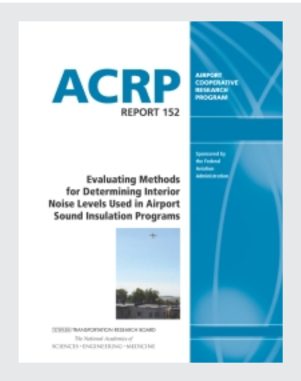

Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs

DETAILS

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AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP REPORT 152

Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs

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AIRPORT COOPERATIVE RESEARCH PROGRAM

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COOPERATIVE RESEARCH PROGRAMS

AUTHOR ACKNOWLEDGMENTS

The research report herein was performed under ACRP Project 02-51 by Paul Schomer, Principal Investigator (Schomer & Associates); Jack Freytag, Lead Researcher (Freytag & Associates); and Randy Waldeck, Project Manager (CSDA Design Group). They were assisted by Herb Singleton at Cross-Spectrum Acoustics and Greg Baker at CSDA Design Group. The team would like to acknowledge San Diego International Airport and Boston Logan International Airport staff for their assistance in organizing the field measurements.

FOREWORD

By Joseph D. Navarrete
Staff Officer
Transportation Research Board

ACRP Report 152: Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs provides guidance for selecting and implementing methods for measuring noise level reduction in dwellings associated with airport noise insulation programs. The research results will be of particular interest to airport industry practitioners who may be implementing such a program or who are responsible for conducting the measurement tests.

Airports often undertake noise insulation programs to reduce impacts on homes within existing or forecast noise contours. Various methods for measuring noise level reduction are used to ensure that acoustical treatments meet the FAA's noise reduction requirements. Yet the measurement of noise level reduction within a home is a complex process. Measurement results are affected by many factors, including instrument error, location of the sound source and microphone, ambient noise, and meteorological conditions. The issuance of FAA's *Program Guidance Letter 12-09, Eligibility and Justification Requirements for Noise Insulation Projects*, resulted in the need to re-examine the methods used to determine whether existing interior noise levels are greater or less than 45 dB, the level required to qualify for federal funding for these projects. Although the criteria for the design of dwelling modifications are fairly well defined, there is limited measurement guidance for confirming a dwelling's eligibility, which can result in inconsistencies when implementing airport sound insulation programs. Research was needed to gain a better understanding of the factors that lead to differences among measurement methods and to understand and minimize inaccuracies in estimating interior noise levels.

The research, led by CSDA Design Group, complements the results of *ACRP Report 89: Guidelines for Airport Sound Insulation Programs* and was undertaken to assess the accuracy and validity of various noise level reduction measurement procedures currently used in airport noise insulation programs. Acoustical field measurements were made at 10 homes near San Diego International Airport and nine homes near Boston Logan International Airport. Seven measurement methods were tested:

- Outdoor ground-level artificial sound source (loudspeaker);
- Outdoor elevated artificial source (loudspeaker);
- Indoor artificial sound source (loudspeaker);
- Aircraft flyover: fixed microphone;
- Aircraft flyover: moving microphone;
- Architectural survey and noise reduction calculations; and
- Acoustic intensity measurements, exterior loudspeaker and interior intensity.

The report includes a summary of sound insulation theory and the science behind noise level reduction, and an overview of FAA-sponsored noise insulation programs. The report also provides guidance, including a decision matrix, for selecting an appropriate acoustical testing method. Lastly, the report provides suggested practices for each measurement technique, based on the results of the research.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

CHAPTER 1

Overview

1.1 Purpose of Report

The primary purposes of this report, *ACRP Report 152: Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs*, are to discuss and clarify acoustical testing issues associated with airport sound insulation programs administered by the Federal Aviation Administration (FAA) and to provide proposals for improvement. The first ACRP report related to sound insulation programs, *ACRP Report 89: Guidelines for Airport Sound Insulation Programs* was published in 2013 (Payne et al. 2013) to describe and suggest procedures for conducting sound insulation programs. *ACRP Report 89* addresses the major elements of a sound insulation program, including program development, community outreach, acoustical engineering, architectural treatments, historic structures, ventilation, green building initiatives, contracting, funding, and reporting. Much of the background information for this report comes (with some minor updating by the research team) from *ACRP Report 89*, and it remains a good source for more detail on sound insulation programs.

Important elements of airport sound insulation programs are the pre- and post-construction acoustical measurements to quantify the noise level reduction (NLR) of the structures. The purpose of these measurements is to:

- Determine the eligibility of the home for treatment, in accordance with recent FAA guidelines stated in Program Guidance Letter (PGL) 12-09 (FAA 2012b) and FAA Order 5100.38D (FAA 2014). Order 5100.38D (the *Airport Improvement Program Handbook*) requires that structures potentially eligible for sound insulation [i.e., within the DNL/CNEL (day–night average noise level/community noise equivalent level) 65 decibels (dB) noise contour] be evaluated to determine whether interior noise levels are high enough to warrant sound insulation treatment. Structures already providing good sound insulation, reducing interior DNL/CNEL noise exposure to 45 dB or less, are ineligible for treatment under the program.
- Provide a quality control check ensuring that a minimum 5 dB NLR improvement is realized from sound insulation treatment.

Currently, various sound insulation measurement procedures are employed by the many acoustical consultants working on airport sound insulation programs. There are no standardized procedures for airport sound insulation program measurements, although certain American National Standards Institute (ANSI) standards are typically followed as closely as practical. Current practices depend upon consultant capabilities and experience, noise measurement budgets, and logistical constraints. Overall airport sound insulation programs oversight is typically provided by the local FAA Airport District Office (ADO), but these offices rarely address acoustical measurement techniques.

With a program typically providing $25,000 to $30,000 of retrofit treatments at no cost to the homeowner (whose home is affected by airport noise), the acoustical measurements take on added importance within the updated handbook (FAA Order 5100.38D: FAA 2014).

Based on field measurements conducted at 10 homes near San Diego International Airport and nine homes near Boston Logan International Airport, this report assesses the accuracy and validity of various NLR measurement procedures currently employed in airport sound insulation programs. The field measurements consisted of alternative NLR measurement methods. The measurement results were compared, and various measurement errors and the typical magnitude of each were evaluated and documented. Measurement tolerances were proposed, and specific measurement procedures were identified as "best practices."

1.2 Summary of Findings

The measurement of NLR of rooms within a home is complex because it is affected primarily by instrument error, microphone location, sound source location, and ambient (or background) noise in both the source and receiver locations, and further by meteorological conditions between. Additionally, measurement results vary with the sound spectra of the aircraft producing the external DNL noise environment, since sound attenuation varies at different frequencies and differs by various building constructions.

1.2.1 Measurement Methods and Findings

In July 2014, a team of three acoustical consultants and four technicians conducted acoustical measurements for a week on 10 homes in noise impacted areas around San Diego International Airport (SAN). These measurements were made using the following test methods:

- Aircraft flyover—for all 10 homes using stationary and moving microphones.
- Exterior ground-level speaker—for all 10 homes.
- Exterior elevated speaker—for five homes.
- Interior speaker—for all 10 homes.
- IBANA (Insulating Buildings Against Noise from Aircraft) calculation—for all 10 homes.
- Spreadsheet populated with industry-standard façade transmission loss (TL) calculations—for all 10 homes.
- Sound intensity—for the first five homes.

This measurement program was then repeated for a week on nine homes in noise impacted areas around Boston Logan International Airport (BOS). This program was less successful than that for the SAN testing due to shifting runway use. However, additional information was obtained, which generally supported the greater database of information obtained at SAN.

Following is a brief description of each measurement method, technique, and results.

1.2.1.1 Aircraft Flyover

- Action: The research team conducted aircraft flyover measurements at 10 homes near SAN and at four homes near BOS. Flyover measurements consist of the placement of one sound level meter outside of the home and one to three sound level meters in each of the rooms under test. The meters concurrently measure aircraft flyovers and the difference in flyover noise level between exterior and interior is calculated. (See Figure 1-1.)
- Findings:
  - Measurements need to be conducted in vacant homes, as occupant contamination easily occurs.
  - On average, the NLR measured using the flyover method is 0.4 dB higher than the overall average NLR.

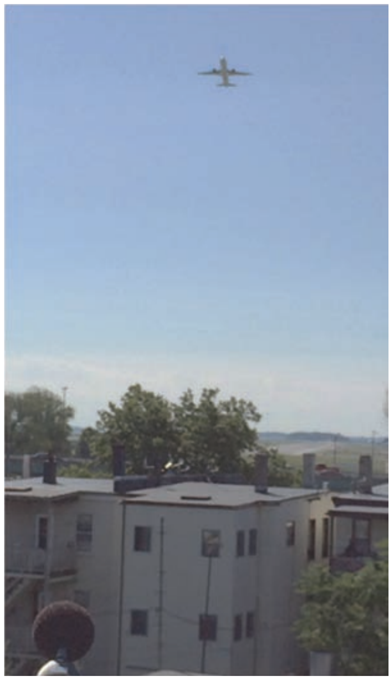


Figure 1-1. Flyover measurement picture.

- There are some rooms with results that are outliers and these findings are discussed in Section 4.1.
- The mean and the median noise reduction should be computed, because comparing the results from the two statistics provides a check on the validity and stability of the NLR results.
- A properly placed single microphone is adequate for most NLR measurements.

1.2.1.2 Ground-Level Exterior Loudspeaker

- Action: The research team conducted ground-level loudspeaker measurements at 10 homes in San Diego. In Boston, the research team conducted measurements in nine homes. The measurements were taken in two rooms per home and were conducted by placing a loudspeaker outside of the room under test, generating a loud test signal (pink noise) and measuring at the exterior façade and inside of the room being tested. (See Figure 1-2.)
- Findings:
  - The NLR measured using the ground-level exterior loudspeaker method is, on average, 1.4 dB lower than the overall average NLR.
  - There are some rooms with results that are outliers, which are discussed in Section 4.8.
  - On average, calculated NLR using the OITC (outdoor-indoor transmission class) spectrum was slightly lower (0.5 dB) than that of the flyover spectrum.
  - In general, the results varied little when the measurements were repeated.
  - Similar to the elevated loudspeaker, the NLR decreased by approximately 1 dB when the roof and walls were measured at the exterior.

1.2.1.3 Elevated Exterior Loudspeaker

- Action: The research team conducted elevated exterior loudspeaker measurements in five homes in San Diego and five homes in Boston. Two rooms per home were measured. The elevated loudspeaker measurement is performed in a manner similar to the ground-level loudspeaker, except the loudspeaker is elevated above the building via a crane or bucket truck. (See Figure 1-3.)

Figure 1-2. Ground-level loudspeaker measurement picture.

- Findings:
  - The NLR measured using the elevated-level exterior loudspeaker method is, on average, 0.5 dB lower than the overall average NLR.
  - There are some rooms with results that are outliers; Section 4.8 discusses this in detail.
  - On average, the calculated NLR using the OITC spectrum was slightly lower (0.3 dB) than that using the aircraft flyover spectrum.
  - With repeated measurements, noise reduction did not significantly change.
  - NLR decreased by 0.8 dB when the measurement included a microphone scan of the roof.

Figure 1-3. Elevated exterior loudspeaker picture.

1.2.1.4 Interior Loudspeaker

- Action: The research team conducted interior loudspeaker measurements in 10 homes in San Diego. In Boston, the research team conducted interior loudspeaker measurements in nine homes. Measurements were taken in two rooms per home. Interior loudspeaker measurements were conducted by placing the loudspeaker inside of the room under test, generating a test signal, and measuring both inside of the room (source) and at the exterior of the room (receive).
- Findings:
  - The interior loudspeaker method yielded NLR values significantly higher than the other methods. Differences like this are frequently systematic; it appears a correction is needed to account for reverberant build-up in the source room. The research team applied a 5 dB correction to the measurement data for reverberant build-up; however, additional investigation is necessary to determine the appropriate correction for the type of measurement.
  - There are some rooms with results that are outliers.
  - On average, the calculated noise reduction using the OITC spectrum was slightly lower (0.9 dB) than that calculated using the flyover spectrum.
  - NLR varied by less than 1 dB when measurements were repeated.
  - NLR increased when the wall and roof were measured. This is opposite of what happened when the loudspeaker was located outside.

1.2.1.5 Acoustical Calculations

- Action: The research team performed noise reduction calculations using two calculation models: IBANA and a spreadsheet populated with industry standard TL formulas. The calculations require detailed information on building element sizes (e.g., window area) along with information on the construction of the building elements. An additional and generally small computation is also made for the acoustical absorption effects of the room interior. Calculations are made using either IBANA computer program or individual consultant spreadsheet programs and TL files for building elements.
- Findings:
  - Both calculation methods resulted in similar NLR values for most rooms.
  - Calculations typically provide similar results as the exterior loudspeaker or flyover testing; however, the accuracy of the calculation is dependent upon a comprehensive field survey.
  - Flanking paths (e.g., noise leaks) can easily be missed in the field survey and calculation, resulting in overstatement of NLR.
  - The acoustical calculations resulted in NLRs that were higher than the average NLR by 0.7 to 1.3 dB.

1.2.1.6 Air Infiltration

- Action: The research team measured air infiltration values via a blower door test, and correlated the air infiltration value to measured noise reduction.
- Findings:
  - There is no correlation between the air infiltration results from blower testing and the measured noise reduction.

1.2.1.7 Sound Intensity

- Action: The research team conducted sound intensity measurements in five homes near the San Diego International Airport. Additional measurements were conducted at a residence in Champaign, IL. The research team took measurements from outdoor to indoor, as well as from indoor to outdoor.

6 Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs

- Findings:
  - Classical acoustic theory presumes that TL is the same in both directions (i.e., a wall performs equally whether the source of noise is inside of a home or outside of a home). Through this study, the research team found this generally to be true.
  - The best strategy when conducting sound intensity measurements is to measure as close to the exterior wall as feasible.
  - Based on the research team's experience with this measurement method, the technology and time required preclude the use of sound intensity for airport sound insulation programs at this time.
  - There are a number of enhancements suggested to provide for better sound intensity results and possibly allow for the use of sound intensity for airport sound insulation programs in the future. Additional research is needed.
  - Sound intensity holds the promise of being an extremely effective method because the results are virtually independent of weather effects, the measurements are independent of resonance effects, there are no neighbor noise disruptions, and nearby reflectors are not a problem.

1.2.2 External Sound Spectra

A significant factor that affects the measured noise reduction is the external sound spectra (i.e., the noise "signature" of aircraft overflights at a given airport). The external DNL frequency spectrum to be modeled (from the FAA Part 150 program Noise Exposure Map) is unknown since it is the annual energy average of all aircraft over a particular location, with the 10 dB nighttime penalty (a single nighttime flyover is equal to 10 daytime flyovers of the same level), under all annual meteorological conditions; it can only be estimated. The spectra of louder aircraft should be biased on an energy basis; for instance, a single flyover at 90 dB should be averaged equally with 10 flyovers at 80 dB.

Since the sound spectra cannot be addressed in the field measurements addressed in this report, the issue of external sound spectra is beyond the scope of this study. Additional research and investigation is suggested.

1.2.3 Relative and Absolute Measurement

Two basic types of measurements are now required:

1. Relative measurements—Those measuring only the difference or change from a previous measurement. For the residential sound insulation program (RSIP), this is the NLR improvement from pre- to post-construction.
2. Absolute measurements—Those measurements without reference to other measurements. For the RSIP's, this requirement is restated in the PGL/FAA Order 5100.38D to measure the pre-construction NLR to determine eligibility for acoustic retrofit.

Prior to PGL 12-09, industry practice concerning noise reduction measurements was principally relative measurements rather than absolute measurements. Relative measurements assess the change in noise reduction performance, whereas absolute measurements assess the absolute interior DNL values.

There are various sources of error or uncertainty with the different NLR test methods. These include the effects of measurement location, instrument error, meteorological conditions, aircraft flight operations and fleet mix, and background noise.

All relative measurements will incur less uncertainty than absolute measurements. Relative measurements may duplicate certain uncertainties, such as instrument error (by using the same instrument for pre- and post-construction measurements). Therefore, for example, if an acoustical instrument had a +0.5 dB error, it would not affect a relative measurement because the +0.5 dB would be added to both measurements and the difference would not be affected. Using the same instrument for an absolute pre-program qualifying measurement would incur the +0.5 dB in interior DNL. Therefore, additional care and enhanced precision are necessary for the interior DNL measurements to reliably determine whether structures are eligible for sound insulation (i.e., interior noise levels are greater than 45 dB).

1.3 Acoustical Testing Matrix

Table 1-1 identifies various situations and measurement elements to be considered when selecting a particular test method. This has been developed to assist in choosing the most effective and efficient test method for NLR measurement in a particular situation. Each method has advantages and disadvantages in terms of both technical accuracy and reliability, and in field implementation and costs. In developing the matrix in terms of errors, all methods are assumed to yield similar results after correction factors are applied (see Note 1 of Table 1-1). Therefore, it was necessary to average results for each method applied to each room of each residence tested. The variation from the average is given in the "average NLR difference." However, this average is necessarily influenced by all test methods evaluated, some of which must be less accurate and reliable than others. So a method yielding a result closest to the average of all methods is not necessarily the best, most accurate, or most reliable.

The best method is a method that is logistically feasible, has the smallest average NLR difference and standard deviation, and conforms to a national/international standard.

1.4 Acoustical Testing Decision Matrix

Table 1-2 is a decision matrix addressing various situations and measurement elements to be considered when selecting a particular test method. This may be used to assist in choosing the most effective and efficient test method for NLR measurement in a particular situation. Each of the measurement issues listed may be reviewed with respect to any particular test program. This should assist in selecting the optimum test method for a particular program. For specific homes and measurement issues, it may be advisable to add to this list for a specific evaluation.

Noise level reduction measurements are made (1) to assess eligibility for acoustical treatment according to PGL guidelines and (2) for quality control to determine the degree of NLR achieved from acoustical retrofit. The three main considerations in selecting a particular testing method are technical issues, administrative issues, and financial issues. There is no single method that is best for every home or program since physical, administrative, and financial issues vary with every program.

The primary technical issues with the aircraft flyover method are the availability of aircraft types and flight tracks in the area to be measured on the day of measurement. The aircraft activity measured should reasonably represent a sampling of the average annual aircraft operation from the Integrated Noise Model (INM)/Aviation Environment Design Tool (AEDT) qualifying the sound insulation program. Particular attention should be paid to nighttime operations, since they are biased by 10 dB in the DNL assessment.

The ground-level loudspeaker measurement method may be constrained by second story homes where it is difficult to produce significant sound energy on the roof. This situation is particularly sensitive for homes with flat monolithic roofs, often the weak acoustical link in the building envelope (i.e., building façade and roof). Also, closely packed residences may not allow for all rooms in a home to be measured, because it may not be possible to place the exterior loudspeaker in the required location for a given room.

Table 1-1. Matrix of acoustical testing methods.

Method	Accuracy	Uncertainty	Cost/home	Logistics	Public Relations	Repeatability	Standardization	Covered under FAA PGL 12-09 / Order 5100.38D?	Limitations
Flyover	Avg. Diff. = 0.4 dB	Std. Dev. = 1.9 dB	Meas: 5.3 hrs Instr: $260 Analysis: 4.0 hrs Other: $23 Total: $1,473	Straightforward. Requires vacant residence. May be contaminated by occupants or exterior noise (e.g., dog bark).	Little effect.	No.	Generally conforms to ASTM E966.	Yes.	Requires substantial flight activity. The measurement may not capture all aircraft types (e.g., package delivery aircraft).
Exterior Ground Level Speaker	Avg. Diff. = 1.4 dB	Std. Dev. = 1.8 dB	Meas: 4.0 hrs x 2 ppl Instr: $65 Analysis: 4.0 hrs Other: $18 Total: $1,600	Straightforward. Not feasible at some rooms due to lack of space/access to required exterior speaker location.	Disturbing to neighbors.	Yes.	Generally conforms to ASTM E966.	Yes.	Does not reach roof, leading to poor results for flat monolithic roofs.
Exterior Elevated Speaker	Avg. Diff. = 0.5 dB	Std. Dev. = 1.7 dB	Meas: 4.0 hrs x 2 ppl Instr: $65 Analysis: 4.0 hrs Other: $618 Total: $2,200	Difficult with bucket truck. Not feasible at some rooms due to lack of space/access to required exterior speaker location.	Disturbing to neighbors. Truck may block traffic.	Yes.	Generally conforms to ASTM E966.	Yes.	Access not always possible due to trees, buildings & wires.
Indoor Speaker	Avg. Diff. = 0.1 dB	Std. Dev. = 2.9 dB	Meas: 5.3 hrs Instr: $43 Analysis: 4.0 hrs Other: $12 Total: $1,233	Straightforward. May be contaminated by high traffic noise levels.	Minor effect.	Yes.	No standards or conformance tests.	No.	Not vetted by acoustical consultant community; correction factors required, but no clear guidance on what to use.
IBANA Calculation	Avg. Diff. = -0.7 dB	Std. Dev. = 1.4 dB	Survey: 5.3 hrs Instr: $0 Analysis: 4.0 hrs Other: $12 Total: $1,190	Straightforward. Requires on-site survey of each room/building.	Little effect.	Yes.	Conforms to Canadian standards.	No.	Assumes built construction per computer database. Does not account for leaks or other building deficiencies.
Spreadsheet Calculation (measured RT_{60})	Avg. Diff. = -1.3 dB	Std. Dev. = 2.1 dB	Survey: 5.3 hrs Instr: $43 Analysis: 6.0 hrs Other: $12 Total: $1,233	Straightforward.	Little effect.	Yes.	Conforms to known acoustical theory.	No.	Assumes built construction per computer database. Does not account for leaks or other building deficiencies.
Sound Intensity			Meas: 4.0 hrs x 2 ppl Instr: $325 Analysis: 6.0 hrs Other: $18 Total: $2,110	Requires use of expensive instrument.	Minor effect.	Likely.	No standards exist.	No.	New method under development.

Notes: Meas. = duration of the text; ppl = people; Inst. = cost of the measuring equipment; RT = reverberation time; RT_{60} = The time it takes for sound to decay 60 dB in a room. Large rooms with hard surfaces, such as concert halls, have reverberation times of around 2 seconds. Smaller rooms with sound absorbing surfaces have shorter reverberation times.

1) Corrections applied - Flyover: 2 A-weighted decibels (dBA), Exterior loudspeaker: 2 dBA, Interior loudspeaker: 5dBA.

2) Average NLR difference calculated by first averaging all of the NLR across all measurement methods (except interior loudspeaker and sound intensity), and then subtracting the NLR from one method (e.g., flyover) from the average NLR. Interior loudspeaker not used in average as this method does not follow national standards and the 5-dB correction applied to the data is based on limited field measurements (i.e., not fully vetted).

3) Loudspeaker measurement accuracy would be improved if flush microphone position is used instead of the 1 to 2 meter position.

4) Costs based upon the best practices outlined in this report, not current practice for sound insulation programs.

Table 1-2. Decision matrix for acoustical testing method.

Measurement Issue	Aircraft Flyover	Exterior Ground Speaker	Exterior Elevated Speaker	Indoor Speaker	IBANA Calculation	Spreadsheet Calculation	Sound Intensity
Method has been accepted for previous FAA testing	X	X	X				
Testing may be repeated for verification		X	X		X	X	
Minimum disruption to occupants					X	X	
Minimum disruption to neighbors	X			X	X	X	X
Perceived as most credible by homeowners	X						
Adequately measures poor roof-ceiling assemblies	X		X	X	X	X	
Runway use varies, limited flyover activity		X	X	X	X	X	X
Testing method supported by national standards or theory	X	X	X		X	X	
Home must be vacant	X						
Elevated interior noise levels (e.g., birds, dogs)	X	X	X	X	X	X	X
Home surrounded by trees or utility wiring	X	X		X	X	X	X
Information on home construction unavailable	X	X	X	X			X
Covered under FAA PGL/5100.38D	X	X	X				

Note: Shaded columns represent the suggested measurement methods.

The elevated loudspeaker method requires a bucket truck with hydraulic lift to be used. Closely packed residences may not afford sufficient room to maneuver the truck to elevate the speaker for measurement. Trees and utility lines often obstruct areas where the speaker should be elevated. Additionally, similar to the ground-level loudspeaker, it may not be possible to measure all rooms when residences are closely packed.

The calculation method has few technical impediments, though currently it is often difficult to accurately determine the acoustical flanking (leaks) from a home survey. However, new methods may be developed to minimize this shortcoming.

Administrative issues are those where homeowner satisfaction may be affected by the measurement method. Most homeowners seem to intuitively trust the aircraft flyover method over other methods. Some skepticism has been expressed in the past over loudspeaker and computation NLR methods, however unfounded. It is important, in all cases when measuring the NLR improvement, to employ the same method for pre- and post-construction measurement. When measuring for qualification for the program under PGL/Order 5100.38D guidelines, homeowners may be particularly sensitive about the measurement method because it may eliminate their eligibility for participation while a seemingly similar neighbor home may qualify. To the extent possible, it is advisable to use a single NLR measurement method throughout the neighborhood to minimize homeowner skepticism about the measurement process.

Financial considerations are fairly straightforward by assessing the data in the Table 1-1 matrix. There is a natural desire to minimize measurement expense to allow for additional funding for the actual noise insulation work. However, with the new PGL/Order 5100.38D guidelines, homeowners may be expected to challenge eligibility, perhaps by lawsuit, if they are eliminated from the program by pre-construction acoustical measurement. Therefore, in sensitive situations it may be advisable to select the most accurate and reliable method from Table 1-3 despite an increased cost for measurement.

Table 1-3. Calculated measurement uncertainty.

Method	Field Meas. Margin of Error	Calculated Total Margin of Error	Outdoor Measurement Factors			Interior Measurement Factors			Meteor-ology	Ground Dip	Mass-air-mass resonance
			Location	Ambient	Instrument	Location	Ambient	Instrument			
Existing Practice											
Aircraft flyover	± 1.9	**± 1.9**	1.2	0.5	0.4	0.4	0.5	0.4	1.0	0.5	
Speaker outside	± 1.8	**± 1.9**	1.3	0.3	0.4	0.4	0.3	0.4	0.5	0.3	1.0
Best Practice											
Aircraft flyover		**± 1.4**	0.2	0.5	0.4	0.2	0.5	0.4	1.0		
Speaker outside		**± 1.1**	0.2	0.3	0.4	0.2	0.5	0.4	0.5	0.2	0.5
Intensity		**± 0.9**	0.4	0.3	0.4	0.4	0.3	0.4			

Notes:
1. Assume no significant grazing incidence (when the angle formed between the façade surface and noise source approaches zero). Accurate measurements are not possible with significant grazing incidence.
2. Flyover method: Assumes only aircraft with a 10 dB or higher signal-to-noise ratio used.
3. Loudspeaker: Assumes only data with a 10 dB or higher signal-to-noise ratio used.
4. Loudspeaker Best Practice: Assumes four loudspeaker positions, two surface-mounted microphones (exterior) per wall/roof, and interior spatial average/manual scan.

Based on the research team's findings, the aircraft flyover and exterior loudspeaker methods provide the best results. Sound intensity and indoor speaker methods show promise for future measurements, but additional research and standardization of the measurements is necessary. Acoustical calculations generally provide accurate results; however, it is possible to miss flanking paths (sound leaks) during the field survey that would result in overstatement of the NLR.

1.5 Measurement Uncertainty—Present and Future

As part of data analysis, the research team used national and international standards for acoustical measurement to correlate and correct measurement results obtained. While the research team was able to measure and analyze the uncertainties associated with the measurements, there are other known factors to influence measurement results. This proved most important for external loudspeaker and microphone position for the flyover and speaker measurements. Table 1-3 shows the measurement uncertainties for current measurement practices and best practices outlined in Section 1.6. The aircraft flyover, exterior speaker, and sound intensity methods are assessed. The cumulative margin of error is given in the second column adjacent the measurement method; this is the convolution of the individual uncertainties for each measurement method and technology.

Appendix D provides detailed information on how the measurement uncertainty was calculated.

The above margins of error are for the absolute measurement conditions and not for the relative measurements. Relative measurement uncertainty will be less because some of the uncertainty factors such as instrument error would be nearly the same for the pre- and post-construction NLR measurements.

1.6 Acoustical Testing Best Practices

Careful measurement protocol will minimize measurement uncertainties, particularly for the relative measurements. All measurement conditions should be carefully documented with field notes and photographs, with particular attention given to measurement locations. Ambient noise levels and sources, aircraft operations, meteorological conditions, and measurement team should be noted. This will be particularly true for the relative post-construction measurements, where accurately replicating the original measurement conditions will minimize uncertainty.

Table 1-4 summarizes the best practices for each measurement method.

1.6.1 Best Practices for Aircraft Flyover Measurements

1. Measurements should be conducted in vacant homes, as occupant noise contamination readily occurs.
2. Consultants should review the general operations of each airport to ensure that the aircraft spectrum being used (based on the airport's fleet mix) is from the INM/AEDT study qualifying the sound insulation program. Special selection of fleet mix to be used may be required in special cases such as military operations occurring at night.
3. Outdoor microphones should be set in the free field or flush mounted to the ground or building façade. Near field measurement, 1 to 2 m from the façade, is not recommended.
4. Measurements should be made in one-third octave bands from 50 Hz through 5 kHz or octave bands from 63 Hz through 4 kHz; the A-weighted value (see Section 3.2.1.3: Frequency Weighting) should be computed from these frequency ranges, rather than using the A-weighted value calculated by the sound level meter.
5. Measurement sample time should not be faster than every 0.5 sec (500 ms). See Section 4.1.1.
6. In general, raw noise reduction is higher with the flyover measurement method than the loudspeaker measurement method; a correction of 2 to 4 dB is recommended to compensate for ground reflection and/or reflected noise off the façade under test.
7. The preferred statistical analysis (1) computes the mean NLR values for all events, (2) orders all NLR values from highest to lowest standard deviation, and (3) sequentially deletes the NLR event with the highest standard deviation computing a new mean, standard deviation, and desired confidence interval. This process, deleting the top value with the highest standard deviation, is repeated until the desired mean, standard deviation, and confidence interval are achieved. The procedure and example are found in Section 4.1.2.
8. A single properly placed microphone in interior rooms is adequate for most NLR measurements.

1.6.2 Best Practices for Ground-Level Exterior Loudspeaker

1. The loudspeaker should be located approximately 6 to 12 m (20 to 40 feet) away from the façade for typical homes; adequate sound levels (e.g., 90 dB minimum) should be generated at the façade to overcome background noise. For rooms with multiple façades (e.g., corner rooms), the loudspeaker should be positioned to generate diffuse sound levels. Noise levels along the façades should not vary by more than 3 dB.
2. Measurements should be made in one-third octave bands from 50 Hz through 5 kHz or octave bands from 63 Hz through 4 kHz; the A-weighted value should be computed, rather than from direct A-weighted measurement.
3. For the exterior (source measurement), the roof should be measured if the noise level at the roof is within 10 dB of the noise level of the wall.
4. For the exterior measurement position, four loudspeaker positions should be used (e.g., 30°, 45°, 60°, 75°). The results should then be averaged using the weighting outlined in ASTM (American Standard for Testing and Materials) E966 (ASTM 2010).

Table 1-4. Best practices summary table.

Test Method	Source Location	Source Microphone Location	Source Correction (Reference)	Receiver Microphone Location	Receiver Correction (Reference)
Flyover	Airborne (aircraft)	Free field above ground	2 to 4 dB, due to ground reflection and reflection from building facade	Interior away from walls, measuring diffuse field	0 dB
Exterior Ground-Level Speaker	10m to bldg/1.5m elev (far field) 10m to bldg / 1.5m elev (far field)	2m off facade (spatial average) flush to facade - recommend (2 locs per wall/roof)	2 dB (ASTM E966) 5 dB (ASTM E966)	Interior away from walls, spatial average Interior away from walls, spatial average	0 dB 0 dB
Exterior Elevated Speaker	10m to bldg / above roof 10m to bldg / above roof	2m off facade (spatial average) flush to facade - recommend (2 locs per wall/roof)	2 dB (ASTM E966) 5 dB (ASTM E966)	Interior away from walls, spatial average Interior away from walls, spatial average	0 dB 0 dB
Indoor Speaker	Room corner, producing diffuse sound field	Moving microphone, measuring diffuse field	5 dB, due to reverberant build-up; research needed	Exterior flush mounted 2m off facade (near field)	? - research needed ? - research needed
Sound Intensity	Room corner, producing diffuse sound field	Moving microphone measuring diffuse field	0 dB	Exterior flush mounted 2m off facade (near field)	? - research needed ? - research needed

5. Exterior microphones should be flush mounted where possible, rather than 1 to 2 m (3 to 6 feet) off the façade. For the flush mount, at least two microphone positions per façade and/or roof should be used (e.g., a corner room without a roof measurement would yield four positions).
6. Measurements should be halted during aircraft flyovers. This requires two technicians (one outdoor and one indoor) and a visual or non-auditory alert system so the interior measurement can be halted during a flyover.
7. Other practices outlined in ASTM E966 should be followed, such as subtraction of background noise, spatial averaging (manual scanning) in the room, etc.

1.6.3 Best Practices for Elevated Exterior Loudspeaker

1. The loudspeaker should be located approximately 6 to 12 m (20 to 40 feet) away from the façade for typical homes; the loudspeaker should be elevated above the roof plane. Adequate sound levels (e.g., 90 dB minimum) should be generated at the façade to overcome background noise. For rooms with multiple façades (e.g., corner rooms), the loudspeaker should be positioned to generate diffuse sound levels. Noise levels along the façades should not vary by more than 3 dB.
2. Measurements should be made in one-third octave bands from 50 Hz through 5 kHz or octave bands from 63 Hz through 4 kHz; the A-weighted value should be computed, rather than direct A-weighted measurement.
3. For the exterior (source measurement), the roof should be measured.
4. For the exterior measurement position, four loudspeaker positions should be used (e.g., 30°, 45°, 60°, 75°); the four angles can be achieved in the horizontal and/or vertical plane. The results should then be averaged using the weighting outlined in ASTM E966.
5. Exterior microphones should be flush mounted where possible, rather than 1 m to 2 m (3.3 ft. to 6.6 ft.) off the façade. For the flush mount, at least two microphone positions per façade and/or roof should be used (e.g., a corner room with roof would yield six positions).
6. Measurements should be halted during aircraft flyovers. This requires two technicians (one outdoor and one indoor) and a visual or non-auditory alert system so the interior measurement can be halted during a flyover.
7. Other practices outlined in ASTM E966 should be followed, such as subtraction of background noise, spatial averaging (manual scanning) in the room, etc.

1.6.4 Best Practices for Interior Loudspeaker

Since there is no national/international standard for the interior loudspeaker noise reduction measurement, the research team has not provided best practices. Additional research is necessary to standardize this measurement and determine which correction factors are required for the data to be comparable to the exterior loudspeaker and flyover measurements.

1.6.5 Best Practices for Acoustical Calculations

1. Compute the composite transmission loss (CTL) for all façades receiving flyover noise using dimensions from field drawings and reliable TL data for the building elements.
2. It is not necessary to measure reverberation time in typical rooms; rather, the research team proposes utilizing typical, conservative reverberation times to adjust the calculated noise reduction.
3. A laser glass gauge or similar should be used during the field survey to determine the exact glazing configuration of the windows. Close review of door gasketing and other fenestration elements is warranted to estimate the “leakiness” of components.

4. It is not generally necessary to consider flanking transmission from air infiltration, because CTL need only be computed in the frequency range 50 Hz through 5 kHz where flanking effects are minimal.
5. Acoustical calculations should be calibrated/back-checked via acoustical measurements. For example, if calculations are performed on 100 homes, then 10 homes should be acoustically tested to verify the calculation model.

1.6.6 Best Practices for Air Infiltration

There was no correlation observed between the air infiltration results from blower door testing and measured noise reduction. Thus, the research team does not recommend utilizing air infiltration to predict noise reduction and has not proposed the procedure in best practices.

1.6.7 Best Practices for Acoustic Intensity

Since there is no national/international standard for sound intensity measurements of the type required, the research team has not provided best practices in this area. Additional research is necessary to standardize this measurement and determine which correction factors are required for the data to be comparable to the exterior loudspeaker and flyover measurements.

Intensity is included here because it has the potential for becoming "the" best practice. In addition to its low measurement uncertainty and immunity from factors that affect other methods, it is the only method that can be used equally well at any airport in the world.

CHAPTER 2

Project Background and Study Scope

2.1 Sound Insulation History

In 1981 the FAA issued interim Federal Aviation Regulation, Part 150, Airport Noise Compatibility Planning, as the primary regulation guiding and controlling planning for aviation noise around airports (Federal Register Notice 46 FR 8316). The FAA can and does influence compatible land use planning, though it has no jurisdiction over local or state land use decisions (i.e., zoning). Part 150 established procedures, standards, and methodologies to be used by airport operators for the preparation of Airport Noise Exposure Maps (NEMs) and Airport Noise Compatibility Programs (NCPs), which they may submit to the FAA under Part 150 and the ASNA (Aviation Safety and Noise Abatement Act of 1979). Part 150 does the following:

- Establishes standard noise methodologies and units.
- Establishes the INM as the standard noise modeling methodology is compatible or non-compatible with various levels of airport noise.
- Provides for voluntary development of NEMs and NCPs by airport operators.
- Provides for review of NEMs to insure compliance with the Part 150 regulations.
- Provides for review and approval/disapproval of Part 150 NCPs submitted to the FAA by airport operators.
- Establishes procedures and criteria for making projects eligible for funding as noise projects through the Airport Improvement Program (AIP).

As part of an NCP, measures to achieve compatibility are proposed and typically characterized as either:

- Noise abatement measures, such as aircraft flight procedures that reduce noise or redistribute it to less populated areas, or
- Land use measures, such as property acquisition or sound insulation of noise-sensitive properties.

After the airport authority submits an NCP, the FAA will respond with a Record of Approval stating which measures are approved or not approved and could be further considered for funding under its AIP. Mitigating the impact of aircraft noise on communities is known by a variety of terms, including noise insulation, noise attenuation, soundproofing, sound insulation, acoustical treatment, sound mitigation, and noise mitigation. Individual airports often give their programs unique names incorporating some of these descriptors. To avoid confusion, this report will use the term *sound insulation* throughout.

