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Investigation of ASTM E966 Adjustment Factors

April 2018

Final Report

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16. Abstract

In 2014, the Federal Aviation Administration amended the Airport Improvement Program Handbook to clarify guidance for the funding of noise mitigation projects requiring eligible structures not only to be located within the day-night average sound level 65-decibel (dB) noise contour, but also experience existing interior noise levels that are 45 dB or greater with the windows closed. This restated guidance places greater emphasis on the accuracy of the measurement of the existing noise reduction of a structure.

Historically, two methods have been used to measure the noise reduction of structures: aircraft overflight and loudspeaker. The most common approach to testing structures has been to adapt the American Society for Testing and Materials (ASTM) E966-10 test procedure that incorporates an outdoor loudspeaker to simulate an aircraft noise source, together with noise level measurements outdoors and indoors. This method is repeatable, but tests have shown that it results in lower measured noise level reduction than the aircraft overflight test by several decibels. The ASTM E966-10 guidance contains adjustment factors to account for reflection from the façade surface when using a loudspeaker as the noise source. However, the appropriateness of these adjustments is in question as a result of the noted discrepancy between measurements using aircraft and loudspeakers for the tests.

The objectives of this study were to determine and understand the contribution of the factors influencing the sound level at and near a building façade, identify appropriate adjustment factors for measurements of noise reduction in airport sound insulation programs, and validate these factors through application to existing data and by conducting field measurements.

A time-domain simulation model, which was validated through a series of field measurements, was developed to aid in this study. Updated adjustment factors were developed from measurements and modelling to account for façade reflection and were validated by application to previously published noise reduction data and additional field measurements.

This study yielded the conclusions that the adjustment factor to account for façade reflection in the measurement of noise reduction using a loudspeaker and flush-mounted microphone should be the theoretical vale of 6dB, and not 5dB as quoted in ASTM E966-10. Additionally, the adjustment factor to account for façade reflection in the measurement of noise reduction using a loudspeaker and near-façade microphone should be 3.5 dB, and not 2 dB as quoted in ASTM E966-10.

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LIST OF SYMBOLS AND ACRONYMS

α	Specific volume
γ	Ratio of specific heats
β	Elevation (vertical) angle of incidence
θ	Angle of incidence
Ω	Porosity
ψ	Azimuthal angle of incidence
ϕ	Angle between building façade and flight path
σ	Flow resistivity
Δ	Difference quantity
∞	Infinite quantity
a	Absorption coefficient
c	Speed of sound in air
A	Interior room absorption
$_{bg}$	Variables for background flow
c_s	Porous medium structure factor
f_{f1}	Fundamental façade reflection interference frequency
f_{g1}	Fundamental ground reflection interference frequency
L_1	Exterior incident sound level
L_2	Interior sound level
NR_θ	Noise reduction at angle of incidence θ
p	Specific pressure
$Pa.s/m^2$	Pascal seconds per square meter
S	Area of the façade
TL_θ	Transmission loss at angle of incidence θ
u	Specific velocity

ACRP	Airport Cooperative Research Program
AEDT	Aviation Environmental Design Tool
AIP	Airport Improvement Program
ASTM	American Society for Testing and Materials
BOS	Boston Logan International Airport
BTV	Burlington International Airport
CSDA	Corlett, Skaer, and DeVoto Architects
dB	Decibel
DNL	Day-night average sound level
FAA	Federal Aviation Administration
FG	Free-field grass surface
FH	Free-field hard surface
Hz	Hertz
HMMH	Harris, Miller, Miller, & Hanson, Inc.
IBANA	Insulating Buildings Against Noise from Aircraft
IBANA-Calc	Insulating Buildings Against Noise from Aircraft Software
INM	Integrated Noise Model
ISO	The International Organization for Standardization

L&B	Landrum & Brown, Inc.
LS	Loudspeaker
m	Meter
MHT	Manchester-Boston Regional Airport
MKE	General Mitchell International Airport
NLR	Noise level reduction for an A-weighted source spectrum
NR	Noise reduction at a given frequency or frequency band
OINR	Outdoor-indoor noise reduction at a given frequency or frequency band
OITL	Outdoor-indoor transmission loss
PGL	Program guidance letter
SAN	San Diego International Airport
SD	Standard deviation
SDF	Louisville International Airport (Standiford Field)
SEL	Sound exposure level
TL	Transmission loss
U.S.	United States

EXECUTIVE SUMMARY

In 2014, the Federal Aviation Administration (FAA) amended the Airport Improvement Program Handbook to clarify guidance for the funding of noise mitigation projects. The clarification addressed requirements that eligible structures not only be located within the day-night average sound level 65 decibel (dB) noise contour, but also experience existing interior noise levels that are 45 dB or greater with the windows closed. This restated guidance places greater emphasis on the accuracy of the measurement of the existing noise reduction of a structure.

Historically, there have been two methods used to measure the noise reduction of structures. The first employs aircraft as the exterior noise source. This method has the definite advantage of precisely simulating the noise problem experienced by the residents and should be considered as the gold standard. However, aircraft are uncontrollable noise sources, and the measurement results can sometimes be difficult to replicate if aircraft fly different tracks on different days. The second approach to testing has been to adapt the American Society for Testing and Materials (ASTM) E966-10 test procedure that incorporates an outdoor loudspeaker in place of an aircraft noise source, together with noise level measurements outdoors and indoors. This method is more repeatable, but tests have shown that it results in lower measured noise level reduction than the aircraft overflight test by several decibels.

The ASTM E966-10 guidance contains adjustment factors to account for reflection from the façade surface when using a loudspeaker as the noise source. However, the appropriateness of these adjustments is in question as a result of the noted discrepancy between measurements using aircraft and loudspeakers for the tests.

The objectives of this study were to determine and understand the contribution of the factors influencing the sound level at and near a building façade, identify appropriate adjustment factors for measurements of noise reduction in airport sound insulation programs, and validate these factors through application to existing data and by conducting field measurements.

A time-domain simulation model, which was validated through a series of field measurements, was developed for the study. Updated adjustment factors were developed from measurements and modelling to account for façade reflection and were validated by application to previously published noise reduction data and additional field measurements.

The results obtained from the study can be summarized as follows:

- The adjustment factor to account for façade reflections in the measurement of noise reduction using a loudspeaker and flush-mounted microphone should be the theoretical value of 6 dB, and not 5 dB as quoted in ASTM E966-10.

- The adjustment factor to account for façade reflection in the measurement of noise reduction using a loudspeaker and near-façade microphone should be 3.5 dB and not 2 dB as quoted in ASTM E966-10.

- The loudspeaker calibration method for measuring noise reduction, whereby the exterior noise level is measured by calibrating the loudspeaker level in a free-field environment, appears to provide results that replicate measurements using flush-mounted and near-façade microphones.

As part of this study, a relationship was developed that explains the difference between the data obtained between measurements of noise reduction using aircraft and loudspeaker noise sources. This difference is largely due to the shielding of the test façade from the aircraft noise exposure by the house structure and the changing angle of incidence of the aircraft noise exposure, neither of which are replicated in the loudspeaker measurement method.

1. INTRODUCTION.

In 2014, the Federal Aviation Administration (FAA) amended the Airport Improvement Program (AIP) Handbook [1] to clarify guidance for the funding of noise mitigation projects. The guidance restates that for a structure to be eligible to participate in an AIP-funded noise mitigation project, it must be located within the day-night average sound level (DNL) 65 decibel (dB) noise contour and experience existing interior noise levels that are 45 dB or greater with the windows closed. Prior to the amendment, the eligibility criteria adopted by many airport sound insulation programs for structures to be treated was simply that they were within the DNL 65 noise contour, regardless of the interior noise level. By confirming that structures with an interior DNL of less than 45 dB would be ineligible for treatment using AIP funds, this restated guidance places greater emphasis on the accuracy of the measurement of the existing noise reduction of a structure.

Historically, two test methods have been used to measure the noise reduction of structures. The first method employs aircraft as the exterior noise source, with exterior and interior noise measurements conducted with aircraft overflights. This method has the definite advantage of precisely simulating the noise problem experienced by the residents and should be considered as the gold standard, provided the measured overflights are representative of the airport's normal operation. However, aircraft as noise sources are uncontrollable, and the measurement results can sometimes be difficult to replicate if aircraft fly different tracks on different days. The result is that the data obtained often lacks consistency. Furthermore, the testing procedure requires multiple noise monitors to conduct measurements simultaneously in multiple rooms; and this can be time-consuming if airport runway usage does not always match the need for measurements.

The second test method has been to adapt the ASTM E966-10 [2] test procedure that incorporates an outdoor loudspeaker to simulate an aircraft noise source, together with noise level measurements outdoors and indoors. The loudspeaker is certainly a controlled source, but tests conducted at several airports have shown that this method leads to a lower measured noise level reduction (higher interior noise levels) than the aircraft overflight test by several decibels. There may be a number of reasons for this.

First, the incident sound wave from an aircraft overflight varies in level, spectrum, and angle of incidence as the aircraft moves along its flight track. Moreover, the maximum interior noise level does not always occur at the same time as the maximum exterior level. Therefore, it is difficult to define a single representative location for an artificial source that exposes a building to the same sound field as does an aircraft overflight.

Second, the two effects that modify the sound level as measured at or near the façade are

- the reflection of the sound from the ground that interacts with the direct sound from the aircraft to produce an interference effect that lowers the incident sound level at low frequencies, and

- the reflection of the combined direct and reflected sound at the surface of the façade.

Since the distance of a passing aircraft from the façade is much greater than the distance of a test loudspeaker, the combined effect of these reflections in a loudspeaker test will not necessarily be the same as that for an aircraft overflight. Furthermore, as the aircraft is a moving source, the interference effects will change with time and overall will be less evident than with a stationary loudspeaker.

The ASTM E966-10 [2] guidance contains adjustment factors to account for reflection form the façade surface when using a loudspeaker as the noise source. However, the appropriateness of these adjustments was in question as a result of the noted discrepancy between measurements using aircraft and loudspeakers for the tests. The current study is designed to evaluate the adjustment factors and recommend appropriate alternatives that lead to more consistent and accurate measurement of noise reduction.

2. LITERATURE REVIEW.

Sections 2.1 and 2.2 of this report contain a review of publications related to the measurement of the noise reduction of buildings exposed to aircraft noise, concentrating specifically on the measurement of exterior noise levels produced by aircraft and loudspeaker noise sources. This report focuses on the evaluation of current adjustment factors in the ASTM E966-10 [2] guidance and the need for development of new adjustment factors more suitable for aircraft noise applications.

First, in section 2.1, the relevant standards for measurement of noise reduction are presented. Second, in section 2.2, the published literature is reviewed to identify studies that might assist in resolving the issues noted in section 1. The literature includes a series of recent research studies conducted in the United States (U.S.) that are described and the results evaluated to determine the current state-of-the-art in noise reduction measurement technology for aircraft noise and to understand and quantify the issues related to measurement accuracy. Finally, in section 2.6, conclusions are drawn from the evaluation of the literature and research needs identified. Appendix A presents the recent U.S. noise reduction data sets.

2.1 STANDARDS FOR MEASUREMENT OF OUTDOOR-INDOOR NOISE REDUCTION.

- **ASTM International, "Standard Guide for Field Measurement of Airborne Sound Insulation of Building Façades and Façade Elements," ASTM E966-10, 2010**. [2]

  The increasing interest in providing protection for buildings against the external noise produced by highway traffic and aircraft and in soundproofing existing buildings has led to the requirement for a closely controlled test procedure. In 1984, the ASTM issued the first Standard Guide, ASTM E966-84 [3]. Note that it is a Standard 'Guide' and not a Standard 'Method,' recognizing that there are many different situations that may require different measurement procedures. The original intent of ASTM E966-84 [3] was to measure the sound insulation of individual façade elements as installed in the field. Subsequent versions have since been issued in 1990, 1999, 2002, 2004, and 2010, expanding the intent to measure the insulation of whole façades. The latest version containing additional minor edits was issued in April 2011 [2].

The Standard is designed to provide guidance for the measurement of the outdoor-indoor noise reduction (OINR) of a building façade, defined in the ASTM E966-10 as

> …the difference between the space-time average sound pressure level in a room of a building and the time-averaged exterior sound pressure level which would be present at the façade of the room were the building and its façade not present. [2]

It should be noted that in the most recent version of ASTM E1332-16, "Standard Classification for Rating Outdoor-Indoor Sound Attenuation," [4] the definition of OINR was slightly modified to read

> …the difference between the time-average free-field sound pressure level at the exterior of a façade and the space-time average sound pressure level in a room of a building exposed to the outdoor sound through that façade. [4]

The procedure can be adapted for measuring individual elements of a structure (such as a window) by incorporating appropriate adjustments for flanking sound transmission.

The ASTM E966-10 [2] procedure allows for measurements to be performed using either traffic (highway or aircraft) or a loudspeaker as the sound source. As the range of vertical angles of incidence from aircraft overflights can be large and vary for each noise event, it is recommended that measurements with aircraft noise sources be restricted to components such as roofs, ventilators, and complete structures that cannot be readily tested by other means. For aircraft noise, it is recommended that the integrated average sound level (the sound exposure level, or SEL) of the outdoor and indoor sound pressures be measured.

If a loudspeaker is used as the source, it is recommended that it be placed to provide incident sound at 45 degrees horizontally to the building façade and perpendicular vertically to the façade. Measurements of OINR can also be made at other angles and the values reported at each angle. If the results are used to estimate transmission loss that is to be compared with that measured in a laboratory, a procedure is described for averaging the data at different angles of incidence.

For a room in a building with multiple surfaces exposed to noise, each surface of the room must be measured separately, but the standard does not address how to combine this data to calculate the combined OINR.

The criteria for selecting the distance of the loudspeaker from the building surface is that the variation of sound level across the façade to be tested is not greater than 3 dB. There is no recommendation for the height of the loudspeaker above ground, and so the effect of ground reflection is essentially ignored.

The ASTM E966-10 [2] procedure allows exterior noise level to be measured in several different ways:

(a) A free-field microphone located away from the building is recommended for measurements using aircraft noise as the source. No adjustment to the measured noise level is required. The Standard itself does not specify the height of the microphone above the ground, but in Appendix X1 of ASTM E966-10 [2], which contains nonmandatory information, the "FAA Measurement Method" is described as recommending a height of 3 m (9.8 ft) above the building roof. [5] (In ASTM E966-10 [2], the FAA Method is referenced incorrectly; it should be FAA 1993 [5] and not FAA 1977 [6].)

(b) A microphone flush with the surface of the façade, with the entire microphone diaphragm within 17 mm of the surface provided that the surface is smooth and hard. An adjustment factor of -5 dB is applied to the measured noise level to account for the effect of façade reflection and thus provide an equivalent free-field incident level. In theory, sound pressure doubling would increase the sound level at the surface by 6 dB, but in practice a 5 dB increase has been considered more reasonable.

(c) A near-façade microphone at a distance of 1.2 - 2.5 m from the façade, averaging over at least five random distances from the façade and heights above the ground to minimize the effect of interference between incident and reflected sound waves. An adjustment of -2 dB is applied to the measured noise level to account for reflection from the surface and provide an equivalent free-field level. This method is recommended to be used only when the flush microphone is not feasible.

(d) A calibrated loudspeaker, where the loudspeaker is calibrated in a free-field environment at the same distance to the façade as that at the test site. The calibration site ground surface must be similar to that at the test site. This method together with a flush microphone is quoted in ASTM E966-10 [2] as being the most repeatable method for loudspeaker sources. As no measurements are taken at the façade itself, no adjustment to the measured noise level is required.

In general, measurements using a loudspeaker as the noise source should be taken in one-third octave bands from at least 80 to 4000 Hertz (Hz), and preferably 5000 Hz. For fluctuating noise sources, such as aircraft overflights, the A-weighted[1] exterior and interior noise levels may be measured to calculate the A-weighted noise reduction. However, the measured value of noise reduction is only applicable for the specific aircraft noise spectrum of the test.

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[1] A-weighting refers to a sound pressure level measured with a frequency weighting that roughly approximates how the human ear hears different frequency components of sounds at typical listening levels for speech. The human ear responds more to frequencies between 500 Hz and 8 kHz and is less sensitive to very low-pitch or high-pitch noises.

As no body of experience in the use of this guide exists currently, it is estimated that the repeatability standard deviation of these test procedure is of the order of 2 to 3 dB, depending on frequency.

The ASTM E966-10 [2] Standard includes recommendations for minimum room volume (at least 40 m^3 for measurements at 125 Hz) for measuring outdoor-to-indoor transmission loss (OITL), but makes no recommendations for measurement of OINR.

- **International Organization for Standardization (ISO), "Acoustics—Field Measurement of Sound Insulation in Buildings and of Building Elements—Part 3: Façade Sound Insulation," ISO 16283-3:2016, 2016**. [7]

  In 1998, the ISO established a standard test procedure, ISO 140-5 [8], which is the European equivalent of the ASTM E966-10 [2]. The latest revision of ISO 140-5 issued in 2016 is identified as the ISO 16283-3 [7] Standard and specifies procedures for measuring the sound insulation of individual façade elements (elements method) and whole façades (global method), using either traffic (including aircraft) or a loudspeaker as the noise source. The ISO 16283-3 Standard [7] recommends using a loudspeaker for the element method and actual traffic for the global method as being the most accurate in each case, although procedures for using loudspeakers for the latter are included.

  For measurements using aircraft noise, the noise reduction is specified as the difference between the exterior SEL for an aircraft event measured with a microphone located 2 m (6.6 ft) from the exterior façade surface, and the interior SEL as measured at one indoor position for the event. The height of the exterior microphone should be 1.5 m (4.9 ft) above the level of the floor in the receiving room. No adjustment factor is provided for adjusting the measured noise reduction for an exterior free-field equivalent (as in ASTM E966-10 [2]). It is recommended that measurements be taken for at least five events.

  When using a loudspeaker as the noise source for the global method, it should be placed either on the ground or as high as possible above ground at a distance of at least 7 m (23 ft) and angled at 45 degrees to the façade surface normal. If there is more than one outside façade to a room, then several loudspeaker locations should be used, and the individual measurements of noise reduction averaged on an energy basis. Measurements are to be made in one-third octave bands, from 100 Hz to 3.15 kHz, with an extension down to 80 Hz if information is required at low frequencies.

  The exterior noise measurement for the global loudspeaker method is taken with a microphone located 2 m (6.6 ft) from the exterior façade surface. The height of the exterior microphone should be 1.5 m (4.9 ft) above the level of the floor in the receiving room. No adjustment factor is provided for adjusting the measured noise reduction to an exterior free-field equivalent (as in ASTM E966-10 [2]). The interior noise level should be measured at a minimum of five locations.

As noted above, the ISO 16283-3 Standard [7] does not provide adjustment factors to determine an equivalent free-field OINR as is required to determine eligibility for AIP-funded sound insulation programs.

2.2 REVIEW OF THE PUBLISHED LITERATURE AND DATA SETS.

This section provides a review of what are considered the more important published literature pertaining to the subject of noise fields produced by aircraft and artificial sources at and near the ground and building façades. The papers are presented in chronological order. In general, papers that repeated the results of previous work by authors were not included in this review.

- **Lewis, P.T., "A Method for Field Measurement of the Transmission Loss of Building Façades," March 1974.** [9]

  Lewis describes procedures for measuring the transmission loss of façades for traffic noise sources using a microphone mounted flush with the façade surface. Lewis notes that the expected adjustment factor of 6 dB is valid within 0.5 dB for frequencies up to 3.15 kHz for a rigid surface. If the surface is not rigid, Lewis quotes a modified relationship for the increase in noise level, ΔL, as $20 \log_{10} [2/ (1+ a)]$, where a is the absorption coefficient, which is incorrect and probably a printing error as it does not give the values of ΔL Lewis states in the paper.

  Measurements of the effect of vertical angle of incidence of the exterior sound (in this case traffic noise with a wide range of horizontal angles of incidence) on transmission loss is shown to roughly follow a 10 log ($\cos\theta$) relationship, where θ is the angle relative to normal incidence.

- **Nash, A.P., "Façade Sound Insulation-A Review of Methods," May 1982.** [10]

  This is a short paper summarizing the experience of the author in conducting noise reduction measurements of façades. Nash notes that the generally accepted adjustment factors of 6 and 3 dB (at that time) for flush and near-façade measurements, respectively, are reasonable (±1 dB) only at frequencies greater than 200 Hz. At lower frequencies, these adjustment factors can be significantly in error. Nash also states, without proof, that the angle of incidence of the exterior sound is a significant parameter.

- **Quirt, J.D., "Sound Levels Around Buildings Near Roadways," January 1982.** [11]

  Quirt uses measured data to demonstrate that the increases in A-weighted level of 6 dB and 3 dB for traffic noise are on average appropriate for a rigid, perfectly reflecting surface, although the data does show considerable scatter at low frequencies. Quirt notes that sound absorption by materials such as window glass or wood siding could reduce the amount of the increase by as much as half a decibel.

- **Schumacher, R. and Mechel, F.P., "Comparison of the Different Methods for Outdoor Measurement of the Airborne Sound Insulation of Windows and Façades," 1983.** [12]

  Schumacher and Mechel examine different methods for measuring the airborne sound insulation of windows and building façades using traffic and a loudspeaker as the noise source. Schumacher and Mechel note that measured results can vary over ±5 dB depending on the method used and the measurement parameters, and recommend that the exterior microphone should either be within 5 cm of the surface (with a -6 dB adjustment), or greater than 150 cm from the surface (with a -3 dB adjustment). Both flush and near-façade methods provide the same results as the loudspeaker calibration method, and all three methods agree quite well with laboratory measurements.

- **Quirt, J.D., "Sound Fields Near Building Façades," 1983.** [13]

  Quirt presents data from field tests showing that there is a difference of 3 dB, ± 1 dB, at one-third octave band frequencies greater than 250 Hz, between noise levels from a loudspeaker measured by a microphone mounted flush with the building surface and one at distance of 2 m from the surface. At lower frequencies, the difference deviates from 3 dB due to interference effects. For a line source, such as traffic, the difference is 3 dB, ± 1 dB, for frequencies greater than 100 Hz. Much of the information in this paper is repeated in an additional paper by Quirt [14].

- **Hall, F.L., Papakyriakou, M.J., and Quirt, J.D., "Comparison of Outdoor Microphone Locations for Measuring Sound Insulation of Building Façades," February 1984.** [15]

  Hall et al. present measured data on the differences between microphones mounted flush with, and at 2 m from, a façade exposed to traffic noise. The objective was to determine the best location for the outdoor microphone. Measurements were conducted on a total of 33 houses adjacent to highways. In each case, the outdoor flush-mounted microphone was taped to the outside of the largest window in the room facing the highway.

  The results showed that the difference in level between the flush and the+ 2-m microphones was close to 3 dB in the frequency range from 200 to 2000 Hz, but could be significantly different at lower frequencies. There was also considerable site-to-site variation in the differences between the two microphones, ranging from 1.8 to 4.1 dB; variations that could not be assigned to any other site parameters.

  Hall et al. also demonstrate theoretically that the results do not change significantly if the façade is assumed to be absorptive with an absorption coefficient ranging from 0.2 at frequencies below 160 Hz to 0.04 above 1 kHz.

- **Quirt, J.D., “Sound Fields Near Exterior Building Surfaces,” February 1985.** [14]

  In this paper, Quirt presents a simple analytical model based on previous work by Waterhouse [16] to predict the sound field near exterior building surfaces together with laboratory measurements using a flush-mounted microphone in a hemi-anechoic chamber to validate the results. The model results agree well with the measurements at single frequencies between 2 and 5 kHz, and demonstrate the rapid variation of sound level with distance ranging from 0.1 to 1 wavelength from the surface. Quirt shows how important it is for the microphone to be mounted within 0.1 wavelength from the surface in order to replicate the sound levels measured by a true flush-mounted microphone.

  Results from the model also agree with measurements at different distances from the surface and at different angles of incidence for one-third octave bands of noise. Quirt demonstrates the complementary feature of incidence angle and microphone-to-surface distance, namely that increasing the angle of incidence moves the minima of the interference pattern further from the surface. He notes that the changing interference pattern from a moving source, such as an aircraft overflight, results in a changing relationship between incident wave and the sound level measured at a distance from the surface.

  In outdoor field measurements, Quirt demonstrates the variations in sound level that occur when loudspeaker and/or microphone positions are changed. Quirt attributes these variations to changes in the path length difference between the direct and ground-reflected waves and the resultant changes in the interference patterns, concluding that several microphone positions may be required to accurately determine the average exterior sound level over the façade surface.

  In the analytical model Quirt prepared, it is assumed that the reflecting façade surface is perfectly rigid with a reflection coefficient of 1. However, calculations show that the sound level near the façade surface is affected by less than 0.5 dB even with relatively high absorption surfaces (reflection coefficient of 0.8 at low frequencies).

  Additional field measurements show that diffraction fringes at the corners of buildings do not noticeably affect the frequency dependence of the measured sound levels on the building surface, and that any variations noted at different microphone positions are the result of changes in ground reflection.

  The results of the field tests demonstrate that for a distributed source, it is reasonable to assume sound pressure doubling at the façade surface and energy doubling 2 m from the surface, at frequencies greater than 100 Hz. The corresponding adjustment factors of -6 and -3 dB, respectively, can be applied to obtain an equivalent sound level as measured in the free-field. However, it is noted that the relationship between incident and reflected waves is altered for a point source, such as a loudspeaker, with the implication that these adjustment factors might not be so certain at low frequencies.

- **Jonasson, H.G., and Carlsson, C.A., "Measurement of Sound Insulation of Windows in the Field," Swedish National Testing Institute Report SP-RAPP 1986:37, 1986**. [17]

  Jonasson and Carlsson measured the transmission loss of windows using a loudspeaker to produce incident sound at different angles of incidence. Jonasson and Carlsson found only small differences in transmission loss at angles from 45 to 60 degrees and recommended using 45 degrees as an average value.

  The effect of loudspeaker height was studied for the measurement of transmission loss of a window of size 2 m. by 2 m. Two loudspeakers were used at a distance of 5 m (16.4 ft) from the surface of the window. One loudspeaker was mounted flush with the ground, the other mounted at a height of 2.9 m (9.5 ft). The variation of noise level over the surface of the window on the ground floor was significantly less for the loudspeaker mounted on the ground than when it was raised above ground, largely due to the effect of ground interference with the raised loudspeaker. As a result, Jonasson and Carlsson recommended using a loudspeaker mounted on the ground to eliminate the influence of ground reflection interference.

- **Bradley, J.S., Lay, K., and Norcross, S.G., "Measurements of the Sound Insulation of a Wood Frame House Exposed to Aircraft Noise," IRC IR-831, November 2001.** [18]

  In this paper, Bradley et al. describe a major study on sound insulation design and measurement conducted as a component of National Research Council Canada's Insulating Buildings Against Noise from Aircraft (IBANA) project and the development of the IBANA-Calc sound insulation software designed to predict the sound reduction of various building types. The first few chapters describe field experiments on a single residence with many variations of façades, windows, vents, etc., the results of which were incorporated into the IBANA-Calc software program. The subsequent chapters of the paper discuss the effects of angle of incidence in loudspeaker tests and variations in façade effects, which were of interest for this study.

  A series of noise reduction measurements were conducted using both aircraft and a loudspeaker as the source. The loudspeaker tests were conducted with the source at various heights (1.8 m, 4.8 m, and 7.8 m) above the ground and at various angles of incidence (30, 60, 90 degrees) to the façade surface. Comparing the average measured values of noise reduction with those measured with aircraft showed that the latter were 1 to 5 dB greater in the frequency range 200 to 500 Hz. Moreover, the noise reduction measured with an elevated loudspeaker was 1 to 5 dB greater than that with a lower loudspeaker, and more similar to the aircraft measurements over this same frequency range. Bradley et al. note that the noise reduction varied most with angle over the frequency range 200 to 500 Hz and imply that this may be due to the mass-spring-mass resonant frequency of the façade that lies in this range.

It should be understood that Bradley et al. measured aircraft noise reduction as the difference between exterior incident noise levels measured by a microphone 8.5 m (27.9 ft) above the ground and the interior levels inside the building. Ground effects in the frequency range of interest should be minimal at this height. In the U.S., the exterior noise level is generally (and correctly for AIP determination of eligibility, see section 2.3.1) measured by a microphone 1.2 m (3.9 ft) above the ground. As a result, the ground effect is included in exterior levels measured in the U.S., whereas it is not in the Canadian measurements. This difference in procedure may explain some of the variations noted by Bradley et al.

Measurements of noise levels produced by an aircraft with microphones mounted flush with the façade surface and positioned 2 m from the surface showed average increases of 4 and 1.5 dB respectively compared to the incident wave noise level over the frequency range 125 to 500 Hz, rather than the anticipated 6 and 3 dB. Increases of 5 dB for flush measurements were noted only at 630 Hz and above, and increases of 2 dB only above 1.25 kHz. At low frequencies (below 100 Hz), the increases were much lower and sometimes negative. Bradley et al. attribute this result to a combination of destructive interference between the direct and ground-reflected sound paths, and diffraction of sound energy from the edges of the finite-sized façade.

To test the hypothesis that diffraction is causing variations in façade measurements, Bradley et al. measured the difference between façade and free-field (8.5-m-high) noise levels from a number of aircraft overflights at different vertical angles of incidence. Bradley et al. show that the difference in levels is almost the expected 6 dB at low angles of incidence, but decreases significantly at higher angles, being negative at very low frequencies. These results also include the effect of ground reflection, and it is not quite clear from this data whether the variations are entirely due to diffraction effects. Bradley et al. conclude by stating,

> Measurements of sound insulation in the field that use a façade microphone to assess the incident sound energy and that assume a 6 dB increase at the façade will underestimate the incident sound energy and the calculated noise reductions. [18]

However, the underestimate may be less when the incident noise level is measured at a height of 1.2 m and therefore already includes the ground-refection effects.

Bradley et al. also conducted laboratory tests on a 1:4 scale model façade in an anechoic room using a small loudspeaker at varying vertical angles of incidence. Since the anechoic room did not have any floor surface, ground reflections were not simulated, and the results showed significantly less variation with vertical angle of incidence than they did with aircraft noise measurements. Variations in vertical angle of incidence, β, seemed to influence the difference between façade and free-field levels according to a $\cos \beta$ relationship. Bradley et al. state,

> Only at angles close to normal incidence and at higher frequencies do the differences approach the simple 6 dB expectation. [18]

Bradley et al. then examine how these variations in façade levels may affect the measurement of noise reduction, which will not be affected by both ground reflections and diffraction. Bradley et al. note that for a passing aircraft the horizontal angle of incidence varies throughout the overflight, and the vertical angle does not vary much for a single flight. Thus, the effects of angle of incidence will be averaged. Data analysis from many of the overflights appear to validate this assumption, and Bradley et al. conclude that there is only "weak evidence to support the expected variation with vertical angle of incidence." [18]

In conclusion, Bradley et al. recommend that flush and near-façade microphones should not be used to measure the incident aircraft noise levels used in calculating noise reduction.

Overall, this paper provides valuable data on the sound fields near building surfaces, but it suffers from some inconsistencies regarding exterior sound fields, the associated noise reduction, and the effects of angle of incidence and diffraction are inconclusive.

- **Bradley, J.S. and Chu, W.T., "Errors When Using Façade Measurements of Incident Aircraft Noise," August2002.** [19]

Much of the information in this paper repeats the findings of Bradley et al. [18], but it includes calculations on the effect of ground reflections on noise levels measured at different heights on the building surface showing that the frequency at which destructive interference occurs is reduced as the microphone height is increased. This result leads the authors to suggest that measurements on ground floor rooms should be avoided.

- **Butikofer, R. and Thomann, G., "Aircraft Sound Measurements: The Influence of Microphone Height," September/October 2005.** [20]

This paper discusses the effect of microphone height and ground reflections on the measurement of noise levels produced by jet and turboprop aircraft. For jet aircraft, the A-weighting corrections effectively diminish the contribution of noise at frequencies lower than about 250 Hz. Note that this does not necessarily mean that frequencies lower than this rate are unimportant in measuring noise reduction. This situation is often different for turboprop aircraft, which is more tonal and levels increase in the low frequencies.

The effect of ground reflections is to produce interference that in turn reduces noise levels at low frequencies. The frequency range where this occurs depends on the microphone height above ground. Microphone measurements at 10 m are less likely to exhibit destructive interference effects at low frequencies than measurements at a height of 1.2 m. The lower the microphone height and the lower the angle of incidence, the more modified is the spectrum at low frequencies and the lower are the measured sound levels.

- **Ismail, M.R. and Oldham, D.J., "A Scale Model Investigation of Sound Reflection From Building Façades," February 2005.** [21]

  The authors review the extent of scattering of sound upon reflection from a façade relative to the normally assumed specular reflection. From experiments conducted on scale-models, the measured value of the scattering coefficient is found to be small and not very sensitive to the degree of surface irregularity. They conclude that prediction models based upon specular reflections might be more appropriate for near field situations in which the direct sound and early reflections dominate.

- **Davy, J.L., "A Model for Predicting Diffraction on a Finite Flat Surface as a Function of Angle of Incidence and Surface Size," August2007.** [22]

  A model was developed to predict the reflection directivity of finite-sized panels, which are excited by sound, including the effect of diffraction due to the finite size of the baffle in which the panel is mounted. Experiments were then conducted to determine the diffraction effect at a point on the rigid surface with sound incident from a specified direction to the normal. It was found that the presence of the baffle doubles the sound pressure provided the baffle is bigger than a limit size, which depends on the wavelength, and provided the angle of incidence or radiation is less than a limit angle, which depends on the ratio of the baffle size to the wavelength. Essentially, this means that diffraction effects are negligible at frequencies greater than c/4L, where c is the speed of sound, and L is the dimension of the panel. In terms of typical façades, this frequency is below the range of interest for sound insulation measurements.

- **Freytag, J.C. and Reindel, E.M., "Noise Level Reduction Measurement Method for Sound-Insulated Structures," July 2008.** [23]

  The authors describe different methods for measuring noise reduction of residences participating in airport sound insulation programs and note that the results typically vary by several decibels among events using aircraft overflights. A comparison of the aircraft and loudspeaker measurement methods conducted on a single room showed a difference of 1.1 dB. It is concluded that the aircraft method simulates the experience of the occupants, whereas the loudspeaker method may provide a better measurement of the noise reduction properties of the façade.

- **Hopkins, C. and Lam, Y., "Sound Fields Near Building Façades - Comparison of Finite and Semi-Infinite Reflectors on a Rigid Ground Plane," February 2009.** [24]

  In this paper, Hopkins and Lam develop a simple analytical model of the sound field in the vicinity of a semi-infinite façade produced by a point source, and they compare the results with measurements conducted on a scale model of a finite façade constructed in a semi-anechoic chamber. The analytical model included contributions from the direct propagation path from the source to the receiver, the ground reflected path, and the reflection of both from the building façade. The objective of the study was to identify the frequency range where diffraction effects need to be taken into account in conducting sound insulation measurements.

