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**Long Range Downwind Propagation
Of Low-Frequency Sound**

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PROPAGATION OF LOW-FREQUENCY SOUND (NASA)
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SUMMARY

The propagation of low-frequency noise outdoors was studied using as the source a large (80-m diameter) 4-megawatt horizontal axis wind turbine. Acoustic measurements were made with low-frequency microphone systems placed on the ground at five downwind sites ranging from 300 m to 10,000 m (6.3 mile) away from the wind turbine. The wind turbine fundamental was 1 Hz and the wind speed was generally 12 - 15 m/s at the hub height (80 m). The harmonic levels, when plotted versus propagation distance, exhibit a 3 dB per doubling of distance divergence. Two plausible explanations identified for this cylindrical spreading behavior were propagation of the low frequency wind turbine noise via a surface wave and downwind refraction. Surface wave amplitude predictions were found to be more than 20 dB smaller than the measured levels. Ray-tracing results were used to qualitatively explain measured trends. A normal mode approach was identified as a candidate method for low-frequency acoustic refraction prediction.

INTRODUCTION

Some acoustic propagation problems of interest involve long propagation distances (ref. 1). As the propagation distances increase, the concern shifts from the higher frequencies for which atmospheric absorption is relatively high to the lower frequencies for which atmospheric absorption is relatively low. In this report, lower frequencies refer to frequencies in the range of 1 to 20 Hz. A problem in performing experimental propagation research in this frequency range is in finding a controllable source to generate adequate low-frequency sound levels. For the present study, use was made of an existing large, horizontal-axis wind turbine as the noise source.

The purpose of this paper is to document acoustic propagation data collected in the fall of 1984 at the Department of Energy test site at Medicine Bow, Wyoming. Noise recordings were obtained during normal operational wind conditions for a large wind turbine for a range of propagation distances. The reason for taking the data was to check the suitability of the site for a follow-on propagation experiment and to evaluate the operation of newly-acquired low-frequency microphones in the high-wind environment found around operating wind turbines.

EXPERIMENTAL SITE AND APPARATUS

Wind Turbine

The wind turbine investigated at Medicine Bow was an 80-m-diameter, two-bladed horizontal axis machine capable of producing 4 Megawatts of electrical power (ref. 2). The turn-on wind speed for the turbine is 7.1 m/s at hub height, 80 m. Figure 1 is a photograph of the WTS-4 wind turbine. It is a downwind configuration, that is, the turbine blades rotate downwind of the turbine support tower and pass through its wake. The wake/blade interaction

produces a characteristic periodic signal. The wind turbine is geared to turn at a constant 30 RPM; therefore, the fundamental of the wake/blade interaction is 1 Hz. The low-frequency source region is near the blade tip as the blade tip passes through the wake.

Acoustic Measurements

Acoustic measurements were made at downwind ranges varying from 300 to 10,000 m. The microphones were placed on the ground and covered with wind-screens. The microphone layout is illustrated in figure 2 along with a schematic diagram of the wind turbine. Elevation angle is defined in the figure as the angle between a horizontal line and the line from the wind-turbine hub to a particular microphone position (the slant range). In the experiment, elevation angles ranged from 8.0 to .2 degrees and are listed in figure 2 along with the slant ranges for each microphone position. The recordings were made with a single four-channel portable FM recorder which was moved to each of the five measurement sites identified in figure 2. Two channels of the recorder were occupied with low-frequency microphones.

The low-frequency wind-turbine harmonic data to be presented were measured with the low-frequency microphones and were recorded in a 4-hour period in a single day. The length of the recording at each site was 1 minute, except at site 5 where a 15-minute recording was made. The consequences of time-varying source characteristics on the validity of comparing data recorded at different times will be addressed later.

The low-frequency microphone systems were employed because of their good low-frequency response and sensitivity. Figure 3 is a photograph of one of the low-frequency systems. The frequency response and sensitivity of the systems vary from unit to unit, but each unit is stable. A calibration procedure and hardware were developed for the systems. The low-frequency response of each unit was adjusted to make the 3 dB down point at 1 Hz. The high-frequency response 3 dB down point is nominally 500 Hz. The large horse-hair wind screen seen in figure 3 was used with each microphone. When tested against various other wind noise reducing techniques, including burying the microphones in the ground and wrapping them in foam and fiberglass, the horse-hair wind screens worked as well and were more convenient.

DATA REDUCTION

The acoustic data were reduced to produce 1-minute average narrow band spectra with a commercially available spectral analyzer. The bandwidth of the analysis was .05 Hz. Recorded pistonphone calibrations were incorporated in the data-reduction process to produce absolute levels. An exception was the site 5 data which were averaged for 30 seconds. The shorter averaging time was necessary for site 5 because of high intermittent background noise levels associated with a nearby highway and railway. Even though 15 minutes of data were recorded at site 5, it was difficult to find 30 seconds of data free of road and rail noise in the recording.

Two spectra are illustrated in figure 4 for the closest and farthest microphone positions. In the plots the vertical axes are in units of sound pressure level (SPL) and the horizontal axes are in units of blade passage frequency (BPF) number which, in this case, is equivalent to frequency in Hz. The 303 m spectrum is rich in harmonics out to 18 Hz. In the long-distance spectrum (10,147 m) identifiable harmonics can be seen in the range of 6 to 12 Hz. The wind-turbine harmonic levels used in the data analysis results which follow are listed in table I for all nine microphone positions. Only harmonic levels which are 3 dB or more above the surrounding background noise levels are listed and presented in the data analysis results.

Because the data were not recorded simultaneously, the question of source variability is of concern. In figure 5 average standard deviations are given as a function of frequency. The results were computed from 10 comparable data sets, reduced as described above, for the closest three microphones. The data were collected over a 2-day period, including the 4-hour period during which the data presented elsewhere in the paper were taken. During the 2 days the wind speed at the hub height was between 12.8 and 15.3 m/s from roughly the same direction. The results given in figure 5 indicate that for the testing period, the source level was quite stable, particularly for the harmonics between 6 and 12 Hz. In this frequency range, variations in the data greater than 1 dB are not attributable to source level variations. The higher harmonics show more variability, as would be expected, due to the effects of inflow distortions (ref. 3). The lower frequencies due to poorer signal-to-noise ratios exhibit more variability than the middle harmonics.

