30. PROPAGATION OF SOUND FROM AIRCRAFT GROUND OPERATIONS

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SUMMARY

An experimental study has been performed to investigate the sound propagation losses associated with aircraft ground operations. The study emphasized downwind propagation because the highest levels observed on the ground generally occur when the receiver is downwind from the source. Noise from the initial part of jet aircraft take-offs was measured at distances up to 9000 feet from the aircraft in field measurements at Los Angeles International and Denver Stapleton airports.

The results show a pronounced increase in low-frequency attentuation reaching a maximum in the frequency range of 125 to 250 Hz. The results also indicate that current industry procedures for estimating atmospheric absorption lead to overestimation of attenuation at frequencies above 1000 Hz. A simple engineering procedure for estimating downwind propagation losses is given.

INTRODUCTION

The operation of aircraft in and around airports has become a major contributor to the American urban and suburban noise environment. Effective planning of such matters as airport layout or adjacent land usage therefore requires realistic estimates of the aircraft noise in nearby areas. (See refs. 1 to 3.) These noise estimates depend upon a knowledge of the source characteristics of the various aircraft and the losses associated with propagation from the source to the receiver. Although there is considerable engineering information available describing many of the aircraft noise sources currently encountered, there is considerable uncertainty as to the proper engineering procedures to use in estimating noise levels at positions distant from the aircraft source.

Figure 1 shows the elements of the aircraft noise problems described in terms of sources, paths, and receivers, This paper is concerned with the propagation of sound arising from aircraft ground operations - either from ground runups or noise generated by aircraft during the take-off roll. This paper is based upon an experimental study (ref. 4) to investigate sound propagation losses associated with aircraft ground operations. Of concern in this study was the relationship between the noise levels measured near an aircraft on the ground with the noise levels measured at distant points in areas or communities around an airport. The primary purpose of the study was to determine how well one could relate the changes in noise levels between near and distant positions with the basic weather information that is typically available at an airport – surface measurements of temperature, winds, and humidity. A second purpose was to develop engineering procedures for estimating aircraft noise levels at relatively large distances from aircraft.

Many of the previous studies of ground-to-ground propagation were concerned with long-range communication systems. Hence, they focused attention of the question as to the least favorable conditions for sound propagation. In this study, concerned with predicting aircraft noise in communities, interest was in the opposite question – what are the noise levels expected under the most favorable conditions for sound propagation?

In general, propagation from a source on the ground to a receiver on the ground is most favorable when the wind is blowing in the direction from the source to the receiver (downwind propagation). *Also,* the lobes of maximum noise from a jet engine lie in the rear quadrants of the aircraft, which are also generally in the downwind direction. For these reasons, the highest noise levels observed in nearby areas are generally associated with downwind propagation. Hence, downwind propagation was emphasized in this study.

MEASUREMENT PROGRAM

Although modern airports are indeed noisy places, it is difficult to find an airport noise source that permits consistent measurements out to 5000 feet, a typical distance of interest in the present program. Of the many types of noise sources found at an airport, field experience soon showed that the noise generated during the initial part of a jet aircraft take-off was the most consistently useful source for the program.

Field measurements using jet aircraft take-offs as sources were made at the Los Angeles International airport over a 6-month period and at the Denver Stapleton airport during a 1-week measurement period. Subsequent analysis is based upon results from measurements at both airports.

The noise was measured during the initial part of a jet transport take-off at three positions as shown in figure 2. One position was located within about 300 feet of the airplane. The other two positions were located at greater distances on a line with the innermost position (station 1) and the airplane. The most distant position was located typically 1 mile or more from the airplane.

Use of the noise from jet airplanes during the initial part of the airplane take-off roll imposed some significant limitations in analysis of the data. Because most jet transport airplanes started their take-off roll before or immediately upon reaching full thrust, the noise source was constantly changing in magnitude and geometrical location.