Exercising the analytical model showed that for a point source located 14.5 m (47.6 ft) from the surface of a semi-infinite surface (infinite width and height above the ground) the sound levels measured at microphones positioned 1 and 2 m from the surface were approximately 2 dB above that of the incident wave level at frequencies greater than 315 and 160 Hz, respectively. This result is taken directly from figure 4 of the published paper. In the text, the authors say that energy doubling, which is 3 dB above the incident wave level, is a reasonable estimate above these frequencies.

Laboratory tests were then conducted on 1:5 scale models of finite surfaces of different dimensions in a semi-anechoic chamber with a concrete floor and the results compared to the analytical model predictions to determine the limiting frequency above which diffraction effects could be ignored. For surface dimensions of 4 by 4 m (13.1 by 13.1 ft), the comparisons showed that the limiting frequencies were approximately 125 and 63 Hz for microphones positioned 1 and 2 m, respectively, from the façade surface. The limiting frequencies were lower for larger façade surfaces.

The authors conclude that for typical façade dimensions, diffraction effects can be considered as negligible above 100 Hz, but that energy doubling may not always be valid at low frequencies.

- **Berardi, U., Cirillo, E., and Martellotta, F., "Measuring Sound Insulation of Building Façades: Interference Effects, and Reproducibility," June 2010.** [25]

  Much of the information in this paper is repeated in reference 26, with some corrections made to the data presentation.

- **Berardi, U., Cirillo, E., and Martellotta, F. "Interference Effects in Field Measurements of Airborne Sound Insulation of Building Façades," March 2011.** [26]

  Berardi et al. investigate the effect of microphone position on measurements of sound insulation by developing a simple model and validating it through laboratory and field experiments. The model predicts the sound level at and near a façade from a point source, including the direct and ground-reflected paths of propagation, and the reflection of both from the façade surface. Applying the model to a configuration with a microphone positioned between 1.8 and 2.2 m from the façade clearly shows the destructive and constructive interference at the correct frequencies. The predicted increase in level due to the presence of the façade shows periodic peaks and dips resulting from these interferences, but approximates to 2 dB at frequencies greater than 400 Hz. At lower frequencies, the predicted increase varied widely over a range +2 to -8 dB. The microphone and loudspeaker heights in this case were 1.5 and 0.22 m, respectively, so that the effect of interference from ground reflections occurred at much higher frequencies.

Field measurements with the same loudspeaker-microphone configuration showed slightly different results, although the trends with frequency were similar. For microphone placements at distances ranging from 1.8 to 2.2 m from the façade, and with the loudspeaker angled at 45 degrees, the increase in level due to the presence of the façade was on average 1.5 dB at frequencies between 200 and 800 Hz. At higher frequencies, the increase varied from +4 to 0 dB. At lower frequencies, the increase varied in the range 4 to -4 dB due to interference between different propagation paths. When the loudspeaker angle was varied ±5 degrees, the increase in level 2 m from the surface varied by ±1 dB over much of the frequency range up to 1 kHz, and ±2 dB at higher frequencies.

Measurements of the difference in level measured at microphones flush with the surface and at a distance of 2 m show noticeable deviations from the expected 3 dB (either 6 - 3, or 5 - 2) implied in ASTM E966-10 [2]. The average difference is about 2 dB over the frequency range 125 Hz to 4 kHz, but at intermediate frequencies there are variations of ±2 dB. At 63 Hz, the difference is between 4 and 8 dB depending on the angle of incidence.

The authors conclude that the effect of reflections from the façade of both the direct and ground reflected paths produce increase in level differing substantially from the expected 6 and 3 dB, and must be considered in the measurement of sound insulation.

- **Olafson, S., "Sound Insulation Measurements of Façades With Variable Microphone Positions," September 2011.** [27]

  The author demonstrates the theoretical effect of reflections from a façade and shows the results of field tests. The tests were conducted on a balcony window and show strange results where the levels measured near the window are greater than those at the window surface. It is difficult to draw specific conclusions from this data other than to note the complexity of measurements at such locations.

- **Berardi, U., "The Position of the Instruments for the Sound Insulation Measurement of Building Façades: From ISO 140-5 to ISO 16283-3," January 2013.** [28]

  In this paper, Berardi reviews the procedures for measuring the sound insulation of façades, and in particular, the relative positioning of the loudspeaker and microphone with respect to the façade. One suggestion for improving the accuracy of the measurements is to reduce the distance from the loudspeaker to the façade in order to move the frequency at which ground reflection occurs to a frequency below the range of interest. Another suggestion is to increase the distance from the microphone to the façade, which reduces the frequency at which interference from the façade reflection occurs.

  The author also stresses the importance of measuring the external noise level at a number of positions on the façade and at a number of distances from the façade in order to average out the interference effects for both ground and façade reflections.

- **Landrum & Brown, Inc. (L&B) "Study of Noise Level Reduction (NLR) Variation," April 2013**. [29]

  This report describes the results of field measurements of NLR in two rooms at each of six houses located adjacent to the runway at Burlington International Airport (BTV). The objective of the study was to identify possible causes of variation in NLR as measured by different test methods. A comprehensive set of measurements were conducted using both jet aircraft and loudspeakers as the noise sources.

  Aircraft noise sources consisted of mostly departures at a low altitude with low elevation angles. Typically, 8 to 15 events were measured. The exterior microphone for these operations was mounted on a tripod of height 4 ft located 20 ft from any reflecting surfaces. Interior noise measurements were taken by two fixed microphones located at least 4 ft from any room surface.

  Measurements using a loudspeaker as the source were conducted for several different configurations with the loudspeaker mounted on a tripod and elevated on a crane, at 25 and 50 ft from the exterior façade surface, and with sound incident at 30, 45, and 60 degrees to the normal. The tests were conducted using pink noise (equal sound energy in each frequency band) and measurements of noise level were taken in octave bands from 63 to 8000 Hz. Exterior noise levels were measured flush with the façade surface and at a distance of 4 ft from the surface. Adjustments of -5 and -2 dB, respectively, were applied to the measured levels to provide an equivalent free-field, incident, noise level. The exterior levels represented spatial averages over five locations on the façade surface. Interior noise levels were measured by a spatial average throughout the center of the room.

  The main conclusions from the study are summarized as follows:

  – Measurement of noise reduction in the 63 and 8000 Hz octave bands have minimal effect on the A-weighted NLR.

  – Values of NLR measured using aircraft as the source are almost always greater than those with a loudspeaker, with a median difference of 2.1 dB.

  – When the appropriate adjustments are applied, measurements of NLR using a flush-mounted microphone on average are within 0.1 dB of those measured at a distance of 4 ft from the façade surface.

  – Values of NLR measured with an elevated loudspeaker are on average 1.6 dB greater than with the loudspeaker on a 4-ft tripod.

  – The NLR measured with incident sound at 30 and 45 degrees is on average 0.7 and 0.1 dB, respectively, greater than that measured for 45-degree incidence.

– The NLR measured with the loudspeaker at 25 and 50 ft from the façade surface are essentially the same, although a more even distribution of sound over the façade surface was obtained at the larger distance.

– Removing acoustic absorption from the room interior reduced the measured NLR by 2.8 dB.

The report discusses the many reasons for variation in measured NLR that are related to aircraft types, operations (departures or arrivals), flight path, artificial source location, exterior and interior microphone placement, and room absorption. It is noted that since flight paths are well defined and do not generally change, this may not be a significant cause of variations in measured NLR when using aircraft as the source.

The main recommendations for additional study are as follows:

– Tests to quantify the difference between measurements using aircraft and loudspeakers as the noise source.

– A detailed comparison of measurements at different external microphone locations when measuring NLR with aircraft and loudspeakers as the source.

– The evaluation of external and internal spectral data as a function of time to explain variations in measured NLR with aircraft as the source.

– An evaluation of loudspeaker noise source height.

A detailed evaluation of the data in this report, combined with data from other recent studies, is presented in sections 2.4 and 2.5.

- **Wyle, Unpublished Data Set of Noise Reduction Measurements Conducted at Westfield Airport, September 2013**. [30]

NLR was measured in 11 rooms located in two houses exposed to the noise from departing military F-15 jet aircraft; these measurements were then compared to the values of NLR measured using a loudspeaker as the noise source. The tests were conducted with the loudspeaker 25 ft from the façade surface at an angle of incidence of 45 degrees and heights of 6, 12, and 25 ft. The NLR for the loudspeaker tests was calculated using the measured F-15 noise spectrum. The exterior noise levels for aircraft were measured by a single microphone 4 ft above the ground surface and located away from any reflecting surfaces. Exterior measurements of the loudspeaker noise levels were taken with a microphone equipped with a windscreen mounted flush with the façade surface, such that the center of the microphone was 1.5 inches from the surface. An adjustment of -5 dB was applied to the measured levels to account for façade reflection. Interior noise levels were measured employing a 30-second manual scan in the center area of each room. With the exception of the kitchen areas, all rooms were fully carpeted but contained no furniture.

A summary table of the data is included in appendix A. A detailed evaluation of the data in this report, combined with data from other recent studies, is presented in sections 2.4 and 2.5.

- **Corlett, Skaer, and DeVoto Architects (CSDA), Unpublished Data Set of Noise Reduction Measurements Conducted at General Mitchell International Airport, June 2015.** [31]

  As part of an AIP-sponsored, sound-insulation program at General Mitchell International Airport (MKE), a limited series of loudspeaker measurements were conducted for varying angles of incidence together with exterior microphones flush mounted at several locations on the façade surface and at 1 m from the surface. Adjustments of -5 and -2 dB, respectively, were applied to the measured levels to provide an equivalent free-field, incident noise level. The loudspeaker was located 25 ft from the façade at a height of 6 ft.

  The resulting data showed little variation of NLR with angle of incidence, although significant variations in the spectra were noted at different exterior locations on the façade. A summary table of the data is included in appendix A. A detailed evaluation of the data, combined with data from other recent studies, is presented in sections 2.4 and 2.5.

- **Robert, R.J., "Measuring Noise Level Reduction Using an Artificial Noise Source," December 2015.** [32]

  Robert describes a series of noise reduction measurements conducted on a test house constructed outdoors on the Georgia Institute of Technology campus. The exterior noise source used was a loudspeaker mounted on a tripod at heights of 3, 5, and 7 ft, and on a man-lift at heights of 15, 20, and 30 ft, at angles of incidence to the façade ranging from 0 to 75 degrees of the normal. The exterior noise levels were measured at six positions flush with the wall of the façade, and at six random positions 1.2 to 2.5 m from the façade at three different heights. Interior levels were measured at six locations. A sample of five microphone locations were randomly selected for both the interior and exterior locations to calculate the noise reduction for fixed flush and near–façade measurements. The exterior noise levels were also measured by sweeping the microphone slowly across the surface of the façade while maintaining an approximate sinusoidal motion upholding a distance of about one meter from the façade.

  The test house façade included a single 3 by 5 ft window that was modified to allow testing of two different windows of sound transmission class (STC) 25 and 31 under closed, half-open, and open conditions.

  The results of the tests showed that the exterior flush microphone method provided the most repeatable results. The moving microphone method was less repeatable with more variation from measurement to measurement since it introduces a human element to the measurement.

  In terms of measured noise reduction, the moving microphone method that averages the exterior level over the surface of the façade produced values about 1 dB less than the fixed flush and near-façade methods, possibly due to an incorrect adjustment factor. Overall, the author found that changes in noise reduction were observed across all of the measurement configurations, but the data did not exhibit consistent angular dependency. It was concluded that an artificial noise test method may be better suited for comparative rather than absolute measurements of noise reduction.

- **Bajdek, C.J., Cox, J.E., Mentzer, R.C., Nicholas, B.L., and Reindel, E.M., "Review and Evaluation of Aircraft Noise Spectra used to Estimate Noise Level Reduction for Airport Sound Insulation Programs based on the Loudspeaker Test Method," Harris, Miller, Miller, and Hanson, Inc. (HMMH) Report No. 305220.008, February 2016.** [33]

  When a loudspeaker is used as the noise source to measure noise reduction the result is normally provided in one-third octave or octave bands. The spectrum of the noise is not important as long as the levels in each frequency band are greater (by 5 to 10 dB) than the ambient levels both outside and inside the building. However, to present the NLR in terms of a single A-weighted number, it is necessary to define the spectrum of the exterior noise. This report presents different ways by which this spectrum can be defined, and makes recommendations for both interim (immediately implementable) and long-term (incorporation into Aviation Environmental Design Tool (AEDT)) approaches. Data is included in octave bands for the noise reduction (NR) of a large number of residences at two airports, together with representative measured exterior noise spectra.

- **Robert, R., Cunefare, K.A., Ryherd, E., and Irizarry, J., "Measuring Noise Level Reduction Using an Artificial Noise Source and Test House," 2016**. [34]

  This presentation replicates the information and conclusions contained in reference 32.

- **Schomer, P., Freytag, J., and Waldeck, R., "Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs," Airport Cooperative Research Program (ACRP) Report 152, 2016.** [35]

  This report describes a study conducted to gain understanding of the factors that lead to differences between measurement methods used to determine the noise reduction of residences exposed to aircraft noise, and to minimize the inaccuracies in these methods. The study evaluated three measurement methods using exterior noise sources (as well as two methods using interior sources and two calculation methods), namely:

  – Aircraft overflight

  – Exterior ground-level loudspeaker

  – Exterior elevated loudspeaker

  NLR was measured in 2 rooms at each of 12 residences (10 in San Diego, 2 in Boston) using each method listed above employing exterior noise sources. The exterior noise level measurement with aircraft as the noise source was made with a microphone mounted on a tripod 2 m (6.6 ft) above the ground in an area free from reflections from other buildings. According to the report, an adjustment factor of -2 dB was applied to the measured exterior levels from aircraft to account for ground reflection.

The tests using a loudspeaker used pink noise[2] as the noise source with measurements conducted in one-third octave bands from 50 to 5000 Hz. The loudspeaker was mounted on a tripod 1.8 to 3 m (5.9 to 9.8 ft) above the ground at a nominal distance of 10 m (32.8 ft) from the façade surface and angled horizontally at 45 degrees. Additional tests were conducted with a loudspeaker elevated to 20 to 25 ft. The exterior noise level was measured by a microphone scan across the surface of the test façade at a distance of 1 to 2 m (3.3 to 6.6 ft). An adjustment factor of -2 dB was applied to the measured exterior level to provide an equivalent free-field, incident noise level. Interior noise levels were measured using a spatial scan in the center of the room. A-weighted values of NLR were calculated using a measured aircraft overflight noise spectrum.

The main conclusions from the study can be summarized as follows:

– There is decent agreement between aircraft and loudspeaker measurement methods, but only after 2 dB is subtracted from the NLR measured using aircraft as the source.

– Tests performed with a loudspeaker mounted on a tripod underpredict the NLR measured with aircraft.

– Discrepancies may be due to differences in angle of incidence and shielding of aircraft noise in some rooms by the house structure itself.

– The measured NLR consistently decreased by about 1 dB for both ground-level and elevated loudspeakers with the exterior level at 1-2 m averaged over the façade and roof as compared to averaging over the façade only.

– Difficulties were encountered in positioning of the loudspeaker and gaining access to suitable locations.

A summary of the test results combining both aircraft and loudspeaker sources taken directly from the report is presented in appendix A. A detailed evaluation of the data in this report, combined with data from other recent studies, is presented in sections 2.4 and 2.5.

[2] Pink noise is a signal with a frequency spectrum such that the power spectral density (energy or power per Hz) is inversely proportional to the frequency of the signal. In pink noise, each octave (halving/doubling in frequency) carries an equal amount of noise power.

2.3 SUMMARY OF CURRENT TECHNOLOGY FOR MEASUREMENT OF NOISE REDUCTION.

This section presents a summary of the current technology for the measurement of sound insulation in residential buildings exposed to aircraft noise, based on the articles, reports, and recent data sets described in section 2.2.

2.3.1 Measurement of Noise Reduction for AIP-Funded Sound Insulation Programs.

According to the Program Guidance Letter PGL 12-09 [36] relating to the General Requirements for AIP funding of Noise Insulation Projects [1], a residence is eligible to participate in the project if the interior noise level from aircraft noise is equal to or exceeds a DNL of 45 dB. The eligibility process involves measuring the NLR of the building façade and subtracting the value from the exterior DNL, as calculated by the FAA's Integrated Noise Model INM/AEDT software program, to determine the interior DNL. The INM/AEDT program calculates the DNL using the certified aircraft noise levels, as measured by the aircraft manufacturer according to the procedures defined in Title 14 Code of Federal Regulations, Part 36, Subpart B, Subsection 36.101 Appendix A [37], in which aircraft noise levels are measured by a microphone 1.2 m (3.9 ft) above the ground in an area free from reflecting surfaces. Thus, it can be assumed that the DNL calculated by INM/AEDT represents the noise level at a point 1.2 m above the ground [38].

The NLR of a building façade exposed to a noise source is defined as the difference between the free-field sound pressure level that would exist at the exterior of a building façade if the building and façade were not present, and the sound pressure level in the room behind the façade. In this case, the exterior free-field level is a measure of the sound incident on the façade. The value of NLR will depend on where the outdoor and indoor noise levels are measured. For the eligibility process to be consistent with the calculation of DNL, the incident exterior noise level used to determine the NLR of the façade for an aircraft overflight is the level measured at a point 1.2 m above the ground, in the close vicinity of the building, but in an area free from reflecting surfaces. The interior noise level should be a measure of the average over the center of the room.

The NLR of a façade should not be confused with the transmission loss (TL) of the façade, which is defined as the fraction of incident sound energy that is transmitted through the façade and into the interior. The TL is a function of the façade structure alone, regardless of its surroundings. The NLR is the difference in sound levels on either side of the façade in the specific surroundings of the building of which it is a part.

For a building in a location where there are no nearby reflecting surfaces, the free-field aircraft noise level measured using this 1.2-m microphone is essentially the same as the level of the incident sound at 1.2 m on the façade under test, and includes both direct and ground-reflected paths. In practice, however, there are often nearby buildings with reflecting surfaces and overhangs that modify the characteristics of the sound incident on the façade. It is important to note that these effects influence the interior noise level in the building, and hence are included in the measured and reported noise reduction of the façade for aircraft overflights. Note also that there are no issues related to the application of adjustment factors for different exterior microphone locations since the exterior levels are taken well away from the influence of reflections from the façade and hence represent the incident sound level.

As noted in section 1, this measurement precisely simulates the noise exposure experienced by residents of the building, and hence the measured noise reduction can be considered the gold standard or true value to which measurements using other procedures should be compared.

Measurements of the noise reduction of a façade using a loudspeaker as the source are made with an exterior microphone mounted either flush with the surface of the building façade or at a distance 1 to 2 m from the surface. The loudspeaker is typically mounted on a tripod of nominal height 6 ft at a distance of 25 ft from the façade surface, and angled at 45 degrees horizontally to the center of the façade. As with measurements using aircraft as the source, the incident sound level includes contributions from the direct path from the loudspeaker and the path reflected from the ground surface. However, in this case, the measured exterior level also includes contributions from these two paths as reflected by the façade. These contributions must be subtracted by applying an adjustment factor to determine the level of the incident sound alone that is used to calculate noise reduction.

If the façade is rigid and infinite in size, the noise level at the façade surface is theoretically 6 dB greater than the level of the incident sound; this phenomenon is known as sound-pressure doubling. At a distance of 1 to 2 m from the façade surface, the increase in level is not deterministic, as it depends on the angle of incidence of the sound and the exact distance of the loudspeaker from the façade. On average, the increase is about 3 dB; this phenomenon is known as energy doubling.

The adjustment factors of -6 and -3 dB were incorporated in all ASTM E966 Standard Guides issued up to and including ASTM E966-04 [3]. Subsequent versions of the ASTM E966 changed the adjustment factors to -5 and -2 dB, respectively, based on field measurements conducted by Bradley et al. [18 and 19] using aircraft noise as the source. The ASTM E966-10 Guide [2] recommends that these adjustment factors are to be applied to the measured exterior levels in each frequency band when measuring noise reduction using a loudspeaker.

With the loudspeaker method, measurements are conducted using pink noise, and the exterior and interior noise levels measured in octave or one-third octave bands. The difference between the exterior and interior levels is the noise reduction (NR) of the building in each frequency band. These values are then applied to an outdoor aircraft noise spectrum to determine the A-weighted noise reduction (NLR), which is subtracted from the calculated exterior DNL to estimate the interior DNL.

<u>2.3.2 Frequency Range of Interest</u>.

In conducting sound insulation measurements, consultants usually measure noise reduction in one-third octave or octave bands over the range 63 to 5000 Hz, in some cases up to 8000 Hz. The ASTM E966-10 Guide [2] specifies a range of at least 80 to 4000 Hz. In conducting research into measurement methods, it is preferable to measure over this full range, but in evaluating the benefits of different measurement methods, it is important to identify the frequency range over which the data at the different frequencies contribute most to the overall A-weighted noise reduction.

For a typical jet aircraft noise spectrum combined with a low value of façade noise reduction, there are negligible contributions to the A-weighted noise reduction (NLR) at frequencies above 2000 Hz. At the other end of the frequency scale, the contributions from frequencies below 100 Hz are also usually minimal. Furthermore, within the frequency range 100 to 2000 Hz, the major contributions to the A-weighted noise reduction are from frequencies in the range 125 to 1000 Hz, termed the frequency range of most interest. For turboprop aircraft, the frequency range of interest may extend down to 63 Hz.

2.3.3 Ground and Façade Interference Effects.

As noted in section 2.3.1, the incident noise level at a façade exposed to noise from an aircraft or a loudspeaker includes contributions from the direct transmission path from the source and from a path reflected from the ground surface. The overall level at any given measurement point will depend on the relative phases of the two contributions, which in turn are related to the differences in their path lengths from the source to the measurement point. If the path length difference is an odd number of half-wavelengths, the sound waves will be out of phase, resulting in destructive interference and a reduction in the sound level [14 and 16]. The lowest frequency, f_{g1}, at which the first destructive interference occurs, depends on the height of the source and receiver and the distance between them. Additional destructive interferences will occur at odd multiples (3, 5, etc.) of f_{g1}, but they will be less pronounced as the coherence between the sound travelling over the two paths decreases with increasing path length difference.

Table 1 shows the values of f_{g1} as a function of source and receiver microphone heights. The center columns of the table show data for a loudspeaker-to-microphone distance of 25 ft, as is common for most loudspeaker measurements of noise reduction. The far right column shows the value of f_{g1} for aircraft overflight heights of 500 and 1000 ft and a horizontal flight path distance of 500 ft. The shaded area in the table identifies frequencies of the first minimum lying below the main frequency range of interest in sound insulation measurements.

Note that the frequency of the first destructive interference is reduced as the microphone or source height is increased. For a microphone height of 6 ft, raising the source from 6 ft to 18 ft decreases the frequency from 207 Hz to 81 Hz, thus moving it to below the most important frequency range for noise reduction measurements. Also, this interference frequency is more sensitive to changes in configuration parameters for a nearby loudspeaker than for a more distant aircraft.

Table 1. Frequency at Which Lowest Destructive Ground Interference Effect Occurs for Loudspeaker and Aircraft Noise Sources

Microphone Height (ft)	Loudspeaker Height (ft)										Aircraft Height (ft)	
	3	6	9	12	15	18	21	24	27	30	500	1000
3	794	405	279	218	183	161	147	136	128	123	133	105
6	405	207	142	111	93	81	74	68	64	61	66	53
9	279	142	97	75	63	55	50	46	43	41	44	35
12	218	111	75	58	49	42	38	35	33	31	33	26
15	183	93	63	49	40	35	31	29	27	25	27	21
18	161	81	55	42	35	30	27	24	23	21	22	18
21	147	74	50	38	31	27	24	21	20	19	19	15
24	136	68	46	35	29	24	21	19	18	17	17	13
27	128	64	43	33	27	23	20	18	16	15	15	12
30	123	61	41	31	25	21	19	17	15	14	13	11

Note: Loudspeaker distance to microphone = 25 ft; aircraft distance to microphone = 500 ft.

Although not shown in table 1, the destructive interference for a given source height will occur at higher frequencies as the source-to-microphone distance is increased. For example, for source and microphone heights of 6 ft, the frequency will increase from 207 to 397 Hz as the source-to-microphone distance is increased from 25 to 50 ft.

The effect of ground reflection interference is shown in figure 1, which is a plot of the noise spectra measured at three heights (3, 6, and 9 ft) above the ground by microphones flush with a façade exposed to noise from a 6-ft loudspeaker at a distance of 30 ft at a 45-degree angle [31].

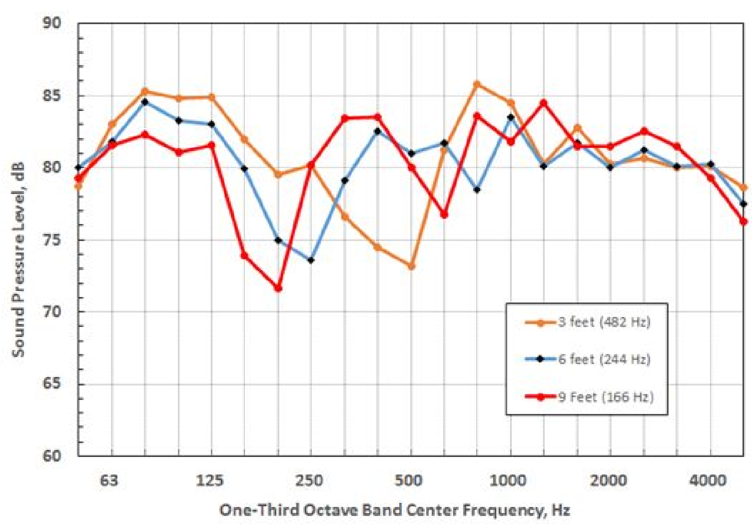


Figure 1. Comparison of Sound Pressure Levels Measured Flush With a Façade at Three Heights Above the Ground

In figure 1, the predicted lowest frequencies of destructive interference shown in the legend correspond to the dips in the spectra at low and medium frequencies. It is important to note that there is a significant spatial variation in noise level measured over the height of a typical residential façade for any given loudspeaker height—a variation that results in noise reduction from 25.4 dB for an exterior measurement at 3 ft to 28.8 dB at 9 ft [31]. For this reason, ISO [7] and Jonasson and Carlsson [17] recommend mounting the loudspeaker at ground level or elevated to remove the first destructive interference frequency above or below the main frequency range of interest. This demonstrates the need to measure the exterior level at multiple positions [2 and 28] or for scanning over the surface of the façade in order to obtain an average value for the incident level. But since the tests for eligibility are performed on untreated houses, for which the major transmission path is via the windows, there is the argument that the exterior level measurement should be made at window height.

The destructive interference effects (described above) that result from ground reflection also occur when the direct and ground reflected waves are reflected from the façade. As before, the lowest frequency, f_{f1}, at which destructive interference occurs, depends on the path length difference between the incident and reflected sound; this will depend on the distance from the façade surface and the angle of the incident sound. Table 2 shows the values of f_{f1} as a function of the distance of the measuring microphone from the façade and the angle of incidence of the incident sound. The shaded area in the table identifies frequencies of the first minimum lying below the main frequency range of interest in sound insulation measurements.

Table 2. Frequency at Which the Lowest Destructive Façade Interference Effect Occurs as a Function of Microphone Distance and Angle of Incidence

	Distance of Microphone From Façade Surface (ft)	0.5	1.0	1.5	2.0	3.3	3.9	5.0	6.0	6.6	8.2	9.0
Frequency of First, Minimum Hz, as Function of Angle of Incidence (With Normal to Façade)	0°	564	282	188	141	86	72	56	47	43	34	31
	15°	584	292	195	146	89	74	58	49	45	36	32
	30°	651	326	217	163	99	83	65	54	50	40	36
	45°	798	399	266	199	122	102	80	66	61	49	44
	60°	1128	564	376	282	172	144	113	94	86	69	63
	75°	2181	1090	727	545	332	278	218	182	166	133	121

The frequency of the first minimum decreases with increasing distance from the façade and with decreasing angle with the normal to the façade. For sound incident at 45°, this frequency decreases from 122 to 61 Hz as the microphone position is moved from 1 to 2 m (3.3 to 6.6 ft) from the façade. For this angle of incidence, it is preferable to use microphone distances greater than 1.2 m (3.9 ft), and perhaps larger [28]. ASTM E966-10 [2] dictates that the microphone distance should be more than 1.2 m (3.9 ft) and less than 2.5 m (8.2 ft) from the façade.

When sound insulation measurements are conducted using aircraft overflights, the frequency of the façade interference will change as the angle with the façade changes. As a result, the effect of the interference will be averaged over the complete overflight.

2.4 COMPARISON OF AIRCRAFT VERSUS LOUDSPEAKER MEASUREMENTS OF NLR.

There are two methods for measuring noise reduction: one uses aircraft as the noise source that provides the true value, and the other, an alternative method, uses a loudspeaker. Since both methods are permitted for the determination of eligibility, it is important that they produce the same results.

A comparison of NLR measurements conducted in the U.S. using aircraft and loudspeaker sources of noise is possible from the recent data sets contained in reports by L&B [29], Wyle [30], CSDA [31], and Schomer et al. [35] These four studies were conducted by different organizations at five different airports (San Diego International Airport (SAN), Burlington (BTV), General Mitchell International Airport (MKE), and Westfield-Barnes Regional Airport (BAF)), on different style single-family residences. The NLR was measured for many different test configurations with both aircraft and loudspeakers as the noise source. For the loudspeaker tests, variables included exterior microphone location, loudspeaker height and distance, and angle of incidence, although not all combinations of variables were tested in each study.
Comparisons of the measurements using aircraft and a loudspeaker as the noise source are shown in figure 2. Figure 2(a) shows measurements for microphones flush with the façade surface (with a -5 dB adjustment to the measured noise level). Figure 2(b) shows measurements for a microphone 1-2 m from the surface (with a -2 dB adjustment). The adjustments are in accordance with the latest guidance in ASTM E966-10 [2].

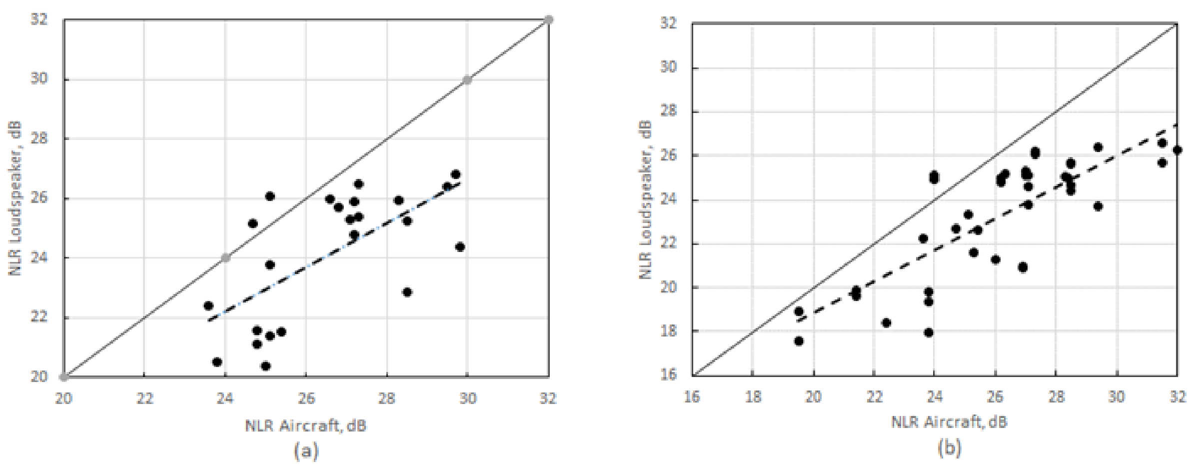


Figure 2. Comparison of NLR Measured With Aircraft and Loudspeaker as the Noise Source With Exterior Microphone (a) Flush With the Façade Surface and (b) 1-2 m From the Surface

In figure 2, the exterior aircraft noise level is measured at a nominal height of 4 ft above the ground surface. The data for the loudspeaker tests are all with the source mounted on a tripod 6 ft above the ground, 25 ft from, and angled at 45° to, the façade surface. The solid lines in figure 2 are the one-to-one relationship between aircraft and loudspeaker measurements; the dashed lines are the best-fit linear trend lines.

Overall, the four data sets are consistent with each other especially considering the variations inherent in field measurements by different organizations using different procedures on different residences at different locales. There is definitely scatter in the test results, but within this scatter, the different data sets overlap consistently.

In both cases, the measurements of NLR using aircraft as the source are noticeably larger than those with a loudspeaker. The statistics of the data sets are presented in table 3 showing that, with an exterior microphone 1-2 m from the façade, the average difference between measurements using aircraft and loudspeaker sources is 2.9 dB with a standard deviation of 1.8 dB. The corresponding difference with a flush-mounted microphone is 2.4 dB with a similar standard deviation of 1.7 dB. Similar trends were reported by Bradley et al. [18] who noted a difference of 1 to 5 dB between aircraft and loudspeaker measurements in the important frequency region of 200 to 500 Hz.

Table 3. Comparison of NLR Data Measured Using Aircraft and Loudspeaker as Noise Source

Exterior Microphone	Loudspeaker Distance ft (m)	NLR Aircraft—NLR Loudspeaker (dB)			
		Tripod Loudspeaker		Elevated Loudspeaker	
		Average (SD)*	Number of Samples	Average (SD)*	Number of Samples
Flush	25 (7.6)	2.4 (1.7)	23	1.2 (1.6)	24
1-2 m	25 (7.6)	2.9 (1.8)	39	1.4 (1.6)	11

Note: * Average ΔNLR (standard deviation (SD) in dB)

If the measurements of NLR using aircraft are taken as the true values, and the data are representative of actual practice, then measurements of NLR at 1-2 m using a loudspeaker on average will be 2.9 dB too low, with 95% of the measurements lying within +0.7 and -6.5 dB of the true value. The likelihoods of loudspeaker measurements of NLR being within ±0.5, ±1.0 and ±1.5 dB of the true values are 6%, 13%, and 21%, respectively. Applying a +2.9 dB adjustment to loudspeaker measurements of NLR would increase the likelihoods to 22%, 42%, and 59%, respectively. The agreement with aircraft measurements is improved slightly with a flush-mounted microphone, where the measured values on average are 2.4 dB too low, but with a similar standard deviation of 1.7 dB.

Measurements of NLR with an elevated loudspeaker at 25 ft will, on average, give results that are 1.2 dB (for a flush microphone) and 1.5 dB (for a microphone at 1-2 m) closer to the true measurements with aircraft noise. This would require adjustments of 1.2 and 1.4 dB, respectively, instead of 2.4 and 2.9 dB, respectively.

