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RESEARCH PROGRAM REPORT **33.1**

# GROUND PLANE WIND SHEAR INTERACTION ON ACOUSTIC TRANSMISSION

RESEARCH PROJECT

Y-1739

JUNE 1978

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WASHINGTON STATE TRANSPORTATION COMMISSION
IN COOPERATION WITH
U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

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UNIVERSITY OF WASHINGTON

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16. Abstract

Experimental data indicate that the combined effects of wind shear and ground plane attenuation can have a strong influence on sound propagation near the ground even at distances as short as 100 ft. The effect manifests itself experimentally as a noticeable difference between sound propagation upwind vis-à-vis downwind that becomes more pronounced with either increased distance or increased wind speed. Differences of up to 25 dBA were found between into-the-wind and with-the-wind propagation for a listening height of 4 ft and a transmission distance of about 300 ft. Even a very moderate wind (4 mph) produced a difference of 12 dB at 150 ft for the same listening height. A large body of spectral data was also taken under a variety of wind conditions for path lengths of 150 ft and 225 ft. The resulting spectra agreed reasonably well with theoretical predictions for frequencies below 500 Hz, where ground and surface waves predominate; an important observation is that these waves were not affected substantially by wind conditions. Above approximately 500 Hz, the attenuation was frequently more than that predicted theoretically, and it was wind sensitive. The effect of wind was, in many cases, large, and could well mean that much experimentally obtained highway noise data is considerably less useful than previously thought, unless wind shear was taken into account during the measurements. In general, to "hear" the full effect of existing traffic, measurements should be made when the test position is downwind from the traffic.

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## TRANSMISSION EFFECTS

### Ground Plane Effects

Sound rays traveling near the ground can be reflected back into the air, refracted into the ground, and/or absorbed. Each of these effects can be produced with a concurrent phase shift. The amount of shift depends on the acoustic impedance of the ground vis-à-vis that of air as well as such parameters as frequency and arrival angle. Transmission close to and nearly parallel with the ground results in considerably more attenuation than predicted by inverse square spreading and atmospheric absorption. Current theory[1-3] maintains that this excess attenuation is caused by a cancellation effect between the primary wave and reflections from an "image" of the source beneath the surface. This theory holds that, if the angle between the reflected ray and surface of the ground is small enough, there is a phase change of up to 180° in the reflected ray, causing the primary ray and the reflected ray to cancel one another and create a shadow zone (increased attenuation). If the surface of the ground had the characteristic impedance of solid earth, the angle at which this cancellation would take place would be extremely shallow, only a tiny fraction of a degree. However, in actual practice, the surface of the ground appears to "breathe"; as a consequence, the mismatch between the acoustic impedance of the air and that of the ground surface is not nearly as severe as it would otherwise seem. The net result is that the predicted canceling effect can take place at somewhat steeper (and practically significant) reflection angles.

This part of the theory is meant to explain the attenuation produced in still, homogeneous air at frequencies from approximately 500 Hz up through the audio region. At lower frequencies (typically below 500 Hz), other transmission phenomena such as ground waves and surface waves[1-3] create a different transmission mode that penetrates the shadow zone.

The results of this experimental study show good correlation with the theoretical predictions for surface and ground wave propagation. At higher frequencies, however, the actual attenuation is often greater than theory predicts.

### Wind Shear Effects

When a fluid (such as air) flows through a system bounded by a rough surface (such as common ground cover), the flow velocity at the rough surface drops toward zero. As the distance from the rough surface increases, the velocity increases until it finally equals the free stream velocity. Hydrodynamic theory indicates that the average, or integrated, wind velocity over a rough surface will vary logarithmically as a function of height, provided that the flow is turbulent. These conditions are met for almost all wind velocities and terrains of interest in highway noise work. The height of this logarithmic region varies from 50-100 ft, for very smooth surfaces, up to as much as 2000 ft for very rough surfaces; for typical grass or field crops, it appears to extend at least several hundred feet.

This nonconstancy of wind velocity with height means that sound rays transmitted through a windy medium will not travel in straight lines. Rays traveling in the same direction as the wind will tend to be bent downward, whereas rays traveling into the wind will tend to be bent upward. This effect is shown schematically in Figure 1. To intersect the receiver, rays traveling downwind from the source, $S_1$, must be initially directed at an upward angle; rays traveling upwind from the source, $S_2$, must be directed somewhat downward. Note that the "cupping" effect on the transmission path due to wind shear is not wavelength dependent; sound of all frequencies will be "bent" the same amount.

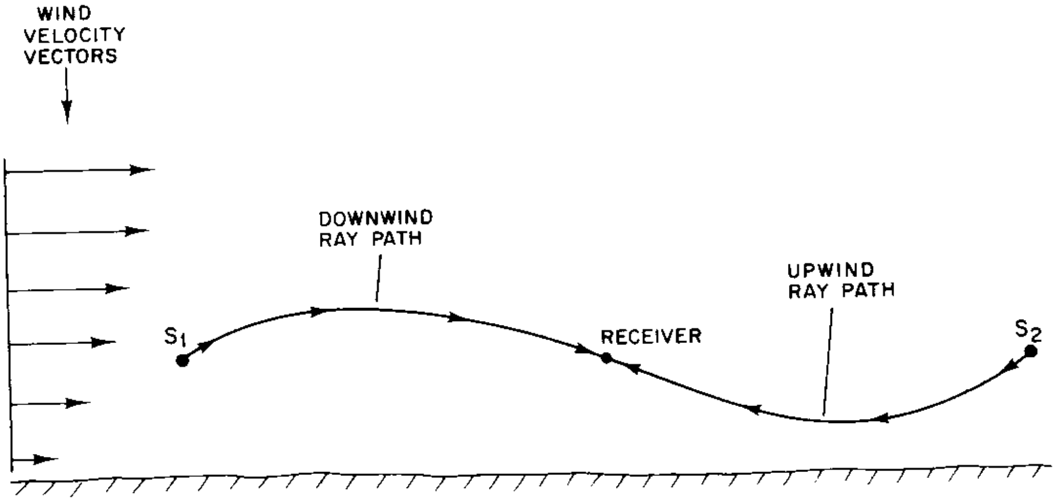

*Figure 1. Schematic representation of sound ray path in upwind and downwind directions when wind shear is present.*

## Combined Effect

Note from Figure 1 that sound traveling with the wind would tend, on the average, to follow a path farther from the ground than it would if no wind were present. Conversely, transmissions into the wind would tend to travel much closer to the ground than they would if there was no wind shear. Thus, propagation in a downwind direction tends to reduce the ground plane attenuation, and propagation in an upwind direction tends to enhance the effect. But how strong, in practice, are these effects? Over what distances and at what listening heights are they important, and what wind velocities are required to substantially affect acoustic transmissions? The experimental measurements show that the combined effects of wind shear and ground plane effects can be quite substantial even at relatively low wind velocities.

## A-WEIGHTED DATA

### Experimental Procedures

To eliminate as many variables as possible, the type of ground investigated was limited to two simple flat surfaces, one covered with grass mown to a height of 2-3 in.*, and the other with weeds 18-24 in. high. Cross sections of the experimental geometries are shown in Figure 2 for the grass field and in Figure 3 for the weed field. In these drawings, the horizontal scale is compressed by a factor of 25 to 1 compared to the vertical scale; as a result, any height irregularities are amplified by a factor of 25. To the eye, both fields appear quite flat.

For all the tests involving A-weighted data, the noise sources were located nominally 1 m above the ground, and aligned as shown in Figures 2 and 3. The receiving microphone was located in the middle of the line at the position labeled "0" on the drawings. The sources were replaced in the same positions each day that experiments were conducted. Because we could not control the wind, many measurements were required to find a sufficient number of conditions similar enough to be grouped together statistically for plotting. (The data in this report were collected over a period of months.)

Testing was done both at discrete frequencies and with a pseudorandom noise source. The results presented in this report are for pseudorandom noise. This noise was generated digitally using a 16-stage shift register. The frequency of the clock used to step the shift register was 10 kHz; thus most of the data shown in this report are labeled "10 kHz clock frequency." The electrical drive to the speakers had the spectrum shown in Figure 4. Note that the energy falls off above 4.5 kHz, with a null occurring at the clock frequency of 10 kHz.

A photograph of the field setup is shown in Figure 5. Since the horns closer to the microphone were in the field of, and could obstruct, the transmissions from the horns farther out, the size of the horns used

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*an intramural athletic (IMA) field, frequently mowed

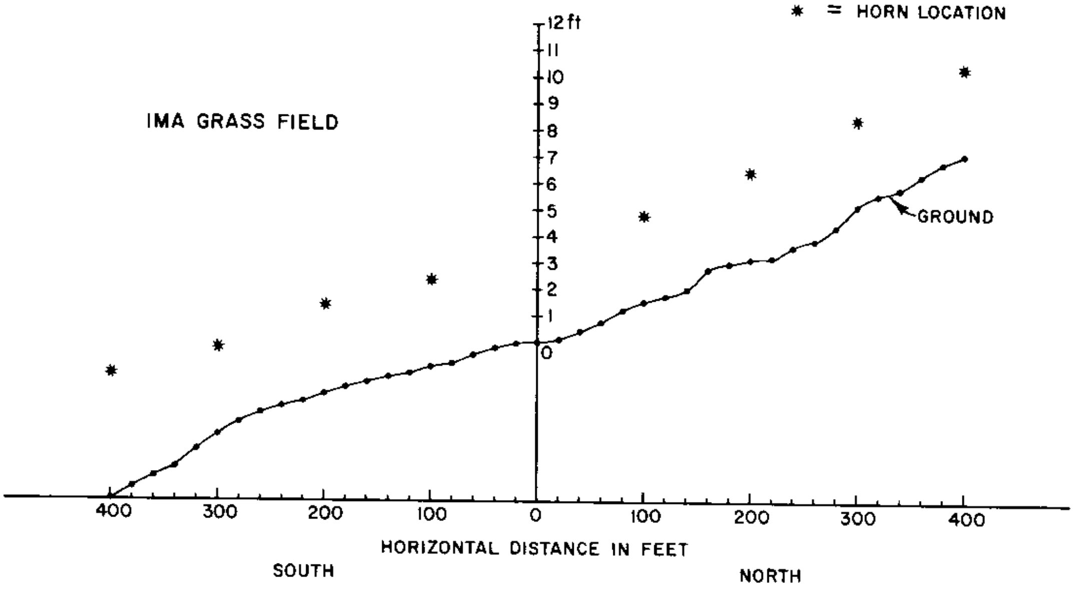

*Figure 2. Profile for grass experiments.*

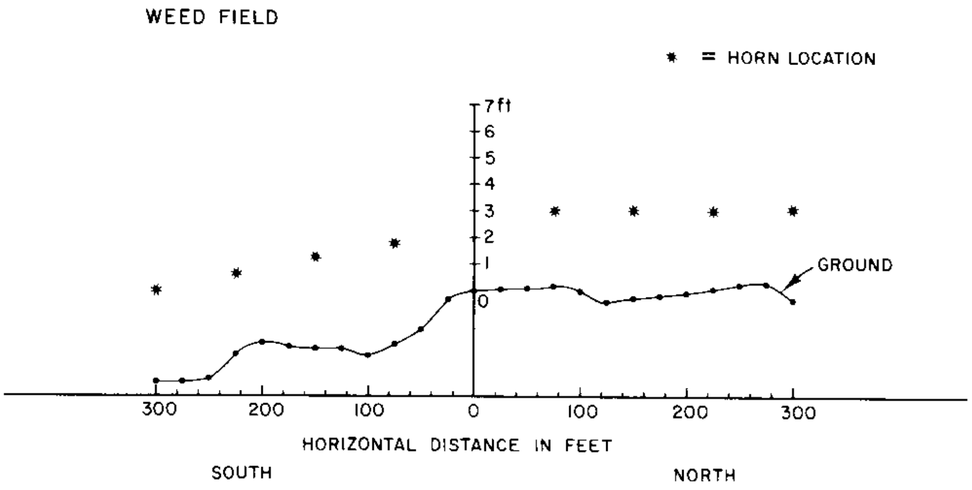

*Figure 3. Profile for weed-field experiments.*

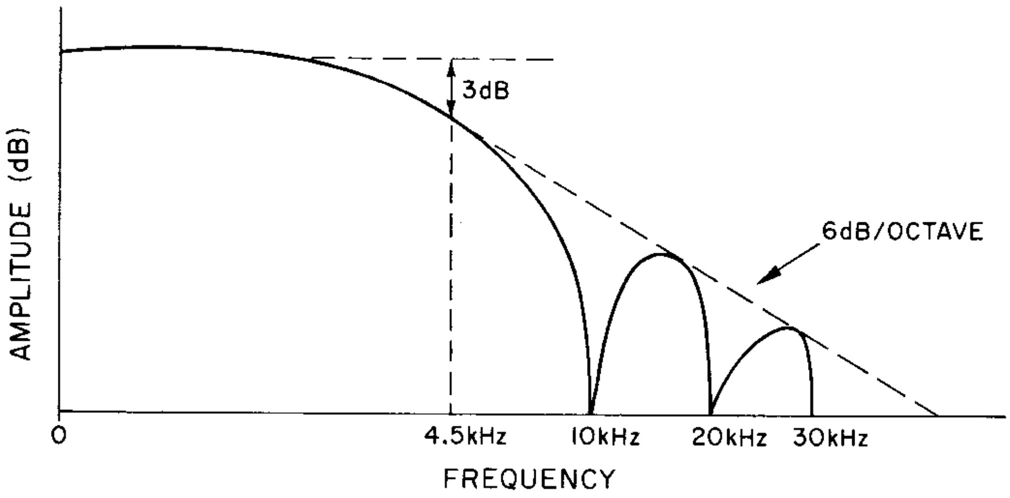

*Figure 4. Frequency spectrum of pseudorandom noise generator, 10-kHz clock frequency.*

*Figure 5. Weed-field test site viewed along the line of speakers.*

in these tests* was rather small (8 in.). Their response fell off rather rapidly below 200 Hz. To the ear, the resultant sound was much like freeway traffic noise, less some of the very low frequency rumble. Since the noise was generated digitally, it was relatively easy to reproduce the amplitude and spectrum exactly.

The horns were all hard-wired to a pickup "camper" used as a control center. From the camper, the signal could be quickly switched to any of the eight horns in the line. The microphone tower at the center of the line was also hard-wired to the camper. This tower was designed so that a microphone placed on the boom could be positioned remotely to any height between 0 and 14 ft (see Figure 6). By turning a knob at the control center, the boom would go up or down and a digital readout

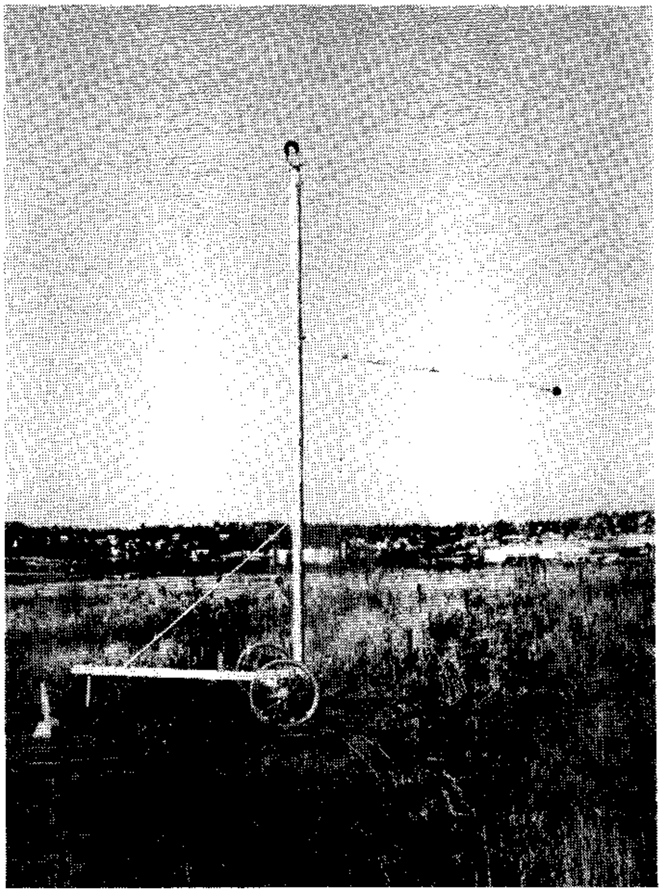

*Figure 6. Remote microphone tower.*

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*University Sound Company, Model IBA-8.

would display the microphone height. The signals received at the microphone were amplified by a General Radio P-42 preamplifier and brought back to the camper, where they were further amplified, processed by an rms detector and logarithmic amplifier, and displayed on a strip-chart recorder. Also at the center position was an instrumented tower which measured the wind speed at heights of 2.17, 4.88, 8.75, and 12.96 ft; because the anemometers used were nondirectional, the tower also included a wind direction indicator so that the measured wind speeds could be broken into components parallel and perpendicular to the line of speakers. The wind tower was offset from the line of speakers by 20 ft (see Figure 5). In this position, it did not disturb the readings at the microphone, and yet it was close enough that the wind data were a good representation of the wind at the microphone tower.

Figure 7 shows a sample of typical data from the strip-chart recorder. The upper trace was time-shared between wind direction and wind speed, as indicated in the figure. Because the recorder was sufficiently

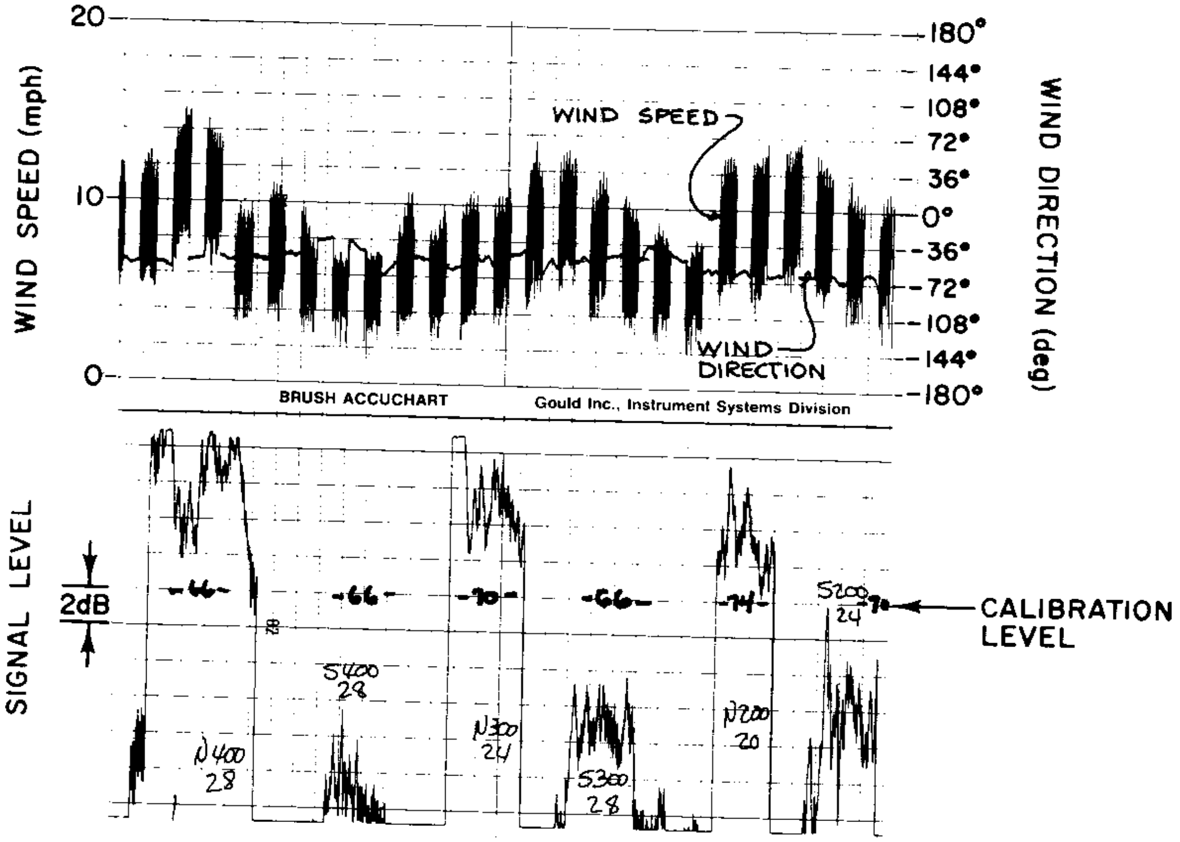


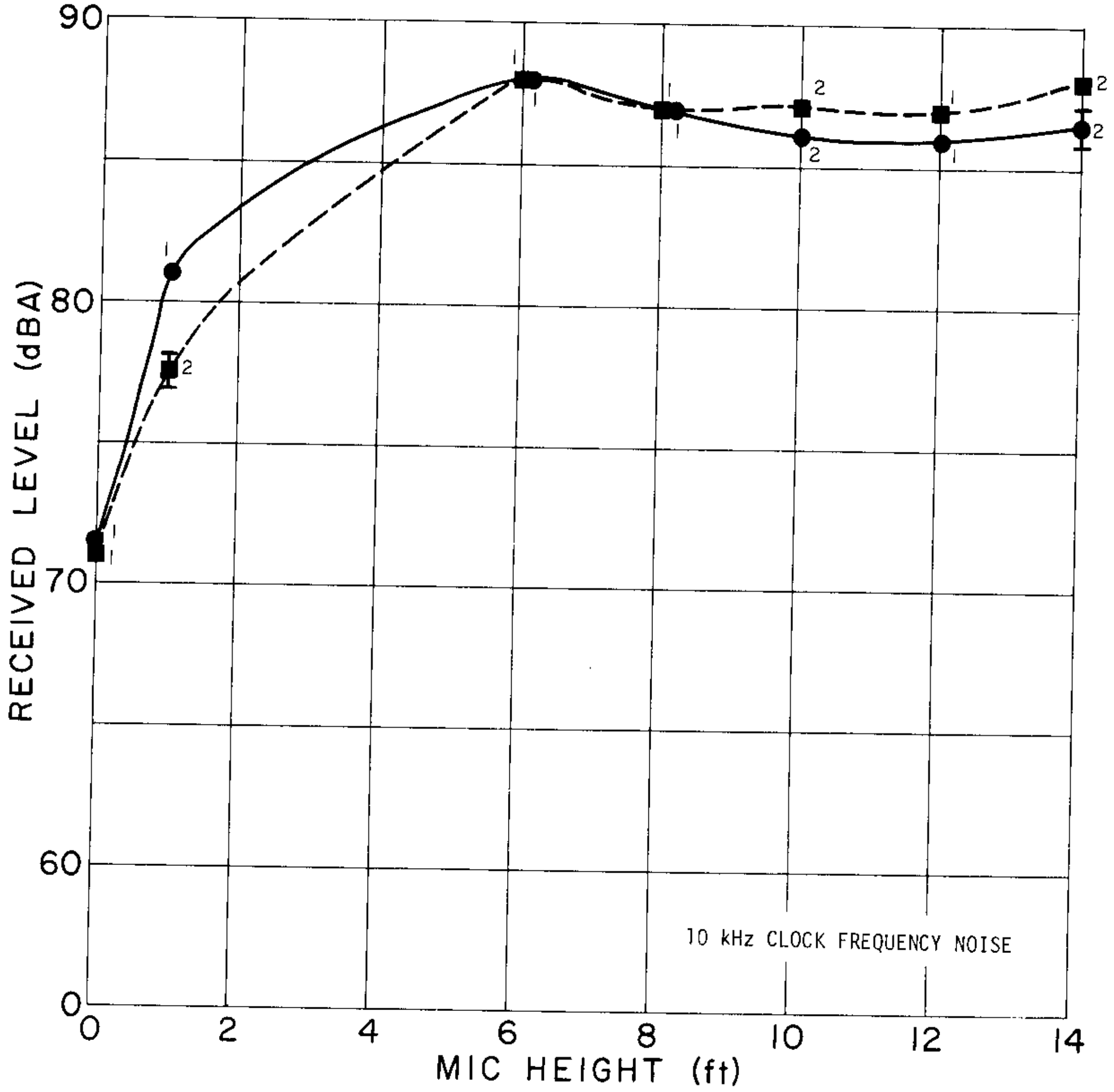
*Figure 7. Typical strip chart, IMA grass field, 10-kHz clock frequency noise.*

fast to resolve the signals from the individual commutator contacts on the direct-current anemometer, there was a clear-cut distinction between the wind speed (wide part of upper trace) and the wind direction (middle line in trace). Wind speeds could be recorded from 0 to 20 mph; wind direction covered 360°, with 0° representing a wind exactly parallel with the direction of transmission and 180° representing the opposite direction. The lower trace in Figure 7 is the signal level at the microphone. At 2 dB per major division, the full scale of this trace was 20 dB. Since the dynamic range frequently exceeded 20 dB, the gain had to be adjusted during the course of the measurements. The calibration level was initially set using a General Radio 1562A microphone calibrator; the initial calibration was then incremented as necessary using an accurate 2-dB per step potentiometer incorporated in the system. The setting of the potentiometer was noted by hand on the chart. The symbol "N400" written under the first signal on the left of the chart means the horn being energized was 400 ft north of the microphone, and the "28" indicates the setting on the calibrated potentiometer. At this setting, the line with the hand-drawn "66" on it represents a sound level 66 dB above the standard sound pressure reference level of 0.0002 dynes per square centimeter. Transmission was then shifted to the horn 400 ft south of the microphone; as can be seen, this caused a change of roughly 20 dB in the signal received, or nearly full-scale deflection. Next, the transmission was switched to N300. Because the signal would have been off scale (as can be seen in the first brief moment after the switch), the operator lowered the potentiometer setting to 24, and the line that previously represented 66 dB now represented 70 dB. The transmission was then switched to S300, which necessitated a potentiometer setting of 28, and so forth. Many hundreds of feet of such data were taken, and it was from these data that the results shown for the A-weighted data were drawn.

## Data Reduction

The wind speed and direction data recorded on the strip chart were "eye averaged" to produce a representative value for wind speed and wind direction; the parallel component of the wind speed was then calculated from these data. The sound levels recorded on the strip chart were eye averaged to arrive at a representative value. The records were then searched to find cases for the same horn on the same field where the parallel components of wind velocity were sufficiently close that they could be grouped. This was done for a variety of microphone heights between 0 and 14 ft.

The A-weighted data in this report have been categorized into two groups, one in which the parallel component of wind velocity is below 2 mph as measured on the 8.75-ft high anemometer, and one in which the parallel component of wind velocity is above 2 mph. Figure 8 is typical of the graphs shown in this report. Each data point is an average value



LOCATION:

IMA Grass Field

DATE:

October 7, 1976
October 29, 1976

WEATHER:

Clear, Sunny, 60$^0$ F.
Ground slightly damp

Cloudy, 53$^0$ F.
Ground damp

WIND:

Parallel Component; blowing from the north

Range: 0-2 mph

Total Wind:

$\bar{X}$ = 1.14 mph; $\sigma$ = 0.72 mph

Parallel Wind:

$\bar{X}$ = 0.60 mph; $\sigma$ = 0.60 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

Speaker to Microphone Distance:

100 ft

SOLID LINE:

Speakers north of microphone

DASHED LINE:

Speakers south of microphone

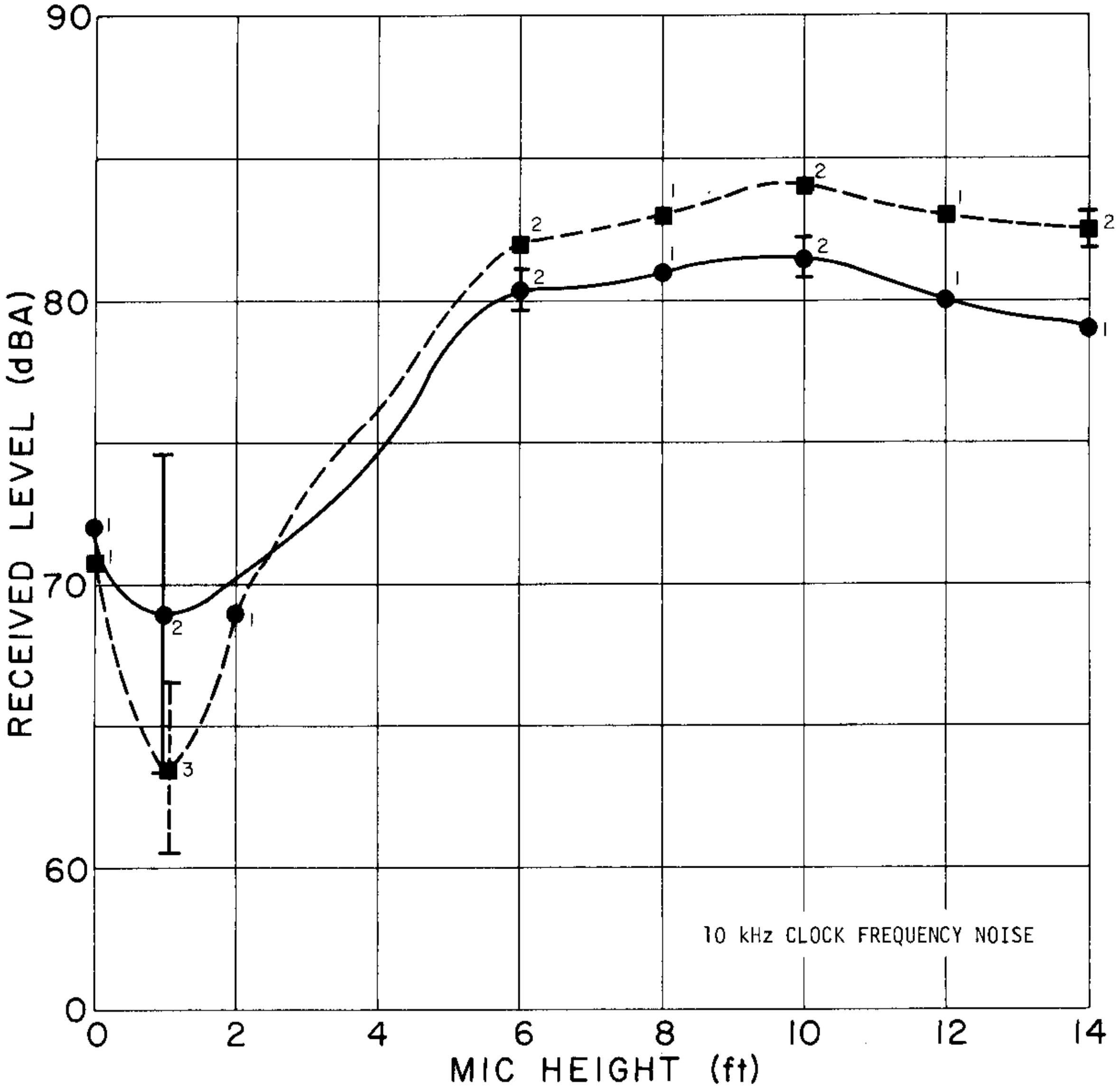
Number by mean is number of data points used to establish the mean.

*Figure 8*

of all data falling in that category; i.e., same microphone height, noise source, horn distance, horn direction, and parallel wind velocity. The range of values indicated by the standard deviation is represented by bars on each side of the data points. The number by the point indicates how many measurements were used to compute the average value. Many of the points in the graphs are based on one or two measurements. The highest number is four. These data were often taken quite far apart in time, even on different days. The average velocity ($\overline{\chi}$) of the winds used to compose the graph, along with the standard deviation ($\sigma$), are shown under "total wind." For the graph in Figure 8, the average value of the winds was 1.14 mph, and the standard deviation was 0.72 mph. The main parameter of interest, the wind component parallel to the transmission, is also indicated on the graph; in this case, it had an average value of 0.6 mph with a standard deviation of 0.6. In general, a solid line is used to represent sound that is being transmitted against the wind and a dashed line to represent sound that is being transmitted with the wind. The height of the noise source was nominally 1 m above the ground in all cases.

## Results

Figures 8-11 represent transmissions in opposite directions over a grassy field under relatively calm wind conditions as a function of the receiving microphone's height. Figure 8 is for a 100-ft transmission. This transmission was very similar for both directions, indicating very little wind shear effect. The ground plane effect appears as a noticeable dropoff in signal level below a height of approximately 6 ft as the microphone approaches ground level. Figure 9 is for the same conditions as Figure 8, except that in this case the transmission path length is 200 ft in each direction. Once again, there is a noticeable dropoff in signal level as the microphone nears the ground due to the ground plane effect, but in this case the effect commences at a somewhat greater height. Figure 10 is for the same wind conditions, but for a distance of 300 ft. In this case, wind shear is obviously exerting an influence at heights below 6 ft, even though the average parallel wind velocity is only 1.2 mph. The effect of wind shear on the ground plane interaction is indicated by the definite difference between the upwind and downwind measurements at microphone heights below 6 ft. Figure 11 is similar to the preceding figures except that the transmission path has been stretched to 400 ft in each direction. The effect of wind shear is apparent over almost the entire transmission, even though the average parallel wind velocity is only 1.3 mph.