Thus, each airplane take-off produced a time-varying signal with a usable duration of about 5 to 10 seconds. The fact that the signal amplitude and geometrical location were changing rapidly with time introduced the need for careful time correlation of the recordings made in the field.

Simultaneous magnetic tape recordings were made at all stations. Annotation by the observer at station 1, recorded directly on the tapes at each of the stations, signaled the start of each event and provided synchronization for all three stations. A tone burst was placed on the station 1 tape as the airplane moved past position A, shown in figure 2. A second tone burst was placed on the tape as the airplane moved past position B on its take-off roll. The recorded signal between the two tone bursts denoted the usable position of the signal at station 1 for that event. During laboratory analysis of the recorded data, octave frequency band levels were examined at the three positions obtained for the same usable time interval (adjusted for the sound propagation time), and the differences in noise levels observed between the three measurement positions were compared.

Meteorological conditions, in terms of wet- and dry-bulb temperatures, wind speed and direction, barometric pressure, and cloud cover were noted at each measurement station at approximately hourly intervals. Hourly sequence surface weather observation data were obtained from the U.S. Weather Bureau offices located at the Los Angeles and Denver airports, for each measurement period. Weather Bureau radiosonde information was utilized to estimate temperature profiles. In the data analysis, the Weather Bureau information was relied upon as the primary description of the weather, field measurement data being used to supplement the Weather Bureau information.

To illustrate some of the actual field measurement locations, figure 3 shows two different measurement radials at Los Angeles International airport. Typically, noise would be measured during several aircraft take-offs with measurement stations located along one radial. Then, during the same period, measurement locations would be shifted to another radial and the noise measurements repeated during several other aircraft take-offs. The two outer positions were usually located in the communities surrounding the airport and only the innermost station had direct line of sight to the aircraft. As the figure indicates, between the innermost station and the outer two stations, there were intervening buildings, elevated freeways, and other obstructions which interfered with direct line-of-sight sound propagation.

SOUND ATTENUATION FACTORS

Figure 4 provides an example of the difference in noise levels that might be measured downwind during favorable sound propagation conditions. The zero reference refers to the noise levels measured at 200 feet from an aircraft source. The first band indicates typical differences in levels between those measured at 1000 feet and those measured at 200 feet from the aircraft source. The lower band indicates the typical differences for downwind sound propagation between those measured 200 feet and 4000 feet from the aircraft. The difference in noise levels at the 1000-foot and 4000-foot positions are shown as shaded bands to provide an indication of the variability that might be expected, even under the same reported surface weather conditions. If noise levels taken at these distances at different times under different reported surface weather conditions were compared, one would likely find much greater spread than is indicated by the bands shown in figure 4.

In the following table are listed the primary factors determining the differences in noise levels at various distances from an aircraft source for downwind propagation:

Noise attenuation component	Dependent upon
Inverse-square spreading	Geometry, distance
Classical attenuation, Molecular attentuation } Standard atmospheric attenuation	Absolute humidity
Miscellaneous meteorological and ground effects - "residual" attenuation	Wind and temperature profiles, terrain

The first component listed, the attenuation due to inverse-square radiation of the sound, may be evaluated from the measurement geometry and distance relationships.

The classical and molecular attenuations are grouped together under the term "standard atmospheric attenuation." The standard atmospheric attenuation is primarily determined by the absolute humidity of the air. This attenuation can usually be predicted from knowledge of the air temperature and relative humidity. There are accepted industry procedures and tables (given in ref. 5) for estimating the standard atmospheric attenuation. The attenuation values given in these procedures are based upon rather precise laboratory measurements of air under uniform temperature and humidity conditions. Although there is little question about the accuracy of these values for air under uniform conditions, there is a question as to the accuracy of using simple surface measurements of temperature and humidity to predict the atmospheric attenuation for propagation over the ground under typical field conditions.