2.1.1 The AIP

The AIP is authorized by Title 49 of the United States Code (USC). Previously, the AIP was authorized by the Airport and Airway Improvement Act of 1982 [Public Law (P.L.) 97-248, as amended]. The AIP's broad objective is to assist in the development of a nationwide system of public-use airports adequate to meet the current needs and projected growth of civil aviation.

The Act provides funding for airport planning and development projects at airports included in the National Plan of Integrated Airport Systems (NPIAS) and authorizes funds for noise compatibility planning and implementation.

2.1.2 FAA Order 5100.38D, the *Airport Improvement Program Handbook*

The *Airport Improvement Program Handbook* (referred to in this report as the *AIP Handbook*) provides FAA staff with guidance about the administration of the AIP. It sets forth policy and procedures to be used in the administration of the AIP. *AIP Handbook* Chapter 2: Who Can Get a Grant?, Appendix C: Prohibited Projects, and Appendix R: Noise Compatibility Planning Projects all discuss sound insulation projects.

Between revisions of the handbook, additional information and guidance is provided to users through a variety of FAA publications such as PGLs, Advisory Circulars (ACs), and FAA directive orders.

2.1.3 FAA PGL 12-09

Prior to the recent publication of 5100.38D, the FAA issued PGL 12-09 to address confusion and ambiguity in the application of the two-step requirement for AIP eligibility for residential and other sound insulation projects. The previous AIP Handbook (5100.38C) and Title 14 Code of Federal Regulations (CFR) Part 150 have been interpreted as requiring that structures only need to be located in the existing or forecast yearly DNL 65 dB noise contour to qualify for sound insulation; noise insulation projects were to be designed to achieve interior noise levels of DNL 45 dB to qualify for federal funding.

Most of the policy revisions and clarifications contained in PGL 12-09 have been incorporated into the new AIP Handbook (5100.38D: FAA 2014). The FAA has also provided guidance for sound insulation projects currently underway in their document, *Handling Noise Insulation Programs That Are Currently Underway* (FAA 2012a). It establishes a transition period (fiscal years 2012 through 2014) during which the FAA will allow sponsors to complete the sound insulation of structures as planned, provided that all sound insulation projects undertaken during this time meet all required federal contract provisions (e.g., Buy American). Any sound insulation project that is started during the transition period must have been completed prior to September 30, 2015.

Projects for which construction is ongoing after September 30, 2015, must fully meet the AIP requirements, including experiencing pre-insulation interior DNL noise levels of 45 dB or greater with windows closed.

Additional information regarding the PGL was issued as follows:

- November 7, 2012: Revised memorandum regarding the PGL issued by the FAA as a Record of Changes to remove "AIP" from title of the PGL; three other corrections noted.
- November 9, 2012: Additional information regarding the PGL posted to the FAA's website in the form of nine frequently asked questions (FAQs).

These updated guidelines reflect information provided by the FAA inclusive of the PGL and these two items. Users can access these documents on the FAA website at www.faa.gov/airports/environmental/airport_noise/#part150guidance.

2.1.4 Acoustical Measurement Changes from the PGL

Prior to PGL 12-09, industry practice was to assess the improvement in NLR resulting from sound insulation treatment. The criteria were a minimum 5 dB improvement in NLR and an interior DNL noise environment not greater than 45 dB. The 5 dB improvement was always the primary criterion, since it almost always guaranteed compliance with the 45 dB criterion, and because the allowable noise retrofit treatments seldom resulted in NLR improvements much above 5 dB.

Also, prior to PGL 12-09 and the updated *AIP Handbook*, industry practice concerning noise reduction measurements was principally relative measurements rather than absolute measurements. Relative measurements assess the change in noise reduction performance, whereas absolute measurements assess the absolute interior DNL values.

The subject of this report is the accuracy and validity of relative NLR measurement and that of absolute interior DNL performance for assessment with respect to the absolute PGL criteria for pre-retrofit minimum interior DNL values. There are a number of factors that influence the accuracy and validity of the various measurement techniques. Factors influencing accuracy tend to offset measurement results by a fixed amount, resulting in a fixed error. When measurements are carefully repeated in the same fashion for the pre- and post-construction measurements, this offset is nearly the same and a valid relative measurement is made by simply subtracting the post-construction measurement values from the pre-construction values. However, the offset error also affects the absolute measurement of interior DNL. Therefore, additional care and enhanced precision are necessary for the interior DNL measurements to reliably determine whether structures are eligible for sound insulation (i.e., interior noise levels are greater than 45 dB).

Accurate and valid measurement is important due to the possibility that homes may not meet the interior noise level criteria and homeowners may choose to challenge the testing protocol. If a homeowner sees nearby neighbors with similar homes receiving the valuable noise insulation treatment, while they are ineligible, they may challenge their ineligibility. This may be pursued through local government agencies, the FAA, and/or the courts. Therefore, it is important to accurately and reliably measure pre-construction interior DNL values, with known measurement tolerances.

Errors from NLR measurement may be positive or negative, that is, errors may either overestimate or underestimate the NLR and the attendant interior DNL level. This may render a residence falsely eligible or falsely ineligible. Table 2-1 shows the effects of a 3 dB error in either direction.

Table 2-1. Measurement error and effect on eligibility.

TRUE DNL_{in}	MEASUREMENT ERROR						
	-3	-2	-1	0	1	2	3
42	39	40	41	42	43	44	45
43	40	41	42	43	44	45	46
44	41	42	43	44	45	46	47
45	42	43	44	45	46	47	48
46	43	44	45	46	47	48	49
47	44	45	46	47	48	49	50
48	45	46	47	48	49	50	51

Correctly eligible — True positive (lower right)

Incorrectly eligible — False positive (upper right)

Correctly ineligible — True negative (upper left)

Incorrectly ineligible — False negative (lower left)

Note: DNL_{in} = interior day-night average noise level.
Courtesy of Freytag & Associates.

CHAPTER 3

Research Approach

3.1 Objectives and Tasks

The objectives of this research study were to:

1. Identify and evaluate the accuracy of NLR measurement methods for non-compatible structures.
2. Propose procedures to minimize the measurement inaccuracies of each method.
3. Develop a matrix to help program sponsors identify the most appropriate methodology for determining interior noise levels for their airport sound insulation programs.

To accomplish this, the research was broken up into eight main tasks:

1. Kick-off Meeting with the ACRP Panel.
2. Additional Development of Measurement and Analysis Plan.
3. Acoustical Field Measurements.
4. Data Analysis.
5. Preparation of Interim Report #1.
6. Preparation of Interim Report #2.
7. ACRP Panel Meeting and Draft Report.
8. Final Report.

The following sections describe these steps in detail.

3.1.1 Task 1—Kick-off Meeting with the ACRP Panel

On June 30, 2014, the research team held a conference call with the ACRP Project 02-51 panel to discuss the work plan submitted by the research team after receiving the project Notice to Proceed. In addition to questions and clarifications discussed during the call, the research team received additional comments and questions in writing from the panel. Subsequent to the kick-off meeting, the research team provided responses and clarifications to ACRP.

3.1.2 Task 2—Additional Development of Measurement and Analysis Plan

Incorporating feedback received from the ACRP panel, the research team refined the measurement and analysis plan and also identified prior relevant research and standards that would be reviewed by the team. These documents are listed in the bibliography section of this report. A summary of the research review and applicability to this research is provided in Appendix C.

3.1.3 Task 3—Acoustical Field Measurements

The objective for the field measurements was to focus on the quality of the research versus the quantity of measurements. This means taking a thorough approach to each individual home's noise assessment, which provided greater data for the analysis.

The acoustical field measurements were conducted in 10 homes adjacent to San Diego International Airport and nine homes adjacent to Boston Logan International Airport. Measurements were conducted between July 14 and 18, 2014, in San Diego, and July 27 through August 1, 2014, in Boston. For each home, the research team conducted a variety of acoustical measurement and field analyses. These are summarized as follows; detailed descriptions of each measurement method are contained in subsequent chapters.

- Outdoor Ground-Level Artificial Sound Source (Loudspeaker)
- Outdoor Elevated Artificial Sound Source (Loudspeaker)
- Indoor Artificial Sound Source (Loudspeaker)
- Fixed Microphone Flyover Measurement
- Moving Microphone Flyover Measurement
- Architectural Survey and Noise Reduction Calculations
- Acoustic Intensity Measurements, Exterior Loudspeaker plus Interior Intensity

Additional acoustic intensity measurements were conducted at one test home in Champaign, Illinois. This is described in further detail in Section 4.7: Sound Intensity.

3.1.4 Task 4—Data Analysis

Upon completion of the field measurements, the team began the data analysis process. An enormous quantity of data was generated in performing the field measurements. In order to maintain the project schedule, the data analysis tasks were divided up among the research team, with team members analyzing the data from the measurement method they oversaw/conducted while in the field. A brief description of the data analysis process for each measurement method follows.

3.1.4.1 Flyover Measurement

For each measured room, the sound level meter logged the sound level two times per second (500 ms sampling) to create a time history of the noise level within a room over the measurement period. This time history was then processed to identify any noisy periods (events) where the sound level was more than 10 dB above the background noise level. For each identified event, the research team then correlated its events with flyovers measured by each airport's automated noise monitoring system (ANOMS). This allowed the research team to positively identify each flyover and append the airline, flight number, and aircraft type to each event. This provides certainty that the measured event was a flyover rather than a non-aircraft event such as a motorcycle passby.

3.1.4.2 Artificial Sound Source (Loudspeaker)

Data analyses were performed using spreadsheet calculations, using the one-third octave noise measurement data gathered in the field. For each loudspeaker test, there were four key noise measurements: loudspeaker source, loudspeaker receive, exterior ambient, and interior ambient. For each loudspeaker measurement, the ambient (background) noise was subtracted from the loudspeaker data to effectively eliminate any non-loudspeaker noise sources from affecting the results of the measurement. The loudspeaker-received noise was then subtracted from the loudspeaker source data. The result of this calculation is the measured noise reduction of a building façade. To finalize the noise reduction calculation, two corrections are then applied: a correction to account for the specific noise "signature" of aircraft and a correction to account for the reverberant field created when noise from the loudspeaker impinges upon a building façade. These corrections and their effect on the data are discussed in detail in Chapter 4.

After identifying all aircraft events, the research team then subtracted the measured exterior noise level from the noise level measured by each interior meter. This subtraction was performed for each event. A statistical analysis of all events was then performed to quantify the average NLR and standard deviation for each meter.

3.1.4.3 Architectural Survey and Noise Reduction Calculations

At each home, an architectural survey was conducted to capture details on the architectural and acoustical features of each tested room. The gathered data was then used to calculate the expected noise reduction. The research team employed two calculation methods: the IBANA software tool and a spreadsheet utilizing industry-standard façade TL calculations. Both tools are described in more detail in Chapter 4.

Each calculation utilizes the following inputs: surface area and TL characteristics of exterior wall(s), roof, window(s), and door(s), and the effect of furnishings and finishes in the room.

3.1.4.4 Sound Intensity

The purpose of the intensity measurements was to see if sound power can be used to determine a building envelope's TL, and if so, to gauge the accuracy, complexity, and costs of using sound intensity with respect to conventional sound pressure measurements.

In order to evaluate sound intensity, there are a few factors that need to be ascertained. These factors include:

- Does reciprocity work for indoor versus outdoor loudspeaker locations?
- Can one make a traditional TL measurement using intensity or is it different?
- General measurement techniques: how and where to measure, how long, at fixed points or using an area scan, how to read and manipulate the measured data, etc.

Chapter 4 describes, in detail, the answers to the above questions.

3.1.5 Task 5—Preparation of Interim Report #1

Interim Report #1 summarized the results of the measurements and calculations for review by the panel. The report consisted of the background to this project, along with an introduction that explained the content of this report and the planned content of the final report. The data collection methodology was explained and virtually every measurement made was presented. Measurement results from individual tests were paired against those for other specific tests to identify various potential errors. For example, the moving microphone measurements were evaluated with those from the stationary microphones to assess the effects of various room acoustic aberrations.

As part of the overall statistical analyses, the research team attempted to quantify the uncertainty that results from the sound level meter itself and the equipment operators' technique (e.g., the microphone, its placement, its windscreen's effects) into a basic measurement uncertainty; these variables are at least to some degree controllable by the technician. In addition to this basic measurement uncertainty is an uncertainty of the noise source (e.g., sound, level, duration of overflying aircraft, the difference between using a real source and a loudspeaker); these items are not directly controllable by the technician. There are two fundamental sources to the variance: the measurement uncertainty and this source-related and method-related uncertainty. These two independent sources of uncertainty, assuming normality, will be combined into an estimate of the total uncertainty. Group members (all the houses that have the same measurement method) were analyzed within groups and across groups.

3.1.6 Task 6—Preparation of Interim Report #2

After the panelists reviewed Interim Report #1, the research team incorporated their comments to produce Interim Report #2. This report included an analysis of the difference between flyover and loudspeaker results, photos of all homes, an analysis of air infiltration data, and a discussion of outlier data. In addition, in-depth discussion of sound intensity and airport sound insulation programs was included.

3.1.7 Task 7—ACRP Panel Meeting and Draft Report

After submission of Interim Report #2, the research team met with the panel to discuss, in detail, the contents of Interim Report #2 and the contents of the Draft/Final Reports. Based on this meeting, the research team agreed to draft a report that would provide the following:

- A decision matrix that would allow airport and consultant staff to select the most appropriate measurement method for a given airport.
- Statistical assessment of all measurement and modeling results.
- Identification of factors affecting variations in results.
- Suggestions for improving measurement consistency and accuracy, including loudspeaker positioning, microphone locations, and aircraft types and operations for measurements.
- Proposed standards and correction factors for various measurement methods.
- Measurement uncertainty for each method.
- An assessment of modeling accuracy in predicting the NLR of structures.

The Draft Report was then submitted to the panel for review and comment.

3.1.8 Task 8—Final Report

After receiving comments on the Draft Report from the panel, the research team incorporated the comments and made the necessary revisions.

3.2 NLR Science

This section is intended to provide sufficient background to explain the rationale behind the procedures for NLR measurement. A brief discussion of the physics of acoustics, principles, measurement metrics and standards, and acoustical measurement issues is included. Since most readers interested in this report already have a basic understanding of NLR measurement, they may wish to skip much of this chapter. For others, the discussions herein may be too cursory, and it is recommended that Chapter 4 of *ACRP Report 89* [from which much of the information in this chapter comes (with minor updates made by the research team)] or a basic acoustical text be consulted for more detailed discussions and explanations.

3.2.1 Acoustical Fundamentals

Airborne sound is a rapid fluctuation of air pressure and local air velocity traveling through normal sea-level atmosphere at approximately 342 meters/second (766 miles per hour; 1,122 feet/second). The fluctuating pressure wave is at a maximum when the velocity is at a minimum, and the velocity wave is at a maximum when the pressure wave is a minimum. The sound intensity is defined as the sound power per unit area. Thus, sound has both magnitude and direction.

However, it is difficult to measure sound velocity, and, generally, those measuring sound are only concerned with the sound level and not the direction of the sound. Therefore, those in the field measure only the sound pressure, the local pressure deviation from the ambient (average, or equilibrium) atmospheric pressure, caused by a sound wave. Sound pressure level (SPL), or sound level, is a logarithmic measure of the effective square of the sound pressure of a sound relative to a reference value. It is measured in dB above a standard reference level. The standard reference sound pressure in air or other gases is 20 μPa, which is usually considered the threshold of human hearing (at 1 kHz).

Sound has properties of both fluids and waves. As it propagates outward from its source, it bends around interposing structures (diffracts), is partially reflected and partially absorbed by incident surfaces, and radiates structures that attenuate (i.e., reduce) the transmitted sound. Improved interior NLR (the difference in sound level from exterior to interior) is the objective of airport sound insulation projects, and this NLR is achieved by retrofitting structures with building elements having higher sound TL properties.

Three aspects of noise are important in determining subjective (human) response:

- Level (i.e., magnitude or loudness) of the sound.
- The frequency composition or spectrum of the sound.
- The variation in sound level with time.

3.2.1.1 Sound Perception and Combination of Sound Levels

The characterization of sound level magnitude with respect to frequency is the sound spectrum. Changes in sound level and combinations of sound levels are nonlinear. Two sounds from the same source are not perceived as twice as loud as that from the single source (it takes 10 such sources to be judged as twice as loud). Because the level and frequency of sound are perceived in a nonlinear way, the dB scale is used to describe sound levels; the frequency scale is also measured in logarithmic increments. Decibels, measuring sound energy, combine logarithmically.

Decibel addition is also nonlinear. Two sources within 1 dB of each other total to the higher level plus 3 dB; two sources between 2 dB and 4 dB of each other total to the higher level plus 2 dB; two sources within 5 dB and 9 dB total to the higher level plus 1 dB; and two sources beyond a 9 dB difference total to a negligible contribution of less than 1 dB.

3.2.1.2 Subjective Response to Noise

The effects of noise on people can be (1) interference with activities such as speech, sleep, and learning; (2) physiological effects such as anxiety or hearing loss; or (3) subjective effects of annoyance, nuisance, and dissatisfaction. Wide variation of individual attitude is found regarding noise sources. For aircraft noise, typical reactions vary from annoyance to anxiety to fear. Small changes in noise level typically go unnoticed. Changes in noise exposure generally follow these conditions:

- Except under special conditions, a change in sound level of 1 dB cannot be perceived.
- Outside of the laboratory, a 3 dB change is considered to be a just-noticeable difference.
- An increase or decrease in level of at least 5 dB is required before any noticeable change in response would be expected.
- A 10 dB increase is subjectively heard as an approximate doubling in loudness.

Humans may perceive changes in noise exposure with less sensitivity since there is typically a time period, or latency, between exposure intervals.

3.2.1.3 Frequency Weighting

Many rating methods exist to analyze sounds of different spectra. The simplest method, A-weighting, is widely used internationally so that measurements can be made and assessed using basic acoustical instrumentation. This method evaluates audible frequencies by using a single weighting filter that progressively de-emphasizes frequency components below 1000 Hz and above 5000 Hz. This frequency bias reflects the relative decreased human sensitivity to low frequencies and to extreme high frequencies. Figure 3-1 shows the A-weighted network.

3.2.1.4 Noise Exposure

Noise exposure refers to a measure of noise over a period of time, whereas noise level is a value at an instant in time. Although a single sound level may adequately describe the noise at any instant in time, airport and other community noise levels vary continuously. Most community noise is produced by many noise sources, which create a relatively steady background noise that has no identifiable source, punctuated by discrete noise events such as aircraft flyovers.

For purposes of quantifying noise that varies over a period of time, a standard term, "equivalent sound level," has been adopted in the United States and internationally (see ANSI S1.8 and ISO 1996-1:2003). Equivalent sound level is a single number whose value is referenced by the

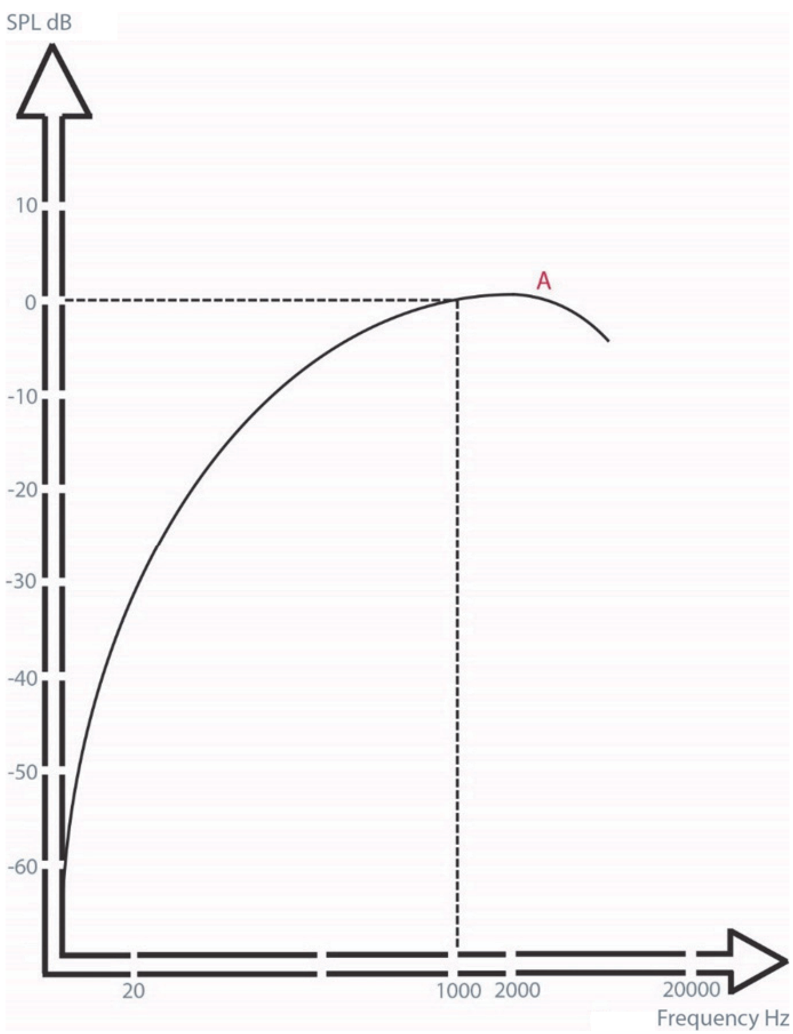


Figure 3-1. A-weighted network.
Courtesy of Charles M. Salter Associates, Inc.

symbol L_{eq}. Equivalent sound level is that constant sound level containing the same acoustic energy as the varying sound level during the same time period.

Discrete, short-duration transient noise events, such as aircraft flyovers, may be described by their maximum A-weighted noise level or by their sound exposure level (SEL). The SEL value is preferred over maximum noise levels in defining individual events, because measured results may be more reliably repeated and because the duration of the transient event is incorporated into the measure (thereby better relating to subjective response). Maximum levels of transient events vary with instantaneous propagation, measurement system time constant, and receiver conditions, while SEL is more stable. The SEL of a transient event is a measure of the acoustic energy normalized to a constant duration of 1 second. Figure 3-2 depicts how a SEL is computed.

SEL values may be summed on an energy basis to compute L_{eq} values over any period of time. This is useful for modeling noise in areas exposed to numerous transient noise events, such as communities around airports. Hourly L_{eq} values are called hourly noise levels (HNLs).

In determining the daily measure of community noise, it is important to account for the difference in human response to daytime and nighttime noise. During the night, people are more often at home and exterior background noise levels are generally lower than during the day, which causes exterior noise intrusions to become more noticeable. For these reasons, most people are more sensitive to noise at night than during the day.

To account for human sensitivity to nighttime noise, the DNL (value represented by the symbol L_{dn}) descriptor is a U.S. and international standard adopted by the Environmental Protection Agency (EPA) in 1974 that describes community noise exposure from all sources. The DNL represents the 24-hour, A-weighted equivalent sound level with a 10-dB penalty added for nighttime noise between 10:00 p.m. and 7:00 a.m. The FAA has officially used DNL as its standard since 1981. The DNL is computed by (1) adding 10 dB to the nighttime noise exposure, (2) then summing the adjusted noise exposure, and (3) expressing this sum as an average by dividing by the 24-hour time period. Thus, DNL truly represents a daily energy sum, and not an energy average. California has adopted the CNEL, a similar descriptor but with an additional small penalty

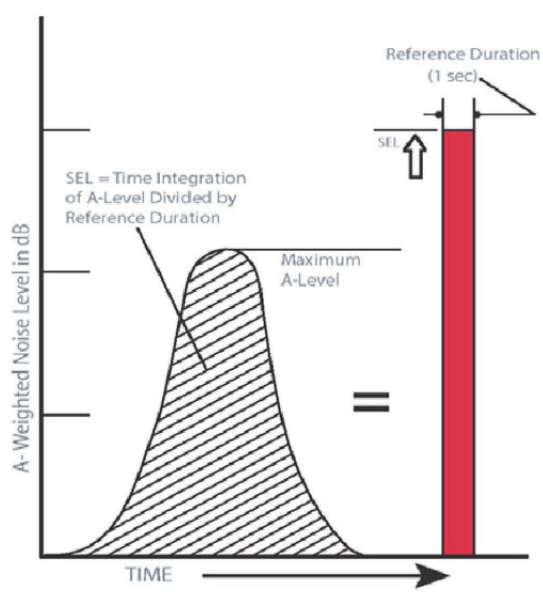


Figure 3-2. Sound exposure level graph.

for evening noise making CNEL values typically 0.5 dB to 1 dB greater than the DNL value for the same noise measurement.

3.2.2 Sound Propagation

3.2.2.1 Sources

There are two kinds of sources considered when dealing with airport noise: (1) point sources and (2) line sources. An example of a point source is a fixed source such as a loudspeaker on a stand in a front yard or a speaker positioned higher in a bucket truck. A car idling at a stoplight or an airplane idling while waiting in a line to take off both represent point sources, *at those times.* However, when these point sources traverse a line, they approximate a large number of point sources equally spaced along the line that turned on and off sequentially with increasing time. This summation of sources becomes a line source. Why is this important? It is important because a point source decays by 6 dB for a doubling of distance, while a line source only decays by 3 dB for a doubling of distance. The SEL of an aircraft flyover or car passby approximates a line source when the distance from the observation point to the flyover or car passby line is less than about half the length of the line.

3.2.2.2 Sound Decay

The FAA's INM uses SEL versus distance for various aircraft and their modes of operation. In the study discussed herein, SEL is the metric used to describe the aircraft sound as it impinges on the exterior of the house, and it is what is used to describe the received aircraft sound indoors. In addition to the sound spreading out with distance, there are several other factors that affect decay of sound. These factors include air absorption, the diffraction of sound behind barriers, and the diminution of sound by enclosures.

3.2.2.3 Air Absorption

The first two of these factors, air absorption and diffraction, are dealt with by the international and national standards, respectively, ISO 9613–2 and ANSI S12.62. Both absorption and diffraction can be major factors in the decay of sound with distance. Air absorption is very much a function of distance and frequency, and is also dependent on relative humidity. As a general rule, absorption increases rapidly with frequency. Table 2 of ISO 9613–2 (recreated herein as Table 3-1) illustrates some of the functional relationships of air absorption. This table shows the increase in absorption with frequency.

Table 3-1. ISO 9613-2 atmospheric attenuation coefficient.

Temp °C	Relative Humidity	Pure-tone Atmospheric-absorption Attenuation Coefficients (dB/km)*							
		Nominal, Mid-octave-band frequency (Hz)							
		63	125	250	500	1000	2000	4000	8000
10	70%	0.1	0.4	1.0	1.9	3.7	9.7	32.8	117.0
20	70%	0.1	0.3	1.1	2.8	5	9	22.9	76.6
30	70%	0.1	0.3	1	3.1	7.4	12.7	23.1	59.3
15	20%	0.3	0.6	1.2	2.7	8.2	28.2	88.8	202
15	50%	0.1	0.5	1.2	2.2	4.2	10.8	36.2	129
15	80%	0.1	0.3	1.1	2.4	4.1	8.3	23.7	82.8

* Coefficients, α, at an air pressure of one standard atmosphere (101.325 kPa). Acoustical Society of America/American National Standards Institute, ASA/ANSI S1.26-1995 (R2014). American National Standards Method for Calculation of the Absorption of Sound by the Atmosphere. Acoustical Society of America, Melville, NY.

The air absorption only reaches about 1 dB per kilometer in the 250 Hz octave band, being lower than this 1 dB rate at lower frequencies.

The air absorption generally increases with temperature up through the 1,000 Hz octave band and then begins to reverse the order and by the 8,000 Hz octave band, the air absorption decreases with temperature. Within the temperature and humidity region encompassed by Table 3-1, the air absorption decreases with increasing humidity in a regular fashion but the rates become large. As a result of these humidity and temperature effects, it is not usually possible to compare measured and predicted levels in bands above the 2,000 Hz octave band.

In summary, air absorption is insignificant in the 250 Hz octave band and below, and it is too large to accurately predict in bands above the 2,000 Hz octave band. So, as a practical matter and for expediency, when using INM or similar predictive software, the temperature and humidity are set to just one pair of values for use throughout the entire year, frequently 15°C (59°F) and 50% to 70% relative humidity.

3.2.2.4 Diffraction

Noise barriers are frequently used to reduce unwanted outdoor noise. Just as the sun visor in a car can cast a shadow across your face and shield your eyes from the glaring sun, a noise barrier can cast a sound shadow across your ears and shield them from a specific noise. Diffraction is the process whereby light enters its shadow region and sound enters its shadow region. The amount of diffraction into the shadow region is dependent on the sound wavelength and the size of the barrier with respect to the source and receiving positions. In general, the higher the frequency, the more effective the barrier (less diffraction into the shadow region). The lower the frequency, the longer the wavelength. At 50 Hz the wavelength is 6.1 meters (20 feet); so a 3 meter (10-foot) tall barrier wall will only make a small difference. Since aircraft noise in residential areas is typically generated by airborne aircraft, noise barriers are not a feasible option for aircraft noise reduction.

3.2.2.5 Sound Isolation and TL Overview

Once the sound is measured or predicted at the receiving property (including spreading, absorption, and diffraction), the next step is to determine how much of this outdoor sound impinges the structure with the windows closed. One may think that the ability to protect residents from the unwanted sound can be determined from measurements that are essentially the aircraft sound with and without the building present. This is known as the insertion loss; it is dependent on both the TL characteristics of the building and the sound absorbed by room furnishings. For the same aircraft sound outdoors, the corresponding aircraft sound inside the house will be lower in a room with considerable sound absorption versus a room with minimal sound absorption. So to develop a measure that is sensitive to just how the building is constructed and not its furnishings, the sound isolation is adjusted essentially by the amount of sound absorbing material in the receiving room. This sound isolation, so adjusted, is defined to be the TL. TL is discussed in detail in Section 3.3.3.

3.3 Basics of FAA-Sponsored Sound Insulation

3.3.1 The Building Envelope

While a building may have been consistently constructed, each room may provide a different NLR depending on (1) the noise reduction properties of the façade's building materials exposed to incident aircraft noise and (2) the area of the exposed building material (i.e., ratio of wall to window). This is important in developing and implementing NLR design criteria for airport sound insulation programs.

Design approaches include:

- Designing a room to achieve a ≥5-dB ΔNLR and a DNL ≤45 dB.
- Applying a uniform noise reduction treatment standard to create a homogeneous building envelope using consistent treatments.
- Providing a hybrid approach where consistent treatments are applied across the building envelope. Rooms that need additional treatments to achieve the DNL ≤45 dB will receive additional design attention.

PGL 12-09 and FAA Order 5100.38D are not specific as to which of these design objectives meet FAA noise reduction goals. Depending on a building's location in the contour and its existing noise reduction capabilities, treatments may need to achieve greater than 5 dB of reduction to meet the DNL interior 45-dB criteria.

In the first approach, each room could have a different existing NLR depending on the ratio and composition of building materials. Achieving a uniform minimum 5 dB treatment could require different treatments for each room to achieve the required NLR. The second approach allows for use of uniform building materials and construction procedures throughout the sound insulation program. This provides considerable cost savings in both material and labor. Using this second approach, each room receives a slightly different NLR improvement but a similar interior noise environment after retrofit. In the third approach, the exterior envelope of the whole building is reviewed for consistency of construction and building elements, and then individual rooms are verified for specific performance issues. This allows for use of uniform building materials and construction procedures for the majority of the treatments and acknowledges that more retrofit may be needed in limited cases.

The majority of residential airport sound insulation programs employ some form of the second or third approaches for treatment design; few programs attempt to achieve specific NLR performance for each room. Consequently, when applying a uniform sound transmission class (STC) performance envelope across a program, older homes and those having poorer pre-retrofit NLR performance will realize a greater NLR improvement (on average 7 dB to 8 dB) than newer (better built) and well-maintained homes, which may only realize a 4 dB to 5 dB improvement from the same treatments.

In addition to the TL properties of basic building elements, another significant noise path is the presence of acoustical leaks, termed "flanking paths." These are typically cracks or poor seals where air and sound may infiltrate. Flanking may significantly degrade sound insulation performance and requires treatment in every instance. Sound has the property of always infiltrating the weakest spot. It is not feasible to apply excessive acoustical treatment in one location while allowing for flanking in another; therefore, attention must be paid to the building envelope beyond the major fenestration openings.

3.3.2 Achieving an NLR of at Least 5 dB

Prior to sound insulation treatments, a structure will typically provide various degrees of noise reduction in various rooms. Corner rooms with three exposed façades, containing large non-sound-rated windows (including most of dual-pane thermal insulating glass) that make up a large percentage of the exposed exterior, will be much noisier inside than a contained first floor room with a single exposed façade. The solid wall in the basic façade structure, typically stucco or wood siding, has much better sound attenuation properties than non-sound-rated windows. Certain uninsulated façades and lightweight façades (such as those of aluminum and lightweight vinyl) fall short of the standard sound TL level; in these cases, the windows provide more noise reduction than the façade. Heavy brick and stucco façades, on the other hand, typically provide more than the standard sound TL level; in these cases the windows provide less noise reduction than the façade.

Given differences in room exposure, there has been considerable discussion as to how the minimum 5-dB NLR improvement criterion is to be applied in sound insulation programs. Alternative interpretations include:

- Every room treated must achieve a minimum 5-dB NLR improvement.
- The average NLR improvement for all tested rooms in a single dwelling must be at least 5 dB.
- The average NLR for all dwellings in a single project or a single program must be at least 5 dB.

FAA Order 5100.38D (which supercedes PGL 12-09) is not specific as to which of the above is consistent with FAA noise reduction goals; however, it does state, "The measurement of interior noise levels is an average for all habitable spaces in a particular residential unit." This is consistent with the practice of many sound insulation programs that the second interpretation (i.e., the average NLR improvement should be at least 5 dB) is the prevailing NLR improvement objective for programs to meet.

3.3.3 Sound TL Concepts

Sound TL of individual building elements depends on three factors: the material's mass, resiliency, and acoustical decoupling properties; the spectra of the aircraft producing the noise environment; and the angle of incidence of all aircraft noise impinging on each building element on the structure's façade.

The first and most fundamental principle of sound TL is the mass law, which relates the TL at each frequency as a function of surface weight. According to the mass law, TL increases linearly with ascending octave or one-third octave bands. This law works well only for limp monolithic (i.e., no composite structure) materials, but also forms the basis for TL properties for all materials and structures. Specifically, all materials and systems exhibit a general trend of increasing TL performance with increasing frequency. That is, higher frequencies are attenuated more effectively than lower frequencies in all structures.

The second TL principle is resiliency (or its inverse, stiffness); resilience is an important property for TL in composite materials. Sound does not pass through materials but, rather, impinges on a material and reradiates from the other side at some reduced level. Materials attenuate sound energy through consuming mechanical vibration energy and converting it to small (almost immeasurable) quantities of heat. Thus, the more resilient a composite material, the more energy will be consumed and the greater the sound attenuation.

The third principle in sound attenuation is decoupling, which is a property of composite materials to structurally and acoustically isolate parallel elements of the composite structure. One example of acoustical decoupling is the dual-glazed windows used in airport sound insulation programs. Here sound impinges on the exterior glazing panel, which must then reradiate the sound through a substantial air space (typically more than an inch) and then through a second layer of glass. This acoustical transmission inefficiency reduces sound transmission through the assembly. The glazing panels are in resilient zipper gaskets, which minimize structural coupling through the framing system (Department of the Navy, 2005).

High TL is most efficiently achieved by double-wall construction, allowing for greater TL with lighter-weight assemblies. Best results are achieved when the parallel panels are mechanically and acoustically isolated. Mechanical isolation is achieved by independent support of the parallel panels (no structural coupling), and acoustical isolation is achieved by increased air space between the panels. The net TL of two isolated panels may be computed from the individual TL properties of each (Sharp, 1978).

Several prediction methods may be used to compute the TL properties of building elements and assemblies. These models incorporate the mass, stiffness, geometry, mechanical isolation, and acoustic isolation properties of the building assembly. However, these models do not often yield precise results because of the difficulty in measuring the various properties, particularly stiffness and mechanical isolation in building elements. For this reason, laboratory TL testing is required for acoustical materials and assemblies used in airport sound insulation programs.

3.3.4 STC Rating

While the TL characteristics of building materials and assemblies may generally be computed with reasonable accuracy and reliability or tested in sample field installations, the best method of ensuring TL performance is acoustical testing in an accredited laboratory and according to ASTM E90. Laboratory accreditation is by the National Voluntary Laboratory Accreditation Program (NVLAP) under the oversight of the National Institute of Standards and Technology (NIST). Architectural product manufacturers are generally required to submit such laboratory test results for all major building elements in order to obtain approval for use in airport sound insulation programs.

The sound TL properties of building elements are tested and reported according to national standards in one-third octave bands, classified as an STC rating (refer to ASTM E1332). Each building element, such as a particular window, may be expected to have a unique TL signature represented by 16 TL values from 125 Hz to 4000 Hz. As mentioned in the previous section discussing mass law, the nature of sound attenuation through structures is such that all TL tests have generally up-sloping properties from low frequency to high frequency, indicating generally increasing noise reduction in higher frequencies. Figure 3-3 depicts a typical TL test result.

3.3.5 TL Metrics

STC is the oldest and most established rating for the TL properties of building elements and systems. STC is computed by using the standard three-straight-line-segment curve in Figure 3-3 and computing the TL deficiencies (differences in measured TL and curve value) in each of the 24 one-third octave bands. The STC rating is determined as the highest value of the curve at 500 Hz for which the sum of deficiencies does not exceed 32 and no single deficiency exceeds 8. This procedure was developed for two purposes: to consider the subjective response of the human ear at various frequencies with the shape of the segmented curve and to account for the annoyance effects of panel resonance and coincidence dips. These later effects are most prevalent with lightweight structures, where specific frequencies are reinforced and cause annoying buzzing tones. However, with most building elements of STC 40 or greater, these effects become imperceptible. Coincidence dip is a drop in the TL of a material or assembly at a certain frequency caused by resonance effects.

Another TL standard was adopted by ASTM, the OITC (see ASTM E1332). The OITC method is simpler and more easily understood than STC. It was developed specifically to assess the TL properties of materials and systems subjected to transportation noise. Specifically it (1) employs a reference sound spectrum composed of the average from railroad, freeway, and aircraft noise sources; (2) subtracts the 18 one-third octave band TL values from 80 Hz to 4 kHz; and (3) A-weights the resulting sound spectrum to produce the OITC value. Some airport sound insulation programs have shown interest in OITC, and some have accepted OITC tests as an option to STC test results.