LOCATION:

IMA Grass Field

DATE:

October 7, 1976
October 29, 1976

WEATHER:

Clear, Sunny, 60$^{o}$ F.
Ground slightly damp

Cloudy, 53$^{o}$ F.
Ground damp

WIND:

Parallel Component; blowing from the north

Range: 0-2 mph

Total Wind:

$\bar{\chi} = 1.70$ mph; $\sigma = 0.70$ mph

Parallel Wind:

$\bar{\chi} = 1.20$ mph; $\sigma = 0.70$ mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

Speaker to Microphone Distance:

200 ft

SOLID LINE:

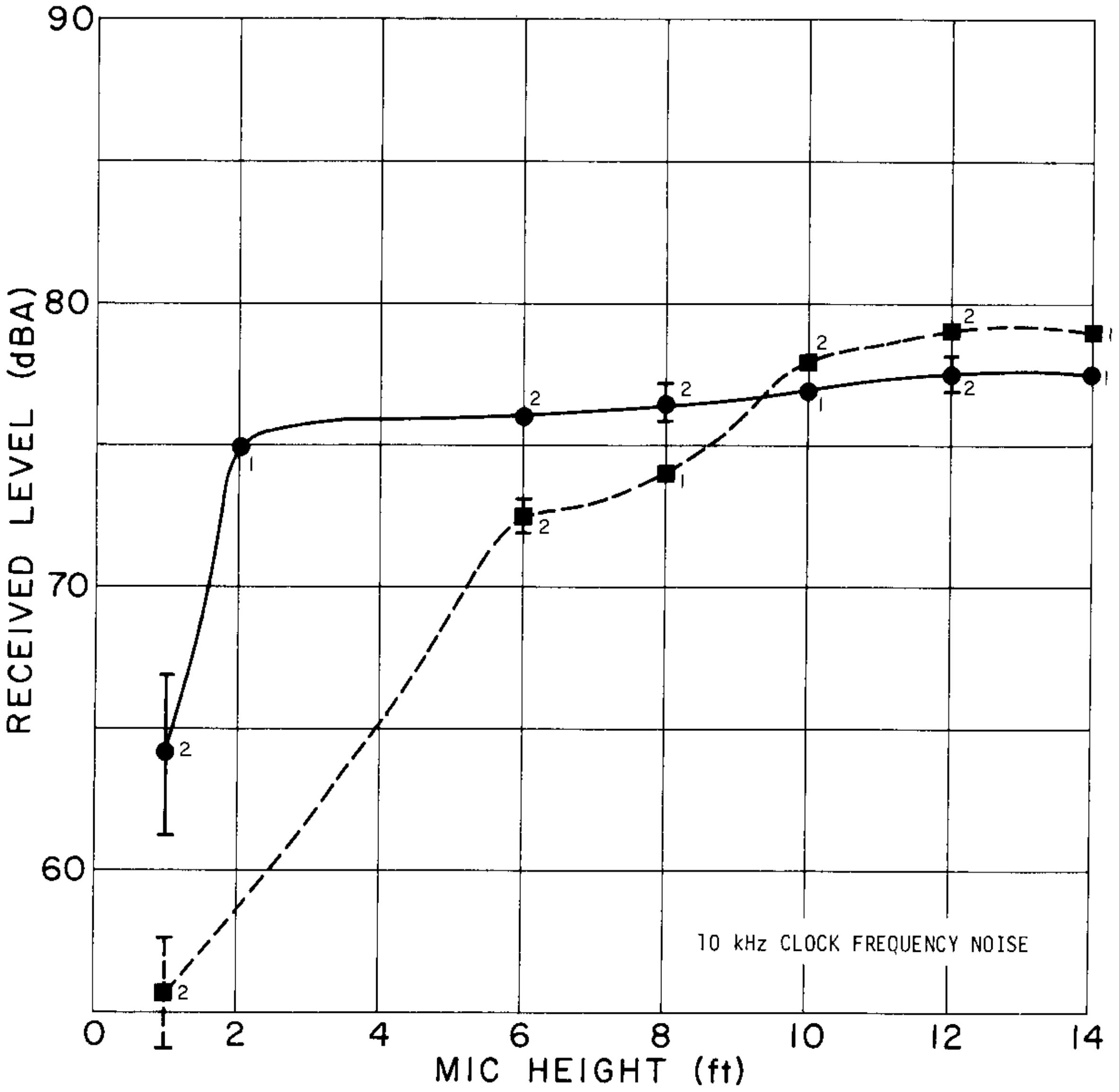
Speakers north of microphone

DASHED LINE:

Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 9*



LOCATION:
IMA Grass Field

DATE:
October 7, 1976
October 29, 1976

WEATHER:
Clear, Sunny, $60^{\circ}$ F.
Ground slightly damp

Cloudy, $53^{\circ}$ F.
Ground damp

WIND:
Parallel Component; blowing from the north

Range: 0-2 mph

Total Wind:
$\bar{x} = 1.90$ mph; $\sigma = 0.70$ mph

Parallel Wind:
$\bar{x} = 1.20$ mph; $\sigma = 0.60$ mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile

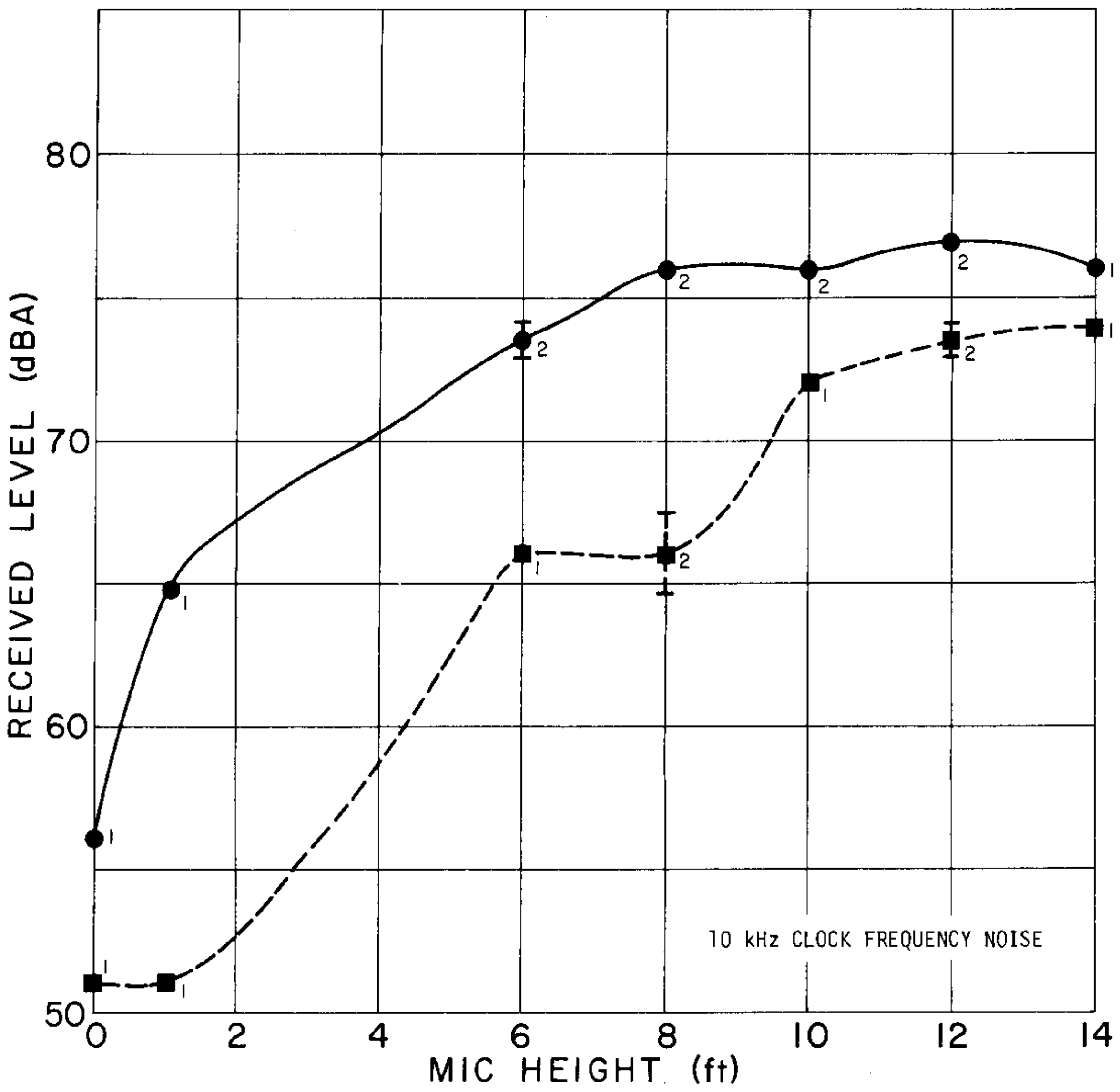
Speaker to Microphone Distance:
300 ft

SOLID LINE:
Speakers north of microphone

DASHED LINE:
Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 10*



LOCATION:

IMA Grass Field:

DATE:

October 7, 1976
October 29, 1976

WEATHER:

Clear, Sunny, $60^{\circ}$ F.
Ground slightly damp

Cloudy, $53^{\circ}$ F.
Ground damp

WIND:

Parallel Component; blowing from the north

Range: 0-2 mph

Total Wind:

$\bar{x} = 1.80$ mph; $\sigma = 0.80$ mph

Parallel Wind:

$\bar{x} = 1.30$ mph; $\sigma = 0.50$ mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile

---

Speaker to Microphone Distance:

400 ft

SOLID LINE:

Speakers north of microphone

DASHED LINE:

Speakers south of microphone

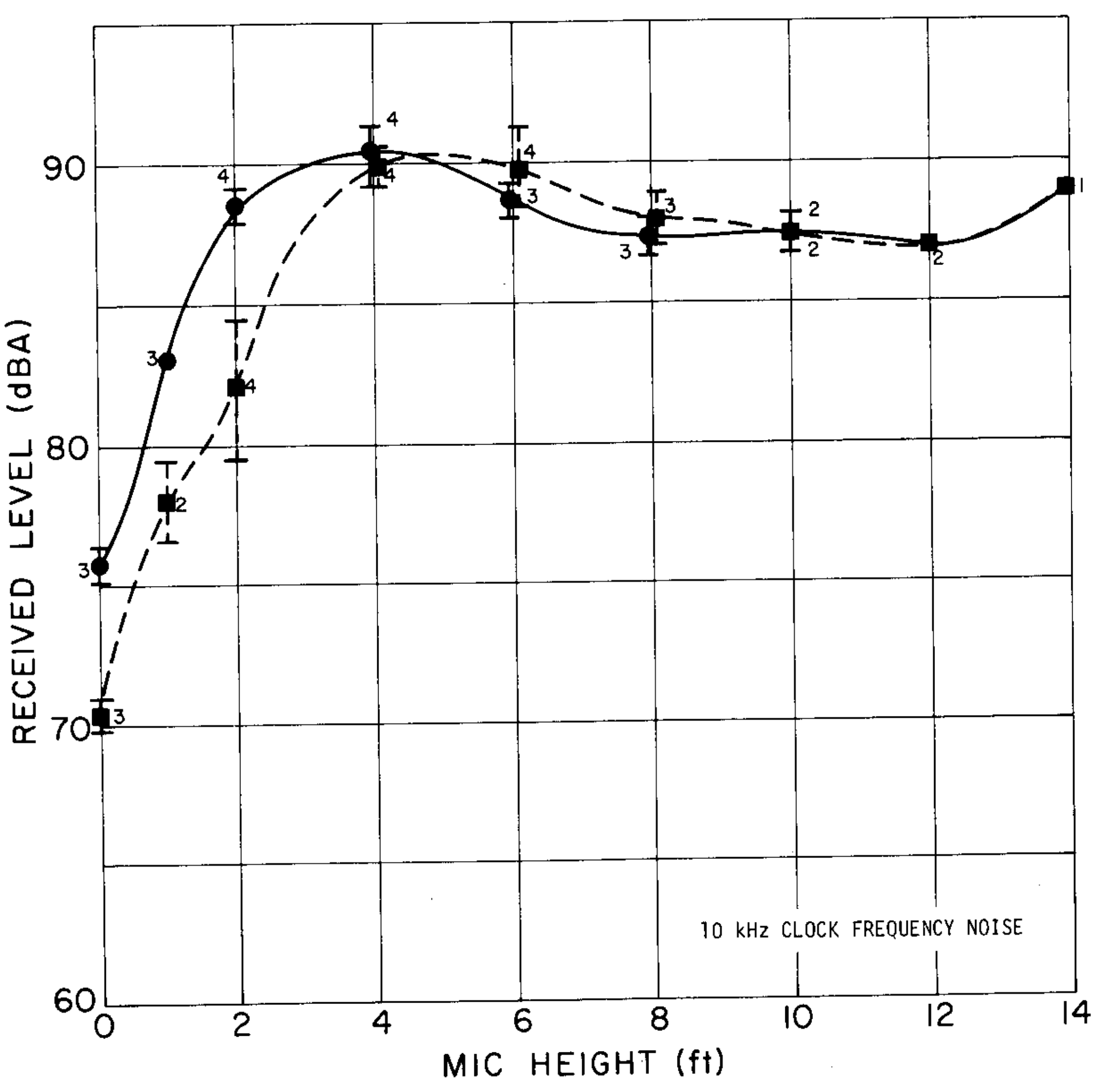
Number by mean is number of data points used to establish the mean.

*Figure 11*

Figures 12-15 are for transmissions over the grassy field at winds above 2 mph. Again, at 100 ft (Figure 12) the wind shear effect is not strong, although the ground plane effect is obvious below 2-3 ft. At 200 ft (Figure 13), a definite difference begins to appear between the two directions; at heights below 6 ft, the sound level received at the north microphone is about 6 dB higher than that received at the south microphone. The average parallel wind velocity was 3.4 mph. Figure 14 is for a distance of 300 ft; the average parallel wind velocity was 3.8 mph. There is a very pronounced wind-shear effect below 12 ft. At 6 ft, which is close to a typical ear height, there is a difference of about 18 dB between the two paths. Figure 15 is similar to Figure 14 (the parallel wind velocity was 3.9 mph) except that the distance is 400 ft. Once again, the very big difference that relatively small winds can create is clearly visible. At a height of 4 ft, the difference between the transmissions over the two paths is nearly 20 dB.

The topography of the weed field, as determined by survey, is indicated in Figure 3. (Note that the horizontal scale is compressed by a factor of 25 to 1 compared to the vertical scale.) Since the only sufficiently flat region available for the tests was approximately 600 ft long, the horns were located at 75-ft increments. Figures 16-19 show the results obtained at wind speeds below 2 mph. Figure 16 is for a distance of 75 ft. Little wind shear is evident, and ground plane effects are limited to below 2 ft. Figure 17 is for a distance of 150 ft. Again, there is little difference between the transmissions in the two directions, indicating little wind-shear effect; however, the ground-plane effect begins to appear at a somewhat greater height. At 225 ft (Figure 18), there is still not much effect from wind shear, although the effect of the ground plane extends even higher. Figure 19, for a 300-ft spacing, shows definite effects of wind shear, particularly around the 4-ft elevation, even though the average parallel wind velocity is scarcely over 0.5 mph.

Figures 20-23 show the results obtained at winds above 2 mph. Figure 20, for a distance of 75 ft, shows little evidence of wind shear. However, Figure 21 begins to show a strong wind-shear effect, even though the distance is only 150 ft and the average value for parallel wind is only 4.2 mph. At a microphone height of 4 ft, there is a difference of about 15 dB between the two directions. Figure 22 is similar to Figure 21 except that it is for a distance of 225 ft, and the wind shear-ground plane effect begins at a higher microphone height. At a distance of 300 ft (Figure 23), ground plane-wind shear effects produce a very pronounced difference in the transmissions over the two paths even at the maximum microphone height of 14 ft. There is a difference of nearly 15 dB over almost the whole range of microphone heights.



LOCATION:

IMA Grass Field

DATE:

October 7, 1976
October 29, 1976

WEATHER:

Clear, Sunny, $60^{\circ}$ F.
Ground slightly damp

Cloudy, $53^{\circ}$ F.
Ground damp

WIND:

Parallel Component; blowing from the north

Range: 2-7 mph

Total Wind:

$\bar{X}$ = 4.70 mph; $\sigma$ = 1.80 mph

Parallel Wind:

$\bar{X}$ = 3.70 mph; $\sigma$ = 1.10 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

---

Speaker to Microphone Distance:

100 ft

SOLID LINE:

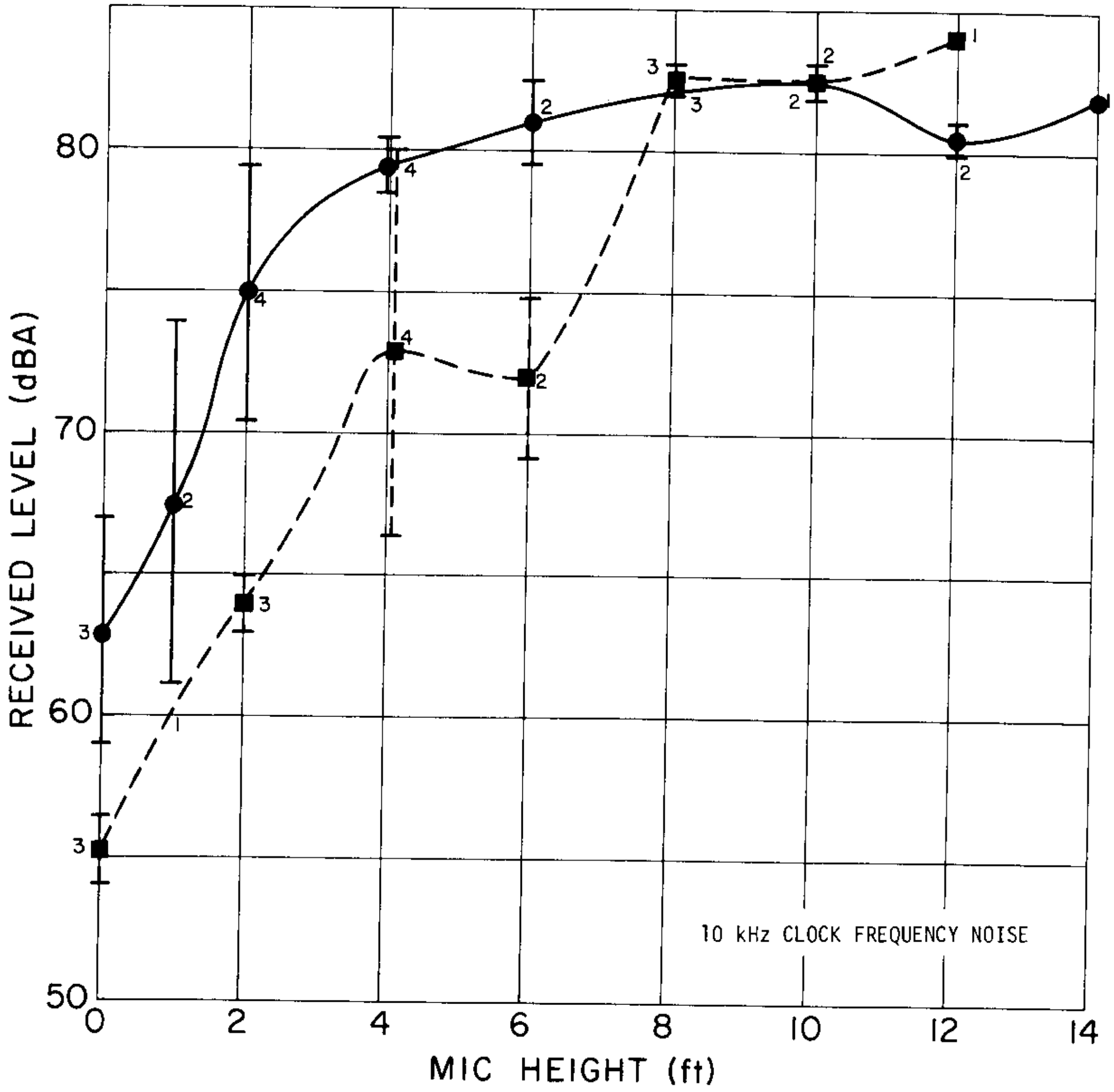
Speakers north of microphone

DASHED LINE:

Speakers south of microphone

Number by mean is number of data points used to establish the mean.

Figure 12



LOCATION:

IMA Grass Field

DATE:

October 7, 1976
October 29, 1976

WEATHER:

Clear, Sunny, 60$^{0}$ F.
Ground slightly damp

Cloudy, 53$^{0}$ F.
Ground damp

WIND:

Parallel Component; blowing from the north

Range: 2-7 mph

Total Wind:

$\bar{X}$ = 4.80 mph; $\sigma$ = 1.80 mph

Parallel Wind:

$\bar{X}$ = 3.40 mph; $\sigma$ = 0.70 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

---

Speaker to Microphone Distance:

200 ft

SOLID LINE:

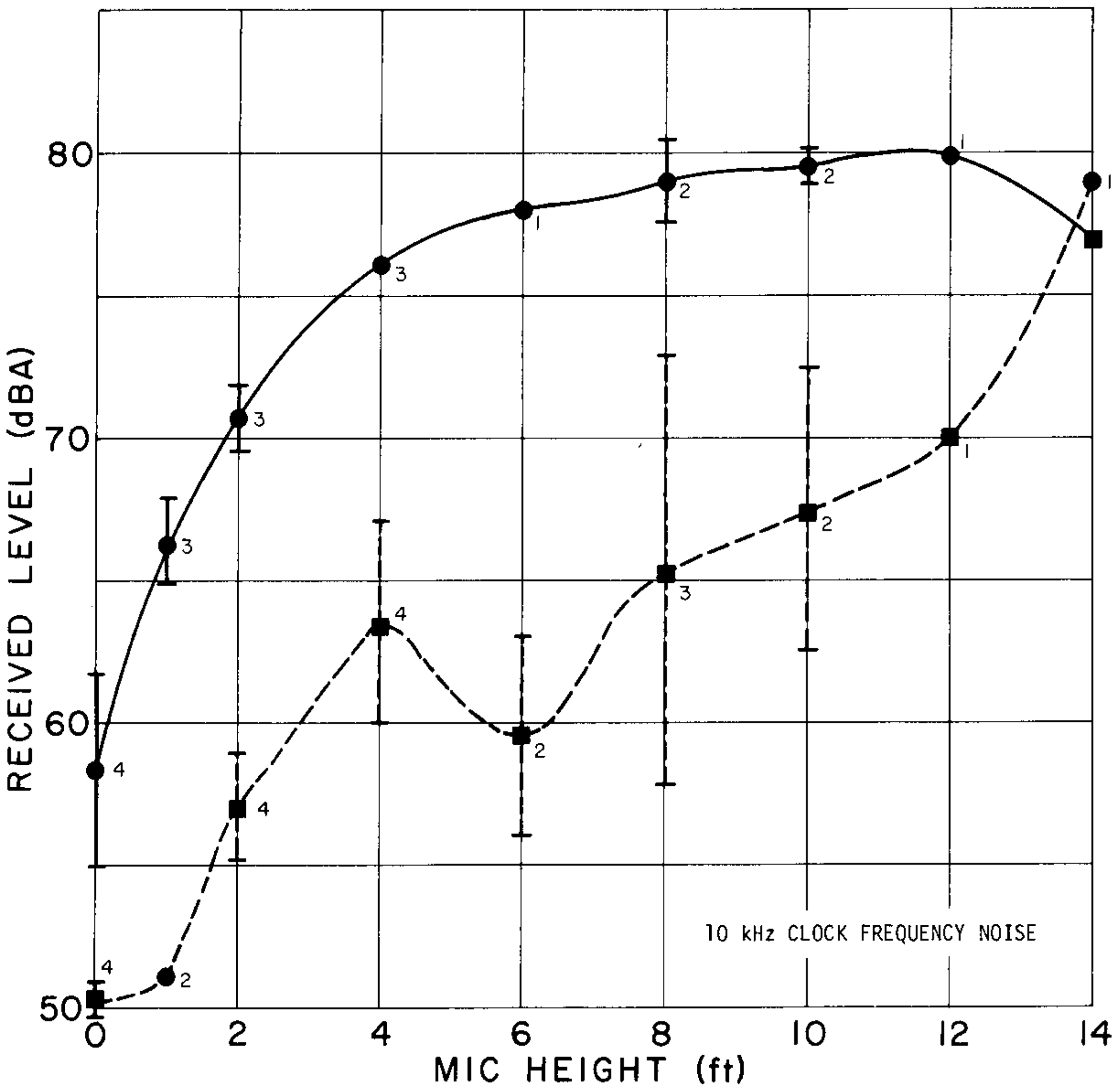
Speakers north of microphone

DASHED LINE:

Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 13*



LOCATION:

IMA Grass Field

DATE:

October 7, 1976
October 29, 1976

WEATHER:

Clear, Sunny, $60^{\circ}$ F.
Ground slightly damp

Cloudy, $53^{\circ}$ F.
Ground damp

WIND:

Parallel Component; blowing from the north

Range: 2-7 mph

Total Wind:

$\bar{x}$ = 5.00 mph; $\sigma$ = 1.80 mph

Parallel Wind:

$\bar{x}$ = 3.80 mph; $\sigma$ = 1.20 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

---

Speaker to Microphone Distance:

300 ft

SOLID LINE:

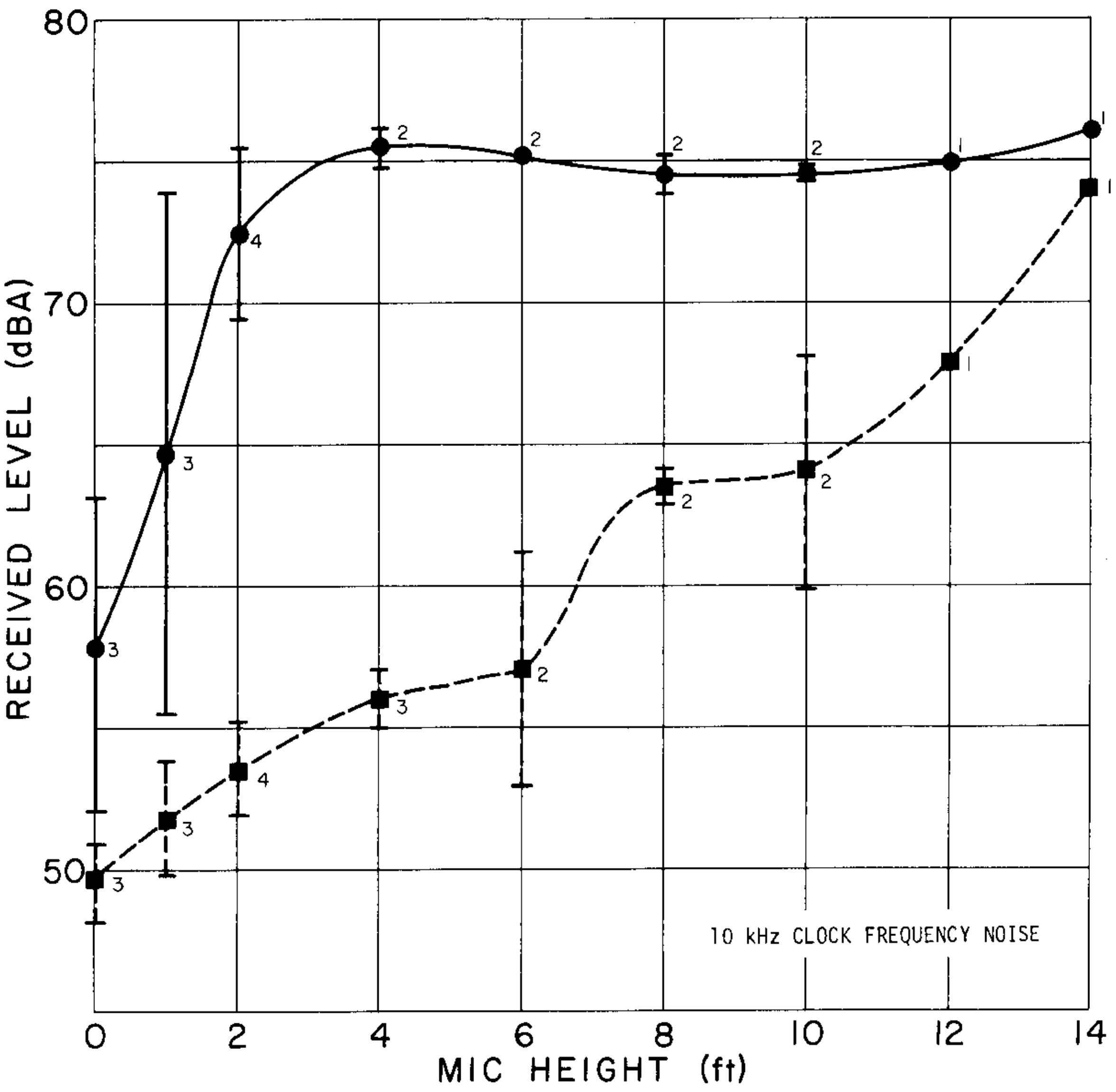
Speakers north of microphone

DASHED LINE:

Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 14*



LOCATION:

IMA Grass Field

DATE:

October 7, 1976
October 29, 1976

WEATHER:

Clear, Sunny, 60° F.
Ground slightly damp

Cloudy, 53° F.
Ground damp

WIND:

Parallel Component; blowing from the north

Range: 2-7 mph

Total Wind:

$\bar{X}$ = 4.90 mph; $\sigma$ = 2.10 mph

Parallel Wind:

$\bar{X}$ = 3.90 mph; $\sigma$ = 1.50 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

Speaker to Microphone Distance:

400 ft

SOLID LINE:

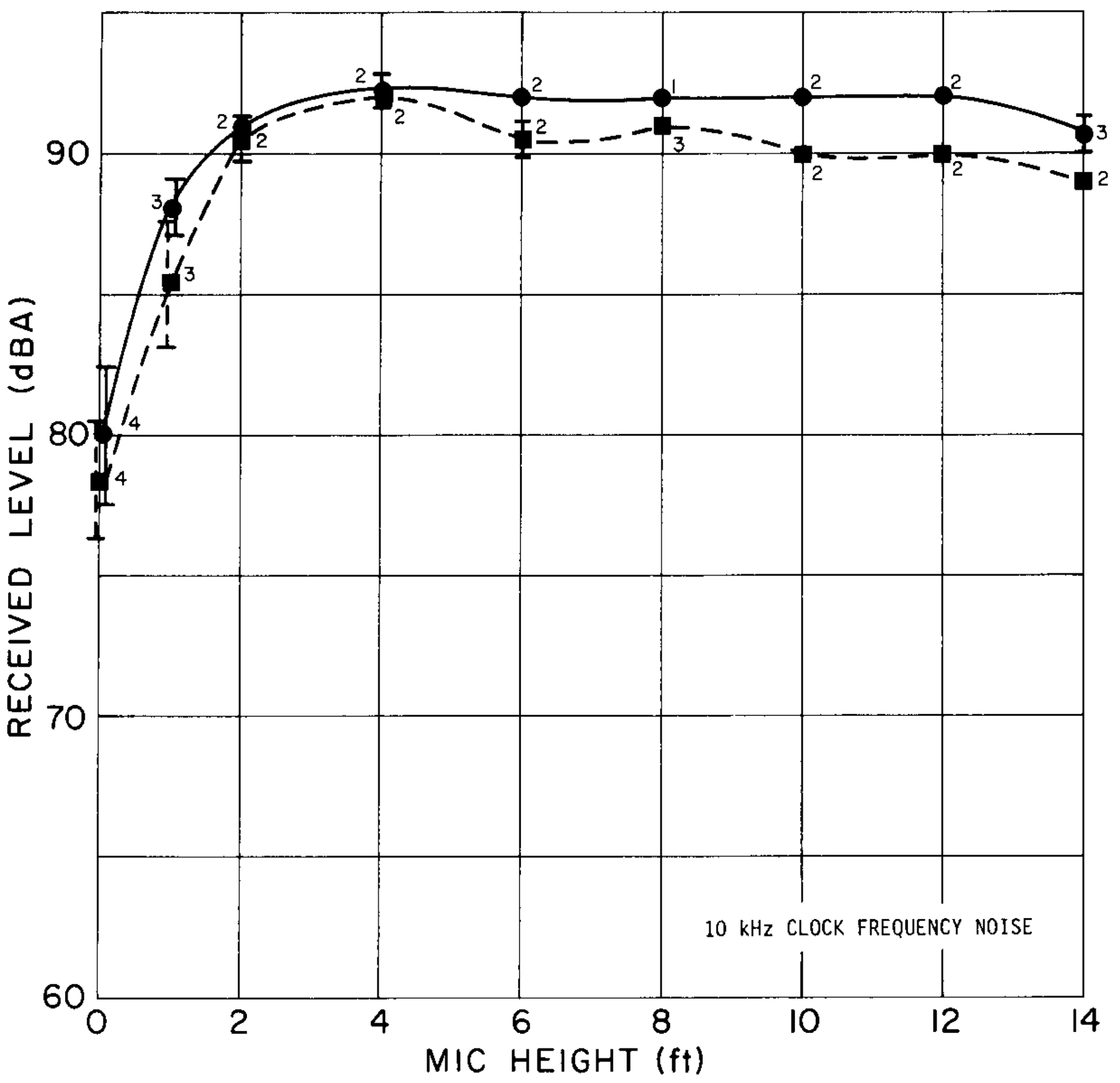
Speakers north of microphone

DASHED LINE:

Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 15*



LOCATION:
Weed Field

DATE:
November 3, 1976

WEATHER:
Clear, Sunny, 60°F

WIND:
Parallel Component; blowing from the north
Range: 0-2 mph
Total Wind:
$\bar{x}$ = .95 mph; $\sigma$ = 1.04 mph
Parallel Wind:
$\bar{x}$ = .66 mph; $\sigma$ = .73 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

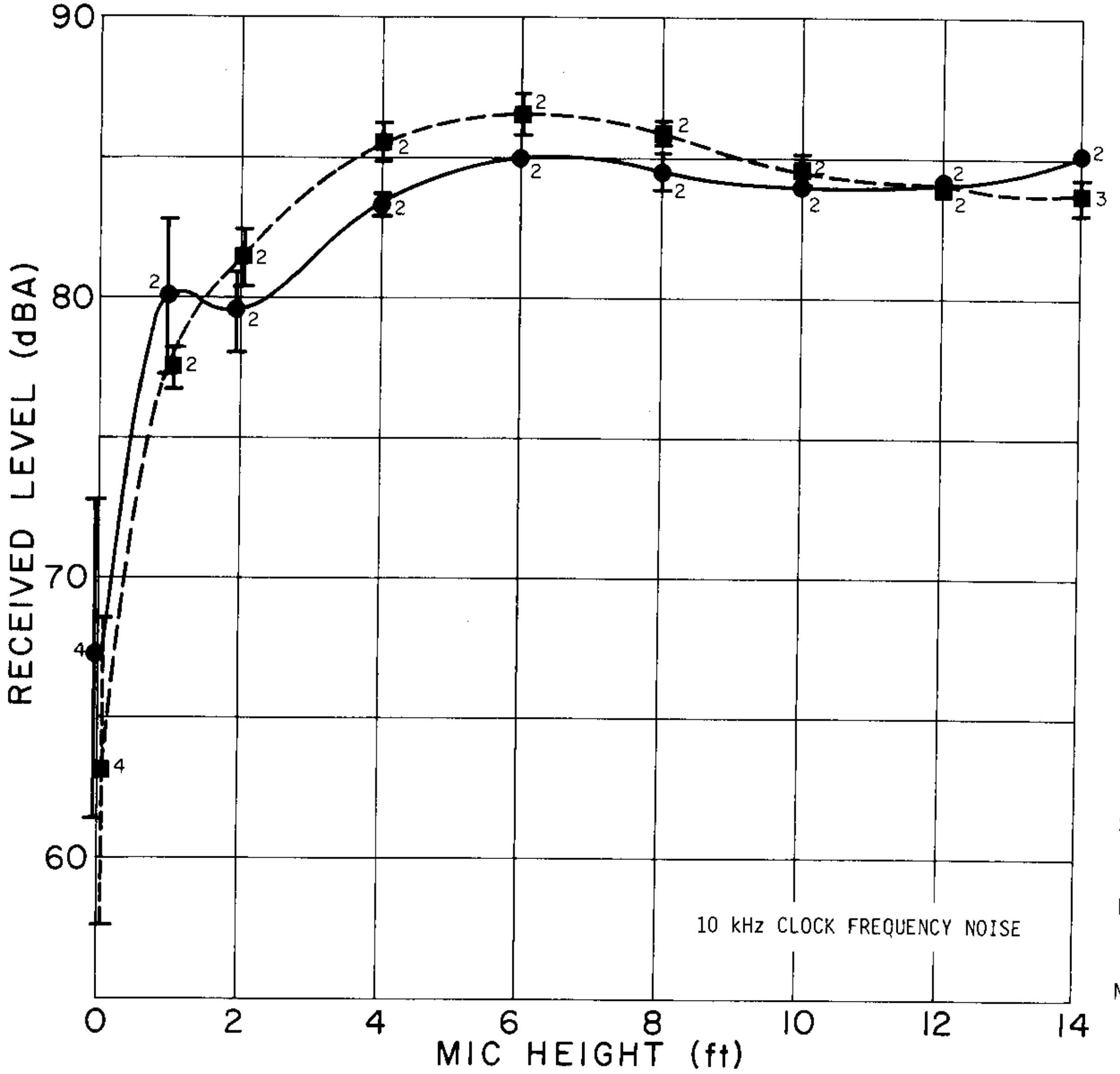
Speaker to Microphone Distance:
75 ft

SOLID LINE:
Speakers north of microphone

DASHED LINE:
Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 16*



LOCATION:
Weed Field

DATE:
November 3, 1976

WEATHER:
Clear, Sunny, $60^{\circ}$ F.

WIND:
Parallel Component; blowing from the north
Range: 0-2 mph
Total Wind:
$\bar{X}$ = .56 mph; $\sigma$ = .80 mph
Parallel Wind:
$\bar{X}$ = .43 mph; $\sigma$ = .63 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

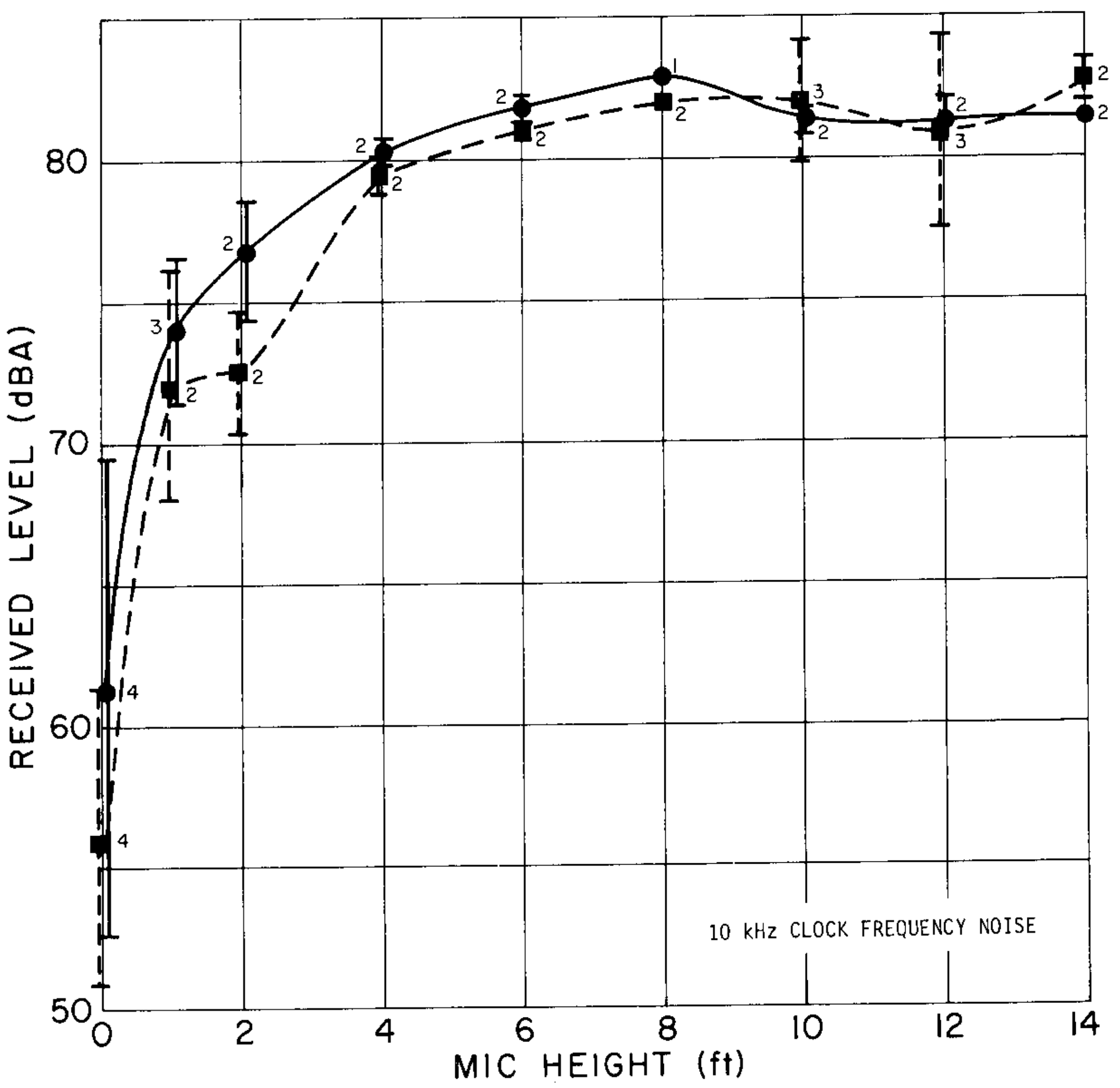
Speaker to Microphone Distance:
150 ft

SOLID LINE:
Speakers north of microphone

DASHED LINE:
Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 17*



LOCATION:
Weed Field

DATE:
November 3, 1976

WEATHER:
Clear, Sunny, $60^{0}$ F.

WIND:

Parallel Component; blowing from the north

Range: 0-2 mph

Total Wind:

$\bar{X}$ = 1.20 mph; σ = 2.30 mph

Parallel Wind:

$\bar{X}$ = 0.55 mph; σ = 0.63 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

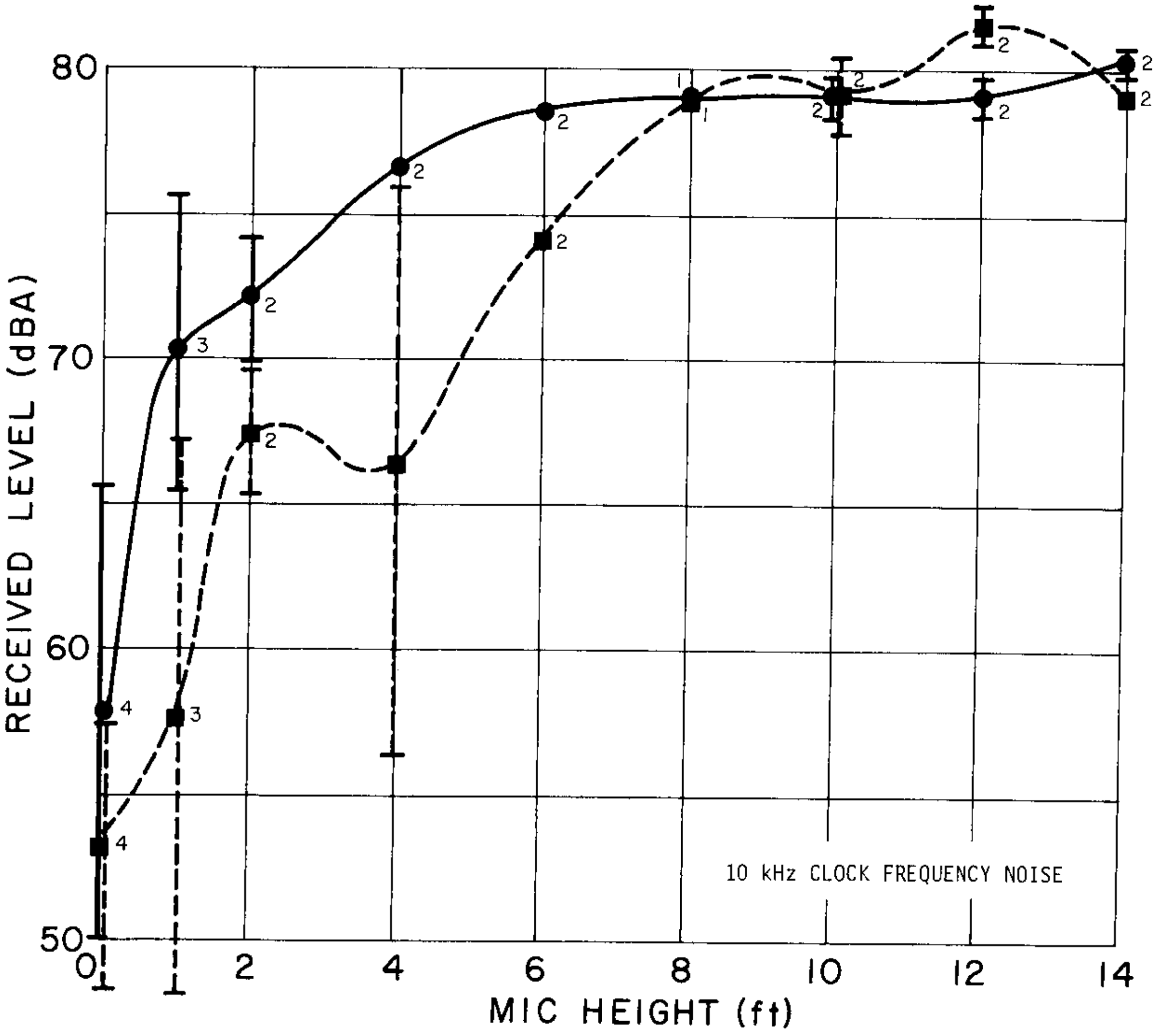
Speaker to Microphone Distance:
225 ft

SOLID LINE:
Speakers north of microphone

DASHED LINE:
Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 18*



LOCATION:

Weed Field

DATE:

November 3, 1976

WEATHER:

Clear, Sunny, 60° F.

WIND:

Parallel Component; blowing from the north

Range: 0-2 mph

Total Wind:

$\bar{X}$ = 0.96 mph; $\sigma$ = 1.11 mph

Parallel Wind:

$\bar{X}$ = 0.58 mph; $\sigma$ = 0.65 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

Speaker to Microphone Distance:

300 ft

SOLID LINE:

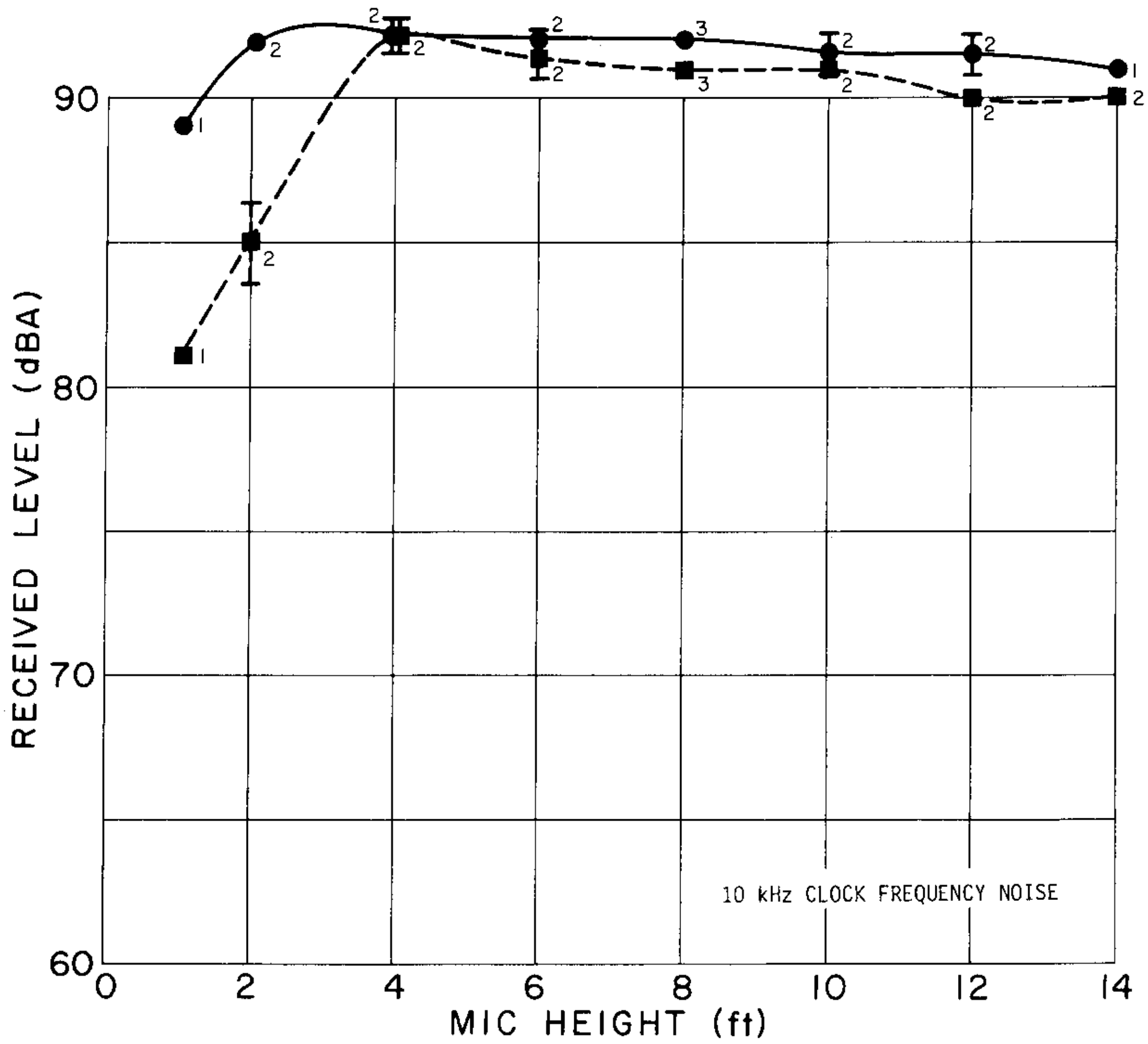
Speakers north of microphone

DASHED LINE:

Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 19*



LOCATION:

Weed Field

DATE:

November 3, 1976

WEATHER:

Clear, Sunny, 60° F.

WIND:

Parallel Component; blowing from the north

Range: 2-7 mph

Total Wind:

$\bar{x}$ = 4.71 mph; $\sigma$ = 1.05 mph

Parallel Wind:

$\bar{x}$ = 4.33 mph; $\sigma$ = 0.97 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

Speaker to Microphone Distance:

75 ft

SOLID LINE:

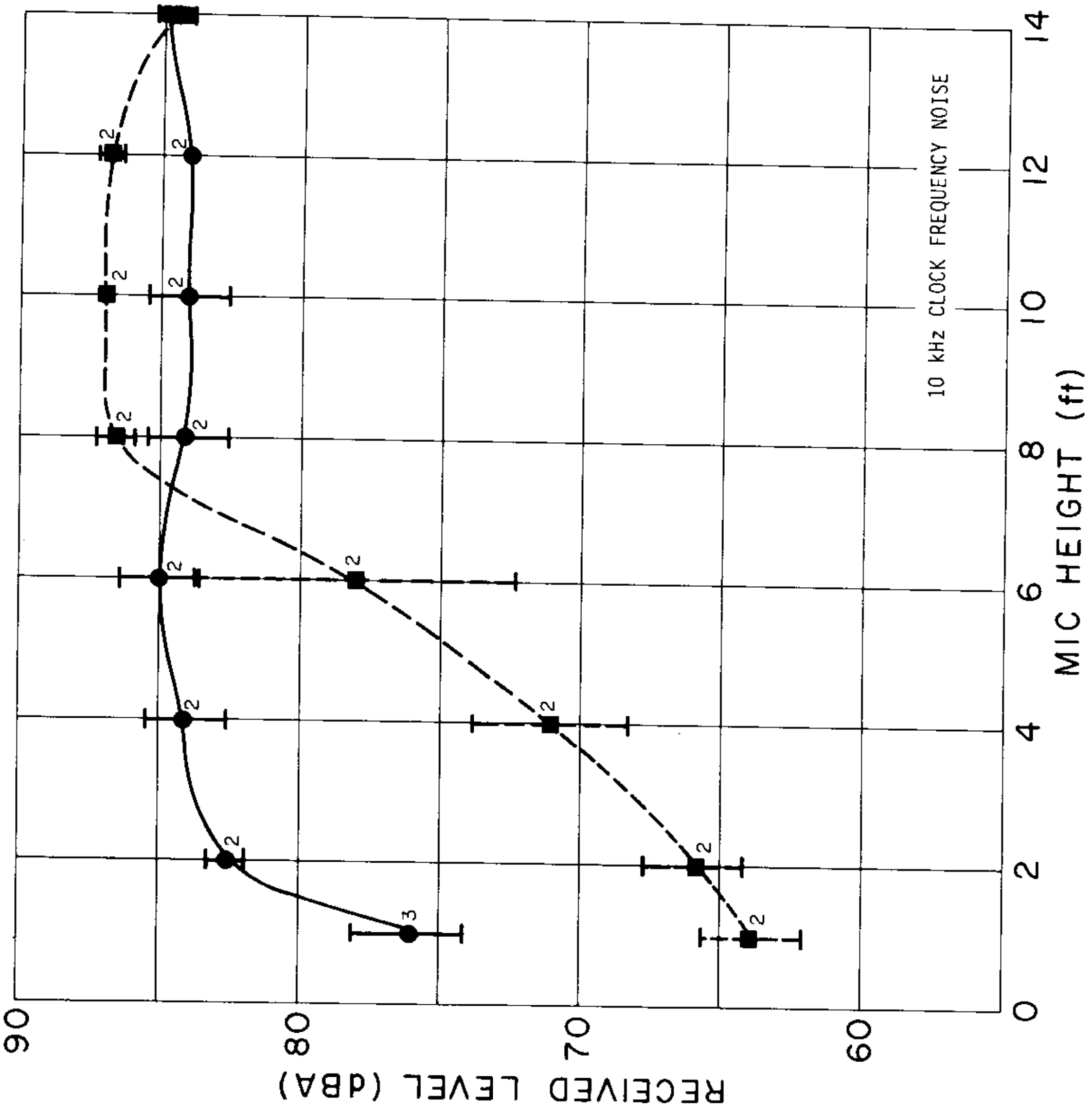
Speakers north of microphone

DASHED LINE:

Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 20*



LOCATION:
Weed Field

DATE:
November 1976

WEATHER:
Clear, Sunny, 60° F.

WIND:
Parallel Component; blowing from the north
Range: 2-7 mph
Total Wind:
$\bar{X}$ = 5.18 mph; σ = 3.75 mph
Parallel Wind:
$\bar{X}$ = 4.20 mph; σ = 1.30 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

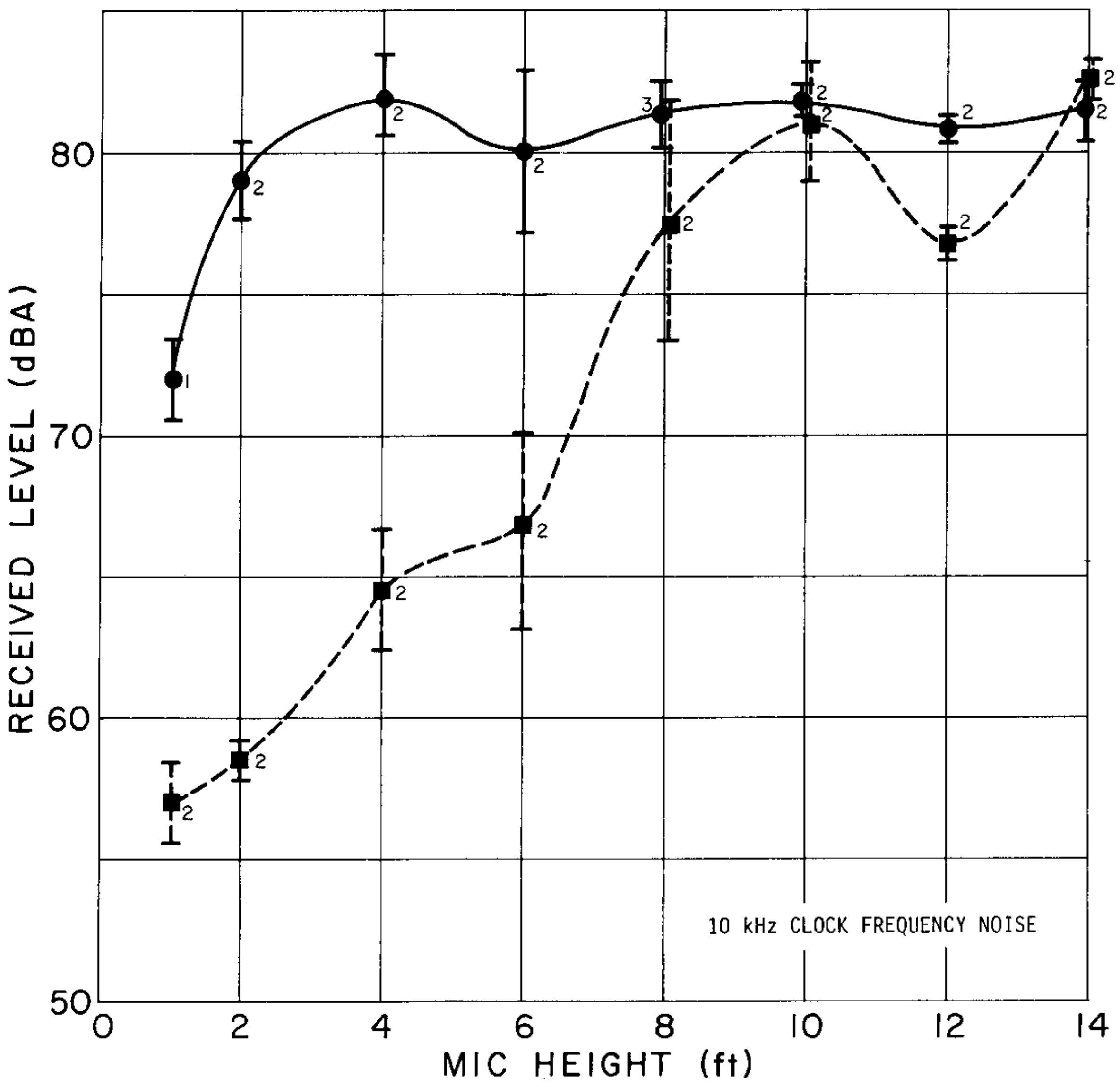
Speaker to Microphone Distance:
150 ft

SOLID LINE:
Speakers north of microphone

DASHED LINE:
Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 21*



LOCATION:
Weed Field

DATE:
November 3, 1976

WEATHER:
Clear, Sunny, 60° F.

WIND:
Parallel Component; blowing from the north
Range: 2-7 mph
Total Wind:
$\bar{X}$ = 4.37 mph; $\sigma$ = 1.04 mph
Parallel Wind:
$\bar{X}$ = 3.94 mph; $\sigma$ = 1.11 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

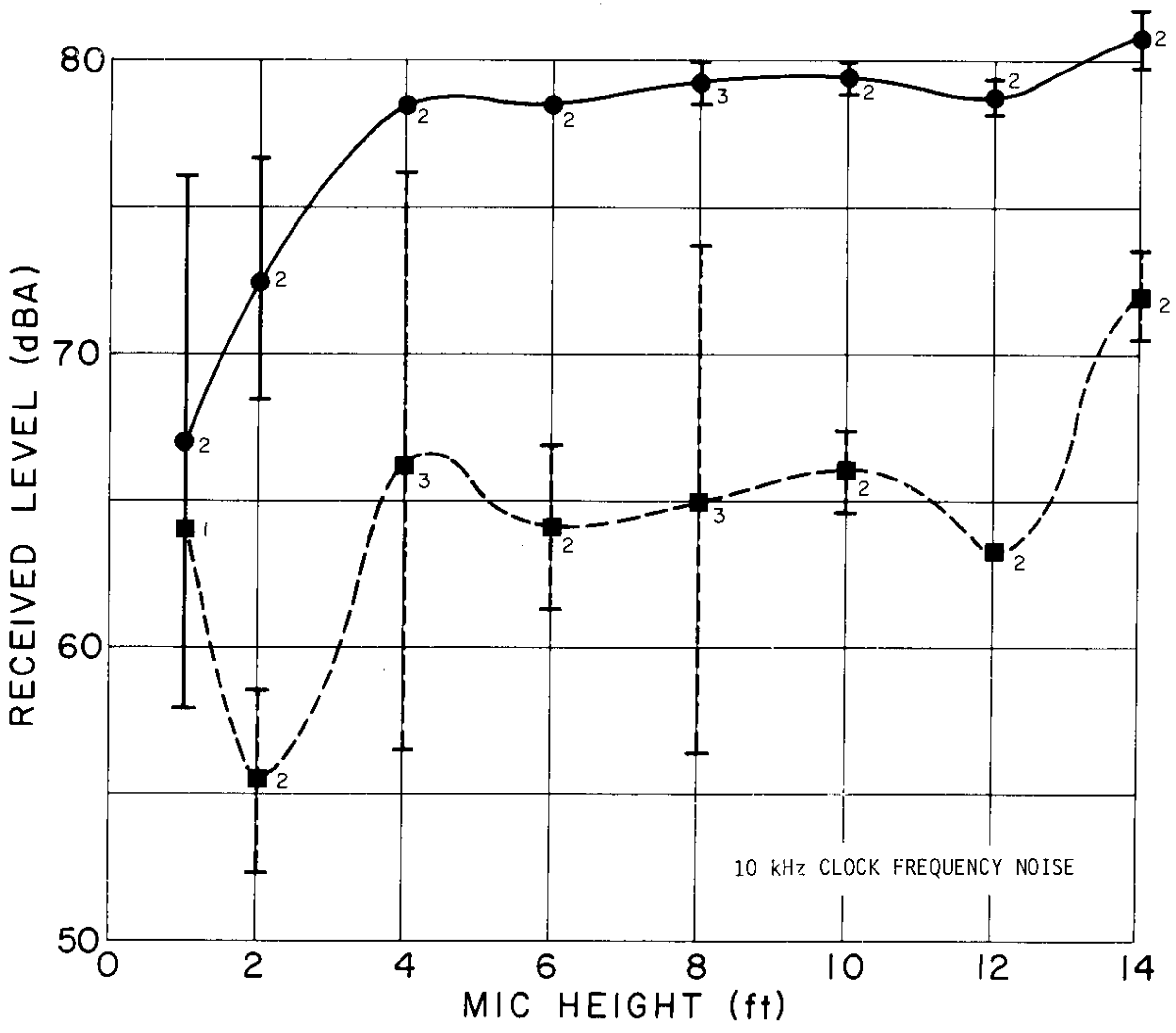
Speaker to Microphone Distance:
225 ft

SOLID LINE:
Speakers north of microphone

DASHED LINE:
Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 22*



LOCATION:
Weed Field

DATE:
November 3, 1976

WEATHER:
Clear, Sunny, $60^0$ F.

WIND:
Parallel Component; blowing from the north
Range: 2-7 mph
Total Wind:
$\bar{X}$ = 4.36 mph; σ = 2.53 mph
Parallel Wind:
$\bar{X}$ = 3.64 mph; σ = 1.08 mph

Wind measured at camper height of 10 ft

Speakers all one meter high nominal--see profile.

Speaker to Microphone Distance:
300 ft

SOLID LINE:
Speakers north of microphone

DASHED LINE:
Speakers south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 23*

The foregoing data have been for relatively small horns with a clock frequency of 10 kHz. Noise propagation data were also taken using larger horns at a slightly different location on the weed field during a previous part of the study. These larger horns produced good transmissions to frequencies slightly below 100 Hz. The resulting noise (particularly with a lower, 3.6-kHz clock frequency) sounds to the ear much like that of a large waterfall. Figure 24 shows the results obtained at the lower frequency for a nominal distance of 300 ft and a parallel wind velocity component of slightly over 8 mph, which is almost twice as high as that in Figure 23. As can be seen, there is a very pronounced difference between the downwind and the upwind propagation.* At the 1-ft level, there is about a 30-dB difference between the two directions; this differential remains to heights above 4 ft. Figure 25 also shows data taken in the weed field using the larger horn, but with a clock frequency of 10 kHz. Again, there is a very large difference between noise propagation in the two directions of transmission. The parallel wind velocity component was 8.5 mph.