What is left after the first three components (inverse-square spreading and classical and molecular attenuation) have been removed from the sound pressure level differences is associated with the meteorological and ground effects and is denoted as "residual attenuation." The residual attenuation is likely to vary drastically for upwind and downwind conditions. It results from such factors as scattering due to inhomogeneities in the atmosphere and from temperature and wind gradients which cause bending of the sound waves. It also is affected by the terrain which causes absorption and reflections.

Figures 5 and 6 provide some indication as to the relative size of these four components at low frequencies and at high frequencies. Figure 5 shows the expected downwind sound attenuation at 250 Hz. The major factors contributing to the attenuation are the inverse square spreading and the residual attenuation. The standard atmospheric attenuation due to the air absorption is relatively small. At these low frequencies, even considerable error in estimating the standard atmospheric attenuation values would not lead to serious errors in estimating the total attenuation.

Figure 6 shows the expected downwind attenuation at high frequencies, in this case, 4000 **Hz.** Typically, the total attenuation is much greater. The two primary contributors are now the inverse-square spreading and the standard atmospheric attenuation. The residual attenuation may be very small. In this case, it is easy to see that errors in estimating the standard atmospheric attenuation may lead to large errors in estimating the total sound attenuation.

In the field measurements, only the total attenuation was measured directly. The inverse-square losses were determined from knowledge of the distances between the measurement positions, and the standard attenuation was estimated from the surface measurements of temperature and relative humidity. These calculated values were then subtracted from total observed field attenuations and the remaining residual attenuation values were examined. Thus, the residual attenuation values from the field measurements contained the true residual attenuation plus any measurement errors or errors in the determination of the standard atmospheric attenuation. Particularly at high frequencies, errors in the estimation of the standard atmospheric attenuation could cause large errors in the determination of the residual attenuation from the field measurements.

In the field measurements, many data were taken at many different distances and under many different weather conditions. In the analysis, the residual attenuation information was grouped in terms of three distance ranges. Different groupings of the data were then examined in terms of absolute wind speed, wind vector magnitudes, and temperature profile behavior. For all these groupings, there was considerable scatter of the data, and it was not possible to give any more consistent presentation than that based on a division of data in terms of absolute wind speed – greater than 10 knots per hour and less than 10 knots per hour.

Typical results of the measurements are shown in figures 7 and **8.** These figures show the mean residual attenuation, observed in octave bands, for three distance ranges. The solid line is for a mean distance of 2600 feet; the short-dashed line, for a mean distance of 5200 feet; and the long-dashed line, for a mean distance of 7000 feet. Figure 7 presents data for wind speeds less than 10 knots; figure 8, for wind speeds greater than 10 knots. In these figures, the attenuation is positive in an upward direction; thus, the higher the line is on the graph, the greater the amount of residual attenuation. One will note that there is considerable residual attenuation at the low frequencies; as a result, there is a peak in the attenuation in the 125- and 250-Hz octave bands.

In the frequency bands above 1000 Hz, there are three features of unusual behavior:

(1) The attenuation values become negative and represent "amplifications" that are as large as 40 dB and 50 dB at the highest frequencies

(2) The order of the mean attenuation curves becomes inverted so that the largest distances show the smallest (rather than the largest) attenuations

(3) The standard deviations become large, typical values rising from 6 dB to 12 dB below 1000 Hz to 30 dB to 40 dB at 4000 Hz.

Although it is true that greater level fluctuations are expected at high frequencies than at low frequencies, the fact that the increases in standard deviation are coupled with these other effects suggests strongly that the procedure for standard atmospheric attenuation at high frequencies has generated values that are very high. In other words, by using the standard atmospheric attenuation values of reference 5, "amplifications" have been artificially introduced at the higher frequencies and have also increased the scatter in the data. Based on this reasoning, the high-frequency attenuation values were recalculated, the SAE procedure being modified in two steps. In one set of data (figs. 9 and 10), the values obtained from the SAE procedure in the frequency bands centered at 2000 and 4000 Hz were arbitrarily halved. In the second step, the standard SAE attenuation was omitted completely.