RESULTS AND DISCUSSIONS

In figures 6, 7, and 8, sound-pressure level is plotted for the 6, 8, and 11 Hz harmonics, respectively, as a function of slant range. These frequencies were chosen because of their low source variability. In the figures the symbols are the measured data. The top line in each figure is a 3 dB per doubling of distance line, referenced to the measured 300 m level. Three dB per doubling of distance is characteristic of cylindrical spreading, where the acoustic pressure varies inversely with the square root of distance. The lower line in each figure is a 6 dB per doubling of distance line, referenced again to the 300 m level. Six dB per doubling of distance is characteristic of spherical spreading, where the acoustic pressure varies inversely with distance. In all three figures the 450 m data point falls nearly on the 6 dB/doubling line, while the remaining data fall roughly on the 3 dB/doubling line.

The data illustrated in figures 6 through 8 clearly exhibit 3 dB for doubling of propagation distance. One explanation investigated for this behavior was propagation of the low-frequency wind turbine noise via a surface wave. Surface waves are known to propagate horizontally with a combination of cylindrical spreading and exponential decay with distance (ref 4).

In figure 9, the 8 Hz data of figure 7 are compared with surface wave predictions. The model for the surface wave predictions is due to Donato (ref. 5). The equation for the amplitude of the surface wave for the receiver on the ground is

$$\frac{|P_s|^2}{|P|^2} = \frac{8\pi kd(1+H^2/d^2)}{(R^2+\chi^2)^{1/2}} e^{\frac{2k\chi d}{R^2+\chi^2}} e^{2k|Q|^{1/2}H\sin(\phi/2)}$$

with

$$1 - (1/z)^2 = |Q| e^{i\phi}$$

where

P_s	surface wave acoustic pressure
P	free field acoustic pressure
k	wave number, $2\pi f/c_0$
f	frequency
c_0	ambient speed of sound
d	horizontal distance between source and receiver
H	height of source
z	normalized acoustic impedance of surface, $z = R+\chi i$

In figure 9 predictions of the logarithm of the ratio of the amplitude of the surface wave to the amplitude of the free-field wave are shown for hard ground. To put the measured results in this form, the 300 m measured level was taken as the free-field level minus 6 dB for the pressure doubling associated with a ground-mounted microphone. Spherical spreading corrections were made to the free-field level for a particular slant range to form the ratio of the measured level at that slant range to the free-field level. In this format, a horizontal line represents spherical spreading. The test site ground was dirt with little vegetation. Donato's model for surface waves requires as input the acoustic impedance of the ground surface. The empirical model of Delaney and Brazey (ref. 6) was used with a value of 1000 cgs units for the ground flow resistance to predict the value of ground impedance to input into the Donato model. The resulting surface-wave predicted levels are in excess of 20 dB below the measured results in figure 9. The cylindrical spreading of the surface wave is seen as an enhancement over spherical spreading (positive slope) for propagation distances to 1000 m, but the exponential decay of surface waves becomes dominant for longer distances. For the surface wave to be a primary cause of the 3 dB for doubling of propagation distance, the effects of refraction due to the downwind propagation would have to be equal or less than the effects of the surface wave propagation. The comparison of the surface-wave predictions with the measured results does not support the possible surface-wave explanation of the observed 3 db/doubling in the measured results.

Another possible explanation investigated for the 3 dB/doubling behavior is downwind refraction. While the low-frequency wind turbine data presented here were being measured, independent measurements were being made of the wind turbine noise for higher frequencies using standard laboratory quality microphone systems (ref. 7). In figure 10, wind turbine noise one-third-octave band levels from reference 7 for the 63, 250, and 1000 Hz bands are plotted versus slant range. The source of this middle-frequency wind-turbine noise is primarily boundary-layer trailing-edge noise. This broadband noise is emitted throughout the blades' rotation, but is a maximum, due to the wind velocity profile, when a blade is at the top of the rotation disk. The primary source height for this noise is thus between 80 to 120 m. The data shown in this figure corrected for atmospheric absorption exhibit spherical spreading. Atmospheric absorption is negligible for the low-frequency wind-turbine harmonic results (frequencies less than 20 Hz) for the propagation distances measured. Shepherd and Hubbard's low-frequency wind turbine harmonic results, not shown here, exhibit 3 dB/doubling as the earlier presented low-frequency results did. Why the difference in low- and middle-frequency results? Are the low frequencies influenced more than the middle frequencies by refraction? With the aid of a ray-tracing diagram, a qualitative argument can be made to explain the observed difference in behavior in the propagation of the low- and middle-frequency wind-turbine noise which is consistent with the refraction hypothesis.

In figure 11 a ray-tracing result is given for downwind propagation for two source heights: 40 m, the approximate source height of the wind turbine low-frequency harmonic data, and 100 m, the average source height for the middle-frequency broadband noise. In the ray-tracing example the wind velocity at hub height was 12.8 m/s. Note the vastly different scale factors of the two-distance axes in the figure. The first ray to reflect from the ground a second time is the 90-degree initial ray. The horizontal distance from the source to the second reflection point is the second reflection distance; therefore, the shortest second reflection distance is the one corresponding to the 90-degree initial ray. For distances less than the shortest second reflection distance, only a single ray is received for a point on the ground. For distances greater than the shortest second reflection distance multiple rays are received. For distances less than the shortest second reflection distance behavior close to spherical spreading would be expected, because even though the ray paths are curved, a single ray is received and the distance traveled is not dramatically longer than for straight-line propagation. When the source height is increased, the ray-tracing pattern is magnified and the closest second reflection distance is increased. Sound from a higher source height would be expected to exhibit spherical spreading for larger distances than from a lower source height. The middle-frequency data by this argument should exhibit spherical spreading behavior for greater propagation distances than the low frequency harmonic data. The middle-frequency data do not deviate from spherical spreading in the measured 1000 meters, while the low-frequency data deviate from spherical spreading between 450 and 1000 m. The difference in the measured middle- and low-frequency propagation results is consistent with this qualitative refraction argument. A similar argument is found in reference 7.