The different results from the two measurement procedures may be due to several factors. The noise reduction of a building façade exhibits a strong dependence on the characteristics of the noise source. For aircraft noise, the exterior sound field is essentially a plane wave incident at varying angles of incidence as the aircraft passes by the building; whereas the exterior sound field from a nearby loudspeaker is a spherical wave at a single angle of incidence. Furthermore, during an overflight, the aircraft noise level changes and exposes different parts of the building envelope differently over the course of time; whereas the loudspeaker noise source exposes all the façades continuously and represents an exposure, which is the case only for a brief period during an actual overflight. As a result, it is difficult to define a single representative location for a loudspeaker that captures the same exposure as does an aircraft overflight.

However, even given these fundamental differences in noise simulation, there are other differences, discussed in section 2.5, between the two methods related to the test configuration and adjustment factors that are applied to the levels measured at or near the building façade when the loudspeaker method is used.

2.5 THE EFFECT OF DIFFERENT TEST CONFIGURATIONS.

The data sets from recent studies as reported in L&B [29], Wyle [30], CSDA [31], and Schomer et al. [35] contain information that can be used to determine the effect of different parameters in the measurement of noise reduction. This analysis has been performed using the A-weighted noise reduction data included in the four studies.

A typical test configuration used by most consultants for loudspeaker measurements is with the loudspeaker 6 ft above the ground, 25 ft from the façade surface, and angled at 45° to the surface. This is the standard configuration to which alternatives are compared in the following sections.

2.5.1 Loudspeaker Measurements With Flush Versus Near-Façade Microphone.

The relationship between loudspeaker measurements of NLR at 45° using a microphone mounted flush with the façade surface and a near-façade position 1.22 m (4 ft) from the surface is shown in figure 3 [29]. This data includes the application of the currently accepted adjustment factors (-5 and -2 dB, respectively, as recommended in ASTM E966-10 [2]) to provide the equivalent noise level of the incident sound. Figure 3 includes measurements with the loudspeaker at 25 and 50 ft from the façade, mounted on a 5-ft tripod and elevated to heights ranging from 25 to 39 ft above the ground. The solid line in figure 3 is the one-to-one relationship between the two parameters.

The data points all cluster around the one-to-one relationship without any clear trend with loudspeaker height for a loudspeaker distance of 25 ft (average difference of 0.2 dB), but the flush level is slightly higher than the near-façade level at 50-ft distance (average difference of 0.7 dB). The average difference over all these conditions is 0.5 dB with a standard deviation of 1.1 dB, indicating that the difference of 3 dB between the currently accepted adjustment factors of -5 and -2 dB seems reasonable. Thus, it appears that measurements at the two microphone positions are consistent with each other, even though they both result in values of NLR lower than the true values measured with aircraft overflights.

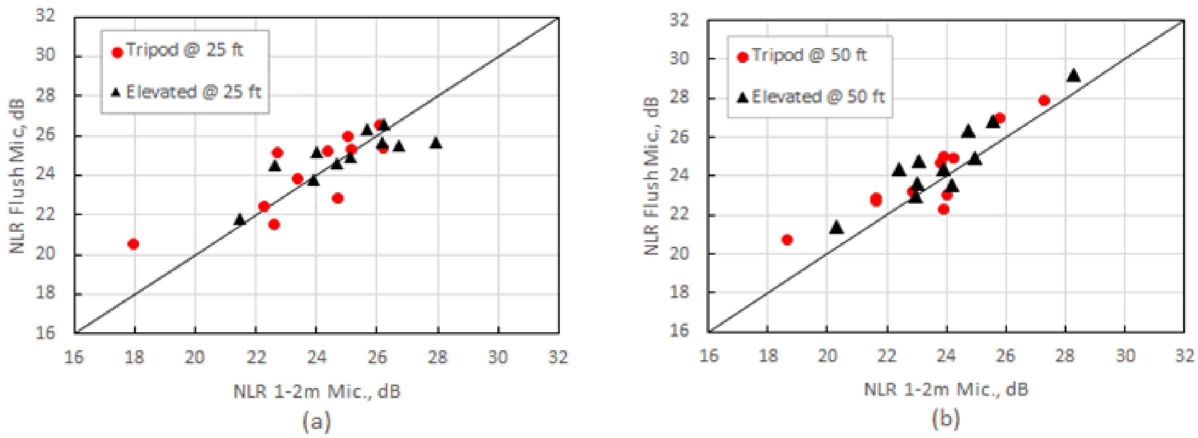


Figure 3. Comparison of NLR Measured With Flush and Near-Façade Microphone at 1.2 m for Loudspeaker Distances of (a) 25 ft and (b) 50 ft

This is consistent with data from field tests presented by Quirt [13] that showed a difference of 3 dB, ±1 dB, at one-third octave band frequencies greater than 250 Hz. At lower frequencies, the difference deviated from 3 dB due to ground interference effects. However, Hopkins and Lam [24] showed that flush levels were 2 dB greater than those measured at 1 and 2 m from the surface at frequencies greater than 315 and 160 Hz, respectively.

An example of the effect of façade reflection is shown in figure 4, which is a plot of the difference in level measured by a single microphone mounted flush with the façade, 6 ft above the ground, and a microphone scan over the façade at a distance of 1 m from the surface [31]. Figure 4 distinctly shows the effect of façade reflection interference for the 6-ft microphone at 1 m from the surface (the blue line) at the predicted frequency of 122 Hz (see table 2), as well as the interference from ground reflection at odd multiples of 244 Hz.

A second plot (the red line) in figure 4 shows the difference between flush levels averaged over heights of 3, 6, and 9 ft, at the façade and the level measured from a scan at 1 m from the façade. This demonstrates that the variation in level at different microphone heights due to ground reflection can be reduced by averaging measurements taken at different heights.

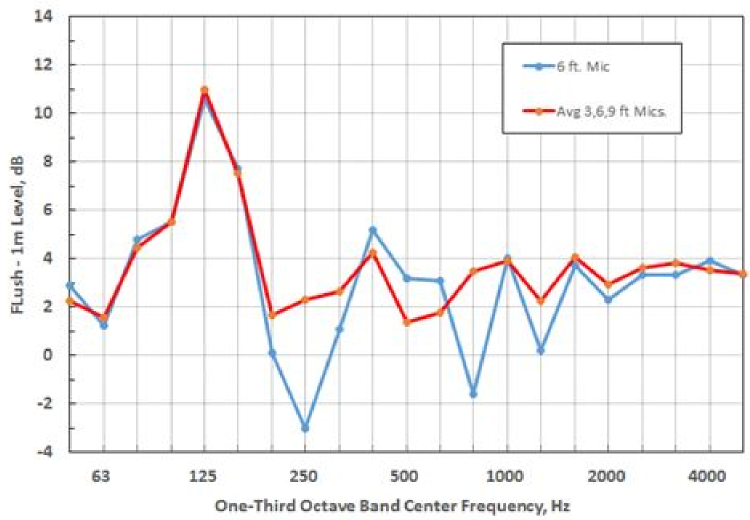


Figure 4. The Difference Between the Noise Level Measured Flush With the Façade and a Scan at 1-m Distance From the Façade With Incident Sound at 45°

According to current practice [2], the difference between flush and 1.2-m noise levels is assumed to be 3 dB (5 minus 2 dB). Figure 4 shows that this is true at frequencies greater than about 200 Hz for an average of three flush measurements (the red line), but is noticeably different at lower frequencies. However, for a single flush measurement at 6 ft (the blue line), there are major deviations from 3 dB up to 1.25 kHz. The difference between flush and near-façade noise levels also depends on the angle of incidence of the sound. Figure 5 shows this variation with angles of incidence 30°, 45°, and 60° at a single microphone height of 6 ft [31].

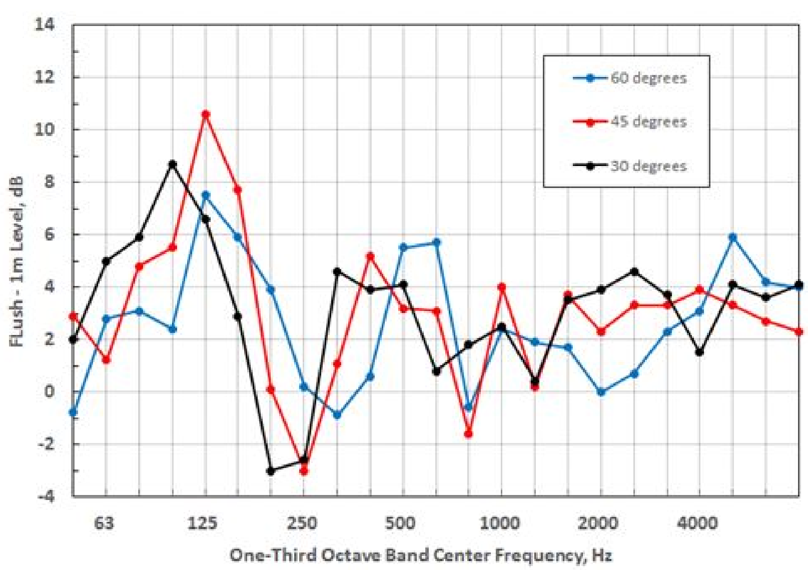


Figure 5. The Effect of Angle of Incidence on the Difference Between Flush and 1-m Microphone Measurements

The difference in levels shows significant variations with frequency, but the average is 3 dB, ±2 dB, at frequencies greater than 315 Hz.

2.5.2 Azimuthal Angle of Incidence.

The effect of changing the azimuthal angle of incidence in a measurement of noise reduction using a loudspeaker at a height of 5 ft and distances of 25 and 50 ft is shown in figure 6 [29 and 31]. As shown, there is no significant change in NLR with azimuthal angle at either loudspeaker distance for flush or near-façade microphone placement. In both cases, the average difference across angles ranging from 30° to 60° is less than 0.2 dB. There is more scatter in the data for the flush measurements, but no definable trends with configuration parameters.

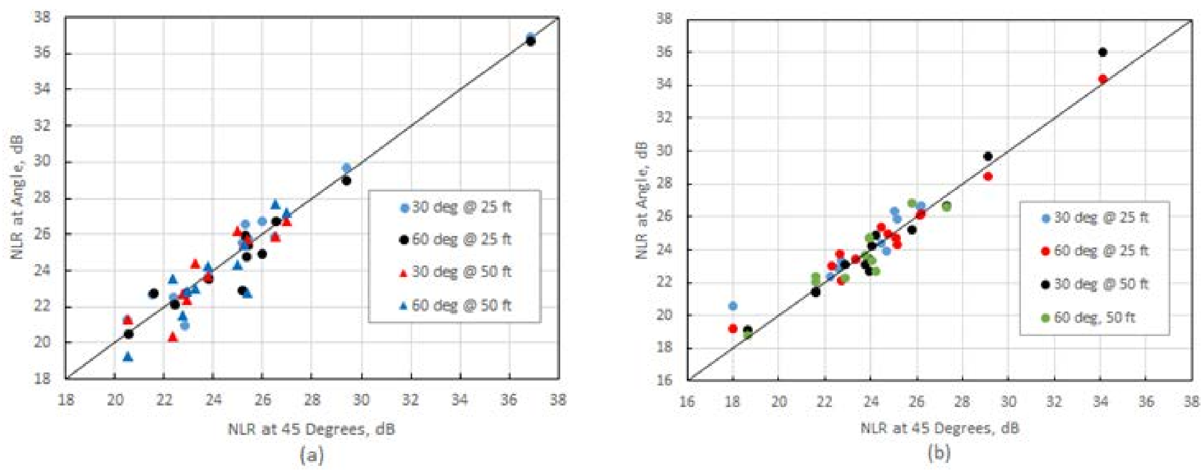


Figure 6. The Effect of Angle of Incidence on NLR Relative to Measurements With a Loudspeaker Mounted at a Nominal Height of 6 ft and Angled at 45° for an Exterior Microphone (a) Flush With the Façade Surface and (b) Near-Façade at 1-2 m From the Surface

These findings are consistent with those of Robert [32] and of Jonasson [17] whose field tests showed little variation in noise reduction with angles of incidence ranging from 30 to 60 degrees. Note that changing the azimuthal angle of incidence while maintaining the same distance to the center of the façade does not alter the frequency of the ground reflection interference at this center point as the path length difference does not change. However, changing the angle of incidence does change the interference frequency at other lateral points on the façade.

Subsequent review of the test procedure used in developing some of the data in figure 6 indicates that the measurements conducted at different angles of incidence actually exposed two perpendicular façades of corner rooms, such that increasing the angle of incidence on one façade reduced the angle on the other façade. As a result, any effect of angle of incidence on noise reduction was essentially nullified.

Bradley et al. [18] conducted tests using aircraft and a loudspeaker as noise sources and found a variation in noise reduction with angle of incidence, but not specifically for azimuthal angle.

2.5.3 Elevation Angle of Incidence.

There is less uncertainty in the dependence of noise reduction as a function of elevation angle of incidence. Figure 7 compares measurements using a loudspeaker elevated to heights ranging from 25 to 39 ft above the ground with measurements with the loudspeaker mounted on a 5-ft tripod, both angled at 45° to the façade surface. Data are shown for the average of five microphone positions flush with the façade [29 and 30] and for a spatial scan at a near-façade position 1-2 m from the façade [29 and 35].

The noise reduction measured with an elevated loudspeaker and a flush-mounted exterior microphone is on average 1.1 dB greater than for a loudspeaker mounted on a tripod at 5 ft at the same distance. The average difference is 0.6 dB for a microphone scan at 1-2 m from the façade surface. The corresponding differences for an elevated loudspeaker (LS) at 50 ft are 0.7 and 0.5 dB, respectively.

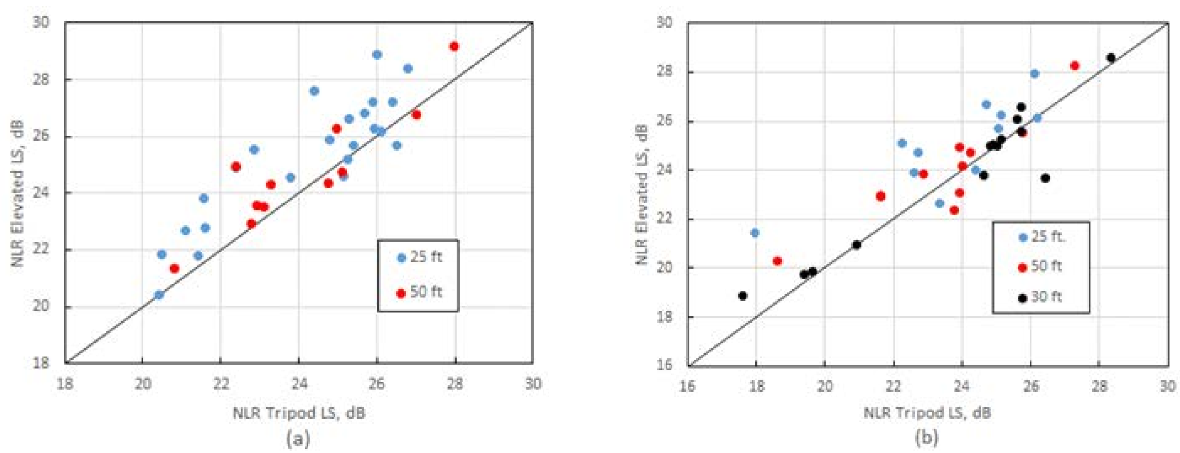


Figure 7. Comparison of NLR Measured With an Elevated and 5-ft Tripod-Mounted Loudspeaker for an Exterior Microphone (a) Flush With the Façade and (b) 1-2 m From the Façade for Different Loudspeaker Distances

These results are consistent with those of Bradley et al. [18] who noted increases in noise reduction and better agreement with aircraft measurements as the loudspeaker height is increased. Bradley et al. note that the main increase occurred in the 250 Hz region for both low (1.8 m) and elevated (7.8 m) loudspeaker positions and attribute this to variations in excitation of the mass-spring-mass resonance of the window in the façade at different angles of incidence. However, there are indications in the data presented of a change in ground reflection interference frequency from the 250 Hz to the 80 Hz one-third octave band that suggests the variation could be due to changes in source-microphone configuration. Moreover, if it is the mass-spring-mass resonance that causes the variations, then this effect should also be apparent when the azimuthal angle is changed.

Elevating the loudspeaker reduces the frequency at which ground reflection destructive interference occurs to a value below the important frequency range for determining NLR. As a result, the spatial variation in noise level over the façade in this frequency range will be less than for a tripod-mounted loudspeaker (see section 2.3.3) where the interference frequency is in the range important for determining NLR. The reduction in level at this interference frequency therefore has a lesser effect on the measurement of noise reduction for an elevated loudspeaker than for a tripod loudspeaker, and may be responsible for the increase in measured NLR with loudspeaker height. Note that the increase in NLR for an elevated loudspeaker is less when measured by a microphone scan over the façade at 1-2 m (figure 7(b)) than for the average of five fixed flush positions (figure 7(a)), indicating that insufficient spatial sampling may be the cause.

2.5.4 Loudspeaker Distance.

Increasing the distance of the loudspeaker from the façade reduces the path length difference between direct and ground-reflected waves and consequently increases the frequency at which the ground-reflection interference occurs. Thus, the reduction in level that occurs at this interference frequency moves upwards into the important frequency range for determining noise reduction resulting in a reduction in NLR. On this basis, Berardi [28] recommends reducing this distance in measurements of sound insulation. The effect on the measured noise reduction of increasing the loudspeaker distance from the façade surface (at 45°) from 25 to 50 ft is shown in figure 8.

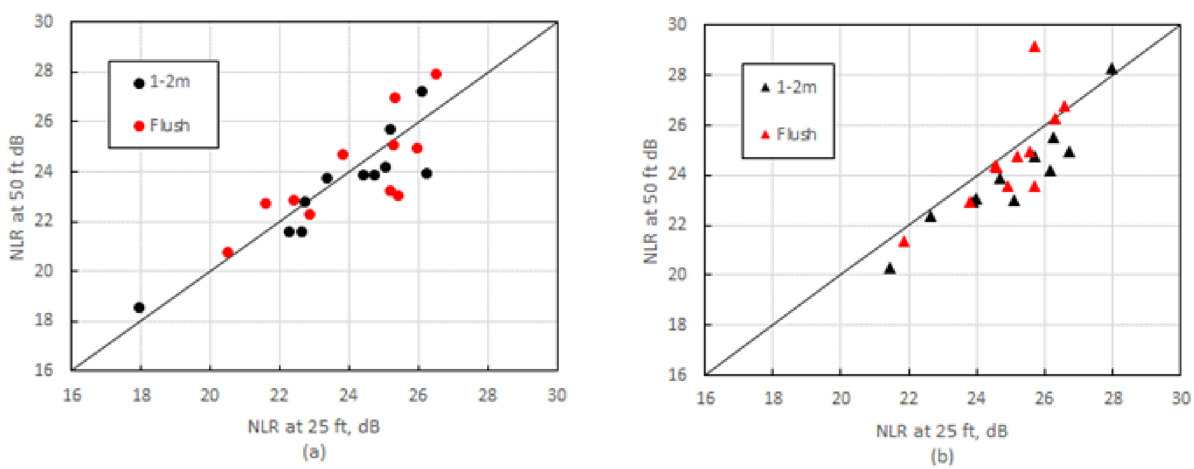


Figure 8. Comparison of NLR Measured at 45° With a Loudspeaker at 25 ft and 50 ft for Loudspeaker Height at (a) 5 ft and (b) Elevated

There is a slight reduction in NLR with distance for the microphone mounted on a 5-ft tripod, but when elevated, the measured noise reduction tends to definitely decrease with increasing distance. The average difference (NLR at 25 ft minus NLR at 50 ft) is 0.1 dB for a loudspeaker on a 5-ft tripod and the standard deviation is 1.1 dB. For the elevated loudspeaker, the average difference is 0.6 dB and the standard deviation is also 1.1 dB. This latter value is largely influenced by one data point without which the standard deviation would be 0.7 dB.

2.5.5 Diffraction Effects.

Several authors have addressed the issue of diffraction of sound at the edges of a finite size façade that could modify the noise level at positions along the façade surface. Such an effect would be most noticeable at low frequencies. Diffraction effects, if significant, will affect both the loudspeaker and aircraft measurements, so if they are the same, they may not explain the difference between measurements using the two sources.

Quirt [14] conducted field measurements to demonstrate that diffraction fringes at the corners of buildings do not noticeably affect the frequency dependence of the measured noise levels on the surface of the façade. Bradley et al. [18] attribute some of the variations in adjustment factors to diffraction effects, but it is not clear from the reported data that the variations are entirely due to diffraction and not to ground reflection. Davy [22] found that diffraction effects on a panel are minimal at frequencies of interest to sound insulation measurements.

Hopkins and Lam [24] identified the upper-limiting frequencies where diffraction effects need to be taken into account in conducting sound insulation measurements, concluding that for typical façade dimensions, diffraction effects can be considered as negligible above 100 Hz for near-façade microphones positioned 1 to 2 m from the façade.

The general consensus seems to be that diffraction effects are not important in the frequency range of interest for sound insulation measurements, although Bradley's results need further examination.

2.5.6 Façade Surface Properties.

In developing the adjustment factors to obtain an equivalent incident noise level, it is assumed that the façade surface is completely rigid with a reflection factor, r, equal to one. This is equivalent to an absorption coefficient, a, of zero since,

$$a = 1 - r^2$$

Lewis [9] quotes a relationship for the increase in noise level, ΔL, at the façade surface as $20.\log[2/(1+ a)]$. However, the values of ΔL given in the paper do not correspond with this expression, which leads to the conclusion that it may be misprinted in the paper. A simple expression for the increase in level at the surface of a façade would be:

$$\Delta L = 20 \times \log[1 + (1 - a)^{1/2}], \text{ dB}$$

which would result in an increase in level of 5.6 dB (rather than the theoretical value of 6 dB) if the absorption coefficient is 0.2, which according to Quirt [14] is high for a typical building surface, except perhaps at very low frequencies. Quirt [14] and Hall [15] demonstrate theoretically that the increase in level at the façade does not change significantly if the façade is assumed to be absorptive with an absorption coefficient ranging from 0.2 at frequencies below 160 Hz to 0.04 above 1 kHz. The conclusion is that realistic values of surface absorption do not significantly affect the sound pressure at the surface.

Measurements of noise reduction using a microphone mounted flush with the surface of a window have shown little difference to levels measured on a nearby vinyl siding wall surface, as shown in figure 9 [31].

Furthermore, in noise reduction measurements conducted on school buildings, no detectable difference in measured noise levels was noted between positioning the microphone over window glass or the external wall [6]. Quirt [14] found a large variation in noise level at the surface of recessed doors and windows, but this was due to interference from waves reflected from the surrounding frame and not to the window surface itself.

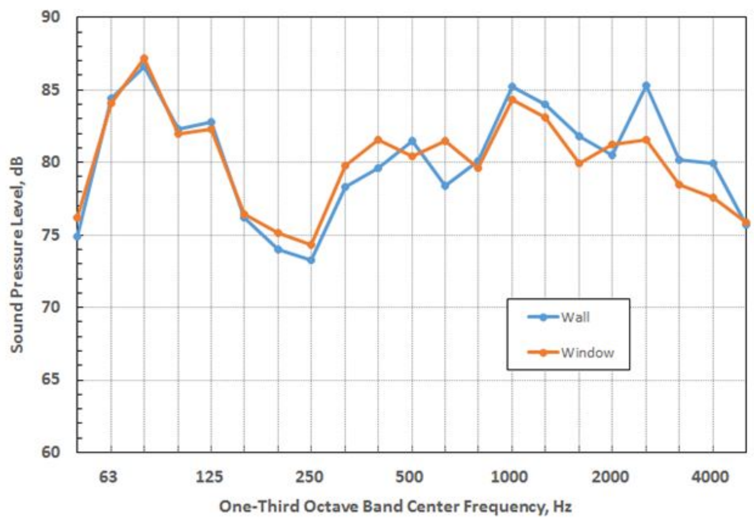


Figure 9. Comparison of Sound Pressure Levels Measured Flush With a Wall and Adjacent Window

Finally, Ismail and Oldham [21] conducted experiments to study the extent of scattering of noise in reflections from walls. The authors concluded that the magnitude of the façade scattering coefficient appears to be small and not very sensitive to the degree of surface irregularity. This suggests that prediction models based upon specular reflections are appropriate for near-field situations at a façade surface.

It can be concluded that measurement of flush and near-façade noise levels on typical residential structures are not significantly influenced by absorption or scattering by the façade surface.

2.5.7 Adjustment Factors.

The noise reduction of a façade is the difference between the level of noise incident to the façade and the level inside the room behind the façade. The incident level is the noise level that would be measured at the location of the façade if the building was not present. However, measurements of the noise level at or near a façade include contributions from the sound waves reflected from the façade. Adjustment factors are therefore applied to these measured levels to determine the incident noise level.

Many publications and reports described in section 2.2 address the validity of the theoretical values of the adjustments, which are -6 dB for flush-mounted and -3 dB for near-façade microphone measurements. Early papers by Nash [10], Quirt [11], Schumacher and Mechel [12], and Quirt [13] acknowledge that these factors are reasonable, although scatter in the values was evident from measurements. Later papers by Bradley et al. [18], Hopkins and Lam [24], and Berardi [26] have questioned these values and suggested that they are too large.

ASTM E966-10 [2] has adopted adjustment factors of -5 and -2 dB for flush and near-façade measurements, basing these numbers on work presented by Bradley and Chu [19], which in turn are based on a previous 2001 paper by Bradley et al. [18]. However, the data in Bradley et al. [18] show that the adjustments for aircraft noise vary with frequency, and are not -5 and -2 dB, but average at -4 and -1.5 dB, respectively, over the frequency range 125 to 500 Hz, which is the frequency range that determines the A-weighted noise reduction of most residences. Increases of 5 dB for flush measurements were only noted at 630 Hz and above, and increases of 2 dB for near-façade measurements were only noted above 1.25 kHz. At low frequencies (below 125 Hz), the adjustments are much smaller than -5 and -2 dB and sometimes positive. Moreover, Bradley et al. [18] show that the adjustment factor for aircraft measurements is reduced significantly as the elevation angle of the aircraft increases; it should be noted that the façade tested had a fairly large roof overhang that may have influenced the data at high elevation angles. Bradley et al. [18] attribute the reduction to destructive interference between the direct and ground reflected sound paths and diffraction from the edges of the façade.

It is important to note that the adjustment factors Bradley et al. [18] present, which are incorporated in ASTM E966-10 [2], were measured for aircraft overflights and are the difference between the noise level measured by a remote microphone 25 ft above the ground and the level measured at a height of 5 ft on a façade. The remote measurement has a fundamental ground reflection interference frequency on the order of 20 Hz, with odd harmonics at about 60 and 100 Hz, whereas the façade measurement at 5 ft has a fundamental interference frequency on the order of 100 Hz, with odd harmonics at about 300 and 500 Hz. The remote measurement does not represent the incident level that would exist at the façade if the building was not present because the ground reflection interference frequencies of the two measurements are quite different. This explains why Bradley's [18] adjustment factors determined from aircraft noise measurements vary with frequency and are lower than the theoretical values of -6 and -3 dB.

Using a loudspeaker as the source, the incident noise level on the façade also contains contributions from both direct and ground reflected paths, and so is heavily influenced by destructive interference from ground reflection. But the difference is that the incident exterior level is measured at or near the surface of the façade and includes the same destructive interference frequencies as does the incident level in the absence of the building façade.

Based on the research reviewed in section 2, the adjustment factors recommended in ASTM E966-10 [2] appear to be too simplistic. The adjustments were measured for aircraft noise measurement configurations and do not necessarily apply to loudspeaker test configurations. The current adjustments of -5 and -2 dB appear to be incorrect.

2.6 SUMMARY OF RESULTS.

The following results are based on the analyses performed in section 2.

1. The current guidance in ASTM E966-10 [2] does not lead to agreement between noise reduction measured by an aircraft overflight and a loudspeakers noise source. On average, the loudspeaker method produces values of noise reduction that are 2 to 3 dB less than with for an aircraft overflight, depending on the positioning of the exterior microphone and loudspeaker relative to the façade under test. Comparison statistics between measurements using aircraft and loudspeakers in different configurations are shown in table 4.

Table 4. Statistics for the Comparison of NLR Measurements Using Aircraft and Loudspeakers for Different Test Configurations

Exterior Microphone	Loudspeaker Distance ft (m)	NLR Aircraft—NLR Loudspeaker (dB)			
		Tripod Loudspeaker		Elevated Loudspeaker	
		Average (SD)*	Number of Samples	Average (SD)*	Number of Samples
Flush	25 (7.6)	2.4 (1.7)	23	1.2 (1.6)	24
	50 (15.2)	2.2 (2.0)	11	1.8 (1.6)	11
	All	2.4 (1.8)	34	1.4 (1.6)	35
1-2 m	25 (7.6)	2.9 (1.8)	39	1.4 (1.6)	11
	50 (15.2)	2.9 (1.6)	11	2.4 (1.7)	11
	All	2.9 (1.8)	50	1.9 (1.7)	22

Note: *Average ΔNLR (standard deviation (SD))

2. There are fundamental differences in noise simulation between an aircraft overflight and a loudspeaker test. During an overflight, the aircraft noise level changes and exposes different parts of the building envelope differently over the course of time; whereas the loudspeaker noise source exposes all the façades continuously and represents an exposure, which is the case only for a brief period during an actual overflight. As a result, it is difficult to define a single representative location for a loudspeaker that captures the same exposure as does an aircraft overflight, which may be one reason why the two methods give different results.

3. Measurements of the exterior noise level with a loudspeaker as the source are made at or near the façade; when an aircraft overflight is the source, the measurements are made at a location remote from the façade. It is possible that the latter are not truly representative of the sound incident to the façade.

4. There appears to be very weak dependencies between measured noise reduction and azimuthal angle of incidence and loudspeaker distance, but a stronger dependency with vertical angle of incidence. Elevating the loudspeaker reduces the frequency at which ground reflection destructive interference occurs to a frequency range less important to the determination of NLR, resulting in an overall increase in measured exterior noise

level in the important frequency range. This leads to the conclusion that it may be the change in ground effect that results in an increase in NLR with loudspeaker height.

5. For a given loudspeaker position, the frequency at which ground reflection interference occurs changes with microphone measurement position on the façade. Spatial sampling of the noise level is therefore important in order to measure the average exterior level.

6. The noise reduction of a façade is determined largely by the acoustic performance of its weakest element, usually a window or door. As a result, consideration should be given to measurement of the exterior noise level at or near the weakest element.

7. Diffraction effects may result in a variation in adjustment factor with vertical angle of incidence.

8. The currently accepted adjustment factors in ASTM E966-10 [2] are based on data that are not representative of FAA measurement protocol.

9. The main reasons for the lack of agreement between aircraft and loudspeaker measurements are

   a. poor simulation of the aircraft overflight, and/or

   b. incorrect adjustment factors in ASTM E966-10 [2].

As a result, there is a need for further research to

- develop more appropriate adjustment factors by comparing the measured exterior level at a façade to the incident level that would exist if the façade were not present. This is essentially the process of loudspeaker calibration as described in ASTM E966-10 [2].

- develop a model to better understand the influence of test site parameters on the sound fields in and around buildings.

- relate the level measured remotely for aircraft noise to the level actually at the façade.

- evaluate the extent of diffraction effects.

3. INITIAL FIELD MEASUREMENTS.

A goal of this study was to develop and validate a simulation model for predicting the noise level distribution at and near the façade of a building produced by nearby and distant noise sources. The model was validated by means of a series of noise measurements designed to encompass the range of conditions likely to be encountered in sound insulation measurement programs. This section of the report contains a description of these initial, fundamental field measurements. The model development and validation is described in section 4.

3.1 MEASUREMENT METHODOLOGY.

The field measurements were conducted using both aircraft and a loudspeaker as the noise sources to develop an understanding and contribution of the factors influencing the sound level at and adjacent to a building façade.

First, the propagation over ground element was checked by measuring and comparing the noise levels at varying distances and heights from a loudspeaker at varying heights above the ground with no nearby structures, as shown in figure 10(a). Aircraft overflight noise levels were also measured at the same site.

Second, the façade reflection element was validated by measurements conducted close to a reflecting surface at a height above the ground sufficient to minimize the ground effect, as shown in figure 10(b). Both loudspeaker and aircraft noise sources were used.

Third, the combination of ground and façade reflections was validated with similar measurements at the same site, but closer to the ground surface, again with both loudspeaker and aircraft to determine an equivalency between measurements of the two sources.

(a)

(b)

Figure 10. Validation Test Sites for (a) Free-Field and (b) Wall Configurations

The noise tests were conducted in the immediate vicinity of Manchester-Boston Regional Airport (MHT) and included measurements for over 200 different aircraft-loudspeaker-microphone configurations taken over grass and concrete surfaces, in the free field and adjacent to a vertical wall (see appendix B for the test parameters). For the free-field tests, loudspeakers and microphones were positioned at nominal heights of 0, 5, 15, and 25 ft above the ground surface in an area free of reflecting surfaces, separated by distances of 25 ft and 50 ft. Measurements were conducted over a hard concrete surface and a grass surface.

The tests were repeated using the same loudspeaker-microphone configurations (with an angle of incidence of 45° and a separation distance of 25 ft) with the microphones positioned flush with and at distances of 2, 4, 5.3, and 7.1 ft from the surface of a 25-ft-high wall. Measurements were conducted over a hard concrete surface and a grass surface.

For all configurations, a reference microphone was placed at a distance of 3.3 ft (1 m) on the loudspeaker axis. All microphones were covered by a 90-mm windscreen to minimize wind noise at the diaphragm and to protect the diaphragm when mounted flush with the wall surface.

The measurement data were processed in one-third octave frequency bands covering a range from 12.5 Hz to 20 kHz, from which the data for the range 50 Hz to 8 kHz was extracted for analysis. The resultant noise level data at each microphone for every configuration was corrected for the angular directivity of the loudspeaker in each one-third octave frequency band. The levels in each frequency band were also normalized to a reference microphone level of 100 dB, so that the resulting data represents that which would be obtained from an omnidirectional noise source with a flat frequency output.

3.2 FREE-FIELD TEST RESULTS.

The tests conducted in the free-field essentially follow the loudspeaker calibration procedure described in ASTM E966-10 [2], namely, measuring noise levels generated by the loudspeaker at distances and heights corresponding to the proposed measurement positions at and near the surface of the 25 ft wall, but in an area free of reflecting surfaces.