From figures 9 and 10, it may be seen that the removal of half of the standard attenuation in the highest frequency bands reduces the artificial amplifications of figures 7 and 8. Furthermore, data scatter and standard deviations were also significantly reduced at 2000 and 4000 Hz. Complete removal of the standard attenuation forces the resulting attenuation values negative and suggests that the values are now overcorrected by removing all the high-frequency air attenuation.

The most pronounced feature of the curves shown in figures 9 and 10 is the low-frequency peak occurring around 125 and 250 Hz mentioned earlier. This low-frequency peak in residual attenuation was observed occasionally by earlier workers (refs. 6 to 9) and has been ascribed to destructive interference between the direct sound and sound partly reflected from the ground surface. However, the field-measurement geometry does not fit in with any such interference models. Some earlier workers had also suggested that the presence of a wind greater than about 5 miles per hour would destroy this interference effect. However, the data shown here for winds much greater than 5 miles per hour show the effect very markedly. Parkin and Scholes making measurements with a jet engine in Great Britain have also seen this low-frequency behavior and present some data to show that the effect is dependent upon the source and measurement height. (See ref. 10.) However, no detailed understanding of the effect is available.

By cross plotting the residual attenuation data shown in figure 10, one has some of the information needed for an empirical engineering procedure for estimating attenuation for downwind sound propagation. Such a procedure is presented in the appendix, together with an example of its application. The residual attenuation values to be used in this procedure are shown in figure 11. In figure 11, the attenuations for different octave frequency bands from 31.5 to 500 Hz are plotted as a function of distance from the source. The residual attenuation at large distances is greatest at 125 and 250 Hz and decreases in magnitude at higher as well as at lower frequencies.

Within the last several years, other procedures have been suggested by industry (ref. 11) for predicting downwind sound propagation.* These procedures use values for the residual attenuation that do not provide for the large attenuation values that were observed at 125 and 250 Hz. These procedures also predict sizable residual attenuations at the higher frequencies, contrary to what has been found in this investigation. Thus, if one were to compare the two procedures by applying them to predict noise levels at large distances from an aircraft located on the ground, one would arrive at significantly different answers. The results presented herein would produce lower estimates of noise levels at the lower frequencies and higher estimates of the noise levels at the higher frequencies.

CONCLUSIONS

The study of the residual attenuation associated with the downwind propagation of noise from an aircraft on the ground provides the following conclusions:

1. The attenuation data show a pronounced increase in low frequencies. This increase reaches a maximum in the frequency range of 125 to 250 Hz, a frequency range of considerable interest for turbojet engine noise.

2. Current industry procedures for estimating the standard attenuation associated with classical and molecular absorption lead to overestimation of attenuation at frequencies above 1000 Hz. This effect may be of particular interest for large bypass-ratio turbofan engines.

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*In reference 11, the term "extra ground attenuation" corresponds to the term "residual attenuation" used in this paper.

3. Under the most favorable conditions, the values of standard deviations associated with propagation over distances of 3000 to 6000 feet are in the range of 6 dB to 12 dB. Thus, under typical downwind conditions, rather large variations in distant noise levels may be expected even for the same gross weather conditions as measured in' terms of surface temperature, humidity, and surface winds.

4. A simple engineering procedure for estimating downwind propagation losses has been developed. This procedure incorporates the findings of conclusions 1 and 2.

5. Like many experimental programs, this study has raised a number of questions. The low-frequency residual absorption peak is not fully understood even though it is certain that it exists. Also, the reason that the standard absorption values appear to be so excessive at high frequencies is not known. Thus, considerably more work remains to be done to develop reliable methods for predicting ground-to-ground noise propagation. There is also reason to suspect that the application of current methods for estimating standard atmospheric absorption for air-to-ground propagation during aircraft flyovers may also be in error. For these reasons, NASA has recently begun a study to examine the propagation losses observed in a number of carefully controlled aircraft flyovers undertaken during recent tests at Wallops Island, Virginia.