Ray tracing is a high-frequency approximation and is not considered applicable to frequencies as low as 20 Hz. At low frequencies a normal mode approach is valid. A low-frequency normal mode refraction model was recently published in an article entitled "Field of a Low-Frequency Point Source in an Atmosphere with a Nonuniform Wind-Height Distribution" by I. P. Chunchuzov (ref. 8). His formulation appears to be valid for comparison to the wind turbine problem for frequencies greater than 2 Hz and slant ranges less than 40,000 m. The far-field approximate solution exhibits cylindrical spreading. A normal-mode model is currently being developed for comparison with the measured results. This work is not complete at this time and no results are available.

CONCLUSIONS

Periodic noise signals from a large wind turbine were measured in the frequency range of 2 to 20 Hz with new low-frequency microphones in the high wind environment found around operating wind turbines. Measurements were made at nine downwind locations with propagation distances ranging from 300 to 10,000 m. Analysis of the low-frequency wind turbine acoustic data revealed an interesting cylindrical dependence on propagation distance. Two causes of the measured 3 dB per doubling of propagation distance were investigated: propagation via a surface wave and downwind refraction. Surface wave amplitude predictions were more than 20 dB below the measured results. As a result downwind refraction is considered the most probable cause. A normal-mode refraction model was suggested for comparison with the low-frequency measured results.

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Table I. Wind Turbine Harmonic Level Data

Slant range, m	<u>Frequency, Hz</u>																			
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
303	72	72	76	75	75	75	74	73	72	70	69	67	65	63	61	60	57	--	--	
452	--	70	72	72	71	70	70	69	68	66	64	61	60	58	55	--	--	49	--	
1051	--	68	69	70	70	71	70	69	68	67	65	64	63	62	60	60	57	55	55	
1355	--	69	69	69	70	69	69	69	67	66	64	64	63	61	59	58	55	54	53	
2448	--	--	--	--	--	68	65	64	63	61	60	59	57	55	53	--	--	--	--	
2753	--	--	--	--	69	65	64	67	62	61	58	55	53	51	--	48	--	--	--	
3953	--	--	--	69	66	66	64	63	60	60	57	56	55	52	--	46	--	--	--	
4258	--	--	--	--	66	64	65	63	61	59	56	53	--	--	--	--	48	48	47	
10147	--	--	--	65	62	63	58	56	55	54	50	48	--	--	--	--	--	--	--	

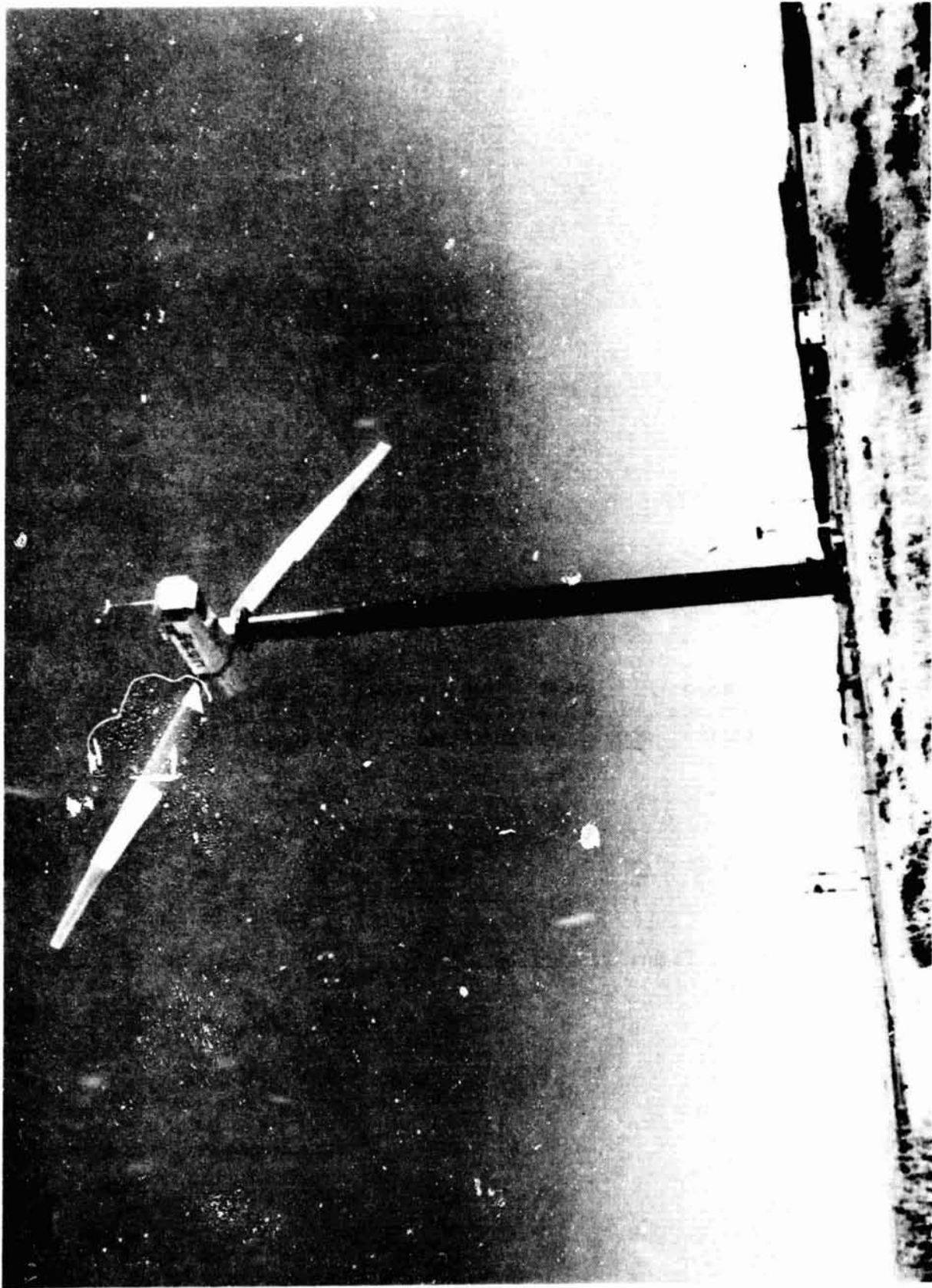


Figure 1. Photograph of WTS-4 wind turbine (foreground).

