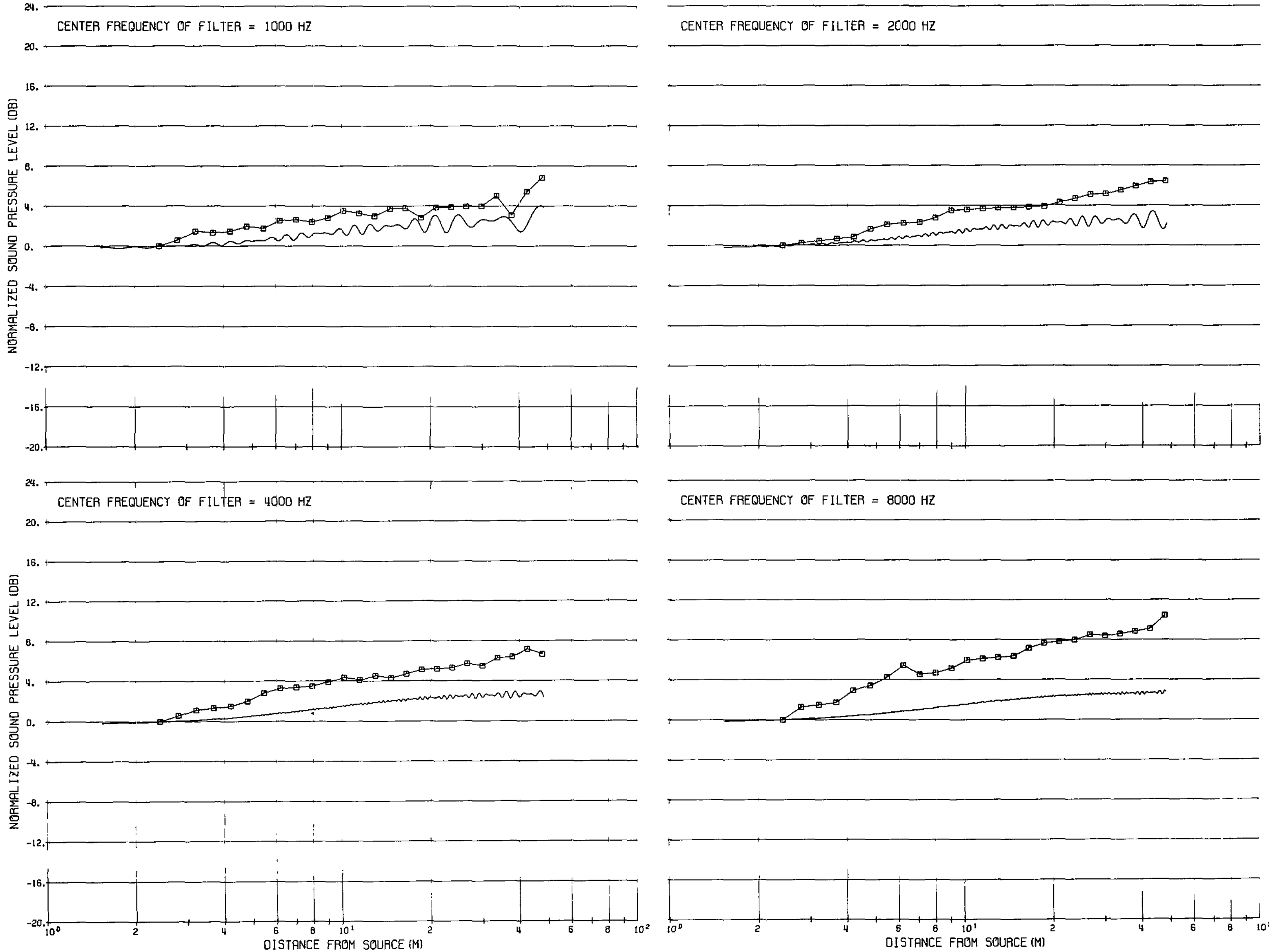
(a) Height of receiver, 4.95 meters.