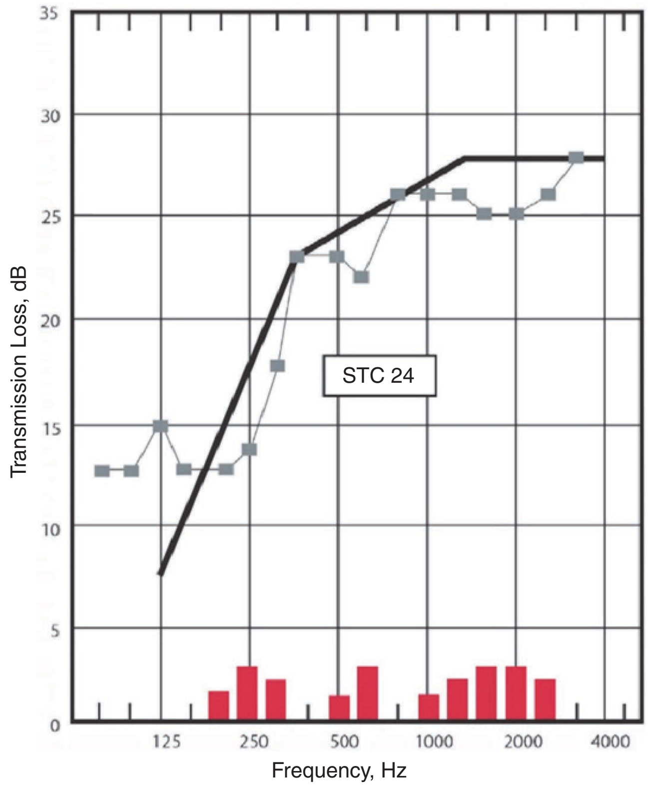


Figure 3-3. Typical TL test results. (Figure reprinted from ASTM E413-10, Classification for Rating Sound Insulation, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428. A copy of the complete standard may be obtained from ASTM International, www.astm.org.)

3.3.6 The Acoustical Design Process

The acoustical consultant plays a key role throughout the acoustical design process, extending from the project planning phase through conceptual and detail design, construction consulting, acoustical testing, and project performance reporting to the FAA.

After selection of program structures for treatment, the acoustical consultant performs pre-retrofit acoustical testing of representative structures in the program. Established or ongoing programs typically test 10% of program structures. Pilot programs or programs with widely variant housing types may test a higher percentage, from 25% to 100%, depending on the amount of data needed to make decisions on treatments.

Based on test results, the consultant prepares an acoustical conceptual design, which identifies the performance needs for various treatment elements. Following the review, the project architect and engineers develop drawings for each structure to be sound insulated, list specifications for all building materials and systems, and outline project details for on-site construction and installation of building elements and systems. Customized treatments for each residential structure are developed based on a standard set of treatments as well as program policies and procedures.

The following are typical acoustical treatments for building elements and systems:

- Replacement of windows with sound-rated windows.
- Replacement of exterior doors into habitable/occupied spaces with sound-rated entry doors, or addition of sound-rated storm doors over new or existing doors. Also, new perimeter gaskets and threshold systems are installed.
- Addition of attic insulation. Often fiberglass or cellulose insulation is added by blowing in, although roll out insulation works equally well.
- Addition of vent baffles for outsized gable vents in the attic. Eave vents are typically not treated due to their small size.
- Addition of flex ducting to bath fans and dampers atop kitchen fan exhaust stacks.
- Addition of chimney-top dampers or glass doors on fireplaces.
- Patching and sealing of extraneous protrusions through the façade such as mail slots, pet doors, through-wall air conditioning, and various homeowner modifications.
- Addition of or modification to heating, ventilating, and air conditioning (HVAC) systems to ensure air quality and comfort.
- Addition of secondary glazing to skylights.
- Addition of ceiling or wall materials where needed.

On completion of construction, the acoustical consultant performs post-construction acoustical testing on the same structures originally tested. Testing locations, procedures, and conditions are replicated to the maximum extent possible in order to determine NLR improvement as accurately and reliably as possible.

The final step in the acoustical design process is preparation of sections of the project's final report that are specific to acoustical treatments. Topics and issues typically covered are structures treated, design criteria, treatments effected, special structures, the pre- and post-retrofit DNL and NLR, and assessment of compliance with the FAA acoustical objectives for the program. These reports are typically submitted to the airport sponsor, which submits the full report to the local FAA ADO.

3.4 Acoustical Testing

The program objectives are to meet the interior DNL ≤ 45 dB and ΔNLR ≥ 5 dB on the basis of the design year NEM. FAA Order 5100.38D goes on to clarify this requirement:

> In general, Noise Exposure Maps (NEMs) less than five years old are considered current, unless conditions have created a significant change that would affect noise contours. NEMs older than five years old must be certified by the sponsor and updated as required as discussed in the PGL.

Therefore, the aircraft noise environment used for acoustical design and for acoustical testing of NLR should consider the aircraft fleet mix, flight tracks, and other parameters for all flight operations from the NEM.

An ideal acoustical test program for pre- and post-retrofit would accomplish the following for each structure tested:

- Consider only aircraft noise, ignoring all other noise sources.
- Integrate the sound spectra from all aircraft used in the NEM.
- Integrate the runway use and flight tracks by aircraft type from all aircraft used in the NEM.
- Integrate the sound incidence angles of all aircraft on all flight tracks, by aircraft type, from all aircraft used in the NEM.
- Integrate the change in meteorological conditions with all other parameters used in the NEM.

The only way all of these goals can be accomplished would be through continuous attended noise monitoring and simultaneous monitoring inside and outside each residence for the NEM scenario, while manually deleting non-aircraft acoustic events. Since this is infeasible, testing methods that allow for data generation that can be further analyzed by computer models are a benefit for an acoustical testing program.

Two methods have been most commonly used in airport sound insulation programs for field testing the NLR of rooms within a structure: the aircraft flyover test and the artificial noise source test. A third method has also been employed: the indoor-outdoor speaker test. Each method has technical and logistical advantages and disadvantages.

The most valid and precise acoustical testing for sound TL is laboratory testing of building systems and materials (ASTM E90); field testing procedures (ASTM E966) are designed to parallel laboratory procedures as much as is practicable. Laboratory testing is performed by inserting the window, door, or other building element into an opening between two large rooms in the testing facility, then generating a diffuse sound field on the source room side, recording the spatial average diffuse sound level in each room, and subtracting the receiver room noise level from the source room noise level to obtain the NLR. Laboratory measurements employ moving microphones and moving vanes to break up room modes and ensure proper measurement of the diffuse sound field. A small correction is then applied to account for the noise build-up and absorption effects of the receiving room. The diffuse sound field has sound waves traveling in all directions with equal probability. This is necessary because the incidence angle at which sound impinges on a material affects its TL properties. However, it is impossible to field test existing buildings using this laboratory-based method, even though an interior room approximates one room with a diffuse sound field. The sound field outside the structure constitutes both a free field, not influenced by local sound reflection, and a far field, not close to or influenced by the noise source size.

The specific shortfalls of field NLR testing not encountered with laboratory testing include:

- NLR measurement of a composite façade typically includes the wall assembly, windows, door(s), vents, etc. rather than a single building element.
- Flanking transmission of sound through various leaks.
- Small source and receiving rooms that limit the ability to properly measure low frequency NLR.
- Directional properties of sound from loudspeaker systems rather than a diffuse sound field.
- Standing wave effects from stationary microphones and a lack of moving vanes with the aircraft flyover method.

FAA Order 5100.38D specifies several testing procedures and protocols for AIP-funded programs:

- Interior noise testing is to be conducted with windows and doors closed. This protocol applies without regard to the presence of ventilation systems.
- The measurement of interior noise levels is an average for all habitable spaces in a particular residential unit.
- FAA-accepted guidance on testing frequency, sampling, and other statistical measures is contained in the *Guidelines for Sound Insulation of Residences Exposed to Aircraft Operations*, prepared for the Department of the Navy by Wyle Laboratories in 1992.
- The ADO must approve or disapprove a sponsor request for reimbursement for testing more than 10% of the residences of a particular construction type.
- For requests for reimbursement for more than 30% of the residences of a particular type, the ADO must receive APP-400: FAA Planning and Environmental Design approval.
- Occasionally, residents may request that their residence be tested specifically. This may be because of the condition of the home or because the resident believes that the residence will test differently than others. These additional tests are generally allowable. However, if an additional residence is tested, it must be tested both before and after any noise insulation work to ensure that the 5 dB NLR is achieved.

3.5 Overview of Tested Homes

3.5.1 San Diego Homes

The following pages offer pertinent details of the homes measured around San Diego International Airport.

Residence	San Diego #1
Measurement Date	July 14, 2014
Rooms Measured	Living room, dining room
Residence Type	Single-family house
Roof Type	Gable roof with wood trusses and asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 5-1/2" consisting of 2 X 4 wood studs and two layers of wood shingles
Interior Wall Type	Painted gypsum board interior finish
Door	Wood panel "Hollywood" doors with half-lite of 3/16"-thick glazing
Window Type	Typical window is single pane with glazing thickness of 1/8"–3/16"
Ceilings/Floors	Ceiling height of 8'-0", wood floors with area rugs

Residence	San Diego #2
Measurement Date	July 14, 2014
Rooms Measured	Living room, office (bedroom 4, above living room)
Residence Type	Single-family house
Roof Type	Gable roof with wood trusses and asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 5-1/8" consisting of 2 X 4 wood studs and one layer of wood shingles
Interior Wall Type	Painted gypsum board interior finish
Door	Wood panel "Hollywood" doors with half-lite of 1/2"-thick glazing
Window Type	Typical window is single pane with glazing thickness of 1/8"–1/4"
Ceilings/Floors	Ceiling height of 9'-0", wood floors with area rugs

Residence	San Diego #3
Measurement Date	July 15, 2014
Rooms Measured	Living room, master bedroom 3 (front of house, adjacent to living room)
Residence Type	Single-family house
Roof Type	Hip roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 5-1/2” consisting of 2 X 4 wood studs and stucco exterior finish
Interior Wall Type	Painted gypsum board interior finish
Door	Wood flush solid entry door, rear wood “Hollywood” door with half-lite of 1/8”-thick glazing
Window Type	Typical window is single pane with glazing thickness of 1/8”
Ceilings/Floors	Ceiling height of 8’-0”, wood floors with linoleum in kitchen

Residence	San Diego #4
Measurement Date	July 15, 2014
Rooms Measured	Living room, bedroom 1
Residence Type	Single-family house, one of four detached units on lot
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 4-3/8” consisting of 2 X 4 wood studs and wood siding
Interior Wall Type	Painted gypsum board interior finish
Door	Wood glass panel door with 1/8”-thick glazing at entry, rear wood flush solid door
Window Type	Typical window is dual pane with glazing thickness of 1/8” around 1/2” airspace
Ceilings/Floors	Ceiling height of 8’-3”, wood floors with area rugs

Residence	San Diego #5
Measurement Date	July 16, 2014
Rooms Measured	Living room, front bedroom 1
Residence Type	Single-family house
Roof Type	Flat built-up roof
Exterior Wall Type	Exterior wall thickness of 7” consisting of 2 X 6 wood studs and stucco exterior finish
Interior Wall Type	Painted lath and plaster interior finish
Door	Wood panel solid entry door with peep lite of 1/8”-thickness
Window Type	Typical window is single pane with glazing thickness of 1/8”
Ceilings/Floors	Ceiling height of 8’-0” at top of vault, tile floors with linoleum in bedrooms

Residence	San Diego #6
Measurement Date	July 16, 2014
Rooms Measured	Living room, dining room
Residence Type	Multi-family single-story duplex unit
Roof Type	Flat built-up roof
Exterior Wall Type	Exterior wall thickness of 5-1/4” consisting of 2 X 4 wood studs and stucco exterior finish
Interior Wall Type	Painted gypsum board interior finish
Door	Wood panel solid entry door
Window Type	Typical window is single pane with glazing thickness of 1/8”–1/4”
Ceilings/Floors	Ceiling height of 8’-0”, wood floors with tile in kitchen, laundry room, bathrooms

Residence	San Diego #7
Measurement Date	July 17, 2014
Rooms Measured	Living room, family room
Residence Type	Single-family house
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 4-5/8” consisting of 2 X 4 wood studs and wood siding
Interior Wall Type	Painted gypsum board interior finish
Door	Wood panel solid entry door, rear sliding glass door with 3/16”-thick glazing
Window Type	Typical window is single pane with glazing thickness of 1/8”
Ceilings/Floors	Ceiling height of 8’-0”, wood floors with tile in kitchen, laundry room, and bathrooms

Residence	San Diego #8
Measurement Date	July 17, 2014
Rooms Measured	Dining room, master bedroom
Residence Type	Single-family house
Roof Type	Flat built-up roof
Exterior Wall Type	Exterior wall thickness of 6-1/2” consisting of 2 X 6 wood studs and stucco exterior finish
Interior Wall Type	Painted gypsum board interior finish
Door	Wood panel solid entry door
Window Type	Typical window is single pane with glazing thickness of 1/8”
Ceilings/Floors	Ceiling height of 8’-0” except 9’-0” living room at top of vault, wood floors with tile in kitchen

Residence	San Diego #9
Measurement Date	July 18, 2014
Rooms Measured	Living room, bedroom 1 (first floor, bay window on left side)
Residence Type	Single-family house
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 5-1/4" consisting of 2 X 4 wood studs and wood siding, shingle accents
Interior Wall Type	Painted gypsum board interior finish
Door	Wood solid "Hollywood" entry door, rear wood glass "French" doors with 1/8"-thick glazing
Window Type	Typical window is single pane with glazing thickness of 1/8"
Ceilings/Floors	Ceiling height of 9'-0" except 8'-0" family room, wood floors with tile in kitchen and baths

Residence	San Diego #10
Measurement Date	July 18, 2014
Rooms Measured	Front bedroom 1, bedroom 2 (bound on right side, near entry)
Residence Type	Single-family house
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of ~5-1/2" consisting of 2 X 4 wood studs and stucco exterior finish
Interior Wall Type	Painted gypsum board interior finish
Door	Wood hollow flush entry door, rear sliding glass door with ~1/8"-thick glazing
Window Type	Typical window is single pane with glazing thickness of 3/32"–1/8"
Ceilings/Floors	Exposed ceiling of height 9'-6" at top of vault, carpet floors with tile in kitchen and baths

3.5.2 Boston Homes

The following pages show pertinent details of the homes measured around Boston Logan International Airport.

Residence	Boston #1
Measurement Date	July 28, 2014
Rooms Measured	Living room, bedroom 2 (above rear deck)
Residence Type	Multi-family two-story duplex unit, upper floors of three-story building
Roof Type	Flat built-up roof
Exterior Wall Type	Exterior wall thickness of 6” consisting of 2 X 6 wood studs and vinyl siding
Interior Wall Type	Painted gypsum board interior finish
Door	Wood panel “Hollywood” entry door with glazing thickness of ~1/8”
Window Type	Typical window is dual pane with glazing thickness of 1/8” around 5/8” airspace
Storm Window Type	Aluminum storm windows 1-5/8” from main window, 1/8”-glazing thickness
Ceilings/Floors	Ceiling height of 8’-0”, wood floors with carpet in bedrooms

Residence	Boston #2
Measurement Date	July 28, 2014
Rooms Measured	Living room, bedroom 2 (above living room)
Residence Type	Single-family house
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 6” consisting of 2 X 6 wood studs and aluminum siding
Interior Wall Type	Wood veneer interior finish, painted gypsum board in bedrooms
Door	Wood solid “wagon wheel” entry door with 1/8”-thick dual-pane glazing around 3/8” air space
Window Type	Typical window is dual pane with glazing thickness of 1/8” around 5/8” airspace
Storm Window Type	Aluminum storm windows 3” from main window, 1/8”-glazing thickness
Ceilings/Floors	Ceiling of height 7’-10” at first floor, 7’-4” above; carpet floors with linoleum in bedrooms

Residence	Boston #3
Measurement Date	July 29, 2014
Rooms Measured	Living room, front bedroom 1 (adjacent to living room)
Residence Type	Multi-family two-story duplex unit, upper floors of three-story building
Roof Type	Flat built-up roof
Exterior Wall Type	Exterior wall thickness of 6” consisting of 2 X 6 wood studs and vinyl siding
Interior Wall Type	Painted gypsum board interior finish
Door	Wood panel “Hollywood” entry door with glazing thickness of ~1/8”
Window Type	Typical window is dual pane with glazing thickness of 1/8” around 5/8” airspace
Storm Window Type	Aluminum storm windows 1-5/8” from main window, 1/8”-glazing thickness
Ceilings/Floors	Ceiling height of 8’-0”, wood floors with carpet in bedrooms

Residence	Boston #4
Measurement Date	July 30, 2014
Rooms Measured	Second-floor rear bedroom 2, third-floor rear bedroom 4
Residence Type	Multi-family three-story duplex unit
Roof Type	Flat built-up roof
Exterior Wall Type	Exterior wall thickness of 8” consisting of 2 X 6 wood studs and vinyl siding over wood shingles
Interior Wall Type	Painted gypsum board interior finish, insulated walls
Door	Wood “Hollywood” entry door
Window Type	Typical window is dual pane with glazing thickness of 1/8” around 5/8” airspace
Storm Window Type	Aluminum storm windows 3” from main window, 1/8”-glazing thickness
Ceilings/Floors	Ceiling height of 8’-11” at first floor, 8’-3” above; wood floors with area rugs

Residence	Boston #5
Measurement Date	July 30, 2014
Rooms Measured	Living room, bedroom
Residence Type	Multi-family unit, first floor of three-story building
Roof Type	Flat built-up roof
Exterior Wall Type	Exterior wall thickness of ~7” consisting of 2 X 6 wood studs and vinyl siding over wood shingles
Interior Wall Type	Wood veneer interior finish
Door	Wood “wagon wheel” entry door
Window Type	Typical window is dual pane with glazing thickness of 1/8” around 5/8” airspace
Storm Window Type	Aluminum storm windows 3” from main window, 1/8”-glazing thickness
Ceilings/Floors	Ceiling height of 9’-0”, wood floors with area rugs in bedrooms

Residence	Boston #6
Measurement Date	July 31, 2014
Rooms Measured	Dining room, rear bedroom 2 (above kitchen)
Residence Type	Single-family house
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 7” consisting of 2 X 6 wood studs and vinyl siding over wood shingles
Interior Wall Type	Painted gypsum board interior finish
Door	Solid wood “Hollywood” entry door with dual-pane 1/8” glazing around 1/4” airspace
Window Type	Typical window is dual pane with glazing thickness of 1/8” around 5/8” airspace
Storm Window Type	Aluminum storm windows 3”–4” from main window, 1/8”-glazing thickness
Ceilings/Floors	Ceiling height of 7’-10”, wood floors with area rugs in dining room

Residence	Boston #7
Measurement Date	July 31, 2014
Rooms Measured	Living room, master bedroom
Residence Type	Multi-family two-story duplex unit, upper floors of three-story building
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 7” consisting of 2 X 6 wood studs and vinyl siding over wood shingles
Interior Wall Type	Painted gypsum board interior finish
Door	Wood panel entry door with storm door
Window Type	Typical window is dual pane with glazing thickness of 1/8” around 5/8” airspace
Storm Window Type	Aluminum storm windows 3” from main window, 1/8”-glazing thickness
Ceilings/Floors	Ceiling height of 8’-10”, wood floors with area rugs

Residence	Boston #8
Measurement Date	August 1, 2014
Rooms Measured	Living room, study (adjacent to living room)
Residence Type	Single-family house
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 6-1/2" consisting of 2 X 6 wood studs and vinyl siding
Interior Wall Type	Painted gypsum board interior finish, insulated walls
Door	Solid wood "wagon wheel" entry door with ~1/8"-glazing thickness
Window Type	Typical window is dual pane with glazing thickness of 1/8" around 5/8" airspace
Storm Window Type	Aluminum storm windows 3" from main window, 1/8"-glazing thickness
Ceilings/Floors	Ceiling height of 10'-9" except 7'-6" study, wood floors with area rugs in living room

Residence	Boston #9
Measurement Date	August 1, 2014
Rooms Measured	Living room, bedroom (above living room)
Residence Type	Single-family house
Roof Type	Gable roof with asphalt composite shingles
Exterior Wall Type	Exterior wall thickness of 6-1/2" consisting of 2 X 6 wood studs and vinyl siding
Interior Wall Type	Painted gypsum board interior finish, insulated walls
Door	Solid wood "Wagon wheel" entry door with ~1/8"-glazing thickness
Window Type	Typical window is dual pane with glazing thickness of 1/8" around 5/8" airspace
Storm Window Type	Aluminum storm windows 3" from main window, 1/8"-glazing thickness
Ceilings/Floors	Ceiling height of 9'-4" except 9'-2" bedrooms, wood floors with area rugs in living room

CHAPTER 4

Findings and Applications

4.1 Aircraft Flyovers

The aircraft flyover test is used in a number of sound insulation programs. This method simultaneously measures the exterior free-field incident sound of flyovers and the diffuse sound field in the test room within the structure. The difference in the two A-weighted SEL values is subtracted to yield the NLR of the room. In practice, synchronized digital programmable sound level meters (SLMs) are positioned in the free field outside the home and in the room to simultaneously record the SEL of each flyover event.

The SLMs record multiple SEL events, allowing for computation of the NLR for each event and statistics for a series of flyover events. Typically, multiple interior rooms are measured simultaneously. These measurements generally follow a national standard for field NLR measurement: ASTM E966.

The flyover method is assumed to provide a reasonable approximation of the NLR in each room, but does have limitations and sources of error, as indicated in detail later in this section.

Summary: The research team conducted aircraft flyover measurements at ten homes near the San Diego International Airport (SAN) and at four homes in Boston. The conclusions are as follows:

- Measurements need to be conducted in vacant homes, as occupant contamination easily occurs.
- Outdoor microphones should be set in the free field or flush mounted to the ground or building façade (Figure 4-1). Near field measurement [1 m to 2 m from (3.3 ft. to 6.6 ft.) façade] is not suggested.
- Measurements should be made in one-third-octave bands from 50 Hz through 5 kHz or octave bands from 63 Hz through 5 kHz, and the A-weighted value would be computed rather than using direct A-weighted measurements.
- Measurement sample time should not be faster than every 0.5 sec (500 ms).
- In general, noise reduction is higher with the flyover measurement method than the loudspeaker measurement method; a correction of 2 to 4 dB is suggested to compensate for ground reflection and/or reflected noise off the façade under test.
- To determine the NLR from sequential measurement and computation of single events the research team suggests (1) sorting NLR values by standard deviation from the mean from highest to lowest, (2) computing the standard deviation and confidence interval for the initial list, then (3) sequentially deleting the top value in the list until the desired standard deviation and/or confidence intervals are obtained.
- The research team finds the use of a properly placed single microphone in interior rooms to be adequate for most NLR measurements.

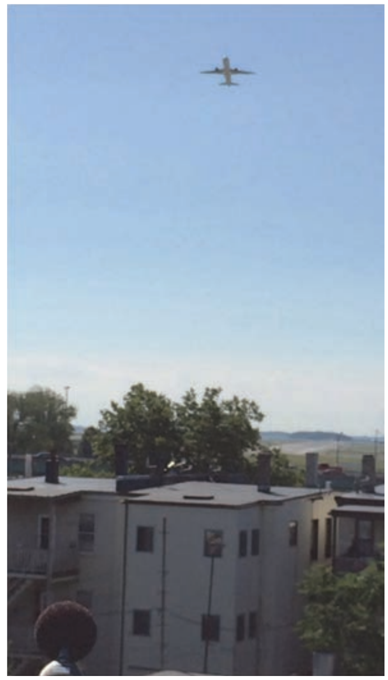


Figure 4-1. Exterior microphone for flyover measurement in Boston.

4.1.1 Measurement Procedures

Aircraft flyover measurements are made using a pair of synchronized digital programmable SLMs. One is located outside in the free field away from reflecting surfaces and extraneous noise sources; the other is located in the room to be measured for NLR, locating it away from the impinging façade and away from locations amplifying room acoustic effects. Both meters run continuously, recording aircraft flyover noise and all noise between aircraft flyover events. The meters are interrogated by computer software that matches events by time, computes the SEL value of the simultaneous events, and subtracts the interior SEL from the exterior SEL to yield the NLR.

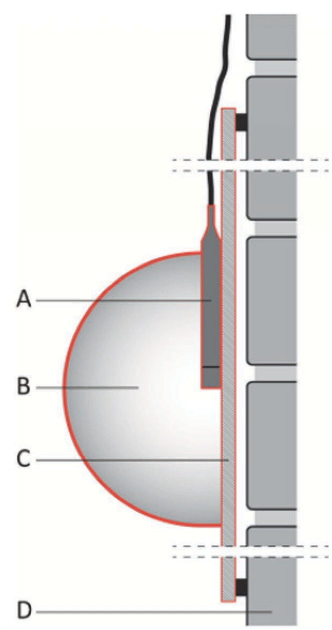
The preferred microphone locations are either free field, away from reflecting surfaces or flush mounted on either the ground or against the façade (whichever provides the best normal incidence to the flyovers). Free-field measurements require that 2 to 4 dB be subtracted from measured values to eliminate the influence of ground reflections and reflections from the façade under test. The reasoning for the correction is as follows: ASTM E966 and ISO 1996-2 include a correction for reflected noise when the sound source (e.g., loudspeaker) is located a horizontal distance away from the façade. The flyover measurement is similar, except that it is in the vertical plane and the reflection comes from the ground rather than the façade. There are also secondary reflections that occur with both the flyover and exterior loudspeaker methods. For the loudspeaker measurement, there are reflections from the ground and neighboring buildings. For the flyover measurement, there are reflections from neighboring buildings and the façade of the home being tested. In general, these secondary reflections are minor. Other factors that affect the correction are ground surface type (e.g., soft soil versus hard concrete), microphone location (height above ground or distance from reflecting objects), and aircraft angle.

Also, as verification, the research team conducted both measurements and computer modeling. First, the research team conducted simultaneous exterior measurements of flyovers with one microphone flush with the ground and one microphone 2 m (6 ft.) above the ground. The team measured a 2 dB difference between the flush and elevated positions, thus supporting the 2 dB correction used in the analysis. Second, the research team modeled various outdoor conditions in acoustical modeling software for flyover measurements (e.g., concrete vs. grass, the effect of neighboring building reflections) and found that exterior noise levels can increase by 1 to 2 dB with reflective ground surfaces and numerous surrounding buildings.

Surface-mounted microphone measurements require that 5 dB (per ASTM E966) be subtracted for the reflected near field. Figure 4-2 shows the flush microphone configuration.

Modern programmable digital SLMs allow a variety of sampling rates, often as rapidly as every few milliseconds. They also enable recording of overall A-weighted levels, octave band, or one-third octave band values. Care must be taken in the setting of SLMs. It may seem advisable to use very rapid sampling rates in order to maximize the sound level data, but this incurs a problem. Digital SLMs have a limitation of sampling rate with bandwidth; very fast sampling at wide bandwidths (such as A-weighting) produces significant errors. The research team proposes a sampling rate of a half second (i.e., 500 ms).

As discussed in Section 4.9.2, a situation arises with moderate flyover sound levels and substantial ambient interior sound levels where the interior level matches or exceeds the exterior level. This only occurs in the high frequencies where flyover noise is greatly attenuated. In order to avoid this situation, the research team proposes that all interior and exterior sound level data be recorded in one-third octave bands from 50 Hz through 5 kHz or octave bands from 63 Hz through 4 kHz, but at no higher frequencies; A-weighted sound levels are then computed in post processing. Therefore, overall A-weighted monitoring is not suggested.



Key

A Microphone
B Windscreen
C Mounting plate
D Wall or reflecting surface

Figure 4-2. Flush microphone mounting.

4.1.2 Data Analyses

The example results of the flyover measurement procedure above are shown in Table 4-1. This is from a measurement for the living room of test subject San Diego #1. This event was selected because it recorded the many flyover events. There are several obvious "outliers" or events where the NLR value is obviously incorrect (see events at 10:05:52 and 10:12:13). These occur from corrupted or missing data.

Table 4-1. Flyover data analysis examples.

San Diego #1: Living Room ANOMS Event Time	Flight #	Aircraft	SEL_{out}	SEL_{in}	NLR
9:27:42				66.1	
9:30:35				61.2	
9:34:02	SWA4602	B737	90.30	62.7	27.6
9:35:27	SWA758	B737	86.40	61.6	24.8
9:37:08	SWA1582	B737	82.00	53.7	28.3
9:40:34	AWE2040	A320	88.40	59.7	28.7
9:42:33	SWA4105	B733	89.50	60.7	28.8
9:44:04	SKW2599	CRJ2	85.90	57.6	28.3
9:45:37	SWA736	B737	87.20	59.6	27.6
9:47:35	ASA718	B738	87.30	59.9	27.4
9:49:32	SKW6323	E120	84.90	57.9	27.0
9:50:59	SWA4657	B737	86.60	58.9	27.7
9:53:11	CPZ5743	E170	85.90	57.9	28.0
9:57:14	N301KR	LJ45	84.40	55.3	29.1
9:59:29	SWA1582	B737	90.30	62.5	27.8
10:01:24	UAL289	A319	86.60	58.8	27.8
10:02:59	ASA240	B739	88.70	61.8	26.9
10:05:52	JBU619	A320	63.40	59.5	3.9
10:09:01	G/A	JET	82.40	54.4	28.0
10:12:13	RGY710	BE40	81.80		
10:15:08	UAL1563	B738	88.50	60.8	27.7
10:19:13	UAL229	B752	90.00	60.8	29.2
10:21:26	DAL833	B739	88.80	61.1	27.7
10:23:47	EJA669	C56X	82.60	54.8	27.8
10:26:22	AWE581	A320	87.10	58.8	28.3
10:28:05	SWA4791	B738	82.30	56.7	25.6
10:30:18	UAL709	A320	84.50	58.2	26.3
10:31:46	NKS470	A319	86.20	58.3	27.9
10:36:17	SWA2468	B738	88.80	61.8	27.0
10:38:24	DAL1687	MD90	85.40	58.3	27.1
10:40:35	SKW171Z	CRJ9	85.20	58.9	26.3
10:43:21	SWA777	B737	89.00	62.8	26.2
10:45:18	SWA4791	B738	90.20	62.2	28.0
10:47:29	SWA633	B733	90.20	60.3	29.9
10:49:34	DJR829	C550	79.30	50.4	28.9
10:51:37	SWA2397	B738	89.00	61.6	27.4
10:53:02	AAL1565	B738	89.50	61.9	27.6
10:54:54	SKW2621	CRJ2	85.80	56.5	29.3
10:56:55	AAL1228	B752	91.40	63.6	27.8
10:59:33	SWA4679	B737	88.70	66.0	22.7
11:01:08	SWA1532	B737	87.20	59.3	27.9
11:03:17	SWA238	B737	88.50	60.0	28.5
11:05:07	JBU189	A320	81.00	52.6	28.4

Table 4-1. (Continued).

San Diego #1: Living Room	Flight #	Aircraft	SEL_{out}	SEL_{in}	NLR
11:07:50	SWA2029	B737	85.70	57.3	28.4
11:09:37	SWA665	B737	87.70	61.2	26.5
11:17:50	JBU189	A320	82.40	56.4	26.0
11:20:02	DAL2506	B738	89.80	62.4	27.4
11:22:13	SWA2144	B737	86.90	59.1	27.8
11:24:41	SKW6325	E120	85.00		
11:28:17	SWA4761	B737	86.90		
11:30:33	VRD956	A319	87.10		
11:32:36	JBU189	A320	87.90	59.5	28.4
11:34:31	SWA3339	B737	87.20	58.8	28.4
11:36:08	FFT551	A320	87.70	59.9	27.8
11:38:30				53.5	
11:40:36				65.3	
11:43:03	JAL66	B788	90.00	61.5	28.5
11:45:49	N818SE	C650	80.70	49.9	30.8
11:50:42				63.4	
11:55:52				61.6	
11:59:52				57.9	
12:01:50	SWA4479	B737	87.80	59.8	28.0
12:11:07	ASA238	B738	88.90	60.6	28.3
12:13:08	DAL2378	A320	88.80	60.5	28.3
12:15:45	DAL2267	B739	88.50	60.7	27.8
12:17:58	UAL284	A320	86.90	59.1	27.8
12:20:27	WJA1435	B738	88.20	56.3	31.9
12:23:34	SKW2611	CRJ2	84.00	56.0	28.0
12:25:08				44.2	
12:27:33	SWA4317	B737	86.30	57.3	29.0
12:31:27	UAL356	A320	87.20	59.4	27.8
12:44:40	SWA3538	B737	89.80	62.1	27.7
12:47:52	SWA2076	B737	85.40	57.4	28.0
12:49:29	UAL1155	B739	88.50	60.5	28.0
12:55:16	AAL2382	B738	89.20	61.3	27.9
12:57:08	CPZ5749	E170	86.30		
12:59:47	DAL513	MD90	86.00	57.3	28.7
13:03:07	SWA2280	B737	80.20		
13:05:23	SWA2052	B733	91.50		

Note: The 2 dB reflection correction has not been applied to the above data. A blank indicates either no event recorded at interior or no event noted by the airport monitoring system.

A general rule of thumb is to measure about 25 flyover events to obtain a valid assessment of the NLR to within 0.5 dB. This varies with each individual measurement site. A site with quieter flyovers, noisy interior, and/or background (exterior) noise will require more measurements to converge to a steady average value.

It is typical to compute a running average of the NLR and the standard deviation with successive flyover events. As one progresses down the running average, the change in average and standard deviation value will become less and eventually stabilize to within a small range, such as 0.5 dB. This convergence may be increased by first discarding outliers.

However, there is no established rule for identifying outliers, and there is no standard by how much a value deviates from the mean before it is discarded. Some consultants suggest two standard deviations. Even with outliers, the rate of convergence depends upon the order in which values of various variances from the mean are encountered. That is, the chronology of the events affects the analysis.

To avoid this problem, the research team recommends that all flyover event values, including even the most obvious outliers, first be ordered by their deviation from the mean from highest to lowest. Then events may be discarded sequentially down the list with a new mean and standard deviation computed for the new list. This allows for much more rapid convergence to a small standard deviation. Also, it may be useful to sequentially compute the convergence interval for each new list. One standard that may be considered in selecting a mean and standard deviation is a confidence interval (CI) of ±0.5 dB at the 95% probability level. That is, 95% of all events in the sample fall within ±0.5 dB of the mean.

The confidence interval is:

$$CI = \overline{X} \pm Z * \frac{\sigma}{\sqrt{n}}$$

Where

X = mean value
σ = standard deviation
n = number of events
Z = random variable related to probability level (Z = 1.96 for 95%: Z = 1.645 for 90%; and Z = 2.576 for 99%)

Note that, unlike the standard deviation, the CI does not continue to drop with fewer values. This is because the CI is proportional to the standard deviation and inversely proportional to the square root of the number of values. Table 4-2 is a table of this method for the data presented in Table 4-1.

Table 4-2. Sorting of flyovers to find outliers.

San Diego #1—Sorted by Standard Deviation					
n	NLR	$\lvert NLR-NLR_{Avg}\rvert$	NLR AVG	Std Dev	95% CI
65	80.7	52.4	80.7		
64	3.9	24.4	28.3	7.35	± 1.80
63	22.7	5.6	27.5	3.25	± 0.80
62	31.9	3.6	27.8	1.27	± 0.32
61	24.8	3.5	27.9	1.10	± 0.28
60	25.6	2.7	27.9	0.98	± 0.25
59	30.8	2.5	27.9	0.90	± 0.23
58	26.0	2.3	28.0	0.85	± 0.22
57	26.2	2.1	27.9	0.77	± 0.20
56	26.3	2.0	27.9	0.74	± 0.19
55	26.3	2.0	28.0	0.70	± 0.19
54	26.5	1.8	28.0	0.67	± 0.18
53	29.9	1.6	28.0	0.64	± 0.17
52	26.9	1.4	28.1	0.61	± 0.16
51	27.0	1.3	28.0	0.55	± 0.15
50	27.0	1.3	28.1	0.54	± 0.15
49	27.1	1.2	28.1	0.52	± 0.15
48	29.3	1.0	28.1	0.50	± 0.14
47	29.2	0.9	28.1	0.48	± 0.14
46	27.4	0.9	28.1	0.46	± 0.13
45	27.4	0.9	28.1	0.43	± 0.13

Table 4-2. (Continued).

San Diego #1—Sorted by Standard Deviation					
n	NLR	$\lvert NLR-NLR_{Avg} \rvert$	NLR AVG	Std Dev	95% CI
44	27.4	0.9	28.1	0.42	± 0.13
43	29.1	0.8	28.1	0.42	± 0.12
42	29.0	0.7	28.1	0.41	± 0.12
41	27.6	0.7	28.1	0.38	± 0.12
40	27.6	0.7	28.1	0.36	± 0.11
39	27.6	0.7	28.1	0.35	± 0.11
38	28.9	0.6	28.1	0.35	± 0.11
37	27.7	0.6	28.1	0.34	± 0.11
36	27.7	0.6	28.1	0.32	± 0.10
35	27.7	0.6	28.1	0.32	± 0.11
34	27.7	0.6	28.1	0.32	± 0.11
33	28.8	0.5	28.1	0.31	± 0.11
32	27.8	0.5	28.1	0.31	± 0.11
31	27.8	0.5	28.1	0.29	± 0.10
30	27.8	0.5	28.1	0.29	± 0.10
29	27.8	0.5	28.1	0.29	± 0.10
28	27.8	0.5	28.1	0.29	± 0.11
27	27.8	0.5	28.2	0.28	± 0.11
26	27.8	0.5	28.2	0.28	± 0.11
25	27.8	0.5	28.2	0.28	± 0.11
24	27.8	0.5	28.2	0.27	± 0.11
23	28.7	0.4	28.2	0.26	± 0.11
22	28.7	0.4	28.2	0.25	± 0.11
21	27.9	0.4	28.2	0.24	± 0.10
20	27.9	0.4	28.2	0.22	± 0.09
19	27.9	0.4	28.2	0.21	± 0.10
18	28.0	0.3	28.2	0.21	± 0.09
17	28.0	0.3	28.2	0.20	± 0.09
16	28.0	0.3	28.2	0.19	± 0.09
15	28.0	0.3	28.3	0.19	± 0.10
14	28.0	0.3	28.3	0.18	± 0.10
13	28.0	0.3	28.3	0.17	± 0.09
12	28.0	0.3	28.3	0.16	± 0.09
11	28.5	0.2	28.3	0.13	± 0.08
10	28.5	0.2	28.4	0.08	± 0.05
9	28.4	0.1	28.4	0.07	± 0.05
8	28.4	0.1	28.3	0.05	± 0.04
7	28.4	0.1	28.3	0.05	± 0.04
6	28.4	0.1	28.3	0.05	± 0.04
5	28.3	0.0	28.3	0.04	± 0.04
4	28.3	0.0	28.3	0.00	± 0.00
3	28.3	0.0	28.3	0.00	± 0.00
2	28.3	0.0	28.3	0.00	± 0.00
1	28.3	0.0	28.3	0.00	± 0.00

Note: The 2 dB reflection correction has not been applied to the above data. A blank cell indicates either no event recorded at interior or no event noted by the airport monitoring system.