APPENDIX

SUGGESTED PROCEDURE FOR ESTIMATING DOWNWIND ATTENUATION

The purpose of this procedure is to suggest a method for predicting the propagation of noise over open terrain from an aircraft on the ground to other locations in nearby residential areas. The procedure is restricted to the case of downwind propagation, that is, a nonnegative component of the wind in the direction from the aircraft source to the residential receiver. This case of downwind propagation is expected to be the most favorable for sound propagation to nearby areas. Upwind propagation, that is, a negative component of wind velocity in the direction of source to receiver, tends to provide larger values of residual attenuation and under some circumstances produces marked attenuation regions called shadow zones.

For the purpose of this procedure, the wind velocity is assumed to be 10 miles per hour. The wind velocity averaged for about 60 airports in the United States has been found to be approximately this value. The source and receiver heights are also assumed to be approximately 6 feet above the ground.

The following information is required to calculate the attenuation between point A (a convenient reference point located within a few hundred feet of the aircraft) and point B (the residential measurement point of interest):

x_A, x_B distances from aircraft to points A and B, respectively

T ambient temperature

RH ambient relative humidity

The total downwind attenuation (TDA) is given as the sum of three components

$$TDA = IA + SA + EA$$

where

IA inverse-square attenuation, $20 \log_{10}(x_B/x_A)$

SA standard atmospheric attenuation, calculated from reference **5,** as modified

EA residual attenuation

3

APPENDIX

Figure 11 presents plots of residual attenuation **EA** as functions of propagation distance, for frequency bands below 1000 Hz. For frequency bands at or above 1000 Hz, **EA** is taken to be zero.

For frequency bands centered at 1000 Hz and below, the standard atmospheric attenuation **SA** is calculated directly from reference 5 as a function of temperature T and relative humidity RH. For frequency bands centered at 2000 Hz and above, **SA** as a function of temperature and humidity is taken as one-half the values obtained from reference 5.

If one-third octave frequency bands are used, the values of **TDA** for the frequency bands between the octave band center frequencies should be obtained by interpolation from a smoothed curve based on the octave band values. The standard deviations associated with the predicted values of **TDA** are of the order of 6 dB to 12 dB.

For the example shown in table I, the total downwind attenuation in preferred octave frequency bands between two points that are 200 ft and 4000 ft from an airplane was determined. The temperature was 59° F and the relative humidity, 70 percent.

TABLE I.- EXAMPLE OF TOTAL DOWNWIND ATTENUATION CALCULATIONS

Octave band center frequency, Hz	Inverse-square attenuation, dB	Standard atmosphere attenuation per 1000 ft[1], dB	Standard atmosphere attenuation[2], dB	Residual attenuation[3], dB	Total downwind attenuation, dB
31.5	26	0	0	6	32
63	26	0	0	10	36
125	26	0	0	15	41
250	26	0	0	15	41
500	26	.7	3	2	31
1000	26	1.4	5	0	31
2000	26	3.0	6	0	32
4000	26	7.7	15	0	41
8000	26	14.4	28	0	54

[1]Reference 5, paragraph 5.0.

[2]Based upon one-half the values of the third column for frequencies of 2000 Hz and higher.

[3]From figure 11.