Figure 22. - Comparison of one-third octave base line results with theoretical results of Howes (ref. 2).



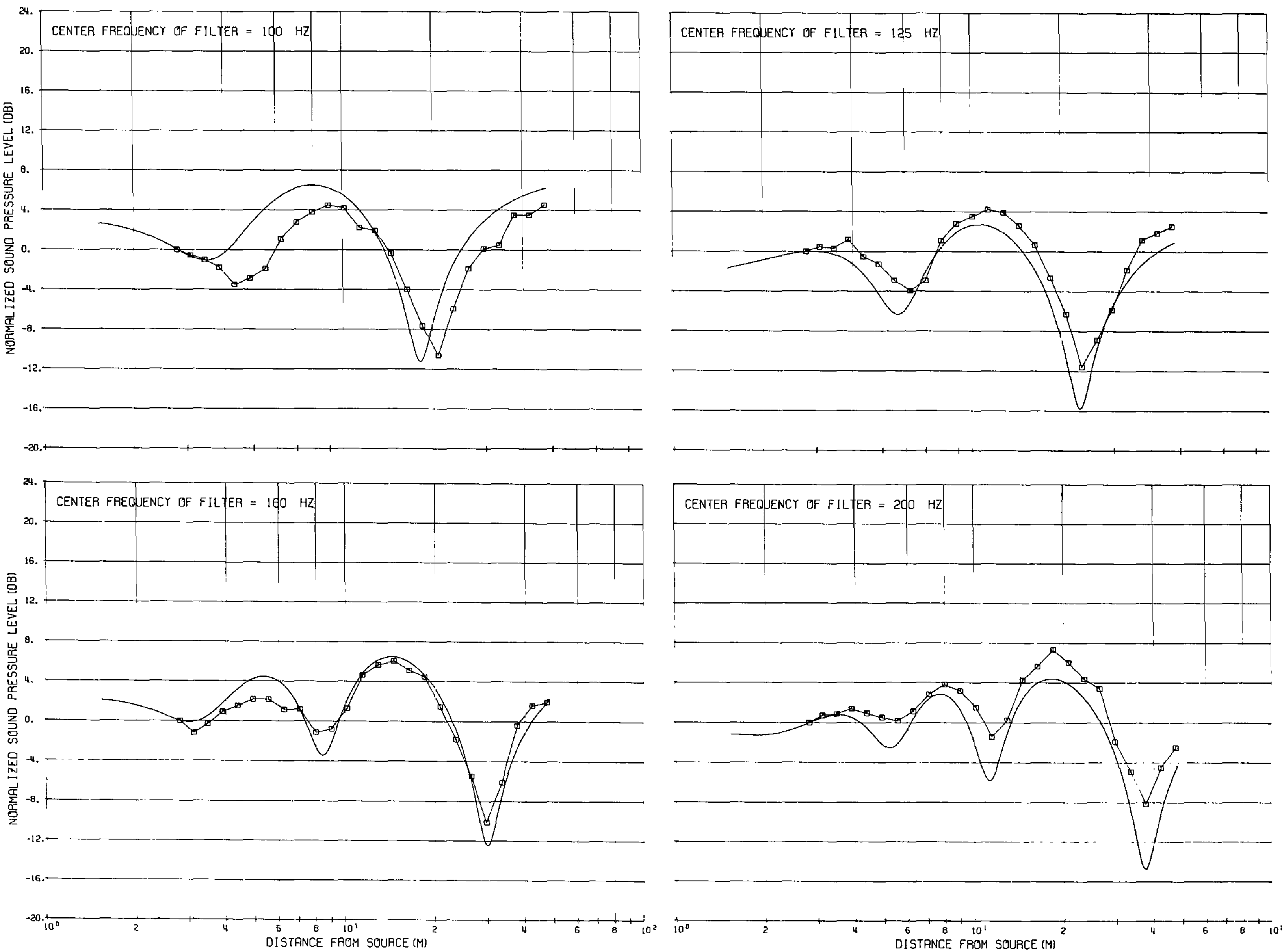
(a) Continued.