4.1.3 Sources of Error: Overview

Reflections: Up to 4 dB increase in sound level from ground reflections and reflections from the façade under test (if the outdoor microphone is located near the building façade). This requires a −2 to −4 dB adjustment to all exterior measurements.

Non-NEM fleet mix: The sound spectra of the aircraft flyover samples should reflect the energy average for all aircraft used in the NEM from the FAR Part 150 study for the airport. Average annual fleet mix may not be measured on a single day. Typical flyover measurements record aircraft during a single operation type (i.e., all landings or all takeoffs) and cannot reflect that of the annual mix.

Extraneous noise sources: Non-flyover noise, both on the exterior and interior, is recorded and is included with the aircraft noise measurements. These sources include occupants, local vehicles, construction, recreation, and other neighborhood activities.

Non-reverberant sound field: A single stationary microphone in a room does not give a good measure of the diffuse sound field. Laboratory tests use large rooms of special dimensions, often with moving microphones and/or vanes, and nonparallel walls to minimize standing wave effects. Microphones in small rooms are significantly influenced by location, particularly with pre-retrofit testing where the location relative to a poor sound-attenuating window may have considerable effect.

Room absorption: The total NLR is primarily from the CTL characteristics of the structure but also from the room acoustics controlled by the size and absorptive properties of the receiving room (NLR = TL ± room absorption). Therefore, a considerable change in room furnishing between the pre- and post-retrofit testing causes a significant change in room absorption and will affect the measured NLR.

Varying sound spectra: Different aircraft under different operating conditions are recorded for the pre-construction and post-construction acoustical measurements. These different operating conditions result in different spectra and incidence, therefore posing another source of error.

4.1.3.1 Reflections

The NLR results for all rooms in all homes were compared with those from the ground-level and elevated loudspeaker measurements. A strong trend was found that the NLR values from the flyovers exceeded those measured by the loudspeaker methods by approximately 2 dB. Assuming that the main noise transmission paths are the same for both the flyover and the loudspeaker methods, this indicated that the exterior flyover SEL values were biased 2 dB high, since the interior measurements for both methods were the same. This 2 dB increase is discussed in acoustical standards and may arise from ground reflections in the neighborhoods measured. There was no discernible trend between hardscape or softscape ground surfaces. Based on the above, all flyover data in this report was corrected by 2 dB. It should be noted that this correction is not commonly used by acoustic consultants in the existing airport sound insulation programs, and more research is needed to further understand the correction for ground reflection.

It also appears, based on measurements and modeling, that some reflections may occur if the outdoor microphone is placed near the home under test. The combined ground and façade reflection correction may approach 4 dB, but more research and analysis is needed.

4.1.3.2 Non-NEM Fleet Mix

The ideal procedure for measuring the NLR at a home would be to use an exterior sound spectrum representing the energy average of all aircraft operations from the NEM for the design year. This would entail computing the spectral contribution from all aircraft types, climb profiles, power settings, volume of daytime and nighttime operations, landings, etc. used to prepare the NEM. This would be a practically impossible task.

However, the noisiest aircraft operations dominate the noise contribution at any location. For instance, it would take 10, 80-dB-SEL events to provide the same NEM contribution as a single 90-dB-SEL event. When recording the NLR results from a series of flyovers, consultants typically compute the arithmetic average of valid NLR results. But, this may not provide the best estimate of the NLR because:

- The loudest events dominate the exterior noise exposure value from the NEM, as explained above, and
- The loudest events are the least affected by extraneous noise sources, because they have a greater capability to mask, or drown out, the extraneous noise.

For this study, the research team compared the arithmetic average results with energy average results. Energy average results strongly bias the loudest events.

The equations for the two averages are:

Arithmetic average: $NLR = \frac{\sum_{i=1}^{n} NLRi}{n}$

Energy average: $NLR = 10 * \log\left\{\left[\sum_{i=1}^{n} 10 \uparrow \left(\frac{SEL_{out}}{10}\right) - \sum_{i=1}^{n} 10 \uparrow \left(\frac{SEL_{in}}{10}\right)\right] \middle/ n\right\}$

Table 4-3 shows the differences between arithmetic average and energy average for the flyover tests of 10 homes near San Diego International Airport (SAN).

The results in Table 4-3 show no clear trend in the difference between the arithmetic and energy average NLR values. The mean difference between the two is an almost negligible 0.1 dB. Biasing the NLR values from the loudest events may not always be advisable since extraneous noise in a single loud event tends to override the average of other uncontaminated events.

4.1.3.3 Extraneous Noise Sources

The potential for contamination from extraneous noise sources exists with every NLR measurement technique. An advantage of the flyover test method is the array of results allowing for statistical assessment and identification of outlying, or far-off, NLR results not close to the other values. Two methods of identifying outlying results for elimination are:

- Flagging and eliminating those NLR values that are two standard deviations from the mean and
- Using the median rather than the mean results.

Flagging those events two standard deviations from the mean is a standard statistical technique. However, it is arbitrary in that it provides no means for identifying the source of the deviation; that particular event may in fact be valid, but for reasons not understood. Similar arbitrary data screening techniques are also available such as a more lenient three standard deviations from the mean, or simply some static value for the mean, such as ±3 dB from the mean.

Using the median in lieu of the mean is a simpler way of screening outliers. The mean, or average, sums all values and divides by the number of values to obtain the result. The median, on the other hand, is the L_{50} percentile or that value where half of the values exceed it and the other half are below it. Table 4-4 compares the average and median values for the SAN flyover NLR events.

It is evident from Table 4-4 that the mean and median values are entirely similar for "well-behaved" statistical results; the average difference between the mean and median values in the table is 0 dB. Therefore, median values seem to provide a good statistical sample.

Table 4-3. Flyover measurements, comparison of arithmetic average and energy average NLR values.

Residence	Room	Arithmetic Average (dB)	Energy Average (dB)	Difference (Energy - Arith), dB
San Diego #1	Living Room	26.3	26.4	0.1
	Dining Room	28.0	28.1	0.1
San Diego #2	Living Room	24.3	24.3	0.0
	Bedroom 4	20.4	20.4	0.0
San Diego #3	Living Room	23.7	23.8	0.1
	Master BR	24.7	24.8	0.1
San Diego #4	Living Room	23.2	23.2	0.0
	Bedroom 1	26.3	26.4	0.1
San Diego #5	Living Room	24.0	24.3	0.3
	Bedroom 1	30.0	30.1	0.1
San Diego #6	Living Room	24.9	25.0	0.1
	Dining Room	27.4	27.5	0.1
San Diego #7	Living Room	25.1	25.2	0.1
	Family Room	26.5	26.7	0.2
San Diego #8	Dining Room	19.4	19.6	0.2
	Master BR	22.2	22.5	0.3
San Diego #9	Living Room	21.8	22.0	0.2
	Bedroom 1	31.7	31.9	0.2
San Diego #10	Bedroom 1	17.5	17.6	0.1
	Bedroom 2	25.0	25.2	0.2
			Average	**0.1**

4.1.3.4 Non-Reverberant Sound Field

Acoustical consultants have long recognized the lack of an ideal reverberant sound field in measuring rooms within homes. This problem exists with all measurement methods, but is ameliorated to some degree with the loudspeaker method where the measurement within the room is attended by manually moving the microphone to achieve a better spatial average of the sound field. The long duration of measurements with the flyover method makes attended measurements infeasible, so a single stationary microphone is typically used. This microphone is located away from the incident building elements to avoid bias from the particular TL properties of nearby building elements. Additionally, microphone locations also avoid corner areas and sites midway between parallel wall surfaces in order to minimize standing wave effects.

This project studies the effects of a single stationary microphone in two ways, both taken from the laboratory standard for TL testing:

- Use of multiple microphones in the receiving room to view differences in interior noise levels and to average their results and
- Use of a moving microphone as is the standard practice for laboratory TL testing.

Table 4-5 shows the test results for the various rooms tested with moving microphone and/or with multiple microphones.

Table 4-4. Flyover measurements, comparison of average and median NLR events.

Residence	Room	Arithmetic Average	Median	Difference (Arith - Median)
San Diego #1	Living Room	26.3	26.3	0.0
	Dining Room	28.0	28.2	-0.2
San Diego #2	Living Room	24.3	24.2	0.1
	Bedroom 4	20.4	20.4	0.0
San Diego #3	Living Room	23.7	24.0	-0.3
	Master BR	24.7	24.4	0.3
San Diego #4	Living Room	23.2	23.5	-0.3
	Bedroom 1	26.3	26.3	0.0
San Diego #5	Living Room	24.0	24.3	-0.3
	Bedroom 1	30.0	30.2	-0.2
San Diego #6	Living Room	24.9	24.9	0.0
	Dining Room	27.4	27.5	-0.1
San Diego #7	Living Room	25.1	25.1	0.0
	Family Room	26.5	26.8	-0.3
San Diego #8	Master BR	22.2	21.7	0.5
	Dining Room	19.4	19.2	0.2
San Diego #9	Living Room	21.8	21.9	-0.1
	Bedroom 1	31.7	31.6	0.1
San Diego #10	Bedroom 1	17.5	17.5	0.0
	Bedroom 2	25.0	25.3	-0.3
			Average	**0.0**

Table 4-5. Comparison of averaged microphone alternative NLR results.

Residence	Room	Mic 1	Mic 2	Rotating Mic	Average Mic1 : Mic2	Std. Dev. All Values	95%CI
San Diego #1	Living Room	25.9	27.4	25.6	26.7	0.79	±0.89
San Diego #2	Living Room	24.4	23.9	24.5	24.2	0.26	±0.30
San Diego #3	Living Room	24.0	23.1	24.0	23.6	0.45	±0.62
San Diego #4	Bedroom 1	26.9		25.8	26.9	1.14	±1.58
San Diego #5	Living Room	24.2		23.8	24.2	0.39	±0.54
San Diego #6	Dining Room	26.9	27.8	27.4	27.4	0.37	±0.42
San Diego #7	Family Room	26.2	26.9	26.5	26.6	0.29	±0.32
San Diego #8	Dining Room	19.1	19.9	19.1	19.5	0.38	±0.43
San Diego #9	Living Room	20.9	22.4	22.0	21.7	0.63	±0.72
San Diego #10	Bedroom 1	18.2	17.0	17.2	17.6	0.52	±0.59

Note: The configuration of microphones in the San Diego #4 and San Diego #5 homes allowed for only one fixed microphone in the same room as the rotating microphone.

The long boom length of the rotating microphone required that large rooms be measured; most rooms were living rooms. The two stationary microphones were generally placed in opposite room quadrants to measure the noise environment in distinct areas.

The measurement results in Table 4-5 show:

- Little distinction among the independent values, average values, and values from the rotating microphone and
- No trend among the measurement techniques; rotating microphone NLR values do not trend either higher or lower than those from the stationary microphones.

The rotating microphone selected was the same model used in laboratory testing. However, it never worked properly under power and was therefore rotated manually for all measurements. This complicated the measurements because it required the receiving room to be occupied and added to the potential for noise contamination.

4.1.3.5 Room Absorption

The issue with acoustical absorption in rooms exists with all NLR measurement techniques. Typically, an empty room of moderate size without carpeting or curtains may be 3 dB louder than the same room fully furnished. That is, the overall noise reduction is controlled primarily by the sound TL characteristics of the building elements and also by the room absorption. The basic relationship is (DOT-FAA-AEQ-77-9, 1977):

$$NLR = TL - 10 * log_{10}(S/A) - 6$$

where S = surface area of the assembly exposed to the noise source
and A = the total absorption in the room at the source frequency

The absorption varies with frequency as does the TL, so this computation must be done in octave bands or one-third octave bands. Typically the 6 dB term for perfect acoustic reflection is reduced to 5 dB to reflect actual less-than-perfect reflection.

The total room absorption may be determined by measuring the room dimensions and the reverberation time (symbol RT_{60}), or time for an impulsive sound to decay by 60 dB. Reverberation time is measured by emitting a high level broadband impulsive sound, often by a large balloon, and recording the decay rate. Many contemporary SLMs have a feature built in for this measurement. The general relationship between reverberation times is given by the Sabine equation (Bies and Hansen, 2003):

$$RT_{60} = \frac{55.25V}{S\,c\,\propto}$$

where RT_{60} = reverberation time (60 dB decay) in seconds
V = room volume (m^3)
c = speed of sound (m/s)
$\propto$ = the acoustical absorption coefficient at the source frequency

Those homeowners desiring to qualify for the sound insulation program under the PGL/5100.38D guidelines may increase their chances of qualifying by removing furnishings from rooms to be tested prior to the qualification NLR measurements, thereby increasing measured receiving room sound levels and reducing the reported interior DNL values.

4.1.3.6 Varying Sound Spectra

Flyover events of varying sound spectra with the same A-weighted SEL value produce different NLR results. This is related to the issue of a non-NEM fleet mix (see 4.1.3.2) and it exists with other measurement techniques as well. For example, an 80-dB flyover with a concentration of low frequency energy will produce a lower NLR than another 80-dB flyover with more energy concentrated in the higher frequencies. This is due to the TL property of all building assemblies to attenuate sound more effectively in the higher frequencies. The NLR effects of any particular case may be examined by viewing the SEL spectrum of the flyover, the CTL properties of the room, and the room absorption characteristics. To examine this more thoroughly, the research team (a) analyzed the differences in NLR from specific aircraft types from the SAN flyovers measurements and (b) computed the CTL for various typical aircraft in the INM database.

Table 4-6 shows the results from the homes for which the research team recorded the most valid flyovers. These are the living room in the San Diego #3 residence for aircraft departures and the San Diego #6 dining room for aircraft arrivals.

From Table 4-6, there is no clear NLR trend for the specific aircraft currently operating from SAN. However, certain classes of aircraft do not operate from SAN, so an independent study was subsequently conducted.

The effect of spectral changes from other aircraft was computed by selecting the standard spectra for certain classes of aircraft from the database for the FAA standard INM computer program used to develop the noise contours for the Part 150 studies (DTS-34-FA065-LR1, 1999), and an ideal "mass law" TL curve for a residence. The mass law curve at STC 39 (OITC 31) slopes upward at 8 dB per octave from 24 dB at 125 Hz to 54 dB at 4 kHz. This curve is a good average for the CTL, or the TL from all incident sound on all exposed surfaces of non-retrofit homes. The aircraft spectra are taken from the FAA noise certification tests (under 14CFR36) for the specific aircraft in a class.

Table 4-6. Comparison of NLR values for several SAN aircraft.

Aircraft	San Diego #3 Departures			San Diego #6 Arrivals		
Type	Count	Average	Std Dev	Count	Average	Std Dev
All MD	3	23.7	0.2			
A319	5	23.5	1.8	4	27.7	0.6
A320	6	24.9	0.4	5	27.3	0.9
B733				5	27.1	0.6
B737	19	23.8	1.1	12	27.4	1.0
B738	13	23.2	1.0	9	27.0	1.2
B739				2	27.3	0.1
B752	3	24.4	0.7	3	27.6	0.6
All CRJ#				3	28.4	1.3
All E##	1	24.2		3	26.6	0.7
	Average	**24.0**		**Average**	**27.4**	
	Std Dev	**0.58**		**Std Dev**	**0.50**	

Legend:

All MD	All MD 80 models
A319	Airbus A319
A320	Airbus A320
B733	Boeing 737-300
B737	Boeing 737-700
B738	Boeing 737-800
B739	Boeing 737-900
B752	Boeing 757-200
All CRJ#	All Canadair Regional Jet
All E##	All Embraer turboprops

Table 4-7. Comparison of SEL values and NLR values for aircraft classes.

Aircraft Types	Departures			Approaches		
	SEL_{out}	NLR	SEL_{in}	SEL_{out}	NLR	SEL_{in}
B737-300, 3B2, 400, 500	73.5	30.5	43.0	75.4	31.3	44.1
B757 & B767; A300, 310, 320	75.7	31.0	44.7	77.5	33.4	44.1
MD81, 82, 83	72.8	29.9	42.9	72.6	28.7	43.9
B747-10Q, 200, 720A, 420B, 400	77.0	32.4	44.6	77.5	33.8	43.7
2-engine turboprop, DHC6	77.7	24.8	52.9	69.8	27.3	42.5
4-engine turboprop, DHC7, DHC8	77.8	22.8	55.0	69.8	27.3	42.5

Table 4-7 compares the computed exterior and interior SEL (an integrated measure of the total sound energy of a noise event), values for the aircraft classes, and computes the attendant NLR values.

Table 4-7 shows that there is generally little difference among the medium, heavy, and regional jet aircraft classes for the turbofan aircraft. However, the NLR values for the turboprop aircraft show a significant reduction in NLR of about 5 dB. This is due to the strong low frequency components from prop blade pass frequencies that attenuate less than the more broadband jet noise from turbofan jets.

No airport operation is composed exclusively of a single class of aircraft, so the NLR differences in Table 4-7 are significantly moderated in the mix of aircraft for any particular airport. The SEL values and the varying sound spectra both play a significant role in determining the proper noise spectrum to use for evaluating the NLR of a residence in terms of the NEM spectrum at a particular location.

NLR results from turboprop approaches and departures were compared with those from other aircraft. Little change was found, contradicting the theoretical analysis using the FAA INM spectral classes. But the INM data is 16 years old and modern commuter turboprops now typically employ five or six-bladed propellers which are often in the scimitar configuration. These significantly diminish the tones emitted by earlier turboprop versions. Therefore it can be concluded that turboprop spectral changes are generally not a significant factor in NLR assessment.

4.2 Ground-Level Exterior Loudspeaker

The ground-level exterior loudspeaker measurement method follows the measurement procedure outlined ASTM E966, and this method is commonly employed by acoustical consultants working on sound insulation projects (Figure 4-3). The method involves locating a loudspeaker approximately 6.1 m to 12.2 m (20 to 40 feet) from the façade of the room under test, at a height of 6 to 8 feet above grade. The only difference between the elevated exterior loudspeaker method (discussed in the following section) and the ground-level method is the height of the loudspeaker above grade.

Summary: The research team conducted ground-level loudspeaker measurements at 10 homes in San Diego. In Boston, the research team conducted ground-level loudspeaker measurements in nine homes, but the aircraft flyover source spectrum was only available in four of the homes. The conclusions are as follows:

- On average, calculated noise reduction using the OITC spectrum was slightly lower (0.6 dB) than that of the flyover spectrum. This slight difference was similar to the results of the elevated loudspeaker measurements.

Figure 4-3. Ground-level loudspeaker measurement in San Diego.

- In general, the results varied little from measurement to measurement; however, there were a few outliers which warranted closer examination.
- Similar to the elevated loudspeaker, the NLR decreased by approximately 1 dB when the roof and walls were measured at the exterior (rather than just the walls).
- On average, the calculated noise reduction using the OITC spectrum was slightly lower (0.9 dB) than that calculated using the flyover spectrum.
- Noise reduction varied by less than 1 dB when measurements were repeated.
- Noise reduction increased when the wall and roof were measured, which is the opposite of what happened when the loudspeaker was located inside of the building.

4.2.1 Measurement Procedure

The ground-level exterior loudspeaker noise reduction measurement was conducted as follows:

1. A loudspeaker capable of generating 90 dB to 100 dB was mounted at a height of 1.8 to 3.0 meters (6 to 10 feet) above grade, at a distance of, on average, 9.1 m (30 feet) from the building façade. The loudspeaker was pointed in the direction of the room under test, at a horizontal angle of 45° from the façade.
2. Ambient (background) noise measurements were conducted outside and inside of the room under test. The ambient measurement allowed the technician to verify that the noise generated by the loudspeaker was sufficiently above the ambient noise level; corrections to the measurement were made if the ambient noise level approached the level of the loudspeaker. This ensured that noise reduction was accurately measured and quantified.
3. Pink noise was generated by the loudspeaker. A measurement of the diffuse sound field just outside of the room under test [e.g., 1 to 2 meters (3 to 6 feet) from the façade] was made. This measurement consisted of a spatial average of the noise levels at the façade (and roof, where applicable).
4. A measurement of the loudspeaker-generated pink noise was then made inside of the room. Again, a spatial average was conducted with the technician maintaining a minimum distance of 0.3 to 0.6 m (1 to 2 feet) between the microphone and walls, ceilings, floors, etc.
5. The one-third octave measurement data (50 Hz to 5 kHz) were then analyzed in a spreadsheet, where the interior pink noise level was subtracted from the exterior pink noise level. Three corrections were then applied: (a) the subtraction of ambient noise, (b) a 2-dB correction (based

on ASTM E966-10) to account for the reverberant noise build-up at the façade, and (c) a correction to account for the different frequency spectrum of an aircraft as compared to pink noise. These corrections are discussed in more detail in the following section.

4.2.2 Data Analysis and Correction Factors

To calculate the amount of noise reduction provided by the building envelope, the data must be analyzed and corrected after completion of the measurement. There are three primary corrections that are made to the measured data; each is summarized below:

4.2.2.1 Ambient Noise Correction

Ambient noise can affect the accurate determination of noise reduction. For the exterior, ground-level loudspeaker measurement, ambient noise is typically only an issue inside of the room under test. This is because exterior ambient noise is significantly below the level of the loudspeaker (e.g., 50-dB ambient as compared to 90-dB pink noise from the loudspeaker); measurements are not conducted during an aircraft overflight, as overflights could approach the noise level of the loudspeaker. Inside the room, ambient noise is generated by household items such as refrigerators, HVAC systems, and other domestic equipment. Typically, the technician will turn off noisy devices; however it is not always possible to do so.

If the ambient noise level is within 10 dB of the pink noise level inside the room, then the ambient noise level is logarithmically subtracted from the pink noise level. This ensures the calculated noise reduction is only based upon pink noise intrusion through the building envelope, and not contaminated by interior noise sources.

4.2.2.2 Reverberant Noise Build-Up

The second correction applied is to account for reverberant (reflected) noise build-up at the façade. This correction is outlined in ASTM E966 and ISO 1996-2. When noise from the loudspeaker impinges on a building façade, some of the noise transmits through the façade into the residence, while some of the noise reflects back away from the façade. At a measurement distance of 1 to 2 meters (3 to 6 feet) from the façade, this reflected noise yields a noise level 2 to 3 dB higher than what would be measured without the presence of the building façade. Since the measure of concern is noise that transmits through the building envelope, it is important to eliminate the reverberant noise from the measurement data. ASTM E966 (2004) stipulates a 3-dB correction, while E966 (2010) stipulates a 2-dB correction. Effectively, correcting for the reverberant field reduces the measured noise reduction by 2 to 3 dB (depending on which correction factor is used).

The correction was lowered in the 2010 version of the standard, as purportedly the 2-dB correction more closely aligns to actual field experience (per ASTM), while the 3-dB correction is a laboratory/theoretical value. Based on analysis of the measurement data, the 2-dB correction factor more closely aligns with the true noise reduction of a façade.

4.2.2.3 Spectral Correction

As discussed in Section 4.2.1, pink noise is generated by the loudspeaker. Pink noise is used because it is a reference sound source with equal energy across all frequency bands, and it is not logistically feasible to accurately generate the same frequency spectrum as generated by typical aircraft. However, the FAA eligibility standards are based upon aircraft noise levels, and not pink noise levels. As such, it is necessary to "convert" pink noise reduction into aircraft noise reduction. In order to convert pink noise reduction to aircraft noise reduction, the pink noise reduction is subtracted from a reference aircraft spectrum to yield a theoretical aircraft noise level inside of the tested room.

While the conversion utilizes standard acoustical calculations, there is no standard guidance on how to determine the reference aircraft spectrum. Many consultants involved with sound insulation programs measure multiple arrivals and departures at a given airport and then average these events to calculate the reference spectrum. However, there are many questions raised by this practice: (a) how many aircraft flyovers need to be measured to produce a statistically valid sample, (b) how does one account for homes located at varying distances from the runway ends (i.e., the aircraft spectrum at a home far from the runway will be different from that of a home near a runway), and (c) how does one account for future aircraft fleet mix changes.

For this report, the research team has converted pink noise reduction into aircraft noise reduction using two reference spectra: the OITC reference spectrum and the average aircraft spectrum measured at each test home over a period of 3 to 5 hours (measured as a part of the flyover noise reduction measurements). The research team has analyzed the difference in measured noise reduction using the OITC and the average aircraft spectrum measured at each test home. Table 4-8 shows the noise reduction calculated using both of these frequency spectra.

For the San Diego measurements, ground-level loudspeaker measurements were conducted in 10 homes. At Boston, ground-level loudspeaker measurements were conducted in nine homes, but aircraft flyover noise spectrum was only available in four out of the nine homes.

Conclusion: On average, the calculated noise reduction using the OITC spectrum was slightly lower (0.6 dB) than that calculated using the flyover spectrum, and this difference was similar to that for the elevated loudspeaker.

Table 4-8. Exterior ground-level loudspeaker, NLR comparison of source spectra.

Residence	Room	Reference Spectrum	NLR (dB)
San Diego #1	Living	SAN	24.5
		OITC	22.2
		Difference	2.3
	Dining	SAN	22.2
		OITC	20.1
		Difference	2.1
San Diego #2	Living	SAN	25.2
		OITC	25.8
		Difference	-0.6
	Office	SAN	18.4
		OITC	17.5
		Difference	0.9
San Diego #3	Living	SAN	21.9
		OITC	22.0
		Difference	-0.1
San Diego #4	Living	SAN	21.6
		OITC	19.9
		Difference	1.7
	Bedroom 1	SAN	25.0
		OITC	23.2
		Difference	1.8

(continued on next page)

Table 4-8. (Continued).

Residence	Room	Reference Spectrum	NLR (dB)
San Diego #5	Living	SAN	21.3
		OITC	20.7
		Difference	0.6
	Bedroom 1	SAN	26.3
		OITC	25.0
		Difference	1.3
San Diego #6	Living	SAN	20.9
		OITC	20.2
		Difference	0.7
	Dining	SAN	26.4
		OITC	24.9
		Difference	1.5
San Diego #7	Family	SAN	25.7
		OITC	26.4
		Difference	-0.7
	Living	SAN	24.6
		OITC	24.4
		Difference	0.2
San Diego #8	Dining	SAN	19.6
		OITC	19.2
		Difference	0.4
	Master Bedroom	SAN	28.3
		OITC	27.1
		Difference	1.2
San Diego #9	Living	SAN	19.4
		OITC	18.8
		Difference	0.6
	Bedroom 1	SAN	25.6
		OITC	25.0
		Difference	0.6
San Diego #10	Bedroom 1	SAN	17.6
		OITC	17.7
		Difference	-0.1
	Bedroom 2	SAN	25.1
		OITC	25.9
		Difference	-0.8
Boston #1 (storm windows closed)	Living	BOS	37.0
		OITC	37.4
		Difference	-0.4
	Bedroom 2	BOS	30.5
		OITC	29.7
		Difference	0.8
Boston #3 (storm windows closed)	Living	BOS	25.3
		OITC	25.4
		Difference	-0.1
	Bedroom 1	BOS	26.4
		OITC	26.3
		Difference	0.1

Table 4-8. (Continued).

Residence	Room	Reference Spectrum	NLR (dB)
Boston #6 (storm windows open)	Dining	BOS	25.0
		OITC	25.4
		Difference	-0.4
	Bedroom 2	BOS	24.9
		OITC	24.9
		Difference	0.0
Boston #8 (storm windows open)	Living	BOS	24.8
		OITC	24.2
		Difference	0.6
	Study	BOS	25.7
		OITC	26.5
		Difference	-0.8
Average Difference (Flyover – OITC)			**0.5**
Standard Deviation			**0.9**

Note: SAN and BOS reference spectrum refers to the average flyover spectrum measured at the home.

4.2.3 Repeatability

At one of the test homes, the research team repeated the ground-level loudspeaker measurement with no change in loudspeaker position to determine whether the results changed from test to test. The goal was to determine whether the measurement engineer could induce significant variation in the test results. Table 4-9 summarizes the findings.

Conclusion: In general, the results varied little from measurement to measurement; however, there were a few outliers which warrant closer examination.

4.2.4 Measurement of Exterior Wall and Roof vs. Exterior Wall Only

Similar to the elevated exterior loudspeaker method, the research team conducted measurements of noise reduction using two methods: (1) making an exterior spatial measurement of the wall and roof-ceiling assembly and (2) making a spatial measurement of just the exterior wall. The resultant difference in noise reduction is presented in Table 4-10.

Conclusion: Similar to the elevated loudspeaker, the NLR decreased by approximately 1 dB when the roof and walls were measured at the exterior (rather than just the walls).

4.3 Elevated Exterior Loudspeaker

The elevated exterior loudspeaker measurement method generally follows the measurement procedure outlined in ASTM E966; this method has been employed by various acoustical consultants working on sound insulation projects. The method involves the suspension of a loudspeaker approximately 6.1 m to 12.2 m (20 feet to 40 feet) above grade, set back 6.1 m to 12.2 m (20 feet to 40 feet) from the façade of the room being measured. In theory, the elevated position is used because it more closely approximates the origin of the elevated aircraft noise (i.e., up in the sky). The loudspeaker generates a diffuse sound field at the exterior building

Table 4-9. Exterior ground-level loudspeaker, repeatability of measurement.

Residence	Room	Ref. Spectrum	Description	Measured Noise Reduction (dB) Msmt. 1	Msmt. 2	Difference	Standard Deviation
San Diego #1	Living	OITC	Exterior Wall Only	22.1	22.7	0.6	0.4
		SAN	Exterior Wall Only	24.3	25.0	0.7	0.5
	Dining	OITC	Exterior Wall Only	20.1	20.0	0.1	0.1
		SAN	Exterior Wall Only	22.3	22.0	0.3	0.2
San Diego #2	Living	OITC	Exterior Wall Only	25.7	26.9	1.2	0.8
		SAN	Exterior Wall Only	24.7	25.6	0.9	0.6
San Diego #3	Living	OITC	Exterior Wall Only	21.7	22.3	0.6	0.4
		SAN	Exterior Wall Only	21.5	22.2	0.7	0.5
San Diego #4	Living	OITC	Exterior Wall Only	19.7	20.0	0.3	0.2
		SAN	Exterior Wall Only	21.2	21.9	0.7	0.5
	Bedroom 1	OITC	Exterior Wall Only	23.0	23.3	0.3	0.2
		SAN	Exterior Wall Only	24.8	25.1	0.3	0.2
					Average	**0.6**	**0.4**

Note: SAN reference spectrum refers to the average flyover spectrum measured at the home.

Table 4-10. Exterior ground-level loudspeaker, comparison of wall/roof and wall-only measurement.

Residence	Room	Ref. Spectrum	Description	Noise Reduction (dB)
San Diego #6	Living	OITC	Exterior Wall and Roof	19.8
			Exterior Wall Only	20.6
			Difference	-0.8
		SAN	Exterior Wall and Roof	20.4
			Exterior Wall Only	21.4
			Difference	-1.0
	Dining	OITC	Exterior Wall and Roof	24.4
			Exterior Wall Only	25.4
			Difference	-1.0
		SAN	Exterior Wall and Roof	25.6
			Exterior Wall Only	27.1
			Difference	-1.5

Table 4-10. (Continued).

Residence	Room	Ref. Spectrum	Description	Noise Reduction (dB)
San Diego #5	Living	OITC	Exterior Wall and Roof	20.0
			Exterior Wall Only	21.3
			Difference	-1.3
		SAN	Exterior Wall and Roof	20.6
			Exterior Wall Only	22.0
			Difference	-1.4
San Diego #7	Family	OITC	Exterior Wall and Roof	24.1
			Exterior Wall Only	24.7
			Difference	-0.6
		SAN	Exterior Wall and Roof	24.4
			Exterior Wall Only	25.0
			Difference	-0.6
San Diego #8	Dining	OITC	Exterior Wall and Roof	18.7
			Exterior Wall Only	19.7
			Difference	-1.0
		SAN	Exterior Wall and Roof	18.9
			Exterior Wall Only	20.2
			Difference	-1.3
	Master Bedroom	OITC	Exterior Wall and Roof	26.2
			Exterior Wall Only	27.9
			Difference	-1.7
		SAN	Exterior Wall and Roof	27.5
			Exterior Wall Only	29.1
			Difference	-1.6
San Diego #10	Bedroom 1	OITC	Exterior Wall and Roof	17.3
			Exterior Wall Only	18.0
			Difference	-0.7
		SAN	Exterior Wall and Roof	17.4
			Exterior Wall Only	17.8
			Difference	-0.4
	Bedroom 2	OITC	Exterior Wall and Roof	25.9
			Exterior Wall Only	25.9
			Difference	0.0
		SAN	Exterior Wall and Roof	25.1
			Exterior Wall Only	25.1
			Difference	0.0
Average Difference		**OITC**		**-0.9**
		SAN		**-1.0**
		Overall		**-0.9**
Standard Deviation		**OITC**		**0.5**
		SAN		**0.6**
		Overall		**0.5**

Note: SAN reference spectrum refers to the average flyover spectrum measured at the home.

Figure 4-4. Exterior elevated loudspeaker in San Diego.

façade; measurements of this diffuse field are taken along with measurements of the reverberant sound field in the room under test. Section 4.3.1 describes the measurement procedure in detail. (Figure 4-4.)

Summary: The research team conducted elevated loudspeaker measurements in five homes in San Diego. In Boston, the research team also conducted elevated loudspeaker measurements in five homes, but aircraft flyover noise spectrum was only available in two out of the five homes. The conclusions are as follows:

- On average, the calculated noise reduction using the OITC spectrum was slightly lower (0.3 dB) than that of the flyover spectrum.
- When measurements were repeated, the noise reduction did not significantly change.
- Noise reduction decreased by 0.8 dB when the exterior measurement included the roof.

4.3.1 Measurement Procedure

The elevated exterior loudspeaker noise reduction measurement was conducted as follows (in a manner similar to the ground-level loudspeaker):

1. A loudspeaker capable of generating 90 dB to 100 dB at a distance of 9.1 m (30 feet) was elevated above the roof plane of the home under test. Typically, the height was 6.1 m to 12.2 m

(20 feet to 40 feet) above grade; a bucket/crane truck was required to accomplish this. The loudspeaker was pointed in the direction of the room under test, with the goal of a 45 degree horizontal angle from the façade.
2. Ambient (background) noise measurements were conducted outside and inside of the room under test. The ambient measurement allows the technician to verify that the noise generated by the loudspeaker was sufficiently above the ambient noise level; corrections to the measurement were made if the ambient noise level approached the level of the loudspeaker. This ensured that noise reduction is accurately measured and quantified.
3. Pink noise was generated by the loudspeaker. A measurement of the diffuse sound field just outside of the room under test [e.g., 1 to 2 meters (3 to 6 feet) from the façade] was made. This measurement consisted of a spatial average of the noise levels at the façade (and roof, where applicable).
4. A measurement of the loudspeaker-generated pink noise was then made inside of the room. Again, a spatial average was conducted with the technician maintaining a minimum distance of 0.3 to 0.6 meters (1 to 2 feet) between the microphone and walls, ceilings, floors, etc.
5. The one-third octave measurement data (50 Hz to 5 kHz) was then analyzed in a standard spreadsheet, where the interior pink noise level was subtracted from the exterior pink noise level. Three corrections were then applied: (1) the subtraction of ambient noise, (2) a 2 dB correction (based on ASTM E966-10) to account for the reverberant noise build-up at the façade and, (3) a correction to account for the different frequency spectrum of an aircraft as compared to pink noise. These corrections are discussed in more detail in the following section.

4.3.2 Data Analysis and Correction Factors

To calculate the amount of noise reduction provided by the building envelope, the data must be analyzed and corrected after completion of the measurement. There are three primary corrections that are made to the measured data, as previously discussed in Section 4.2.2.

For the spectral correction, the research team converted pink noise reduction into aircraft noise reduction using two reference spectra: the OITC reference spectrum and the average aircraft spectrum measured at each test home over a period of 3 to 5 hours (measured as a part of the flyover noise reduction measurements). Table 4-11 shows the noise reduction calculated using both of these frequency spectra.

For the San Diego measurements, elevated loudspeaker measurements were conducted in five homes. At Boston, elevated loudspeaker measurements were also conducted in five homes, but aircraft flyover noise spectrum was only available in two out of the five homes.

Conclusion: On average, the calculated noise reduction using the OITC spectrum was slightly lower (0.3 dB) than that calculated using the flyover spectrum.

4.3.3 Repeatability

At one of the test homes, the research team repeated the elevated loudspeaker measurement with no change in loudspeaker position to determine whether results changed from test to test. The goal was to determine whether the measurement engineer could induce significant variation in the test results. Table 4-12 summarizes the findings.

Conclusion: When measurements were repeated, the noise reduction did not significantly change.

Table 4-11. Elevated loudspeaker, comparison of source noise spectra.