Figure 26 represents one of the checks that was made on the validity of the measurement system. In this case, the data are for the weed field transmissions. It was assumed that the signal levels received at the highest microphone elevation for each of the four distances in the downwind direction (when the signal levels were not changing much with receiver height) approximated free-field transmission. The median value for these data was plotted along with the standard deviation. These data points were then compared with a falloff of 6 dB/octave (the solid line in Figure 26), which is the predicted falloff due to inverse square spreading only. As can be seen, there is very good agreement between simple inverse square spreading and the readings at the highest microphone position. This helps confirm that the sources were all equally intense and that the distances the sound traveled were approximately the distances that were measured; it also implies that the rest of the recording system was not grossly out of calibration at any time during the tests.

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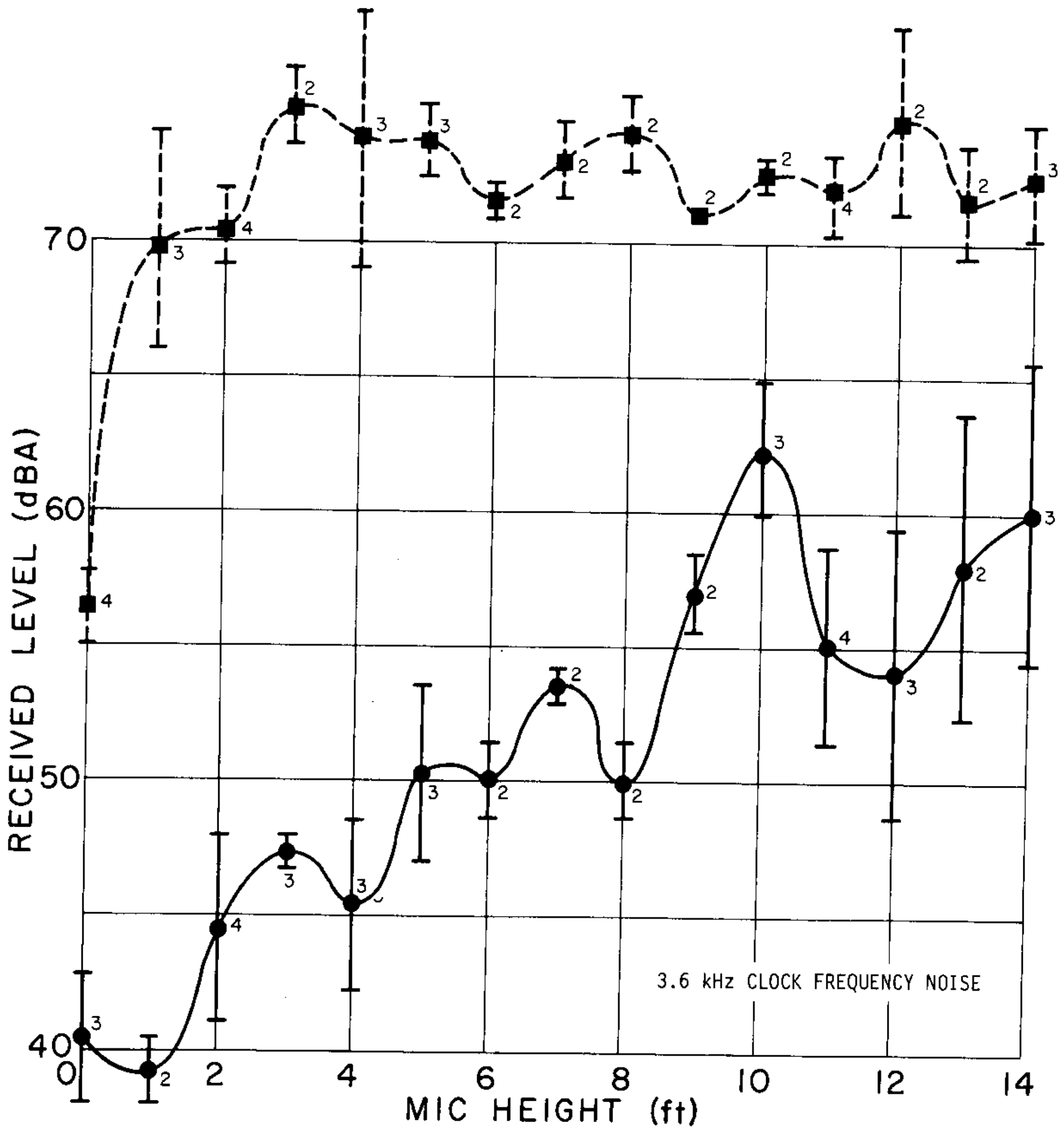
*In Figures 24 and 25, the dashed lines represent the downwind direction and the solid lines the upwind direction.



LOCATION:

Weed Field

DATE:

September 1, 1976

WEATHER:

Partly Cloudy, 60$^{0}$ F.
Ground is dry

WIND:

Parallel Component; blowing from the south

Range: 2-17 mph

Total Wind:

$\bar{X}$ = 10.80 mph; $\sigma$ = 6.50 mph

Parallel Wind:

$\bar{X}$ = 8.10 mph; $\sigma$ = 3.00 mph

Wind measured at camper height of 10 ft

Speakers:

North: 56 inches high
South: 59 inches high

---

Speaker to Microphone Distance:

North: 281.5 ft
South: 309.5 ft

SOLID LINE:

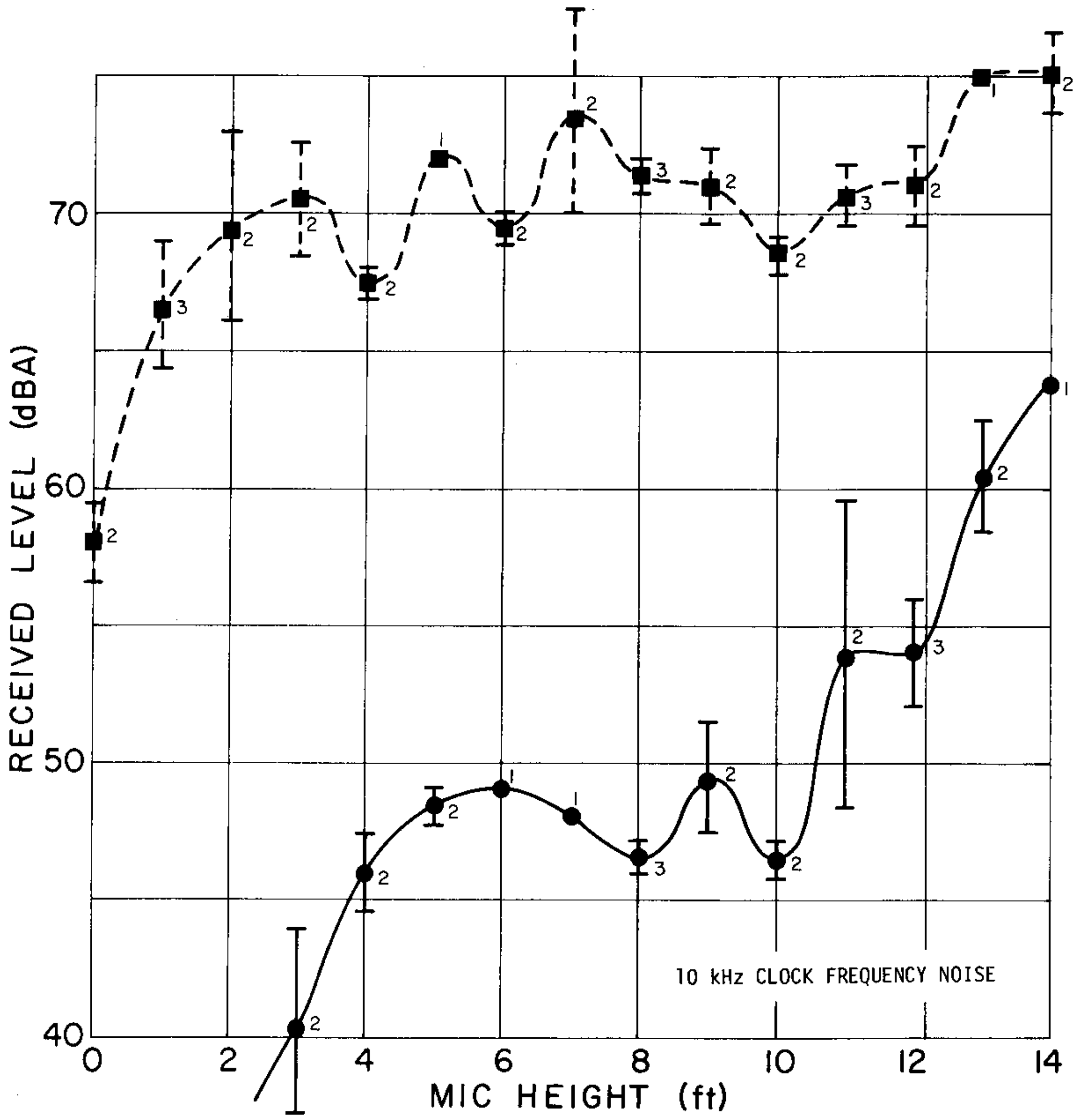
Speaker north of microphone

DASHED LINE:

Speaker south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 24*



LOCATION:
Weed Field

DATE:
September 1, 1976

WEATHER:
Partly Cloudy, $60^{\circ}$ F.
Ground is dry

WIND:
Parallel Component; blowing from the south
Range: 2-17 mph
Total Wind:
$\bar{X}$ = 11.00 mph; σ = 7.10 mph
Parallel Wind:
$\bar{X}$ = 8.50 mph; σ = 2.60 mph

Wind measured at camper height of 10 ft

Speakers:
North: 56 inches high
South: 59 inches high

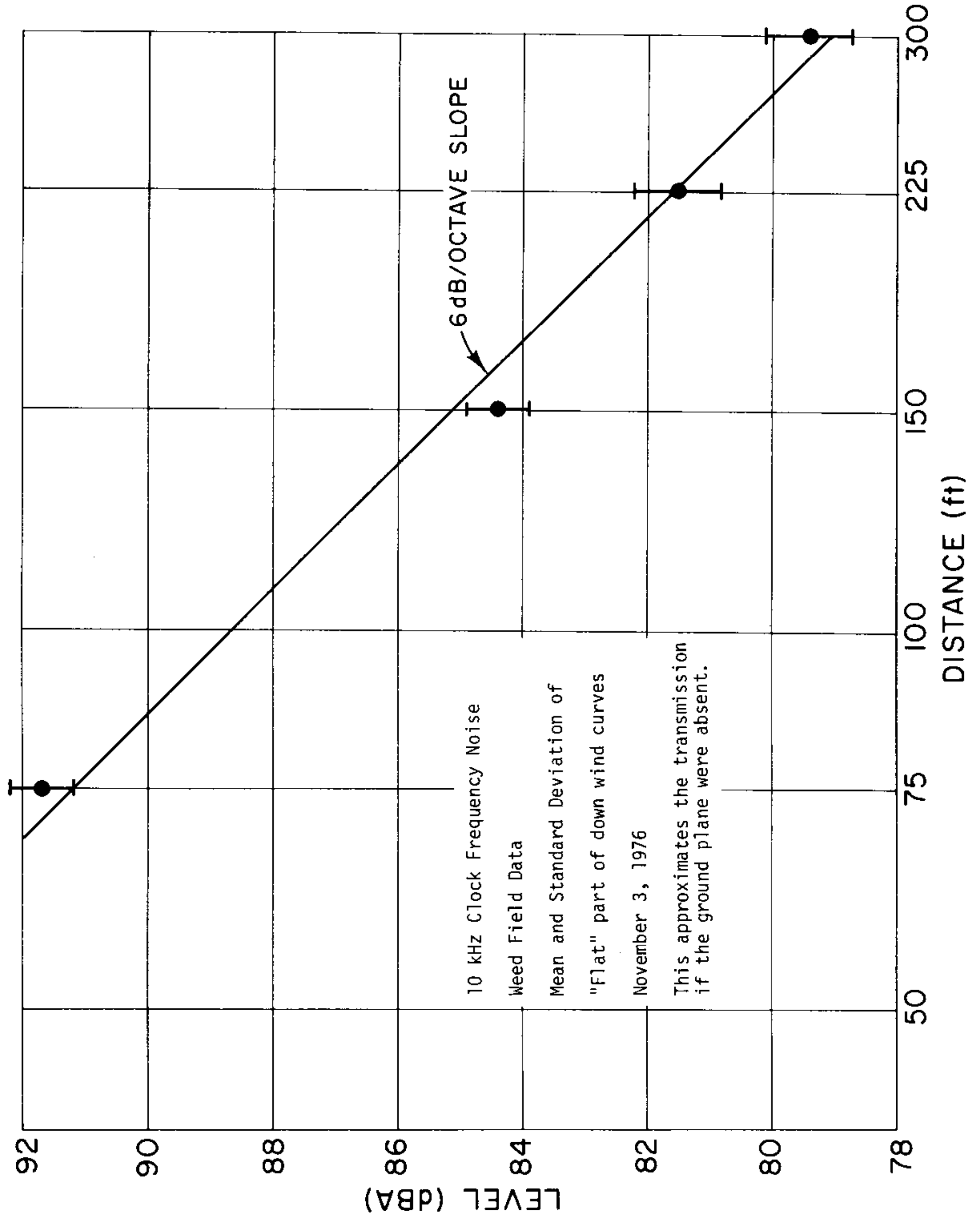
Speaker to Microphone Distance:
North: 281.5 ft
South: 309.5 ft

SOLID LINE:
Speaker north of microphone

DASHED LINE:
Speaker south of microphone

Number by mean is number of data points used to establish the mean.

*Figure 25*



10 kHz Clock Frequency Noise

Weed Field Data

Mean and Standard Deviation of

"Flat" part of down wind curves

November 3, 1976

This approximates the transmission if the ground plane were absent.

*Figure 26.* *System check.*

## SPECTRAL DATA

### Test Site

The same site was used to collect the spectral data that was used for the A-weighted weed-field tests (see Figure 3). The setup was the same as before except that this time two larger, 20-in. diam horns with I-60 drivers were used.* One of the speakers was placed north of the microphone and one south of it. The speakers were moved to the desired test distance by hand, and the center of the driver was always 4 ft from the ground.

The speakers were driven by a pseudorandom digital noise generator using a clock frequency of 10 kHz. The speaker-driver combination used for the tests was such that data as low as 200 Hz could be analyzed.

The signals from the 1/2-in. electret microphone were fed through a General Radio Model 1560 P-42 preamplifier and back to the instrumentation camper, where they were processed by the B&K 2131 one-third octave spectrum analyzer shown in Figure 27.

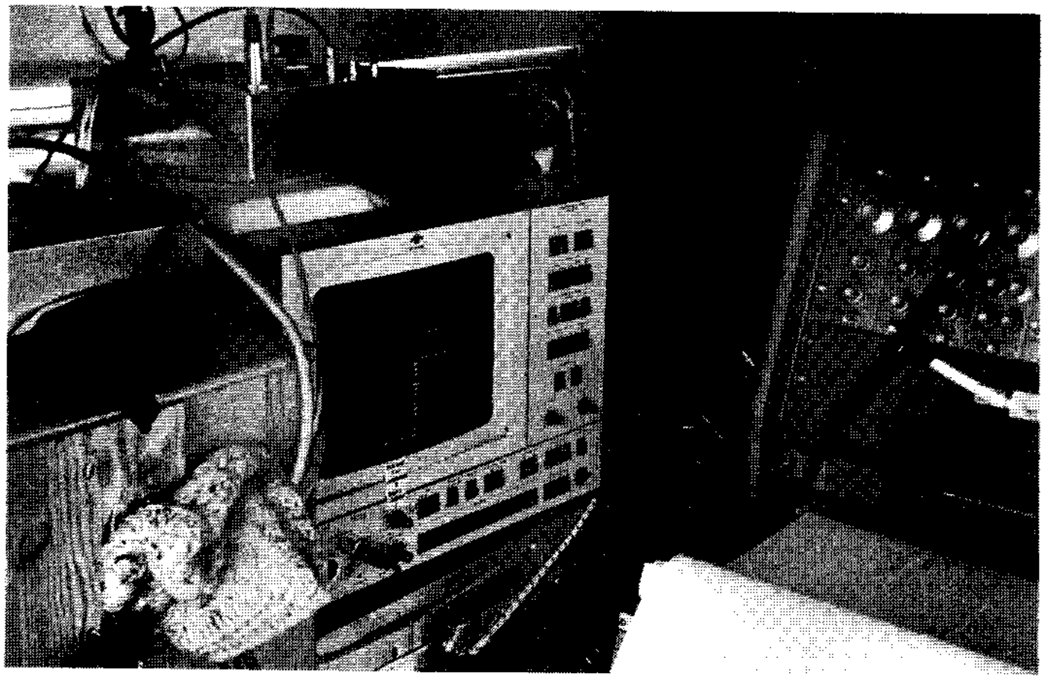


*Figure 27. View inside instrumentation camper showing B&K one-third octave spectrum analyzer and other equipment.*

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*University Sound Company, Model PH Trumpet.

## Experimental Procedures

The general procedure used for taking the spectral data was similar to that for the A-weighted data reported earlier except that an individual measurement was somewhat more time consuming both to make and to reduce. As a result, measurements were made only on the weed field and, predominantly, at distances of 150 ft and 225 ft. During each measurement, data were taken from two directions, north and south of the microphone. Because of slight differences in the terrain, each section was treated independently during the data analysis. Once again, since we could not control the wind, it was necessary to take several hundred spectra to acquire data under a sufficiently wide variety of wind conditions.

The procedure for each measurement was as follows. First the ambient noise level was recorded using the B&K 2131 one-third octave analyzer so that any one-third octave data bins that did not show a signal-to-noise ratio of at least 8 dB could be removed from the data file. Next, the Brush multi-channel strip-chart recorder was activated to monitor the wind speed and direction while, at the same time, the north speaker was activated. After approximately 1 sec (to ensure the sound had traveled to the microphone), the B&K 2131 integration period of 4 sec was started, and upon completion of the sampling period the spectrum was stored in the digital memory of the spectrum analyzer. The output of the noise generator was then switched from the north speaker to the south and, after a 1-sec delay, the B&K 2131 integration period of 4 sec was started, the data sampled, and the spectrum stored.

This completed one run. The spectra produced by the north and south speakers were read out frequency by frequency and recorded by hand on a data sheet. The wind speed and direction data, recorded on the strip chart, were then eye averaged and recorded on the same sheet as the spectral data.

The switch from the north to the south speaker was made as quickly as possible to increase the chance that wind conditions would be the same for both terrains.

The microphone was calibrated each day before the beginning of the runs and at numerous intervals during the course of a day's testing. This was done using a General Radio Model 1562A calibration unit which generated a 1000-Hz tone at 114 dB.

## Data Reduction

Each horn, while being driven by the stable pseudorandom noise source, was calibrated by raising it approximately 8 ft off the ground and pointing it straight into the air where, at a distance of 11 ft, a precision B&K 1/2-in. microphone was suspended on a line between two towers. The resulting frequency spectrum is shown in Figure 28.

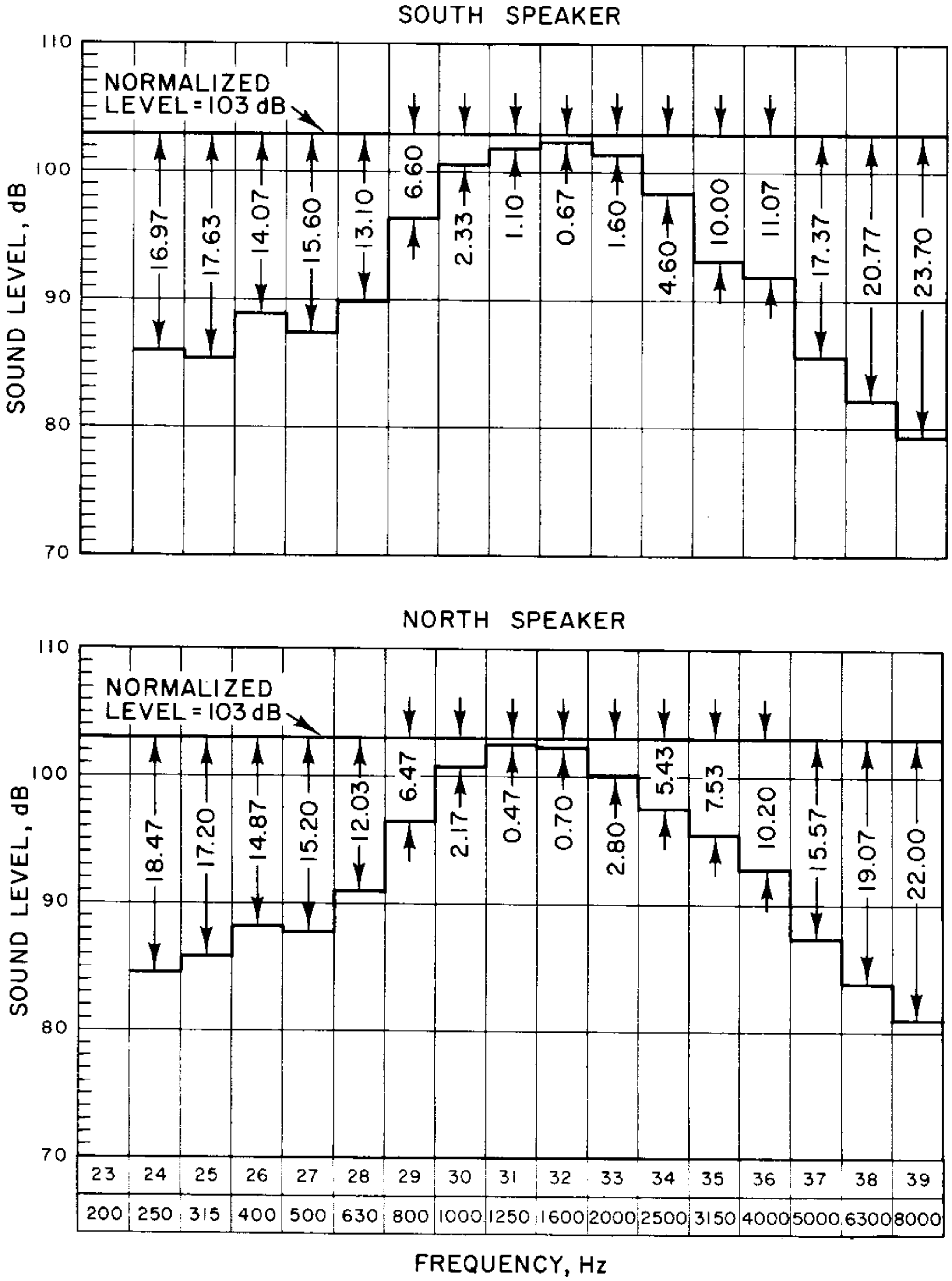


*Figure 28.* *Speaker calibration/normalization. The decibel level shown at each one-third octave frequency is the average of three calibration tests 11 ft from the microphone.*

The field data were put on computer cards to facilitate analysis. As part of the data reduction, the received levels for all the one-third octave frequency bins were adjusted to an effective source level of 103 dB at 11 ft by adding the amounts shown in Figure 28. All of the spectra, together with their associated wind velocities and other data such as microphone height, were entered into a CDC 6400 computer. The computer then sorted the data into various wind velocity bins using, in turn, each anemometer as the reference. In addition, the difference between various anemometers was investigated as a possible reference for the wind bins. Trials were made using, in turn, the data for each of the anemometers and also the differential wind shear as the wind criterion to determine which would yield the least scatter in the data. After a number of trials, it became apparent that differential wind shear was no better a parameter than the wind velocities at the higher anemometers. Therefore the data presented in this report have all been referenced to the wind velocity at the 8.75-ft high anemometer. The wind velocity used for the data ordering was the component parallel to the "flight" direction of the sound rays measured.

Since the wind was uncontrollable, the data were not uniformly distributed among wind bins. Data were fairly dense in some wind velocity ranges and rather thin in others. In many cases, the data were too sparse to simply divide the wind speeds into relatively narrow bins and then average the data points falling within that bin. Instead, a method was needed that would use nearby data points to help enhance the validity of any given bin. With this in view, we chose five overlapping wind-velocity bins ±3 mph wide and centered at -10, -5, 0, +5 and +10 mph (see Figure 29). A least-squares regression fit to a linear curve was obtained for each bin. This was done for all frequencies, wind bins, distances, and microphone heights for which there were sufficient data to justify the procedure. Each of the resulting best-fit curves was then read at its center point to determine the acoustic effects at that wind velocity. To give the reader a feel for the amount of "smoothing" produced by this process, Figure 30 shows two typical "sound level vs wind speed" plots together with the piecewise linear fit. Note that at 250 Hz the top figure shows almost no variation with wind, whereas at 2000 Hz the bottom figure shows considerable wind dependence.

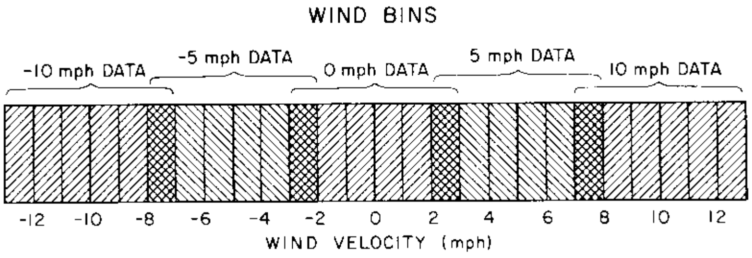


*Figure 29. Wind bin selection.*

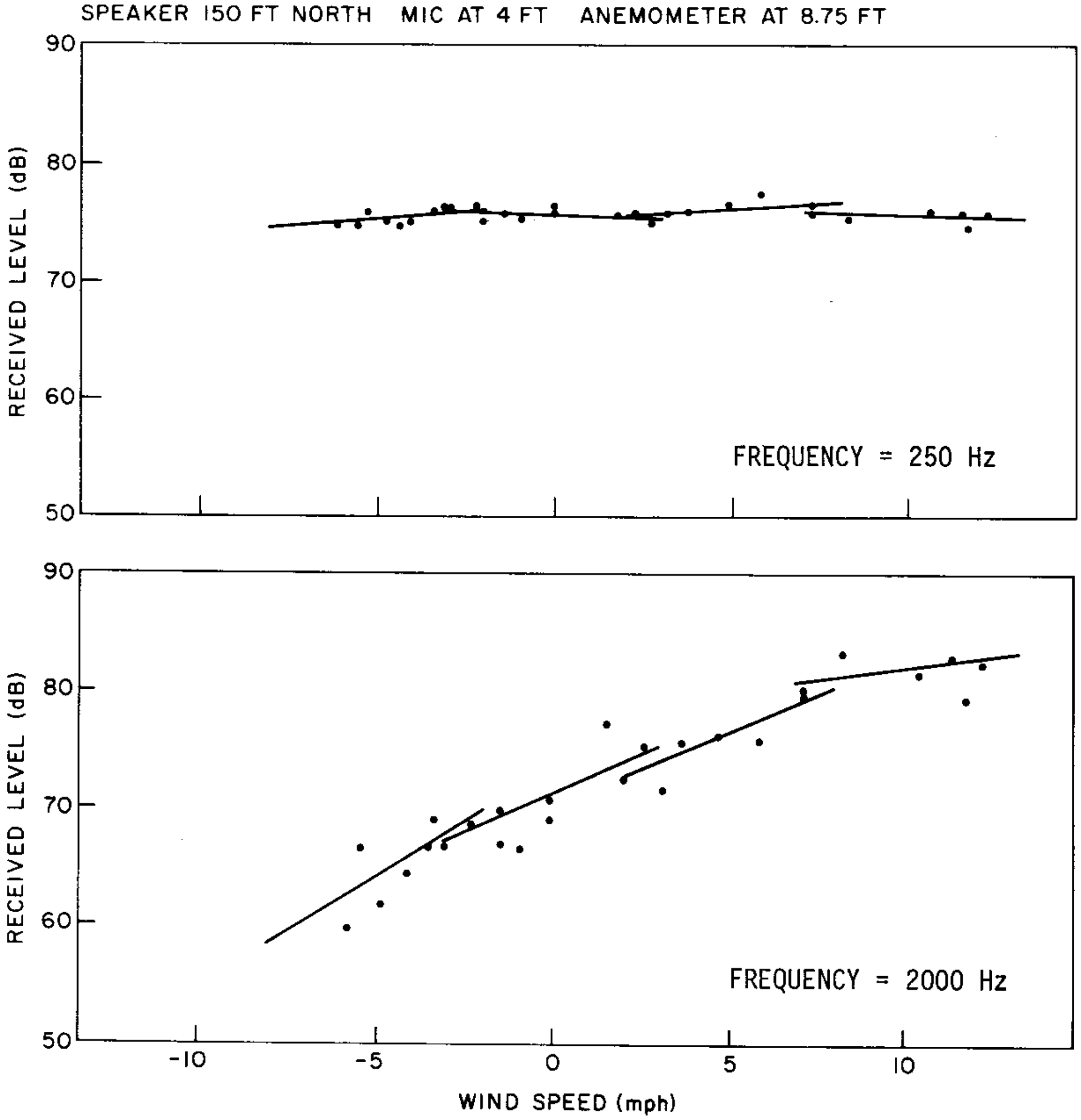


*Figure 30. Least-squares regression fit to data points.*

## Results

### *Comparison of Zero-Wind Data with Theoretical Predictions*

Current theory indicates that the excess attenuation for sound propagating near the ground is caused by the canceling effect facilitated by a large phase change that occurs in reflections from the ground at low angles of incidence; it also predicts that this shadow zone will be penetrated to some degree by surface and ground waves (see References 1-3). This theory applies only to isotropic propagation (i.e., when there is no wind shear or thermal gradients) and to flat ground. Figures 31 through 46 show the experimental results for zero wind at 150 ft and 225 ft. Also plotted in the figures are the theoretical curves for (1) ground and surface wave effects and (2) the ground reflection effect. The theoretical predictions for surface and ground waves agree rather well with the spectra obtained at low frequencies. In Figure 38, for example, the ground and surface wave predictions taken alone do a remarkably good job of predicting the actual levels obtained at a microphone height of 0 ft. However, at the higher frequencies (where the surface and ground wave predictions are not applicable), the ground reflection theory does not do a particularly good job of predicting the experimental results actually obtained.

Figures 31 through 38 show the results obtained at the various microphone heights for a distance of 150 ft. If the system had been in free space (and only inverse square spreading had occurred), the expected level at this distance (adjusted for all frequency bins) would have been 80.3 dB. At some frequencies, the data for the 14-ft high microphone (Figure 31) exceed this level by as much as 4 dB. At 6 ft and below, the received levels show more attenuation than predicted by simple inverse square spreading at all frequencies. At 4 ft, this excess attenuation amounts to at least 9 dB; at 0 height it is perhaps as much as 27 dB for frequencies where the ground and surface waves are not dominant. This amount of attenuation was not predicted by the theory given in References 1 and 3.

Figures 39 through 46 show the results obtained at 225 ft. Once again, the theory does not predict the attenuation found experimentally for frequencies above 500 Hz, where ground and surface waves have no effect.