Figure 22. - Continued.



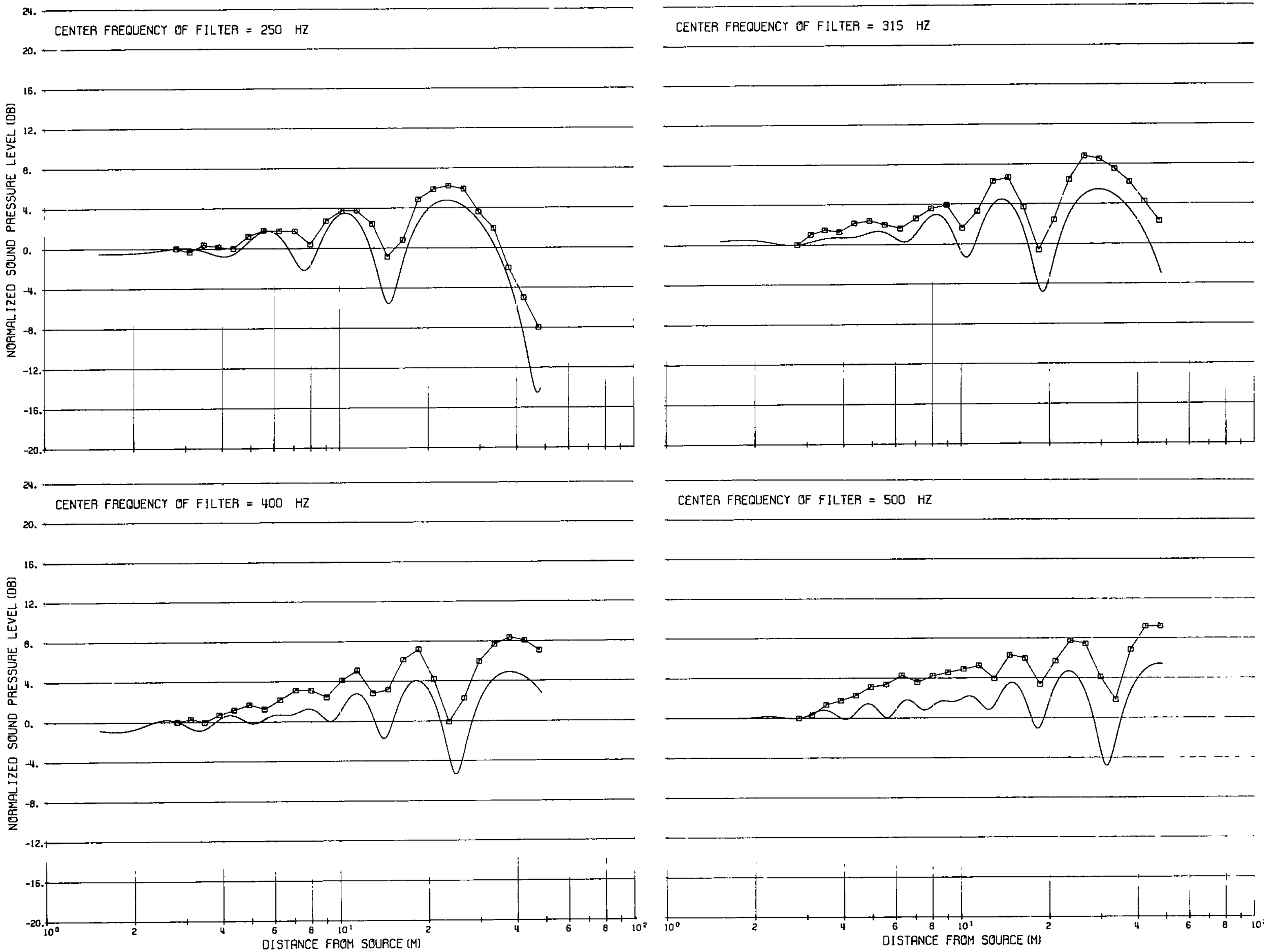
(a) Concluded.