Residence	Room	Reference Spectrum	NLR (dB)
San Diego #6	Living	SAN	21.0
		OITC	20.1
		Difference	0.9
	Dining	SAN	23.7
		OITC	22.4
		Difference	1.3
San Diego #7	Family	SAN	25.6
		OITC	25.3
		Difference	0.3
	Living	SAN	23.8
		OITC	23.4
		Difference	0.4
San Diego #8	Dining	SAN	19.9
		OITC	19.4
		Difference	0.5
	Master Bedroom	SAN	28.6
		OITC	27.8
		Difference	0.8
San Diego #9	Living	SAN	19.8
		OITC	19.0
		Difference	0.8
	Bedroom 1	SAN	26.1
		OITC	25.6
		Difference	0.5
San Diego #10	Bedroom 1	SAN	18.9
		OITC	19.4
		Difference	-0.5
	Bedroom 2	SAN	25.3
		OITC	25.9
		Difference	-0.6
Boston #6 (storm windows open)	Dining	BOS	25.0
		OITC	25.7
		Difference	-0.7
	Bedroom 2	BOS	25.1
		OITC	25.1
		Difference	0.0
Boston #8 (storm windows open)	Living	BOS	25.0
		OITC	24.3
		Difference	0.7
	Study	BOS	26.6
		OITC	27.1
		Difference	-0.5
	Average Difference (Flyover – OITC)		**0.3**
		Standard Deviation	**0.6**

Note: SAN and BOS reference spectrum refers to the average flyover spectrum measured at the home.

Table 4-12. Exterior elevated loudspeaker, repeatability of measurement.

Residence	Room	Ref. Spectrum	Description	Measured NLR (dB) Msmt. 1	Msmt. 2	Difference	Standard Deviation
San Diego #6	Living	OITC	Exterior Wall Only	20.6	20.5	0.1	0.1
		SAN	Exterior Wall Only	21.6	21.5	0.1	0.1
San Diego #6	Living	OITC	Exterior Wall and Roof	19.5	19.8	0.3	0.2
		SAN	Exterior Wall and Roof	20.2	20.7	0.5	0.4
					Average	**0.3**	**0.2**

Note: SAN reference spectrum refers to the average flyover spectrum measured at the home.

4.3.4 Measurement of Exterior Wall and Roof vs. Exterior Wall Only

Aircraft noise enters into a residence via the building envelope. This includes the exterior wall and roof-ceiling assembly. While windows are typically the main path for noise intrusion, the roof-ceiling assembly contributes to noise intrusion and attic insulation or other roof-ceiling treatments are included as a part of the sound insulation treatment package.

Measurements of noise reduction were made following two methods: (1) making an exterior spatial measurement of the wall and roof-ceiling assembly and (2) making a spatial measurement of just the exterior wall. The resultant difference in noise reduction is presented in Table 4-13.

Conclusion: The noise reduction decreased by 0.8 dB when the exterior measurement included the roof.

Table 4-13. Exterior elevated loudspeaker, comparison of wall/roof and wall only measurement.

Residence	Room	Reference Spectrum	Description	NLR (dB)
San Diego #6	Living	OITC	Exterior Wall and Roof	19.7
			Exterior Wall Only	20.6
			Difference	-0.9
		SAN	Exterior Wall and Roof	20.5
			Exterior Wall Only	21.6
			Difference	-1.1
	Dining	OITC	Exterior Wall and Roof	22.0
			Exterior Wall Only	22.7
			Difference	-0.7
		SAN	Exterior Wall and Roof	23.3
			Exterior Wall Only	24.0
			Difference	-0.7

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Table 4-13. (Continued).

Residence	Room	Reference Spectrum	Description	NLR (dB)
San Diego #7	Family	OITC	Exterior Wall and Roof	25.2
			Exterior Wall Only	25.3
			Difference	-0.1
		SAN	Exterior Wall and Roof	25.4
			Exterior Wall Only	25.7
			Difference	-0.3
	Living	OITC	Exterior Wall and Roof	23.1
			Exterior Wall Only	23.7
			Difference	-0.6
		SAN	Exterior Wall and Roof	23.4
			Exterior Wall Only	24.2
			Difference	-0.8
San Diego #8	Dining	OITC	Exterior Wall and Roof	18.7
			Exterior Wall Only	20.1
			Difference	-1.4
		SAN	Exterior Wall and Roof	19.2
			Exterior Wall Only	20.6
			Difference	-1.4
	Master Bedroom	OITC	Exterior Wall and Roof	27.1
			Exterior Wall Only	28.4
			Difference	-1.3
		SAN	Exterior Wall and Roof	27.8
			Exterior Wall Only	29.3
			Difference	-1.5
San Diego #10	Bedroom 1	OITC	Exterior Wall and Roof	19.2
			Exterior Wall Only	19.6
			Difference	-0.4
		SAN	Exterior Wall and Roof	18.6
			Exterior Wall Only	19.1
			Difference	-0.5
	Bedroom 2	OITC	Exterior Wall and Roof	25.5
			Exterior Wall Only	26.3
			Difference	-0.8
		SAN	Exterior Wall and Roof	24.9
			Exterior Wall Only	25.6
			Difference	-0.7
Average Difference		**OITC**		**-0.8**
		SAN		**-0.9**
		Overall		**-0.8**
Standard Deviation		**OITC**		**0.4**
		SAN		**0.4**
		Overall		**0.4**

Note: SAN reference spectrum refers to the average flyover spectrum measured at the home.

4.4 Interior Loudspeaker

The interior loudspeaker measurement method was created by one acoustical consultant working on airport sound insulation programs. This method has been employed at a few airport sound insulation programs, and the research team understands that the local FAA representatives overseeing those airport sound insulation programs approved the measurement method. However, this method is not addressed in ASTM E966 or other national or international standards. The advantage to the interior loudspeaker method is twofold: (1) there are no loudspeaker location logistical issues as there can be with the exterior loudspeaker methods and (2) noise generated by the loudspeaker does not disturb adjacent residents (except when testing multi-family units).

The interior loudspeaker method involves locating a loudspeaker inside of the room under test and conducting measurements of the reverberant sound field inside of the room and at the exterior of the room's façade. Section 4.4.1 describes the measurement procedure in detail.

There is a significant flaw in the interior loudspeaker method. If a façade were comprised of a single building assembly (e.g., wall system with no doors or windows) exterior sound measured from this uniformly radiating surface would decrease minimally close to the façade and then more rapidly with increased distance. The nonlinear rate of sound reduction with distance from a uniformly radiating rectangular plane depends upon the dimensions of the plane (Rathe, 1969; Bies and Hansen, 2003). The measurement issue becomes more complex with a multi-element façade with multiple radiating planes of varying dimensions.

Summary: The research team conducted interior loudspeaker measurements at 10 homes in San Diego. In Boston, the research team conducted interior loudspeaker measurements in nine homes, but aircraft flyover noise spectrum was only available in four out of the nine homes. The conclusions are as follows:

- On average, the calculated noise reduction using the OITC spectrum was slightly lower (0.9 dB) than that calculated using the flyover spectrum.
- The noise reduction varied by less than 1 dB when measurements were repeated.
- The noise reduction increased when the wall and roof were measured. This is opposite of what happened when the loudspeaker was located outside of the building.

4.4.1 Measurement Procedure

The interior loudspeaker noise reduction measurement was conducted as follows:

1. A loudspeaker capable of generating 90 to 100 dB at a distance of 9.1 m (30 feet) was placed inside of the room under test. The loudspeaker was pointed toward an interior room corner (i.e., not towards the façade) so as to generate a diffuse sound field inside of the room.
2. Ambient (background) noise measurements were conducted inside and outside of the room under test. The ambient measurement allows the technician to verify that the noise generated by the loudspeaker was sufficiently above the ambient noise level; corrections to the measurement were made if the ambient noise level approached the level of the loudspeaker. This ensured that noise reduction was accurately measured and quantified.
3. Pink noise was generated by the loudspeaker. A measurement of the reverberant sound field inside the room under test was made. This measurement consisted of a spatial average of the noise levels in the room. The engineer maintained a minimum distance of 0.3 to 0.6 meters (1 to 2 feet) between the microphone and walls, ceilings, floors, and loudspeaker.
4. A measurement of the loudspeaker-generated pink noise was then made at the exterior of the façade of the room under test. The microphone was held a distance of 1 to 2 meters (3 to 6 feet) off the façade and a spatial average was conducted.
5. The one-third octave measurement data (50 Hz to 5 kHz) was then analyzed in a spreadsheet, where the exterior pink noise level was subtracted from the interior pink noise level. Three

corrections were then applied: (1) the subtraction of ambient noise, (2) a 5 dB correction to account for reverberant build-up in the source room, and (3) a correction to account for the different frequency spectrum of an aircraft as compared to pink noise. These corrections are discussed in more detail in the following section.

4.4.2 Data Analysis and Correction Factors

The interior loudspeaker noise reduction measurement employs the same ambient correction and data analysis procedure as the exterior loudspeaker methods. These procedures are outlined in Section 4.2.2.

4.4.2.1 Spectral Correction

Similar to the exterior loudspeaker methods, the research team has analyzed the difference in measured noise reduction using the OITC and the average aircraft spectrum measured at each test home. Table 4-14 shows the noise reduction calculated using both of these frequency spectra.

Table 4-14. Interior loudspeaker, comparison of exterior noise spectra.

Residence	Room	Reference Spectrum	NLR (dB)
San Diego #1	Living	SAN	24.3
		OITC	22.4
		Difference	1.9
	Dining	SAN	25.2
		OITC	22.4
		Difference	2.8
San Diego #2	Living	SAN	23.2
		OITC	22.0
		Difference	1.2
	Office	SAN	22.8
		OITC	21.7
		Difference	1.1
San Diego #3	Living	SAN	23.9
		OITC	23.2
		Difference	0.7
	Master Bedroom	SAN	25.0
		OITC	23.9
		Difference	1.1
San Diego #4	Living	SAN	22.6
		OITC	20.5
		Difference	2.1
	Bedroom 1	SAN	26.9
		OITC	24.8
		Difference	2.1
San Diego #5	Living	SAN	23.6
		OITC	22.9
		Difference	0.7
	Bedroom 1	SAN	35.5
		OITC	32.6
		Difference	2.9
San Diego #6	Living	SAN	23.1
		OITC	22.2
		Difference	0.9

Table 4-14. (Continued).

Residence	Room	Reference Spectrum	NLR (dB)
San Diego #6	Dining	SAN	26.1
		OITC	24.2
		Difference	1.9
San Diego #7	Family	SAN	22.8
		OITC	22.5
		Difference	0.3
	Living	SAN	18.5
		OITC	18.5
		Difference	0.0
San Diego #8	Dining	SAN	20.9
		OITC	20.3
		Difference	0.6
	Master Bedroom	SAN	27.3
		OITC	27.0
		Difference	0.3
San Diego #9	Living	SAN	21.8
		OITC	20.7
		Difference	1.1
	Bedroom 1	SAN	27.6
		OITC	26.1
		Difference	1.5
San Diego #10	Bedroom 1	SAN	23.7
		OITC	22.7
		Difference	1.0
	Bedroom 2	SAN	27.0
		OITC	26.6
		Difference	0.4
Boston #1 (storm windows closed)	Living	BOS	27.7
		OITC	27.4
		Difference	0.3
	Bedroom 2	BOS	27.5
		OITC	27.8
		Difference	-0.3
Boston #3 (storm windows closed)	Living	BOS	23.2
		OITC	23.2
		Difference	0.0
	Bedroom 1	BOS	28.3
		OITC	26.8
		Difference	1.5
Boston #6 (storm windows open)	Dining	BOS	25.0
		OITC	27.1
		Difference	-2.1
	Bedroom 2	BOS	26.9
		OITC	28.3
		Difference	-1.4
Boston #8 (storm windows open)	Living	BOS	27.7
		OITC	25.9
		Difference	1.8
	Study	BOS	23.7
		OITC	23.4
		Difference	0.3
		Average Difference (OITC – Flyover)	**0.9**
		Standard Deviation	**1.1**

Note: SAN and BOS reference spectrum refers to the average flyover spectrum measured at the home.

For the San Diego measurements, interior loudspeaker measurements were conducted in ten homes. In Boston, interior loudspeaker measurements were conducted in nine homes, but aircraft flyover noise spectrum was only available in four out of the nine homes.

Conclusion: On average, the calculated noise reduction using the OITC spectrum was slightly lower (0.9 dB) than that calculated using the flyover spectrum.

4.4.3 Repeatability

At one of the test homes, the research team repeated the ground-level loudspeaker measurement with no change in loudspeaker position to determine whether the results changed from test to test. The goal was to determine whether the measurement engineer could induce significant variation in the test results. Table 4-15 summarizes the findings.

Conclusion: The noise reduction varied by less than 1 dB when measurements were repeated.

4.4.4 Measurement of Exterior Wall and Roof vs. Exterior Wall Only

Similar to the exterior loudspeaker methods, the research team conducted measurements of noise reduction using two methods: (1) making an exterior spatial measurement of the wall and roof-ceiling assembly, and (2) making a spatial measurement of just the exterior wall. The resultant difference in noise reduction is presented in Table 4-16.

Conclusion: The noise reduction increased when the wall and roof were measured. This is opposite of what happened when the loudspeaker was located outside of the building.

4.5 Architectural Survey and NLR Computation

It is not always feasible to measure the noise reduction of each habitable room in a residence, nor to acoustically test every residence potentially eligible for sound insulation. However, there are acoustical calculation methods available to estimate the NLR of a room/home. These calculation

Table 4-15. Interior loudspeaker, repeatability of measurement.

Residence	Room	Ref. Spectrum	Description	Measured NLR (dB) Msmt. 1	Msmt. 2	Difference	Standard Deviation
San Diego #1	Living Room	OITC	Exterior Wall Only	22.5	22.2	0.3	0.2
		SAN	Exterior Wall Only	24.5	24.0	0.5	0.4
San Diego #6	Living Room	OITC	Wall and Roof	22.3	22.9	0.6	0.4
		SAN	Wall and Roof	23.7	23.3	0.4	0.3
	Dining Room	OITC	Wall and Roof	24.3	25.3	1.0	0.7
		SAN	Wall and Roof	26.9	26.7	0.2	0.1
San Diego #4	Living Room	OITC	Exterior Wall Only	20.8	20.2	0.6	0.4
		SAN	Exterior Wall Only	22.8	22.3	0.5	0.4
	Bedroom 1	OITC	Exterior Wall Only	24.6	24.9	0.3	0.2
		SAN	Exterior Wall Only	26.7	27.1	0.4	0.3
					Average	**0.5**	**0.3**

Note: SAN reference spectrum refers to the average flyover spectrum measured at the home.

Table 4-16. Interior loudspeaker, comparison of wall/roof and wall only measurement.

Residence	Room	Ref. Spectrum	Description	NLR (dB)
San Diego #6	Living	OITC	Exterior Wall and Roof	22.6
			Exterior Wall Only	20.2
			Difference	2.4
		SAN	Exterior Wall and Roof	23.5
			Exterior Wall Only	20.8
			Difference	2.7
	Dining	OITC	Exterior Wall and Roof	24.8
			Exterior Wall Only	22.3
			Difference	2.5
		SAN	Exterior Wall and Roof	26.8
			Exterior Wall Only	23.7
			Difference	3.1
San Diego #7	Living	OITC	Exterior Wall and Roof	20.1
			Exterior Wall Only	16.8
			Difference	3.3
		SAN	Exterior Wall and Roof	20.0
			Exterior Wall Only	16.9
			Difference	3.1
San Diego #8	Dining	OITC	Exterior Wall and Roof	21.3
			Exterior Wall Only	19.3
			Difference	2.0
		SAN	Exterior Wall and Roof	21.9
			Exterior Wall Only	19.9
			Difference	2.0
	Master Bedroom	OITC	Exterior Wall and Roof	31.8
			Exterior Wall Only	30.2
			Difference	1.6
		SAN	Exterior Wall and Roof	32.6
			Exterior Wall Only	31.0
			Difference	1.6
San Diego #10	Bedroom 1	OITC	Exterior Wall and Roof	23.0
			Exterior Wall Only	22.4
			Difference	0.6
		SAN	Exterior Wall and Roof	24.0
			Exterior Wall Only	23.3
			Difference	0.7
Average Difference			**OITC**	**2.1**
			SAN	**2.2**
			Overall	**2.1**
Standard Deviation			**OITC**	**0.9**
			SAN	**1.0**
			Overall	**0.9**

Note: SAN reference spectrum refers to the average flyover spectrum measured at the home.

methods are used extensively during the design process of new buildings, and the results are used to inform the architect of the required TL performance of the building envelope components (e.g., windows, doors).

In general, the acoustical calculation methods utilize a library of TL data for typical building components. This performance data comes from a variety of sources, as summarized below:

- Exterior walls: National Research Council of Canada, California Office of Noise Control.
- Windows: National Research Council of Canada, window vendors, glazing manufacturers (glass only).
- Doors: National Research Council of Canada, door vendors.
- Roof-Ceiling Assemblies: National Research Council of Canada, roofing manufacturers (limited).

In order to accurately calculate noise reduction, an architectural survey must be conducted. Section 4.5.1 summarizes the components of an architectural survey.

4.5.1 Architectural Survey

The goal of the architectural survey is to catalog the pertinent details of the building envelope to inform the calculation procedure. The façade and room elements are inspected and pertinent details are logged. The following summarizes the types of data gathered:

- Exterior Wall
  - Wall type: brick, stud, concrete masonry unit.
  - Stud thickness and presence/type of wall insulation.
  - Exterior sheathing type: vinyl siding, wood siding, stucco, brick, etc.
  - Interior sheathing type and thickness: gypsum board, tongue-and-groove, etc.
- Windows
  - Dimensions.
  - Frame material: aluminum, vinyl, wood, etc.
  - Glazing configuration: thickness of panes, air space between panes, laminated or float.
  - Condition of window: leaky, average, good.
  - Operation type: double-hung, horizontal sliding, casement, fixed, etc.
- Doors (including storm doors)
  - Dimensions.
  - Material: wood, fiberglass, metal, etc.
  - Glazing: size, type, thickness of lites, airspace between lites.
  - Gasketing: type, material, condition, quality of seal (credit card test).
  - Door bottom: type, material, condition, quality of seal (credit card test).
- Roof-Ceiling Assembly
  - Type: flat, pitched (e.g., gable, hip), etc.
  - Roof material: asphalt shingle, tile, tar-and-gravel, etc.
  - Attic insulation: thickness, type.
  - Roof vents: type, quantity.
- Room Details
  - Dimensions.
  - Floor type: carpet, hardwood, tile, etc.
  - Wall type: gypsum board, etc.
  - Ceiling: type (flat or vaulted), material.
  - Furnishings: sofas, beds, bookshelves, entertainment center, etc.

The data from the architectural survey is then input into software or a spreadsheet to calculate the noise reduction of the room.

4.5.2 Acoustical Calculation Procedure

In order to calculate the noise reduction of a room, there are three primary steps: (1) determine the TL of each element, (2) calculate the CTL of all elements, and 3) convert TL to noise reduction. For the first step, the engineer must first determine the transmission of each building element. This is accomplished by selecting the laboratory TL of the building element most similar to that of the room being calculated. This requires information from the architectural survey and the use of engineering judgment, as often the building element encountered in the field does not perfectly match the available laboratory TL data.

In addition, for elements that are degraded (e.g., leaky windows, poor door weather stripping), a correction must be applied to account for this less-than-ideal condition (as laboratory TL data is based upon perfect conditions).

After the laboratory data has been selected for each building element, the CTL of the room must be calculated. This is accomplished using a logarithmic formula (shown below), which takes into account the surface area of each building element and its TL performance. In general, the building element with the most surface area will control the CTL; however, since the calculation (and the decibel scale) is logarithmic, the CTL can be significantly degraded by a building element with low TL.

$$\text{Transmission coefficient } \tau_{avg} = \frac{\sum_{i=1}^{n} Si * \tau i}{\sum_{i=1}^{n} Si}$$

$$\text{where } \tau = 10^{\left(-\frac{TL}{10}\right)}$$

$$\text{then composite transmission loss CTL} = 10 \log_{10}\left(\frac{1}{\tau avg}\right)$$

The final step in the acoustical calculation process is to convert TL into noise reduction. This consists of making a correction for room factor, which is the amount of acoustically absorptive material in a room. Section 4.1.3 of this report provides more information on the effect of absorptive materials on noise reduction. In general, the more acoustically absorptive material in a room, the higher the NLR will be. The research team performed reverberation time (RT_{60}) measurements in every tested room. The research team measured reverberation time data to convert TL data to noise reduction using the following formulas:

$$NR = CTL - 10 \log\left(\frac{S}{A}\right)$$

where

NR = Noise reduction (dB), usually A-weighted
CTL = Composite Transmission Loss (dB)
S = area of the transmitting surface(s) (m^2 or ft^2)
A = absorption, $k \times \left(\frac{room\ volume}{RT_{60}}\right)$ per ⅓ octave band from 80 Hz to 5 kHz (Sabine), where $k = 0.049$ in Imperial units, and $k = 0.161$ in International System (SI) units.

For every room acoustically tested, an architectural survey was conducted and noise reduction calculations were performed using two models: IBANA-Calc and a spreadsheet using the reverberation formula and the CTL formulas shown above.

4.5.2.1 IBANA Calculation Model

The first model employed was the IBANA (Insulating Buildings Against Noise from Aircraft) software, which was created by the National Research Council Canada. This model employs a graphical user interface and requires the user to input the following:

- Source spectrum (in one-third octave bands) and exterior noise level (see Figure 4-5); default spectra include:
  - Standard aircraft.
  - Canadian Mortgage Housing Corporation (CMHC) reference source.
  - OITC reference source.
  - Chapter (Stage) 2 jets.
  - Chapter (Stage) 3 jets.
  - Helicopters.
  - Custom spectrum can be added by the user.
- Floor area (m^2 or ft^2).
- Acoustical absorption as a percentage of floor area.
- Surface area and TL of building elements (see Figure 4-6); the software includes transmission loss data for:
  - 2 × 4 stud exterior walls.
  - 2 × 6 stud exterior walls (with and without resilient channels).
  - Staggered stud exterior walls (with and without resilient channels).
  - Doors.
  - Glazing and windows.
  - Wood joist roofs.
  - Wood truss roofs.
  - Raised heel wood truss roofs (with and without vents).
  - Steel deck roofs.
  - Custom building elements can be added by the user.

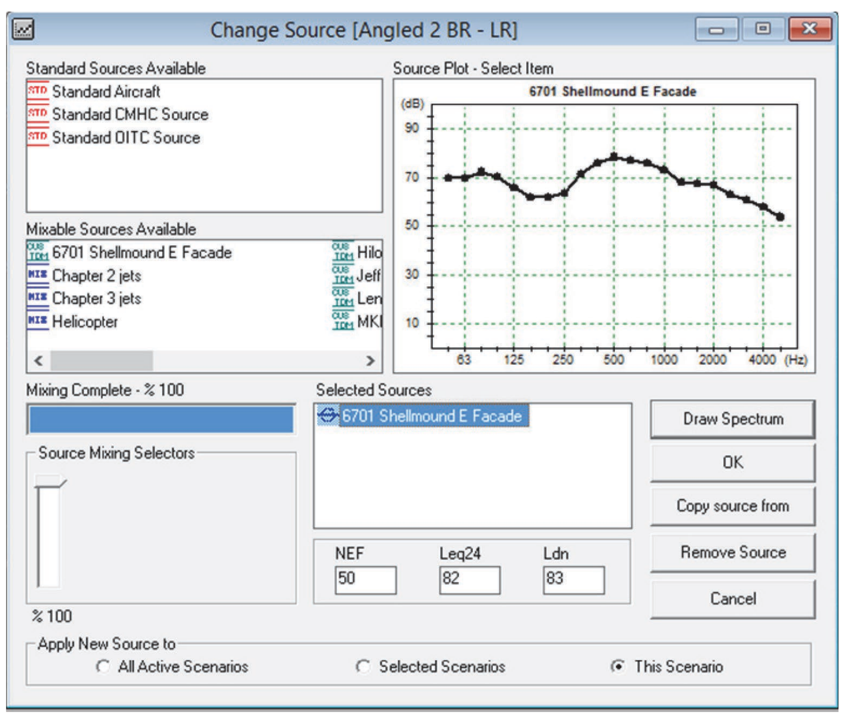

Figure 4-5. IBANA source spectrum selection screen.

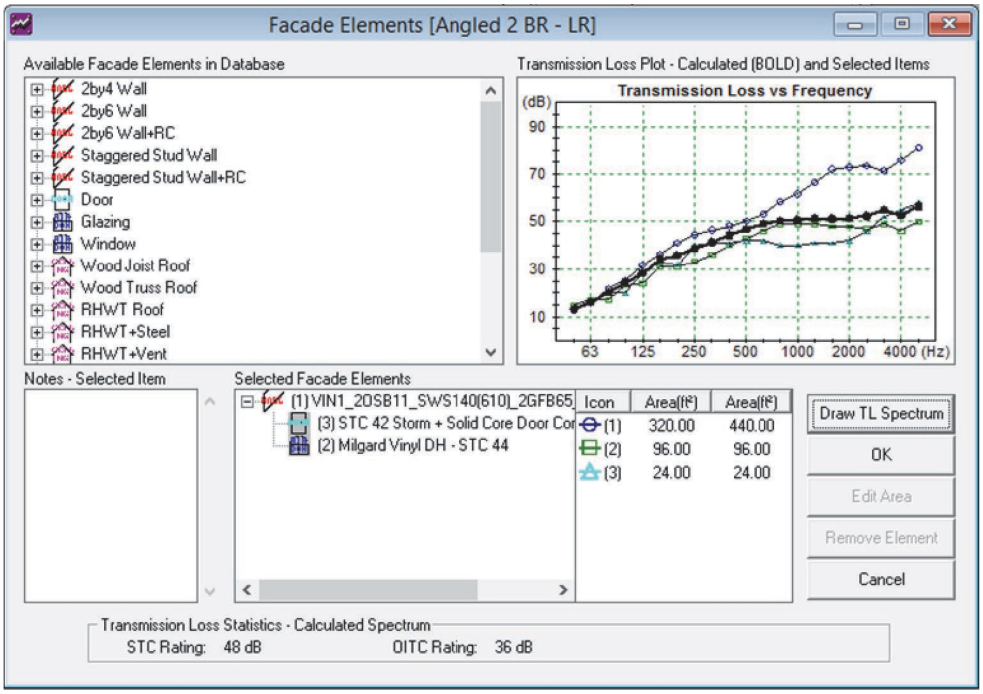

Figure 4-6. IBANA building element input screen.

- Optional correction factors (not used):
  - Air absorption.
  - Vertical angle of incidence.
  - Horizontal angle of incidence.
  - Horizontal angle of view.
  - Ground reflection.

For each set of inputs, a scenario is created. The user is able to name the scenario to allow for tracking of multiple scenarios. The composite noise reduction and resultant interior noise level is calculated by IBANA for each scenario (Figure 4-7).

4.5.2.2 Spreadsheet Calculation Model

The research team created a spreadsheet incorporating the CTL formula shown in Section 4.5.2. For each tested room, the research team input the surface area of each building element and used the same TL values as used in the IBANA modeling. This yielded a composite (or average) TL for each tested room. The research team then used the reverberation time formula contained in Section 4.5.2 to convert the CTL into composite noise reduction.

Figure 4-8 shows a sample calculation spreadsheet.

4.5.3 NLR Calculation Results

The research team calculated the noise reduction of each room that was acoustically tested. Table 4-17 summarizes the results of the calculations and compares them to the loudspeaker and flyover measurement results. Specifically, the average NLR was computed for each NLR testing method, and variation in results from that average was computed for each method. The research team found the following from this comparison:

- The NLR calculations generally agreed with the measurement findings.
- There were some outliers in the NLR calculations, which increased the standard deviation.

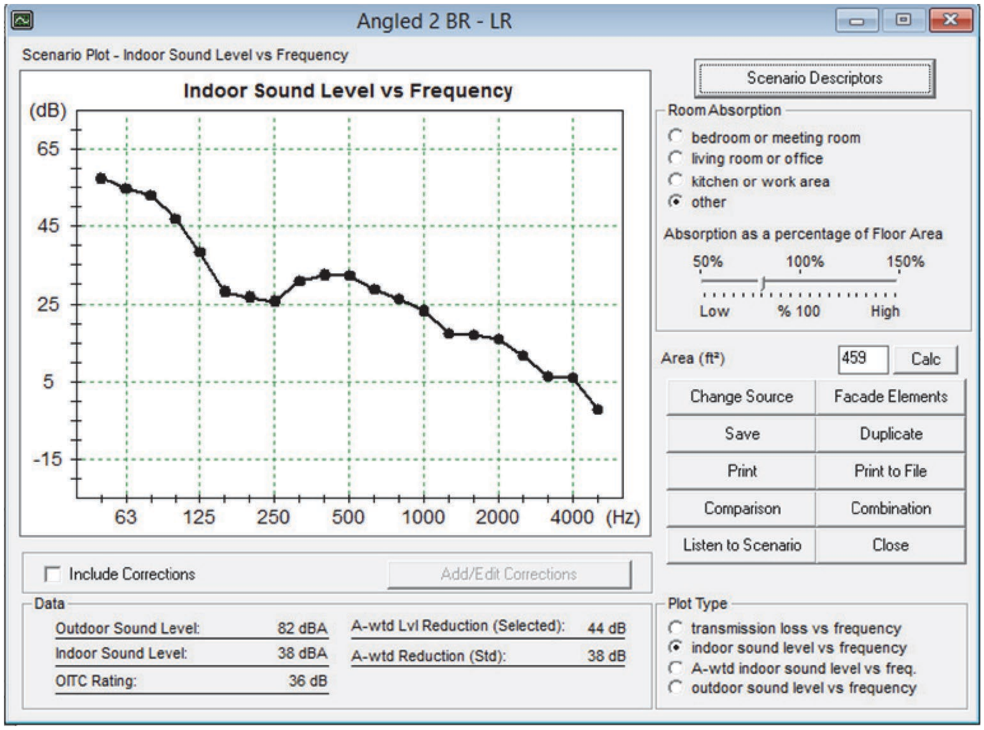

Figure 4-7. IBANA calculation results screen.

- It is important that the field survey be very detailed so the calculations are accurate; even then, it is possible to miss flanking paths (noise leaks) that would overstate the calculated NLR.
- The IBANA computation method was preferable to the spreadsheet method because of the database and other factors incorporated.

4.6 Air Infiltration and Noise Reduction

As a part of the field measurements in San Diego and Boston, the research team conducted air infiltration (blower door) measurements at most of the homes. The purpose of this testing was to determine whether there was a correlation between air infiltration and façade noise reduction as, in theory, higher infiltration values should correspond to lower noise reduction (i.e., the leakier the façade, the more paths for noise to enter the residence).

Summary:

- A comparison of air infiltration to measured noise reduction was made for homes where flyover and loudspeaker noise reduction was measured.
- Based on published data, the research team would expect lower noise reduction when air infiltration was high (i.e., leakier homes allowed more noise intrusion).
- The research team found that higher measured air infiltration with the blower door test did not correspond to lower NLR.

4.6.1 Measurement Procedure

At ten homes in San Diego and five homes in Boston, air infiltration tests were conducted in rooms where acoustical testing took place. The air infiltration tests were conducted per ASTM E-779-10; a brief description of the measurement procedure follows:

1. A blower door fan was set up in the doorway of the room to be tested. If there were doorways or openings to other rooms (e.g., a bathroom), this door/opening was sealed airtight. See Figure 4-9.

ACRP 02-51: 1350 29th Street Noise Reduction Calculation
Calc by GB on 10/23/2014

LIVING ROOM

	80	100	125	160	200	250	315	400	500	630	800	1k	1.25k	1.6k	2k	2.5k	3.15k	4k	5k	Leq(A)	Ldn	% Area	Dimension	Factors	STC	Description
																						100.0%	total area			
OITC Curve	**103.0**	**102.0**	**101.0**	**98.0**	**97.0**	**95.0**	**94.0**	**93.0**	**93.0**	**91.0**	**90.0**	**89.0**	**89.0**	**88.0**	**88.0**	**87.0**	**85.0**	**84.0**	**83.0**	**100.2**						
DNL at Residence																					65					
Exterior Noise Level (OITC Spectra)	67.8	66.8	65.8	62.8	61.8	59.8	58.8	57.8	57.8	55.8	54.8	53.8	53.8	52.8	52.8	51.8	49.8	48.8	47.8	**65.0**						
Transmission Loss Data for Windows	**14**	**21**	**19**	**20**	**21**	**22**	**23**	**23**	**25**	**28**	**29**	**31**	**32**	**33**	**35**	**35**	**33**	**25**	**28**			**5.7%**	11'-0" x 4'-0"		**29**	**1/8" Saflex**
Transmission Loss Data for Exterior Doors	**14**	**11**	**13**	**14**	**14**	**15**	**15**	**16**	**16**	**17**	**17**	**17**	**17**	**18**	**18**	**17**	**19**	**20**	**19**			**2.6%**	3'-0" x 6'-8"		**17**	**Solid core wood door, no seals**
Transmission Loss Data for Exterior Wall	**8**	**11**	**14**	**16**	**21**	**27**	**30**	**33**	**36**	**40**	**43**	**45**	**46**	**44**	**38**	**38**	**42**	**46**	**49**			**32.5%**	37'-1" x 9'-0"		**36**	**Wood shingle siding, plywood, 2x4, GWB**
Transmission Loss for Roof	**20**	**23**	**25**	**28**	**30**	**32**	**32**	**32**	**34**	**38**	**40**	**42**	**44**	**47**	**47**	**44**	**44**	**48**	**53**			**56.5%**	25'-5" x 17'-1"		**40**	**Asph. shingles, plywood, truss, GWB, vents**
Transmission Loss for 3/16" Float Glazing	**19**	**27**	**25**	**22**	**23**	**24**	**26**	**26**	**29**	**30**	**32**	**33**	**35**	**35**	**33**	**27**	**28**	**33**	**37**			**2.6%**	5'-0" x 4'-0"		**31**	**3/16" Saflex float glazing**
Reverberation times	**0.30**	**0.35**	**0.25**	**0.37**	**0.32**	**0.37**	**0.32**	**0.35**	**0.36**	**0.31**	**0.32**	**0.29**	**0.29**	**0.29**	**0.29**	**0.28**	**0.29**	**0.29**	**0.28**							
Approximate room volume																							**3909**			
Exterior window/wall/roof partition area (S)																							**768.24**			
Absorption (A)	638.5	550.4	778.6	520.5	596.7	517.7	594.9	548.8	539.6	613.9	600.5	653.7	662.8	665.1	658.2	681.7	658.2	662.8	681.7							
10*log(S/A)	0.8	1.4	-0.1	1.7	1.1	1.7	1.1	1.5	1.5	1.0	1.1	0.7	0.6	0.6	0.7	0.5	0.7	0.6	0.5							
Estimated composite transmission loss	12	15	18	20	23	26	27	28	29	31	32	32	32	33	33	31	33	33	33							
Estimated composite noise reduction	11	13	18	18	22	25	26	27	28	30	31	31	31	33	32	31	33	33	33							
Calculated Interior Noise Levels	56.4	53.6	48.0	44.8	39.6	35.0	32.6	31.2	30.2	25.6	24.1	22.8	22.5	20.2	20.7	20.9	17.0	16.0	14.9							
Safety factor																								0		
Interior DNL																					40.9					
Noise Reduction																					24.1					

DINING ROOM

	80	100	125	160	200	250	315	400	500	630	800	1k	1.25k	1.6k	2k	2.5k	3.15k	4k	5k	Leq(A)	Ldn	% Area	Dimension	Factors	STC	Description
																						100.0%				
OITC Curve	**103.0**	**102.0**	**101.0**	**98.0**	**97.0**	**95.0**	**94.0**	**93.0**	**93.0**	**91.0**	**90.0**	**89.0**	**89.0**	**88.0**	**88.0**	**87.0**	**85.0**	**84.0**	**83.0**	**100.2**						
DNL at Residence																					65					
Exterior Noise Level (OITC Spectra)	67.8	66.8	65.8	62.8	61.8	59.8	58.8	57.8	57.8	55.8	54.8	53.8	53.8	52.8	52.8	51.8	49.8	48.8	47.8	**65.0**						
Transmission Loss Data for Windows	**14**	**21**	**19**	**20**	**21**	**22**	**23**	**23**	**25**	**28**	**29**	**31**	**32**	**33**	**35**	**35**	**33**	**25**	**28**			**9.2%**	12'-3" x 4'-0"		**29**	**1/8" Saflex**
Transmission Loss Data for Exterior Doors	**14**	**11**	**13**	**14**	**14**	**15**	**15**	**16**	**16**	**17**	**17**	**17**	**17**	**18**	**18**	**17**	**19**	**20**	**19**			**0.0%**				
Transmission Loss Data for Exterior Wall	**8**	**11**	**14**	**16**	**21**	**27**	**30**	**33**	**36**	**40**	**43**	**45**	**46**	**44**	**38**	**38**	**42**	**46**	**49**			**44.2%**	31'-6" x 9'0"		**36**	**Wood shingle siding, plywood, 2x4, GWB**
Transmission Loss for Roof	**20**	**23**	**25**	**28**	**30**	**32**	**32**	**32**	**34**	**38**	**40**	**42**	**44**	**47**	**47**	**44**	**44**	**48**	**53**			**46.6%**	16'-10" x 14'-8"		**40**	**Asph. shingles, plywood, truss, GWB, vents**
Transmission Loss for ???	**19**	**27**	**25**	**22**	**23**	**24**	**26**	**26**	**29**	**30**	**32**	**33**	**35**	**35**	**33**	**27**	**28**	**33**	**37**			**0.0%**				
Reverberation times	**0.30**	**0.20**	**0.37**	**0.42**	**0.41**	**0.39**	**0.39**	**0.39**	**0.43**	**0.34**	**0.30**	**0.33**	**0.34**	**0.33**	**0.33**	**0.34**	**0.32**	**0.33**	**0.33**							
Approximate room volume																							**2223**			
Exterior window/wall/roof partition area (S)																							**530.46**			
Absorption (A)	363.0	539.2	295.1	259.3	266.3	277.1	281.4	280.7	253.3	324.1	358.3	326.1	319.4	326.1	331.0	325.1	342.5	333.1	328.0							
10*log(S/A)	1.6	-0.1	2.5	3.1	3.0	2.8	2.8	2.8	3.2	2.1	1.7	2.1	2.2	2.1	2.0	2.1	1.9	2.0	2.1							
Estimated composite transmission loss	11	14	17	19	23	28	29	30	32	36	37	39	41	41	40	39	40	35	38							
Estimated composite noise reduction	9	14	14	16	20	25	26	27	29	34	36	37	38	39	38	37	38	33	36							
Calculated Interior Noise Levels	58.4	53.0	51.4	46.9	41.5	35.1	32.3	30.3	28.7	22.1	19.1	16.6	15.5	13.6	15.2	14.6	11.3	15.7	11.8							
Safety factor																								0		
Interior DNL																					41.8					
Noise Reduction																					23.2					

Figure 4-8. TL calculation sample spreadsheet.