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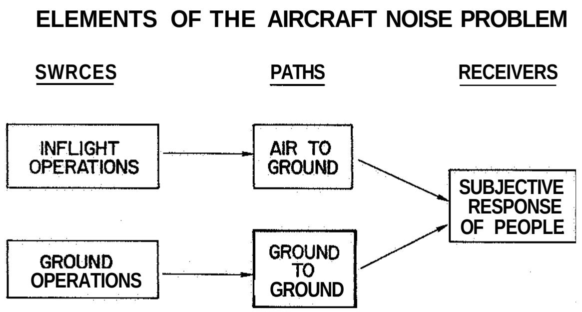


Figure 1

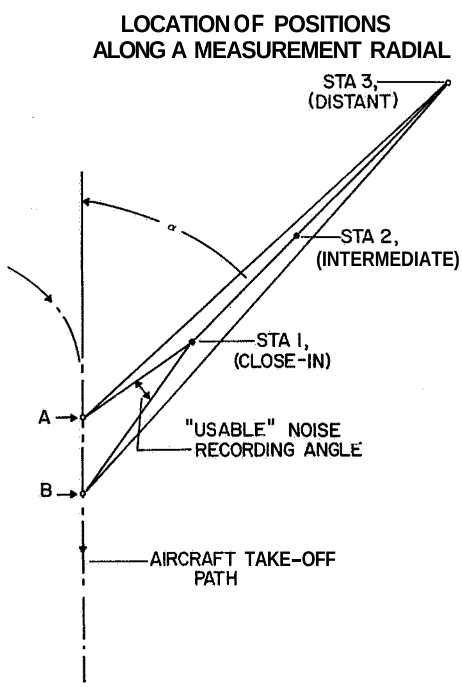


Figure 2

TYPICAL MEASUREMENT POSITIONS
(TAKE-OFFS FROM RUNWAY 25 R)