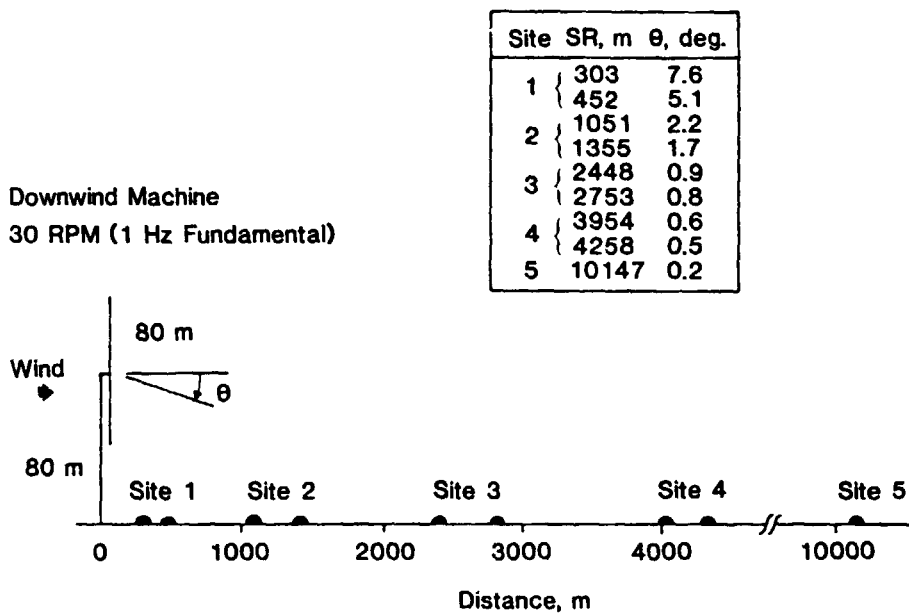


Figure 2. Microphone layout.

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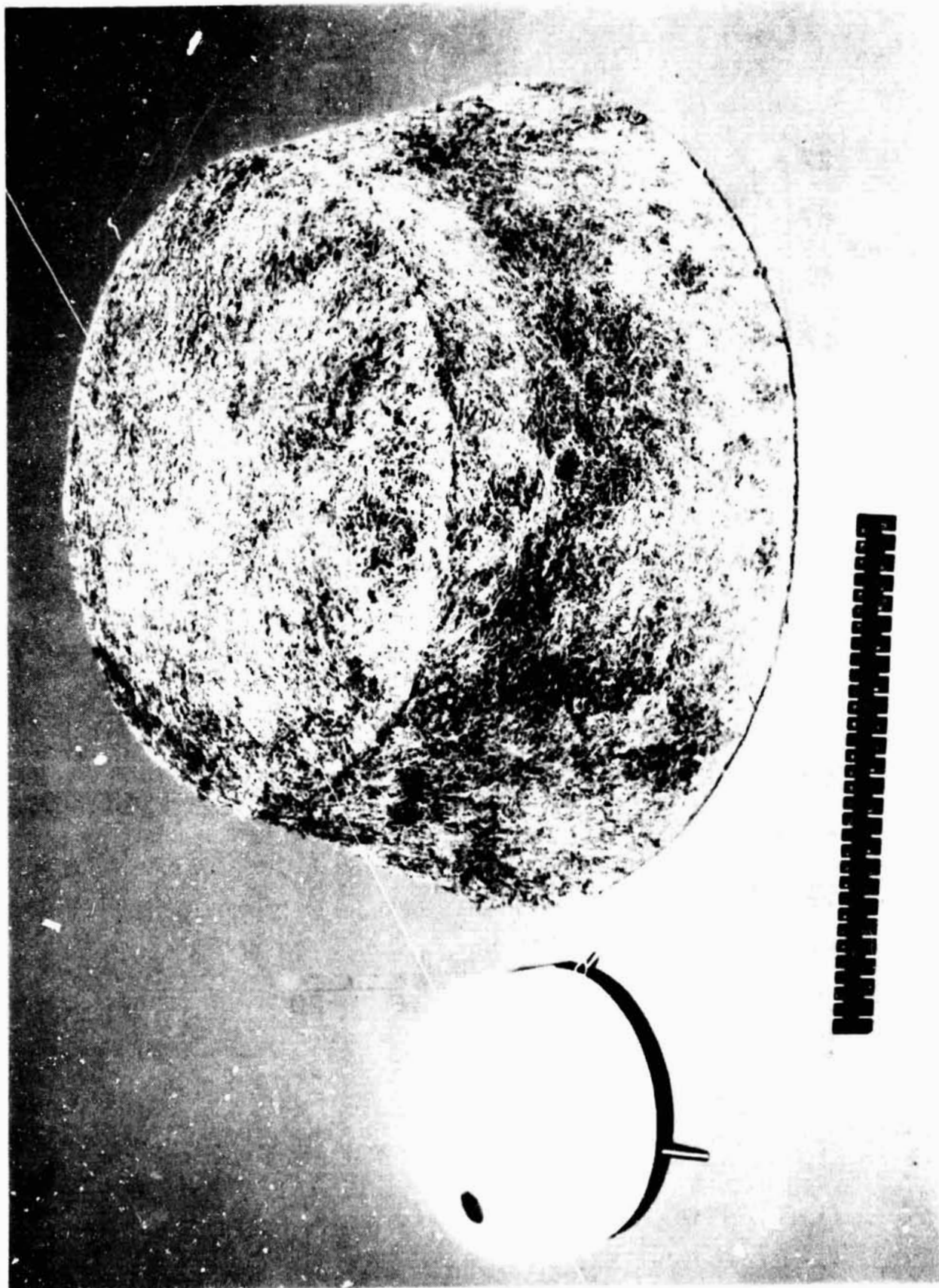


Figure 3. Low frequency microphone system.