Figure 22. - Continued.



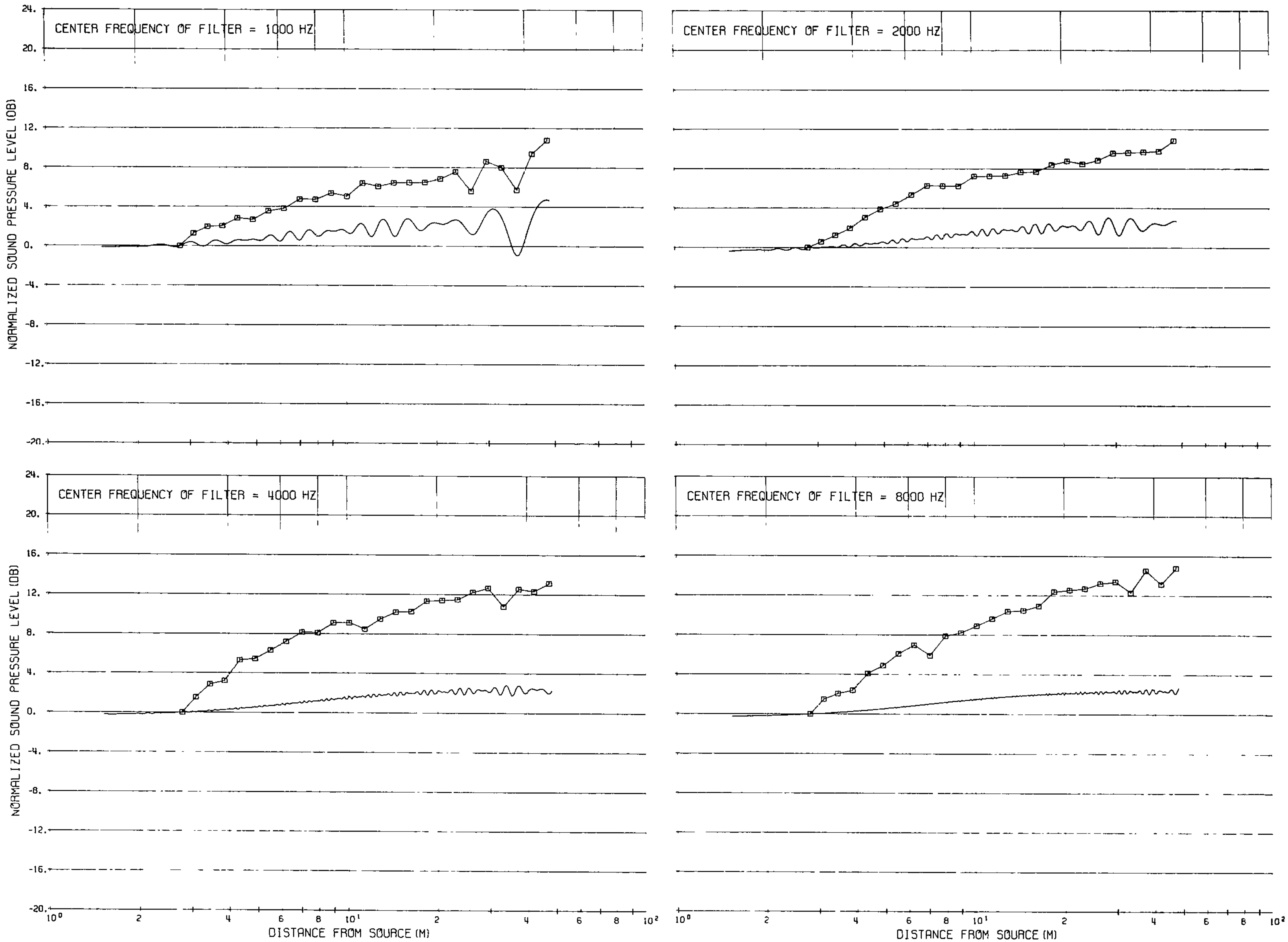
(b) Height of receiver, 1.65.