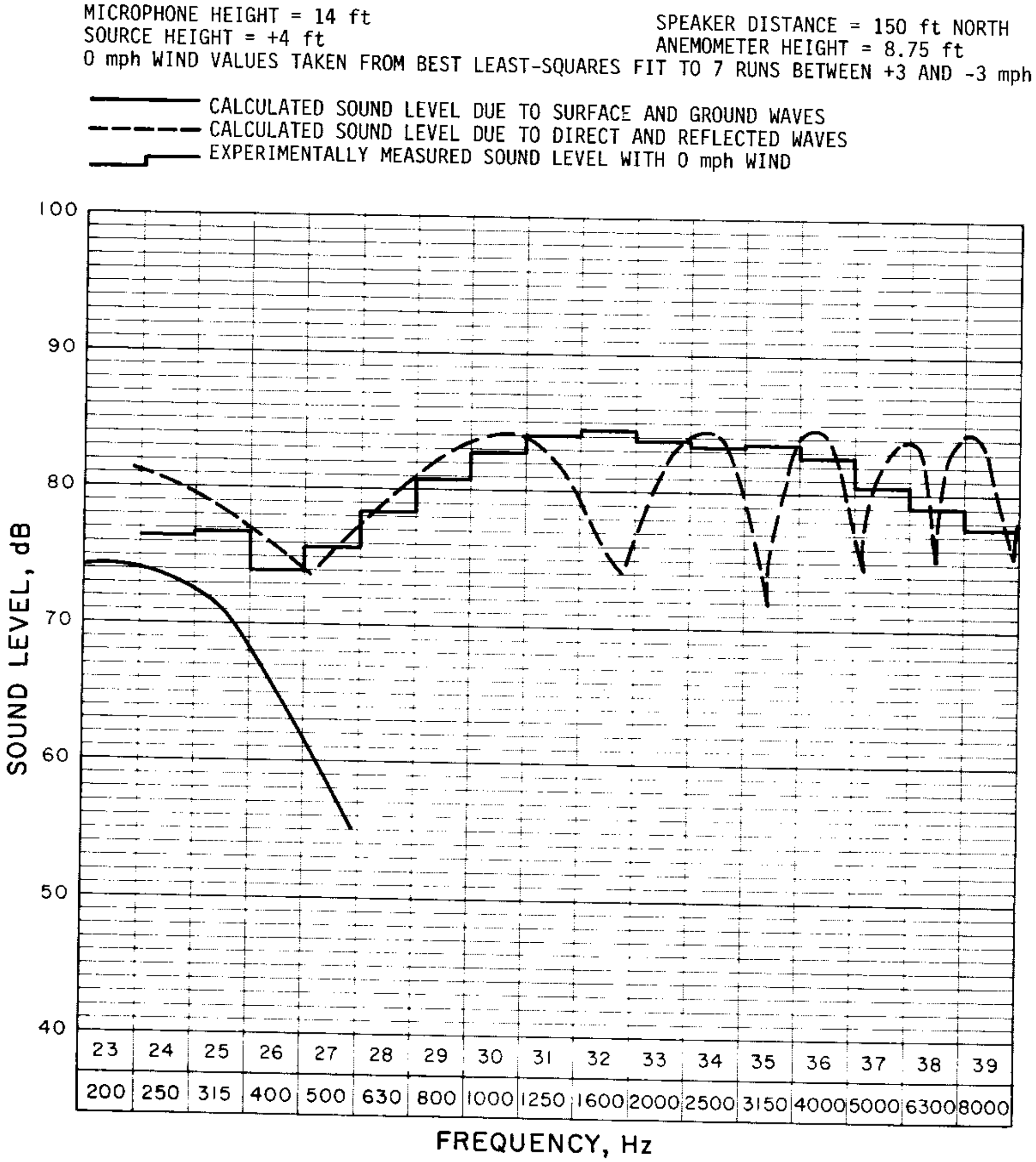

MICROPHONE HEIGHT = 14 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 150 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 7 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
SOUND LEVEL, dB
100
90
80
70
60
50
40
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY, Hz

*Figure 31.*

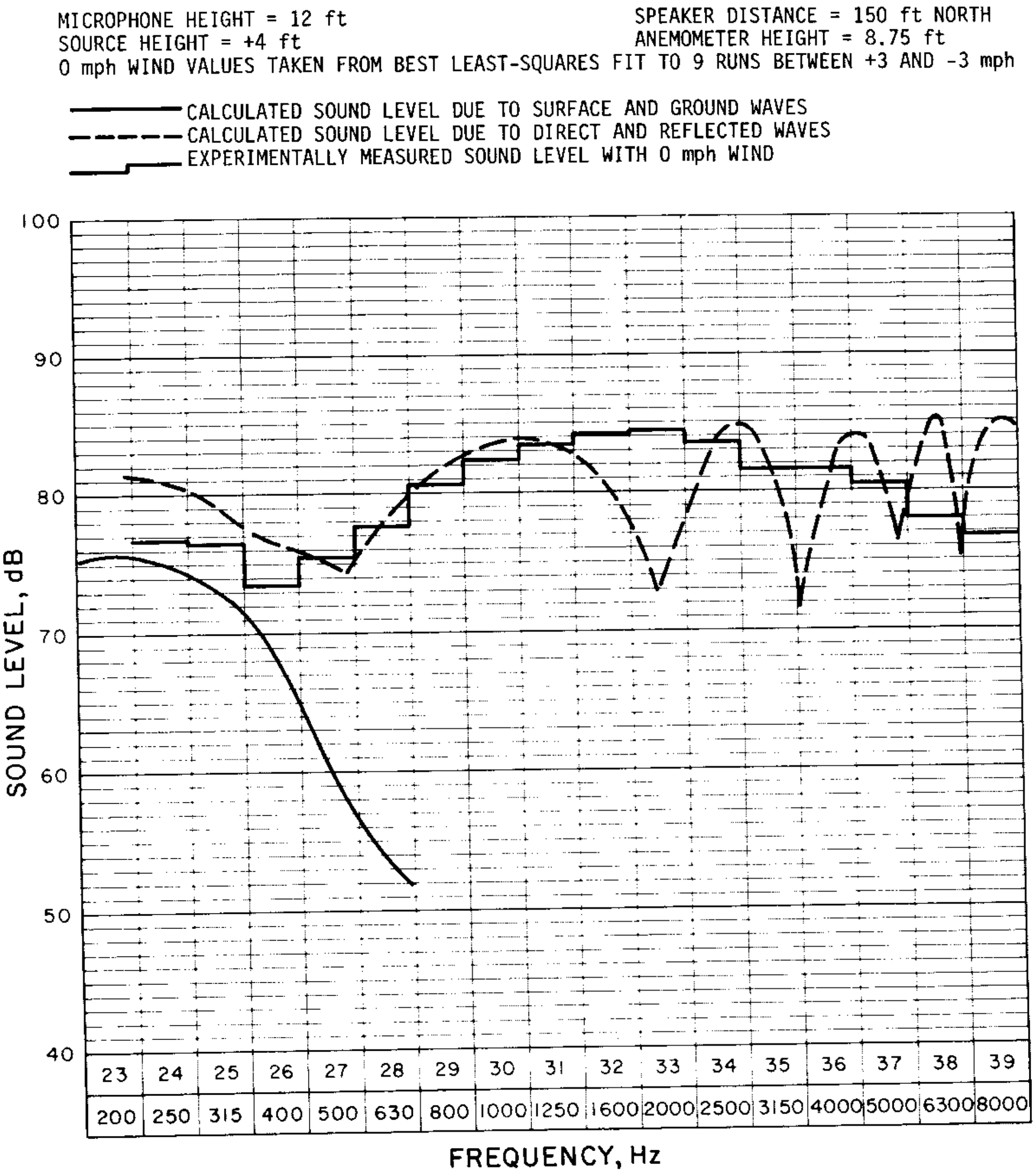

MICROPHONE HEIGHT = 12 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 150 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 9 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
SOUND LEVEL, dB
100
90
80
70
60
50
40
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY, Hz

*Figure 32*

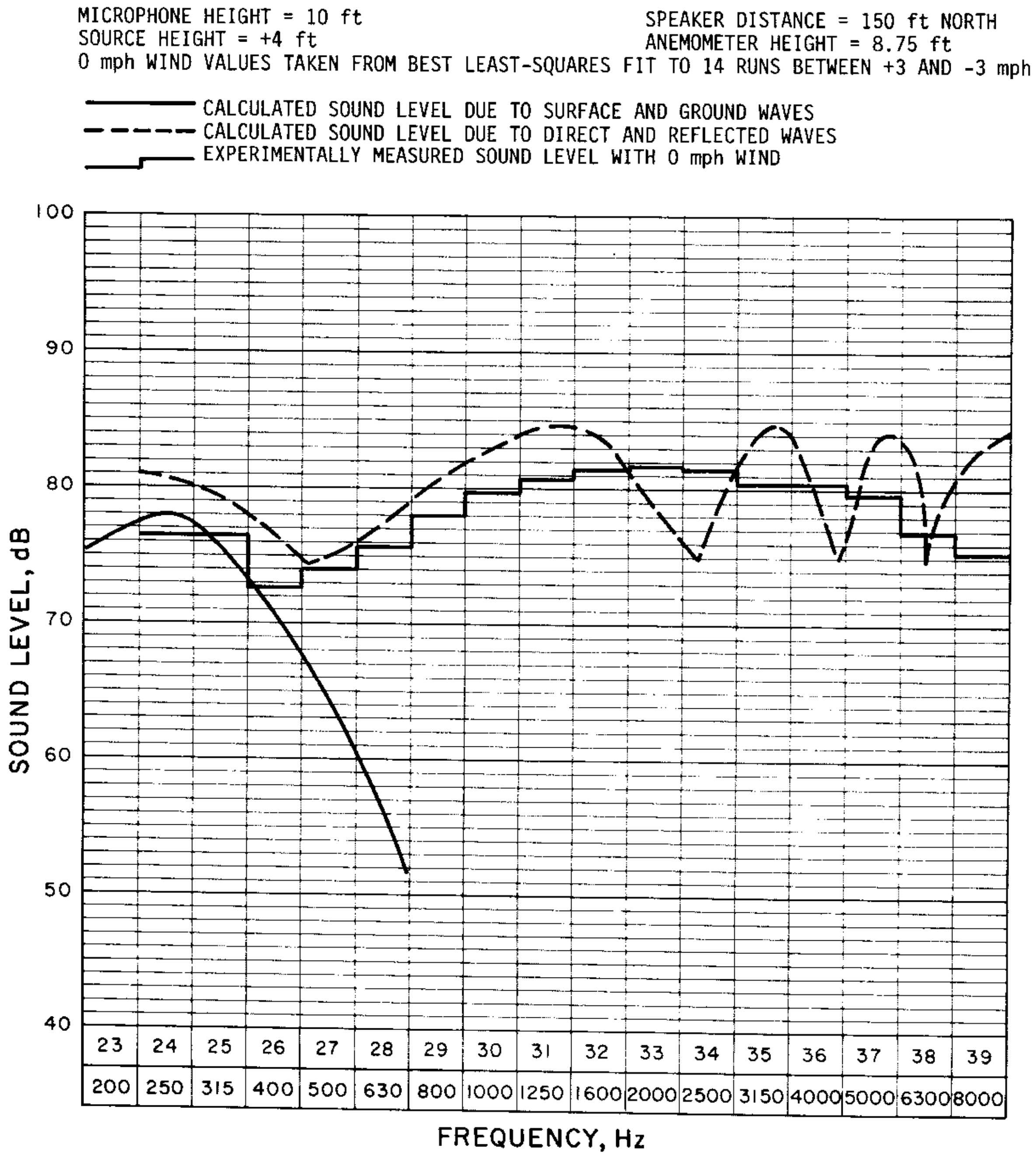

MICROPHONE HEIGHT = 10 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 150 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 14 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
SOUND LEVEL, dB
100
90
80
70
60
50
40
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY, Hz

*Figure 33*

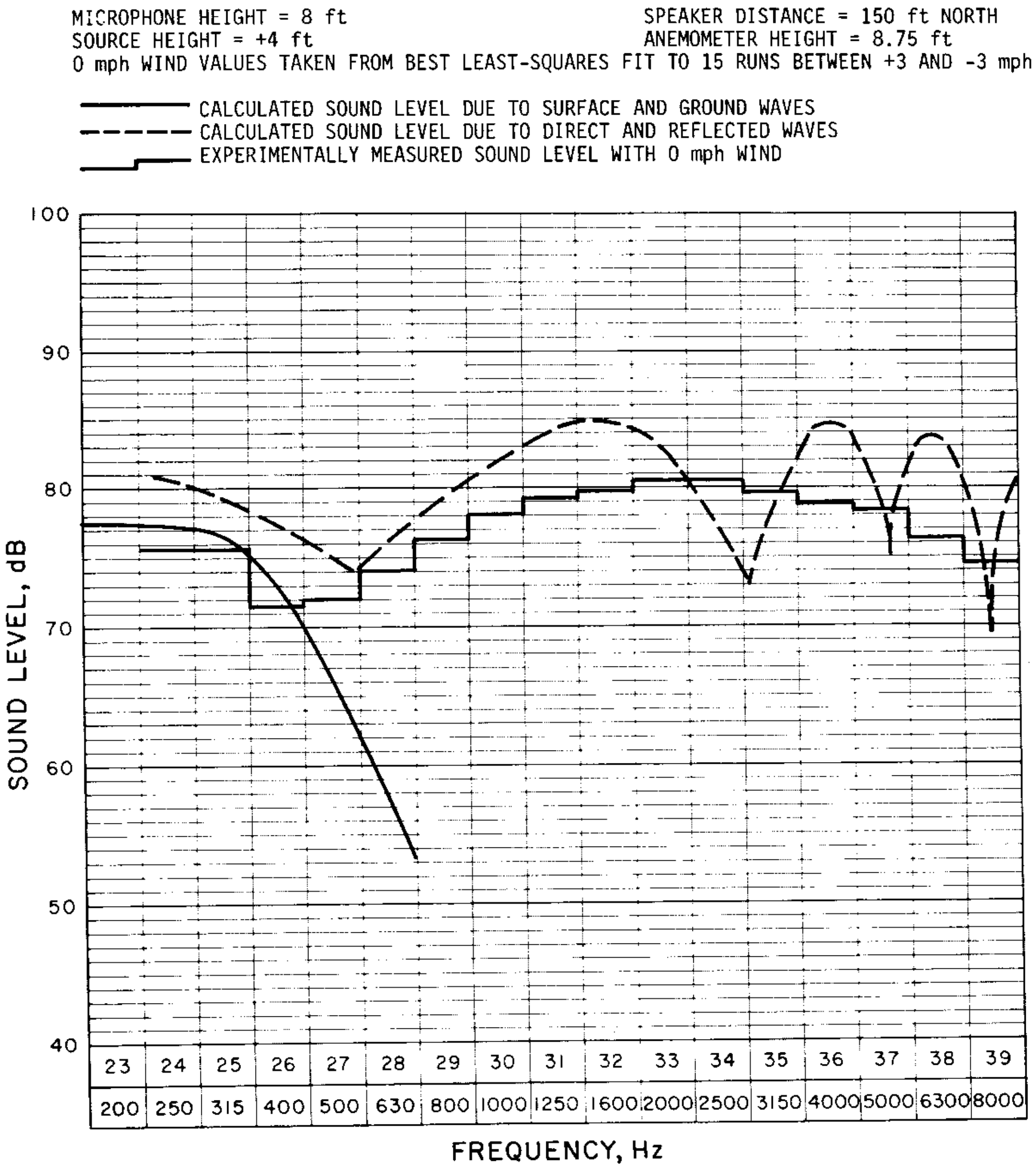

MICROPHONE HEIGHT = 8 ft
SPEAKER DISTANCE = 150 ft NORTH
SOURCE HEIGHT = +4 ft
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 15 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
100
90
80
70
60
50
40
SOUND LEVEL, dB
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY, Hz

*Figure 34*

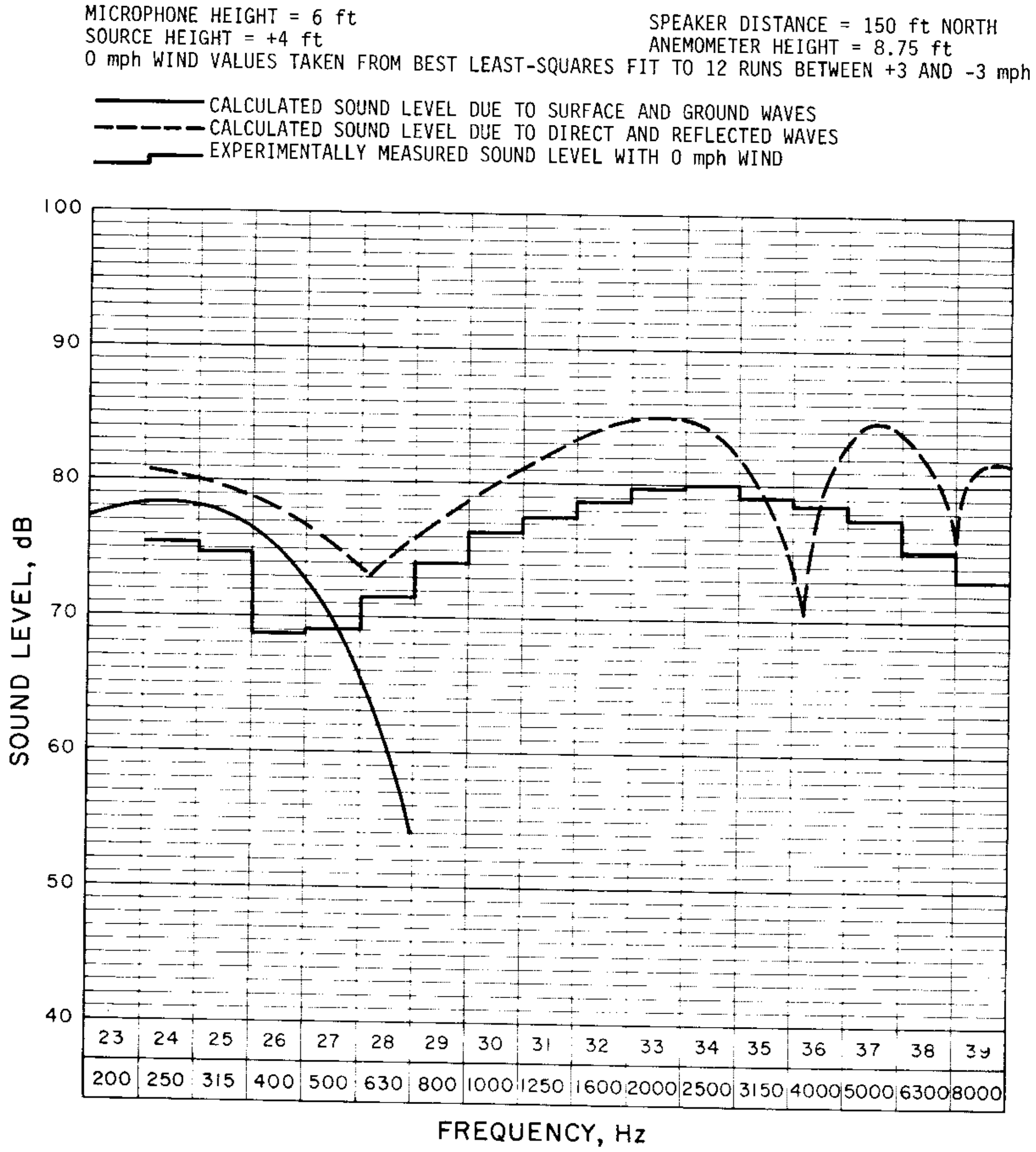

MICROPHONE HEIGHT = 6 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 150 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 12 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
SOUND LEVEL, dB
100
90
80
70
60
50
40
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY, Hz

*Figure 35*

MICROPHONE HEIGHT = 4 ft SPEAKER DISTANCE = 150 ft NORTH
SOURCE HEIGHT = +4 ft ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 11 RUNS BETWEEN +3 AND -3 mph

——— CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
– – – CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
_┌— EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND

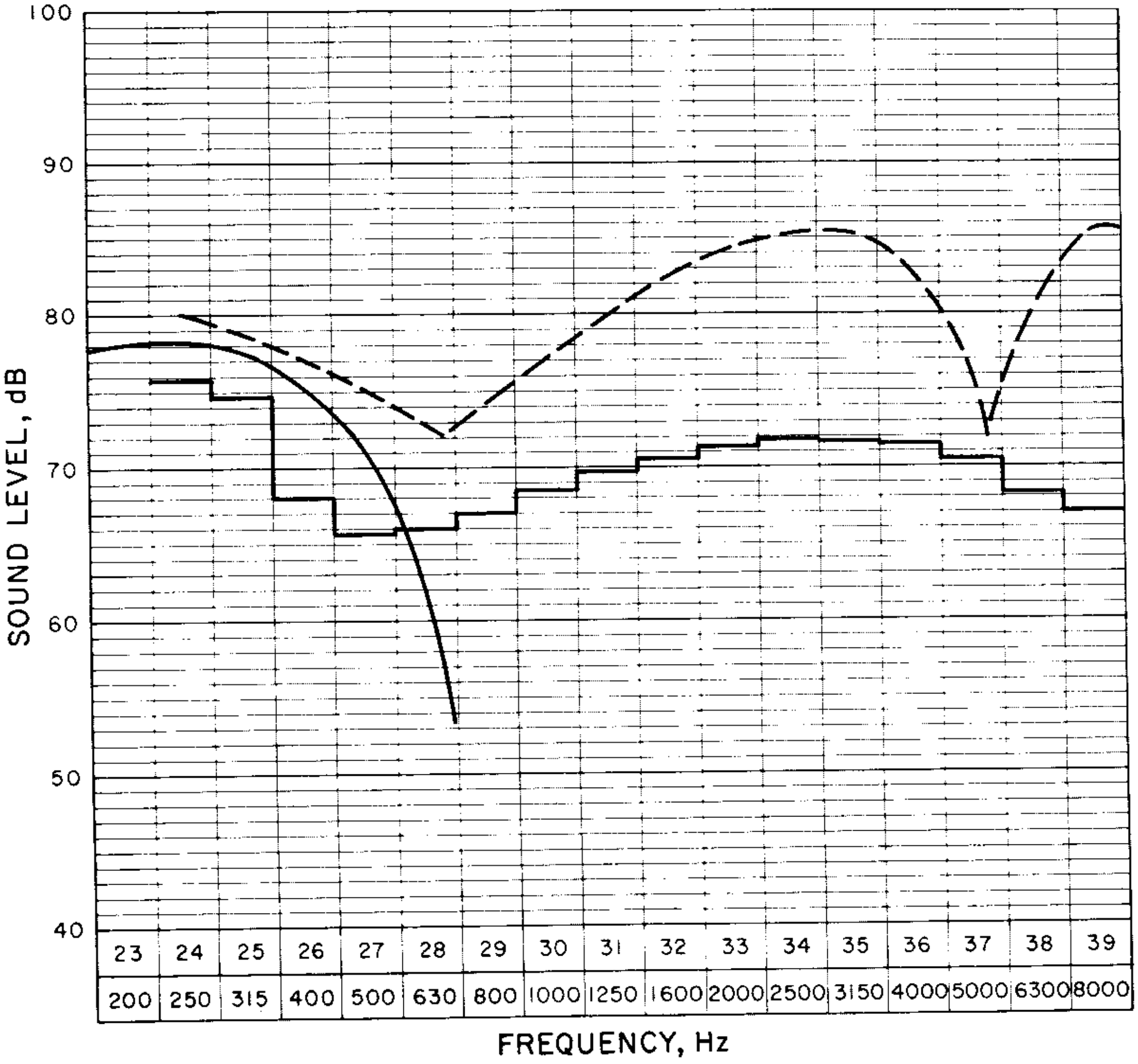


*Figure 36*

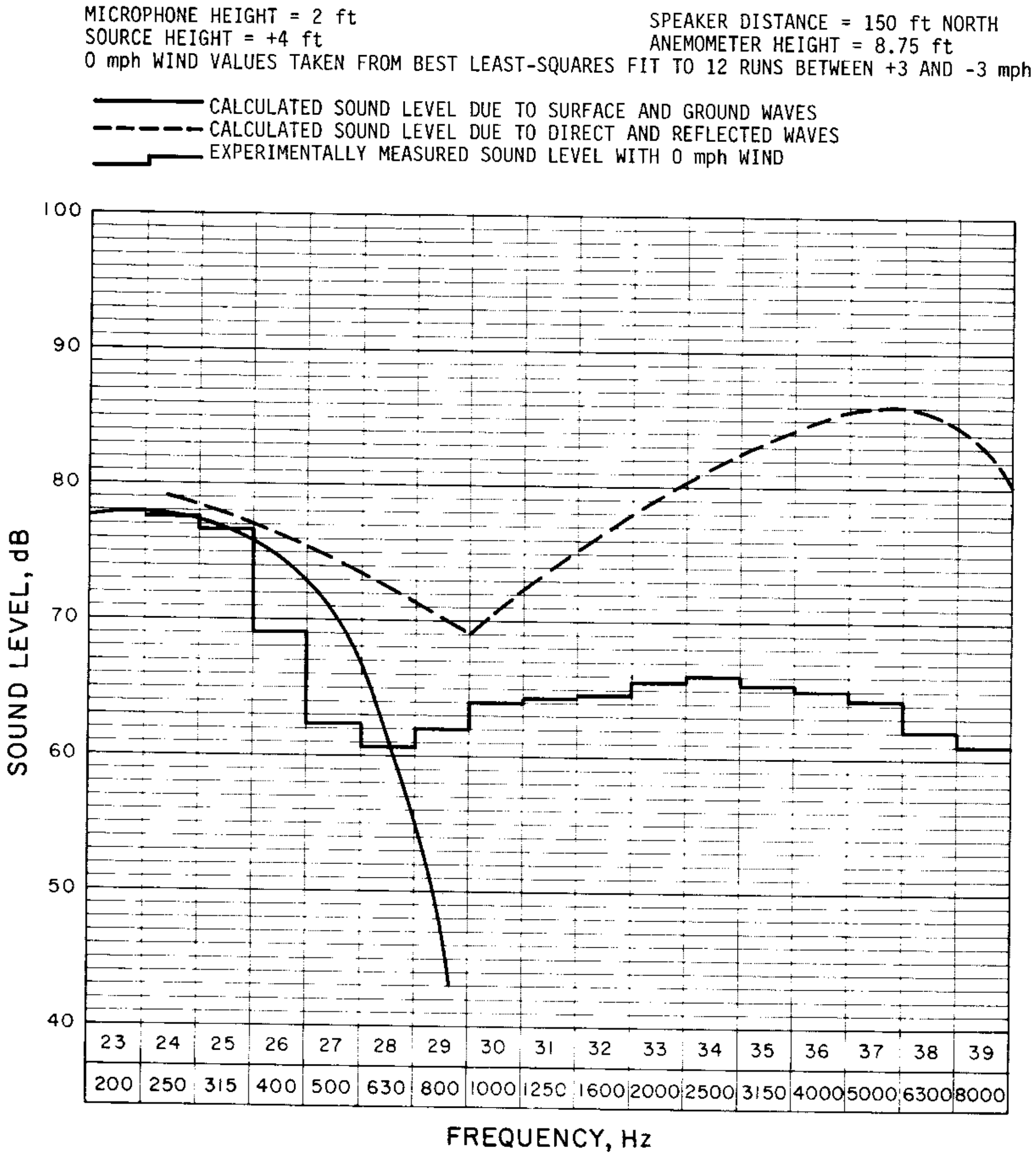

MICROPHONE HEIGHT = 2 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 150 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 12 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
SOUND LEVEL, dB
100
90
80
70
60
50
40
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY, Hz

*Figure 37*

MICROPHONE HEIGHT = 0 ft
SOURCE HEIGHT = +4 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 3 RUNS BETWEEN +3 AND -3 mph

SPEAKER DISTANCE = 150 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft

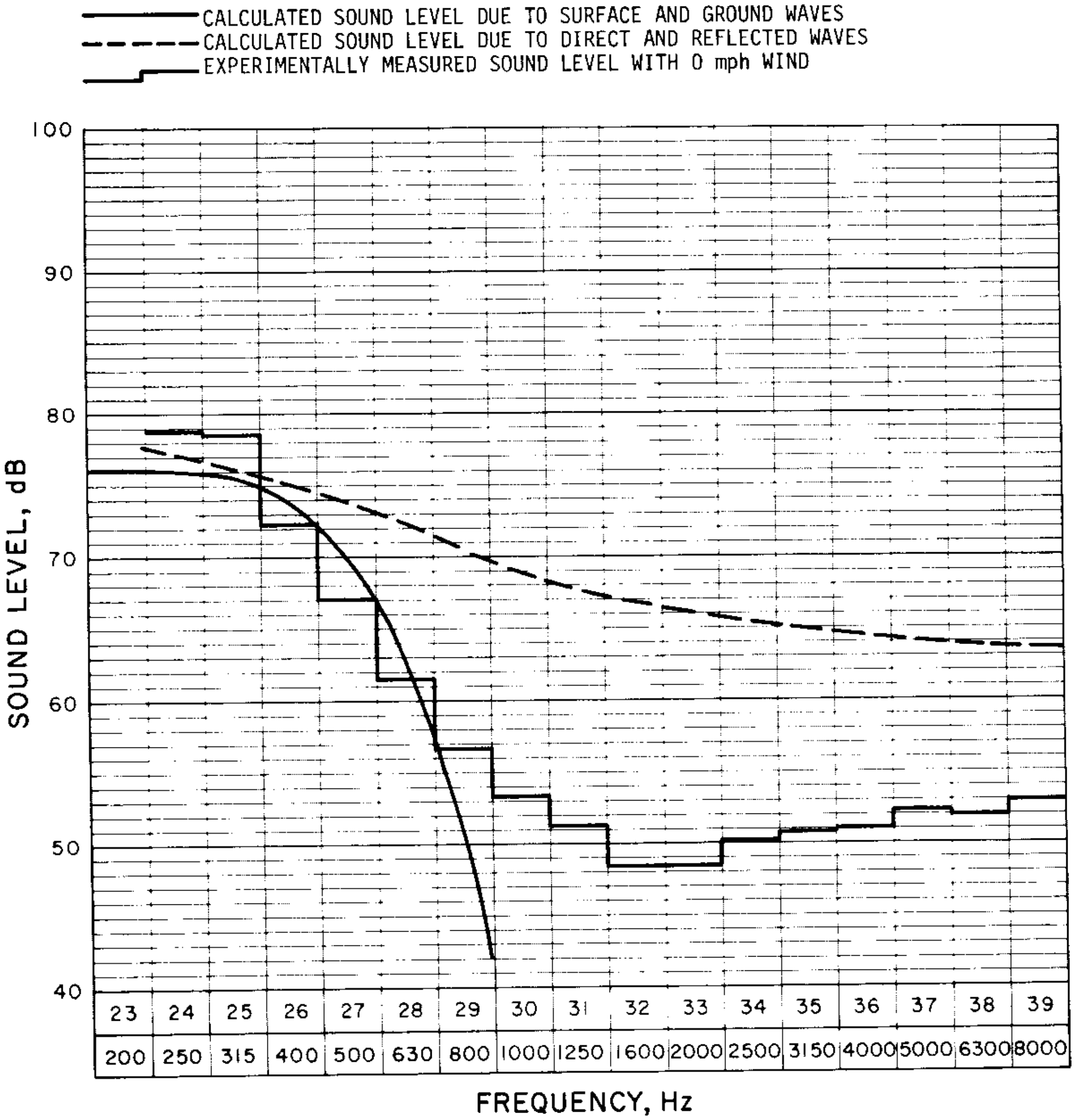


*Figure 38*

MICROPHONE HEIGHT = 14 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 225 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 2 RUNS BETWEEN +3 AND -3 mph

——— CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
– – – CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
__⌐— EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND

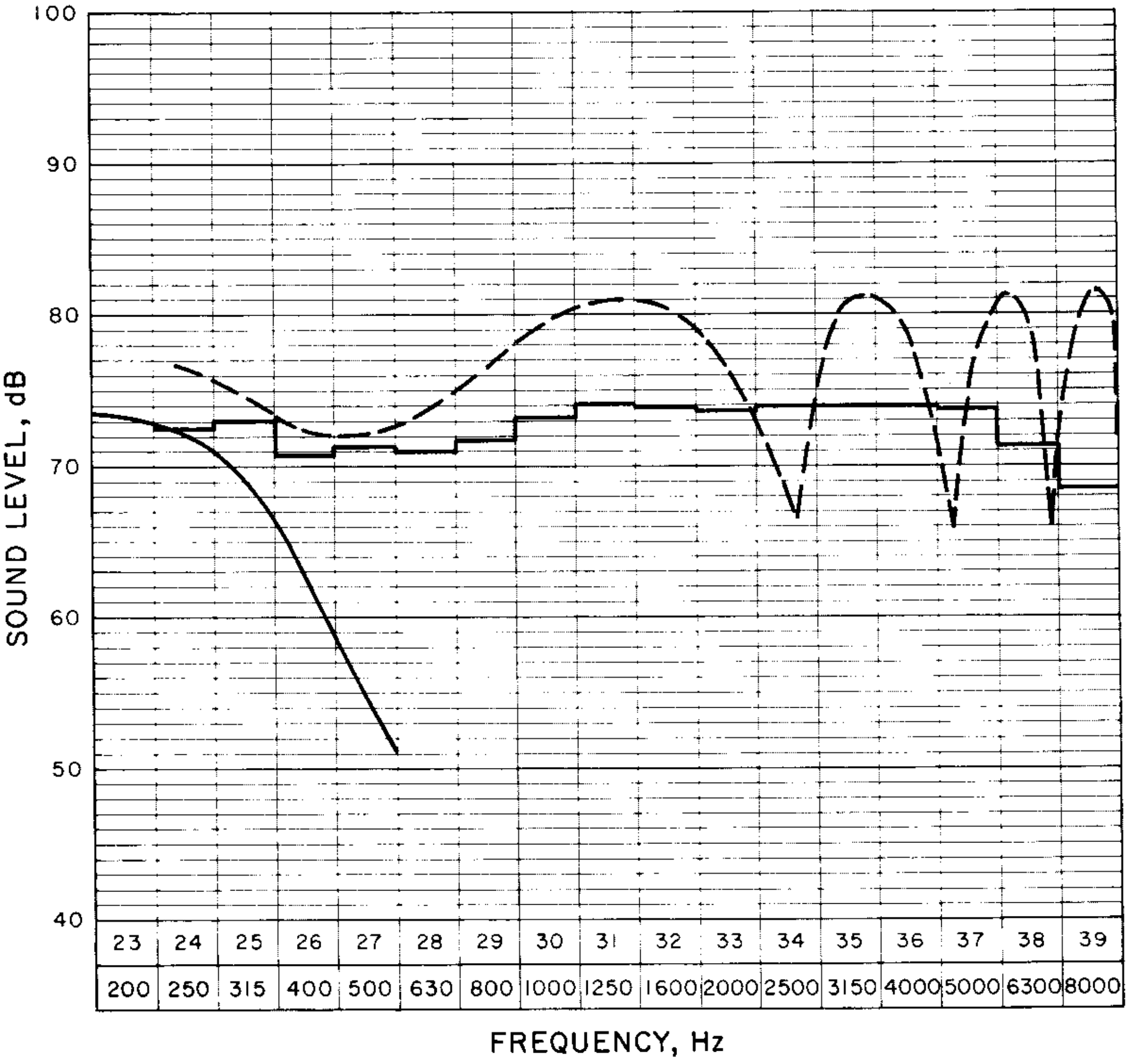


*Figure 39*

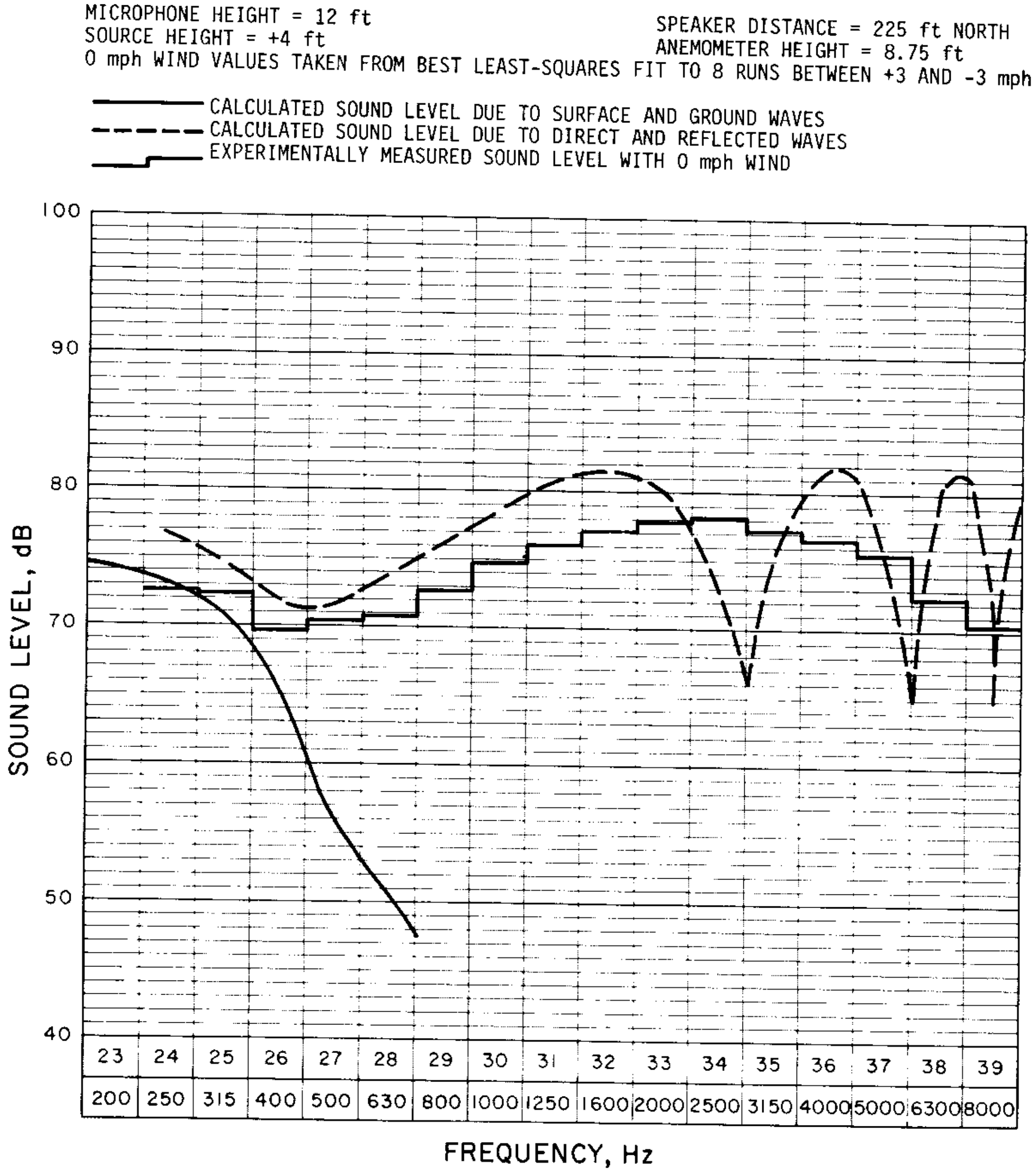

MICROPHONE HEIGHT = 12 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 225 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 8 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
SOUND LEVEL, dB
100
90
80
70
60
50
40
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY, Hz

*Figure 40*

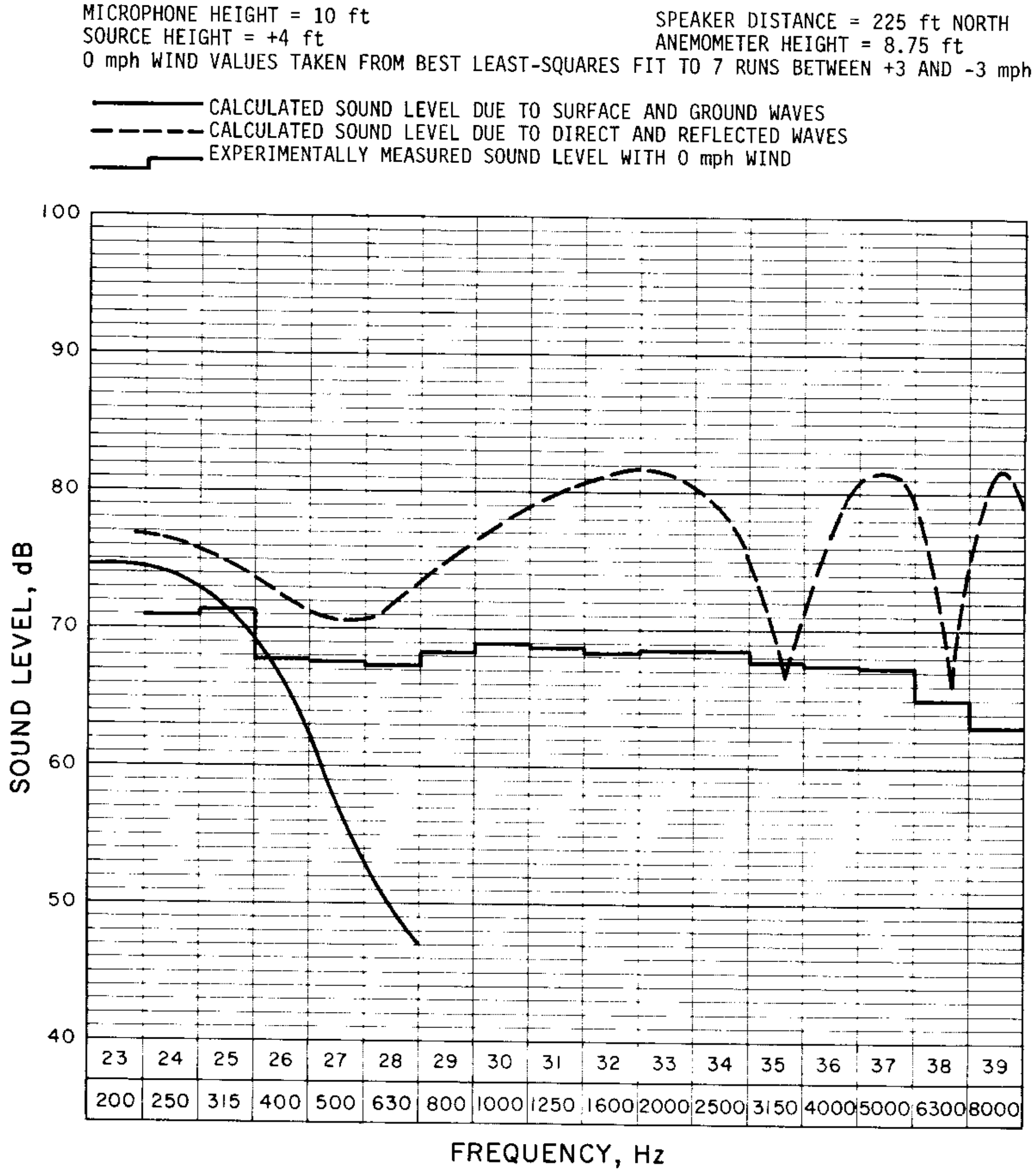

MICROPHONE HEIGHT = 10 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 225 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 7 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
SOUND LEVEL, dB
100
90
80
70
60
50
40
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY, Hz

*Figure 41*

MICROPHONE HEIGHT = 8 ft SPEAKER DISTANCE = 225 ft NORTH
SOURCE HEIGHT = +4 ft ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 13 RUNS BETWEEN +3 AND -3 mph

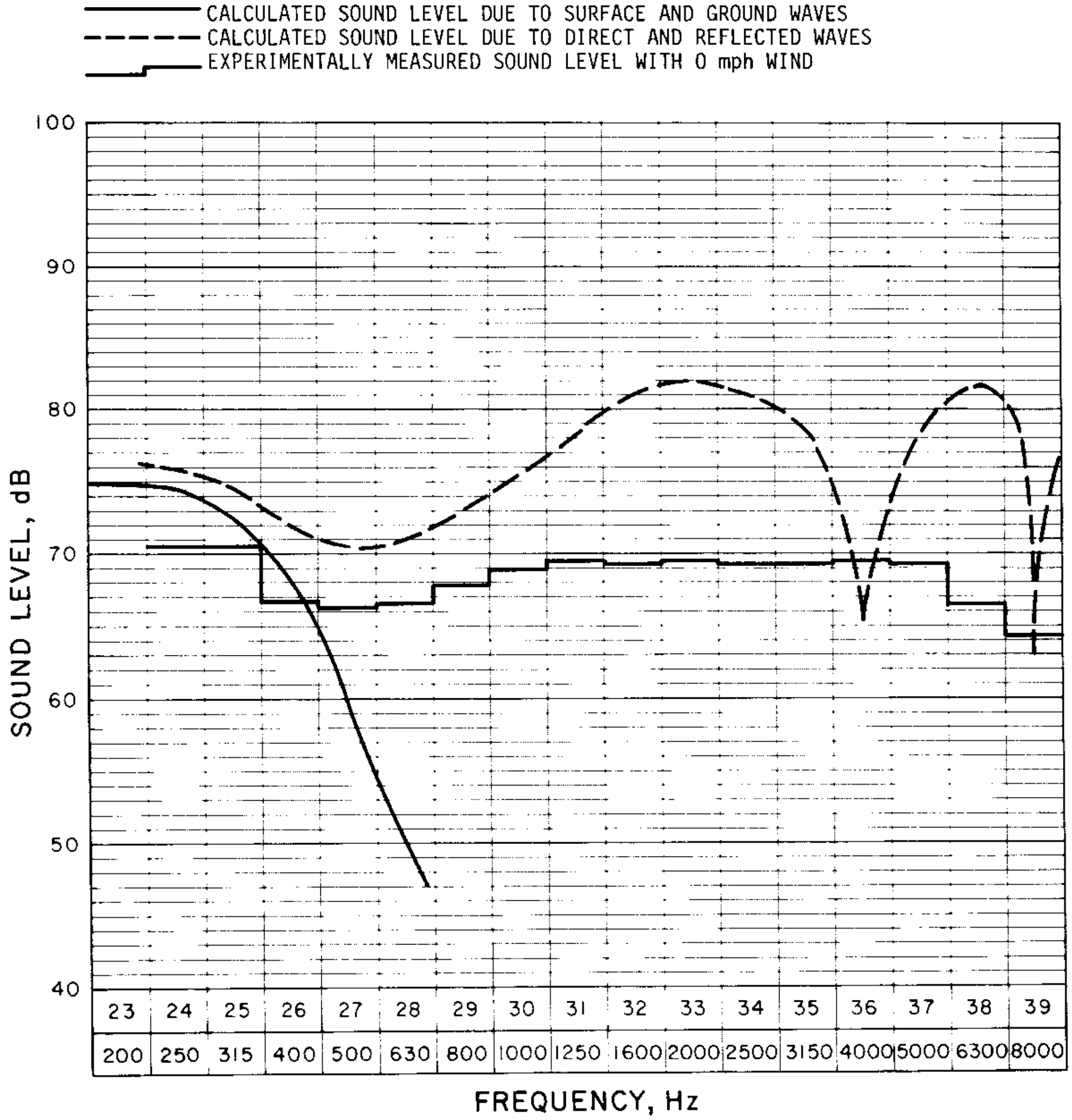


*Figure 42*

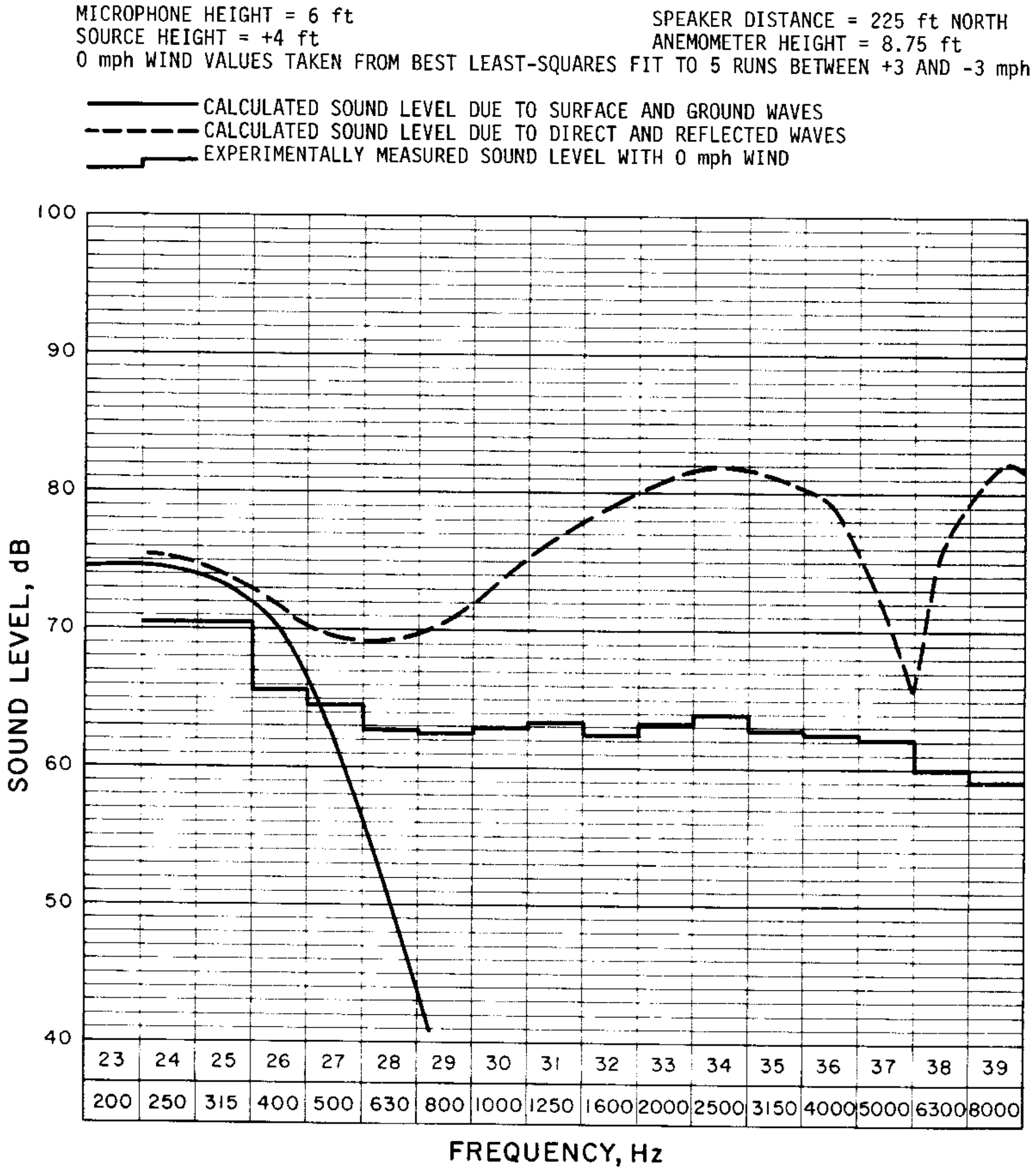
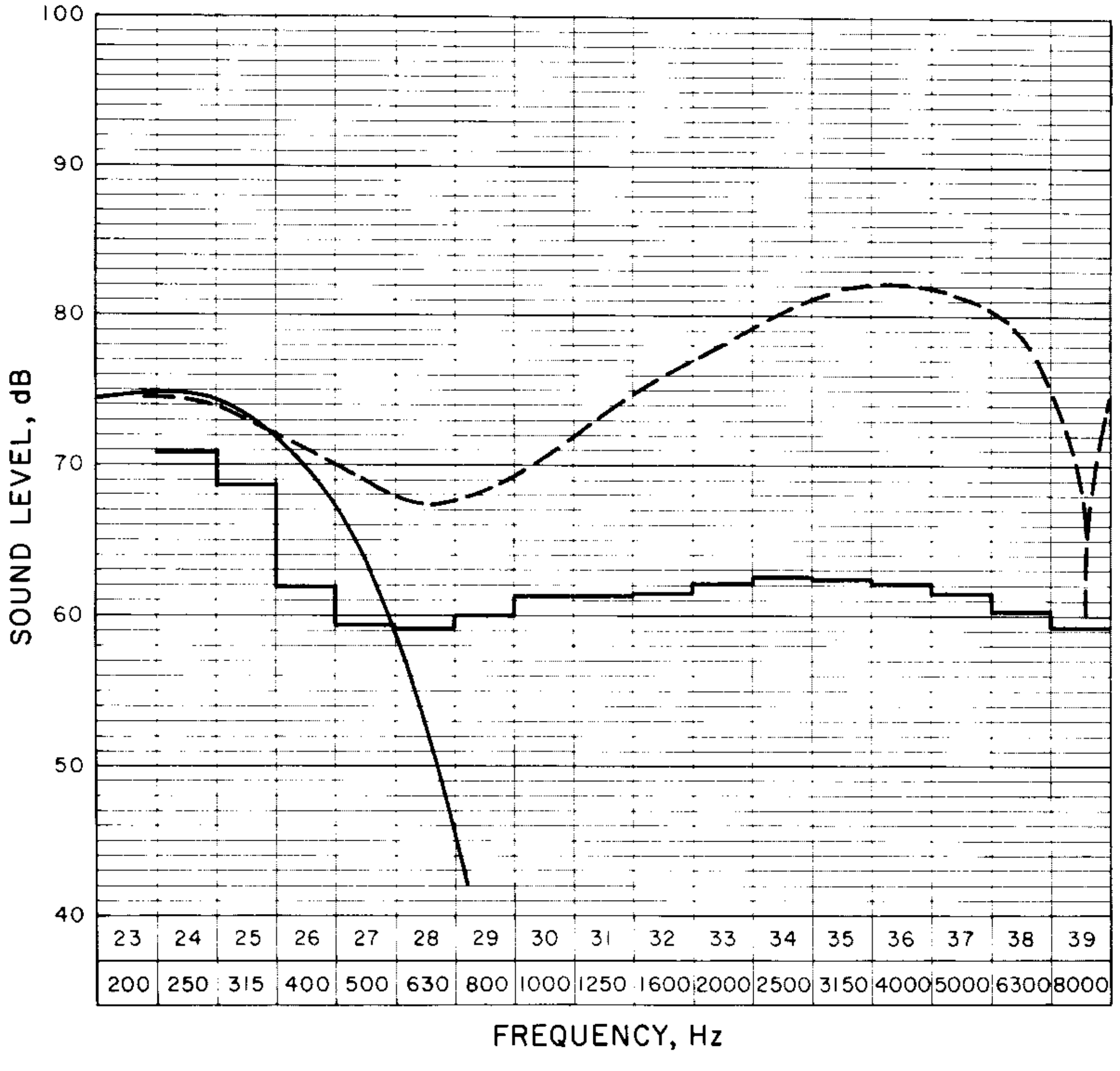

MICROPHONE HEIGHT = 6 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 225 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 5 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
SOUND LEVEL, dB
100
90
80
70
60
50
40
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY, Hz

*Figure 43*

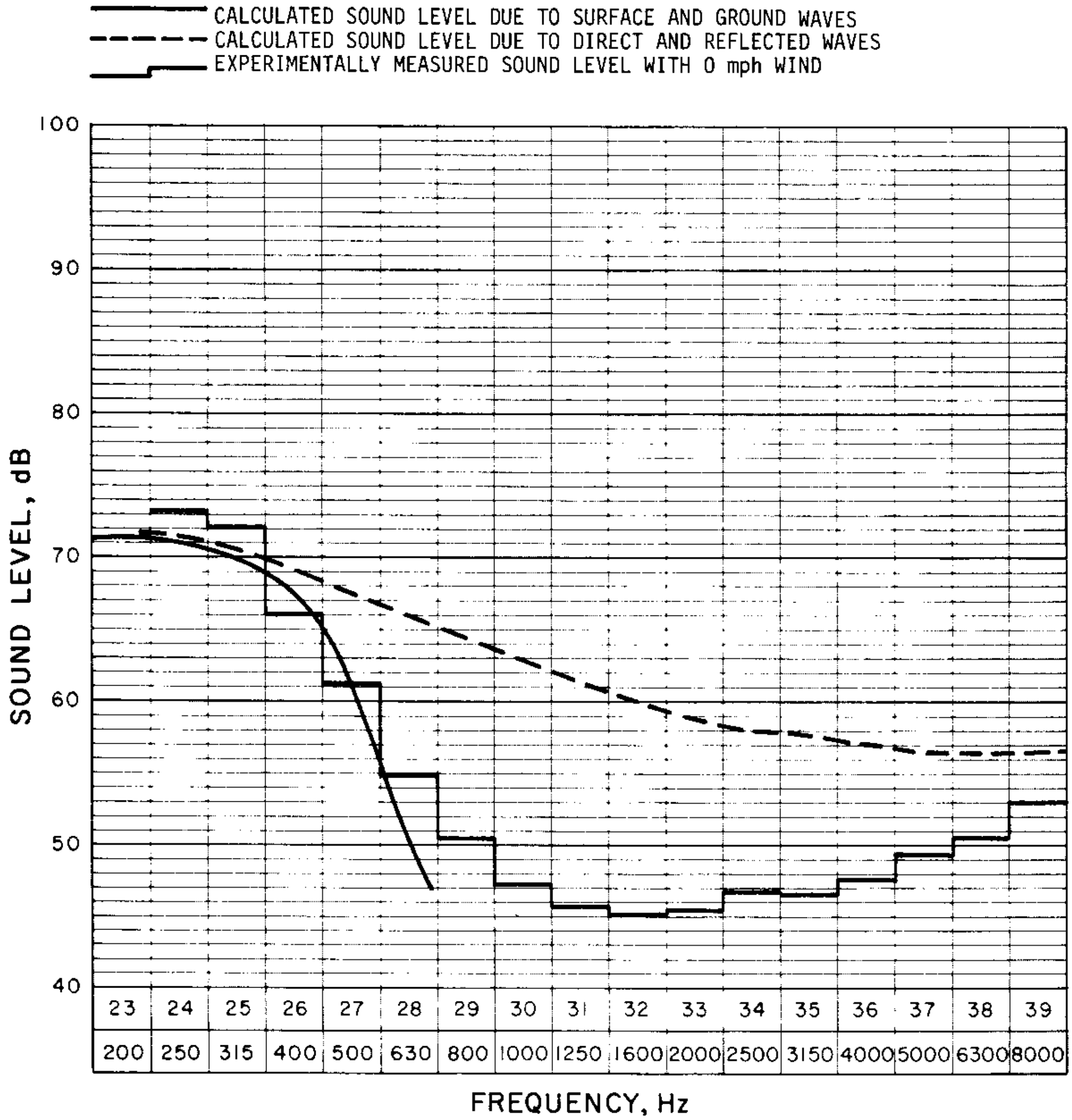


MICROPHONE HEIGHT = 4 ft
SOURCE HEIGHT = +4 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 10 RUNS BETWEEN +3 AND -3 mph

SPEAKER DISTANCE = 225 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft

——— CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
– – – CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
_┌— EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND

*Figure 44*



MICROPHONE HEIGHT = 0 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 225 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 10 RUNS BETWEEN +3 AND -3 mph

*Figure 45*

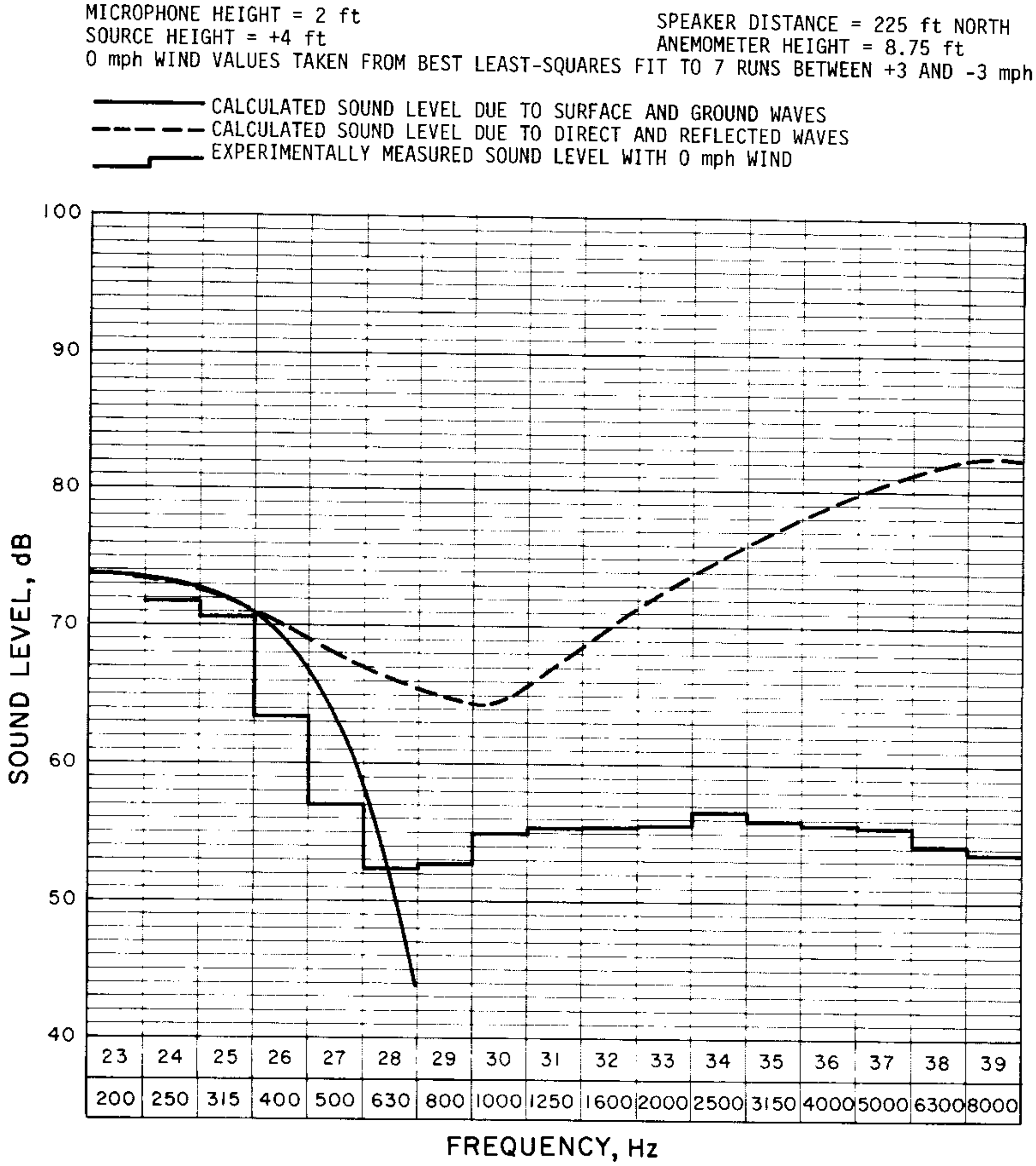

MICROPHONE HEIGHT = 2 ft
SOURCE HEIGHT = +4 ft
SPEAKER DISTANCE = 225 ft NORTH
ANEMOMETER HEIGHT = 8.75 ft
0 mph WIND VALUES TAKEN FROM BEST LEAST-SQUARES FIT TO 7 RUNS BETWEEN +3 AND -3 mph
CALCULATED SOUND LEVEL DUE TO SURFACE AND GROUND WAVES
CALCULATED SOUND LEVEL DUE TO DIRECT AND REFLECTED WAVES
EXPERIMENTALLY MEASURED SOUND LEVEL WITH 0 mph WIND
100
90
80
70
60
50
40
SOUND LEVEL, dB
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY, Hz

*Figure 46*

The theoretical curves were based on the values for ground impedance indicated in Reference 1. One might be tempted to think that a better match to the experimental data could be obtained by a different choice of ground impedance parameters. This is not the case. If the geometry is such that some place within the frequency band the path length of the reflected signal is at least one wavelength longer than the direct path between the source and the receiver, the theoretical model requires that there will be at least one frequency where the received level will rise to a level commensurate with inverse square spreading or up to as much as 6 dB higher, depending on the effective reflectivity coefficient of the ground. The phase change occurring upon reflection can influence where in the frequency band this signal enhancement will occur, but it can not prevent it from happening. However, in many cases (for example, Figure 36) the experimental data show no such fluctuations; in fact, the actual attenuation is considerably higher than the theoretical predictions throughout the spectrum above 500 Hz.

To summarize, the theory given in Reference 1 does a very good job of predicting the effects of ground and surface waves, but does not appear applicable for predicting the experimental results at higher frequencies, where considerably greater attenuation was found than was predicted.

### *Effects of Wind*

Appendix A shows the received spectral levels (normalized to 103 dB at 11 ft for all bin levels) obtained experimentally at each microphone height under five different wind conditions: +10, +5, 0, -5, and, when enough data were available, -10 mph wind. The "+" indicates that the wind component parallel to the transmission was traveling in the same direction as the sound, and a "-" indicates that it was in the opposite direction. For the 14-ft microphone, the effects caused by the wind are not great. However, for the lower microphones, they can be quite dramatic. Figure 47 (Figure A6 in the appendix) shows several interesting characteristics for a distance of only 150 ft and a microphone height of 4 ft. First, note that the lower part of the frequency band is not much affected by wind velocity. These are the frequencies where ground and surface waves predominate. This low-frequency immunity to wind conditions will be seen to hold for all the curves. At the higher frequencies, however, the wind velocity plays a very dominant role. In Figure 47, for example, a 10-mph tailwind increased the received sound level about 9 dB above what was received for zero wind, and a 5-mph tailwind increased the received level by 4 to 5 dB; on the other hand, a 5-mph headwind decreased the sound level by up to 8 dB vis-à-vis still air. Between 1 and 3 kHz (where the ear is most sensitive), the difference in received sound between a headwind of 5 mph (as measured with the anemometer 8.75 ft above the ground) and a wind of 5 mph in the opposite direction was approximately 10 dB.