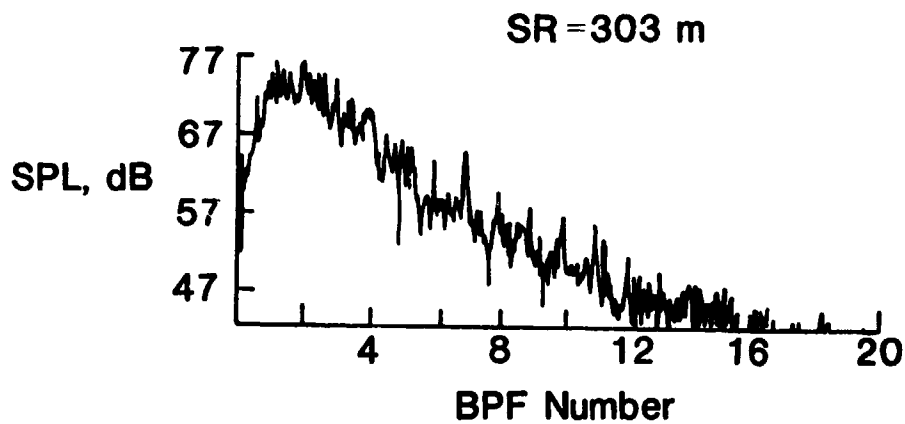
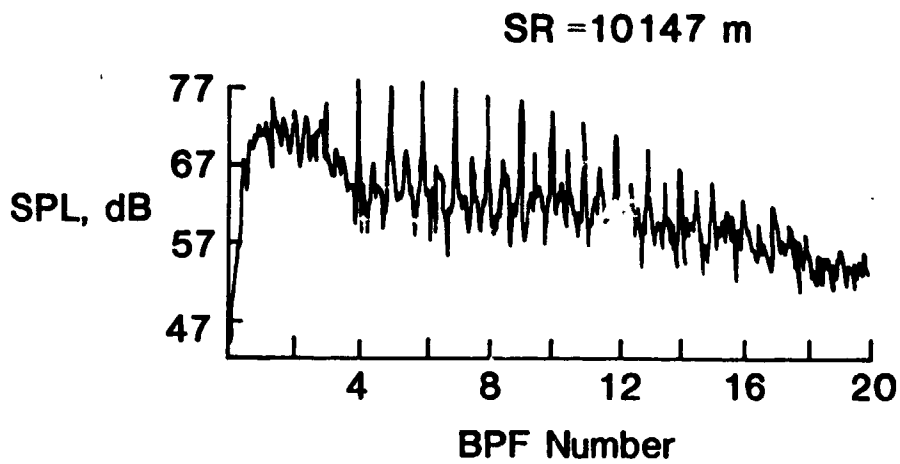


Figure 4. Typical spectra.

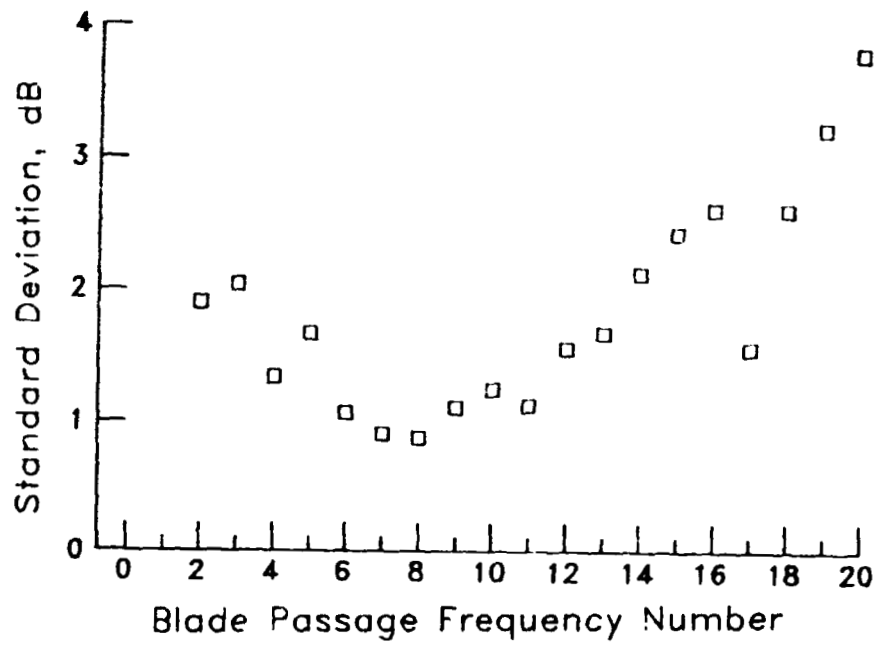


Figure 5. Source level variability.