Figure 22. - Continued.



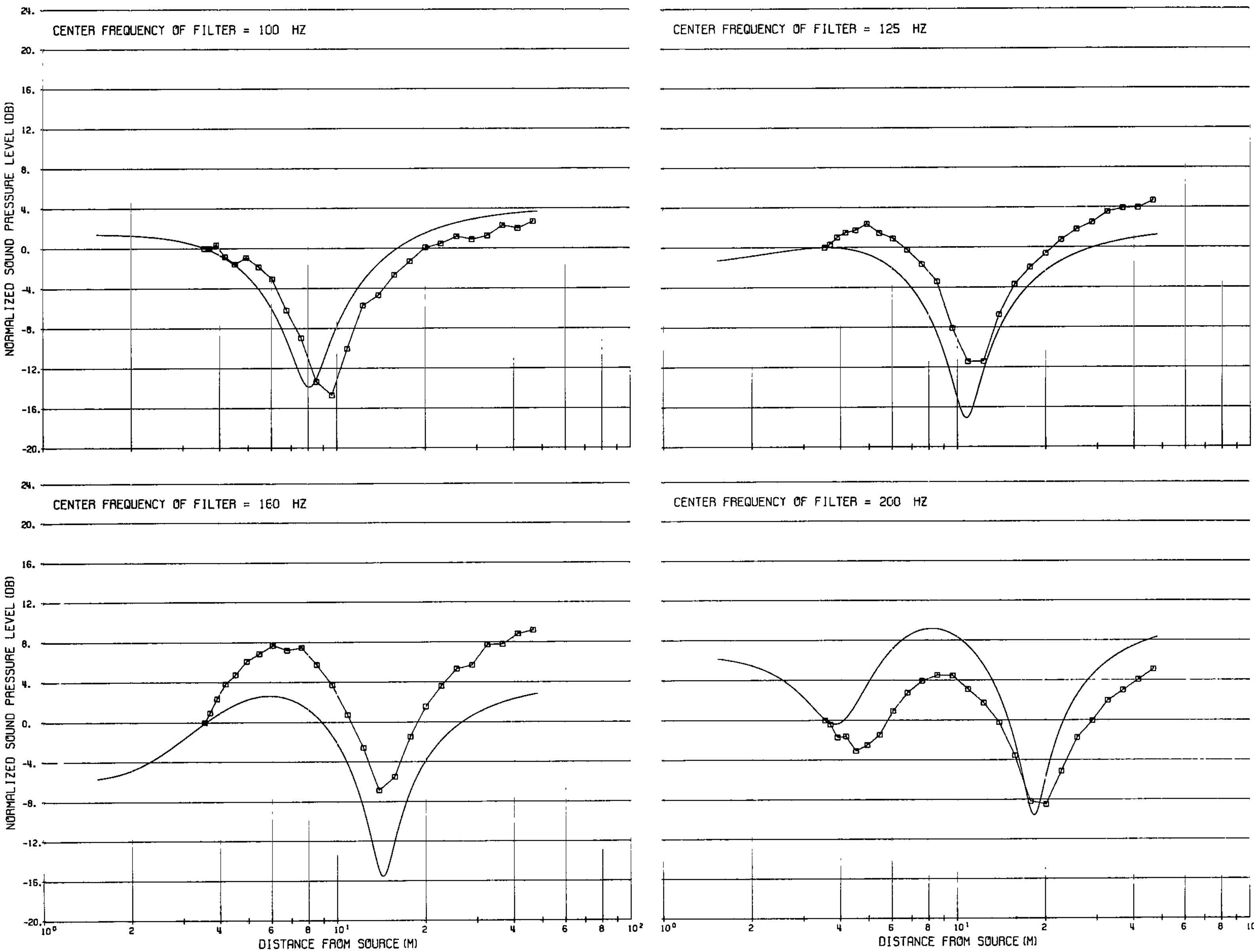
(b) Continued.

Figure 22. - Continued.