First, the propagation from source to receiver was examined. Figure 11 shows the difference in noise level between the reference microphone (at 3.3 ft) and microphones at 25 and 50 ft, where both loudspeaker and microphones are nominally 25 ft above the ground. (See appendix C for test conditions nomenclature.) Assuming free-field propagation with levels decreasing by 6 dB per doubling of distance (inverse-square law), the differences should be 17.7 and 23.7 dB at 25 and 50 ft respectively, indicated by the horizontal lines in figure 11. As shown, the actual differences are slightly lower than those predicted due to the small increases in level due to ground reflections, which are at a levels 7 and 3 dB less than that of the direct propagation path for distances of 25 and 50 ft, respectively. As expected, the levels decrease slightly more with distance over the grass surface.

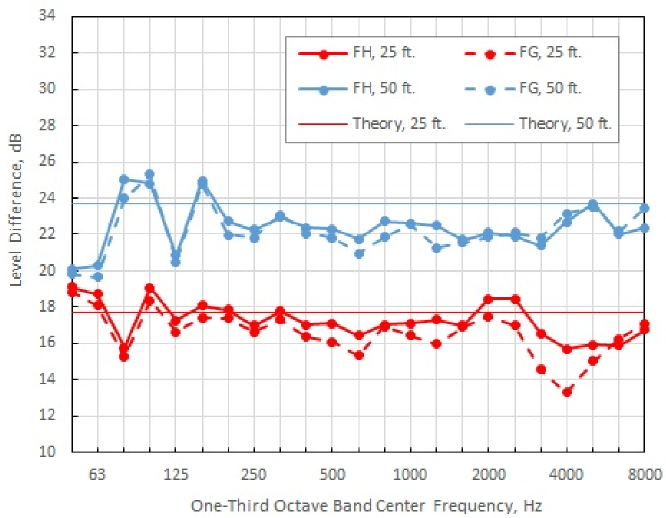


Figure 11. Difference in Sound Level Between the Reference and Measurement Microphone Positions for Distances of 25 and 50 ft Over Hard and Grass Surfaces With Microphone and Loudspeaker Nominally 25 ft Above the Ground

The situation is completely different with the loudspeaker and microphone at 5 ft above the ground, as shown in figure 12. In this case, the effect of ground reflections is noticeable in the 315 and 630 Hz frequency bands where destructive interference occurs at predicted frequencies of 293 and 570 Hz for distances of 25 and 50 ft, respectively.

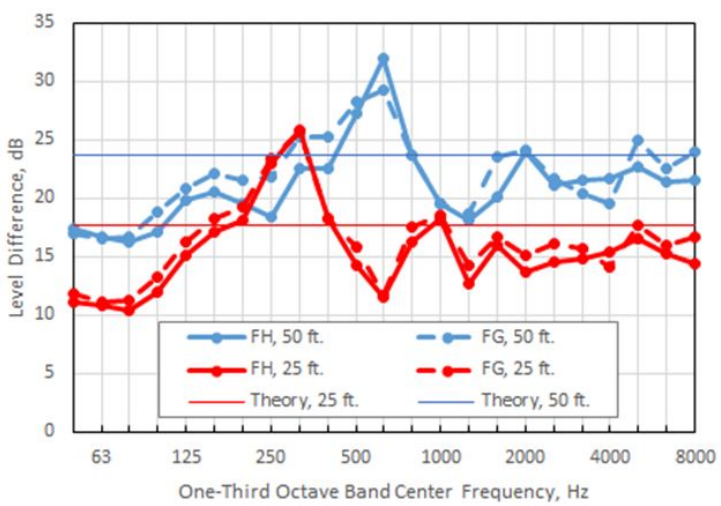


Figure 12. Difference in Sound Level Between the Reference and Measurement Microphone Positions for Distances of 25 and 50 ft Over Hard and Grass Surfaces With Microphone and Loudspeaker 5 ft Above the Ground

Note that the increase in level difference at these frequencies represents a decrease in level due to the destructive interference. The actual sound pressure levels measured at 25 ft are presented in figure 13 clearly showing the destructive interference in the 315 Hz frequency band and at odd multiples of this frequency in the 1000 and 1600 Hz bands. The difference in level between propagation over hard and grass surfaces is about 1 dB.

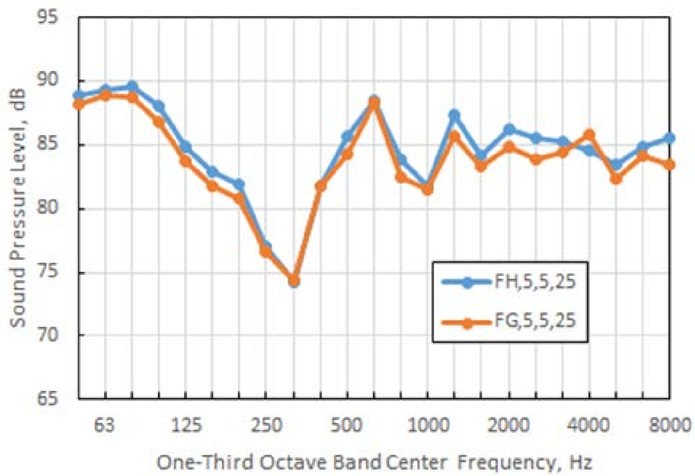


Figure 13. Sound Pressure Levels at 25 ft From a Loudspeaker Over Hard and Grass Surfaces With Microphone and Loudspeaker 5 ft Above the Ground

A further check on the data's validity is provided in figure 14, which demonstrates the reciprocity between levels measured with loudspeaker and microphone positions interchanged. As shown, there is close agreement in the levels when interchanging source and receiver as reciprocity theory would predict. The destructive interference effects from ground reflection occur at the predicted frequencies for all configurations.

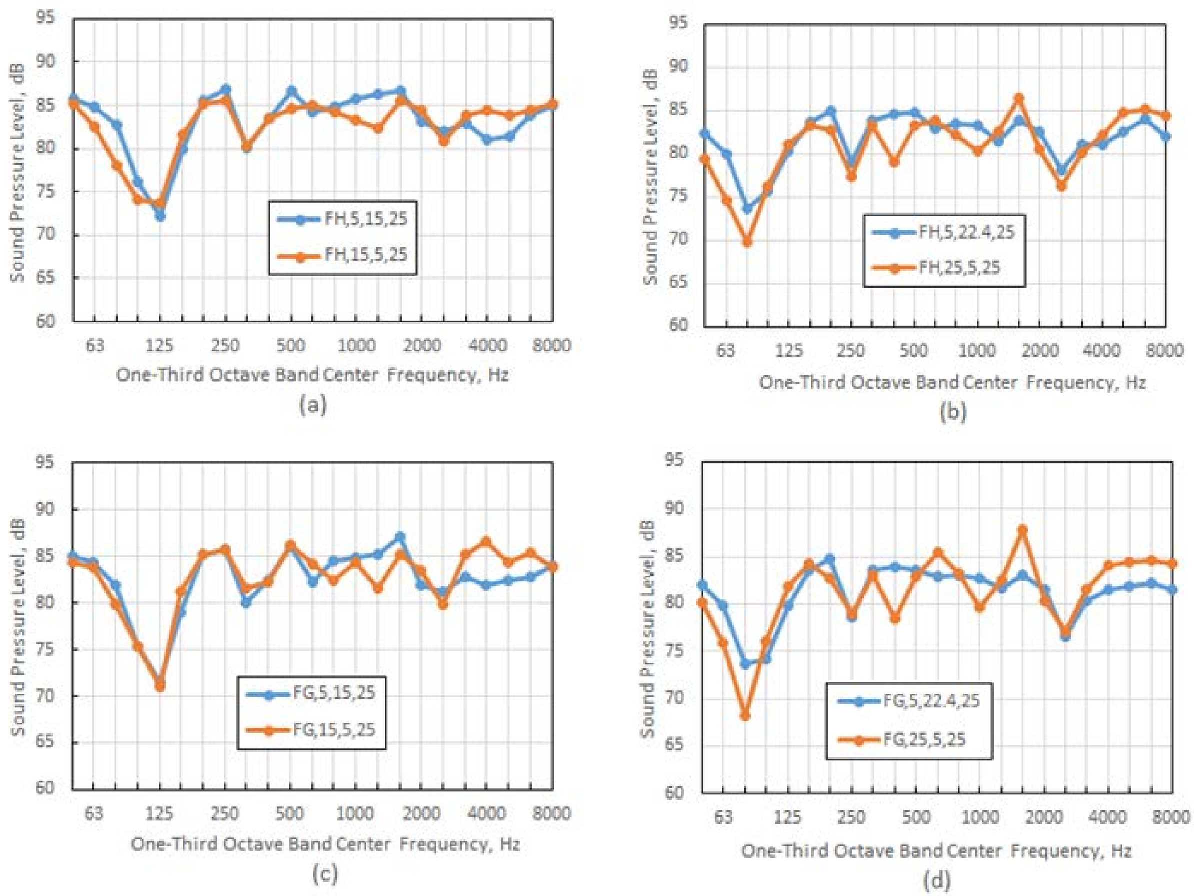


Figure 14. Reciprocity Between Loudspeaker and Microphone Locations at a Distance of 25 ft (a) 5 and 15 ft, (b) 5 and (Nominally) 25 ft Over a Hard Surface, (c) 5 and 15 ft, and (d) 5 and (Nominally) 25 ft Over a Grass Surface

Thus, it was determined that the data from the free-field measurements closely follow the trends expected from theory and practice, and the data show a very good repeatability when comparing results over different ground surfaces.

A comparison of the sound levels measured at a 5-ft microphone with the loudspeaker at nominal heights of 5, 15, and 25 ft are shown in figure 15, where it is clear that the level varies considerably with frequency at frequencies below 400 Hz. Note that the first destructive interference frequency decreases from 293 Hz at a microphone height of 5 ft, to 111 Hz at a height of 15 ft, and to 80 Hz for a height of 25 ft.

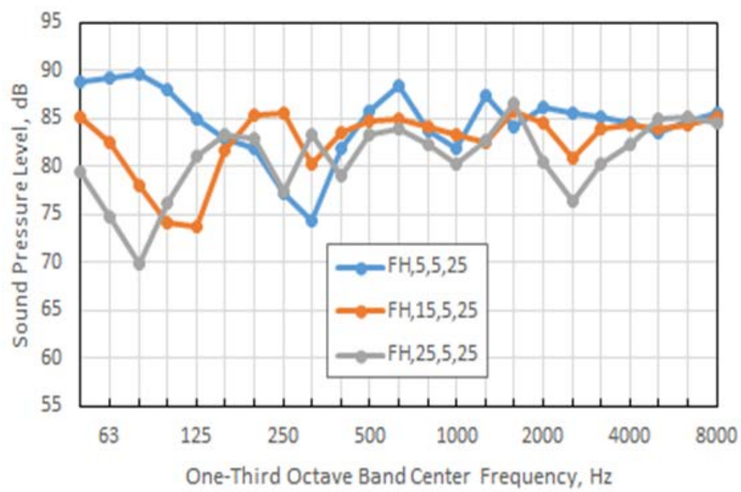


Figure 15. Sound Pressure Levels Measured at a 5-ft Microphone for Different Loudspeaker Heights

Similar plots of sound level measured at different microphone heights for the loudspeaker at 25 and 5 ft are shown in figure 16. Note that the variation in level with frequency is considerably greater as the loudspeaker height is reduced from 25 to 5 ft.

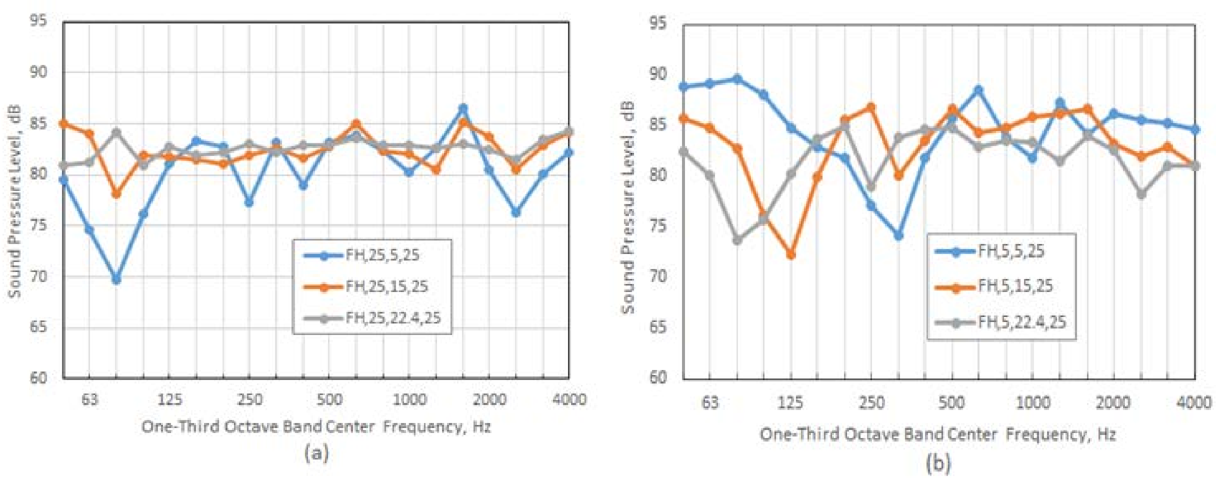


Figure 16. Variation in Sound Pressure Level With Microphone Height, Loudspeaker at (a) 25 ft and (b) 5 ft

ISO [7] and Jonasson and Carlsson [17] suggest that sound-insulation measurements should be performed by mounting the loudspeaker at ground level to move the destructive ground interference frequency above the main frequency range of interest. However, it is never possible to mount the loudspeaker exactly at 0 ft because of its finite size. In the field measurements, the loudspeaker was mounted on its side on the ground, so the center of the cone was about 8 in. above the ground. With this configuration, figure 17 shows the sound pressure level measured at a distance of 25 ft for different microphone heights.

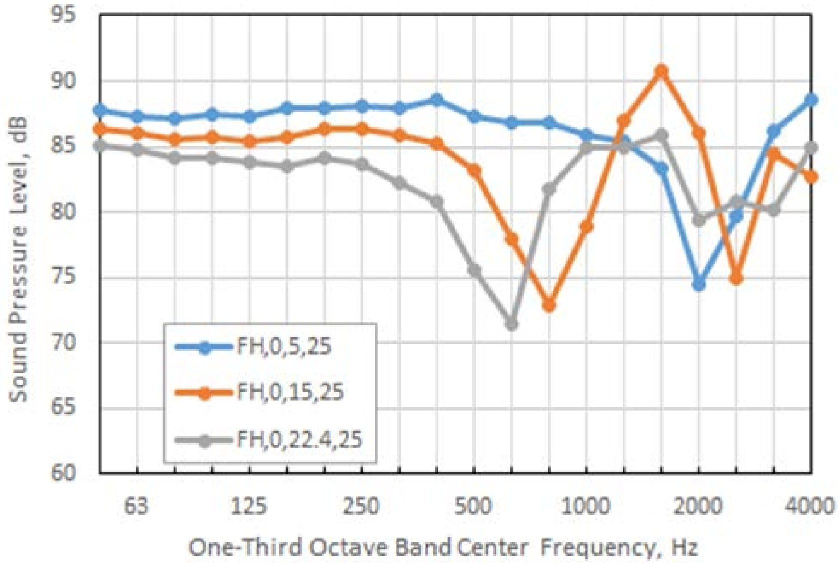


Figure 17. Free-Field Sound Pressure Level Variation With Height for a Ground-Level Loudspeaker

The ground interference frequency for the nominal (0,5) configuration is about 2150 Hz as predicted, reducing to lower frequencies as the microphone height is increased and the path length difference increases. For the nominal (0,5) configuration, the level is fairly constant up to about 1250 Hz.

3.3 FLUSH-MOUNTED AND NEAR-FAÇADE MEASUREMENTS.

The configurations included in the free-field tests were repeated with the microphone mounted flush with a 25-ft wall at heights of 5, 15, and 21.9 ft above the ground and at distances of 2, 4, 5.3, and 7.1 ft from the wall at each of the three heights. The loudspeaker was 25 ft from the wall, providing incident noise to the microphone arrays at 45°. The resulting levels were compared to the levels measured for the identical configurations under free-field conditions to determine the magnitude of the wall effect, namely the adjustment factor necessary to determine the incident level.

The results for a flush-mounted microphone are shown in figures 18, 19, and 20 for loudspeaker/microphone heights of 25/25, 25/5, and 5/5, respectively. The sound levels measured by the flush microphone are compared with the levels measured for the same configuration in the free-field in figures 18(a), 19(a), and 20(a). The increases in level (the adjustment factor) due to the presence of the wall are shown in figures 18(b), 19(b), and 20(b). For the 25/25 configuration shown in figure 18, the effect of the wall is to increase the noise level by 6 dB, ±1 dB, over the free-field level at frequencies in the range 100 to 1250 Hz. Thus, the adjustment factor is 6 dB in this important frequency range.

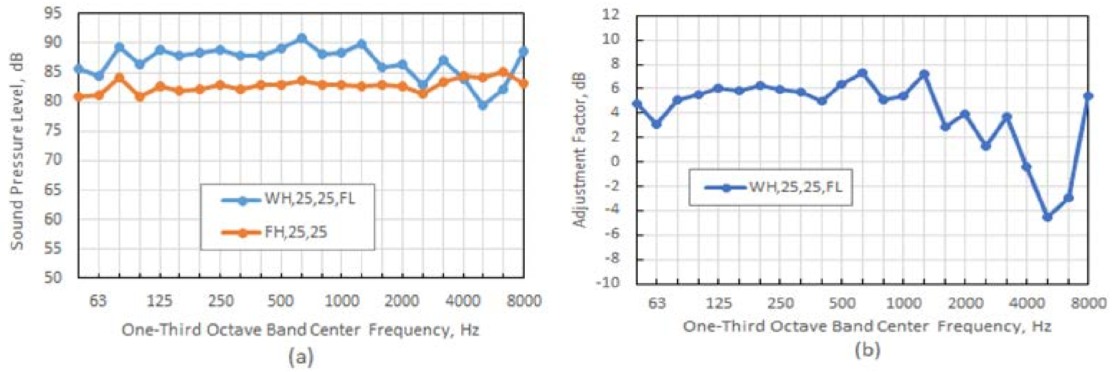


Figure 18. Adjustment Factor for Loudspeaker and Flush-Mounted Microphone Both at 25-ft Heights, (a) Flush Sound Pressure Level and Free-Field Level and (b) Adjustment Factor in Decibels

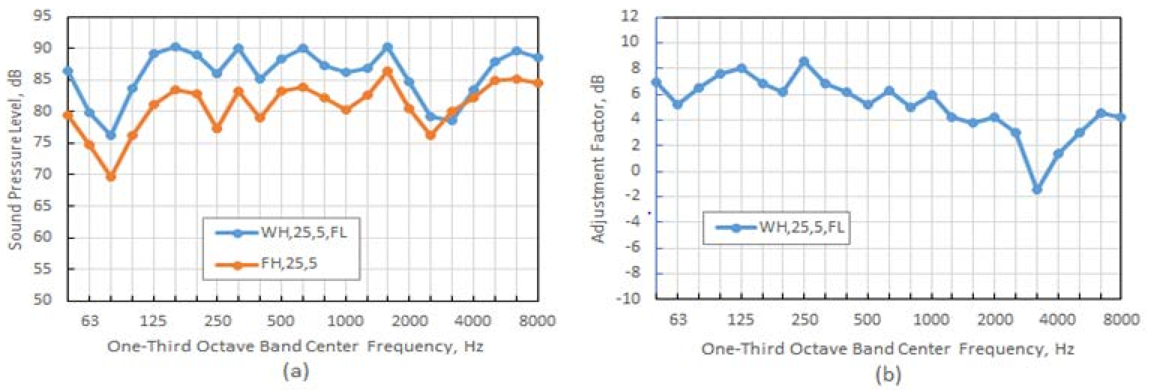


Figure 19. Adjustment Factor for Loudspeaker at 25 ft and Flush-Mounted Microphone at 5-ft Heights, (a) Flush Sound Pressure Level and Free-Field Level and (b) Adjustment Factor in Decibels

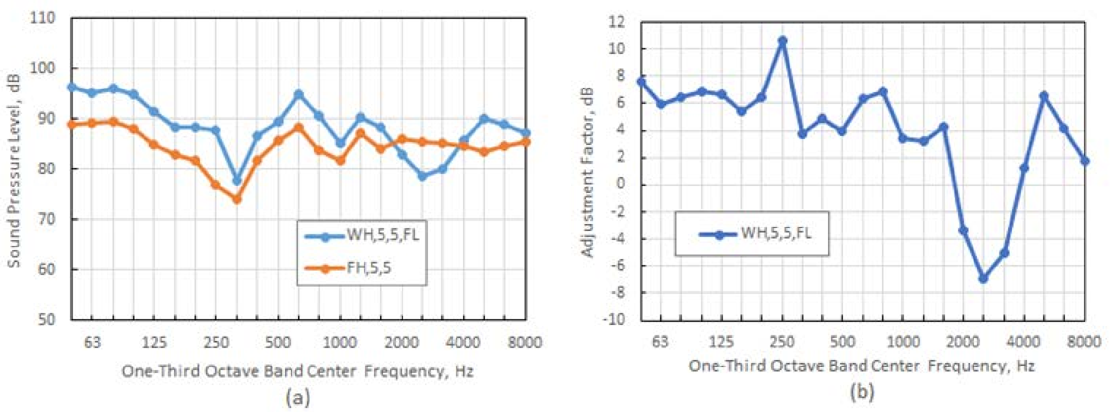


Figure 20. Adjustment Factor for Loudspeaker and Flush-Mounted Microphone Both at 5-ft Heights, (a) Flush Sound Pressure Level and Free-Field Level and (b) Adjustment Factor in Decibels

The large dips at high frequencies in these and subsequent figures are the result of the microphone not being completely flush with the wall. As mentioned in section 3.1, the microphones were protected with a 90-mm diameter windscreen such that the diaphragm was about 0.15 ft from the wall. The destructive interference from the wall reflection occurs in the range 2 to 4 kHz depending on the pressure applied to the microphone to hold it against the wall.

The average over the range 100 to 1000 Hz is generally about 6 dB. The deviation in the 250 Hz band in figure 20(b) is due to small changes in the ground reflection interference frequency (calculated to be 293 Hz and lying almost mid-way between the 250 and 315 Hz bands) between the free-field and wall measurements.

When the loudspeaker is placed at ground level, the sound level at a flush-mounted microphone 5 ft above the ground and 25 ft from the source is uninterrupted by frequency dependent ground effects, as shown in figure 21.

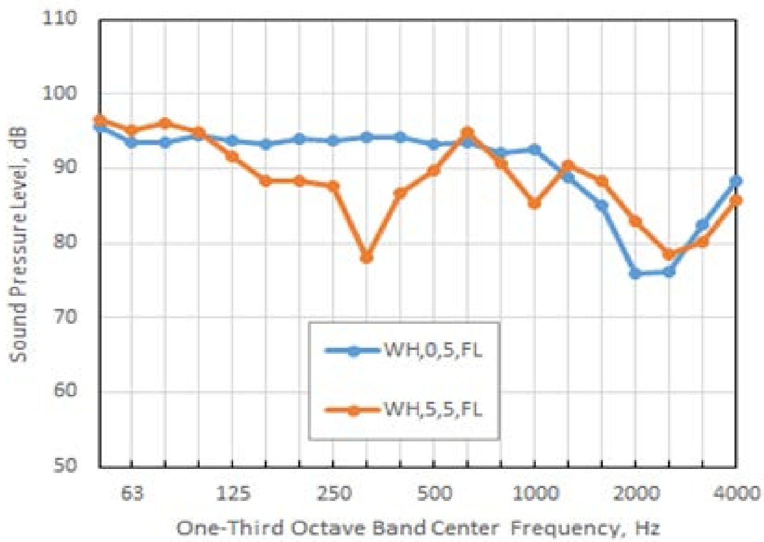


Figure 21. Effect of Loudspeaker Height on Sound Pressure Level Measured With a Flush-Mounted Microphone

The adjustment factors for flush-mounted microphones 5 and 25 ft above the ground with the source at ground level (nominally 0 ft) are shown in figure 22. The adjustment is a fairly constant 6 dB for both microphone heights, indicating that a ground level loudspeaker could be suitable for sound insulation measurements in multistory buildings.

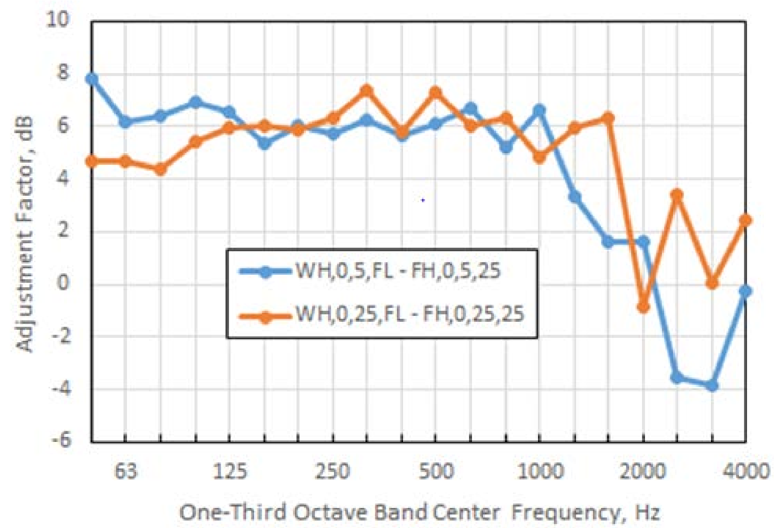


Figure 22. Adjustment Factor for Flush-Mounted Microphones 5 ft and 25 ft Above the Ground With a Ground-Level Loudspeaker

Measurements of the sound level with the loudspeaker and microphone both at 5 ft above a hard concrete surface and with the microphone located at 2, 4, 5.3, and 7.1 ft from the wall are shown in figure 23. The dips in the curve at low frequencies for the near-wall microphones are the result of destructive interference from wall reflections occurring at predicted frequencies of 199, 100, 75, and 56 Hz for microphone distances of 2, 4, 5.3, and 7.1 ft, respectively. The depth of the dips reduces as the microphone distance increases due to the increase in path length difference between the direct and reflected paths. Note that the ground destructive interference is evident at 315 Hz for all microphone distances. As noted in the previous figures, the dip at 2500 Hz for the flush-mounted measurement is due to the actual 0.15 ft separation of the microphone diaphragm from the wall.

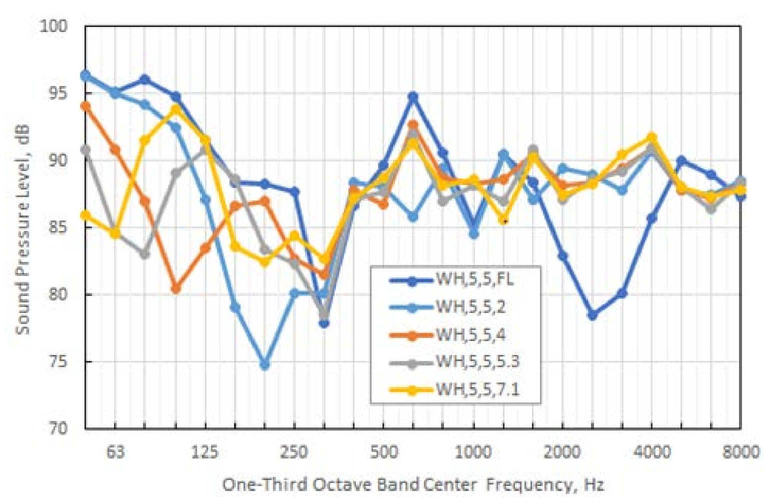


Figure 23. Sound Pressure Levels at Different Distances From a Wall With Loudspeaker and Microphone 5 ft Above a Hard Ground Surface

Comparing the levels in figure 23 with those measured under free-field conditions provided the effect of the wall on the sound incident to the wall. Note that the wall effect, or adjustment factor, is defined as the change in level at a near-wall microphone relative to the level that would exist at the wall if the wall were absent. The latter is given by the free-field measurement. This is shown in figure 24 for the different microphone distances. As shown, there is a large variation in the wall effect at frequencies below 400 Hz. Over the frequency range 100 to 1000 Hz, the average wall effect is about 4 dB but with variations of ±4 dB.

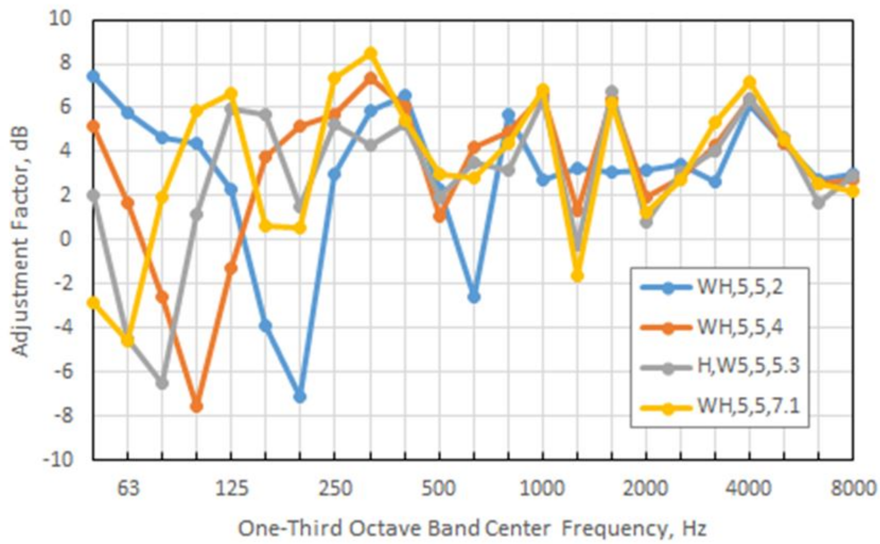


Figure 24. Adjustment Factor for Different Microphone Distances From a Wall With Loudspeaker and Microphones 5 ft Above the Ground

At higher frequencies from 400 to 1000 Hz, the effect averages at about 3 to 3.5 dB, but there is considerable variation (±3 dB) about that average. Some of this variation is due to changes in the ground reflection interference frequency as the microphone moved away from the wall and closer to the loudspeaker. This can move the interference frequency to an adjacent one-third octave frequency band for the wall measurements, whereas the interference frequency for the comparison free-field measurements is based on a constant 25-ft separation. Similar results, but with less variation with frequency, were obtained for propagation over a grass surface.

The result of similar measurements with the loudspeaker and microphones both at 25 ft above the ground are shown in figure 25, where the variation with frequency is considerably less than with the loudspeaker and microphones at 5 ft. For microphone distances at and greater than 4 ft, the wall effect generally averages at 3 to 3.5 dB, ±1.5 dB, over the frequency range 125 to 2000 Hz.

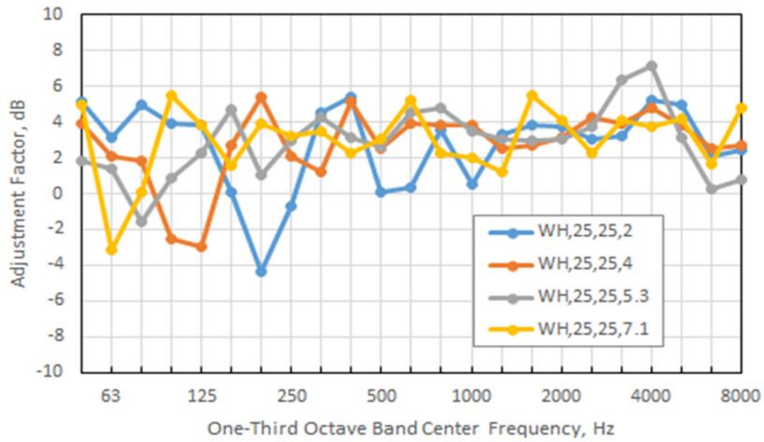


Figure 25. Adjustment Factor for Different Microphone Distances From a Wall With Loudspeaker and Microphones 25 ft Above the Ground

The measured adjustment factors for both flush-mounted and near-wall microphones varies significantly with frequency and is dependent on the specific loudspeaker and microphone configuration. The effect of these factors on the measured A-weighted noise reduction depends on the aircraft noise spectrum used to weight the measured noise levels. Figure 26 shows three aircraft departure noise spectra measured at MHT during the field tests for a Boeing B-737, Propeller (Prop), and Regional Jet (RJ), and two spectra measured by CSDA at MKE [31] and Boston Logan International Airport (BOS) [35], normalized to a level of 70 dB at 1000 Hz.

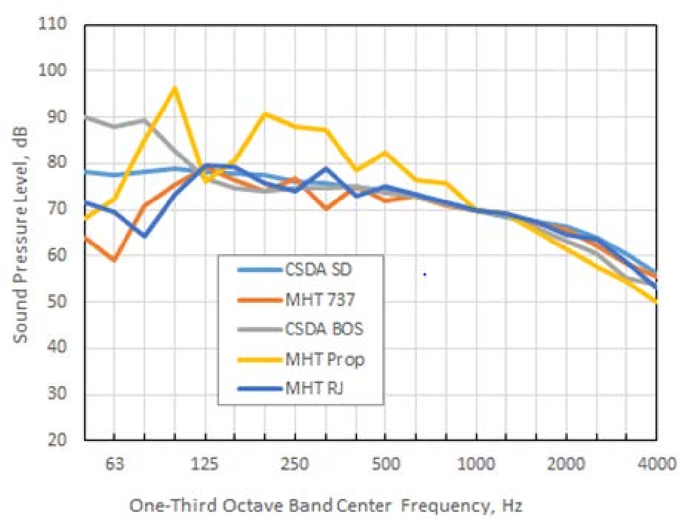


Figure 26. Departure Aircraft Sound Pressure Level Spectra Measured at MHT, MKE, and BOS

The adjustment factors from figures 18, 20, 24, and 25 were applied to each of these spectra resulting in the effective adjustment to the measured A-weighted noise levels shown in figure 27 for flush-mounted and near-façade microphone configurations with a loudspeaker at 5 and 25 ft over hard ground and grass.