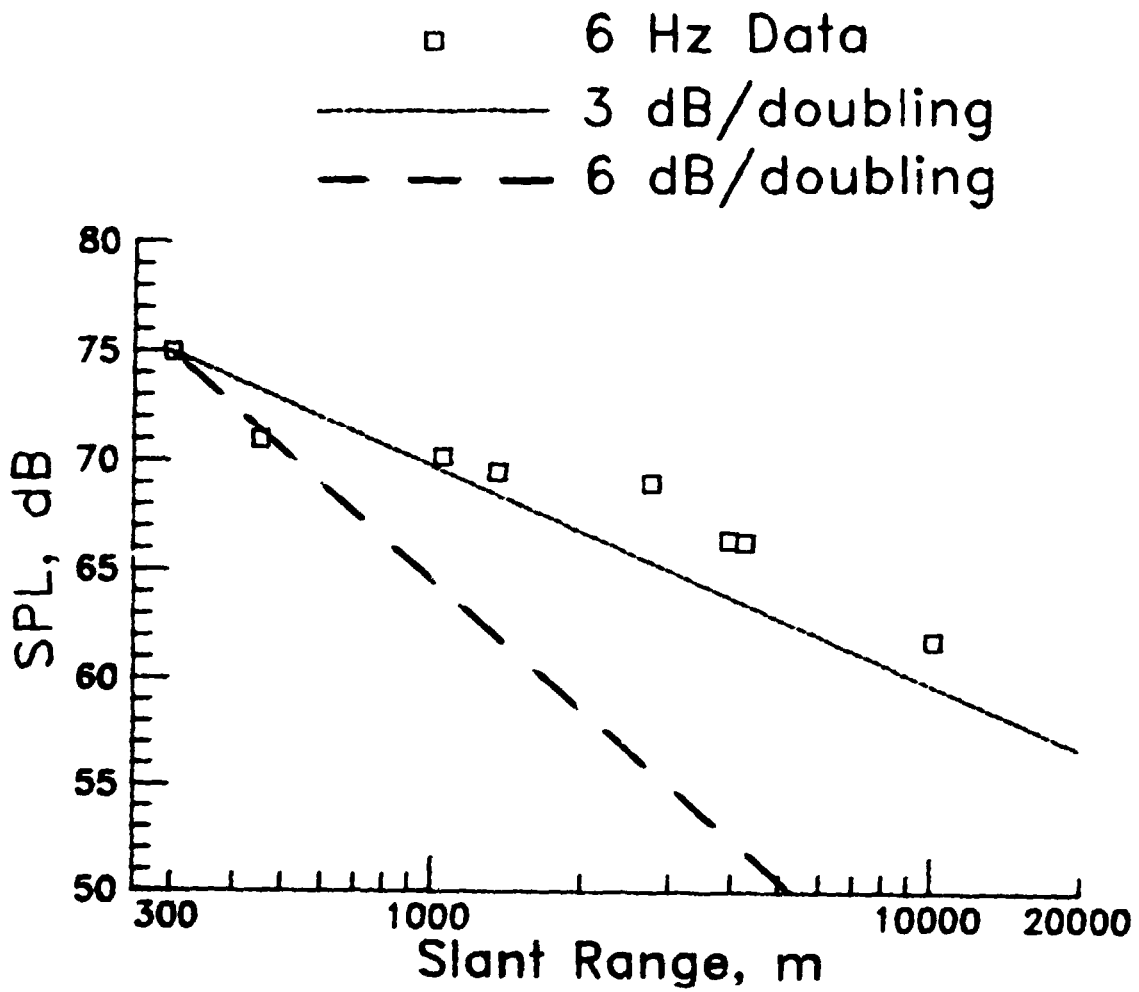


Figure 6. Sound pressure level versus slant range, 6 Hz results.

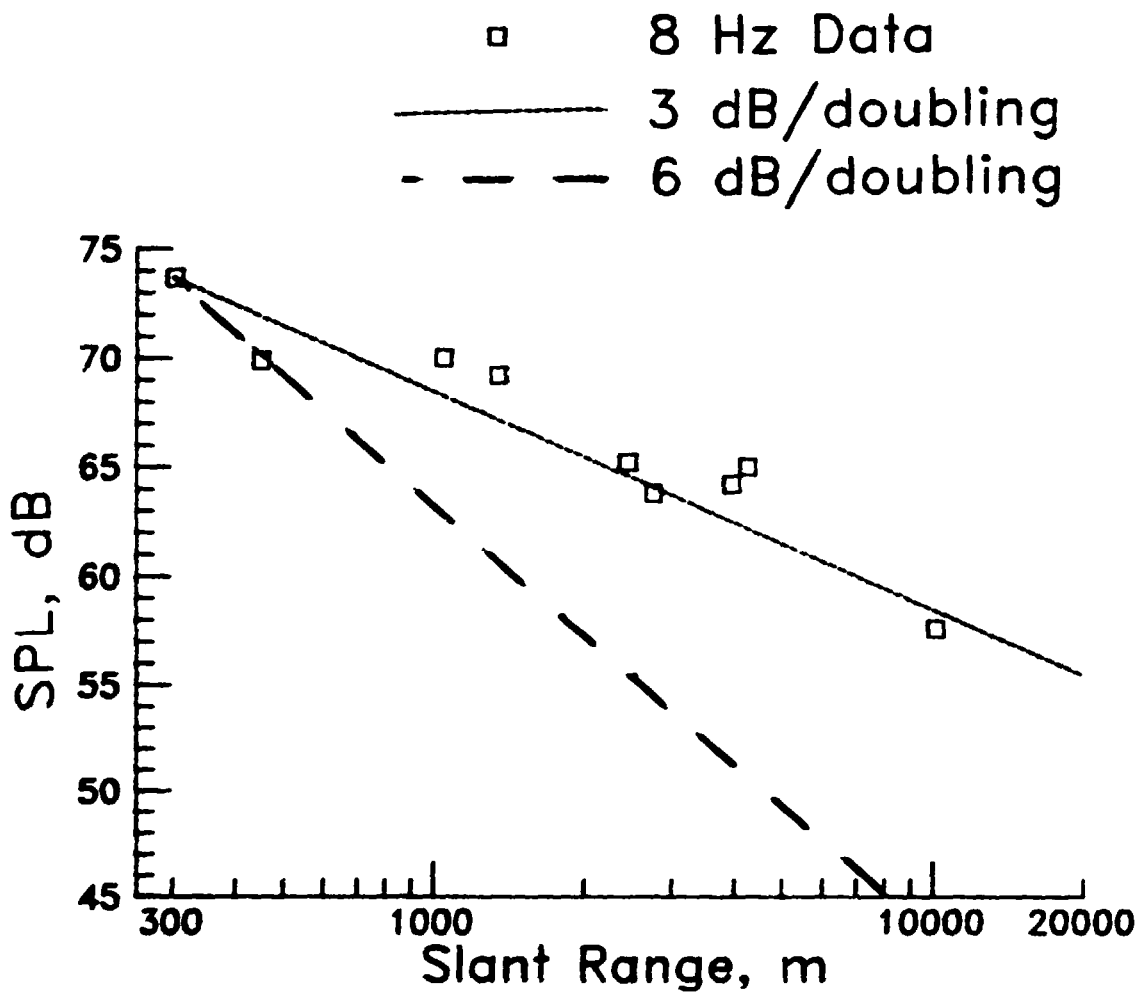


Figure 7. Sound pressure level versus slant range, 8 Hz results.