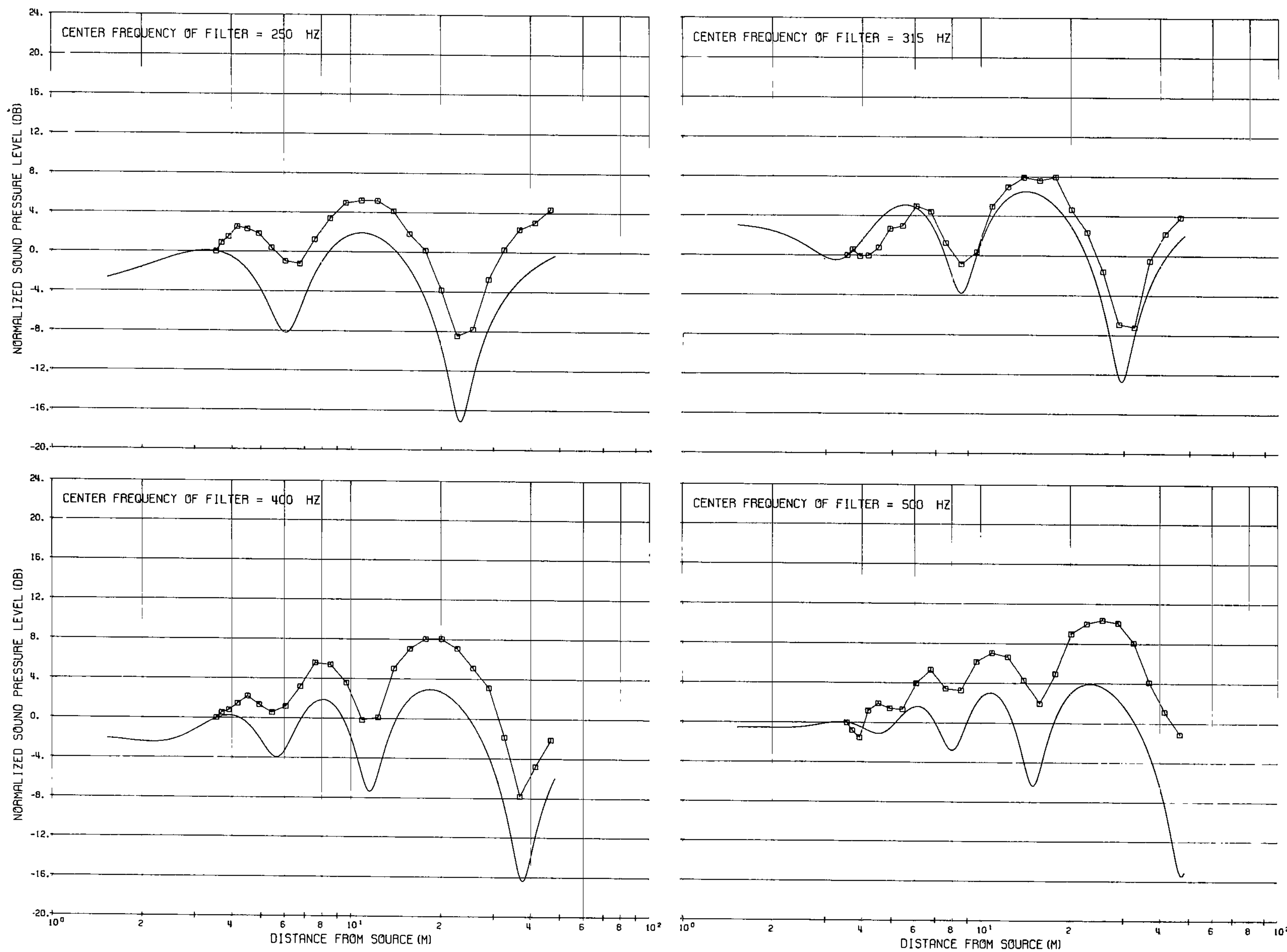
(b) Concluded.

Figure 22. - Continued.



(c) Height of receiver, 1.65.