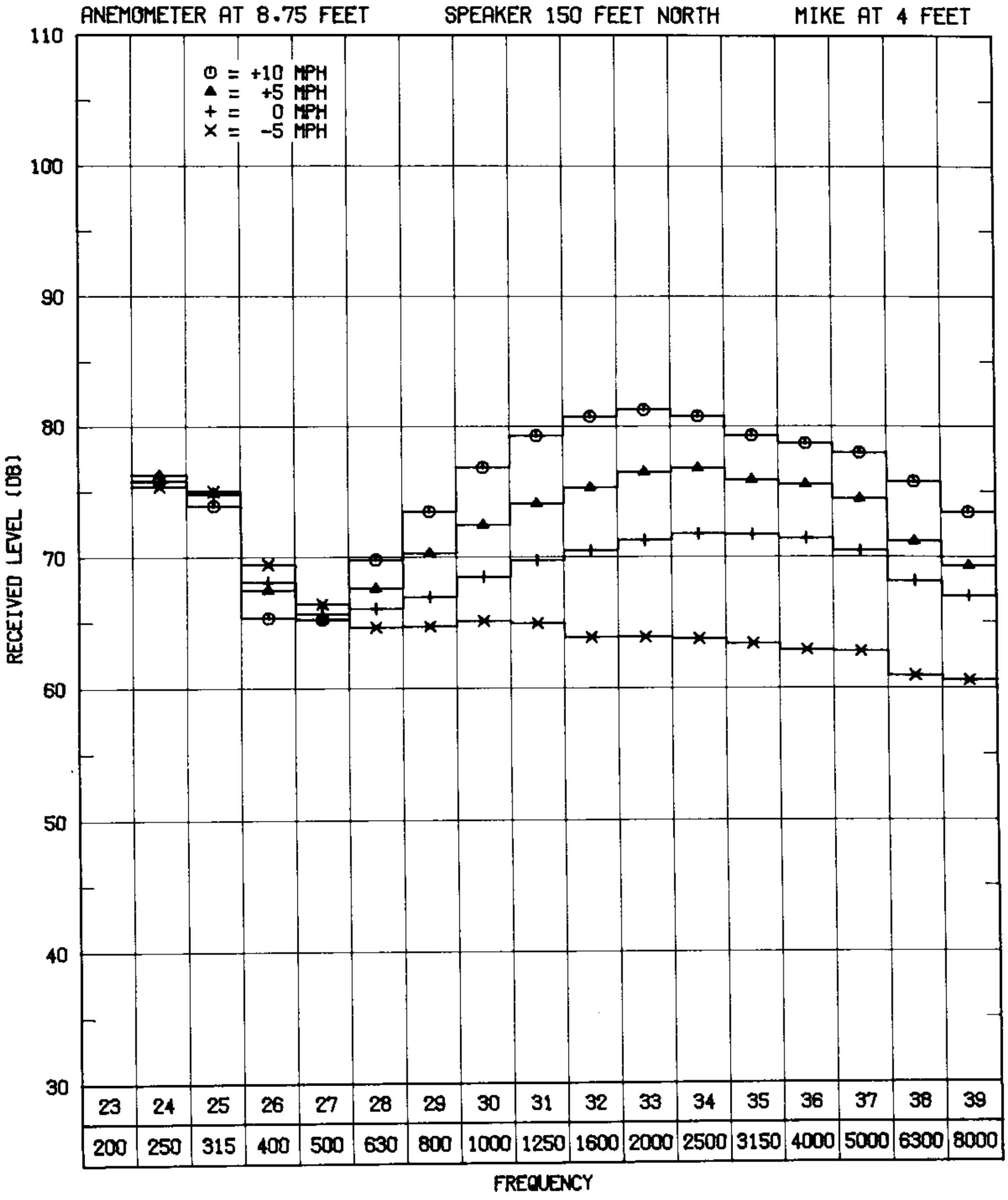


*Figure 47. Received spectral levels at a distance of 150 ft and a microphone height of 4 ft.*

In the downwind case, the sound rays were bent upward (see Figure 1) so that a greater part of their travel was spent farther from the ground; in the upwind case, the rays were forced to travel very near the ground during a greater part of their travel. This raising and lowering of the propagation path reduced and enhanced, respectively, the effect of the ground plane on the transmission. In the case of the 14-ft high receiver, none of the rays were sufficiently near the ground to show much effect. In the case of the lower microphones, however, the differences between the effective ray paths were sufficient to produce a rather great difference between the levels received in the two directions of propagation.

As was seen for zero wind, the theory given in References 1-3 does not adequately account for the effects observed at higher frequencies. That is, the theory that the shadow zone is created by a reflection phenomenon does not account for the amount of excess attenuation actually observed. This could possibly be due to the fact that the ground was not perfectly flat. However, it is the author's opinion that the shadow zone is caused by the ability of the ground surface to absorb and dissipate some of the energy in sound rays passing nearby, and that this phenomenon (although very complicated) is much more closely akin to diffraction than to reflection. A more complicated solution of the wave equation which does not "simplify out" such possible effects would be required to test this hypothesis.

## IMPLICATIONS FOR FIELD MEASUREMENT OF HIGHWAY NOISE

This work clearly shows that wind conditions should be taken into account when measuring noise levels in the field. The level of sound that will be measured from a particular source not only will vary with the emitted level but will be strongly influenced by any existing wind. In general, for transmission paths over ordinary ground at listening heights of 4-8 ft, the noise level will be considerably higher when measured downwind from the noise source than when measured upwind from the noise source. If measurements (even from the same spot and with the same traffic level) are made under different wind conditions, the results obtained can vary widely.

It is particularly important that, when establishing the existing noise level prior to making changes in a roadway, the measurements be made downwind in all cases. In regions with a prevailing wind that occurs at those times of day when the roadway is noisiest, it might be appropriate to make some upwind measurements. However, the wind's velocity and direction relative to the sound's direction should always be measured and this information, along with a statement of the height at which it was gathered, should accompany the acoustic data. The accompanying information should clearly state that the data were taken upwind and that this may well have reduced the sound's intensity, but that this was felt to be a typical condition for this particular measurement site.

For assessing, after construction, whether the noise level meets PPM 90-2 or other specifications, the fairest method would be to measure only during relatively calm periods or when the wind is blowing substantially parallel with the road.

## REFERENCES

1. J.E. Piercy and T.F.W. Embleton, "Review of noise propagation in the atmosphere," J. Acoust. Soc. Am. 61(6): 1403-1418 (June 1977).

2. R.J. Donato, "Propagation of a spherical wave near a plane boundary with complex impedance," J. Acoust. Soc. Am. 60(1): 34-39 (July 1976).

3. T.F.W. Embleton, J.E. Piercy and N. Olson, "Outdoor sound propagation over ground of finite impedance," J. Acoust. Soc. Am. 59(2): 267-277 (February 1976).

# APPENDIX A

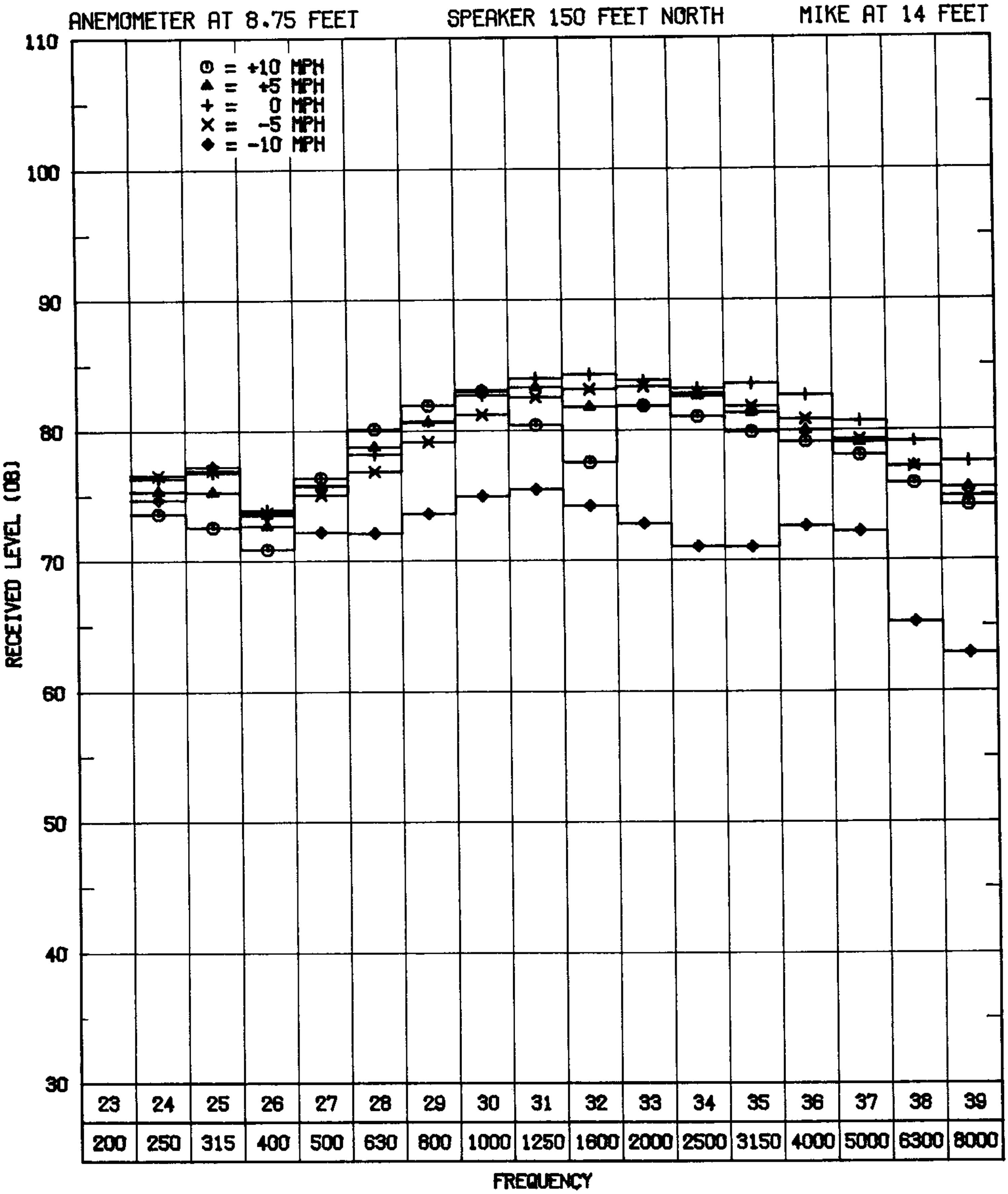

ANEMOMETER AT 8.75 FEET
SPEAKER 150 FEET NORTH
MIKE AT 14 FEET
⊖ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
◆ = -10 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

*Figure A1*

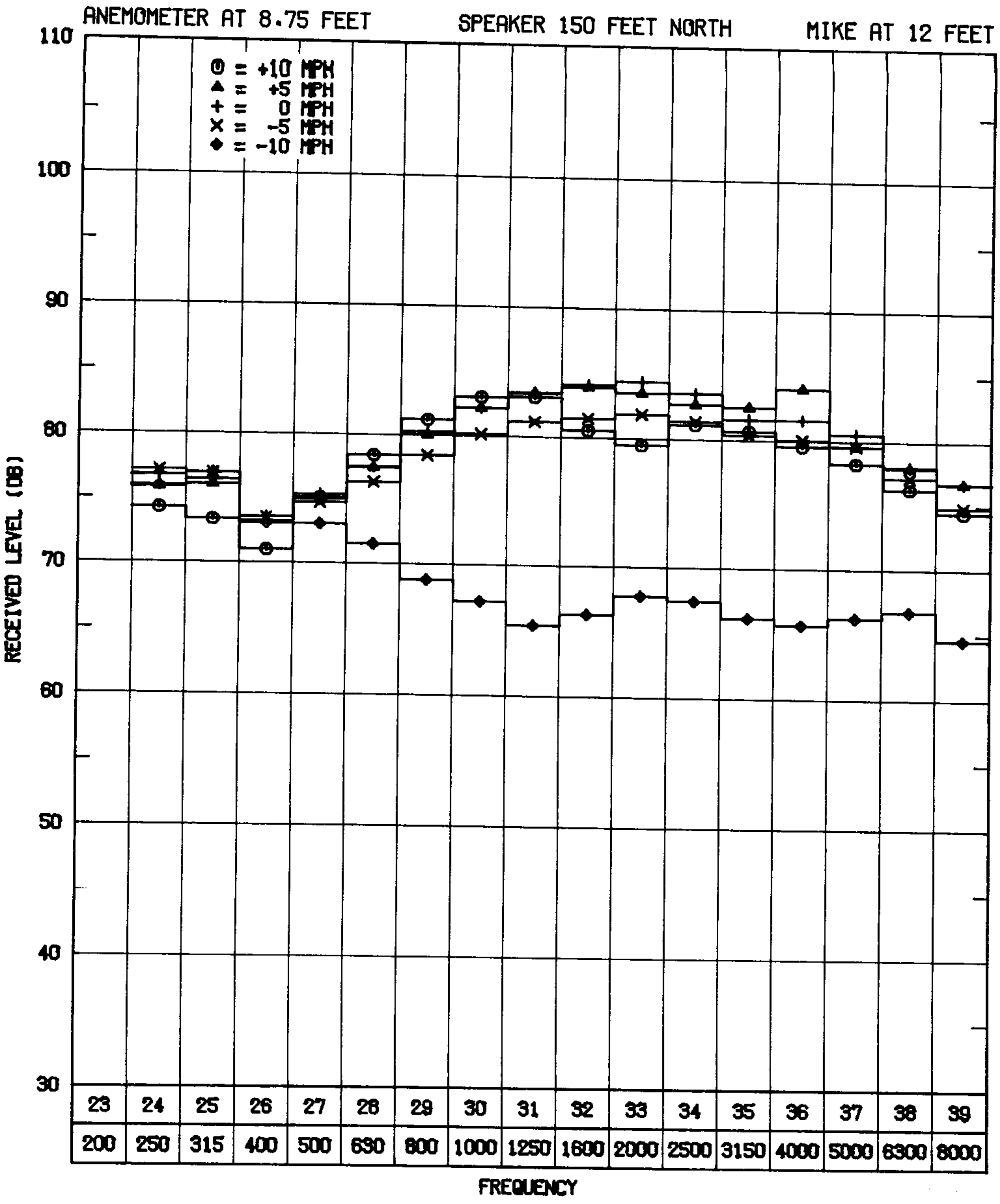

ANEMOMETER AT 8.75 FEET
SPEAKER 150 FEET NORTH
MIKE AT 12 FEET
⊙ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
◆ = -10 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY

*Figure A2*

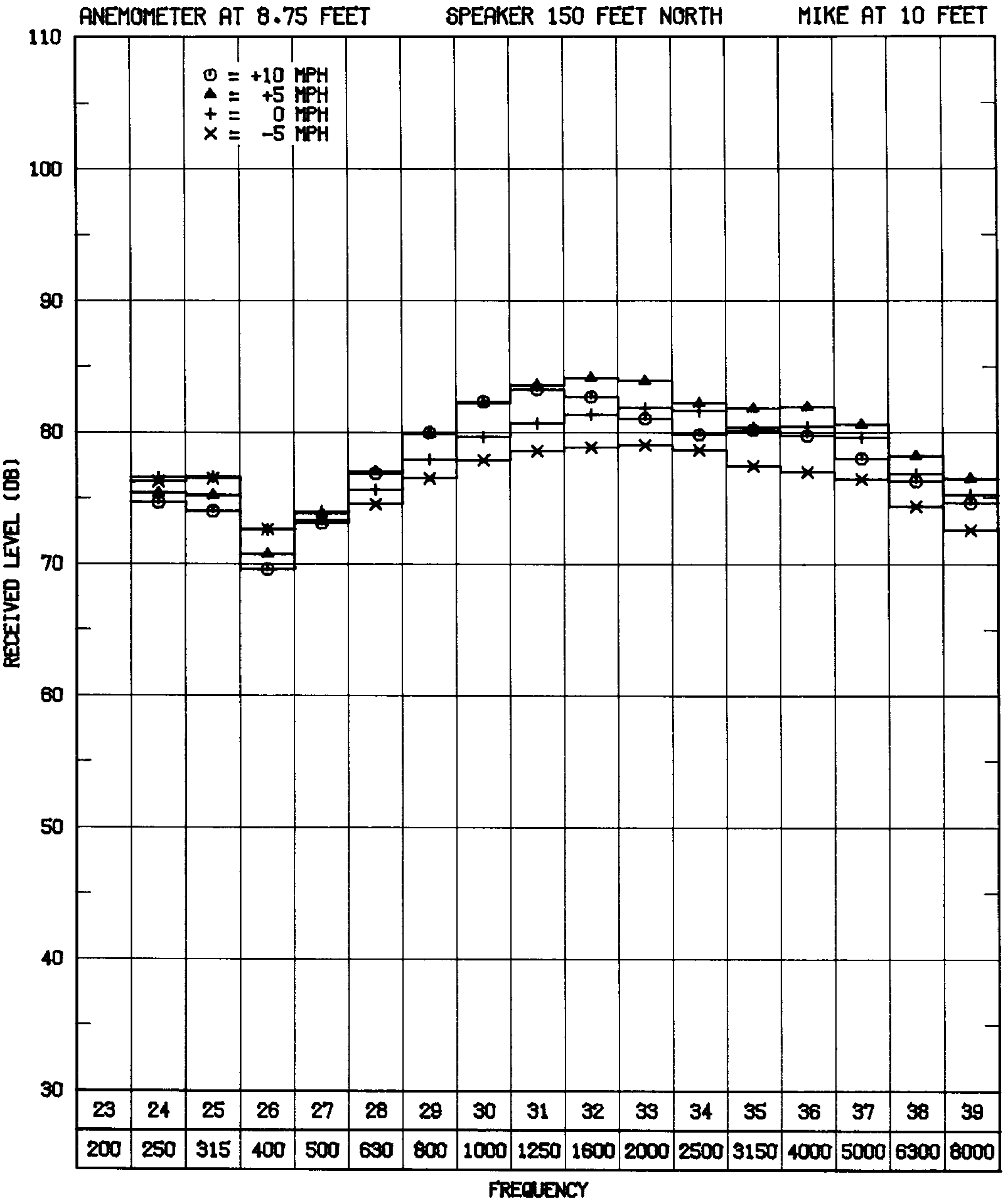

ANEMOMETER AT 8.75 FEET
SPEAKER 150 FEET NORTH
MIKE AT 10 FEET
⊖ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY

*Figure A3*

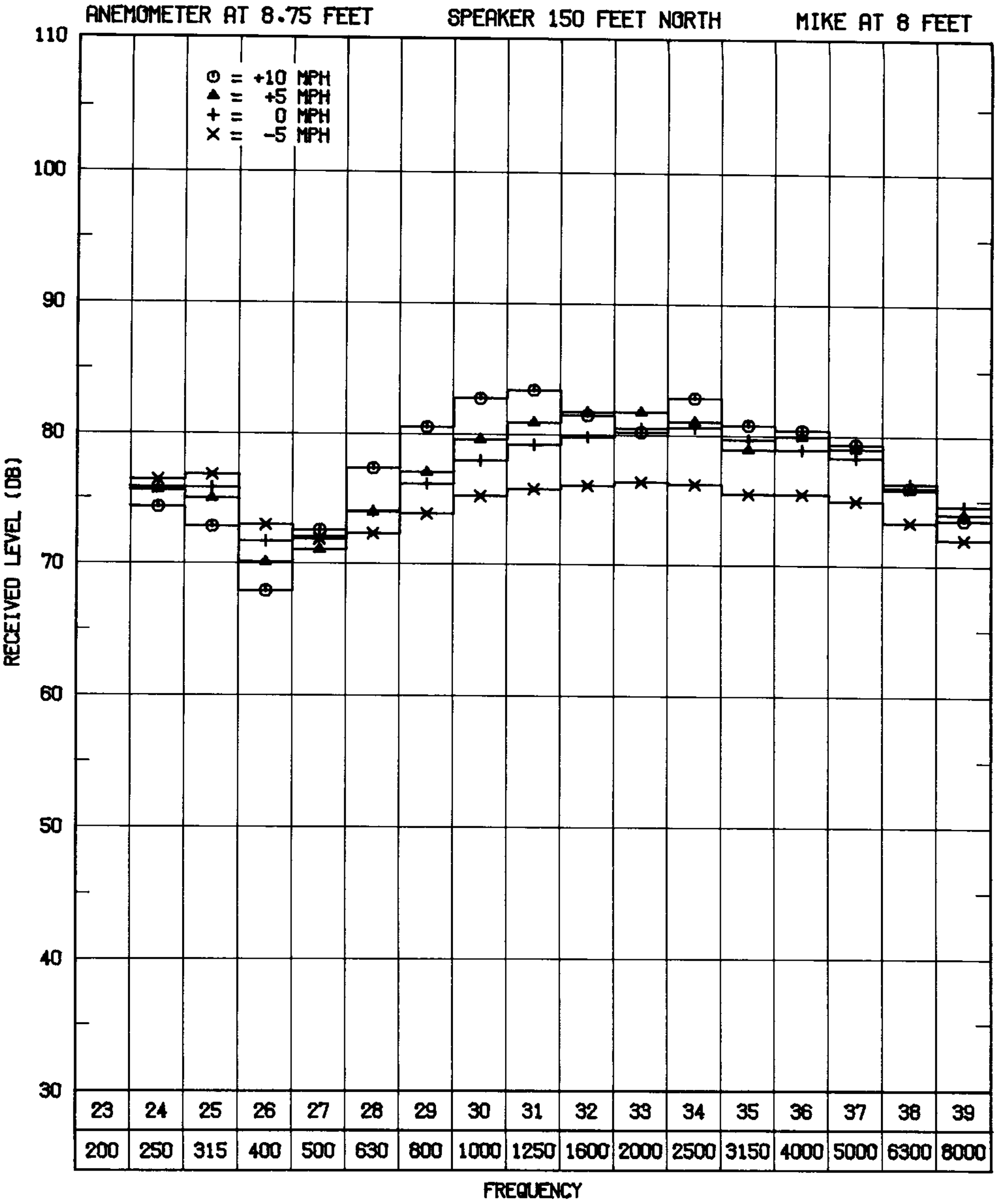

ANEMOMETER AT 8.75 FEET
SPEAKER 150 FEET NORTH
MIKE AT 8 FEET
⊙ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

*Figure A4*

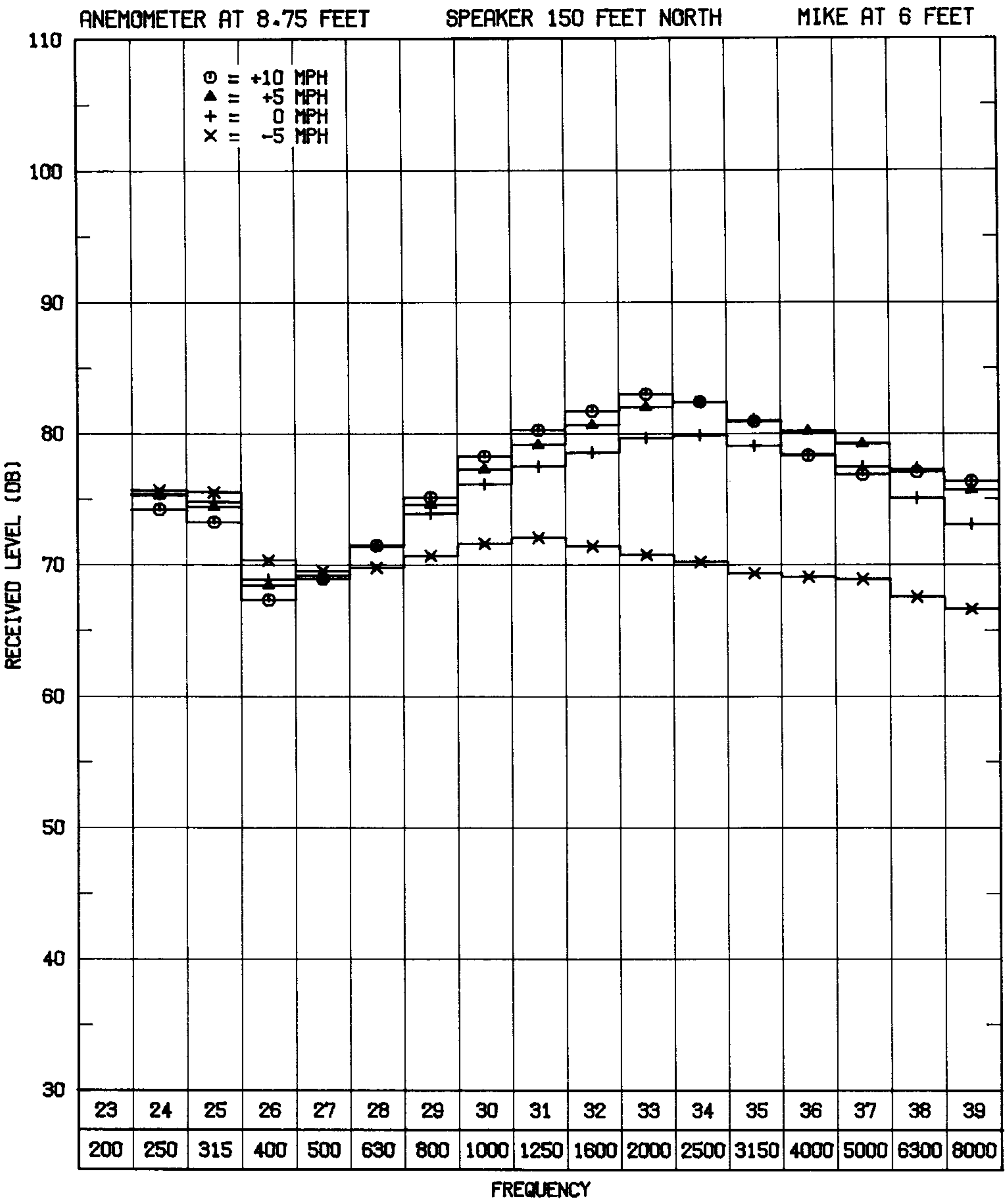

ANEMOMETER AT 8.75 FEET
SPEAKER 150 FEET NORTH
MIKE AT 6 FEET
⊖ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

*Figure A5*

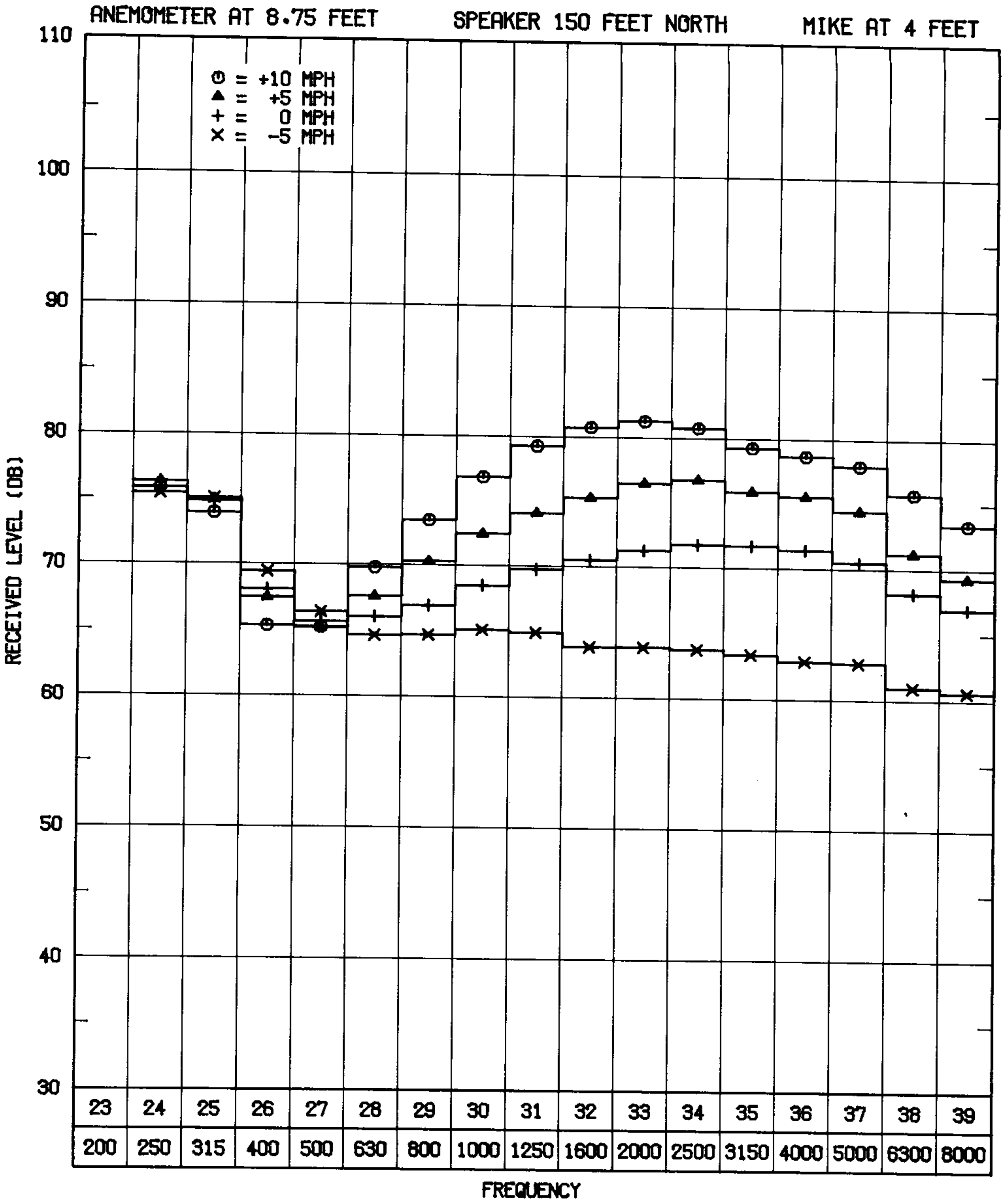

ANEMOMETER AT 8.75 FEET
SPEAKER 150 FEET NORTH
MIKE AT 4 FEET
⊕ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

*Figure A6*

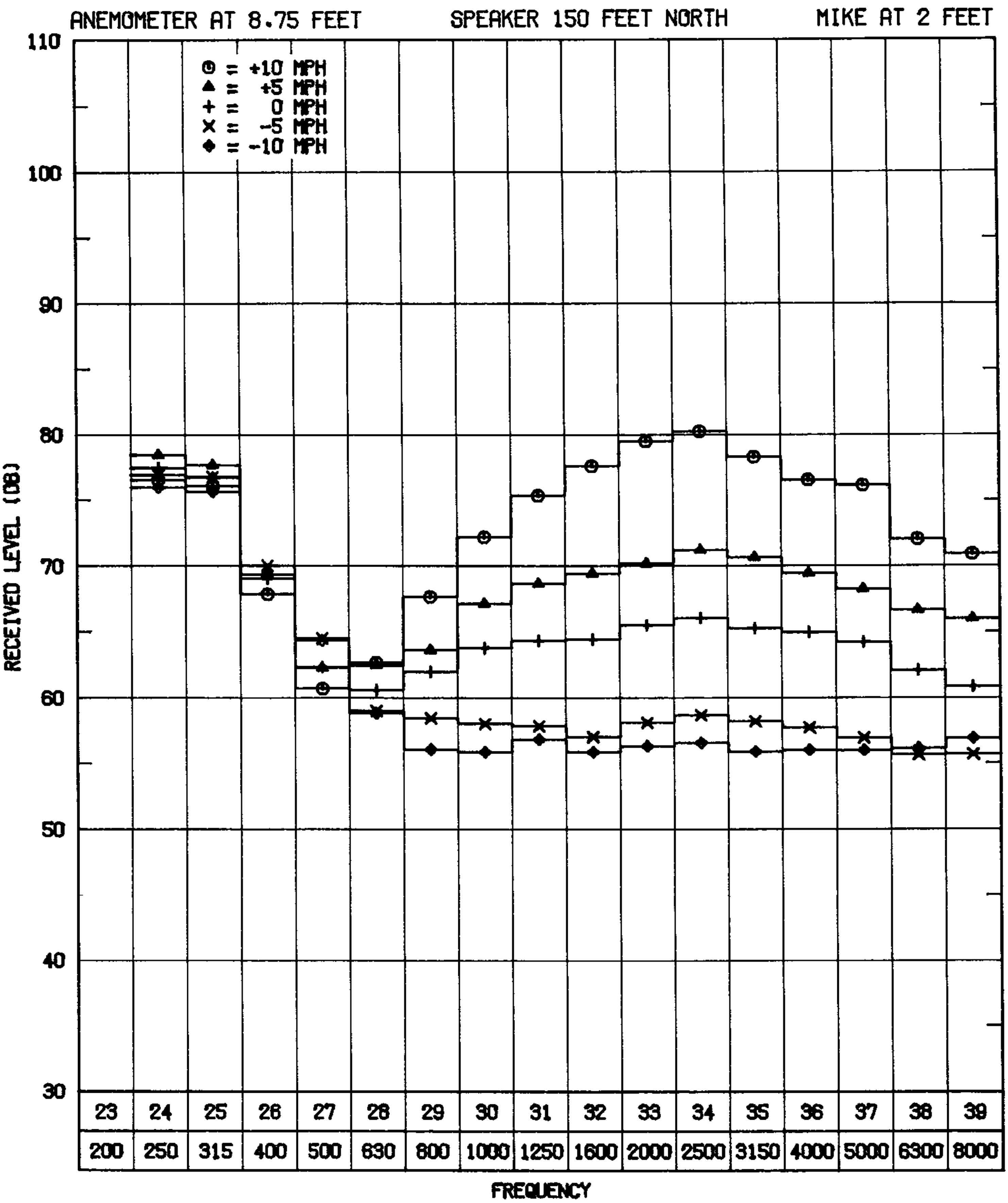

ANEMOMETER AT 8.75 FEET
SPEAKER 150 FEET NORTH
MIKE AT 2 FEET
⊙ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
◆ = -10 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY

*Figure A7*

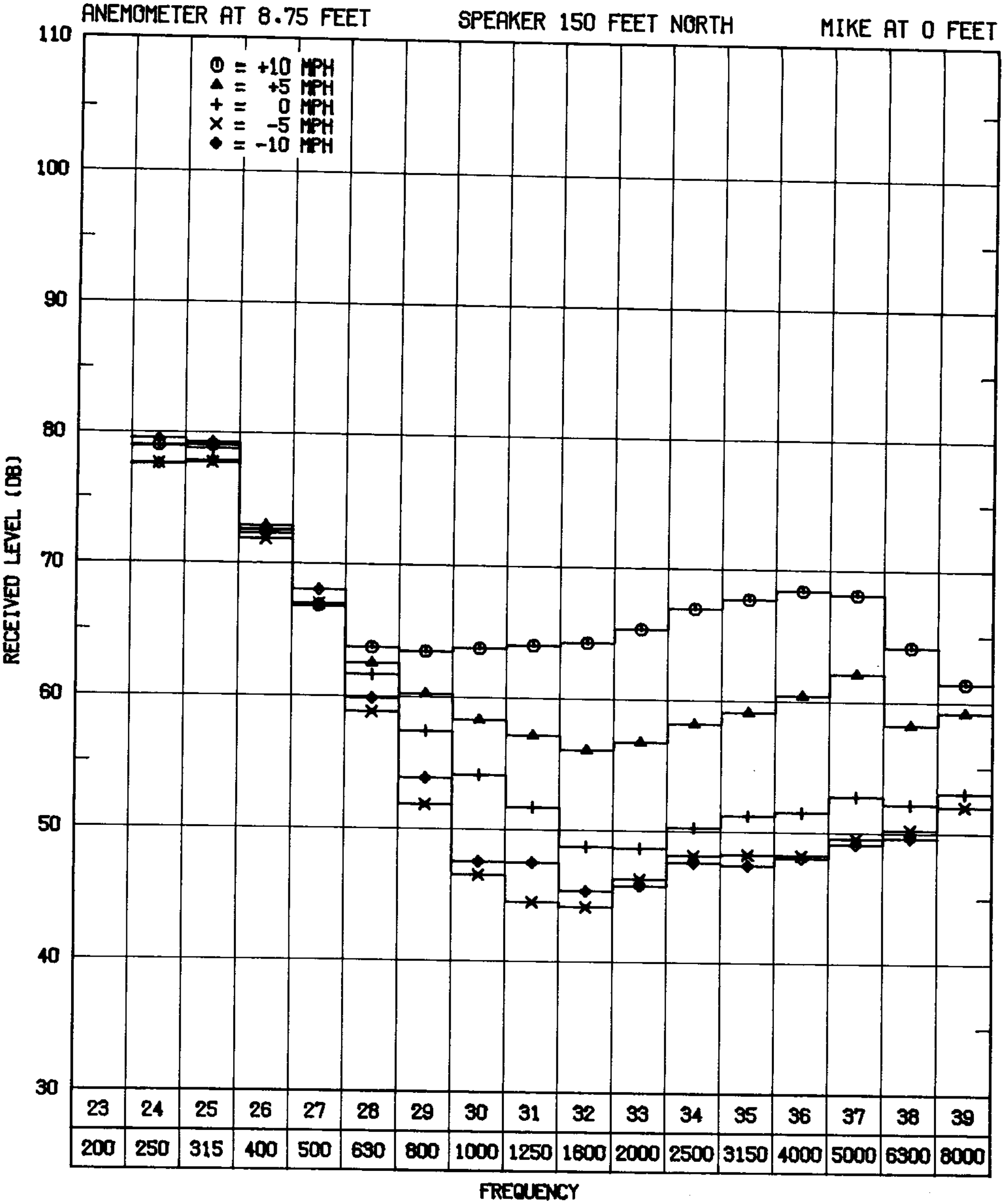

ANEMOMETER AT 8.75 FEET
SPEAKER 150 FEET NORTH
MIKE AT 0 FEET
⊕ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
◆ = -10 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY

*Figure A8*

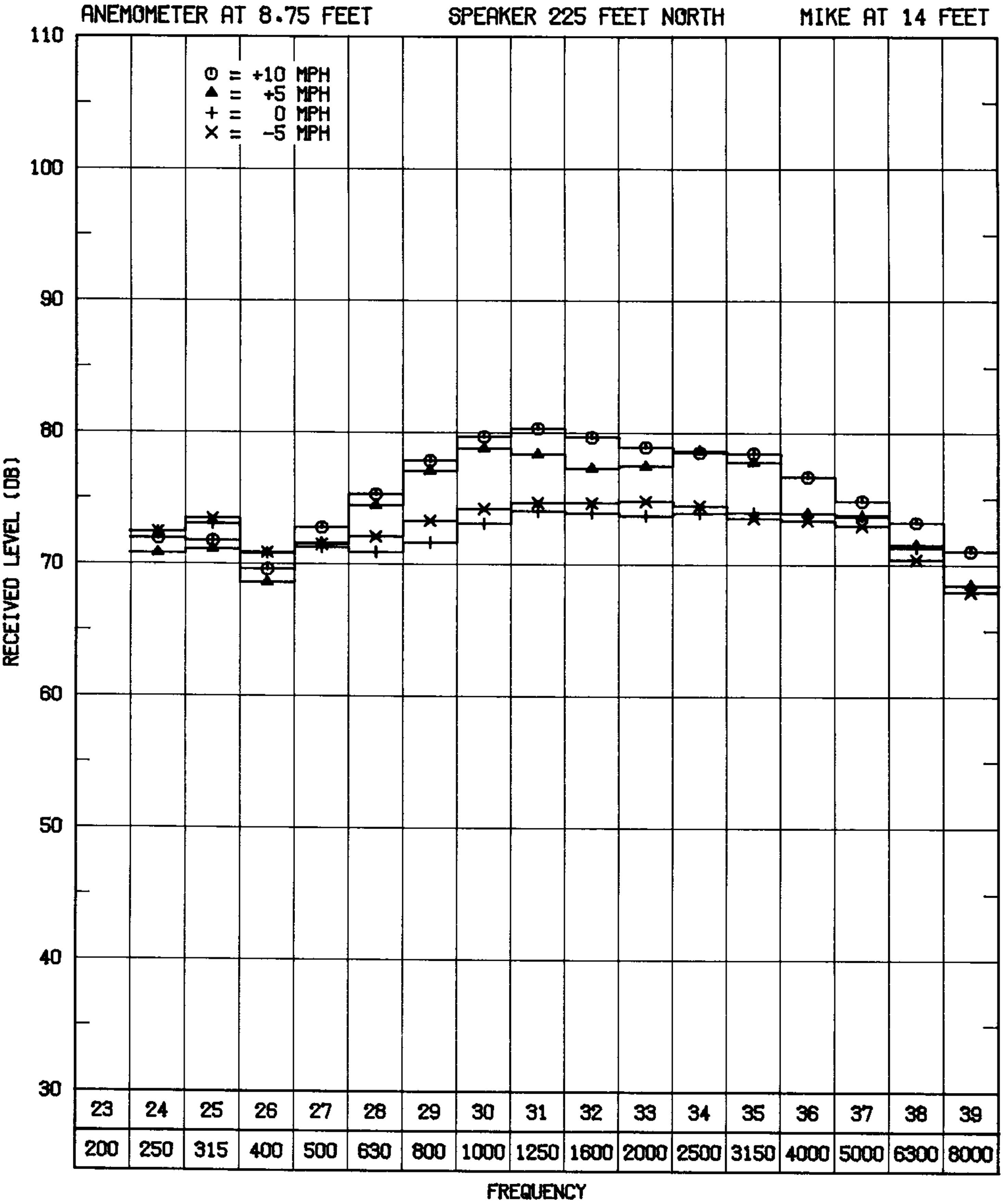
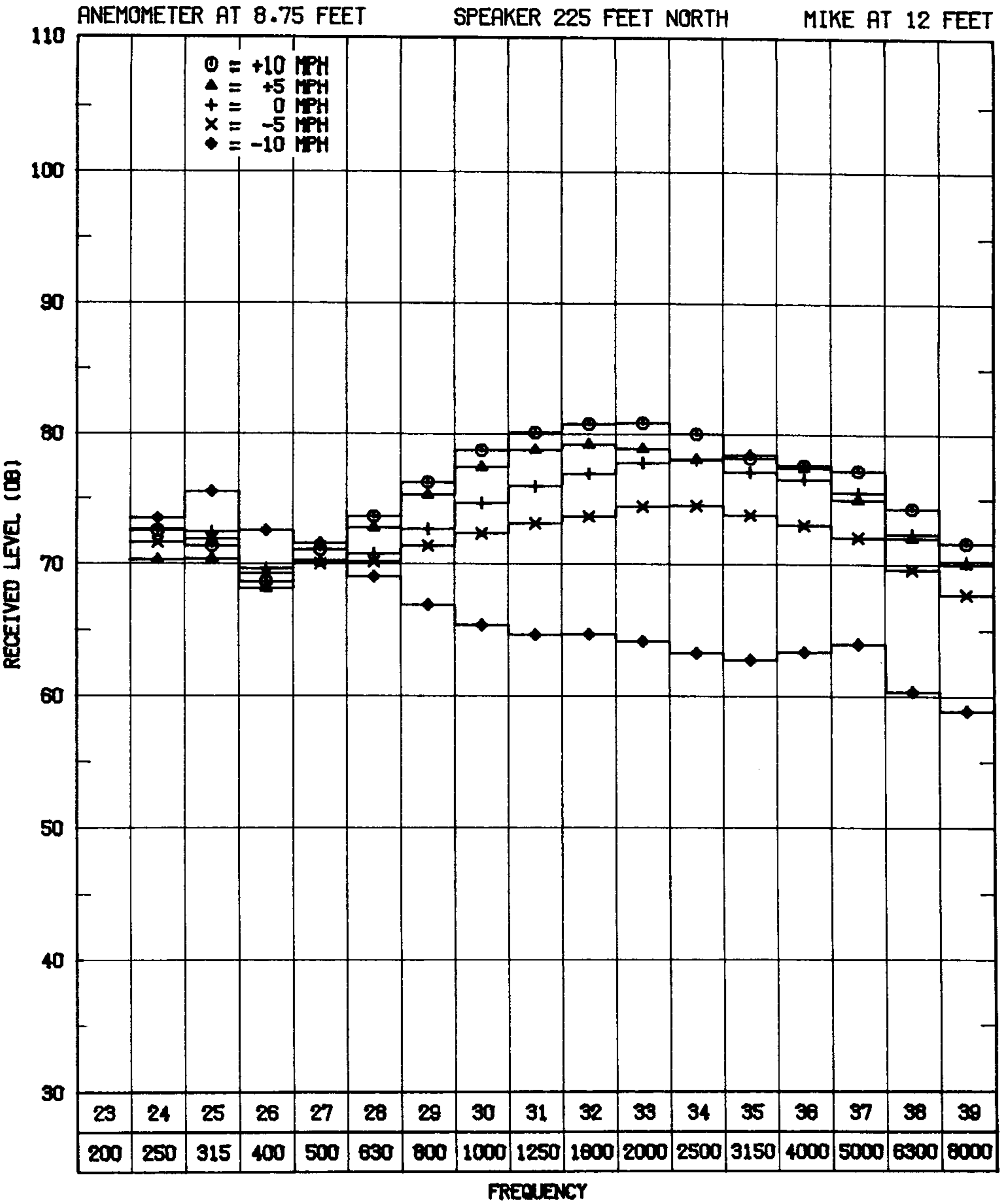

ANEMOMETER AT 8.75 FEET
SPEAKER 225 FEET NORTH
MIKE AT 14 FEET
⊕ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY

*Figure A9*


ANEMOMETER AT 8.75 FEET
SPEAKER 225 FEET NORTH
MIKE AT 12 FEET
⊙ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
◆ = -10 MPH
RECEIVED LEVEL (DB)
110
100
90
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70
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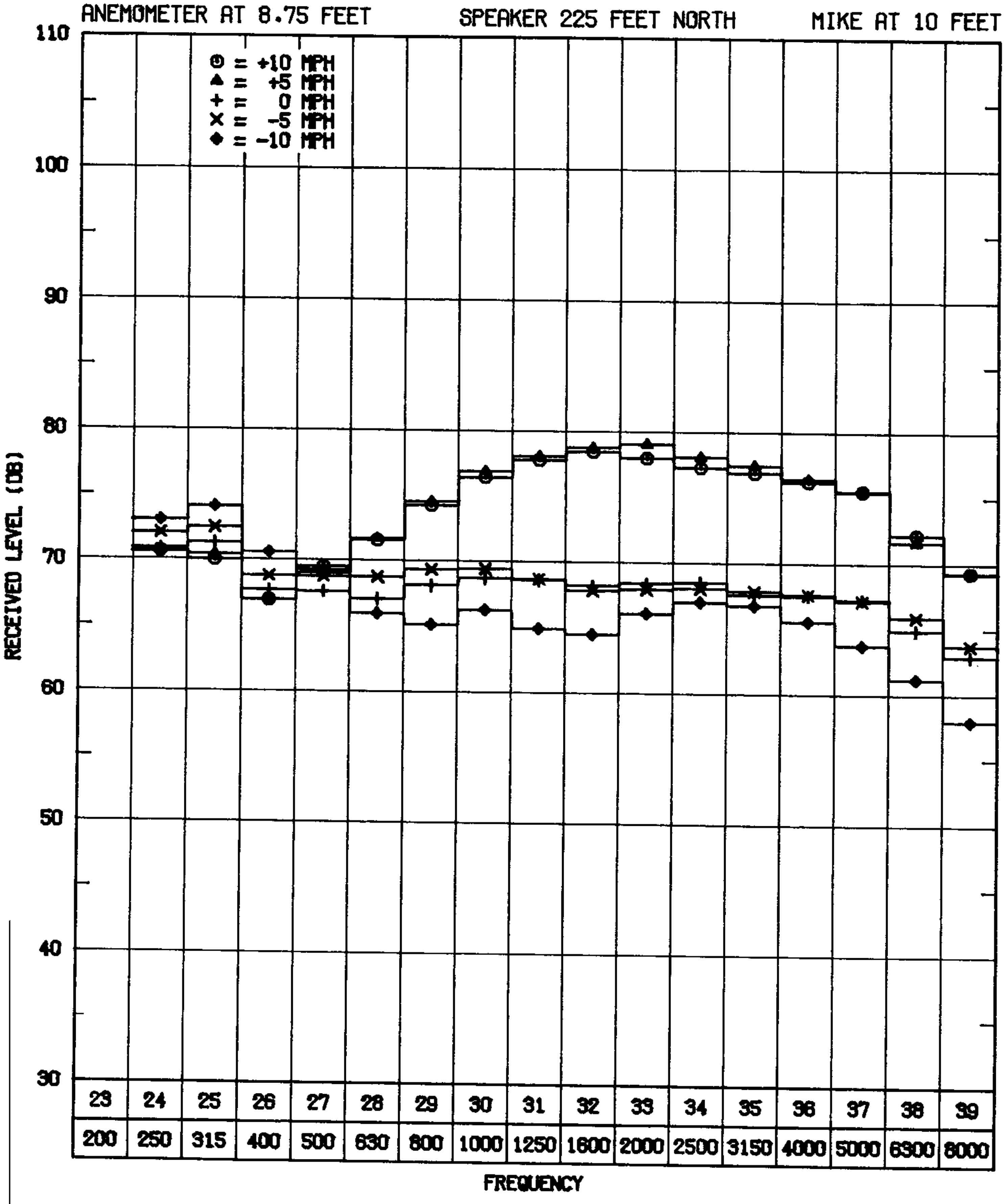
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY

*Figure A10*


ANEMOMETER AT 8.75 FEET
SPEAKER 225 FEET NORTH
MIKE AT 10 FEET
⊖ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
◆ = -10 MPH
RECEIVED LEVEL (DB)
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32
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1250
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3150
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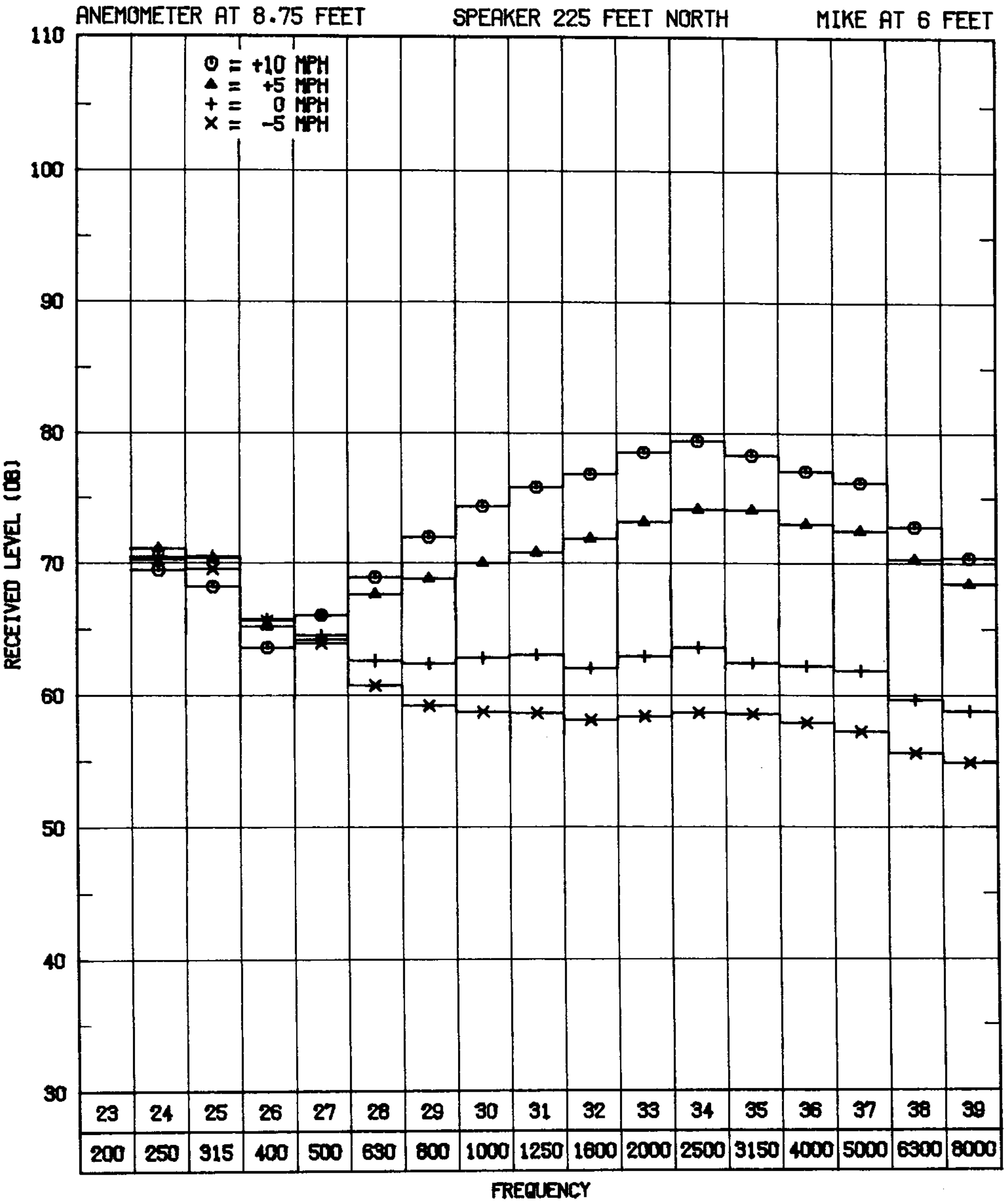
6300
8000
FREQUENCY

*Figure A11*


ANEMOMETER AT 8.75 FEET
SPEAKER 225 FEET NORTH
MIKE AT 6 FEET
⊙ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
RECEIVED LEVEL (DB)
110
100
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80
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60
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6300
8000
FREQUENCY

*Figure A12*

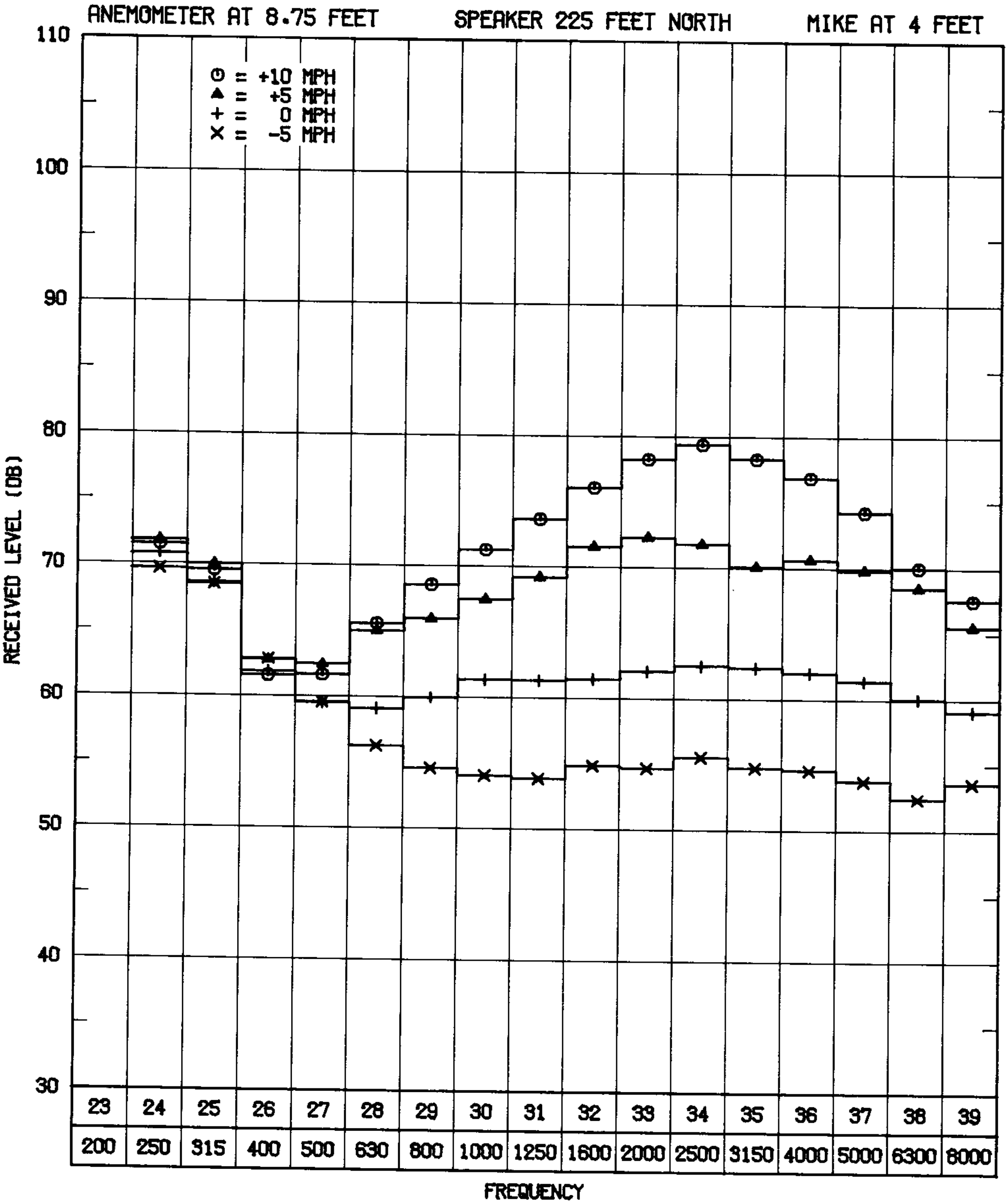
ANEMOMETER AT 8.75 FEET
SPEAKER 225 FEET NORTH
MIKE AT 4 FEET
⊙ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY

*Figure A13*

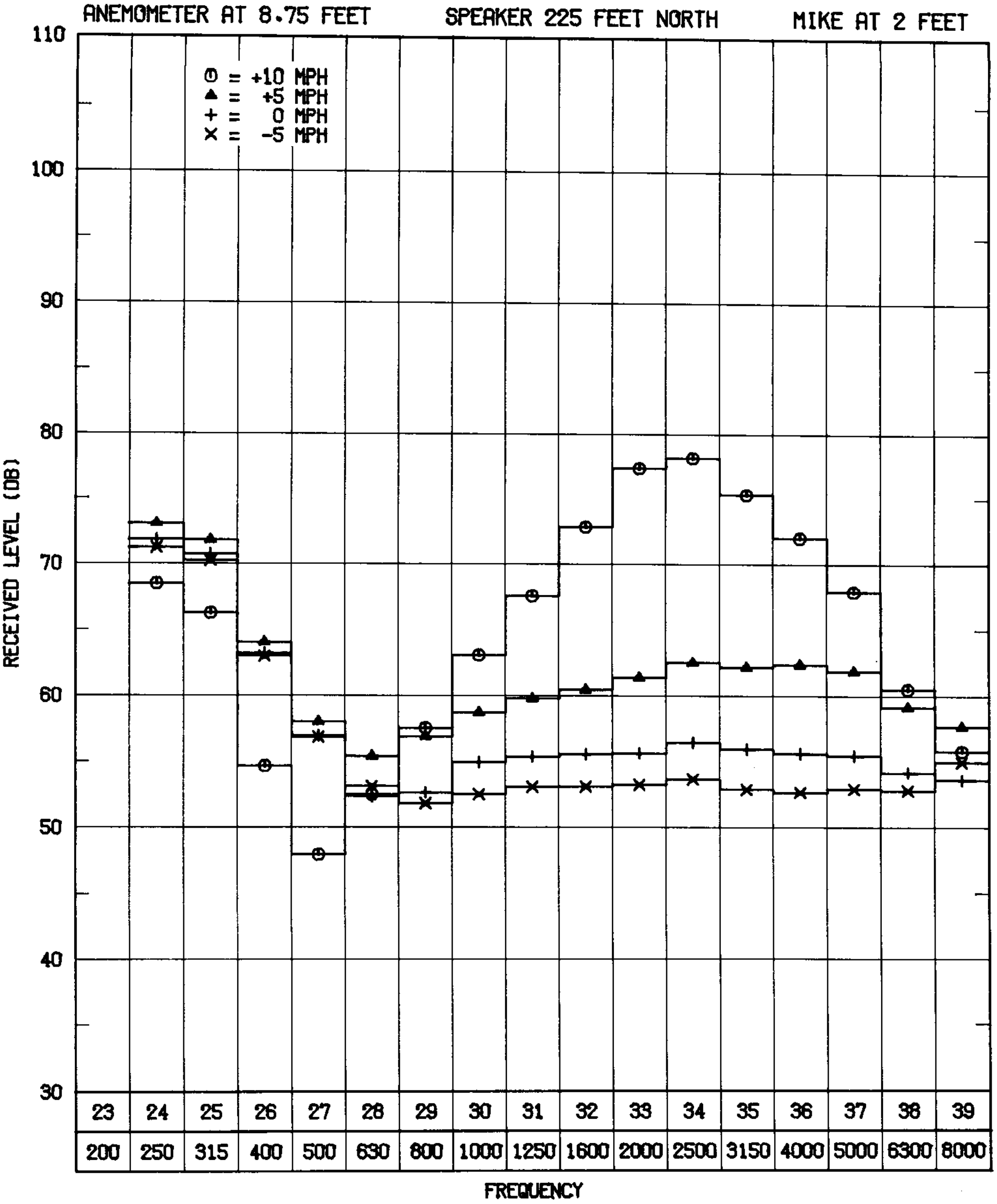
ANEMOMETER AT 8.75 FEET
SPEAKER 225 FEET NORTH
MIKE AT 2 FEET
⊕ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

*Figure A14*

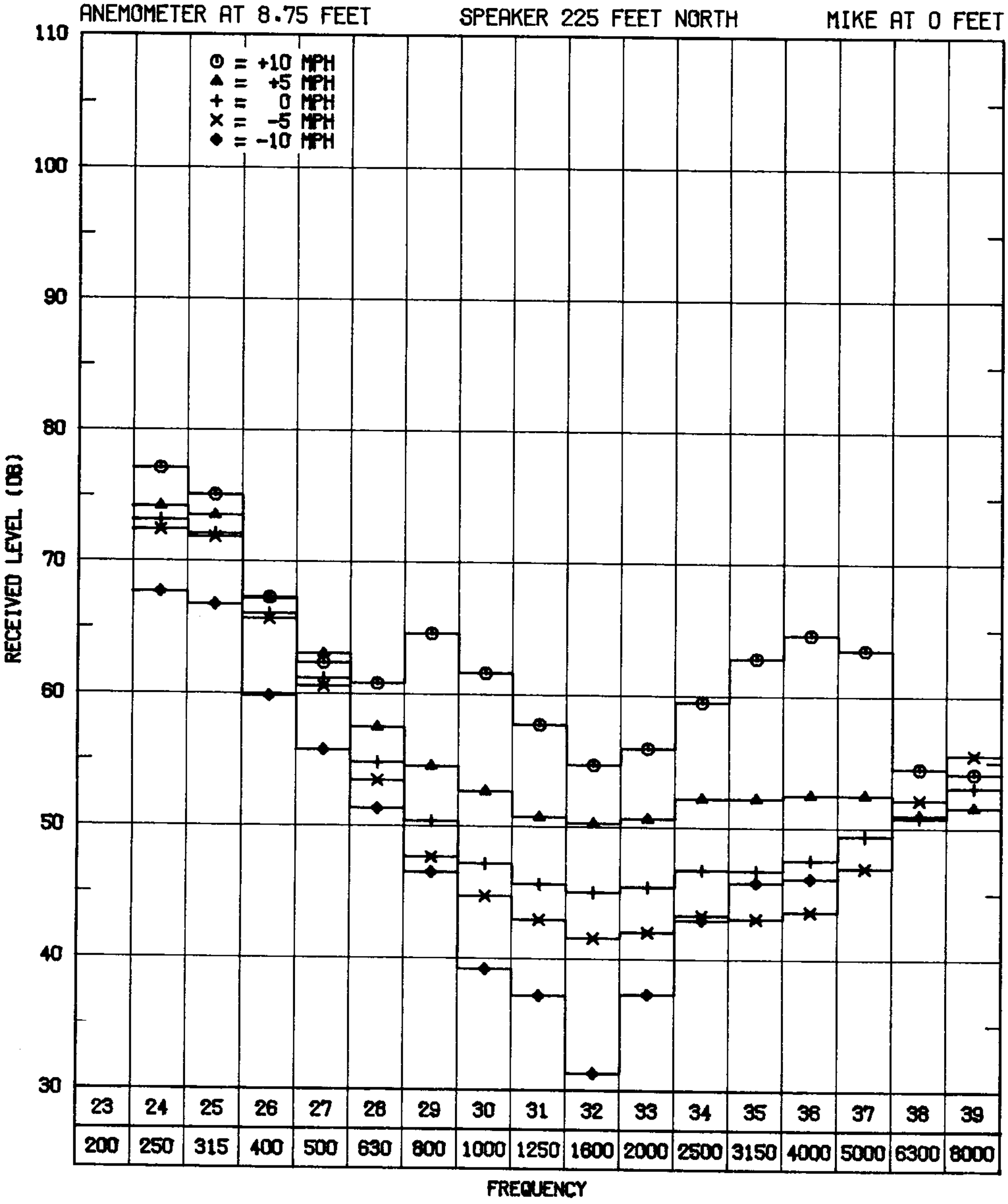
ANEMOMETER AT 8.75 FEET
SPEAKER 225 FEET NORTH
MIKE AT 0 FEET
⊖ = +10 MPH
▲ = +5 MPH
+ = 0 MPH
× = -5 MPH
◆ = -10 MPH
RECEIVED LEVEL (DB)
110
100
90
80
70
60
50
40
30
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
6300
8000
FREQUENCY

*Figure A15*