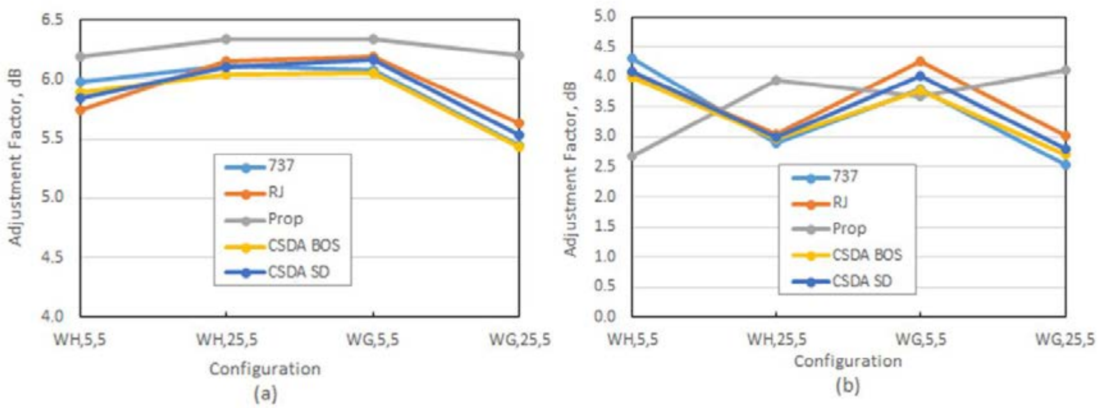


Figure 27. Adjustment Factor for Different Aircraft Spectra for a (a) Flush-Mounted Microphone and (b) Microphone 4 ft From a Wall

As shown, the adjustment factor for a flush-mounted microphone is between 5.5 and 6 dB for jet aircraft, but is larger at 6 to 6.5 dB for propeller aircraft. For a near-façade microphone 4 ft from the façade, the adjustment factor is 3 to 4 dB.

3.4 SUMMARY OF RESULTS.

A summary of the results from the initial field tests is as follows:

- The data indicate that the adjustment factor for a flush-mounted microphone should be the theoretical value of 6 dB and not 5 dB as quoted in ASTM E966-10 [2], nor 4 dB as shown in Bradley and Chu [19].

- The adjustment factor for near-façade microphones varies considerably with frequency and with distance from the wall and the height of the source/microphone configuration. The factor is greater than 2 dB at most frequencies and closer to 3.5 to 4 dB.

It should be noted that the data presented above represent measurements at a single fixed point on a façade, hence the variation with frequency due to ground reflection interference. Common practice among consultants is to measure an average façade level either by averaging the level over several fixed positions for flush measurements, or by scanning over the entire external surface of the façade for near-façade measurements. As noted in section 2.6, the former method requires adequate spatial sampling.

4. FAÇADE NOISE SIMULATION MODEL.

4.1 MODEL FORMULATION.

The façade noise simulation model was developed to estimate the noise levels on and near a building wall surface produced by two sources:

- an aircraft overflight at a distance of about 1000 ft (a plane wave excitation), and

- a stationary loudspeaker at a distance of between 20 and 40 ft and height between 0 and 30 ft (spherical wave excitation) at an angle in the range 0° (normal) to 75°.

The model includes the direct propagation path from source to receiver, the ground-reflected path with varying ground impedance, and the reflection of both from the façade. The model includes diffraction effects that influence the noise level on and near the building façade at low frequencies.

The principles of the time-domain simulation in the current study are based on the basic physical conservation laws (mass, momentum, and energy). The primary advantage of this technique is its ability to accommodate a wide variety of physical phenomena, including ground effects, diffraction over buildings and walls, and acoustic sources and receivers on moving platforms.

The concept of the time-domain approach can be explained by looking at an acoustic propagation problem in the air where sound propagation is assumed to be an adiabatic process without the viscous effect. The governing equations are the Euler equations in the form of:

$$\frac{\partial p}{\partial t} + \mathbf{u}_{bg} \cdot \nabla p + \mathbf{u} \cdot \nabla p_{bg} + \mathbf{u} \cdot \nabla p = -\gamma (p \nabla \cdot \mathbf{u}_{bg} + p_{bg} \nabla \cdot \mathbf{u} + p \nabla \cdot \mathbf{u}) \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}_{bg} \cdot \nabla)\mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u}_{bg} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\alpha_{bg} \nabla p - \alpha \nabla p_{bg} - \alpha \nabla p \tag{2}$$

where α, **u**, and *p* represent the specific volume, velocity, and pressure respectively, and γ is the ratio of specific heats. The subscript, $_{bg}$, indicates the variables that are for the background flow, and the variables without this subscript are the acoustic fluctuation part. Equations 1 and 2 result from conservation of mass and conservation of momentum for the air, respectively. Fluctuations of specific volume can be related to fluctuations of pressure through the adiabatic relation, resulting in a closed set of equations for acoustic velocity and pressure. The last terms at both sides of equations 1 and 2 are nonlinear and can be neglected for linear acoustic propagation.

For rigid ground and walls, the boundary conditions for acoustic variables are specified. For non-rigid ground and walls, the time-domain computational model is based on the Zwikker-Kosten equations for porous media:

$$\frac{\partial p}{\partial t} = -\frac{\gamma p_{bg}}{\Omega} \nabla \cdot \mathrm{u} \tag{3}$$

$$\frac{\partial \mathbf{u}}{\partial t} = -\frac{\Omega}{c_s} \alpha_{bg} (\nabla p + \sigma \mathbf{u}) \tag{4}$$

where Ω is the porosity, c_s is the porous medium structure factor, σ is the flow resistivity, and other parameters have the same meaning as those shown in equations 1 and 2.

A collocated-grid, second-order, finite-differencing in time and space computational scheme, along with an immersed-boundary method, has been developed to solve acoustic propagation represented by equations 1 and 4. The accuracy of the computational program has been validated by comparison with analytical solutions and measurement data available in the literature [39 and 40].

The noise level predictions are provided in terms of one-third octave bands from 50 to 4000 Hz and A-weighted noise levels at the wall surface and close to the surface. These are compared to levels that would be produced at the same locations in the absence of the building.

4.2 MODEL VALIDATION.

The façade noise simulation model described in section 4.1 was validated using the data gathered in the field tests described in section 3. The test conditions that were validated are presented in table 5.

Cases A through C represent the validation of the model in free-field conditions, with no nearby reflecting surfaces. The output of the model in these cases is presented as the difference between the noise level for a particular loudspeaker-microphone configuration and the level that would exist at the microphone in the absence of the ground surface. In other words, the data show the effect of the ground on the sound propagation. Figure 28 is an example of the ground effect for loudspeaker and microphone both 5 ft above ground and separated by a distance of 25 ft. The continuous curve is the modelled ground effect as a function of a sliding one-third octave band center frequency. The individual data points are measured values from the field tests described in section 3. The model results follow the general shape and match the values of the experimental results. The ground interference frequencies also are also accurately predicted.

Table 5. Description of Model Validation Test Cases

ID	Configuration Nomenclature	Case Description
A	FH,5,5,25—FH,25,22.4,25	Free-field (5,5) configuration at 25 ft, hard ground, compared to free-field (25,22.4) at 25 ft
A Grass	FG,5,5,25—FG,25,22.4,25	Free-field (5,5) configuration at 25 ft, grass ground, compared to free-field (25,22.4) at 25 ft
B	FH,5,5,25—FH,5,0,25 -6	Free-field (5,5) configuration at 25 ft, grass ground, compared to ground microphone at 25 ft less 6 dB
C	FH,5,5,25—Est. FF level at 25 ft	Free-field (5,5) configuration at 25 ft, grass ground, compared to free-field at 25 ft estimated from 1 m level
D	WH,25,21.6,FL—FH,25,22.4,25	Flush at wall compared to free-field at same distance with no ground
E	WH,5,5,FL—FH,5,5,25	Flush at wall compared to free-field at same distance with hard ground
F	WG,5,5,FL—FG,5,5,25	Flush at wall compared to free-field at same distance with grass ground
G	WH,5,5,FL—FH,25,5,25	Flush at wall compared to free-field at same distance with hard ground
H	WH,25,21.8,4—FH,25,22.4,25	4 ft from wall compared to free-field at same distance with no ground
I	WH,25,21.8,5.3—FH,25,22.4,25	5.3 ft from wall compared to free-field at same distance with no ground
J	WH,25,21.8,7.1—FH,25,22.4,25	7.1 ft from wall compared to free-field at same distance with no ground
K	WH,5,5,4—FH,5,5,25	4 ft from wall compared to free-field at same distance with hard ground
L	WH,5,5,5.3—FH,5,5,25	5.3 ft from wall compared to free-field at same distance with hard ground
M	WH,5,5,7.1—FH,5,5,25	7.1 ft from wall compared to free-field at same distance with hard ground

Note: See appendix C for test conditions nomenclature.

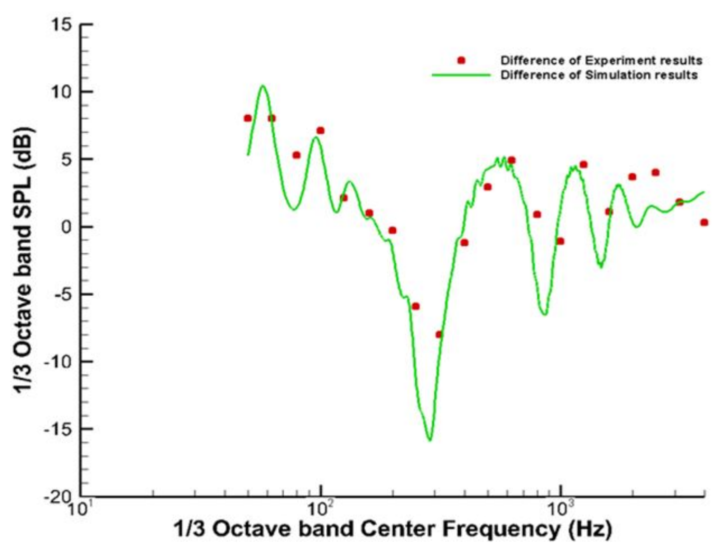


Figure 28. Comparison of Model and Experimental Data for the Change in Noise Level at a 5-ft Microphone Due to the Ground Effect in Sound Propagated From a 5-ft Loudspeaker at a Distance of 25 ft

The comparisons of the model predictions with experimental data for the free-field measurements (cases A through C in table 5) are presented in figure 29 with the modelled values taken at the specific standard one-third octave band center frequencies. The plots in this figure represent the effect of hard and soft ground on the propagation over a distance of 25 ft. In all cases, the model predictions closely followed the experimental data over the frequency range 100 to 2000 Hz. The fundamental and odd number harmonics of the ground-interference frequency (293 Hz) are predicted quite well. Minor differences are the result of averaging the modelled values over the one-third octave frequency bandwidths.

Figures 30 through 32 present the validation of the model for estimating the adjustment factors to be applied to façade and near-façade measurements in order to obtain the equivalent incident noise level that would exist in the absence of the façade.

Figure 30 presents comparisons of the model predictions with experimental data for measurements made with a flush-mounted microphone (cases D through G in table 5). The model accurately predicts the measured data for different combinations of loudspeaker and microphone configurations over hard and grass surfaces. There is close agreement at all frequencies up to 1000 Hz for the flush-mounted microphone, with the adjustment factor averaging at about 6 dB. At higher frequencies, the 0.15-ft separation of the flush microphone from the surface (in both the measurements and modelling) led to interference effects that reduced the adjustment factor. Overall, the model predicts approximately 1 dB high.

Figure 31 (cases H through J in table 5) shows the comparison between modelled and measured results for near-façade microphones with the loudspeaker and microphones heights at 21.8 and 22.4 ft respectively, thus minimizing the effect of ground reflections for microphone distances of 4, 5.3, and 7.1 ft. from the façade.

Figure 32 (cases K through M in table 5) shows the same comparison as figure 31, but with both the loudspeaker and microphones heights at 5 ft, which is the more typical field measurement configuration. Again, the model accurately predicts the measured data for most conditions, except at 315 and 800 Hz for the 5-ft-high configuration. These frequencies are the first and second (odd multiple of 3) ground interference frequencies for 5-ft microphone and loudspeakers separated by a distance of 25 ft, which are apparent in the free-field data to which the near-façade data are compared. As the microphone is moved away from the wall surface, its distance from the loudspeaker is reduced, and the ground interference frequency is also reduced (from 293 Hz at 25 ft to 218 Hz at a spacing of 7.1 ft from the façade). The resulting mismatch of ground interference frequencies in the data comparison creates more noticeable peaks in cases L and M as the distance of the microphone from the façade is increased. The peaks were more pronounced in the model simulation.

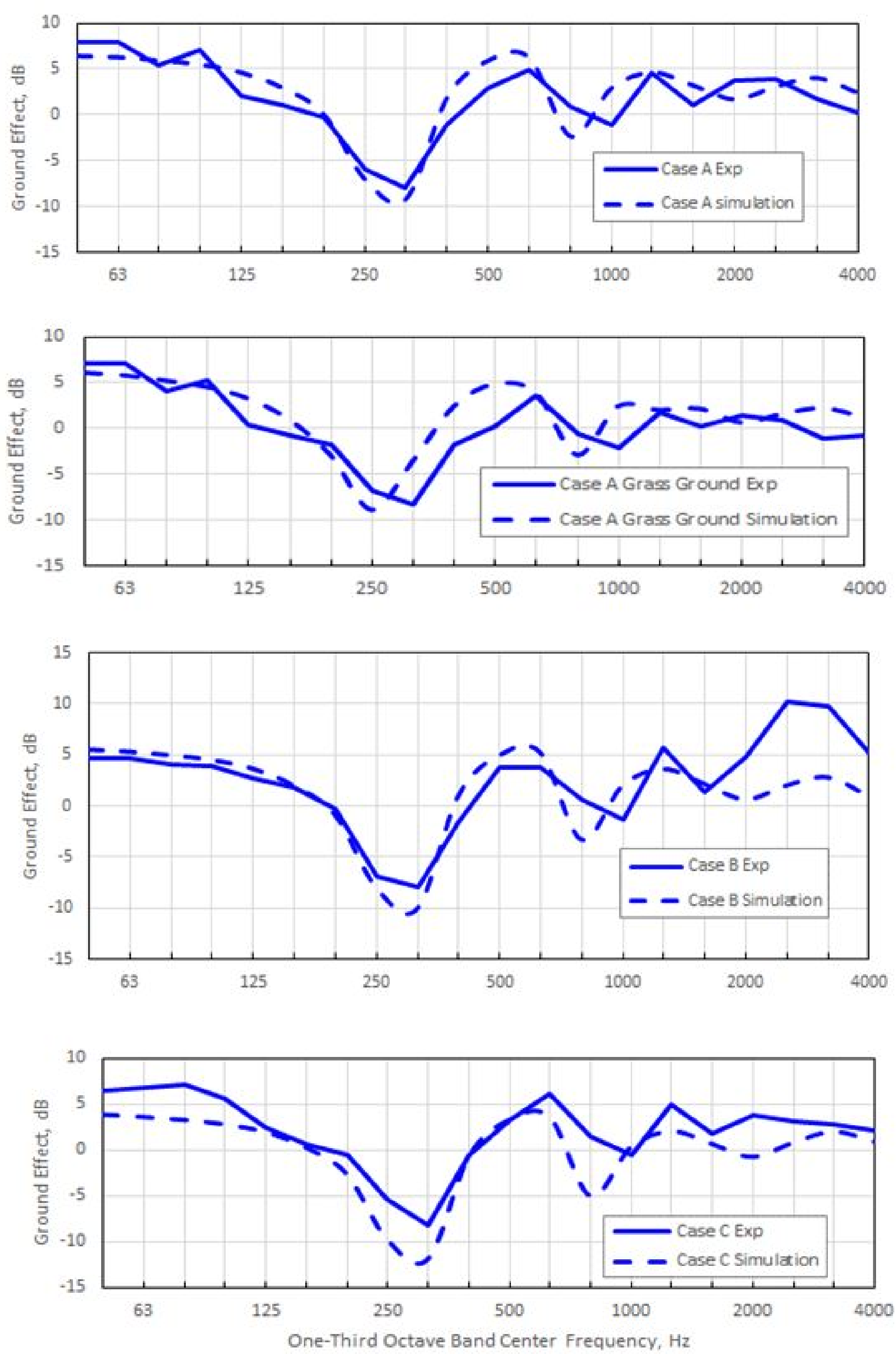


Figure 29. Ground Effect for Loudspeaker-Microphone Configuration: Cases A Through C
(See table 5 for case definition.)

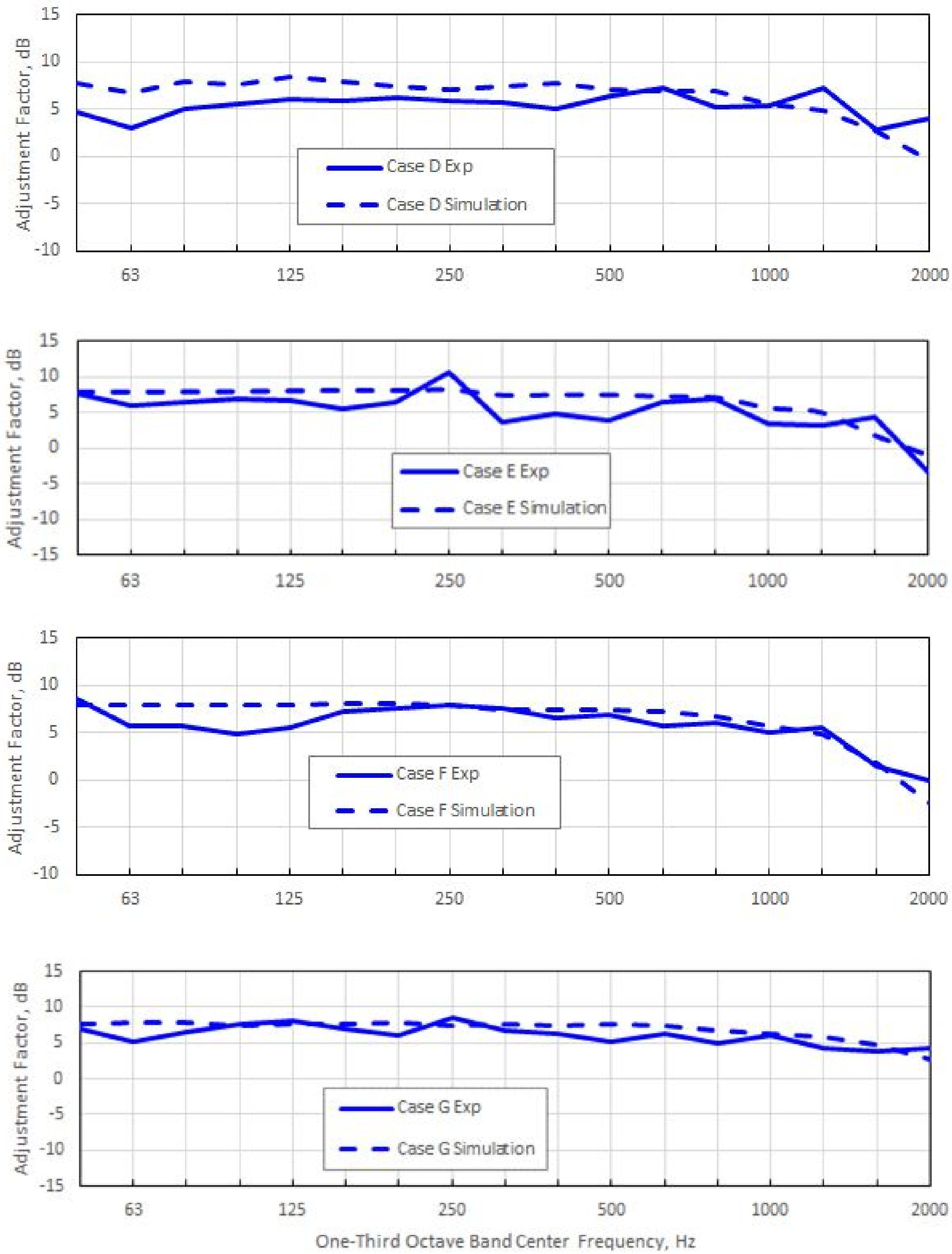


Figure 30. Adjustment Factors for Loudspeaker-Flush Microphone Configuration: Cases D, E, F, and G (See table 5 for case definition.)

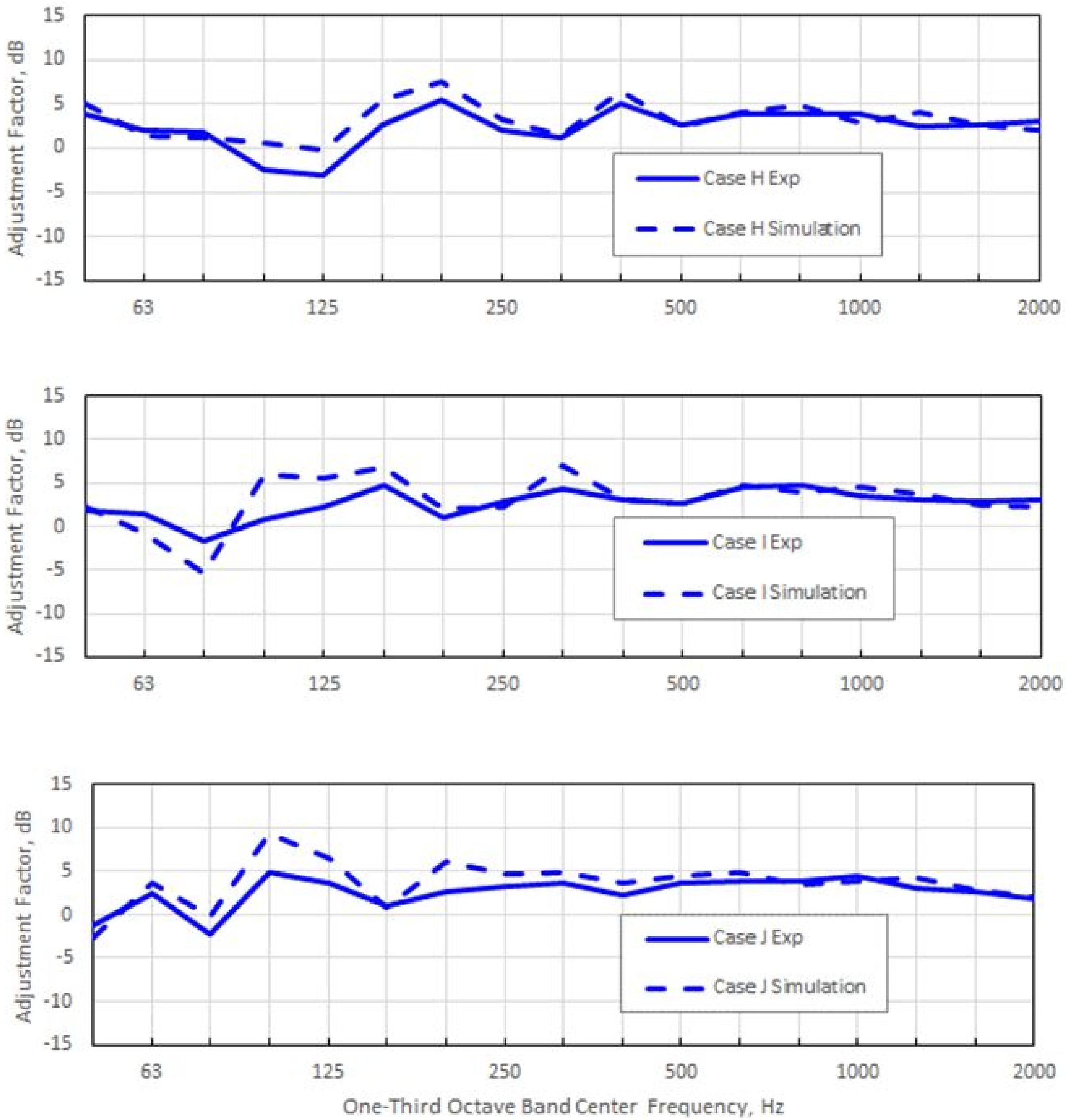


Figure 31. Adjustment Factors for Loudspeaker-Near-Façade Microphone Configuration: Cases H, I, and J (See table 5 for case definition.)

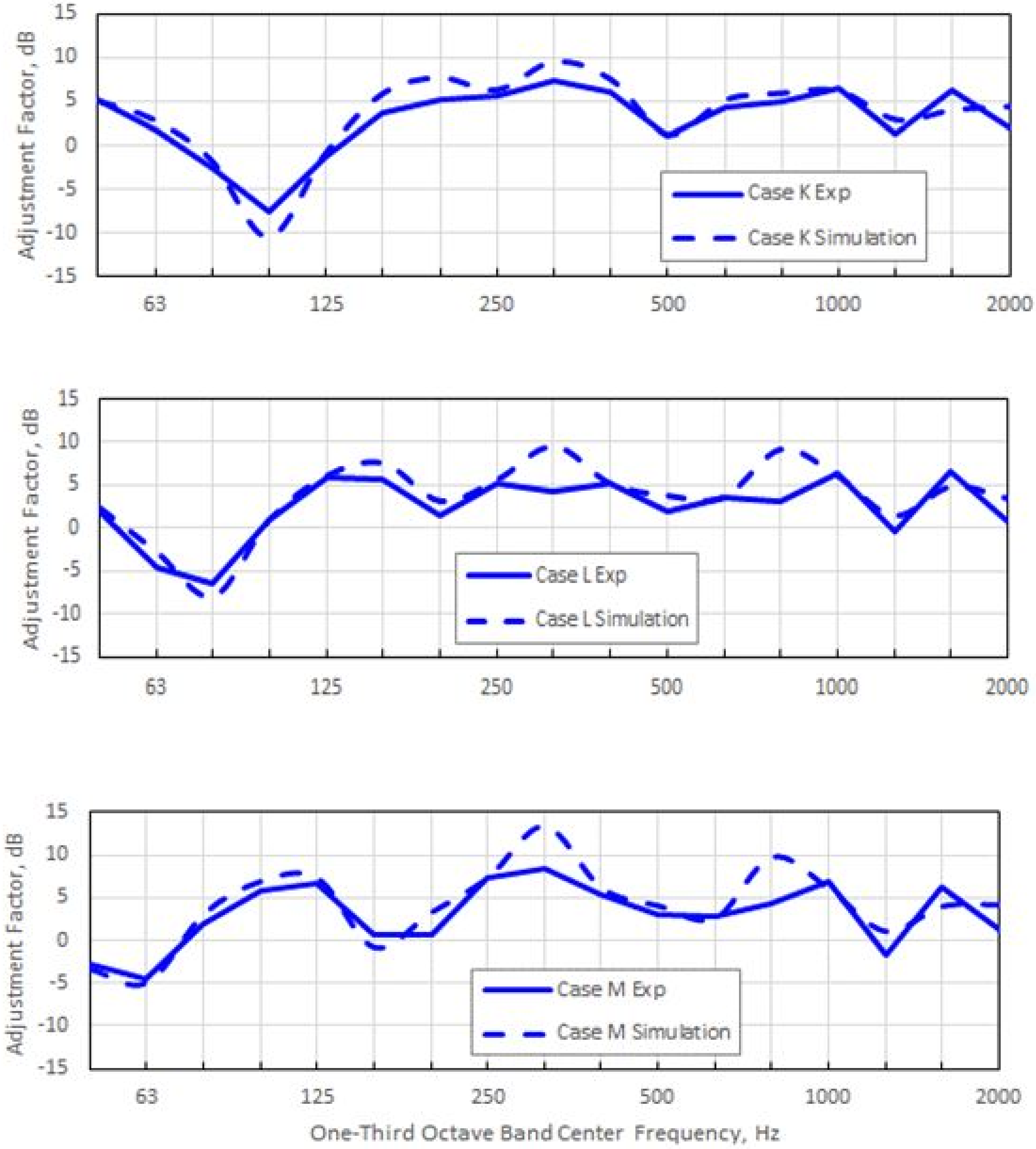


Figure 32. Adjustment Factors for Loudspeaker-Near-Façade Microphone Configuration: Cases K, L, and M (See table 5 for case definition.)

All the validation examples above are for a loudspeaker microphone distance of 25 ft. Figure 33 demonstrates the agreement between model and experimental results for free-field propagation over a hard surface at distance of 50 ft.

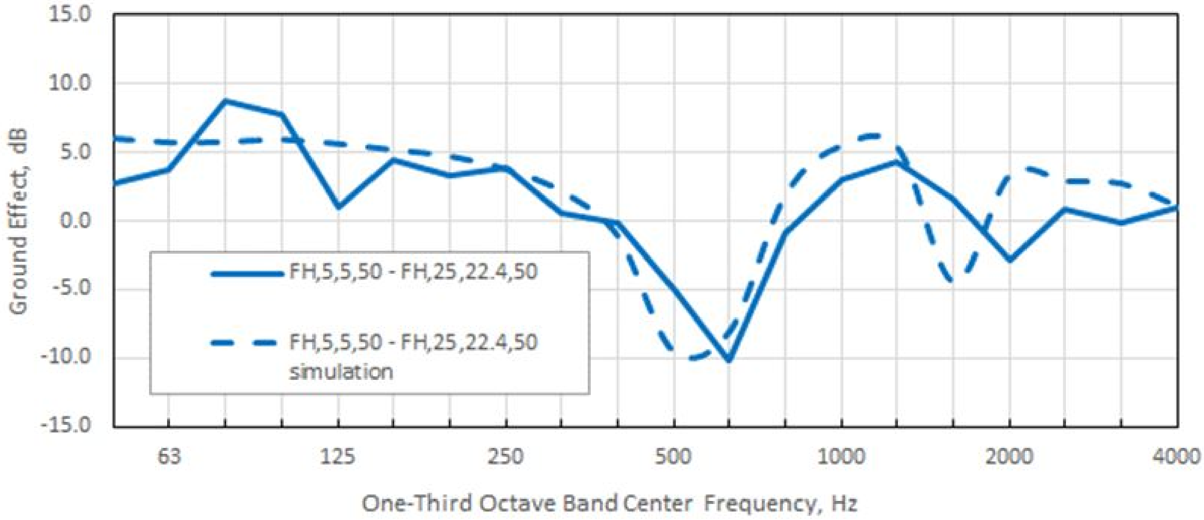


Figure 33. Comparison of Model and Experimental Data for Free-Field Propagation Over a Hard Surface at a Distance of 50 ft With Loudspeaker and Microphone 5 ft Above the Ground

The following observations are made from the model validation measurements:

- The model has been demonstrated to accurately simulate the exterior noise levels in free-field propagation and flush with a façade produced by a nearby artificial noise source as would be typically used in sound insulation measurements according to ASTM E966-10 [2].

- The model currently exhibits some variation with experimental data for near-façade microphone positions, although the general trends are in line with the experimental data.

- The data demonstrate that the adjustment factors for flush-mounted and near-façade microphones should be 6 dB and 3.5 to 4 dB respectively and not 5 dB and 2 dB as quoted in ASTM E966-10 [2].

4.3 DIFFRACTION EFFECTS.

In section 2.5.5, it was noted that several authors of published literature have addressed the issue of diffraction of sound at the edges of a finite-sized façade that could modify the noise level from aircraft and loudspeaker sources. Bradley et al. [18] attributed some variations in adjustment factors to diffraction effects, but Davy [22] found that diffraction effects on a panel are minimal at frequencies of interest to sound insulation measurements. Hopkins and Lam [24] concluded that diffraction effects were negligible above 100 Hz for near-façade measurements 1 to 2 m from the façade. To resolve this issue, the validated façade noise model was exercised to estimate the influence of diffraction on flush- and near-façade measurements.

Figure 34 shows the configuration for the situation modelled. An omnidirectional sound source at coordinate (0,0) was 25 ft from an infinite wall O-A (case 1A). First, the sound level was calculated at each identified point on a 2-ft grid, where levels at (25,Y) were flush with the surface, and levels at (23,Y) and (21,Y) were near-façade estimates at distances 2 and 4 ft from the surface, respectively. The sound levels were then calculated at the same locations for the semi-infinite wall configuration, shown as O-B (case 1B), to determine the extent of diffraction effects resulting from the discontinuity at the point (25, 2).

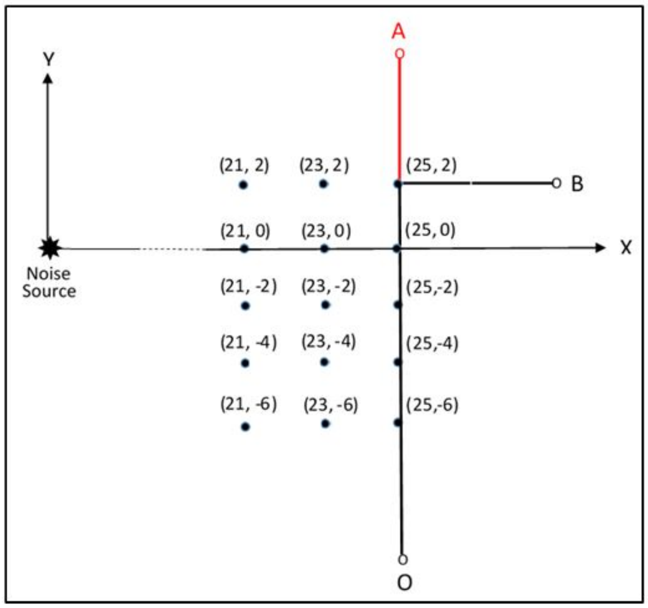


Figure 34. Source–Façade Configuration for Modelling Sound Diffraction

Figure 35 illustrates the diffraction effect. In case 1A, with an infinite wall, the red and blue lines represent the front and back of a pulse emitted by the point source 25 ft from the wall, showing the spherical wave being reflected by the wall with no apparent distortion.