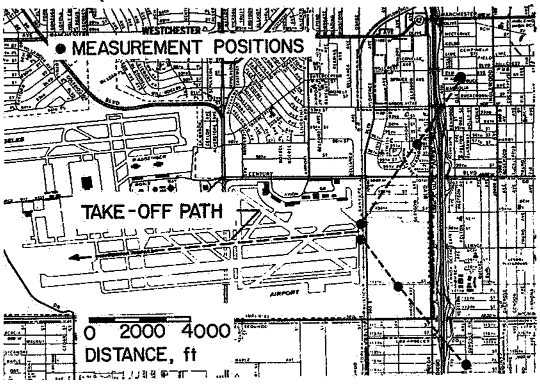


Figure 3

EXAMPLE OF DOWNWIND SOUND PROPAGATION FROM JET AIRCRAFT

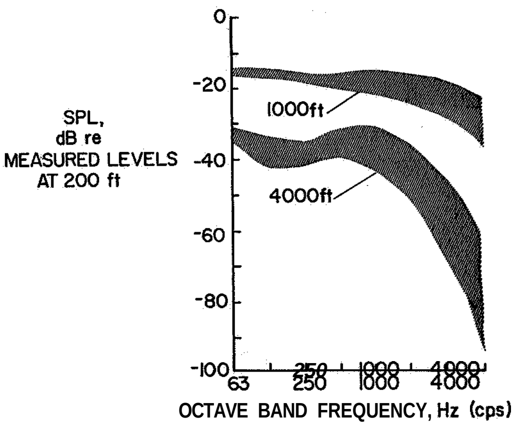


Figure 4

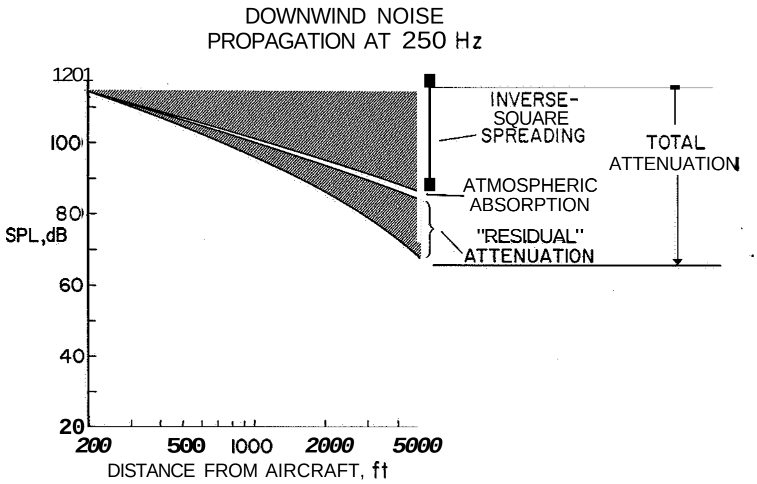


Figure 5

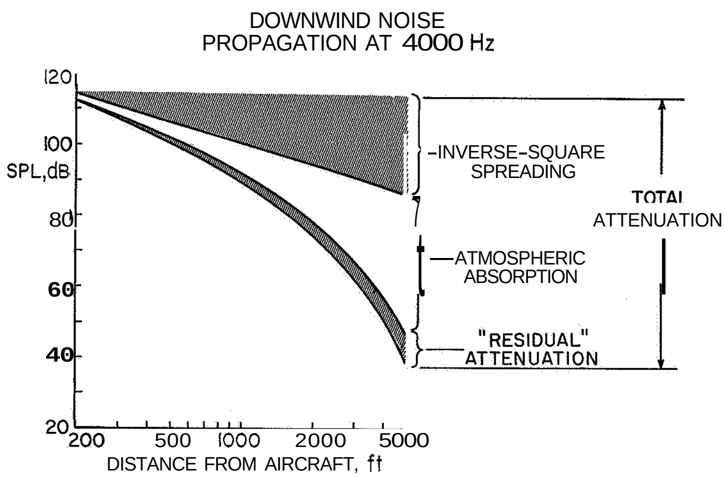


Figure 6

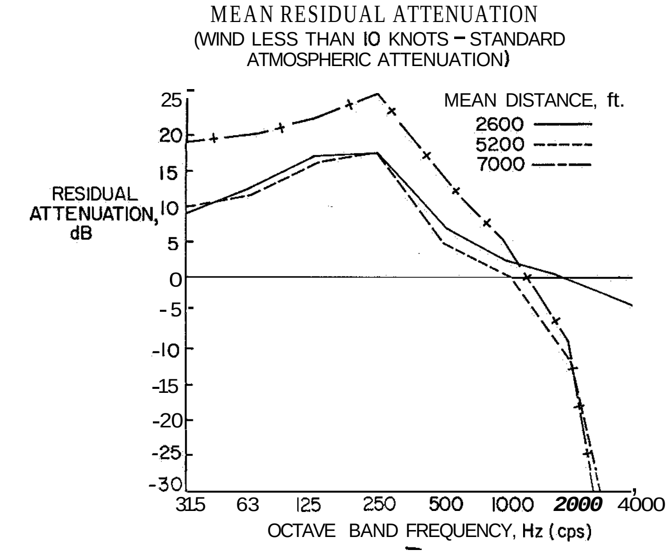


Figure 7

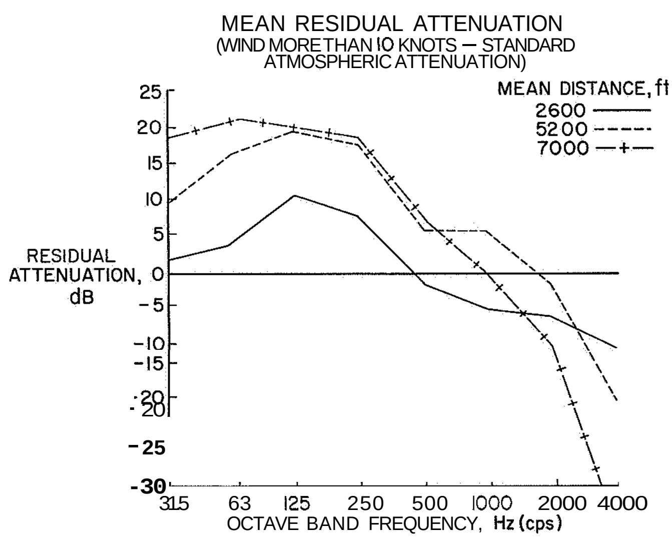