Figure 22. - Continued.



(c) Continued.

Figure 22. - Continued.

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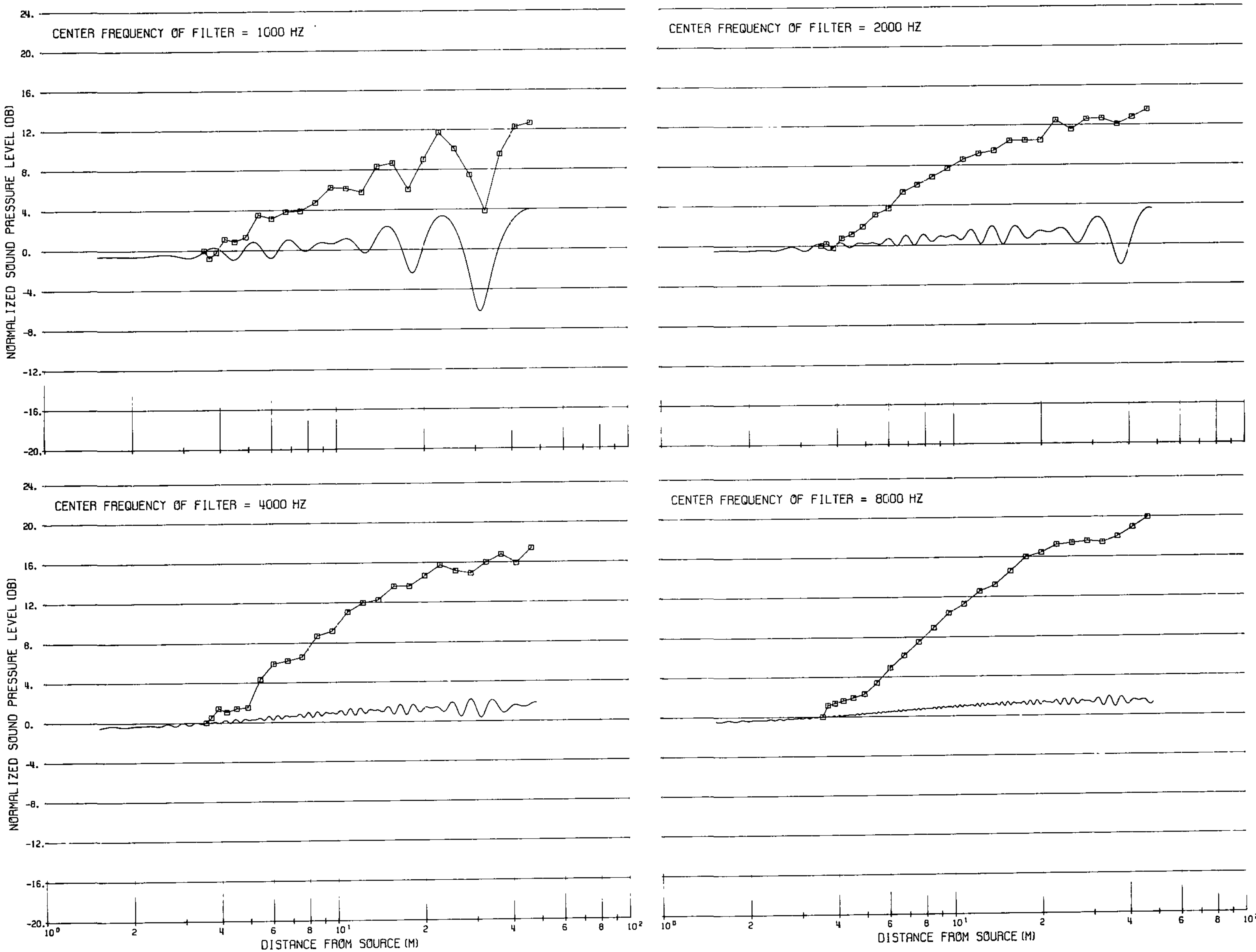

(c) Concluded.

Figure 22. - Concluded.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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