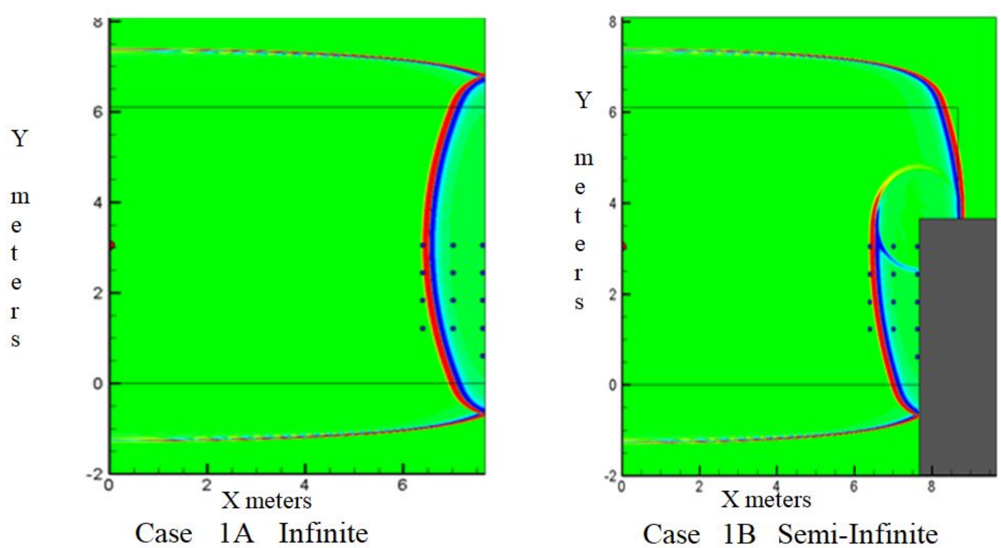


Figure 35. Illustration of Diffraction Effect at a Discontinuity

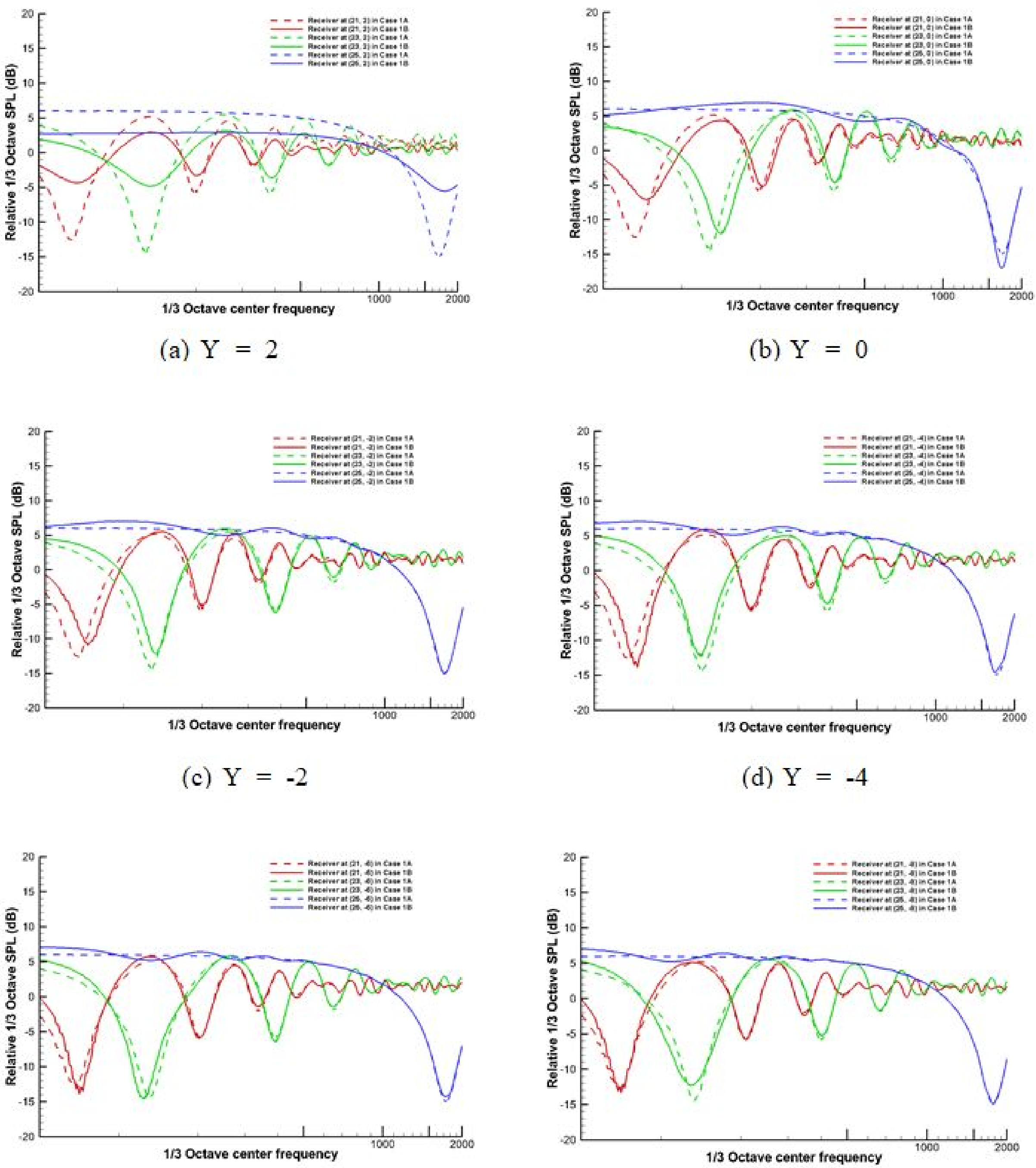
In case 1B, with the semi-infinite wall, the upper part of the wave is not reflected and continues past the discontinuity. The portion of the wave that is reflected undergoes diffraction effects near the discontinuity, which influences the sound levels in the immediate area. Other parts of the reflected wave are undisturbed.

The actual effect of the diffraction is presented in the six plots of figure 36. Each plot shows the sound level versus frequency for points at three different distances from the wall (X = 21, 23, 25 ft) for cases 1A and 1B. The six plots show these sound levels for different values of distance along the wall from the discontinuity (Y = 2, 0, -2, -4, -6, -8 ft).

The solid and dashed blue lines represent the level measured by a flush-mounted microphone. Note that the effect of the discontinuity at Y = 2 increases the flush sound level by about 3 dB for much of the frequency range (figure 36(a)). However, figures 36(b) through 36(f) show the change in level due to the discontinuity reduced to an average of zero for values of Y greater than 0 ft. This leads to the conclusion that diffraction only affects the sound level at distances within 2 ft of the discontinuity.

The green and red solid and dashed lines represent the levels at distances 2 and 4 ft, respectively, from the wall surface, showing the peaks and dips caused by interference from wall reflections. For these positions, the effect of diffraction from the discontinuity becomes insignificant for values of Y greater than -2 ft. This leads to the conclusion that diffraction only affects the sound level for near-façade microphones at distances within 4 ft of the discontinuity.

These results suggest that flush-mounted and near-façade measurements should not be taken within 2 and 4 ft, respectively, from the corners and roofs of buildings, confirming the results presented by Davy [22] and Hopkins and Lam [24].



(a) Y = 2

(b) Y = 0

(c) Y = -2

(d) Y = -4

(e) Y = -6

(f) Y = -8

Figure 36. Predicted Sound Level From an Omnidirectional Noise Source at a Distance of 25 ft From the Surface of an Infinitely High Façade (Case 1A) and a Finite Height Façade (Case 1B) (as shown in figure 34)

4.4 INFLUENCE OF GROUND-SURFACE IMPEDANCE.

The ASTM E966-10 [2] procedure allows exterior noise levels to be measured by calibrating the loudspeaker in a free-field environment at the same distance to that used at the test site. This method, together with a flush microphone, is quoted in the ASTM E966-10 [2] as being the most repeatable method for loudspeaker sources. The one requirement of the procedure is that the calibration site ground surface must be similar to that at the test site.

To examine this requirement, the ground effect for different surfaces was modelled to determine the sensitivity of noise levels measured at 25 ft from a 5-ft-high loudspeaker. The modelling results were compared to measurements conducted at MHT (see section 3) and are shown in figure 37 for three different values of ground surface flow resistivity.

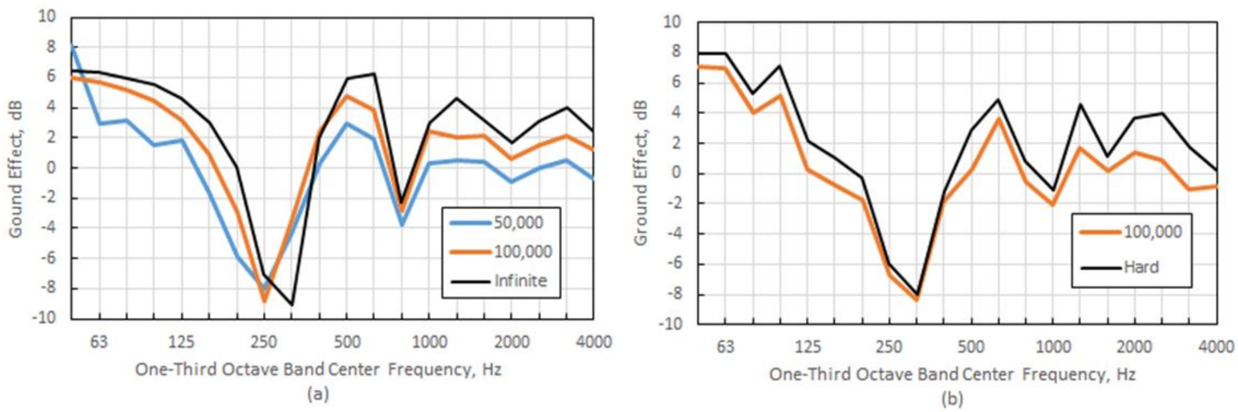


Figure 37. (a) Modelled and (b) Measured Ground Effect for Propagation Over a Distance of 25 ft for Different Ground Surfaces With Loudspeaker and Microphone at 5 ft Above the Ground (Ground Surface Flow Resistivity σ in Pascal seconds per square meter (Pa.s/m^2).)

To provide context, the ground resistivity of different ground surfaces are typically as follows:

- Grass field: σ = 50,000 Pa.s/m^2
- Grass lawn or institutional grass: σ = 100,000 to 300,000 Pa.s/m^2
- Hard concrete: σ = 30 x 10^6 Pa.s/m^2 (essentially ∞)

The measured results represent the typical range of situations encountered in suburban housing with flow resistivity in the range of 100,000 to ∞. For a typical aircraft spectrum (B-737 departure), the corresponding predicted and measured difference in ground effect is about 1.4 dB, which is probably the maximum error that would be introduced by adopting the loudspeaker calibration method.

5. APPLICATION OF UPDATED ADJUSTMENT FACTORS TO EXISTING NLR DATABASE.

In section 3.3, updated adjustment factors were developed to account for façade reflection in the measurement of noise reduction for airport sound insulation programs. The updated factors, based on measurement data from tests conducted at MHT and validated with data from the façade noise model in section 4, modified the existing factors recommended in ASTM E966-10 [2] from -5 and -2 dB to -6 and -3.5 dB, respectively, for flush- and near-façade measurements using a loudspeaker noise source. To assess the appropriateness of these proposed updates, they were applied to the measured loudspeaker noise reduction data contained in study reports prepared by CSDA [31], Schomer et al. [35], and L&B [29], and the resulting values of noise reduction compared to those measured with an aircraft source.

However, in reviewing the noise reduction data developed in these previous studies, it was noted that there is poor agreement between noise reduction measured by an aircraft overflight and a loudspeaker noise source (see section 2.4). On average, the loudspeaker method produces noise reduction values that are 2 to 3 dB less than for an aircraft overflight, depending on the positioning of the exterior microphone and loudspeaker relative to the façade under test. Application of the updated adjustment factors would lower the noise reduction as measured with a loudspeaker and thus further increase the difference between aircraft and loudspeaker measurements.

There are two main reasons for the discrepancy between aircraft and loudspeaker measurements, namely:

- The exterior aircraft noise levels measured in the three studies were not always representative of the sound to which the test façades were exposed. The exterior levels were measured at locations away from the test house to avoid the effect of reflections, whereas the levels of the sound actually incident on the façade(s) were often lower due to shielding by the house itself. Even corner rooms facing the aircraft flight track had a façade that was shielded for a portion of the overflight event. In contrast, the level of the incident sound on the façade(s) from the loudspeaker test was measured directly at flush-mounted or near-façade locations. Thus, the shielding effect must be taken into account when comparing aircraft and loudspeaker noise reduction measurements.

- The incident sound wave from an aircraft overflight varies in level, spectrum, and angle of incidence as the aircraft moves along its flight track. The noise reduction measurement using one single loudspeaker at a 45° degrees angle to the façade can simulate the spectrum, but it does not necessarily represent the variation of incident sound intensity with angle of incidence. This variation needs to be taken into account when comparing aircraft and loudspeaker noise reduction measurements.

These two effects are separate and are individually quantified in this section so that adjustments can be made to the aircraft measurements to resolve the discrepancies between the noise reduction data for aircraft and loudspeaker sources in the CSDA [31] and L&B [29] reports. Once this is achieved, the updated adjustment factors for loudspeaker measurements can be validated by applying them to the loudspeaker data from these reports and comparing them directly to the aircraft measurements.

5.1 SHIELDING EFFECTS IN THE FIELD MEASUREMENT OF NOISE REDUCTION.

To understand the shielding effect and how it can vary from room to room in an exposed house, consider the house-flight track configuration in figure 38 (not to scale), which shows an aircraft flight track parallel to the front façade of a house. The layout shows two rooms (1 and 3) on the front side of the house each having two perpendicular external façades, and one room (2) with just one façade. As the aircraft approaches the house from the left of the figure, the closest façade, AF, of room 1 is directly exposed and façade FA is partially shielded. When the aircraft approaches the building, both façades of room 1 are exposed. It is at this point, or slightly thereafter, that the house is exposed to the maximum noise level. As the aircraft continues along the flight path, façade AF is shielded. The reverse situation occurs for room 3, where façade DF is shielded from the approaching but not from the departing aircraft. Note that room 2 is not shielded from the aircraft noise in this configuration, but it would be partially shielded if the flight track were not parallel to the front surface of the building. Façade RA is shielded from the entire overflight.

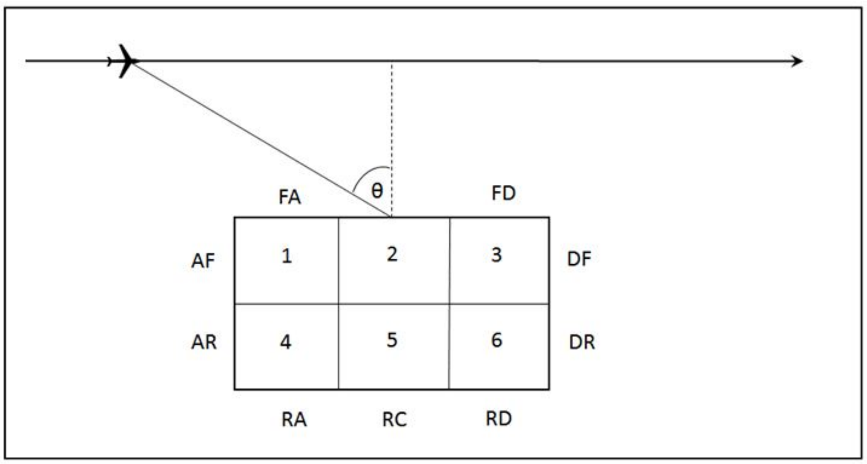


Figure 38. Plan View of a Rectangular Building Exposed to Noise From an Aircraft Overflight

The amount of shielding of the room façades is complicated by the directivity of the noise radiated by the aircraft, which is frequency dependent. In general, high-frequency noise from the engine inlet radiates forward, and low-frequency noise from the exhaust radiates rearwards. Thus façade AF of room 1 receives mainly high-frequency noise from the approach, but it is shielded from low-frequency noise from the departing aircraft. The reverse is true for façade DF of room 3.

Subsequent examination of the detailed data obtained from CSDA [31] and L&B [29] show that, in many cases, the noise exposure of the house's tested façades is quite different for aircraft and loudspeaker sources. Thus, the noise reduction measured using aircraft is actually a combination of the noise reduction of the façade plus the noise reduction provided by shielding. The differences between the measurements of noise reduction using the two sources may be largely due to the shielding, which is specific to the house configuration relative to the aircraft flight track.

5.2 CALCULATION OF THE SHIELDING EFFECT.

To determine the magnitude of the shielding effect, it is necessary to calculate the sound energy transmitted into an exposed room from an aircraft overflight. This then can be compared directly to that transmitted from a loudspeaker exposure to develop a relationship between the noise reduction as measured using the two sources.

As the aircraft approaches the house shown in figure 38, the noise level inside room 1 is largely determined by the sound energy transmitted by façade AF. As the aircraft continues along the flight track, the interior level is largely determined by the sound energy transmitted through façade FA. The noise metric used to measure the exterior and exterior noise levels is the SEL, which represents the total acoustic energy over the entire overflight event. If the aircraft radiated sound equally in all directions, then the interior level in room 1 would be about 3 dB less than it would be if both façades AF and FA were equally exposed. However, because of the aircraft spectrum and directivity and the diffraction of the sound around the building, the actual shielding can be more than this on the approach and less on the departure façades of the building.

The façade noise simulation model described in section 4 was exercised to model the shielding effect of a rectangular building to plane wave sound arriving at angles ranging from 0° to 90°. The model configuration is shown in figure 39, with a plane wave incident from the top right-hand corner. The model calculates the sound levels at various locations around the building, as indicated in the figure, relative to a free-field level (with no building).

Using aircraft noise data obtained from the MHT measurements (see section 3), the directivity of the noise from a B-737 departure event was determined over a range of angles. The free-field noise spectra as a function of angle for a single overflight are shown in figure 40.

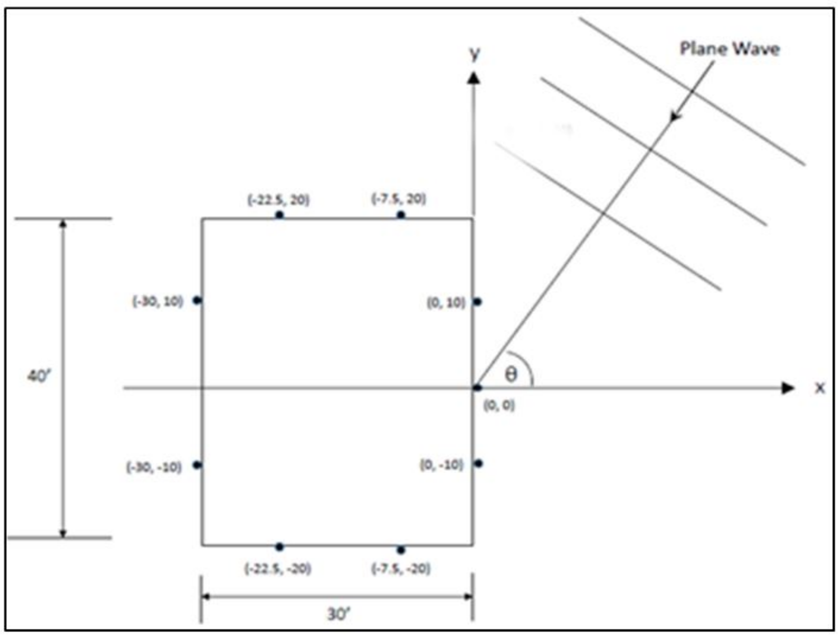


Figure 39. Plan View of Building and Source Configuration for Modelling of Shielding Effect

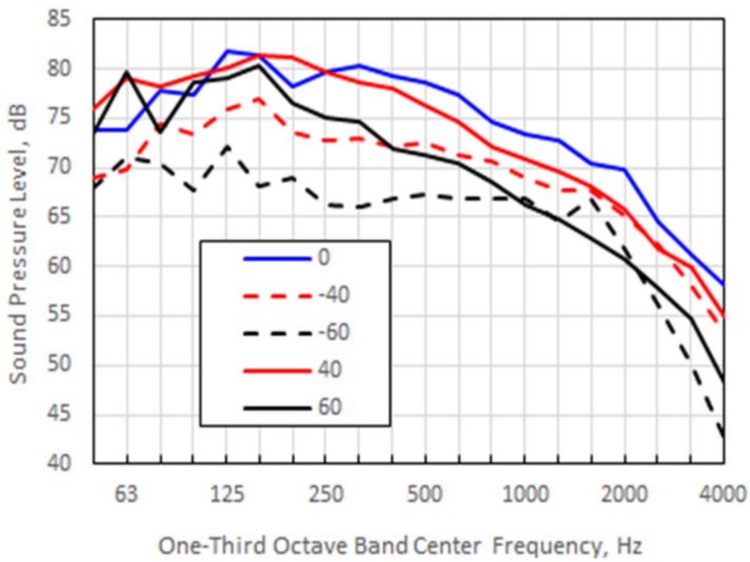
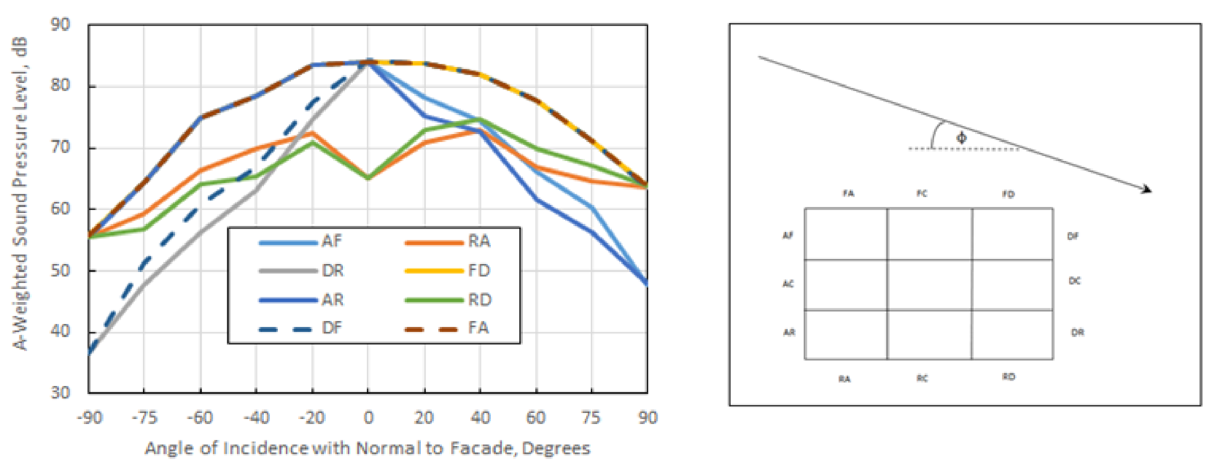


Figure 40. Free-Field Noise Spectra as a Function of Angle for a B-737 Departure

The aircraft spectrum for each angle was applied to the shielding data for the same angle to calculate the A-weighted noise levels at different façades of the building for a complete aircraft overflight event. Figure 41 shows the resulting sound level as a function of aircraft angle θ with the normal to the front façade, where negative angles of incidence represent the approaching aircraft and positive angles represent the departing aircraft. Note that the data in this figure is for a building with the front façade parallel to the flight track, i.e. ϕ = 0. Similar plots were developed for ϕ = -40 and +40 degrees.

Figure 41 demonstrates the effect of shielding on the noise levels at different façades as the aircraft passes by the building.



(a) (b)

Figure 41. A-Weighted Sound Pressure Level at (a) Different Façades of a Building for a B-737 Departure as a Function of Angle of Incidence and (b) Orientation of Building to Flight Track

5.3 ADJUSTMENTS FOR ANGLE OF INCIDENCE.

The sound from an aircraft overflight is incident over a wide range of angles, but the relative importance of sound from different angles is not the same in the degree to which it influences noise reduction. The basic expression for the noise reduction, NR_θ, relating the exterior and interior noise levels of a room exposed to a source of noise is expressed in equation 5 [2] as:

$$NR_\theta = L_1 - L_2 = TL_\theta - 10\times\log(S\times\cos\theta/A) - 6, \text{ dB} \qquad (5)$$

where L_1 is the exterior incident sound level, L_2 is the interior sound level, S is the area of the façade, TL_θ is the transmission loss of the façade at the angle of incidence θ with the normal, and A is the interior absorption. As shown in equation 6, rearranging this expression gives the interior level as:

$$L_2 = L_1 - TL_\theta + 10\times\log(S\times\cos\theta/A) + 6, \text{ dB} \qquad (6)$$

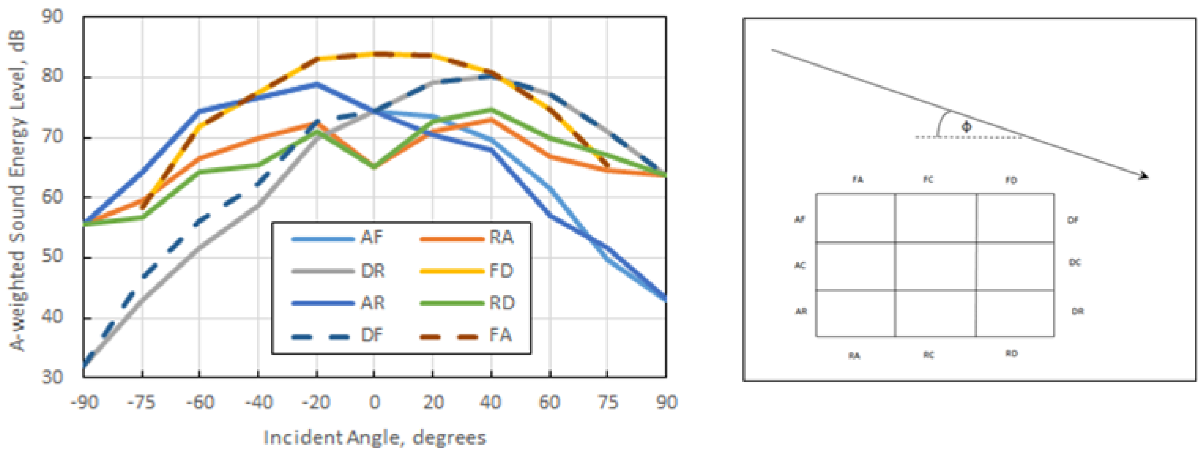
The S.cosθ term in this expression represents the effective area of the façade exposed to the incident sound. For the same exterior sound level, less sound energy is incident onto the façade as the angle of incidence θ (with the normal) is increased because the subtended area of the façade is lower. Thus, at any given time (or angle) the incident sound energy is not represented by L_1 but by the quantity $L_1 + 10\times\log(\cos\theta)$.

For an elevated source, such as aircraft or an elevated loudspeaker, the angle θ is given in equation 7 by the expression:

$$\theta = \arccos(\cos\psi\times\cos\beta) \qquad (7)$$

where ψ is the azimuthal angle, and β is the elevation angle of incidence.

The effective incident sound energy level at each building façade in figure 38 is obtained by applying the log (cos θ) term to the incident noise level on the unshielded façades of the building, where θ is the angle of incidence to the normal of each façade. For façades perpendicular to the front façade of the building, the term applied is log (cos (90-θ)). Figure 42 shows the resulting exterior sound energy level as a function of aircraft angle θ for each room façade. Note that the data in this figure are for a building with the front façade parallel to the flight track, i.e. $\phi = 0$. Similar plots were developed for $\phi = -40°$ and $+40°$.



(a) (b)

Figure 42. A-Weighted Sound Energy Level at (a) Different Façades of a Building for a B-737 Departure as a Function of Angle of Incidence and (b) Orientation of Building to Flight Track

The plots in figure 42 are similar to those in figure 41 with the exception that the effect of angle of incidence is applied. Figure 42 essentially shows the incident sound energy levels from the B-737 departure that influence the amount of sound transmitted into the room and the noise reduction of the façade.

5.4 CALCULATION OF ADJUSTMENTS TO AIRCRAFT NOISE REDUCTION MEASUREMENTS.

The total sound energy inside a room at any given time during an aircraft overflight is the sum of the sound energies transmitted through the different façades of the room. Thus, the sound energy in room 1 of figure 38 at any given time is the sum of the sound energies transmitted through façades AF and FA, which in turn are related to the exterior incident energy level on each façade given in the plots of figure 42.

In determining the noise reduction of a room for an aircraft overflight, the exterior noise level is the measured SEL. The noise level data for a overflight shown in figure 42 as a function of angle is therefore converted to sound energy and summed over the event considering the time at each angle to determine the SEL at each façade for the event. The SELs at different façades of a room are then combined, and the total compared to the free-field SEL corresponding to that as measured by a remote microphone, to estimate the combined effect of shielding and angle of incidence. Figure 43 shows the results for the various rooms of a rectangular building with the front façade at angles of -40°, 0°, and +40° to the aircraft flight track.

ϕ = 0	FA	FC	FD	
AF	-3.2	-1.3	-2.5	DF
AC	-7.1		-4.3	DC
AR	-8.2	-9.3	-6.0	DR
	RA	RC	RD	

ϕ = -40	FA	FC	FD	
AF	-4.5	-2.6	-2.2	DF
AC	-8.2		-1.8	DC
AR	-7.2	-5.8	-3.2	DR
	RA	RC	RD	

ϕ = +40	FA	FC	FD	
AF	-1.6	-1.7	-3.8	DF
AC	-1.6		-7.9	DC
AR	-4.0	-10.6	-9.1	DR
	RA	RC	RD	

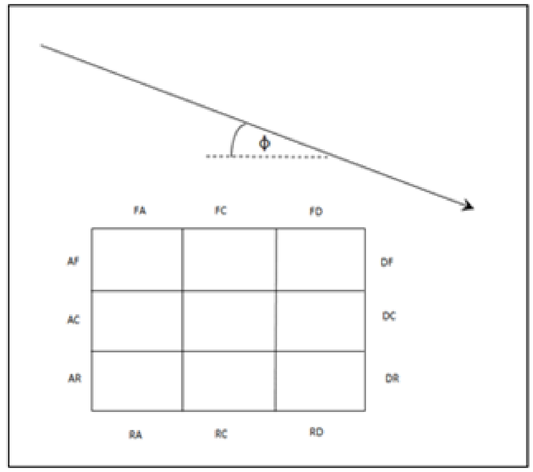


Figure 43. A-Weighted Adjustments in Decibels to Measured Aircraft Noise Reduction for Rooms in a Rectangular Building for Aircraft Departures

As an example, the adjustment for shielding and angle of incidence for the room in the upper left-hand corner of the building in figure 43, with ϕ = 0, is -3.2 dB, based on the contribution of sound levels incident on façades AF and FA.

5.5 APPLICATION OF SHIELDING DATA TO EXISTING NOISE REDUCTION DATABASE.

As noted in section 5, the issues of shielding and angle of incidence need to be considered when comparing noise reduction as measured using aircraft and loudspeaker sources. Accordingly, the A-weighted adjustments for aircraft noise shown in figure 43 are applied to the noise reduction measured in 30 rooms in the Schomer et al. [35] and L&B [29] databases for near-façade measurements, and to 11 rooms for flush measurements, to adjust the measured exterior noise levels; hence, those adjustments account for shielding and angle of incidence. Appendix D provides a table with details of the measurements of noise reduction and the adjustments applied. These modified values of noise reduction can be compared directly with the loudspeaker measured values to assess the updated adjustment factors developed in section 3 to account for façade reflection.

Figure 44 shows the relationship between noise reduction as measured by a loudspeaker mounted on a 6-ft tripod and by an aircraft overflight for the rooms tested by Schomer et al. [35] and L&B [29].

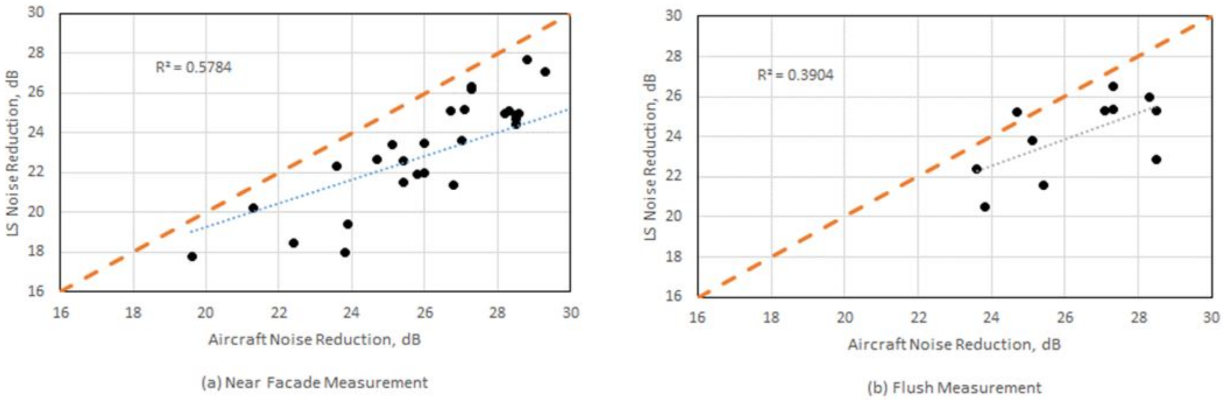


Figure 44. Comparison of Noise Level Reduction Measured With Aircraft and Tripod Loudspeaker Sources Using (a) Near-Façade and (b) Flush Microphones

These data were developed using adjustment factors of 5 and 2 dB for flush and near-façade measurements, respectively. The dashed red line represents the relationship if the two values were equal. The dotted blue line is the best linear trend in the data, with an R-squared (variance) of 0.58 and 0.39 for near-façade and flush measurements, respectively.

Figure 45 shows the comparison when the aircraft measured values are adjusted for shielding and angle of incidence applying the adjustments from figure 43. The spread of data is reduced, showing an R-squared of 0.71 and 0.59 for near-façade and flush measurements, respectively, and the trend line more closely follows a one-to-one relationship, but it is above the equal value line, i.e., loudspeaker noise reduction is greater than the adjusted aircraft noise reduction.

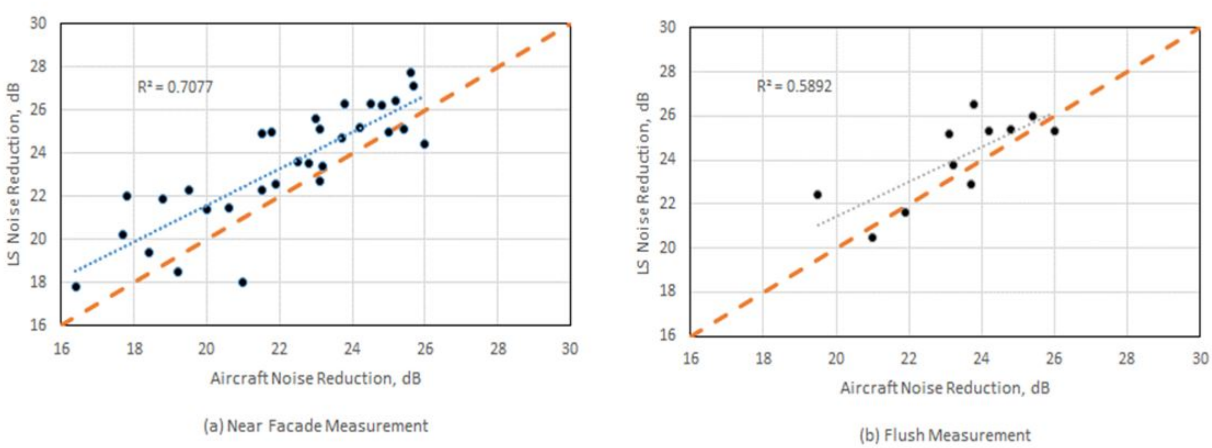


Figure 45. Comparison of Noise Level Reduction Measured With Aircraft and Tripod Loudspeaker Sources Using (a) Near-Façade and (b) Flush Microphone Positions, With Aircraft Data Adjusted for Shielding

Finally, figure 46 shows the comparison when the values of loudspeaker noise reduction are reduced by 1.5 and 1 dB for near façade and flush measurements, respectively, to correspond with the updated adjustment factors of 3.5 and 6 dB developed in section 3 to account for reflection from the façade surface.