Figure 8

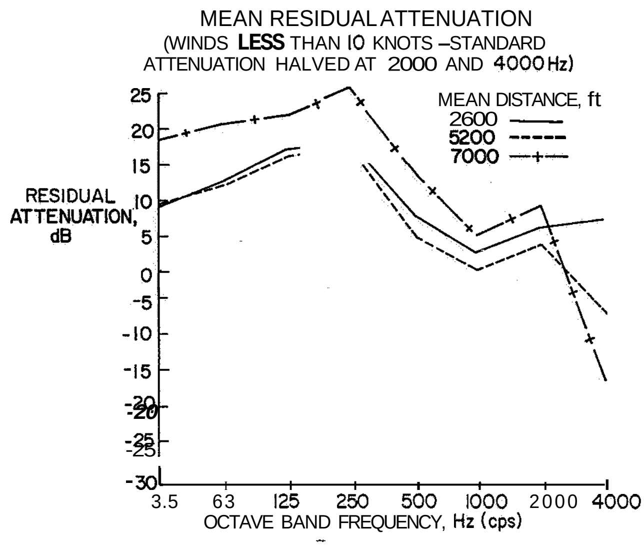


Figure 9

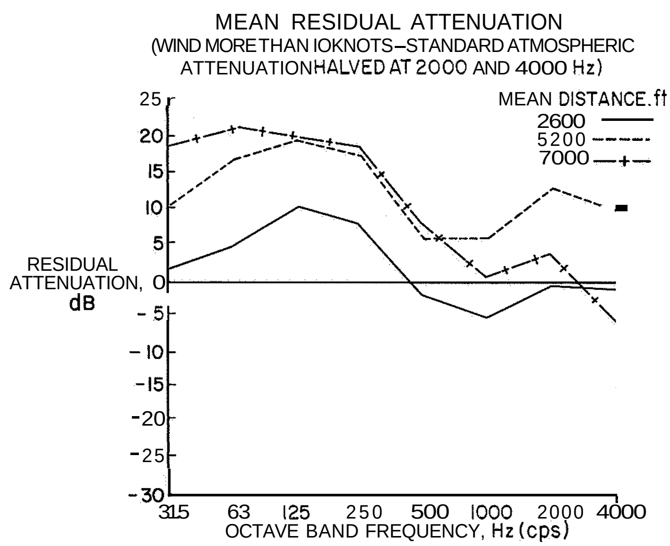
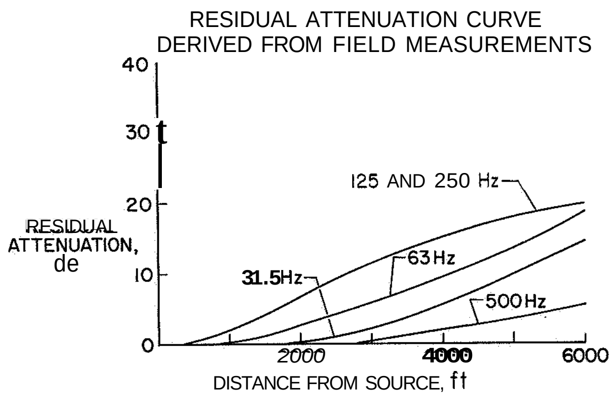


Figure 10



RESIDUAL ATTENUATION CURVE
DERIVED FROM FIELD MEASUREMENTS
40
30
20
10
0
RESIDUAL
ATTENUATION,
de
125 AND 250 Hz
63 Hz
31.5Hz
500 Hz
2000
4000
6000
DISTANCE FROM SOURCE, ft

Figure 11