Table 4-17. Comparison of NLR calculations to acoustical measurements.

Residence	Room	Average NLR (no int. spkr.)	Flyover	Diff. from Avg NLR	Elevated Loudspeaker	Diff. from Avg NLR	Ground Loudspeaker	Diff. from Avg NLR	Interior Loudspeaker	Diff. from Avg NLR	Spreadsheet	Diff. from Avg NLR	IBANA	Diff. from Avg NLR
San Diego #1	Living	26.2	26.3	-0.1			24.5	1.7	24.3	2.0	28.1	-1.9	26	0.2
	Dining	26.4	28.0	-1.6			22.2	4.3	25.2	1.2	28.5	-2.1	27	-0.6
San Diego #2	Living	26.1	24.3	1.9			25.2	1.0	23.2	2.9	28.1	-2.0	27	-0.9
	Office	23.3	20.4	2.9			18.4	4.9	22.8	0.5	27.3	-4.0	27	-3.7
San Diego #4	Living	23.4	23.3	0.1			21.6	1.8	22.6	0.8	24.7	-1.3	24	-0.6
	Bedroom 1	26.8	26.4	0.4			25.0	1.8	26.9	-0.1	29.7	-3.0	26	0.8
San Diego #5	Living	25.0	24.0	1.0			21.3	3.7	23.6	1.4	29.8	-4.8	25	0.0
	Bedroom 1	29.0	30.0	-1.1			26.3	2.7	35.5	-6.6	30.5	-1.6	29	-0.1
San Diego #6	Living	21.9	24.9	-3.0	21.0	0.9	20.9	1.0	23.1	-1.2	17.8	4.1	25	-3.1
	Dining	27.5	27.4	0.1	23.7	3.8	26.4	1.1	26.1	1.4	31.0	-3.5	29	-1.5
San Diego #7	Family	26.4	26.5	-0.1	25.6	0.8	25.7	0.7	22.8	3.6	27.2	-0.8	27	-0.6
	Living	25.1	25.1	0.0	23.8	1.3	24.6	0.5	18.5	6.7	27.5	-2.4	24	1.1
San Diego #8	Dining	21.2	19.4	1.9	19.9	1.3	19.6	1.7	20.9	0.3	23.3	-2.1	24	-2.8
	Master Bed	26.7	22.2	4.5	28.6	-1.9	28.3	-1.6	27.3	-0.6	27.3	-0.6	27	-0.3
San Diego #9	Living	21.3	21.8	-0.5	19.8	1.5	19.4	1.9	21.8	-0.5	22.3	-1.0	23	-1.7
	Bedroom 1	28.3	31.7	-3.4	26.1	2.2	25.6	2.7	27.6	0.7	30.3	-2.0	28	0.3
San Diego #10	Bedroom 1	20.1	17.5	2.6	18.9	1.2	17.6	2.5	23.7	-3.6	23.5	-3.4	23	-2.9
	Bedroom 2	25.9	25.0	0.9	25.3	0.7	25.1	0.8	27.0	-1.1	28.3	-2.4	26	-0.1
Boston #6	Dining	23.1	20.2	2.9	25.0	-1.9	25.0	-1.9	25.0	-1.9	21.3	1.8	24	-0.9
	Bedroom 2	22.3	22.0	0.3	25.1	-2.8	24.9	-2.6	26.9	-4.6	19.3	3.0	20	2.3
Boston #8	Living	24.8	24.2	0.6	25.0	-0.2	24.8	0.0	27.7	-2.9	25.0	-0.2	25	-0.2
	Study	27.0	29.5	-2.5	26.6	0.4	25.7	1.3	23.7	3.3	26.2	0.8	27	0.0
Average Difference				**0.4**		**0.5**		**1.4**		**0.1**		**-1.3**		**-0.7**
Standard Deviation				**1.9**		**1.7**		**1.8**		**2.9**		**2.1**		**1.4**

Notes:

1) Corrections applied—Flyover: 2 dBA, exterior loudspeaker: 2 dBA, interior loudspeaker: 5 dBA.
2) Average NLR difference calculated by first averaging all of the NLR across all measurement methods (except interior loudspeaker and sound intensity), and then subtracting the NLR from one method (e.g., flyover) from the average NLR. Interior loudspeaker not used in average as this method does not follow national standards and the 5-dB correction applied to the data is based on limited field measurements (i.e., not fully vetted).
3) All differences are calculated by subtracting from the average noise reduction.
4) Blank cells indicate no elevated loudspeaker test was performed at the corresponding residence.

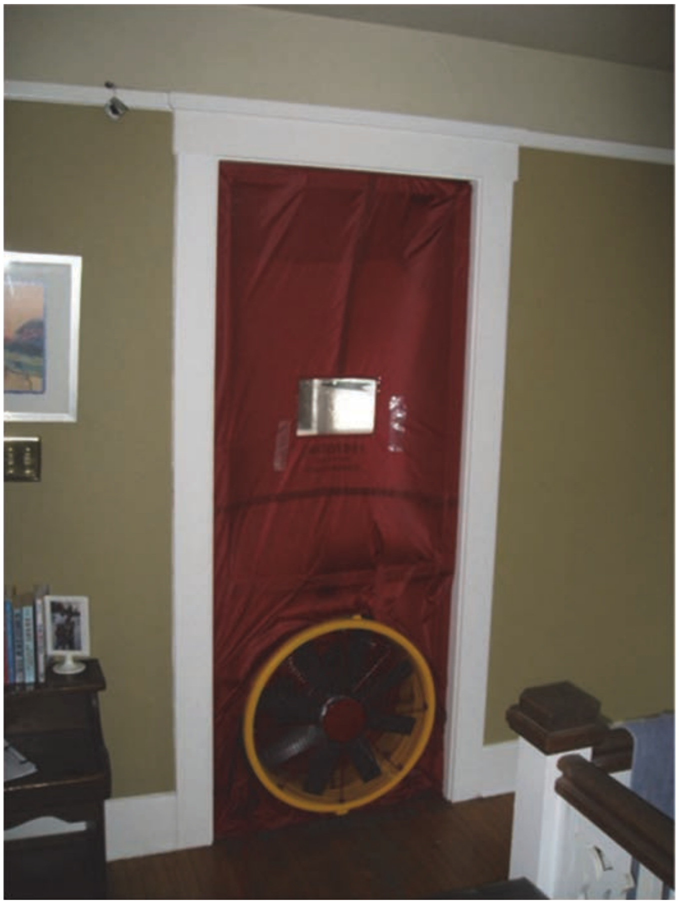

Figure 4-9. Blower door test.

2. The fan was then turned on and either created a positive or negative pressure differential between the room under test and the adjacent spaces (including the outside). Typically, a negative pressure differential was created. The fan was ramped up until there was a pressure difference of 50 Pascals between the room under test and the adjacent spaces.
3. The amount of airflow required to maintain the 50 Pascals was then measured. For this project, multi-point measurements were made, meaning airflow was measured at various pressure differentials to provide for more accurate air infiltration values.

Blower door testing was conducted in most of the rooms acoustically tested; however, there were some instances where it was not appropriate to conduct the blower door measurement. For example, when a living room was acoustically tested, this living room was often open to a dining room and/or kitchen. When the research team acoustically tests this condition, the team is primarily measuring noise entering the living room from the front door and living room windows. However, the air infiltration test is quantifying infiltration from the living room plus the kitchen and/or dining room. Thus, in this case, it would not be reasonable to compare measured air infiltration to noise reduction.

Figure 4-10 shows a sample air infiltration graph.

4.6.2 Comparison of Air Infiltration to Noise Reduction

Figures 4-11 and 4-12 compare the measured air infiltration [in terms of cubic feet per minute (cfm)] to measured façade noise reduction. The research team has included the

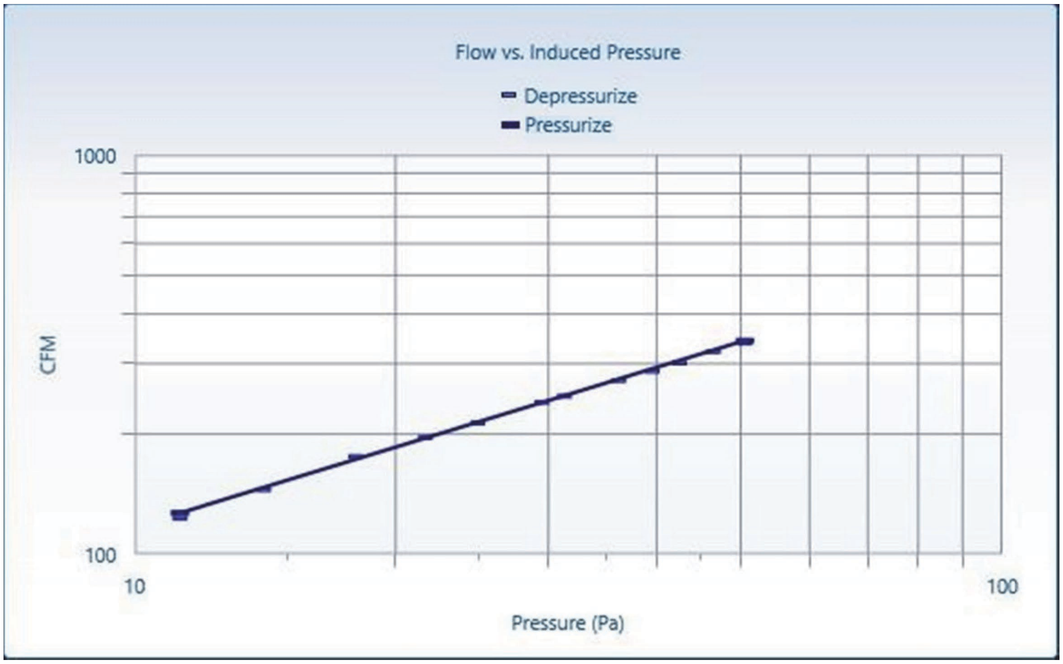

Figure 4-10. Typical air infiltration graph.

measured flyover noise reduction and the noise reduction measured using an exterior loud speaker.

As can also be seen in Figures 4-11 and 4-12, NLR is not correlated to the measured air infiltration. The lack of correlation may be due to the following:

- Air infiltration from interior walls, ceilings, and floors: When an air infiltration test is performed, air can leak into a room via the building façade and interior walls, floors, or ceilings. This would lead to higher infiltration values than infiltration from the façade alone. Unfortunately, it is not feasible with the current testing protocol to only measure infiltration from the façade.
- Some infiltration paths may not be noise paths: leaky doors and windows reduce noise reduction (Sabine et al. 1975); however, infiltration via vents, flues, and other openings may not be a significant path of noise intrusion. For example, a fireplace may allow for significant air infiltration, but not be a significant path of noise when there is a damper and/or solid fireplace doors.

4.7 Sound Intensity

4.7.1 Introduction

Sound intensity is an attractive concept for airport sound insulation programs because it does not require measurement of the reverberant field in the receiving room. Ideally, this would eliminate the errors and anomalies associated with non-uniform reverberant fields and the standing wave effects of reflections from parallel surfaces, as reflections create resonances. Intensity measures both the pressure (a scalar or non-directional parameter) and the velocity (a vector, having both magnitude and direction) of the sound. Therefore, it is theoretically possible to directly measure the intensity or power flow into the receiving room (the room under test). Moreover, in contrast to pressure measurements, intensity measurements made close to room surfaces and with a high enough resolution should reveal hot spots, sound leaks, and other problems, and not just total power flow into the test room.

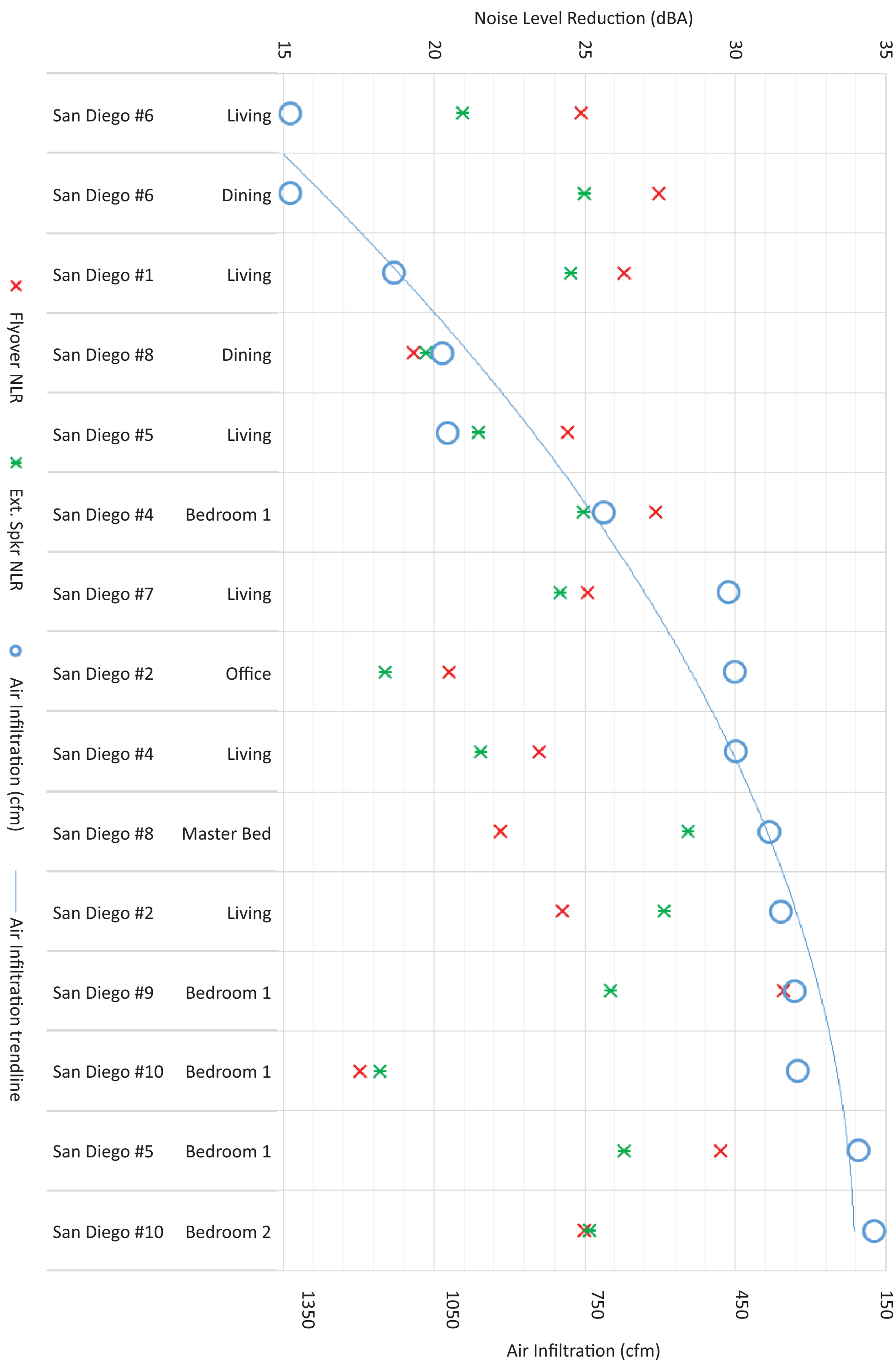

Figure 4-11. San Diego comparison of air infiltration and noise reduction.

82 Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs

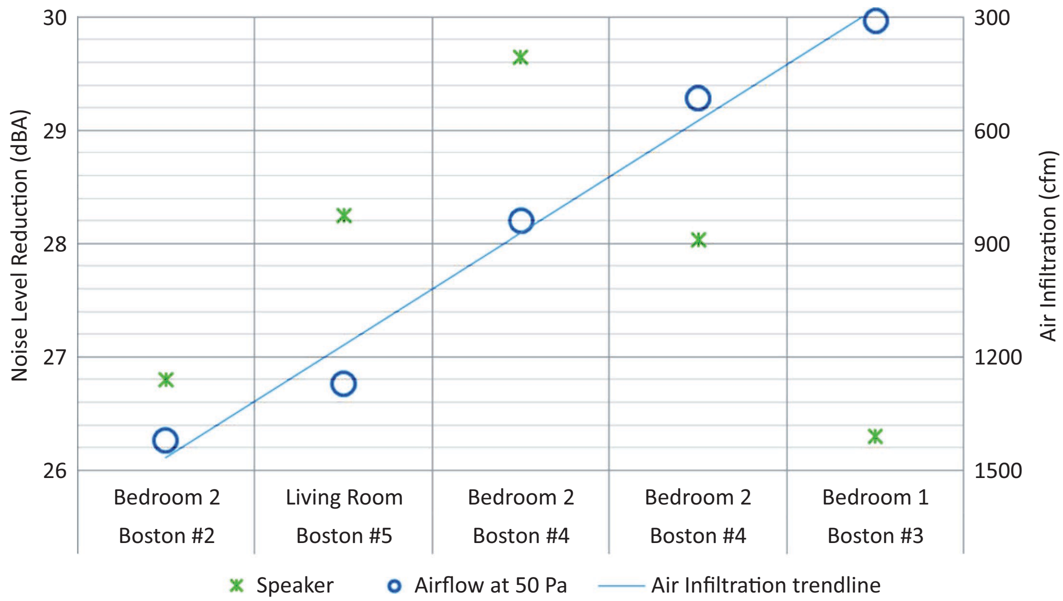

Figure 4-12. Boston comparison of air infiltration to noise reduction.

Summary: The research team conducted sound intensity measurements in five homes within the vicinity of the San Diego International Airport. Additional sound intensity measurements were conducted at a research team member's residence in Champaign, IL, for comparison purposes. The research team took measurements from outdoors to indoors, as well as from indoors to outdoors. The conclusions are as follows:

- Classical acoustic theory presumes that TL is the same in both directions (i.e., a wall performs equally whether the source of noise is inside of a home or outside of a home). Through this study, the research team found this generally to be true.
- In these measurements of the two directions, the research team used the pressure incident on the surface of the source side of the wall and windows rather than positions 0.3 m to 2 m (1 to 6 feet) from the wall surface, and it is believed that the generally equal performance is due to the more equal treatment of the source side measurements.
- The best strategy when conducting sound intensity measurements is to measure as close to the exterior wall as feasible.
- Based on the research team's experience, the technology and time required preclude the use of sound intensity for airport sound insulation programs at this time.
- There are a number of enhancements suggested to provide for better sound intensity results and possibly allow for the use of sound intensity for airport sound insulation programs in the future.
- Sound intensity holds the promise of someday being an extremely effective method because the results are virtually independent of weather effects, the measurements are independent of resonance effects, there are no neighbor noise problems, and nearby reflectors are not a problem.

4.7.2 Purpose

The purpose of the intensity measurements is to see if sound power (i.e., the acoustic intensity over the building element measured) can be used to determine a building envelope's TL and, if so, to gauge the accuracy, complexity, and costs of using sound intensity with respect to conventional sound pressure measurements. One of the most important questions posed about sound intensity measurements is as follows: Does the flow of sound power into or out of a room and its measurement ameliorate the resonance issues that are prevalent with measurements of sound pressure (i.e., the loudspeaker or flyover method). When one uses pressure, measurements from outdoor sources to indoor microphones do not agree well with measurements from indoor sound sources to outdoor microphones; reciprocity does not seem to apply as it should with acoustical theory. This study is concerned with the accurate measurement of the aircraft noise TL from outside to inside residences, and sound intensity measurements were conducted to determine whether they could provide the most accurate TL measurement.

Aircraft noise usually impinges on a residence at an angle, e.g., 45°. With three-dimensional sound intensity, one can measure the angle at which the power is flowing as it travels from outdoors through the building façade into a room.

4.7.3 Background

Acoustic velocity is difficult to measure directly, so a pair of opposing microphones is typically used to approximate the pressure gradient, which is the change in pressure (Δp) with a change in distance (Δx). The original intensity meters, developed in the early 1980's, used a single pair of phase-matched microphones. For middle frequencies (e.g., 100 to 4000 Hz), a 2-cm to 3-cm (0.8 in. to 1.2 in.) space was established between the microphone pair as the distance (Δx). At 100 Hz, a 2.5-cm (1.0 in.) spacing is 1/120 of a wavelength, so the expected change in phase is $(1/120) * 360$ or 3°. Accurate measurement with a resolution of 3° requires that the phase matching be 10 times better than that being measured; in this case, phase matching should be 0.3° or less. A three-dimensional sound intensity system with visualization was used in this study, and the phase error for this assembly is specified as 0.8 dB at 60 Hz and is negligible above 60 Hz.

The configuration of the two microphones in the classical intensity meter form what is called an acoustic dipole (two close acoustic receivers of opposing phase). However, the simple dipole that is formed by the two microphones is rather insensitive to direction. More recently, three pairs of microphones have been used to measure intensity in three dimensions. Nagata et al. (2005) reports on their tests using their three-axis, six-microphone array. Among other things they report and show that they find peaks in a spectrum. This is correct, but they do not find the entire spectrum with sharp resolution; their frequency range is 200 to 2000 Hz.

The latest intensity probes are based on a tetrahedron that uses four phase-matched microphones. In this configuration, there are six unique microphone pairs, with two pairs for each axis. This configuration yields significantly better angular resolution than is given by dipoles. The system's manufacturer reports a resolution of 3 cm to 5 cm (1.2 in. to 1.9 in.) when the camera is positioned at 1.5 m (4.9 ft.) or less. This implies a resolution of at least 5 cm at 1.5 m (1.2 in. at 4.9 ft.), and this indicates an angular resolution of 2°. They also report what is termed "orientation errors" and state that they are less than 10° for the frequency range from 100 to 4000 Hz. Thus, these orientation errors appear to be the limiting factor for angular resolution. The microphone goes one octave higher because with the tetrahedron array, there is a symmetry that permits correction for an error that cannot be done when using six microphones. They achieve the added octave at low frequencies by enhanced phase matching.

The basics of this project's test plan can be summed up in three simple steps:

1. Find and rent equipment,
2. Make measurements, and
3. Analyze the data.

While this plan appears to be straightforward, to obtain the 2.5° resolution specified for this microphone assembly, one has to know the position of the microphone assembly with respect to the object or room under test, and the pitch and yaw of the microphone assembly itself. Since the goal is to gather directional data on sound power flow, it is not sufficient just to know the x, y, and z coordinates of the microphone assembly; one must also know the orientation of the assembly with respect to the source. In this case, the research team needed to know if the assembly was directly facing the wall, pointed up or down, or to the left or right. Pitch is a measure of up or down and yaw is a measure of left or right. This positioning and orientation capability should be at least as precise as the measurements that are being attempted, and preferably by 2 times or more. With the older dipole sensors, this location and orientation were not very significant because they had little directivity. Their resolution capability was about 45° at mid frequencies, poorer at lower frequencies, and better at higher frequencies.

One may ask what dipole intensity meters were good for. It turns out that intensity meters of the type described were used to measure the total sound power radiated by different items of equipment and machinery. This made the measurement of sound power feasible at locations that would otherwise not be suitable, and it obviated the need for a reverberant room or an anechoic chamber to test machinery. The earlier meters did a good job of measuring the total radiated sound, but they were not good at identifying individual sources of radiated sound energy.

4.7.4 Sound Intensity Measurements

4.7.4.1 Instrumentation

The basic instrumentation used for the intensity measurements was the three-dimensional sound intensity system with visualization, a standard Type I sound level meter, and a noise source. The instrument exists mainly as software and runs from a portable computer. The microphone, a wand assembly, and a continuously running video camera were connected to the portable computer via USB. The camera was used to track the position of the microphone wand assembly. Specifically, the camera and computer tracked a light on the wand to determine the position of the wand as a function of time. The angular position of the wand was determined from the angular location of the light bulb in the picture, and the distance of the wand from the camera is determined by the size of the light bulb in the picture (see Figure 4-13). The wand primarily consists of the microphone assembly and two gyroscopes mounted perpendicularly from one another that measured the pitch and yaw.

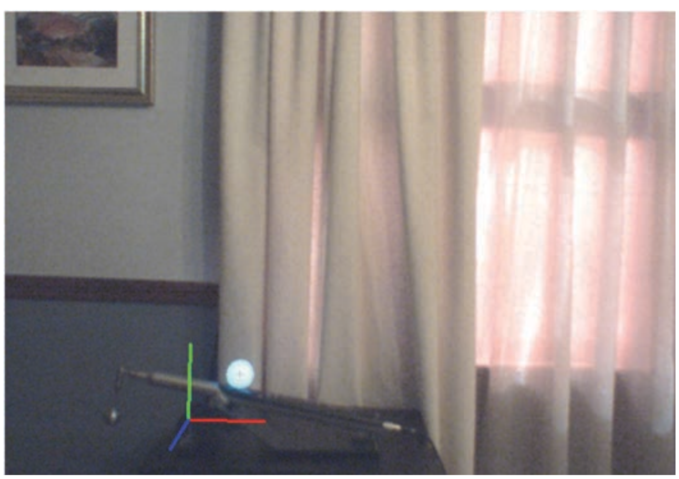

Figure 4-13. Sound intensity system (instrument synchronization).

Figure 4-13 shows the wand being synched to a known coordinate in the room; the wall to be measured is shown in the background. The red, green and blue colors showing the three coordinates are not actually physically in the room, but are superimposed showing the reference for the coordinate system. The wand's light must be easily visible or the system does not work.

4.7.4.2 San Diego Measurements

Measurements were conducted in five homes within the vicinity of the San Diego International Airport. Traditional aircraft sound TL measurements were conducted at these five houses, using a loudspeaker both inside and outside, and aircraft flyover measurements were also made. The intent was to be able to compare the intensity measurements to the traditional measurements, and to a small extent the research team was able to do this. However, even with the manufacturer of the three-dimensional sound intensity system helping (after spending a day doing preliminary measurements in San Francisco), the research team had to overcome the fact that the sound intensity system had been designed to use on a shop floor. The light on the wand works well indoors in a commercial setting, but did not work in sunlit rooms that are typically found in the residences. In an indoor setting, the room is darker and a nearly white bulb sticks out against the dark background. In the outdoor setting, the human eye can't see if the light is on or off. Two or more different bulb colors are needed for different lighting situations. This application was unknown to the instrument manufacturer until the research team talked to them, but the instrument is capable of having different light colors, the software just needs to be created to implement it. As such, the research team had to find ways to make the instrument work in the existing lighting. This involved using shade and dark clothes to block the light coming through windows until the research team achieved enough contrast to make the instrument functional.

There were several other smaller problems, all of which took time to understand and correct. However, the biggest limitation was that the traditional loudspeaker TL measurements were being conducted much more quickly than the intensity measurements could be made. Extra time was required because (1) the research team was not adept in the operation of the sound intensity instrument (a second round of measurements were conducted in Champaign, IL, where more time could be spent on the measurements) and (2) the research team did not (and in retrospect, still does not) know the required measurement time. So being conservative, the research team attempted to sweep broad areas, typically using measurement durations of 1 to 3 minutes (the limit is about 5 minutes). If great resolution is not required, it could be that 2 to 4 seconds of measurements spread over two to three camera positions would suffice.

The following section describes the measurements made in Champaign and is followed by all the data that turned out to be useful from measurements gathered in San Diego.

4.7.4.3 Champaign Measurements

For sound intensity to be useful, the research team needed to be able to measure the net sound energy flowing into the room via all pathways. The starting point was to measure the sound flowing into a room through an outdoor-facing wall having one or more windows. These measurements were conducted at a research team member's Champaign residence. Figure 4-14 shows a partial first floor layout, indicating the dining room as the room where the measurements were conducted and the primary wall on which they were conducted. The dining room has two walls that face the outside, one with a pair of double-hung windows, the other with no openings. The construction is standard 2 × 4 stud wall (actual dimensions 38 mm × 89 mm) construction on 406-mm (16-inch) centers, 122 cm (4 feet) of plywood as corner bracing, and insulation board for remainder of the external facing surface on the 2 × 4 stud wall.[1] The

[1] In this section and for other house construction details, English units are retained, not in small part, because some of these are nominal and not true dimensions (e.g., a 2 x 4 is neither 2 inches on one side nor is it 4 inches on the other).

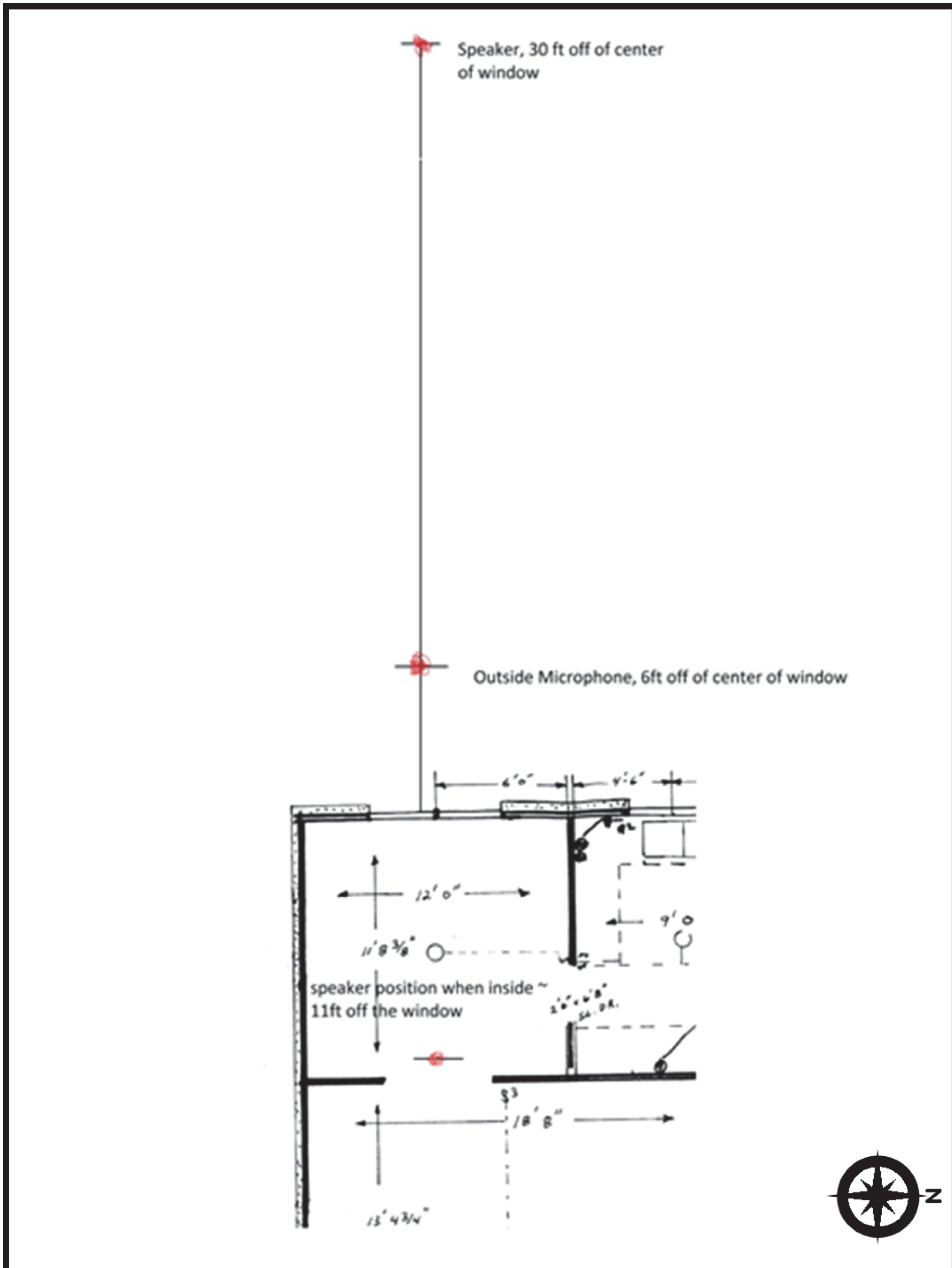

Figure 4-14. Champaign home floor plan and measurement location.

cavities in the wall were fully filled with batt insulation, and the wall was finished with a brick veneer. The windows are 43-year-old narrow line, double pane models. The space between the panes is fairly small, less than 1 cm (2.5 inch). With this construction, the research team expected the vast majority of the sound flow through the window, and that is what the results appear to show.

Since the overall purpose is to measure the transmission loss from outdoors to indoors, the research team concentrated first on measuring the sound power flowing through the wall into the room from an outdoor loudspeaker. The signal source was pink noise (i.e., noise with equal energy per octave). The loudspeaker was mounted 1.8 m (5.9 ft.) in the air and 9.1 m (23.8 ft.) from the face of the house in the normal direction 90° from the wall. An outdoor microphone was always located 1.8 m (5.9 ft.) from the wall. According to ISO and ASTM, with distances that are 1 m to 2 m (3.3 ft. to 6.6 ft.) from a wall, it is normal for the sound level (A-weighted) to be increased by 3 dB over what would occur without the reflecting wall. At the surface of the wall, this increase becomes 6 dB. Therefore, the difference between measurements at the wall and at the microphone is 3 dB minus the change for distance spreading: the change from 7.3 m to 9.1 m (23.9 ft. to 29.8 ft.). For comparison purposes, measurements were made with a second microphone at about 20 positions on the wall with the microphone windscreen just touching the surface of the wall. The discussion later with Table 4-18 shows that the values measured were consistent with the 3 and 6 dB predictions given above.

The three-dimensional sound intensity instrument is specified as being able to measure a 2.0 m by 2.5 m (6.6 ft. by 8.2 ft.) area at a distance of 2.5 m (8.2 ft.) from the camera. However, the measurement accuracy is 3 cm to 5 cm (7.6 in. to 12.7 in.), but only up to a camera distance of 1.5 m (4.9 ft.) beyond which it degrades. At a camera distance of 1.5 m (4.9 ft.), the measurement area is limited to 1.2 m by 1.5 m (3.9 ft. by 4.9 ft.).

The measurements were made by sweeping the microphone array all throughout the designated measurement area. To measure a whole wall, the wall had to be divided into several segments, each measured separately. The sound intensity instrument does this easily and efficiently. The results are a field of vectors that together indicate the sound power flow.

However, it takes time to learn and understand fully how the meter is processing the data. The software reports the total sound power flowing in a normal direction through a designated plane surface, in this case, the dining room wall. In actuality, the total sound power is really a summation of the sound power over all the vectors. This topic, understanding and analyzing the results, is developed in Section 4.7.5

4.7.5 Sound Intensity Results

4.7.5.1 Champaign

Although there is a fair amount of data, the most interesting and elucidating are the composite data for the sound flowing from outdoors to indoors, as well as from indoors to outdoors, and the comparison of these two. Figure 4-15A shows the composite sound flow out of the room. It shows the window space filled with vectors largely normal to the surface. These vectors begin to spread out and diverge as they move away from the window in a very smooth and regular fashion, with the lowest levels being where they have turned the most. In contrast, Figure 4-15B shows the sound going through the window into the room. The sound diverges towards the wall but soon meets the corner where it becomes lower in level and the flow (apparently) becomes turbulent. In some places the direction changes by 90° from one vector to the next. An example of this is circled in red in Figure 4-15B.

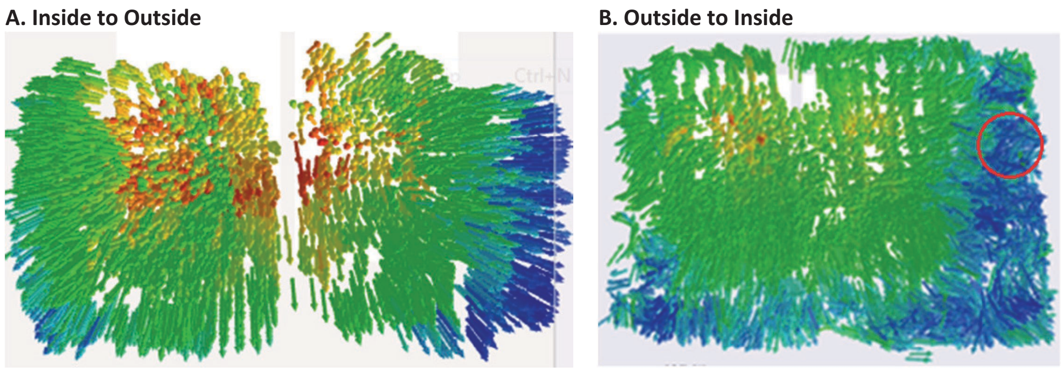

Figure 4-15. Whole wall composite sound flow.

Figure 4-16 shows the composite of the wall stitched together, in this case from five individual measurement episodes, one from each quadrant around the window, and one from the center of the window. To make the comparison of the results for the two flow directions easier to view, Figure 4-17 contains a side view and again shows the frontal view of the composites for each of the two directions of flow. Again, one can see only straight lines of the *inside to outside* composite and the considerable curling turbulent structure of sound flow from *outside to inside* the room.

Appendix A contains the spectra for each of the five measurement episodes shown in Figure 4-16. The sound intensity instrument does not provide composite spectra; spectra are only available for individual measurement episodes.

Figure 4-18 shows the frontal view for each of the three measurement episodes that comprise the *in to out* composite. The sound intensity instrument also outputs a one-third octave spectrum covering the full frequency range from 100 to 4000 Hz; however, it is not quite clear how the spectrum can and should be utilized. Spectra for all measurements are placed in Appendix A and referred to in the text.

4.7.5.2 San Diego

Data were collected at five houses in San Diego, CA. The first house wasn't successfully measured, because the research team was still familiarizing itself with the equipment. For the second house, San Diego #1, the research team was able to collect satisfactory data on one window and wall in the living room. The spectra for these two measurements are somewhat similar, especially when compared with other spectral data that were measured for other building elements.

The vector data of Figure 4-19 for San Diego #1 are consistent with the research team's expectations. In this figure (top view), the reader will note the difference in the depth at which these two measurement episodes were taken: the first episode is at a depth of 2.5 cm to 42 cm (1 in. to 15-18 in.), the second is at a depth of 30 cm to 60 cm (~12 in. to ~24 in.). This difference is used later in the analysis.