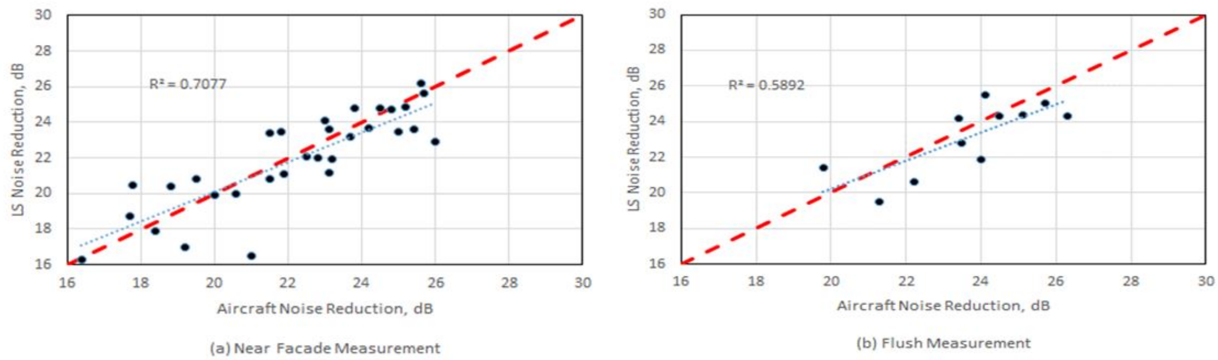


Figure 46. Comparison of Noise Level Reduction Measured With Aircraft and Tripod Loudspeaker Sources Using (a) Near-Façade and (b) Flush Microphone Positions, With Aircraft Data Adjusted for Shielding, and Loudspeaker Data Adjusted Using -3.5 and -6 dB Factors

A comparison of figure 46(a) and (b) show that tripod loudspeaker measurement of noise reduction conducted at an angle of 45° to the façade, including updated adjustment factors, are representative of aircraft measurements of noise reduction.

Figure 47 shows a similar series of relationships between aircraft and elevated loudspeaker measurements of noise reduction. Note that the spread of the data is not changed significantly, but the values corrected for shielding effects and with a 6 dB adjustment factor applied are slightly higher by about 1 dB on average than the one-to-one relationship.

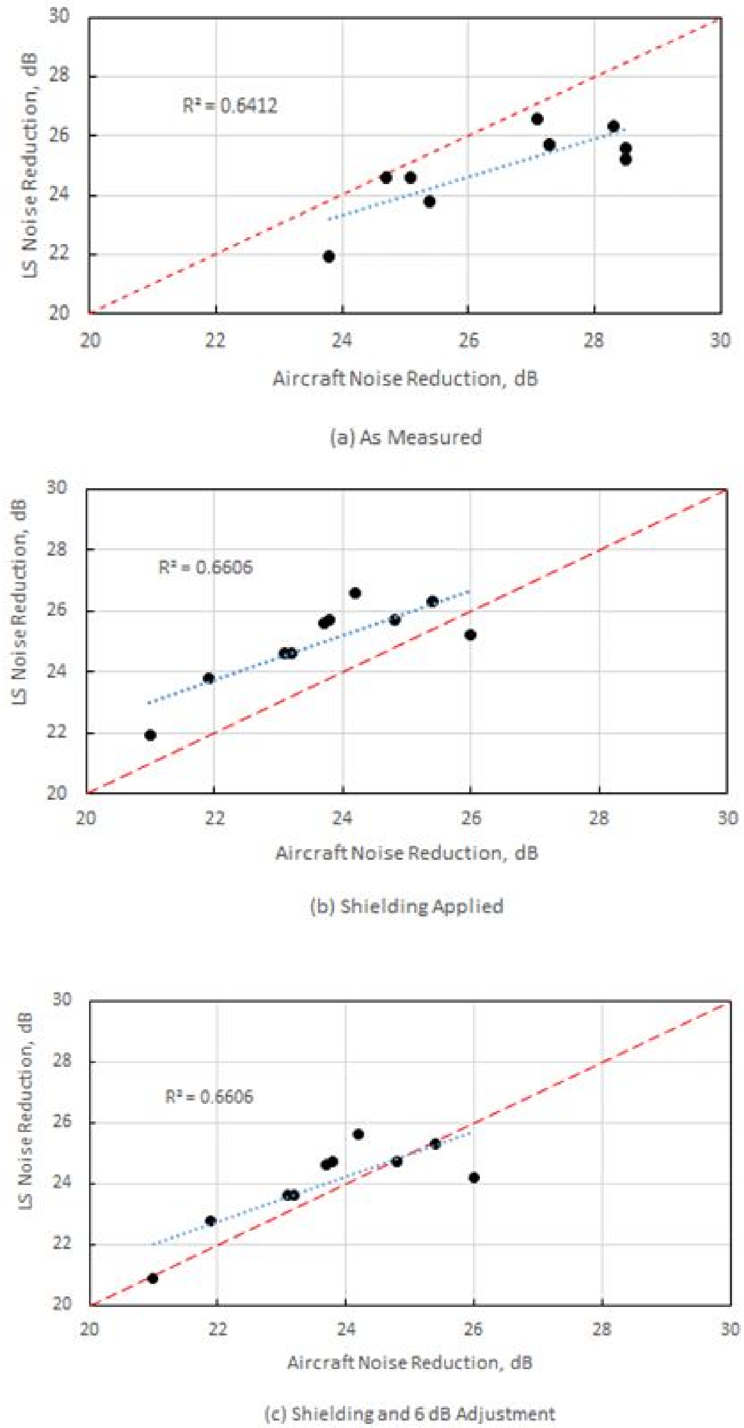


Figure 47. Comparison of Noise Reduction Measured With Aircraft and Elevated Loudspeaker Sources Using a Flush Microphone (a) as Measured, (b) Aircraft Data Adjusted for Shielding, and (c) Loudspeaker Data Adjusted Using -6 dB Factor

6. FIELD MEASUREMENTS TO VALIDATE UPDATED ADJUSTMENT FACTORS.

A series of field tests using both aircraft and loudspeaker noise sources were conducted with the following overall objectives:

- Measure and compare NLR with aircraft and loudspeaker sources for varying loudspeaker and microphone placement.
- Validate modelled shielding effects for different façades.
- Validate updated adjustment factors for flush- and near-façade microphone positions.
- Examine variation of exterior noise level from loudspeaker over façade surface and corresponding estimate of NLR.
  - Flush- and near-façade microphone positions
  - Variation in loudspeaker angle of incidence (center room with one exposed façade)
  - Variation in loudspeaker height
  - Single surface versus corner measurement
- Evaluate loudspeaker calibration measurement method.
  - Sensitivity of calibration ground surface
  - Comparison with other methods

The details of the measurement procedures and the results of the tests are described in the following sections.

6.1 TEST HOUSE DETAILS.

The field measurements were conducted at two houses adjacent to Louisville International Airport—Standiford Field (SDF) on July 11, 12, and 13, 2017. Both were cape-style houses with finished second floors. House 1 had gable windows; house 2 had dormer windows, as shown in figure 48. House plans are shown in figure 49.

- House 1 was an airport demonstration house associated with the airport's ongoing sound insulation program and had been insulated for public viewing as part of that program. The house was situated north of the airport and was exposed to the noise from aircraft in the final stage of landing on the east runway (17L). The front of the house was approximately parallel to the aircraft flight paths.

- House 2 was an occupied house to the east of the airport that had not been insulated and was exposed to the noise from aircraft departing on the more distant west runway (17R).

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 48. House 1: (a) Northwest, (b) North, (c) West, and (d) South Views, and House 2: (e) South, (f) Southwest, and (g) West Views

Figure 49. Test House Plans

6.2 MEASUREMENT OF AIRCRAFT NOISE REDUCTION.

Aircraft measurements of noise reduction were conducted in two to three rooms of the first floor in both houses for five to ten aircraft events. Microphone positions were as follows:

- One exterior microphone was placed 5 ft above ground level in an open area 50 ft from the house.

- One or two interior microphones were placed in each room, one near a window and one near the center of the room.

The noise data was processed to provide 1-second L_{eq} time histories of the aircraft events at each microphone position. Video recordings were made of each aircraft event to subsequently identify aircraft location with respect to the house. The results of the noise reduction measurements for four to five events are shown in tables 6 and 7.

Table 6. Results of Aircraft Measurements of NLR in House 1

Room	Window Microphone NLR (dB)						Room Microphone NLR (dB)				
	1	2	3	4	5	Average	6	7	8	9	Average
Dining	25.7	26.3	26.4	26.6	25.5	26.1	28.5	30.1	28.2	27.6	28.6
Living	26.2	26.8	27.0	26.9	26.1	26.6	28.7	28.5	28.7	28.2	28.5
Bed (North)	30.8	30.8	30.2	30.4	31.8	30.8	33.4	34.0	34.6	32.3	33.6
Bed (West)	33.4	33.1	33.7	33.5	33.7	33.5	33.6	33.8	35.1	32.8	33.8
Den	22.0	22.7	22.4	22.5	22.7	22.5	25.9	26.1	26.5	24.7	25.8

Table 7. Results of Aircraft Measurements of NLR in House 2

Room	Window Microphone NLR (dB)						Room Microphone NLR (dB)					
	1	2	3	4	5	Average	6	7	8	9	10	Average
Main Bed	25.4	21.5	23.9	22.3	23.0	23.2	31.1	28.3	27.0	28.5	26.2	28.2
Bed 2	26.4	20.5	22.6	21.7	22.3	22.7	33.4	27.6	29.5	28.0	28.9	29.5

Noise measurements were conducted separately to validate the modelled shielding effects with the following microphone positions:

- One exterior microphone 5 ft above ground level in an open area 50 ft from the house
- One microphone flush-mounted at a height of 6 ft to each of the four façades

This shielding data is presented and applied in section 6.7.

6.3 FREE-FIELD LOUDSPEAKER TESTS.

At house 1, the loudspeaker used for noise reduction measurements was calibrated in an adjacent area over two different ground surfaces to measure the free-field noise level at the same distance and elevation as the loudspeaker measurements described in section 6.4. Details of the free-field loudspeaker tests included the following:

- Ground surface: Hard and grass, similar to surfaces near the house 1 façades
- Loudspeaker height and distance:
  - 6 ft above ground at distances of 15, 25, 40, and 50 ft
  - 45° elevation at horizontal distances between 25 and 35 ft
- Microphone configurations (at each distance):
  - A 30-second microphone scan over an area between 3 and 9 ft high and approximately 10 ft wide angled at 45° to the loudspeaker axis at each distance
  - A single location at the center of the array at a height of 6 ft

The data were processed to provide 30-second average noise spectra for each microphone position and scan.

The measured data for the free-field measurements are presented in figures 50 and 51. Figure 50 compares the sound levels measured for loudspeaker heights of 6 and 30 ft over hard and grass surfaces. The large dips in the curves are the results of ground-reflection interference nominally at 200 Hz, 600 Hz, and 1000 Hz for the 6-ft loudspeaker and 63 Hz, 189 Hz, and 315 Hz for the elevated loudspeaker. Note that the dips were less severe for the elevated loudspeaker.

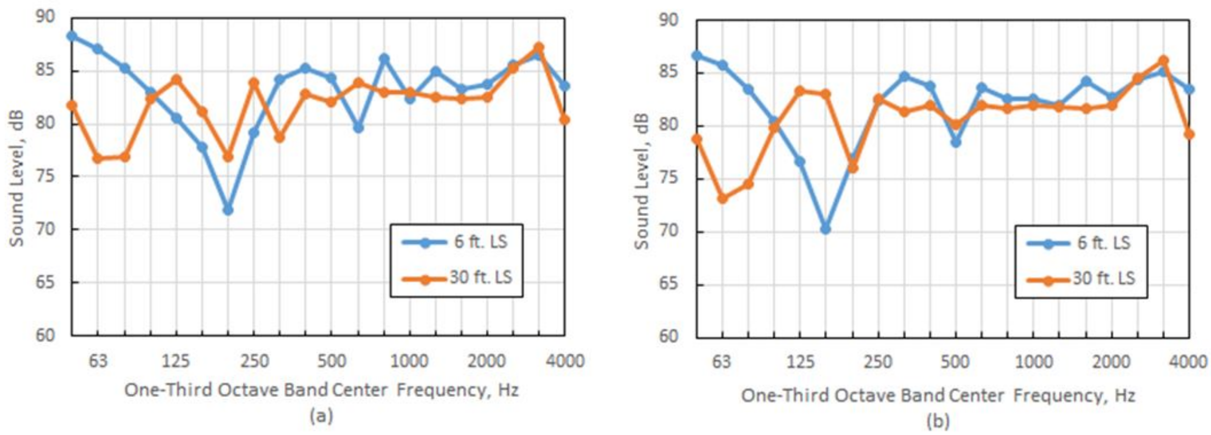


Figure 50. Free-Field Sound Levels Measured at a Height of 6 ft at 25 ft From 6-ft and 30-ft Loudspeakers Over (a) Hard and (b) Grass Surfaces

Figure 51 compares the sound levels measured over hard and grass surfaces for 6-ft and 30-ft loudspeaker heights. The curves are very similar over the two types of surface, especially for the elevated loudspeaker. Note the slight reduction in ground-reflection frequencies for the grass surface with the 6-ft loudspeaker, which was correctly predicted by the façade noise model in section 4.

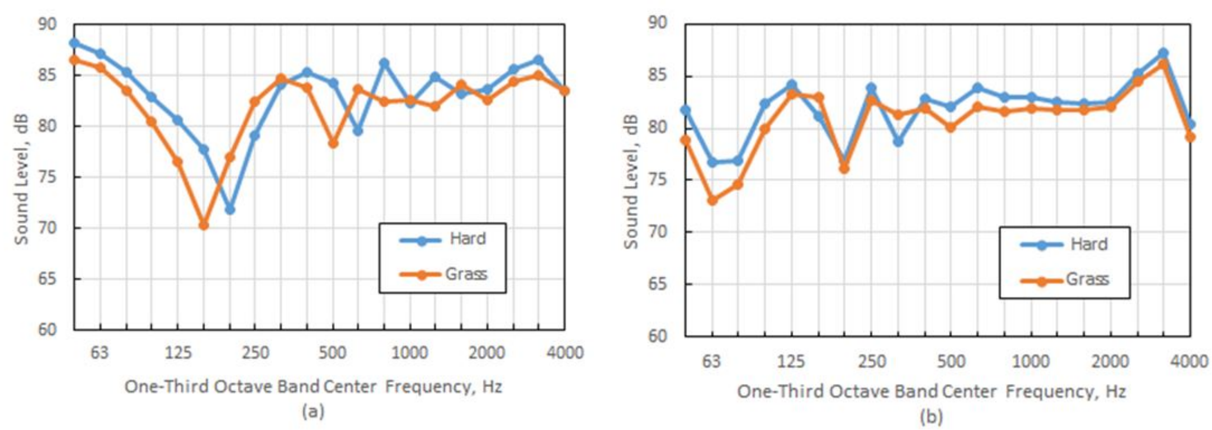


Figure 51. Free-Field Sound Levels Measured at a Height of 6 ft at 25 ft From a Loudspeaker (a) 6 ft and (b) 30 ft Over Hard and Grass Surfaces

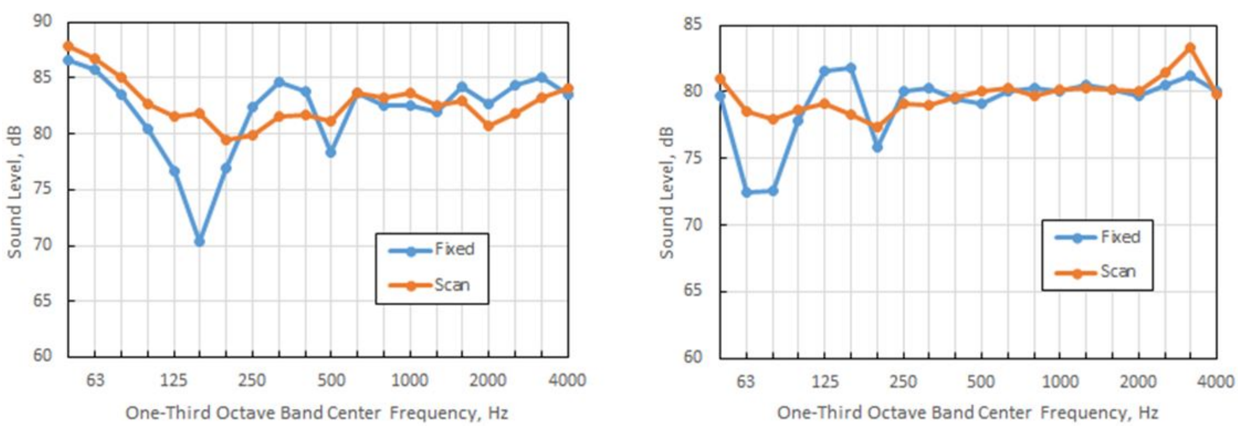
The spectral variations in sound level for the different loudspeaker, and ground-surface configurations assume a lesser importance when calculating the A-weighted levels for a specific aircraft noise spectrum. Table 8 shows the difference in level measured by a microphone at 6 ft above ground and 25 ft from the loudspeaker for the different configurations for typical aircraft arrival and departure noise spectra.

Table 8. Differences in A-Weighted Sound Levels Measured at 25 ft Over Hard and Grass Surfaces From Horizontal and Elevated Loudspeakers for Arrival and Departure Noise Spectra

Ground Surface	ΔNLR Arrival Spectrum (dB)		ΔNLR Departure Spectrum (dB)	
	6-ft Loudspeaker	30-ft Loudspeaker	6-ft Loudspeaker	30-ft Loudspeaker
Hard	0	-1.3	0	-0.7
Grass	-1.2	-2.1	-0.9	-1.8

The differences in this table for each noise spectra are referenced to the hard and 6-ft configuration separately for each spectrum. For example, the difference between levels (measured by a 6-ft microphone at 25 ft) between a 30-ft and 6-ft loudspeaker for an arrival spectrum is -1.3 dB. The difference between levels for a 30-ft loudspeaker over grass and hard surfaces is -0.8 dB (-2.1 +1.3). Overall, the differences between configurations are generally on the order of 1 dB. This result is relevant to the later discussion of the loudspeaker calibration method for measuring noise reduction in section 6.6.

A comparison of the spectra measured at 25 ft for the fixed 6-ft microphone, and the microphone scan is shown in figure 52 for the loudspeaker mounted at 6 ft and 30 ft. Although the overall A-weighted sound levels are about the same, the area scan effectively averages the effect of ground-reflection interference, resulting in a relatively flat spectrum for both tripod and elevated loudspeaker heights. Similar trends are found at distances from 15 to 50 ft, over grass and hard ground surfaces. It is the area scan data that is used in the following analyses.



(a) 6-ft. Loudspeaker (b) 30-ft. Loudspeaker

Figure 52. Sound Levels at a Fixed Microphone 6 ft Above the Ground and 25 ft From a Loudspeaker Compared to an Area Scan for (a) 6-ft and (b) 30-ft Loudspeaker

Figure 53 shows the sound propagation characteristics over hard and grass surfaces for an arrival aircraft spectrum as measured by a microphone area scan for 6-ft tripod mounted and 30-ft elevated loudspeakers. In both cases, the sound level decreases slightly faster over a grass surface as a result of absorption of the ground-reflected contribution.

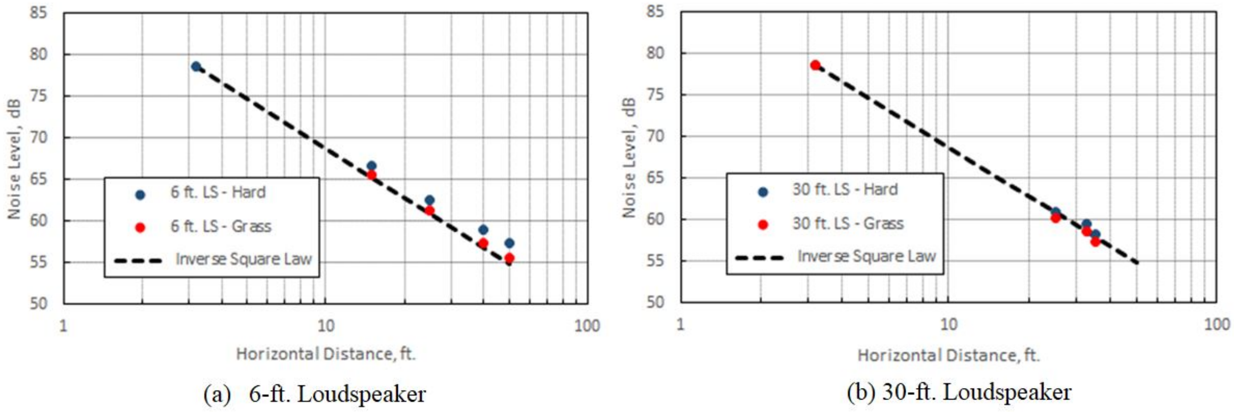


Figure 53. A-Weighted Arrival Noise Level as a Function of Horizontal Distance Over Hard and Grass Surfaces From a (a) 6-ft Loudspeaker and a (b) 30-ft Loudspeaker

The data presented in this section provide the free-field sound levels that will be used in subsequent sections to calculate noise reduction using the loudspeaker calibration method and to calculate adjustment factors to account for façade reflections.

6.4 LOUDSPEAKER MEASUREMENTS OF NOISE REDUCTION.

Measurements of noise reduction using a loudspeaker source were performed in the same two to three rooms and at the same interior microphone positions as for the measurement of aircraft noise reduction at each house. Measurement configurations were as follows:

- Corner rooms were measured with loudspeaker configurations each at 25 ft from the façade:
  - At 45° to the room corner, exposing two façades (loudspeaker at 6 ft above the ground)
  - At 45° horizontal to one façade (loudspeaker at 6 ft above the ground) and 45° vertical to the façade ((loudspeaker at 31 ft above the ground)
  - At 45° horizontal to the other façade (loudspeaker at 6 ft above the ground)
- Single-façade rooms were measured with two loudspeaker configurations each at 25 ft from the façade:
  - At 45° to the façade (loudspeaker at 6 and 31 ft above the ground)
- Exterior noise measurements
  - At five random flush positions on the façade

– A two-dimensional microphone scan (30 seconds) over façade at a distance of 4 to 5 inches, and at five fixed locations on the façade surface

– A two-dimensional microphone scan (30 seconds) over the façade surface at distances of 4 ft and 7 ft (corresponding to the distances used in the MHT measurements)

– A three-dimensional microphone scan (30 seconds) over a volume containing the extent of the façade surface at a distance varying from 4 to 7 ft

- Interior noise measurements at the same locations as for the aircraft noise measurements

The data were processed to provide 30-second average noise spectra for each microphone position or scan.

The spectral noise reduction of a façade is the difference between the exterior incident sound level and the interior level in each one-third octave band. The exterior incident level was taken as the free-field level in each frequency band according to the free-field loudspeaker measurements described in section 6.3 with the loudspeaker output adjusted to be the same level as for the noise reduction measurements. This procedure mirrors the loudspeaker calibration method described in ASTM E966-10 [2] and essentially uses the spectral adjustment factors actually measured to correct for façade reflection.

The interior levels were the levels measured near the center of each room. The spectral noise reduction values were then subtracted from the typical aircraft arrival and departure spectra to determine the corresponding aircraft interior levels for arrivals and departures. The NLR was then calculated as the difference between the A-weighted exterior and interior aircraft sound levels. The results are presented in table 9.

Table 9. Loudspeaker NLR Data Calculated With Spectral Adjustment Factors for a Flush-Mounted Microphone

House	Room (Façade)	Ground Surface	NLR for 6-ft Loudspeaker (dB)	NLR for 30-ft Loudspeaker (dB)
1 (Arrivals)	Bed (North)	Grass	25.0	---
	Bed (West)	Grass	23.0	---
	Den (North)	Grass	16.3	---
	Den (West)	Grass	17.1	17.9
	Dining (South)	Hard	23.4	23.6
	Dining (Southeast)	Mixed	22.1	---
	Living (Northeast)	Mixed	23.4	---
	Living (North)	Grass	27.2	28.9
2 (Departures)	Main Bed (South)	Grass	21.3	---
	Main Bed (West)	Grass	28.0	---
	Bed 2 (West)	Grass	24.3	27.9

It should be noted that house 1 had been sound insulated, and double windows were installed as part of the SDF Sound Insulation Program. For the tests described herein, one sash of each window was raised so as to simulate a non-insulated condition. As a result, the noise reduction values in table 9 do not represent those of the insulated house.

As shown, the noise reduction measured with an elevated loudspeaker is greater than that measured with a 6-ft tripod-mounted loudspeaker. This result is consistent with previously reported data described in section 2.

6.5 THE EFFECT OF ANGLE OF INCIDENCE.

The data presented in section 2.5.2 indicated that there was no significant influence of azimuthal angle of incidence on measured noise reduction, although some of the data may have been compromised by the test procedure employed. In contrast, the data showed a significant effect of the elevation angle of incidence on noise reduction. To understand this apparent anomaly, a series of controlled measurements were conducted as part of the field study.

The test house used for the measurements and an example of the loudspeaker/microphone configurations are shown in figure 54. The room tested had a single façade with one window. The loudspeaker was positioned 6 ft above ground at a distance of 50 ft from the center of the façade at azimuthal angles of 0°, 15°, 30°, 45°, 60°, and 75° to the normal of the façade. Measurements were also made with the loudspeaker normal to the façade at elevation angles of 30°, 45°, and 60°, each at a constant distance of 50 ft from the center of the façade. At each angle of incidence, interior sound levels were measured at two locations, one relatively close to the window, and the other near the center of the room. The exterior incident sound levels were taken from the free-field calibration tests described in section 6.3.

(a) Façade Measurement Locations

(b) Azimuthal Angle Measurements

(c) Elevation Angle Measurements

Figure 54. Test House for Angle of Incidence Measurements

The difference between the spectral exterior level and the spectral interior level was applied to the noise spectrum for an aircraft departure to determine the noise reduction for aircraft noise, or NLR. The measured values of noise reduction for different azimuthal and elevation angles of incidence with the normal to the façade are shown in table 10 and plotted in figure 55.

Table 10. Noise Level Reduction for Different Angles of Incidence

Angle (degrees)		NLR
Azimuthal	Elevation	(dB)
0	0	27.0
0	30	25.9
0	45	27.9
0	60	27.1
15	0	24.3
30	0	25.5
45	0	24.3
60	0	25.4
75	0	24.5

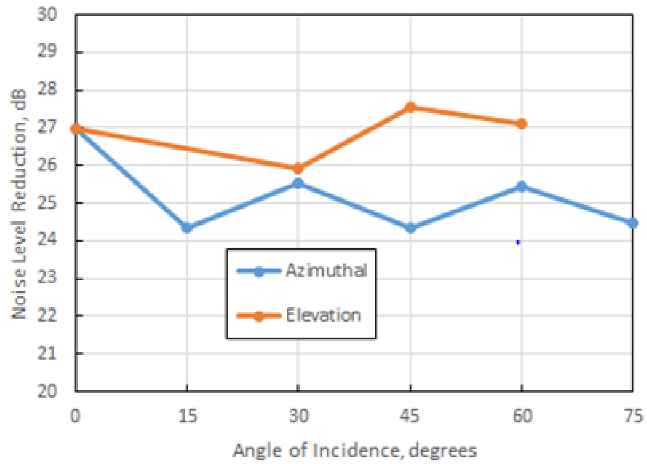


Figure 55. Noise Level Reduction as a Function of Angle of Incidence

Theory predicts that the transmission loss of a simple structure is maximum at normal incidence and decreases as the angle θ is increased according to the term $\cos^2 \theta$. The noise reduction of a façade depends not only on the transmission loss, but also on the angle subtended by the façade to the noise source, which decreases with increasing angle of incidence according to the term $1/\cos \theta$. Combining these two terms results in a decrease in noise reduction with angle of incidence by the term $\cos \theta$. There is an indication of this behavior in figure 55 for changes in azimuthal angle of incidence, where the ground interference effect should be essentially the same for all angles. Significant increases in noise reduction are noted for increases in vertical angle of incidence, where the frequency of the ground interference effect decreases with increasing loudspeaker height. However, this result may be influenced by the acoustic characteristics of the test room, which shows a dominant mode at 315 Hz.

The variation of noise reduction with frequency at different angles of incidence is shown in figure 56. Figure 57 shows comparisons of the spectral variation in noise reduction for the same values of azimuthal and elevation angles.

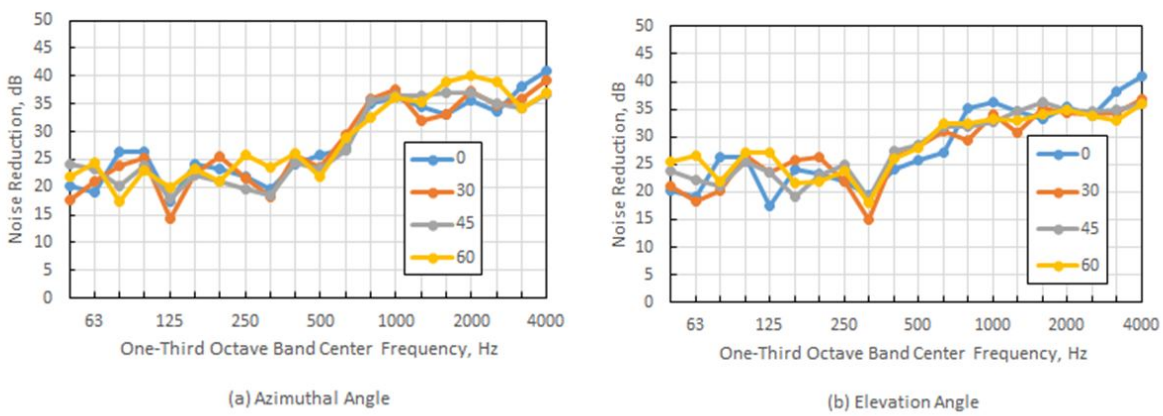


Figure 56. Noise Reduction of a Façade Exposed to Loudspeaker Generated Noise as a Function of Azimuthal and Elevation Angle of Incidence

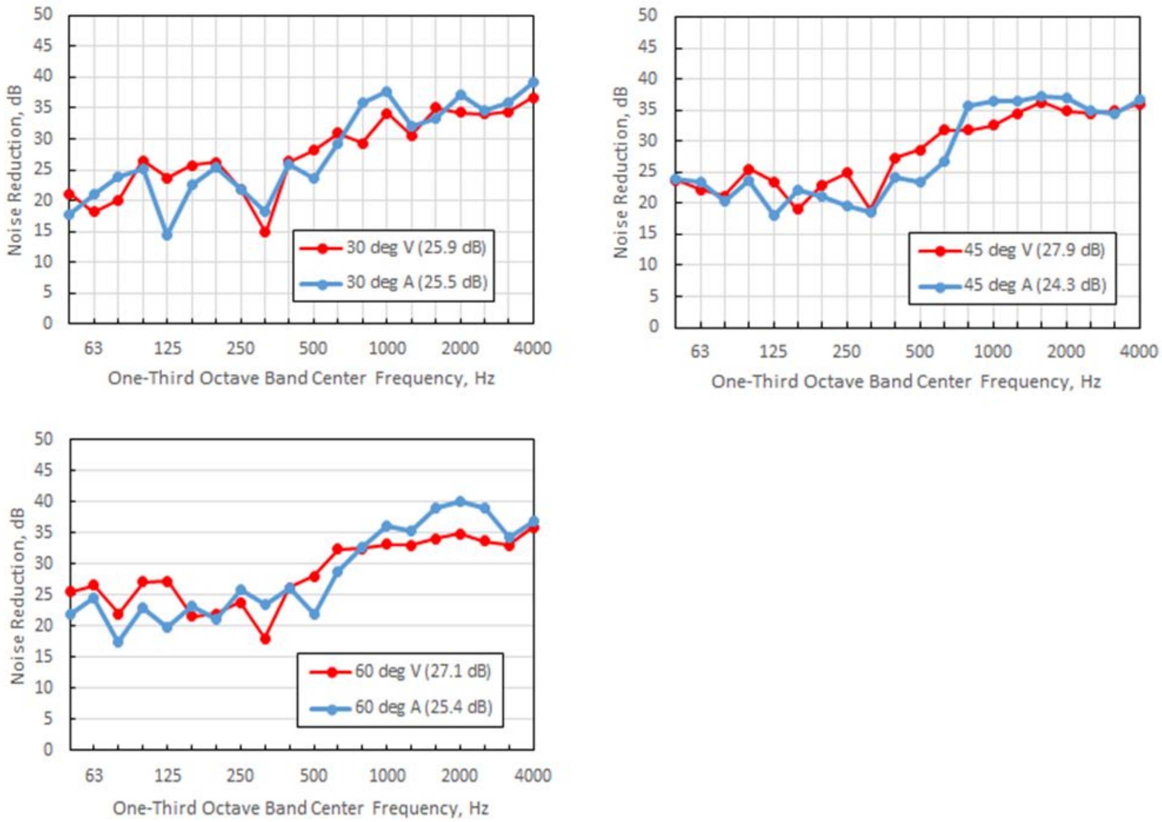


Figure 57. Comparison of Noise Reduction at Horizontal and Vertical Angles of Incidence

The conclusion from this very limited set of data is that there is a small, but probably not significant, reduction in noise reduction with increasing angle of incidence. However, there appears to be an increase in noise reduction for an elevated noise source.

6.6 ADJUSTMENT FACTORS FOR LOUDSPEAKER MEASUREMENT OF NOISE REDUCTION.

In sections 3 and 4, field measurements and model results indicated that appropriate single-number adjustment factors for flush and nearby (near façade) microphones are -6 and -3.5 dB respectively, and not -5 and -2 dB as quoted in ASTM E966-10 [2]. These updated adjustment factors were also validated from the results of applying the modelled shielding data to the measured noise data from the Schomer et al. [35] and L&B [29] studies, as described in section 5 of this report.

The loudspeaker measurements described in this section provided a further field validation of the updated single-number adjustment factors by comparing the A-weighted noise levels measured flush with and near the façade produced by a loudspeaker with the free-field levels measured in the loudspeaker free-field tests. The flush measurements were taken as the energy average of the levels at five randomly selected points on the exposed façade. The near façade measurements were the time average of a three-dimensional scan taken over the area of the façade between 4 ft and 7 ft from the façade surface. The free-field levels from the loudspeaker (LS) calibration tests were taken as the area scan at a distance of 25 ft, as described in section 6.3.

Exterior and free-field noise levels were A-weighted levels taken over the frequency range 100 Hz to 1600 Hz and adjusted to a typical spectrum for arrivals measured at house #1 and for departures at house #2. The single-number adjustment factors were calculated as the difference between the average flush or near-façade levels and the free-field levels from the calibration tests. A tabulation of the adjustment factors for the 16 individual tests conducted in the two houses is shown in table 11 and in the plots of figures 58 and 59.