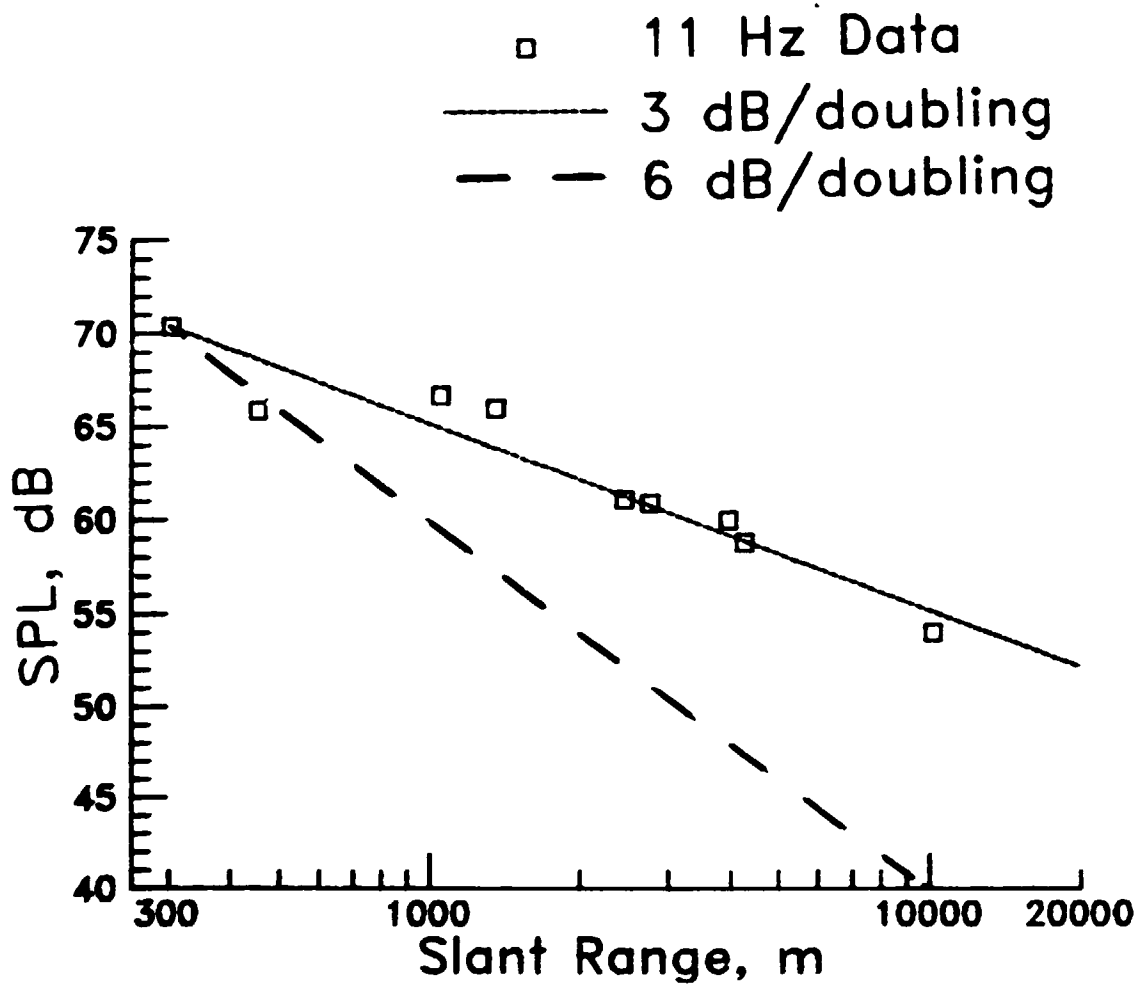


Figure 8. Sound pressure level versus slant range, 11 Hz results.

- 8 Hz Data
 - Prediction (ref. 5)
- $\sigma = 1000 \text{ g cm}^{-3} \text{ s}^{-1}$

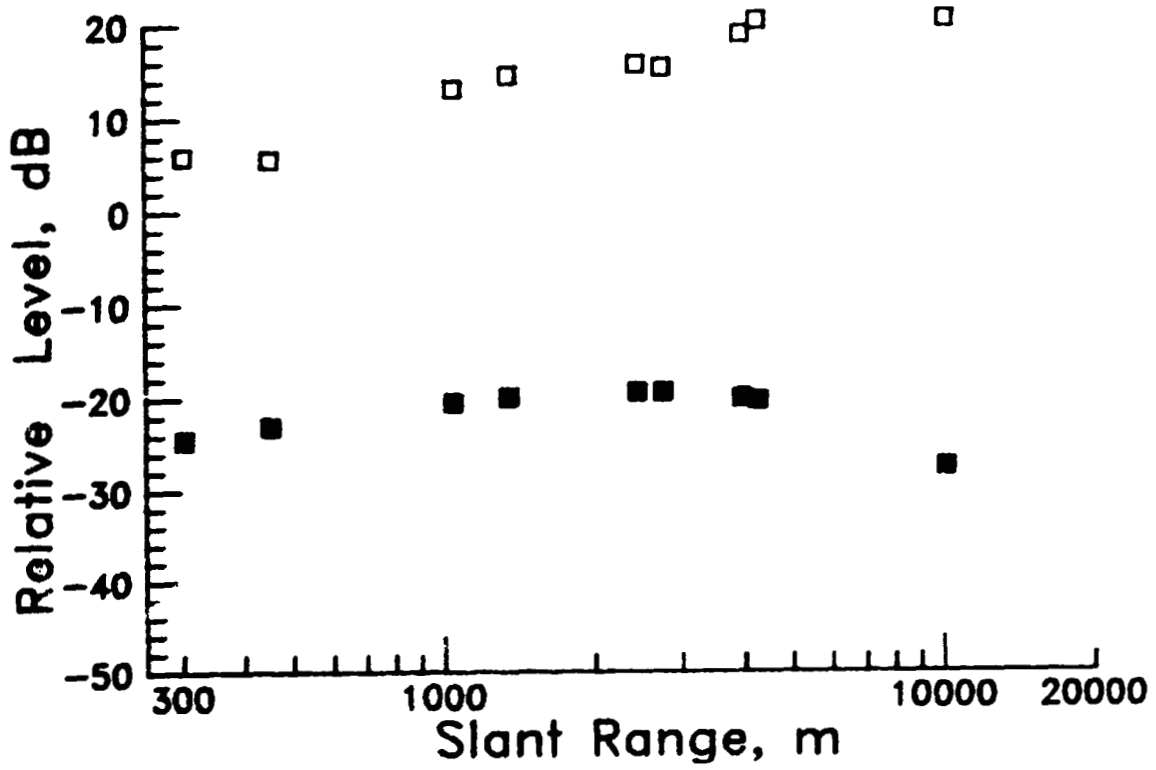


Figure 9. Comparison of 8 Hz data with surface wave predictions versus slant range.