On the second day, the research team was only able to collect usable data at the San Diego #1 residence due to a neighbor's complaint at the San Diego #3 residence. The San Diego #1 home provided the research team with two measurement locations of the same living room window, one focusing on the wall left of the window and including part of the window, and the other focusing only on the window. A discussion of the frequency spectra can be found in Appendix A.

The difference in spectra for these measurements seems to suggest that spectra may not provide very useful data. The spectrum for one of the two left of the window measurement episodes actually looks more similar to the spectrum taken of the window only condition (see Appendix A).

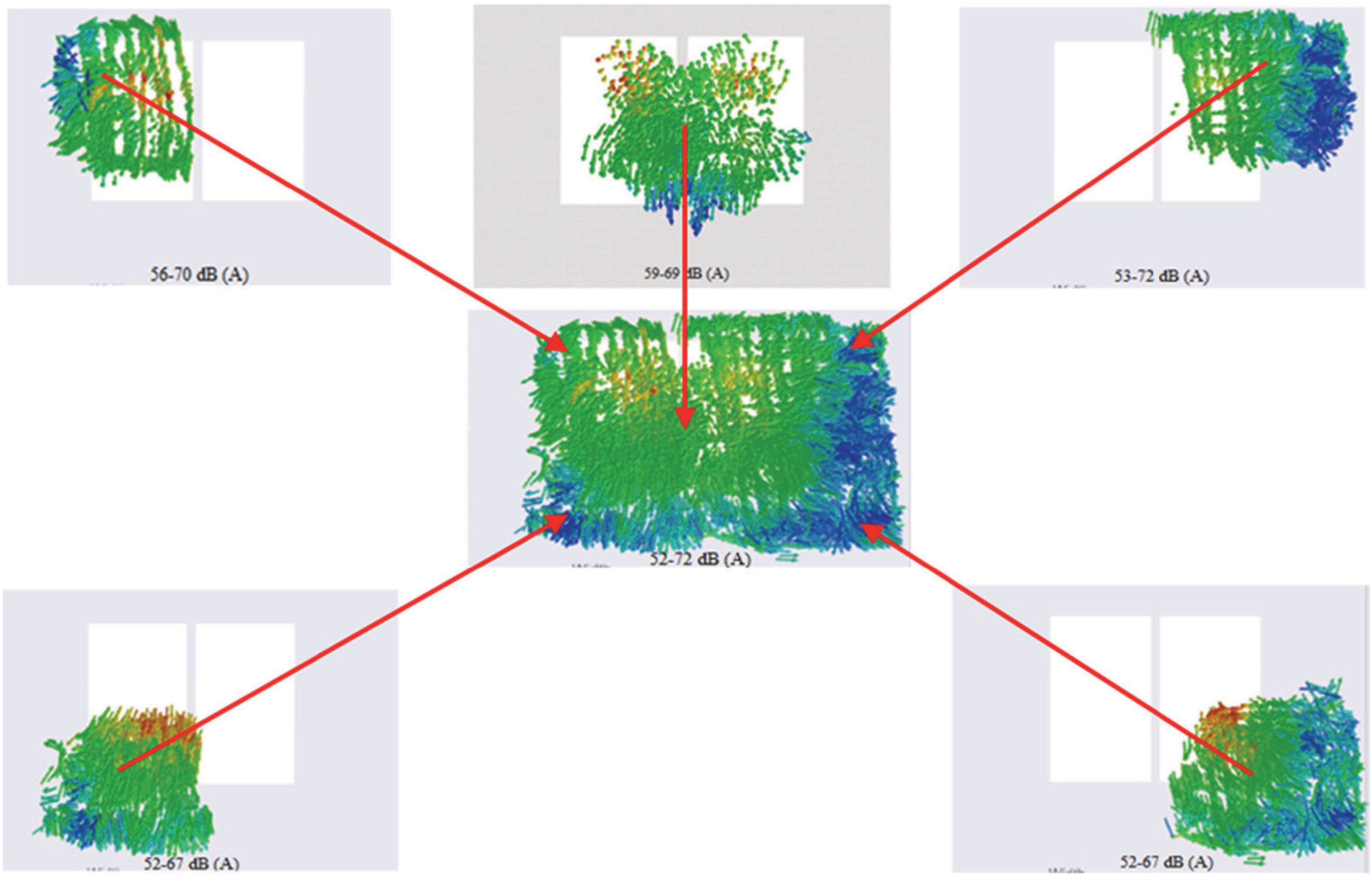

Figure 4-16. The "stitching" together of a composite from individual measurements (the "A" in parentheses signifies that the measure is A-weighted).

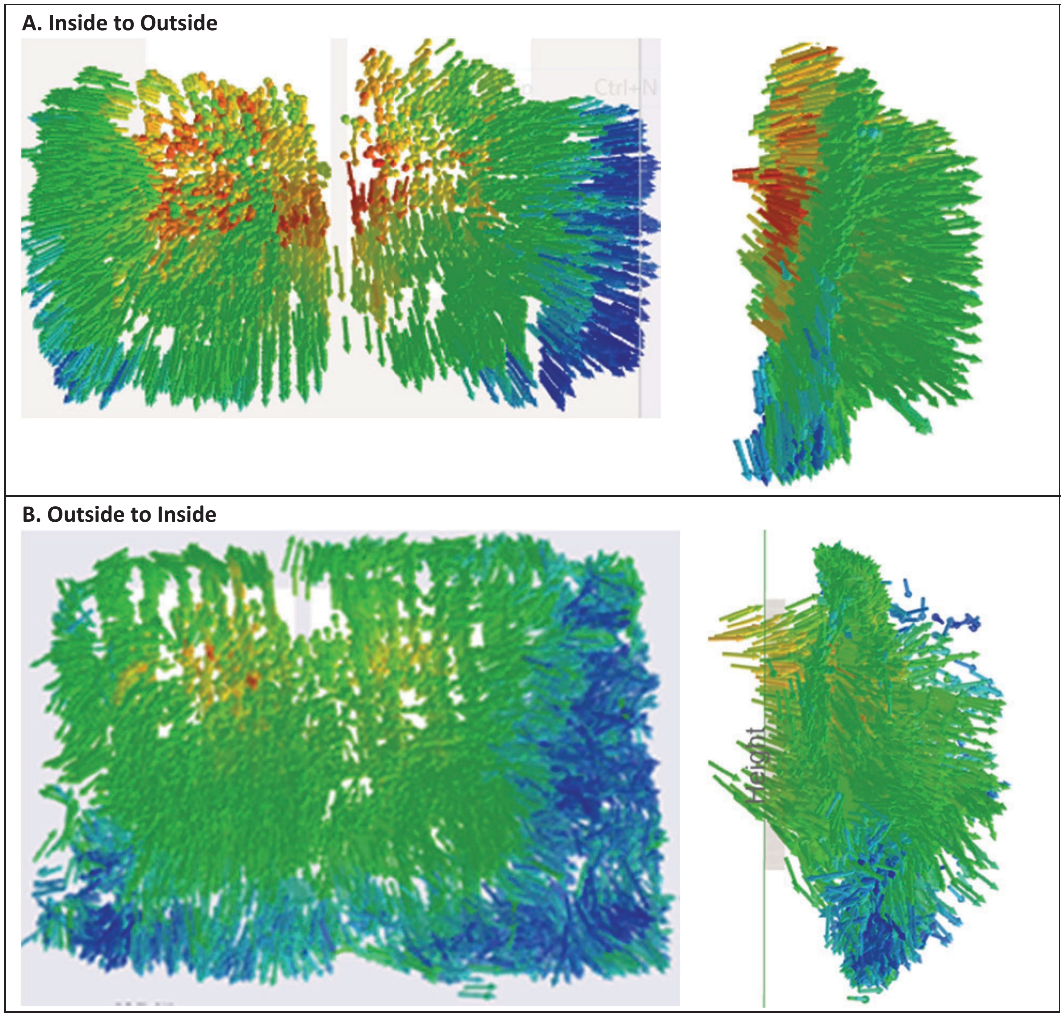

Figure 4-17. Comparative front (left) and side (right) views for the whole wall composite sound flow.

In contrast, the vector plots of power flow that constitute Figure 4-20 show that the two measurement episodes taken left of the window look similar to one another, and different from the measurement episode that was only through the window. The vectors indicate flow in from the window, as expected, but then they appear to turn and split into at least two streams. One stream appears to be going down at an angle into the party wall between the bedroom and the living room, and the other appears to be going down tangentially towards the floor. The measurement episode that only includes flow through the window appears to be different from the measurements taken of the wall. Also, it is clear from the bottom right image that the sound entering through this window is almost perpendicular to it.

The research team took measurements at San Diego #5, focusing on the living room window and wall (Figure 4-21). Two measurement episodes were conducted with the speaker at 45° from the room corner and two more with the speaker at 90° from the room center. These measurements of the living room wall included the front door to the house and a buttress in between the door and window at 90°. The door had large air leaks, which imply sound leaks.

Figure 4-21 shows the combined pair of measurement episodes conducted with the loudspeaker at 45°, and the combined pair with the loudspeaker at 90°. It is not certain if, or how, these structural components affected the data, but it is clear the results were not what were

Figure 4-18. Front view for each of the three measurements shown in Figure 4-17.

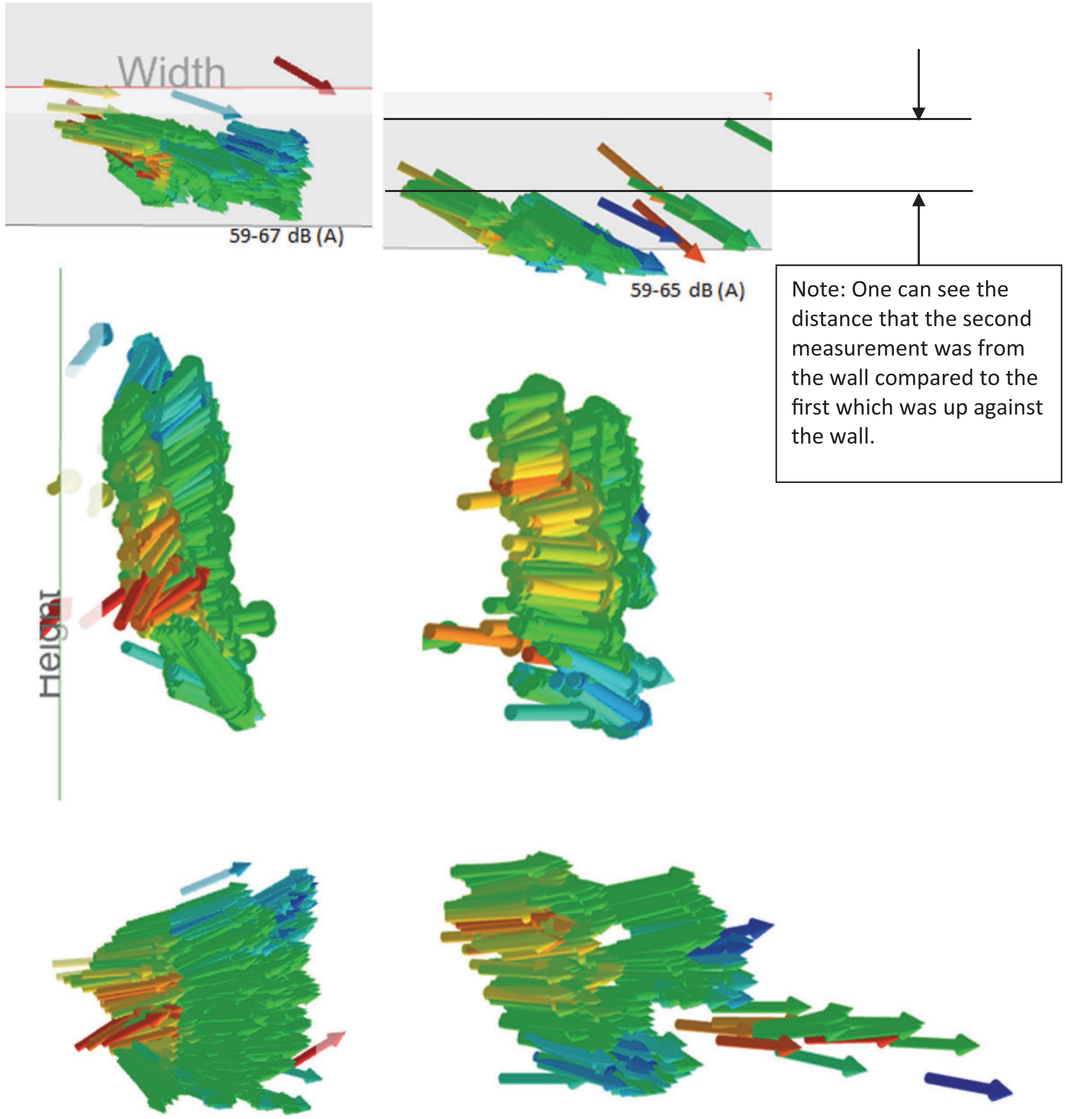

Figure 4-19. San Diego #1 vectors. Note: From the top of the page: top, side, and front views of the measurement near the wall (left side) and the measurement that begins about 30 cm (11.8 in) from the wall (right side), roughly twice the distance of the first measurement.

expected. The data are very complicated, neither straight through nor at a common angle; thus far the research has not been able to interpret the results.

4.7.5.3 Analysis

4.7.5.3.1 Relative Analysis The research team made use of the results collected from the intensity measurements to examine the sound power flow from *out to in* versus *in to out*. Classical acoustic theory is that the TL is the same in both directions. For each comparison, there are SPL measurements on the sound source side of the room wall, and sound intensity measurements on the side opposite of the source. These are the composite images presented, where the *in* composite refers to the source outdoors and the *out* composite refers to the source indoors. The sound level for the source outdoors is 95.1 dB at the face of the wall, and the level is 108.3 dB at the face of the windows when the source is indoors. Figure 4-14 shows the placement of the source with respect to the dining room wall.

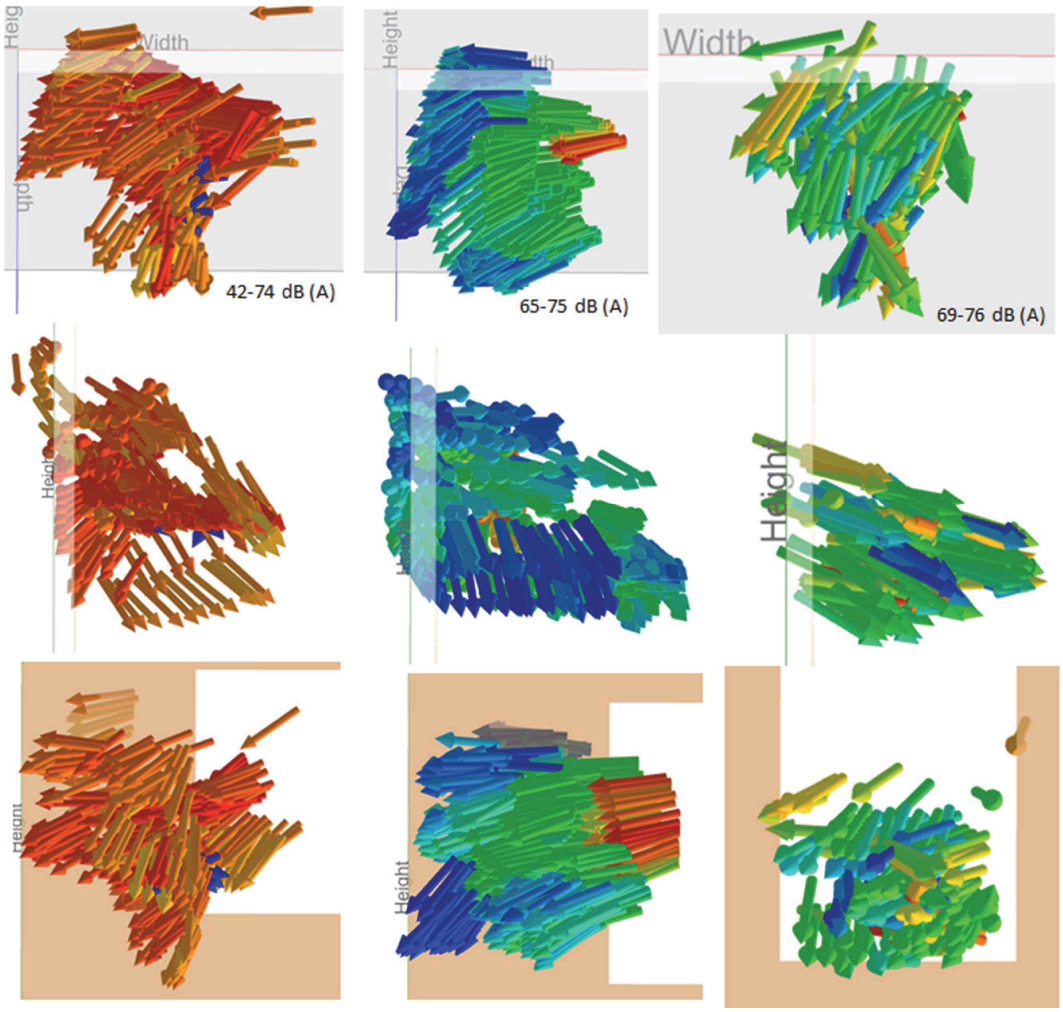

Figure 4-20. San Diego #1 vectors. Note: From the top: top, side, and front views of the two measurements.

As an indication of the reasonableness of the 95.1 dB at the face of the wall, the measurements taken at 1.8 m (5.9 ft.) from the wall were consistently 93.9 dB (the loudspeaker at full volume is a very steady source). Table 4-18 shows a theoretical calculation of the level at the face of the wall based upon the measurement of 93.9 dB at a distance of 1.8 m (5.9 ft.) from the face of the wall. In comparison, the level measured at the face of the wall is 95.1 dB compared to the prediction of 95.0 dB.

For the TL measurements, the source side is given in terms of pressure in decibels and the receiver side is given in terms of power flow, both into or out of the dining room, as appropriate. So this TL result is not the traditional TL. However, the research team also calculates the traditional TL for some of the measurements for purposes of comparison. Above, the source side pressure levels are given as 95.1 dB and 108.3 dB for source outside and inside, respectively. The following discusses and develops the power flows into the receiver region that correspond to the two SPLs given above.

The composite power is calculated in the following fashion. For the on-screen display[2], the intensity meter calculates the total sound power collected over the duration of each of the separate

[2] Inexplicably, the sound intensity instrument displays power in watts on the computer screen, and, as noted, this power is the total of all the vector powers. However, when the sound intensity instrument outputs the vectors to a file, it outputs vectors representing energy in Joules, which are the power multiplied by the duration of the episode.

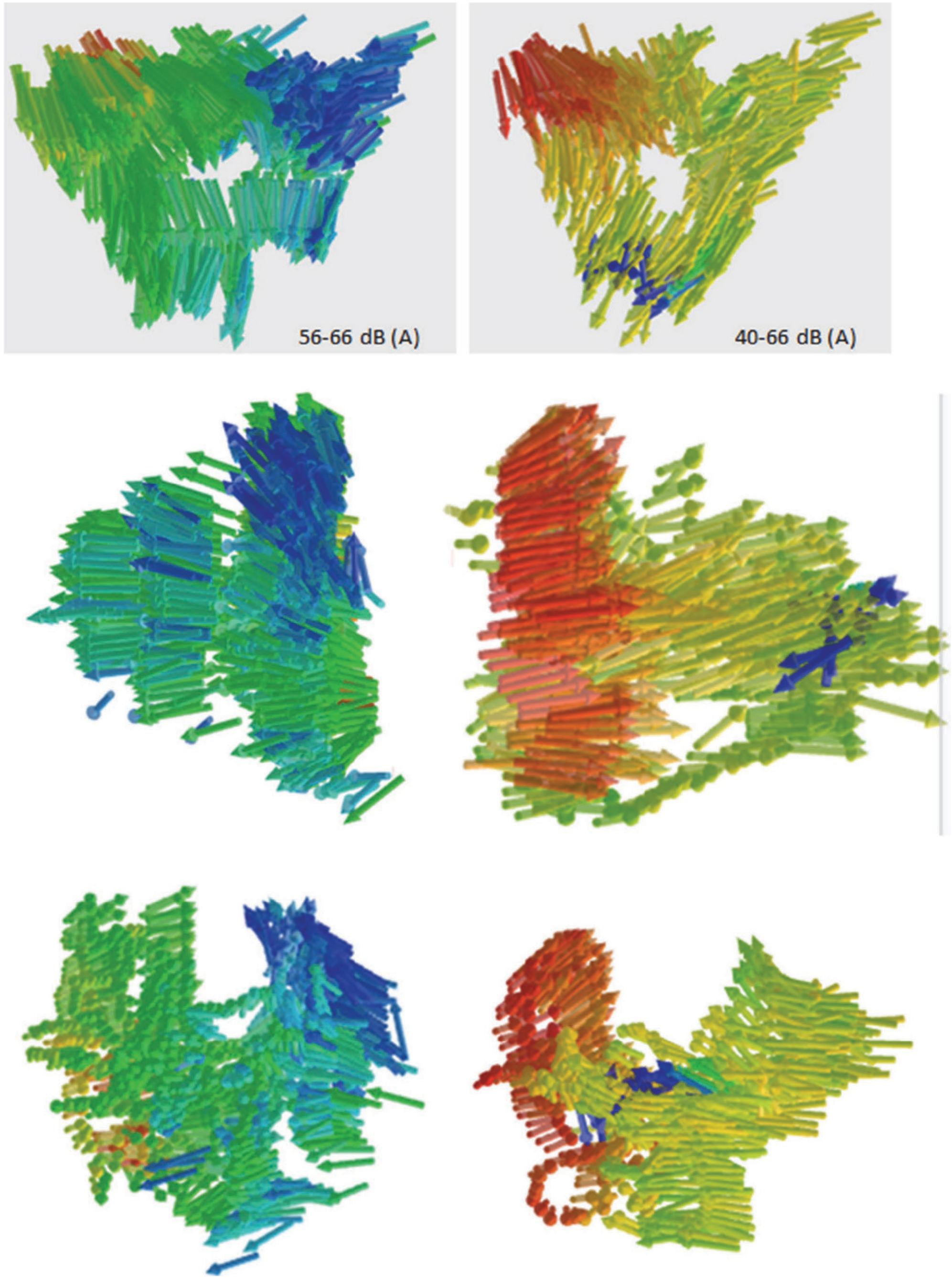

Figure 4-21. San Diego #5 vectors. Note: From the top, side, and front views of the respective pairs of combined measurement episodes with the loudspeaker at 45° (left side) and at 90° (right side).

episodes that make up the composite. In calculating this power, the sound intensity instrument uses only those vectors going through the area of the wall designated by the user. Each vector gathered during a measurement episode is a separate estimate of the power being measured. The sound intensity instrument sums the power normal to the designated surface over all the vectors that constitute the episode. The best estimate of the total is the mean of the vectors, which is the reported total energy divided by the number of vectors. The results of this calculation are shown in Table 4-19 for the outdoor and indoor data separately, given in decibels.

Table 4-18. Validation of pressure measurements for out to in situations.

Assume measured total at wall equals free field at wall plus 6 dB, 1.8 m (5.9 ft.) from wall; 7.3 m (23.9 ft.) from speaker, where the speaker is 9.1 m (29.8 ft.) from wall:	93.9	dB
Assume wall is +6 dB for pressure doubling at ISO +3 dB "position" when 1.8 m (5.9 ft.) from wall (ISO +3 dB range is within 1 to 2 m [3.3 to 6.6 ft.] from wall):	3	dB
Difference for distance (speaker to mic = 7.3 m versus speaker to wall = 9.1 m) is 20*log(7.3/9.1):	-1.9	dB
Result: (Predicted, 93.9 + 3 – 1.9 = 95 dB)	95.0	dB
For comparison, measured at wall:	95.1	dB

Note: All levels in the table are A-weighted.

Table 4-19. Calculation of composite power.

Position measured	Time data collected	Number of vectors	Sum of vector power estimates (watts, dB)	10*log (number of vectors) dB	Average power (watts, dB)
Inside	4:24 p.m.	1,242	72.1	30.9	41.2
	4:58 p.m.	1,896	71.7	32.8	38.9
	5:08 p.m.	1,966	63.9	32.9	31.0
	5:22 p.m.	1,437	67.2	31.6	35.6
	5:52 p.m.	1,540	73.0	31.9	41.1
Outside	7:11 p.m.	1,687	82.9	32.3	50.6
	7:20 p.m.	1,034	85.8	30.1	55.7
	7:27 p.m.	1,642	83.7	32.2	51.5

For example, for the first line in Table 4-19, the total power calculated by the sound intensity instrument and displayed on the meter is a watt level of 72.1 dB, and it is gathered with 1242 vectors. In this case, subtract 10*log(1242) which is equal to 30.9 dB from 72.1 dB to obtain the mean estimated power in watts of 41.2 dB (to divide by a number when using decibels it is more convenient to subtract a dB-like transformation of the number *n* to 10*log(n). In this example, one needs to divide the total energy (joules in dB) by the number of vectors in dB, which is equal to 30.9 dB from 72.1 dB to obtain the mean estimated power in watts of 41.2 dB.

There is one more major issue before the sound power can be estimated. The two composites developed for the Champaign house (*in to out* and *out to in*) each have the problem that the separate measurements going into the composite are not independent. Rather, there is overlap to a greater or lesser degree from one measurement to another. So, these five measurements that make up the *out to in* composite must be viewed as five not-so-independent estimates of the power flow.

As an example, consider the following two limit situations. In situation one, two measurements exactly replicate one another. In this situation, there are two totally dependent measurements and neither one alone is the correct result. In situation two, the two measurements do not overlap anywhere; they each measure different parts of the source. In this situation, the correct process is to sum the two results. In general, if one measurement is dominant, the solution is to take this highest estimate as the best estimate.

Consider Table 4-20, which contains example pairs of decibel numbers and their resulting sum.

In Table 4-20 the "sum" of two decibel levels that are more than 6 dB apart (these are in rows 7 and higher) have a resultant level that is not much higher than the higher of the two levels that are being "added" together. For all situations herein where two levels are being added together and they differ by 6 dB or more, the higher of the two is termed the "dominant" level, and in these situations the "sum" of the two levels is taken to be the higher level itself because the error is 1 dB or less.

When the two decibel levels are less than 6 dB apart, they are usually "added" together, but the result is still relatively small (70 dB + 70 dB = 73 dB). So 3 dB is the largest number that can be added to the higher of the two levels being "summed," and it occurs when the two levels to be combined are equal.

The specific concern is combining the data from more than one measurement of the same general area (e.g., a window or door). As noted above, to get the correct answers, one needs to combine the different measurements on the same element such that data that overlap are only counted once. For combining two sets of measurements, note the following: if the two are totally independent then their sum ranges from 0 to 3 dB above the higher of the two measurements. It is +3 when the two measurements are equal and less than 1 dB when the two measurements differ by more than 6 dB. With respect to Table 4-20, the added level is effectively zero when the difference between the two measurements is greater than 20 dB.

The second endpoint is when the two measurements are totally dependent. In this case, one of the two levels being "summed" is redundant and effectively discarded. The "sum" is just the higher level of the pair. So even if both levels are, for example, 70 dB, the "sum" is 70 dB. That is, one could get a result of 73 dB when the correct result was 70, or one could a result of 70 dB when the correct result was 73. So in both these endpoint cases, the largest an error can be is 3 dB.

Table 4-20. The sums of pairs of decibel numbers.

Row number	A	B	Sum
1	70	70	73.0
2	70	69	72.5
3	70	68	72.1
4	70	67	71.8
5	70	66	71.5
6	70	65	71.2
7	70	64	71.0
8	70	63	70.8
9	70	62	70.6
10	70	61	70.5
11	70	60	70.4
12	70	50	70.0

In the results herein, there is overlap among the 5 *out to in* measurement episodes, in particular, episode 1 and 5 are almost equal, 41.2 and 41.1 respectively. In Figure 4.16 one can see that about 60% of episode 1 is overlapped by episode 5, and about 40% of episode 5 is overlapped by episode 1. A 40% overlap is just under 1.5 dB and a 60% overlap is almost 1.7 dB, so 1.6 dB is added to the highest single value. That is, 1.6 dB is added to 41.2 for a power estimate of 42.8 dB.

For the *in to out* situations, episode 2 is dominant, so the 55.7 dB level of episode 2 is taken as the total power estimate.

4.7.5.3.2 Absolute Analysis In terms of comparing the TL from *out to in* versus *in to out*, A-weighted and flat-weighted source side pressures were measured using a precision sound level meter during the intensity measurements. The sound power levels in Table 4-20 are taken from Table 4-19 and show a reasonably good agreement between *out to in* and *in to out*, especially for the A-weighted values. The intensity meter display was flat-weighted so there was no way of getting A-weighted power levels directly from the meter. However, the sound intensity instrument also outputs a spreadsheet that includes one-third octave bands from 100 to 4000 Hz, and it is possible therefore to calculate the flat-weighted and A-weighted levels in one-third octave bands for both pressure and power. Appendix B provides further discussion on the spreadsheet output and contains a table of differences between flat-weighting and A-weighting.

If two spectra differ only in amplitude, then the difference between A-weighting and flat-weighting for each of these two spectra is a constant. This suggests that for what is being measured here, the difference between the flat-weighted power and the A-weighted power should be about equal for both indoor and outdoor measurements, since both are measurements of the same source with the same spectrum but in two different physical configurations: (1) the outdoor measurement when the loudspeaker is outside and 9.1 m from the wall and (2) the indoor measurement when the loudspeaker is inside and 3.3 m from the wall. The data in Appendix B confirms this constant difference, which is shown in the appendix to be about 3 dB.

The differences are all on the order of 3 dB between flat-weighted and A-weighted values. What this says is that the difference between A-weighted pressure and flat-weighted power is 3 dB compared to what one would get with A-weighted pressure and A-weighted power. That also suggests that to the first approximation, A-weighted pressure minus A-weighted power equals flat-weighted pressure minus flat-weighted power. And indeed in Table 4-21, the difference between pressure (A-weighted) minus power (flat-weighted) and pressure (flat-weighted) minus power (flat-weighted) is 3.8 dB.

Traditional TL A second comparison made is to calculate the traditional TL. This uses the data from the intensity meter, which includes sound pressure and sound velocity in addition to intensity for each vector. Table 4-22 lists the total A-weighted L_{eq} for the entire duration of

Table 4-21. Comparison of the measurement of transmission loss (out to in vs. in to out).

	A-Weighted Pressure (dB)	Flat-Weighted Power (dB)	A & Flat Mixed Difference (dB)	Flat-Weighted Pressure (dB)	Flat-Weighted Power (dB)	Flat-Weighted Difference (dB)
In to Out	107.4	55.7	51.7	111.2	55.7	55.5
Out to In	95.1	42.8	52.3	100.4	42.8	57.6
Differences: In to Out minus Out to In			-0.6	In to Out minus Out to In		-2.1

Table 4-22. A-weighted L_{eq} and sound power for the five measurement episodes that form the outdoor to indoor composite.

Measurement Number	Average A-weighted L_{eq}	Sound Power Levels from Table 4-19
1	67.2	41.2
2	65.8	38.9
3	64.5	31.0
4	64.6	35.6
5	67.4	41.1
Energy Average:	66.1	38.9

each of the five measurements from *out to in.* This table shows a rather large spread of pressure levels, just under 3 dB. However, comparison of the SPL results with the sound power levels of Table 4-22 reveals a strong correlation between pressure and intensity. Because the estimate of sound power was based on only the two higher sound power levels, the estimate of the receiving room SPL is based on the two pressure levels that correspond to these two higher sound power levels. One SPL is 67.2 dB and the other is 67.4 dB, so the clear choice for the estimated sound pressure received in the dining room is 67.3 dB. The corresponding source side pressure as given above is 95.1 dB, so the indicated loss is 27.8 dB, which appears to be a reasonable value for the construction described earlier.

Assessing the reasonableness of the estimate of power flow into the dining room In this section, the reasonableness of the estimate of power flow into the dining room is tested. As expressed above, the intensity meter simultaneously measures and records pressure and velocity as well as intensity. So for the *out to in* situation, the sound power is flowing into the dining room where a moderately reverberant field is established. With reference to Figure 4-14, the west end of the dining room should be the "reverberant" end of the dining room. This was somewhat verified by a walk around the dining room using a hand-held, Type 1 SLM with the loudspeaker as the source positioned indoors at about 30 cm (11.8 in.) before the middle of the entryway to the dining room from the living room. This walk around revealed a constant sound field for about the first 1.5 m (4.9 ft.) to about 1.8 m (5.9 ft.) from the window-wall (west wall). Since the intensity measurements herein extend to at most 0.6 m (2 ft.) or so from the window-wall, the instrument probe should be in a reverberant field.

From the basic theory of room acoustics,

$$p^2 = (4 * \rho c_o / a) * W$$

where ρc_o is the characteristic impedance of an acoustic wave in air, 415 Rayl, a is the room absorption in metric Sabine, P is the reverberant pressure in the room, and W is the sound power flowing into the room. This equation is used to find the total absorption, a, in the room and to compare this total with the calculated absorption based on the room's furnishings.

In decibels with W = 42.8 dB and P = 66.1 dB (the decibel levels measured herein), one gets:

$$P = W + 10 * \log(4 * \rho c_o) - 10 * \log(a),$$

so, $$\log(a) = (W - P)/10 + \log(4 * \rho c_o) = 4.28 - 6.61 + 3.22 = 0.89$$

and $$a = 10\text{^}0.89 = 7.8 \text{ metric Sabine}$$

To assess the reasonableness of the estimate of power flow into the dining room, the total room absorption calculated using the room acoustics formula above is compared with the total room absorption based on surface sizes and their finishes, furnishings, and people in the room. The two openings to the dining room are the doorway to the kitchen and the large opening to the living room. These spaces are treated as having an absorption coefficient of 0.9. With reference to Figure 4-14, one can see that the dining room is open to the kitchen and very open to the living room.

The kitchen is completely open to the family room, which spans the north side of the house and has a 0.97 m (38 in.) by 1.72 m (68 in.) opening to a front hall that is very open to the living room, which extends west to an open doorway to the kitchen. Clearly, all the spaces are very open to one another. Thus, little sound is expected to be flowing back into the dining room and is estimated as equivalent to lowering the absorption coefficient from 1.0 to 0.9.

With these caveats, the total absorption results for the dining room are calculated in Table 4-23 to be 8.3 metric Sabine (88.8 Imperial Sabine). This value of 8.3 metric Sabine, calculated from the room furnishings, compares favorably with the 7.8 metric Sabine (84 Imperial Sabine) calculated above using room acoustics, especially given the limits on the assumption of a reverberant space.

4.7.5.4 Enhancements

What Constitutes TL When Measuring Intensity? The measurement of TL using intensity, of necessity, represents a departure from current airport sound insulation program practice to at least some degree. In theory, the power flow on either side of a wall should differ by the losses only due to the wall itself, whereas the current TL is calculated by the pressures impinging on the outside wall compared to the reverberant energy internal to the room. The research team has shown that, with intensity, the measurement from outdoors to in and indoors to out is the same, where on one side of the wall pressure is measured and the other side of the wall, power is measured. Thus, reciprocity has been demonstrated with the use of intensity.

Table 4-23. Calculation of total absorption in the dining room.

Dining Room Details		Length (in.)	Height (in.)	Area (m^2)	Absorption Coefficient	Absorption (a)
Walls	Whole window (west) wall	144	96	8.9	na	na
	Window area	72	54	2.5	0.10	0.3
	Wall area minus window area	na	na	6.4	0.05	0.3
	South wall	140	96	8.7	0.05	0.4
	Living room (east) wall (2*42")	84	96	5.2	0.05	0.3
	Living room wall continued	57.5	16	0.6	0.05	0.0
	North wall (24" + 42")	66	96	4.1	0.05	0.2
	North wall continued	28.5	16	0.3	0.05	0.0
Floor		144	140	13.0	0.10	1.3
Ceiling		144	140	13.0	0.10	1.3
Openings	Kitchen door	28.5	78	1.4	0.9	1.3
	Living room entryway	57.5	78	2.9	0.9	2.6
Furnishings	Three chairs, cushioned seats	18	18	0.2	0.6	0.1
People	One person					0.2
Total Absorption (metric Sabine)		8.3				

Since there is reciprocity for both directions, the measurement from indoors to outdoors is the more promising direction. In this scenario, one creates a reverberant sound field in the room under test and determines the power flow from inside to outside by measuring the power flow out through the wall surface. It has been shown that this is feasible in the measurements at Champaign, and the difference between power flowing through the wall and power flowing through the window has been clearly measured. In theory one could have extended that and measured the intensity through the south wall that had no window, or through the roof which has a second story between it and the dining room. It would appear that one can measure the main wall and any hot spots, and beyond that it is not clear that measurements are warranted in any case. Measurements taken from indoors to outdoors have a number of advantages. By locating the sound source indoors, one can generate a very loud indoor level and easily measure the power flow from inside to outside by measuring intensity on the outside. With this method there are no resonance problems, so it appears that this methodology offers a means to make more repeatable measurements.

From the research team's measurements, it is clear that this new TL measurement would, of necessity, be numerically different than the old TL because the old TL was on the order of 25 dB and was the pressure difference on either side of the wall. For this new intensity measurement, one can get an idea of the difference between pressure and power as in Table 4-21 where the A-weighted difference between the energy average pressure and power is about 52 dB. This makes sense because it is known that the TL is about 25 dB, and (from Table 4-21) the difference between pressure and power for an intensity measurement is about 27 dB, for a total difference on the order of 52 dB. So, with this new measurement, the numerical values will be on the order of minus ~50 dB, rather than minus ~25 dB.

Basic Power or Intensity Measurements In the scanning of the surface, the research team did essentially a three-dimensional scan that included the wall surface and about 30 to 60 cm (~1 to 2 feet) out from the wall surface, which is a three-dimensional volume being 30 to 60 cm (~1 to 2 feet) times the dimensional surface. When one stops to think about the process, it becomes clear that using more than the minimum depth required to scan the surface is not the right way to measure power through a surface. What one wants is the narrowest surface depth feasible and as close as possible to the wall through which the power flow is being measured. If one measures close to the wall with a depth of 30 cm [i.e., 0 to 30 cm (0 to ~1 feet)] from the wall], and one measures further from the wall such as a depth of 30 to 60 cm (~1 to 2 feet), then to the first order (except for dispersion), the power flow should be the same through either of these surfaces. The research team did this very test at the San Diego #1 site. As shown in Figure 4-19, the power flow from *out to in* looks very similar when measured within 30 cm (~1 foot) of the window, and within 30 to 60 cm (~1 to 2 feet) of the window. The only difference is that there is a little more dispersion at 60 cm (~2 feet) versus 30 cm (~1 foot).