Table 11. Single-Number Adjustment Factors From Field Measurements

House	Test	Room (Façade)	Ground Surface	Adjustment Factor (dB)			
				Flush Microphone		Nearby Microphone	
				6-ft LS	30-ft LS	6-ft LS	30-ft LS
1	1	Bed (North)	Grass	4.3	5.0	2.7	1.9
	2	Bed (West)	Grass	4.7	6.0	3.2	3.2
	3	Den (North)	Grass	6.5	7.0	4.3	3.2
	4	Den (West)	Grass	6.4	6.6	4.3	3.5
	5	Dining (South)	Mix	5.6	3.6	2.9	2.0
	6	Dining (Southeast)	Mix	6.3	---	3.8	---
	7	Living (Northeast)	Mix	5.6	---	2.5	---
	8	Living (North)	Grass	6.1	5.2	2.9	1.6
2	9	Main Bed (South)	Grass	---	4.9	---	2.0
	10	Main Bed (West)	Grass	6.7	---	4.2	---
	11	Bed 2 (0°)	Grass	4.2	---	---	---
	12	Bed 2 (15°)	Grass	5.4	---	---	---
	13	Bed 2 (30°)	Grass	5.6	---	---	---
	14	Bed 2 (45°)	Grass	6.3	5.0	---	2.2
	15	Bed 2 (60°)	Grass	6.2	---	---	---
	16	Bed 2 (75°)	Grass	6.1	---	---	---
Average				5.7	5.4	3.4	2.5
Standard Deviation				0.7	1.0	0.6	0.7

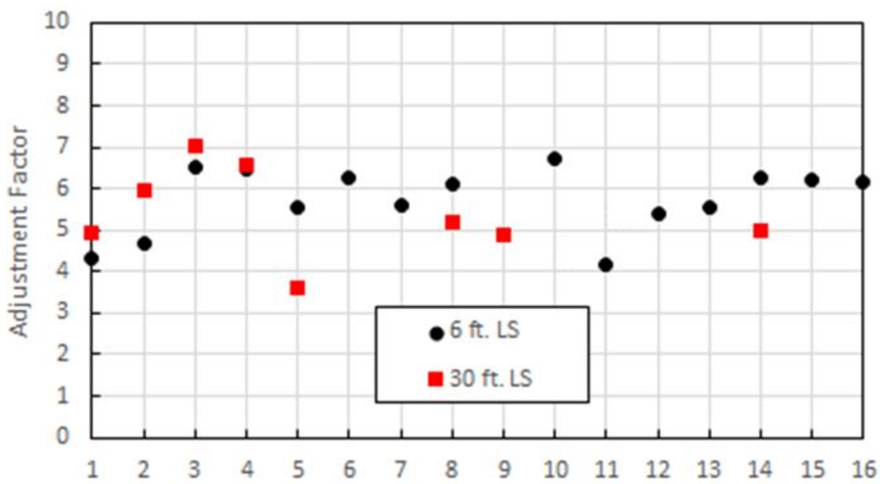


Figure 58. Measured Adjustment Factors for Flush-Mounted Microphones With 6-ft Tripod and 30-ft Elevated Loudspeaker

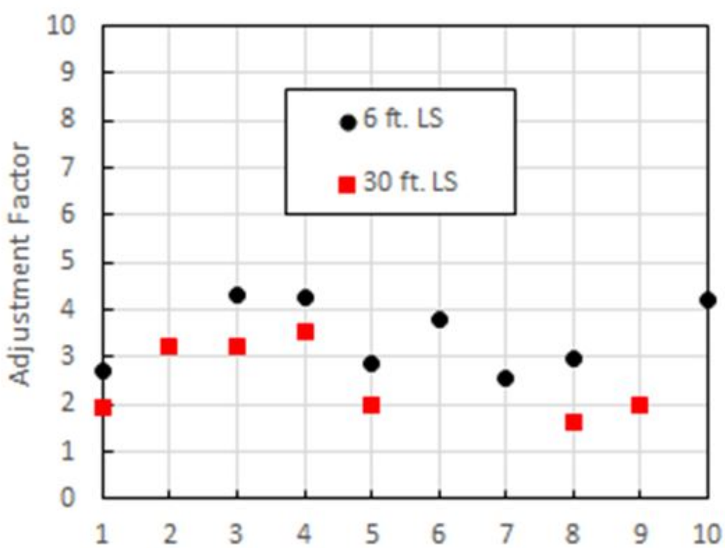


Figure 59. Measured Adjustment Factors for Near-Façade Microphones With 6-ft Tripod and 30-ft Elevated Loudspeaker

Further examination of the data in table 11 indicates that the flush exterior noise levels measured for test 11 with a 6-ft loudspeaker are not consistent (1 to 2 dB lower) with the levels measured for similar tests. In test 10, the exterior levels were probably increased by reflections from a roof over the deck. These are, of course, real situations that are encountered in practice, but they explain deviations from the average values measured in these tests.

The average values of adjustment factor, namely 5.7 dB for flush-mounted microphones and 3.4 dB for a nearby microphone, are consistent with the previous findings of 6 dB and 3.5 dB, respectively. The reduction in adjustment factor for elevated loudspeakers measured with a nearby microphone is due to the different path length from loudspeaker to measuring microphone compared to that with a 6-ft loudspeaker.

Calculating the adjustment factors for alternative aircraft noise spectra resulted in changes of a few tenths of a decibel, indicating that the factors are relatively insensitive to noise spectrum and hence are applicable to both arrival and departing aircraft situations.

Calculating the incident sound level by applying these single-number adjustment factors to the exterior sound levels in all frequency bands will not exactly simulate the free-field spectral levels that would be measured in the absence of the façade. The spectral incident sound level is better defined by the free-field loudspeaker measurements described in section 6.3. As a result, the use of single-number adjustment factors will introduce an error in the calculation of noise reduction. Table 12 presents the values of noise reduction measured using the loudspeaker calibration method together with those for flush-mounted and nearby microphone measurements with applied adjustment factors of -6 dB and -3.5 dB, respectively.

Table 12. Measured Noise Reduction by Loudspeaker Calibration, Flush-Mounted, and Nearby Microphones With Updated Adjustment Factors Applied

House	Room (Façade)	Noise Reduction (dB)					
		Loudspeaker Calibration		Flush (-6 dB)		Nearby (-3.5 dB)	
		Tripod	Elevation	Tripod	Elevation	Tripod	Elevation
1	Bed (North)	25.0	---	23.0	---	24.8	---
	Bed (West)	23.0	---	22.3	---	23.2	---
	Den (North)	16.3	---	17.2	---	17.6	---
	Den (West)	17.1	17.9	15.3	18.6	16.9	17.9
	Dining (South)	23.4	23.6	23.1	21.6	23.0	22.5
	Dining (Southeast)	22.1	---	22.5	---	22.5	---
	Living (Northeast)	23.4	---	24.8	---	23.0	---
	Living (North)	27.2	28.9	27.5	28.0	26.7	27.8
2	Main Bed (South)	21.3	---	23.4	---	23.9	---
	Main Bed (West)	28.0	---	29.6	---	29.0	---
	Bed 2 (0° H)	27.0	---	25.7	---	---	---
	Bed 2 (0° A, 30° V)	---	25.9	---	25.9	---	---
	Bed 2 (0° A, 45° V)	---	27.9	---	27.3	---	---
	Bed 2 (0° A, 60° V)	---	27.1	---	27.1	---	---
	Bed 2 (15° A)	24.3	---	24.0	---	---	---
	Bed 2 (30° A)	25.5	---	25.0	---	---	---
	Bed 2 (45° A)	24.3	---	24.7	27.3	24.6	27.0
	Bed 2 (60° A)	25.4	---	26.6	---	---	---
	Bed 2 (75° A)	24.5	---	26.2	---	---	---

The data from table 12 is plotted in figure 60 for flush-mounted measurements at house 1 alone (where the loudspeaker calibration tests were conducted) and for houses 1 and 2 combined. As shown, there is close to a one-to-one relationship between the two methods at house 1, indicating that the application of single-number adjustment factors to the exterior sound levels in all frequency bands does in fact provide an accurate assessment of the incident sound level. The agreement between the two methods is also good with the addition of data for house 2 where the adjacent ground surface was similar to that at house 1.

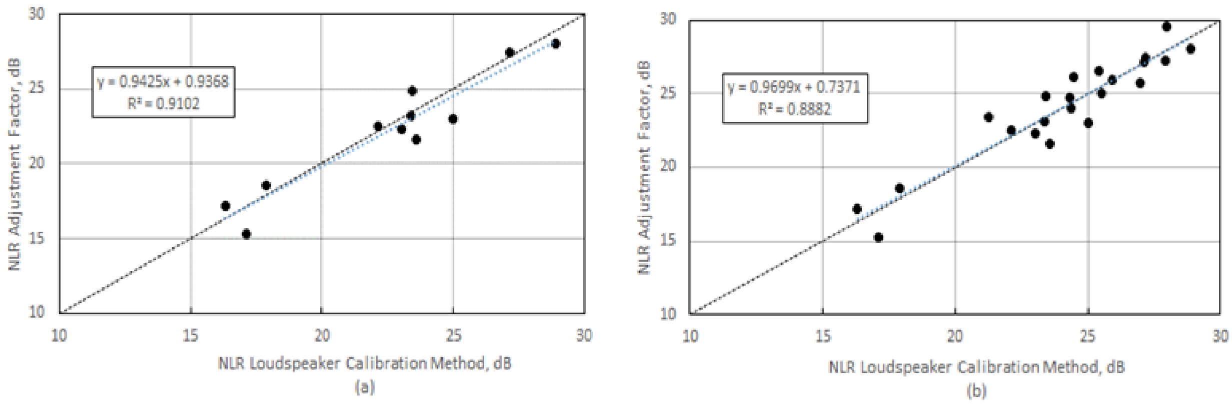


Figure 60. Comparison of NLR Measured by the Loudspeaker Calibration Method With a Flush-Mounted Microphone Method Using 6-dB Adjustment Factor for (a) House 1 and (b) Houses 1 and 2 Combined

Based on this evidence, it would seem that the loudspeaker calibration method is viable, although additional research is required to further examine the sensitivity to variations in loudspeaker and microphone configuration.

The relationship between NLR as measured with a flush-mounted microphone (with an adjustment factor of 6 dB) and near-façade microphone (with an adjustment factor of 3.5 dB) is shown in figure 61.

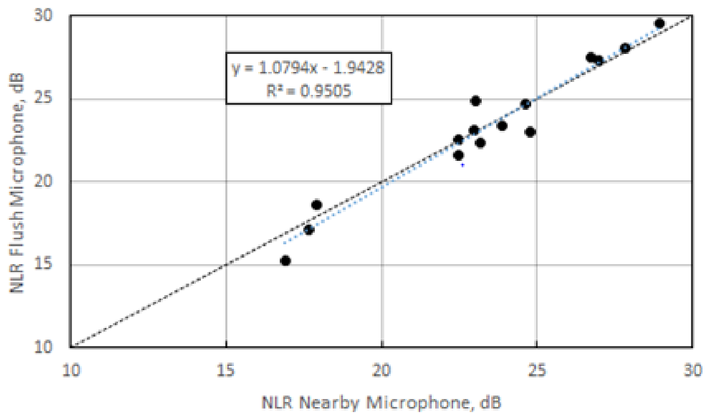


Figure 61. Comparison of NLR as Measured With Flush-Mounted and Near-Façade Microphones With Updated Adjustment Factors

The trend line is close to a one-to-one relationship and the spread of data is small, demonstrating that the two methods, with their associated adjustment factors, are consistent with each other. It therefore appears as though either can be used; the selection can be based on convenience and the local conditions.

6.7 APPLICATION OF SHIELDING DATA TO FIELD MEASUREMENTS OF NLR.

The noise measurements described above provide additional data to validate the updated adjustment factors. For house 1 it is necessary to develop a relationship between aircraft and loudspeaker measurements of noise reduction that is applicable to the noise from aircraft in the final stages of landing. Typical spectra for arrivals as measured at house 1 at SDF are shown in figure 62 as a function of aircraft angle θ to the normal of the front surface facing east almost parallel to the flight track (see figure 49), where negative angles of incidence represent the approaching aircraft and positive angles the departing aircraft. Note that the data in figure 62 is for a building with the front face parallel to the flight track.

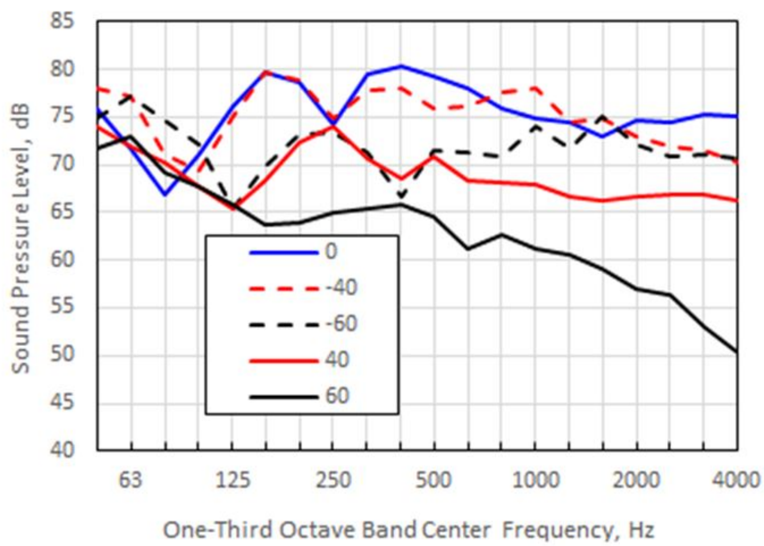


Figure 62. Noise Spectra as a Function of Angle for an Aircraft Arrival

A typical example of the time history of the A-weighted noise level at each of the four façades compared to the level measured in the free-field is shown in figure 63. The vertical dashed line at 17 seconds represents the time when the aircraft was level with the north façade (see figure 49.)

The time history clearly shows the increase in noise level at the north façade (the red line in figure 63) as the aircraft approaches followed at 16 seconds by a sharp decrease as the façade is shielded by the house structure at 17 seconds. The reverse behavior is demonstrated for the south façade (the blue line) as it is shielded during the approach and fully exposed after 18 seconds to the decreasing noise level from the departing aircraft.

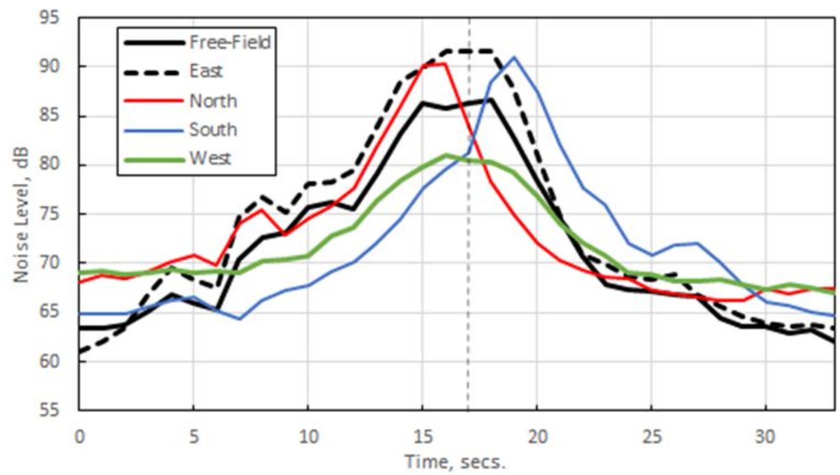
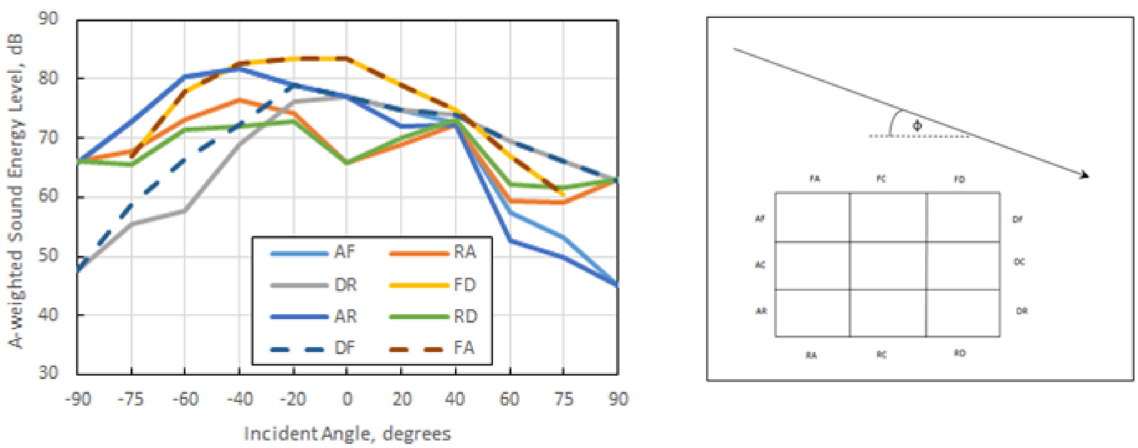


Figure 63. Typical Time History of Noise Levels at Different Façades for an Aircraft Arrival

The procedure for developing the relationship between aircraft and loudspeaker measurements of noise reduction is exactly the same as described in sections 5.2 through 5.4, but with the noise spectra and time history of figures 62 and 63 for aircraft arrivals. Figure 64 shows the resulting exterior incident sound energy level as a function of aircraft angle θ for each of the room surfaces.



(a) (b)

Figure 64. A-Weighted Sound Energy Level at (a) Different Façades of a Building for an Aircraft Arrival as a Function of Angle of Incidence and (b) Orientation of Building to Flight Track

The A-weighted adjustments to measurements of noise reduction from arriving aircraft are shown in figure 65 for the various rooms of a rectangular building with the front façade at an angle ϕ of 0° to the aircraft flight track.

The result of applying the adjustments for shielding in figure 65 to the aircraft arrival measurements of NLR in house 1 at SDF improves the agreement between the aircraft and loudspeaker methods of measurement as shown in the Adjusted ΔNLR column in table 13. Similarly, application of the shielding adjustments in figure 43 for aircraft departures improves the agreement for house 2 as shown in table 13.

$\phi = 0$	FA	FC	FD	
AF	-2.9	-2.5	-4.6	DF
AC	-3.4		-8.6	DC
AR	-5.2	-8.8	-8.7	DR
	RA	RC	RD	

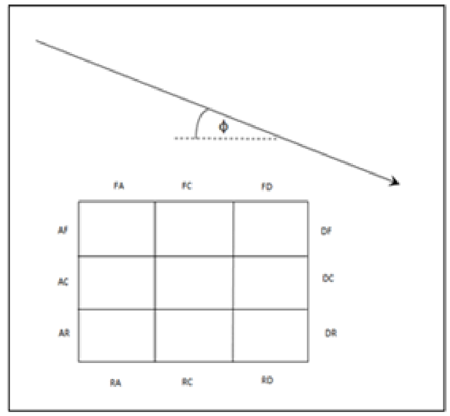


Figure 65. A-Weighted Adjustments to Measured Aircraft Noise Reduction for Rooms in a Rectangular Building for Aircraft Arrivals

Table 13. Relationship Between Aircraft and Tripod Loudspeaker Measurement of NLR Adjusted for Shielding Effects

House	Room	Aircraft NLR (dB)	Loudspeaker NLR (dB)	ΔNL (dB)	Shielding Correction (dB)	Adjusted ΔNLR (dB)
1	Dining	28.6	22.8	5.8	4.6	1.2
	Living	28.5	26.1	2.4	2.9	-0.5
	Bed	33.7	22.7	11.0	5.2	5.8
	Den	25.8	16.2	9.6	8.7	0.9
2	Main Bed	28.2	26.5	1.7	2.5	-0.8
	Bed 2	29.5	24.7	4.8	4.1	0.7

In general, the agreement is good, except for the measurements in the bedroom. For the bedroom (Bed) of house 1, unlike the loudspeaker measurement of NLR, the aircraft measurement is not consistent with that in other rooms; it is measured much higher than that for the adjacent den. As mentioned, house 1 is a demonstration house with improved sound insulation. For the purposes of the tests, however, one pane of each double window was left open to simulate a house with no added sound insulation. It is believed that this was the case with the loudspeaker measurements in the bedroom, but not for the aircraft measurements, hence the significant increase in aircraft NLR. This is clearly an anomaly, which if taken into account results in an average adjusted *Δ*NLR of about 1 dB.

These results further validate the relationship developed between aircraft and loudspeaker measurements of noise reduction.

7. SUMMARY.

The objectives of this study were to determine and understand the contribution of the factors that influence the sound level at and near a building façade, identify appropriate adjustment factors for measurements of noise reduction in airport sound insulation programs, and validate these factors through application to existing data and by conducting field measurements. The results obtained from the study can be summarized as follows:

- The adjustment factor to account for façade reflections in the measurement of noise reduction using a loudspeaker and flush-mounted microphone should be the theoretical value of 6 dB and not 5 dB as quoted in ASTM E966-10 [2], nor 4 dB as shown in Bradley and Chu [19].

- The adjustment factor to account for façade reflection in the measurement of noise reduction using a loudspeaker and near-façade microphone should be 3.5 dB and not 2 dB as quoted in ASTM E966-10 [2].

- These updated adjustment factors are consistent with

  - the data from the MHT measurements described in section 3,

  - the modelling data from the Façade Noise Simulation Model developed in section 4, and

  - the application of modelled shielding data to the measured data from the Schomer et al. [35] and L&B [29] studies with updated adjustment factors of 6 dB and 3.5 dB applied for flush and near-façade measurements respectively in demonstrating the equivalence of aircraft and loudspeaker measurements.

- The loudspeaker calibration method for measuring noise reduction, whereby the exterior noise level is measured by calibrating the loudspeaker level in a free-field environment, appears to provide results that replicate measurements using flush-mounted and near-façade microphones.

- A relationship was developed that explains the difference between the noise reduction data obtained using aircraft and loudspeaker noise sources. This difference is largely due to the shielding of the test façade from the aircraft noise exposure by the house structure and the changing angle of incidence of the aircraft noise exposure.

Finally, in conducting this study, it became apparent that further research is needed to better understand the following issues:

- Measurement procedures that could reduce the difference between aircraft and loudspeaker measurements of noise level reduction should be examined.

- The influence of loudspeaker position needs to be addressed for different housing types to understand variations of measured noise reduction obtained by
  - elevating and orienting the loudspeaker with respect to the façade, and
  - exposing individual façades versus room corners.
- The effects of structural perturbations, such as roof overhangs, porches, adjoining decks, and nearby reflecting surfaces need to be considered.
- The loudspeaker calibration method for measuring noise reduction needs to be further examined as it provides a means for testing without measuring the exterior noise level at or near the test façade.
- The relationship between noise reduction, as measured using aircraft and loudspeaker sources, needs to be refined to account for different housing structures and aircraft noise characteristics, such that it could be used to apply adjustments to loudspeaker measurements.

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APPENDIX A—RECENT UNITED STATES NOISE REDUCTION DATA SETS

Tables A-1 and A-2 present noise reduction data measured for aircraft and loudspeaker (LS) sources as provided in references A-1 and A-2. Noise level reduction (NLR) is measured in decibels (dB).

Table A-1. Summary of NLR Data From Schomer [A-1]

Location	Room	Measured NLR (dB)			Aircraft Tripod (dB)	Aircraft Elevated (dB)	Ground Elevated (dB)
		Aircraft	Tripod Loudspeaker	Elevated Loudspeaker			
1	Living	28.3	24.5	---	3.8	---	---
	Dining	30.0	22.2	---	7.8	---	---
2	Living	26.3	25.2	---	1.1	---	---
	Office	22.4	18.4	---	4.0	---	---
3	Living	25.3	21.6	---	3.7	---	---
	Bed 1	28.4	25.0	---	3.4	---	---
4	Living	26.0	21.3	---	4.7	---	---
	Bed 1	32.0	26.3	---	5.7	---	---
5	Living	26.9	20.9	21.0	6.0	5.9	-0.1
	Dining	29.4	26.4	23.7	3.0	5.7	2.7
6	Family	28.5	25.7	25.6	2.8	2.9	0.1
	Living	27.1	24.6	23.8	2.5	3.3	0.8
7	Dining	21.4	19.6	19.9	1.8	1.5	-0.3
	Master Bed	24.2	28.3	28.6	-4.1	-4.4	-0.3
8	Living	23.8	19.4	19.8	4.4	4.0	-0.4
	Bed 1	33.7	25.6	26.1	8.1	7.6	-0.5
9	Bed 1	19.5	17.6	18.9	1.9	0.6	-1.3
	Bed 2	27.0	25.1	25.3	1.9	1.7	-0.2
10	Dining	22.2	25.0	25.0	-2.8	-2.8	0.0
	Bed 2	24.0	24.9	25.1	-0.9	-1.1	-0.2
11	Living	26.2	24.8	25.0	1.4	1.2	-0.2
	Study	31.5	25.7	26.6	5.8	4.9	-0.9
Average	---	---	---	---	3.0	2.2	-0.1
Standard Deviation	---	---	---	---	2.9	3.3	0.9
Spread	---	---	---	---	12.2	12.0	4.0

Note: The measured NLR values for aircraft are the actual measured values and do not include the factor of -2 dB applied by Schomer [A-1] to account for ground reflection.

Table A-2. Summary of NLR Data From Wyle [A-2]

NLR With Take-Off Spectrum (dB)			ΔNLR (dB)		
Elevated Loudspeaker	Tripod Loudspeaker	Aircraft	Aircraft—Tripod Loudspeaker	Aircraft—Elevated Loudspeaker	Tripod Loudspeaker—Elevated Loudspeaker
22.8	21.6	24.8	3.2	2.0	-1.2
22.7	21.1	24.8	3.7	2.1	-1.6
28.9	26.0	26.6	0.6	-2.3	-2.9
26.2	26.1	25.1	-1.0	-1.1	-0.1
21.8	21.4	25.1	3.7	3.3	-0.4
20.4	20.4	25.0	4.6	4.6	0.0
26.8	25.7	26.8	1.1	0.0	-1.1
28.4	26.8	29.7	2.9	1.3	-1.6
25.9	24.8	27.2	2.4	1.3	-1.1
27.2	25.9	27.2	1.3	00	-1.3
27.6	24.4	29.8	5.4	2.2	-3.2
27.2	26.4	29.5	3.1	2.3	-0.8
28.1	N/A	28.2	---	0.1	---
Average			2.6	1.2	-1.3
Standard Deviation			1.7	1.8	0.9

Δ = Difference quantity

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APPENDIX B—TEST CONFIGURATIONS AT MANCHESTER-BOSTON REGIONAL AIRPORT

Tables B-1 and B-2 show the test configurations for the field tests at Manchester-Boston Regional Airport. Table B-1 shows the measurements in free-field with no nearby structures. Table B-2 shows the measurements near a 23.5-ft-high building surface.

Table B-1. Measurements in the Free-Field With No Nearby Structures

Test	Noise Source[1]	Source Height (ft)	Angle (°)	Microphone Height (ft)	Source-Microphone Distance (ft)	Ground Surface	Validation
1	Loudspeaker	25	---	0, 5, 15, 25	25	Grass	Ground Reflection Model
2	Loudspeaker	15	---	0, 5, 15, 25	25	Grass	
3	Loudspeaker	5	---	0, 5, 15, 25	25	Grass	
4	Loudspeaker	0	---	0, 5, 15, 25	25	Grass	
5	Loudspeaker	25	---	0, 5, 15, 25	50	Grass	
6	Loudspeaker	15	---	0, 5, 15, 25	50	Grass	
7	Loudspeaker	5	---	0, 5, 15, 25	50	Grass	
8	Loudspeaker	0	---	0, 5, 15, 25	50	Grass	
9	Loudspeaker	25	---	0, 5, 15, 25	25	Concrete	
10	Loudspeaker	15	------	0, 5, 15, 25	25	Concrete	
11	Loudspeaker	5	---	0, 5, 15, 25	25	Concrete	
12	Loudspeaker	0	---	0, 5, 15, 25	25	Concrete	
13	Loudspeaker	25	---	0, 5, 15, 25	50	Concrete	
14	Loudspeaker	15	---	0, 5, 15, 25	50	Concrete	
15	Loudspeaker	5	---	0, 5, 15, 25	50	Concrete	
16	Loudspeaker	0	---	0, 5, 15, 25	50	Concrete	
As Available	Aircraft	---	---	0, 5, 15, 25	---	Grass	
As Available	Aircraft	---	---	0, 5, 15, 25	---	Concrete	

The loudspeaker was placed upright for all configurations except for source height = 0 when it was placed on its side.

The microphone faced upwards with the diaphragm horizontal for all configurations except for Microphone height = 0 when it was taped to the center of a 3/4-in. plywood sheet (1-m diameter) on the ground with the diaphragm vertical.

Table B-2. Measurements Near a 23.5-ft-High Building Surface

Test	Noise Source[1]	Source Height (ft)	Angle (°)	Microphone Height (ft)	Source-Microphone Distance (ft)	Microphone to Wall (ft)	Ground Surface	Validation
20	Loudspeaker	0	45	5, 15, 21.9	25	Flush, Nominal 2, 4, 6, 8	Grass	Combined Wall/ Ground Model
21	Loudspeaker	5	45	5, 15, 21.9	25		Grass	
22	Loudspeaker	15	45	5, 15, 21.9	25		Grass	
23	Loudspeaker	25	45	5, 15, 21.9	25		Grass	
30	Loudspeaker	0	45	5, 15, 21.9	25		Concrete	
31	Loudspeaker	5	45	5, 15, 21.9	25		Concrete	
32	Loudspeaker	15	45	5, 15, 21.9	25		Concrete	
33	Loudspeaker	25	45	5, 15, 21.9	25		Concrete	

The loudspeaker was placed upright for all configurations except for source height = 0 when it was placed on its side.

APPENDIX C—TEST CONFIGURATION NOMENCLATURE

Test configurations are identified using the following notations:

A, B, C, D, E, where:

- A is either F for Free-Field or W for Wall,
- B is either H for Hard surface or G for Grass surface,
- C is the loudspeaker height above ground in feet,
- D is the microphone height above ground in feet, and
- E is either the distance (in feet) of the microphone from the wall for W measurements or the distance (in feet) from loudspeaker to the microphone for F measurements. The notation FL is used for a microphone mounted flush with the wall surface.

Thus, a notation of WG,25,5,4 indicates a wall measurement over a grass surface with a loudspeaker height of 25 ft, a microphone height of 5 ft, and with the microphone 4 ft from the wall surface.

APPENDIX D—ADJUSTMENT FACTORS APPLIED TO EXISTING NOISE LEVEL REDUCTION DATA

Table D-1 shows the adjustment factors applied to the existing noise level reduction (NLR) data from Schomer et al. [D-1] and Landrum & Brown [D-2]. The following symbols and abbreviations are used in the table:

Δ	Difference quantity
BR	Bedroom
DR	Dining room
FR	Family room
K	Kitchen
LR	Living room
LS	Loudspeaker
Mic.	Microphone
NLR	Noise level reduction

Table D-1. Adjustment Factors Applied to the Existing NLR Data

	LS Measurements								
Room	Flush Mic.	Near Façade Mic.	Façades Directly Exposed to LS	LS NLR (dB)	Aircraft NLR (dB)	Aircraft LS (ΔdB)	Shielding Correction (dB)	Corrected Aircraft NLR (dB)	Aircraft - LS With Correction (dB)
LR		x	2	25.0	28.2	3.2	2.2	26.0	1.0
DR		x	2	22.3	30.5	8.2	8.0	22.5	0.2
LR		x	2	23.5	26.0	2.5	2.2	23.8	0.3
Office		x	2	18.5	22.4	3.9	2.2	20.2	1.7
LR		x	2	21.9	25.8	3.9	6.0	19.8	-2.1
LR		x	2	21.5	25.4	3.9	3.8	21.6	0.1
BR		x	2	24.9	28.5	3.6	6.0	22.5	-2.4
LR		x	2	22.0	26.0	4.0	7.2	18.8	-3.2
BR		x	2	26.3	32.2	5.9	6.7	25.5	-0.8
LR		x	1	21.4	26.8	5.4	5.8	21	-0.4
DR		x	1	27.1	29.3	2.2	2.6	26.7	-0.4
FR		x	1	25.0	28.6	3.6	5.8	22.8	-2.2
LR		x	1	23.6	27.0	3.4	3.5	23.5	-0.1
DR		x	1	20.2	21.3	1.1	2.6	18.7	-1.5
LR		x	2	19.4	23.9	4.5	4.5	19.4	0.0
BR		x	1	25.6	33.3	7.7	9.3	24.0	-1.6
BR		x	2	17.8	19.6	1.8	2.2	17.4	-0.4
BR		x	2	26.4	36.6	10.2	10.4	26.2	-0.2
LR		x	2	27.7	28.8	1.1	3.8	25.0	-2.7
K	x		2	23.8	25.1	1.3	1.6	23.5	-0.3
K		x	2	23.4		1.7			0.1
LR	x		2	22.4	23.6	1.2	3.8	19.8	-2.6
LR		x	2	22.3		1.3			-2.5
LR	x		1	25.3	27.1	1.8	2.6	24.5	-0.8
LR		x	1	25.2		1.9			-0.7

Table D-1. Adjustment Factors Applied to the Existing NLR Data (Continued)

Room	LS Measurements				Aircraft NLR (dB)	Aircraft LS (ΔdB)	Shielding Correction (dB)	Corrected Aircraft NLR (dB)	Aircraft - LS With Correction (dB)
	Flush Mic.	Near Façade Mic.	Façades Directly Exposed to LS	LS NLR (dB)					
BR	x		2	26.5	27.3	0.8	2.2	25.1	-1.4
BR		x	2	26.1		1.2			-1.0
LR	x		1	26.0	28.3	2.3	2.6	25.7	-0.3
LR		x	1	25.1		3.2			0.6
BR	x		2	25.3	28.5	3.2	2.2	26.3	1.0
BR		x	2	24.4		4.1			1.9
DR	x		1	22.9	28.5	5.6	4.5	24.0	1.1
DR		x	1	24.7		3.8			-0.7
BR	x		2	25.4	27.3	1.9	2.2	25.1	-0.3
BR		x	2	26.2		1.1			-1.1
DR	x		1	25.2	24.7	-0.5	1.3	23.4	-1.8
DR		x	1	22.7		2.0			0.7
BR	x		2	20.5	23.8	3.3	2.5	21.3	0.8
BR		x	2	18.0		5.8			3.3
BR	x		2	21.6	25.4	3.8	3.2	22.2	0.6
BR		x	2	22.6		2.8			-0.4

REFERENCES.

D-1. Schomer, P., Freytag, J., and Waldeck, R., “Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs,” Airport Cooperative Research Program (ACRP) Report 152 prepared for the Transportation Research Board, ACRP, Washington, DC, 2016.

D-2. Landrum & Brown, Inc., (L&B) “Study of Noise Level Reduction (NLR) Variation,” L&B report prepared for the FAA (Report No. FAA TO-43), Washington, DC, February 2016.