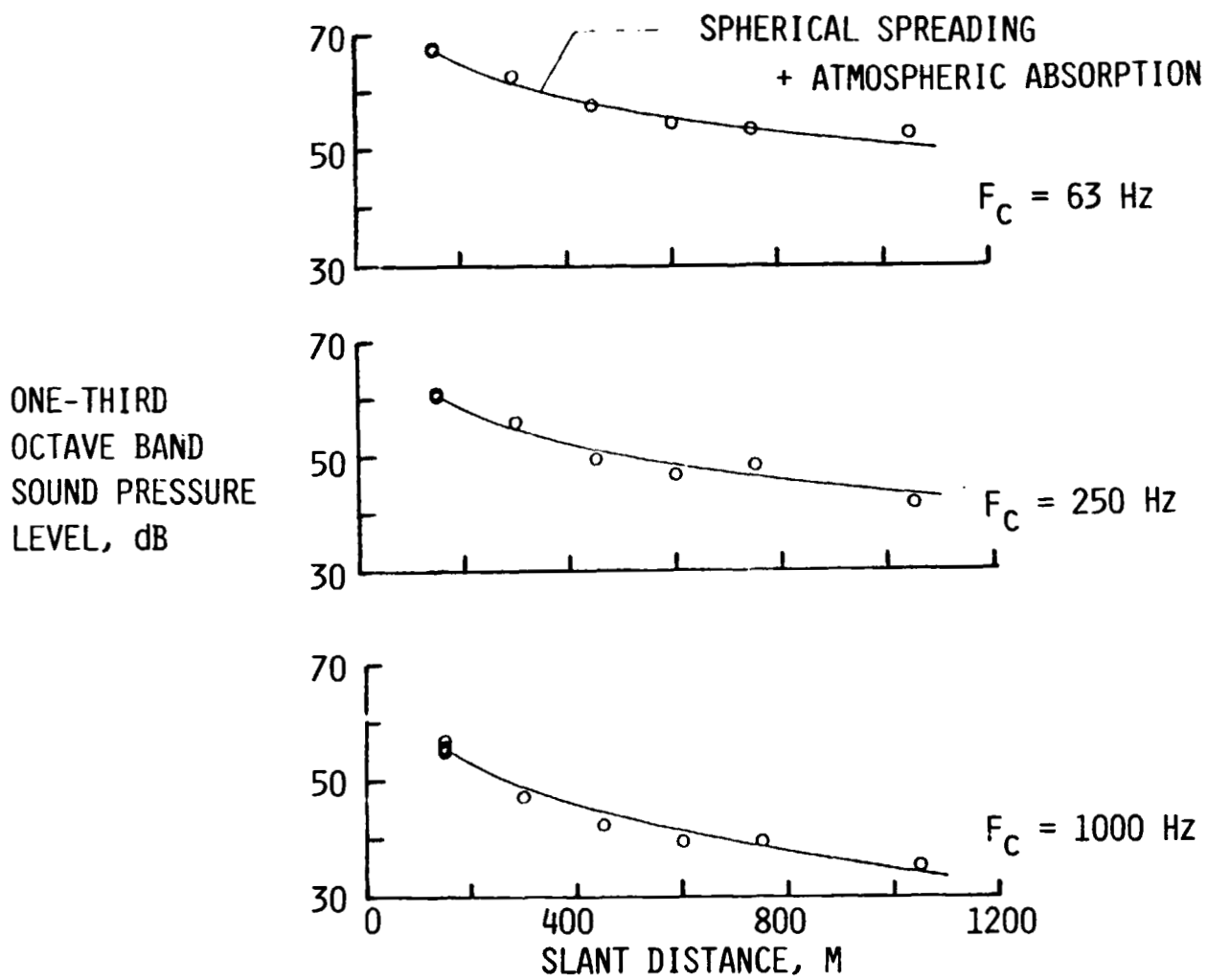


Figure 10. Middle frequency band data versus slant range from reference 7.

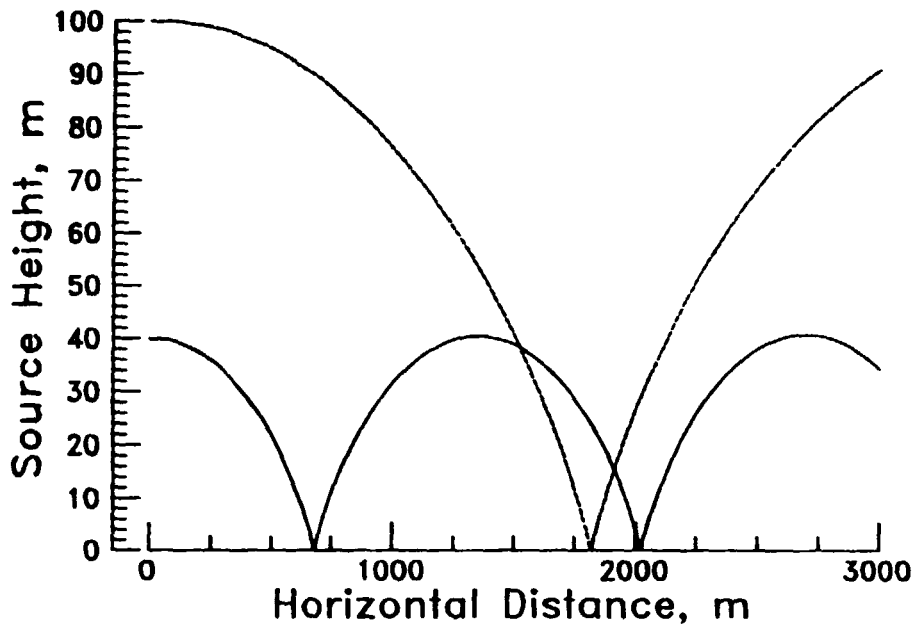


Figure 11. Downwind ray tracing diagram for two source heights.

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