A similar test was done in Champaign for one of the five measurements for the indoor-measured cluster. The sound intensity was scanned both close to, and further from the wall/window for about the same time. To analyze this, the research team found the total energy within 30 cm (~1 foot) of the wall/window and within 60 cm (~2 feet) of the wall/window. As expected, when the distance (depth) from the wall is doubled, double the energy is measured. But, as noted earlier, the power should be energy per unit time and for purposes of this discussion the research team considers the time to flow 1 foot as the unit of time. So, flowing from 0 to 30 cm (0 to ~1 foot) yielded half the energy realized by flowing from 0 to 60 cm (0 to ~2 feet). But, in both cases, to calculate the power the vector sum is divided by time, where the time to go from 0 to 60 cm (~0 to 2 feet) is double the time required to go from 0 to 30 cm (0 to ~1 foot); therefore, the totals get divided by a given time increment for going from 0 to 30 cm (0 to ~1 foot) and double that time increment to go from 0 to 60 cm (~0 to 2 feet). So the power flow does not change and it is clear that the power flow should have been measured with just one layer from

0 to 30 cm (0 to ~1 foot) from the wall. Any greater depth, or surface removed from the wall, is either unnecessary, less precise, or both.

The best strategy is to measure as close to the wall as possible, with the shortest depth possible. For most of the situations in this study, this ideally would have been 0 to 10 cm (~0 to 4 inches) from the wall or perhaps as much as 0 to 15 cm (~0 to 6 inches) from the wall. The goal should be to measure within this narrow distance from the wall, uniformly across the entire surface under test. A great assistance to the user would be software that divided the wall into sectors designated by the user and based on such things as hot spots and the resolution desired.

For example, consider the wall in the Champaign dining room discussed in Section 4.7.4.3. As shown in Figure 4-22, the window is designated as a hot spot and divided into four elements for measurement. The adjacent walls are subdivided in a similar but not equal fashion. As shown, the dividing lines for the window are normally maintained to the extremities of the wall, giving the same spacing in one direction off the window. Beneath the window, two wall elements are shown that have the same width as elements of the window, but the vertical height of these wall elements is not generally equal to the vertical spacing of the window elements. Four more elements are shown to the sides of the window, two on each side, that follow the vertical spacing of the window, but for these four elements the horizontal spacing will not generally equal that of the window. In the two lower corners, neither direction will normally equal that of the window. In the top two corners, the vertical spacing of the windows is not used because of the small distance from the top of the window to the ceiling, about 20 cm (8 inches). Rather, these two corner elements are set as shown. Finally, directly above the window it again departs from following the lines of the window because of the short height. In a practical way this might be accomplished by the computer drawing the standard witness lines outside the hot spot and the user designating to the computer which elements to merge. As a special case, if one had a uniform wall without windows, then the entire wall would be treated as a "hot spot," with no part of the wall outside the hot spot.

More complicated situations would need to be accomplished by dividing the wall into subwalls. For example, if there was a room with two separate windows of different size, one could

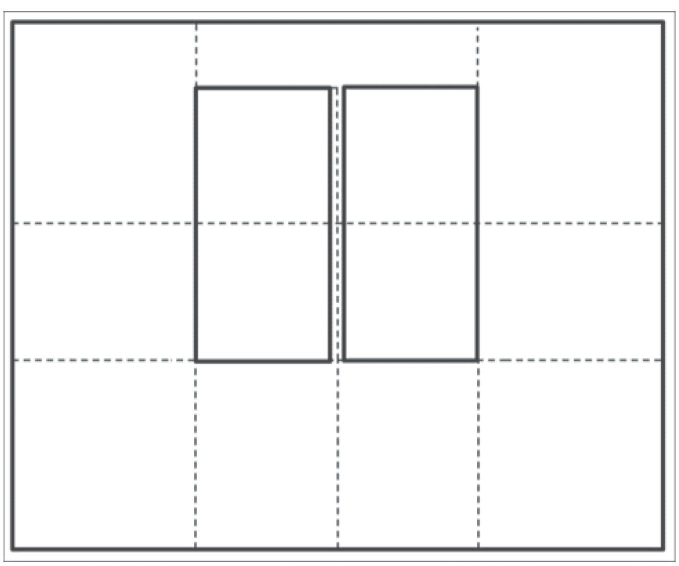

Figure 4-22. Test wall divided into hot spot (window) and the remainder (hard wall), with each divided into sub-elements.

take the point midway between the two windows, or something close to that, and use the vertical line that goes through that point as the line dividing the wall into two sub-walls, each of which would be treated separately as above.

In designating elements, the smallest permitted element dimension would be (for the current sound intensity microphone assembly) 5 cm (2 in.), and as a practical matter the smallest element dimension should be closer to 10 cm (4 in.). In any event, no element dimension should be shorter than the distance that sound intensity instrument can resolve based on the setup in use.

As a practical aid to the user, a screen should display the division of the wall into elements, where each element would initially be portrayed in some color such as red. This color would change to a contrasting color, such as green, when the requisite number of vectors had been gathered in that element. In this way, the operator can see what has been filled in adequately and what still needs to be filled in. Also, the software should produce a big (very prominent) warning in real-time when the instrument is outside of the specified box (e.g., too far from the wall). These capabilities become increasingly important as the elements become smaller.

Given that the largest surface area the sound intensity instrument can address at one time is about 2 × 2.5 m (6.5 to 8.2 ft.), and that the camera must be 2.5 meters back from the wall, the resolution is certainly no more than 10 cm (3.9 in.), and perhaps even larger. If the maximum resolution was 10 cm (3.9 in.), then one could divide the 2 × 2.5 meter (6.5 × 8.2 ft.) area into 500 10 × 10 cm (3.9 in.) elements, 25 across the 2.5 meter (8.2 ft.) width and 20 spanning the 2 meter (6.5 ft.) height. With 5 vectors per element, this would result in 2,500 vectors, which is probably the maximum that could be envisioned.

The overarching requirement for making unambiguous measurements of power flow through a surface is that there be a single defining vector for each element that represents the average of all the vectors through that element, that all the elements be independent and not overlapping, and that the sum of the elements equals the area of the surface under test. The single defining vector for each element would represent the power flowing through that element. The component of the real power normal to that element would be the real power flowing through that element's portion of the wall under test. The report should provide the intensity for the surface of each element, which is the power through that element divided by the area of that element. The data included in the report should be the area of the element, the unique element number given to that element by the software or the user, the position of that element in the wall surface, and the intensity at the surface of the element, or alternatively, the power normal to the surface of the element, or both. (Although not relevant to sound through walls, similar concepts, although more complicated geometrically, could be applied to conformal surfaces that were used to surround a test object.)

The most important point is that **all overlap must be avoided.** One cannot tolerate a situation where there is overlap between two or more elements, and the sum of elements must cover the entire wall under test. With the current version of the sound intensity instrument software, it appears to be virtually impossible to precisely measure the sound power flow through a wall.

Additional Processing Problem to Avoid in Addition to Overlap As indicated above, when the sound intensity instrument calculates a power as displayed on the attached computer screen, this power is the sum of the individual vectors that go through the user-selected rectangular area. In this application, the vectors apparently have units of watts. When one prints out the vectors in a spreadsheet, the vectors, apparently, have units of joules (watts multiplied by time). Appendix B has a detailed discussion of the screen displayed vectors and the outputted vectors, and how they differ.

Advanced Analysis Possibilities Potentially, software can be developed to more or less automate the total measurement process on the basis of just a few user-specified parameters. In general, the user is interested in mapping the power flow through a wall or through a conformal surface that surrounds some machine. The most general analysis would divide the surfaces into logical relatively large elements. Logical means that the window might be broken into certain-sized elements and the wall would be broken into similar but not necessarily identical elements.

Steps to the automate process would be:

1. The user would designate to the sound intensity instrument the number of vectors through each element desired.
2. The user would then proceed to measure for as long as it took for all the elements under measurement to turn from "red to green" as described above.
3. The user would specify the largest standard deviation acceptable.
4. The software would calculate the mean and standard deviation of the data measured for each element. It is expected that a minimum of about 25 vectors will be required to meet standard deviations on the order of a couple of dB. Note: with a scan size of 2 by 2.5 m (6.5 to 8.2 ft.), this 25 vector per element requirement suggests that the smallest element size be about 20 by 25 cm (8 × 10 inches) in order to keep the total number of vectors in a reasonable range.
5. The measurements would be complete for elements having standard deviations within the specified limit and the power flow would be given by the average of the vectors measured for that element.
6. If the standard deviation for any element exceeded the standard deviation criterion, this would indicate that that element had some hot spots in part of the area of the element compared to the rest. In that case, the software should divide that element into four sub-elements and the measurement for just *that element* should be again repeated until the user-specified number of vectors is measured for each sub-element. The standard deviation should then be calculated by the sound intensity instrument for each sub-element to see if it now meets the standard deviation criterion.
7. This process should continue until the element size is smaller than the maximum resolution that the system is capable of, about 5 cm (1.8 in.) in a 1 m × 1.5 m (3.2 ft. × 4.9 ft.) area or 10 cm (3.6 in.) in a 2 m × 2.5 m (6.5 ft. × 8.2 ft.) area.

The only things the user would need to specify would be the number of vectors per element (generally 25 vectors should be a sufficient quantity), and the standard deviation desired (it is expected that the standard deviation will be in the range from 2.5 to 5 dB). Of course, the user would need to wave the sound intensity instrument over the surface area in question until all areas were covered to the degree required. This may entail several data collections necessitated for resetting the gyroscopes. Measuring more than the minimum number of vectors in any element is not a problem, as long as all the vectors in that element or sub-element are averaged together. But again, ultimately, there must be one average vector for each element or sub-element, and the power flowing normal to the surface of that element or sub-element must be the real part of the single average vector through that element or sub-element, and the intensity must be the power represented by this vector divided by the area of the element or sub-element.

In addition to the above there are several minor suggestions as follows:

1. As it is now, the cradle of the sound intensity instrument must be placed on a level surface such as a table, some ledge, or a chair or the floor. The sound intensity instrument cradle could be supported by a camera tripod if there were a 1/4-20 camera tripod mount situated at the balance point for the sound intensity instrument cradle with wand. This would provide much greater flexibility in positioning the cradle.
2. As it is now, the calibration tool must be placed on a flat surface and must lean against some vertical surface. The checkerboard, like the cradle, needs greater flexibility in positioning and supporting it. The checkerboard should include holes in the two upper corners with a small cord affixed to these two holes for hanging the checkerboard in various places. This could

include a pair of magnets with a hook on one of the magnets so that magnets could be on either side of drapery, or a shade, and would then support the checkerboard cord on the hook. Or, the magnet with the hook could be affixed to metal surfaces like a filing cabinet, and again supporting the checkerboard cord by the hook on the magnet. Also, the cord on the checkerboard could be attached to a hook that had a 1/4-20 camera tripod mount, and supported by another tripod. There needs to be more ways to conveniently support the instrument cradle and the checkerboard.

3. There needs to be several colors for the light on the sound intensity instrument so that good contrast is obtained with various lighting conditions and various wall colors. The current whitish light works well indoors with little sunlight in the room, but does not work well outdoors or in a sunlit room, except at dusk or night.

4.7.5.5 Conclusions

1. From the measurements, the research team has been able to conclude that intensity can form the basis for portraying sound flow through a wall into a room, but that the enhancements described above are necessary for these measurements to be feasible and obtainable in acceptable time duration.
2. Measuring intensity minimizes, or eliminates, the problem generated by reflections off of surfaces and other problems generated by complex (i.e., real and imaginary) pressure waves, because only the real power through the wall is measured.
3. The research team has shown that measuring from indoors to outdoors, and using reciprocity is the clearest way to use intensity for TL measurements. Under this scenario, one creates a loud reverberant field in the indoor space and measures the power flow out of that space to the precision and the extent required. This likely amounts to a redefinition of TL, but, as discussed in the report, measurements made this way hold the promise of being much more repeatable because the resonant effects of using pressure are eliminated. However, the definition and numerical value for measured TL change and the numerical values will be on the order of minus ~50 to 55 dB, rather than minus ~25 dB.
4. Currently, resonance effects for a microphone outdoors and close to the house under test are subject to ground reflection and wall reflection issues that can create large errors. The most obvious means to gain regularity is to position the microphone where it measures the free field impinging on the house. On the other hand, creating a reverberant field inside a room and measuring intensity outside makes measurements feasible on any day that the weather is not too poor outside to make acoustical measurements, e.g., too much wind or precipitation. These measurements will be repeatable and will have good signal-to-noise ratio.

4.8 Comparison of Results Across All Methods

Table 4-24 provides a comparison of all results across measurement and calculation methods. The research team found the following:

1. There is decent agreement between all methods, once corrections have been applied.
2. The flyover and elevated loudspeaker methods had the lowest NLR difference and lowest standard deviation.
3. The ground-level loudspeaker had a relatively high standard NLR difference, meaning it may be under predicting NLR performance. This may be because of the difference in angle of incidence between a ground-level source and an elevated source such as an aircraft/elevated loudspeaker.
4. The interior loudspeaker, with the 5-dB correction, had a low NLR difference but high standard deviation. This puts into doubt its validity at this time.
5. The spreadsheet and IBANA calculation methods tended to over predict NLR.

Table 4-24. Comparison of NLR calculations to acoustical measurements.

Residence	Room	Average NLR (no int. spkr.)	Flyover	Diff. from Avg NLR	Elevated Loudspeaker	Diff. from Avg NLR	Ground Loudspeaker	Diff. from Avg NLR	Interior Loudspeaker	Diff. from Avg NLR	Spreadsheet	Diff. from Avg NLR	IBANA	Diff. from Avg NLR
San Diego #1	Living	26.2	26.3	-0.1			24.5	1.7	24.3	2.0	28.1	-1.9	26	0.2
	Dining	26.4	28.0	-1.6			22.2	4.3	25.2	1.2	28.5	-2.1	27	-0.6
San Diego #2	Living	26.1	24.3	1.9			25.2	1.0	23.2	2.9	28.1	-2.0	27	-0.9
	Office	23.3	20.4	2.9			18.4	4.9	22.8	0.5	27.3	-4.0	27	-3.7
San Diego #4	Living	23.4	23.3	0.1			21.6	1.8	22.6	0.8	24.7	-1.3	24	-0.6
	Bedroom 1	26.8	26.4	0.4			25.0	1.8	26.9	-0.1	29.7	-3.0	26	0.8
San Diego #5	Living	25.0	24.0	1.0			21.3	3.7	23.6	1.4	29.8	-4.8	25	0.0
	Bedroom 1	29.0	30.0	-1.1			26.3	2.7	35.5	-6.6	30.5	-1.6	29	-0.1
San Diego #6	Living	21.9	24.9	-3.0	21.0	0.9	20.9	1.0	23.1	-1.2	17.8	4.1	25	-3.1
	Dining	27.5	27.4	0.1	23.7	3.8	26.4	1.1	26.1	1.4	31.0	-3.5	29	-1.5
San Diego #7	Family	26.4	26.5	-0.1	25.6	0.8	25.7	0.7	22.8	3.6	27.2	-0.8	27	-0.6
	Living	25.1	25.1	0.0	23.8	1.3	24.6	0.5	18.5	6.7	27.5	-2.4	24	1.1
San Diego #8	Dining	21.2	19.4	1.9	19.9	1.3	19.6	1.7	20.9	0.3	23.3	-2.1	24	-2.8
	Master Bed	26.7	22.2	4.5	28.6	-1.9	28.3	-1.6	27.3	-0.6	27.3	-0.6	27	-0.3
San Diego #9	Living	21.3	21.8	-0.5	19.8	1.5	19.4	1.9	21.8	-0.5	22.3	-1.0	23	-1.7
	Bedroom 1	28.3	31.7	-3.4	26.1	2.2	25.6	2.7	27.6	0.7	30.3	-2.0	28	0.3
San Diego #10	Bedroom 1	20.1	17.5	2.6	18.9	1.2	17.6	2.5	23.7	-3.6	23.5	-3.4	23	-2.9
	Bedroom 2	25.9	25.0	0.9	25.3	0.7	25.1	0.8	27.0	-1.1	28.3	-2.4	26	-0.1
Boston #6	Dining	23.1	20.2	2.9	25.0	-1.9	25.0	-1.9	25.0	-1.9	21.3	1.8	24	-0.9
	Bedroom 2	22.3	22.0	0.3	25.1	-2.8	24.9	-2.6	26.9	-4.6	19.3	3.0	20	2.3
Boston #8	Living	24.8	24.2	0.6	25.0	-0.2	24.8	0.0	27.7	-2.9	25.0	-0.2	25	-0.2
	Study	27.0	29.5	-2.5	26.6	0.4	25.7	1.3	23.7	3.3	26.2	0.8	27	0.0
Average Difference				**0.4**		**0.5**		**1.4**		**0.1**		**-1.3**		**-0.7**
Standard Deviation				**1.9**		**1.7**		**1.8**		**2.9**		**2.1**		**1.4**

Notes:
1) Corrections applied—Flyover: 2 dBA, Exterior loudspeaker: 2 dBA, Interior loudspeaker: 5 dBA.
2) Average NLR difference calculated by first averaging all of the NLR across all measurement methods (except interior loudspeaker and sound intensity), and then subtracting the NLR from one method (e.g., flyover) from the average NLR. Interior loudspeaker not used in average as this method does not follow national standards and the 5 dB correction applied to the data is based on limited field measurements (i.e., not fully vetted).
3) All differences are calculated by subtracting from the average noise reduction.
4) Blank cells indicate no elevated loudspeaker test was performed at the corresponding residence.

4.8.1 Outliers

There were some rooms measured where the noise reduction results fell outside of the expected range of noise reduction and/or the flyover noise reduction varied significantly from the exterior loudspeaker noise reduction. A deeper analysis was performed for each of these rooms to determine why the results were atypical. The following summarizes the findings:

- San Diego #1
  - Dining Room: The difference between the flyover and exterior loudspeaker noise reduction was 9 dB, which is significantly more than the expected 3 to 4 dB.
    Why: Based on the review of the airport's typical arrival flight tracks (viewed via the airport's tracking software), a majority of the arrival flight paths are just south of the home. The dining room is at the north end of the home, and the dining room windows would be

shielded from aircraft noise during the flyover measurements from the large overhang at the east façade and the building itself for the north façade. The living room windows are not shielded (i.e., they have full line-of-sight to the arriving aircraft), and the room did not have the large flyover vs. loudspeaker noise reduction difference.

- San Diego #6
  - Living Room: The difference between the flyover and exterior loudspeaker noise reduction was 7 dB, which is significantly more than the expected 3 to 4 dB.
    Why: Based on the field notes, the large difference between the flyover and loudspeaker measurements is due to the presence of a pass-through air conditioning (PTAC) unit in the living room window. PTAC units provide little noise reduction and serve as a significant path of noise intrusion into a unit. The exterior loudspeaker test resulted in much lower noise reduction than the flyover test, as the loudspeaker is pointed directly at the PTAC, whereas an aircraft flyover is above the PTAC. During an aircraft flyover, there is shielding provided by the PTAC sheet metal enclosure and, possibly, the angle of incidence from the flyover results in less aircraft noise intrusion via the PTAC. The measurement results show significantly more mid- to high-frequency noise intrusion.
  - Dining Room: The difference between the flyover and elevated loudspeaker measurement was 6.8 dB, whereas the difference between the flyover and ground-level loudspeaker was 4.1 dB.
    Why: The reason for this difference is the same as the living room explanation above, as the dining room is open to the living room.
- San Diego #8
  - Master Bedroom: In this case, the flyover noise reduction was lower than the loudspeaker noise reduction by approximately 3 dB; typically, flyover NLR are 3 dB higher than loudspeaker NLR.
    Why: The loudspeaker noise reduction was higher than the flyover noise reduction because the research team was only able to generate loudspeaker noise at the side wall of the bedroom. The rear wall of the bedroom contained additional windows and a door (which was acoustically weak), but the research team was not able to direct the loudspeaker noise to the rear façade due to the detached garage located just outside of the bedroom. The research team would have expected much lower noise reduction from the loudspeaker test if it were able to generate noise at both the side and rear bedroom walls.
- San Diego #9
  - Bedroom 1: The difference between the flyover and exterior loudspeaker was approximately 9 dB versus the expected 3 to 4 dB.
    Why: There is a solid overhang at the bedroom window. Using noise modeling software, the research team modeled the noise level from an aircraft flyover with and without the overhang. The noise level at the bedroom window was 7 dB lower with the overhang. The overhang does not shield noise generated by the loudspeaker, thus it makes sense that the measured flyover noise reduction was significantly higher than the loudspeaker noise reduction (the overhang serves to increase the noise reduction of the windows).
- Boston #6
  - Dining Room: The flyover noise reduction was lower than the loudspeaker noise reduction by approximately 2 dB; typically, flyover NLR are higher than loudspeaker NLR.
    Why: The dining room is open to the living room and kitchen. During the flyover measurements, noise enters the home via all of these rooms and is measured by the meter in the dining room. For the loudspeaker measurement, noise is only generated toward the dining room and the meter only picks up noise intrusion via the dining room façade. There are significant paths of noise in the connected living room and kitchen (e.g., exterior doors, PTAC units), which lowers the measured noise reduction during the flyover test.

4.9 Comparison of Measurement Results from Loudspeaker and Flyover Testing

It is reasonable to assume that if both the loudspeaker and the flyover measurement methods are valid and properly conducted, the NLR results from the two should closely agree. Unfortunately, this is not always the case, as shown by measurements for this study and previously those for the ATAC study, "Study of Noise Level Reduction (NLR) Variation" (Landrum and Brown, 2013). The ATAC study concludes,

> Figure 39 and Figure 40 summarize the measured variations as a result from various measurement methods, parameter changes, and absorption changes. The total variation of NLR measurements is comprised of many causes, each introducing their own variations to the total. This study includes a subset of a number of possible causes that contribute to the total NLR variation. Section 6.1 listed various aspects that contribute to the NLR variation. To quantify the total NLR variation, the variation of individual components that contribute to the total NLR needs to be quantified separately.

This ACRP Project 02-51 study carefully conducted loudspeaker and flyover measurements at SAN on the same rooms, identically furnished, generally on the same day. Thus, certain parameters such as changes in acoustical absorption or architectural modifications were eliminated. Nonetheless, notable differences in NLR measurement results were encountered from the raw data results. However, when various adjustments were made in accordance with national and international standards for microphone position, the various methods agreed closely.

To the knowledge of the research team, the ATAC study and this study are the first time that careful comparative acoustical measurements had been made to assess the differences in measurement results from the flyover and loudspeaker methods. Measurements made in the course of the RSIP's do not make redundant measurements in the interest of time, efficiency, and cost.

Acoustical theory and experience leads to two likely alternative possible causes for the discrepancies:

- **Angle of incidence:** Acoustical theory and measurement show that under some circumstances, sound impinging on a building element at a grazing angle may transmit sound more effectively (providing less sound attenuation) than that normal to the element or at moderate angles.
- **Insufficient flyover high-frequency sound energy:** Most of the high-frequency sound energy from aircraft flyovers is absorbed by the atmosphere before it reaches a home, and the sound insulation of the building envelope further reduces this energy to levels that may be at or below the ambient high-frequency sound level in the residence.

4.9.1 Angle of Incidence

All U.S. and international standards for sound insulation measurement and reporting specify "random incidence" testing whereby sound impinges the test specimen equally at all angles. This is achieved by creating a diffuse and random sound field in the sound source room while recording a spatial average of the sound field in the receiving room. Early laboratory sound TL tests for various window glass (circa 1960's) often report STC values two to three points above those from later tests. This is because the early tests failed to create a random sound field; sound at grazing incidence was not effectively achieved. However, the effect of grazing incidence is complex and varies considerably with the type of material being acoustically tested.

Figure 4-23 conceptually shows the primary TL effects in various frequency regions for a composite building element such as a wall section composed of wood paneling or stucco on one side, batt insulation in the interstitial space, and gypsum board on the other face. At random

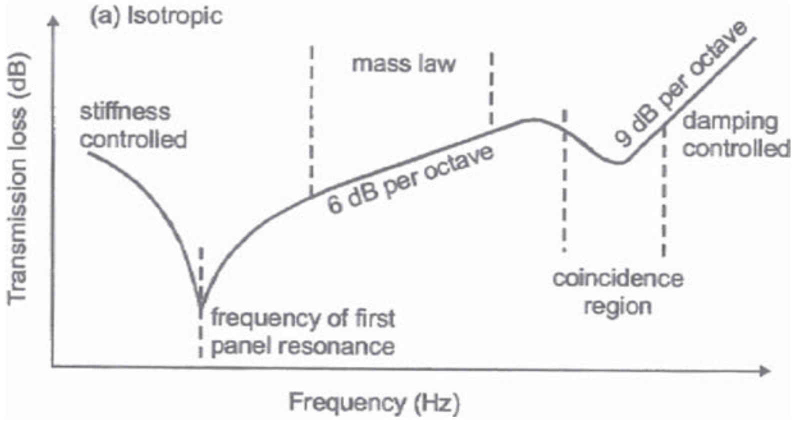

Figure 4-23. Theoretical transmission loss (Bies and Hansen, 2003).

incidence, materials are typically acoustically isotropic in that they produce the same TL when tested from either side of the building element.

The actual frequencies for the first panel resonance, other resonances, and coincidence areas may be computed from the mass and stiffness properties of the various materials. However, incidence effects are more prominent in monolithic materials, such as glass, than in composite building elements like walls and roof/ceiling systems. Additionally, incidence effects are greatest in the high frequencies, above the coincidence region, and generally minimal at low frequencies. Under ideal conditions, a difference in TL between random and optimum grazing angle (90°) of 5 dB is possible for monolithic materials, and up to 3 dB for composite materials.

The effects of grazing incidence on residential sound insulation from aircraft have been studied by the National Research Council, Canada (Bradley et al. 2002, Bradley 2002). Incidence effects were found to be entirely negligible at loudspeaker angles down to 30°. However, at full grazing incidence a nominal 3 dB correction is found. The effective (corrected) incident level Ls″(f) is calculated:

$$Ls''(f) = Ls(f) + 10\log\left\{\left(\frac{\phi}{180}\right)\cdot D(f)\right\}dB$$

Where ϕ is the horizontal angular view of the fly-by and $0 \le \phi \le 180$. (Note that ASTM E966 and this report Figure 4-24 use 'ϕ' for the vertical angle and 'θ' for the horizontal angle.)

The optional correction simply relates the incident sound energy to the portion of the aircraft flyover that is visible at the façade with a small empirical correction for diffraction. That is, the incident sound energy is reduced when the aircraft flyover is not completely visible at the façade.

However, the application of angle of incidence is more complicated in practice for the following reasons:

- Building facades are composed of several various sized elements, monolithic and composite, each with different angle of incidence TL properties.
- While the vertical angle, ϕ, from the flyover may be fairly constant, the horizontal angle, θ, varies throughout the event.
- While one façade is receiving grazing incidence, the perpendicular side is receiving normal incidence. In corner rooms both occur at once.
- As shown in Figure 4-24, part of the home is shadowing another portion of the home during part of the flyover.

- Façades are composed of different elements, some more susceptible to angle of incidence than are others.
- The TL is not isotropic but orthotropic, meaning that the TL varies with direction. The actual model for orthotropic TL is more complicated than that outlined in Figure 4-23.

It is therefore highly impractical to establish a protocol to account for angle of incidence effects. These effects also make it difficult to distinguish the effects of angle of incidence from insufficient flyover high-frequency sound energy in quantifying the sources of the loudspeaker and flyover NLR result discrepancies.

The incidence effects discussed here are different than the coincidence dip effects of dual-glazed windows discussed in Appendix C.

4.9.2 Insufficient Flyover High-Frequency Sound Energy

Turbine aircraft noise is generally broadband near the source; that is, it has fairly equal acoustic energy per bandwidth. However, the effects of spherical radiation and atmospheric absorption substantially attenuate the noise at RSIP residences, particularly in the higher frequencies. Figure 4-25 shows the attenuation of a Boeing 737 (300 thru 500 series) departure using the FAA standard spectra at 305 meters (1,000 feet) (John A. Volpe National Transportation Systems

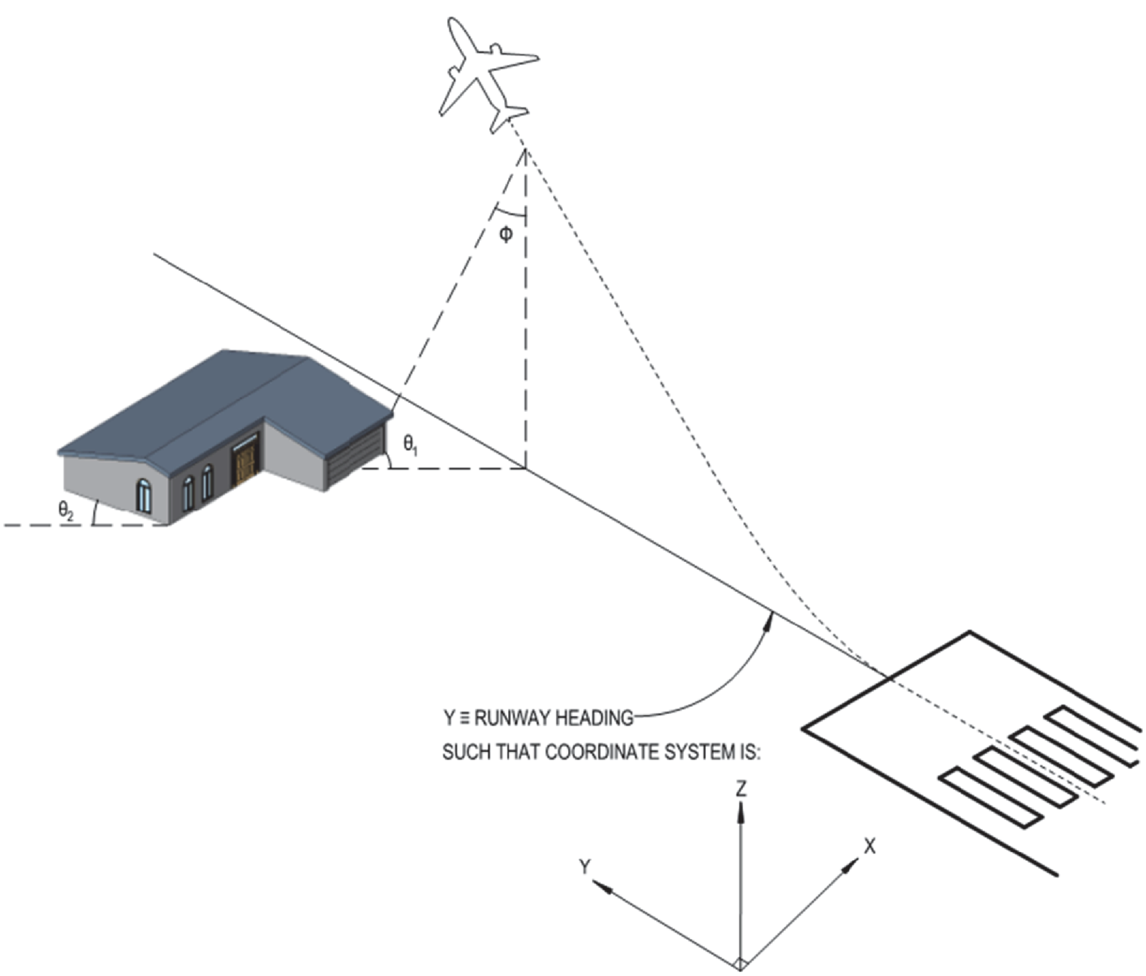

Figure 4-24. Aircraft flyover diagram.

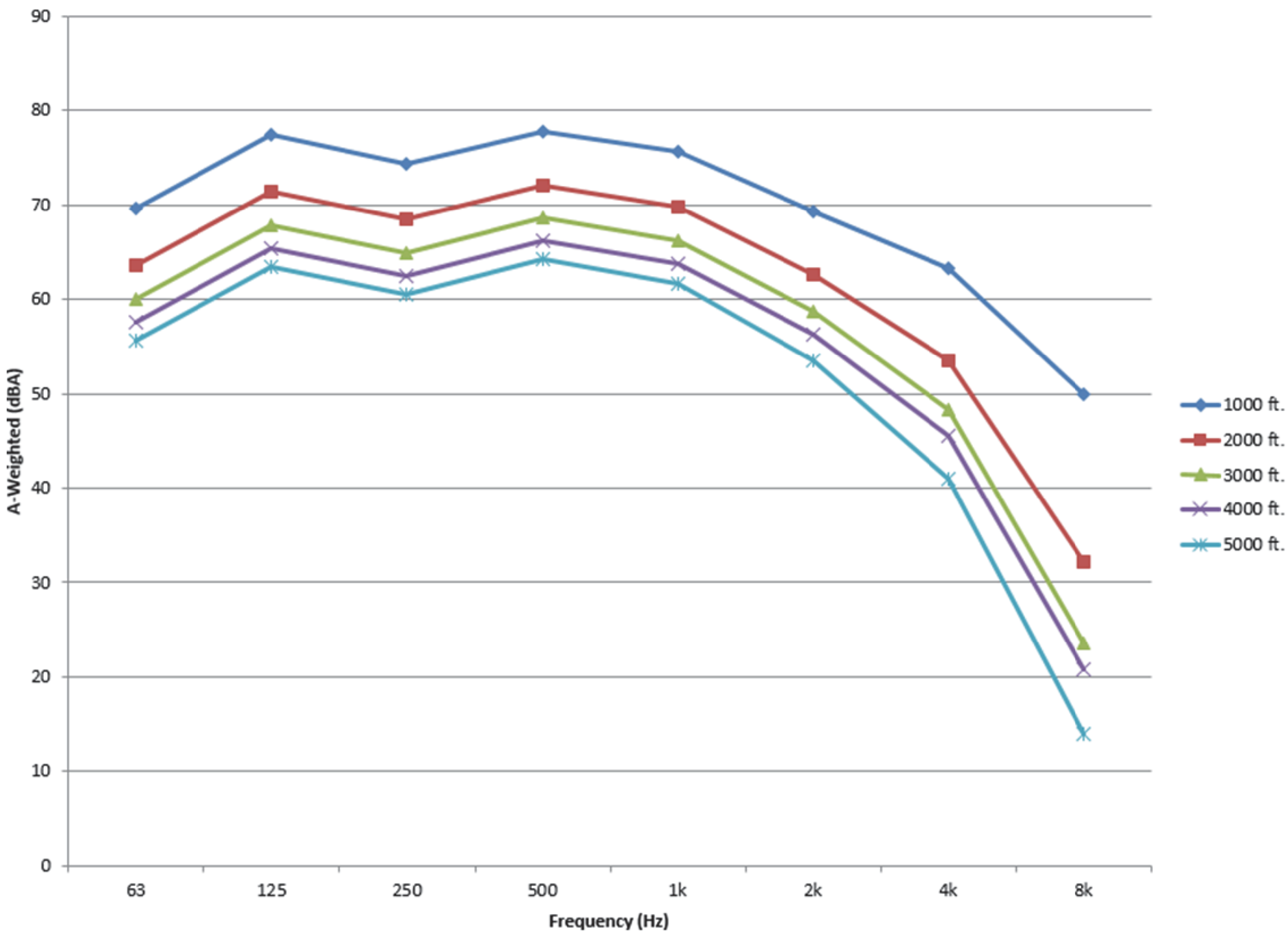

Figure 4-25. B737 departure noise level by distance.

Center, 1999). The attenuated spectra were computed from the FAA spectrum at 1,000 ft., taking into account spherical radiation and atmospheric absorption from the ANSI S1.26 standard.

If insufficient flyover high-frequency sound energy were a significant factor, it would be expected that those residences with higher ambient interior noise would be the most influenced; that is, the difference between the loudspeaker and the flyover NLR would be the greatest for the higher ambient noise rooms measured. However, when this hypothesis was examined, it was determined that the low signal-to-noise ratio of interior flyover noise in the higher frequencies is a minor issue and generally does not create a significant discrepancy.

However, several homes did encounter alteration of NLR results when the interior high-frequency ambient noise levels came close to the interior flyover noise levels. For this reason, the research team recommends that all exterior and interior measurements be band limited to an upper frequency limit of 5 kHz.

4.10 Suggested Research

With this project, the research team has clarified several sources of systematic error and identified improved ways to do these tasks. But not all of the improvements have been accomplished, since some of these improvements require further research.

4.10.1 External Sound Spectra

A significant factor that affects the measured noise reduction is the external sound spectra (i.e., the noise "signature" of aircraft overflights at a given airport). The external DNL frequency spectrum to be modeled (from the FAA Part 150 program Noise Exposure Map) is, in itself, unknown since it is the annual energy average of all aircraft over a particular location, with the 10 dB nighttime penalty (a single nighttime flyover is equal to 10 daytime flyovers of the same level), under all annual meteorological conditions; it can only be estimated. The spectra of louder aircraft should be biased on an energy basis; for instance, a single flyover at 90 dB should be averaged equally with 10 flyovers at 80 dB.

Many commercial airports with significant incompatible residential land use (i.e., above 65 DNL) have noise monitoring systems. These currently only measure A-weighted SEL values of individual flyover events, and compute daily DNL values. However, these monitors may be modified to collect spectral information in terms of SELs. This would allow for computation of the daily DNL aircraft spectrum at that location. Future programs could use this information to design the exterior sound spectrum to be used in testing and evaluation of NLR values.

Since the sound spectra could not be addressed in the field measurements conducted for this report, the issue of external sound spectra is beyond the scope of this study. Additional research and investigation is suggested.

4.10.2 Ground and Façade Reflection for Flyover Measurements

As noted in the study, the research team applied a 2-dB correction to the exterior flyover measurements to account for ground reflection. The research team believes that up to a 4 dB correction is needed if there is ground reflection in combination with reflections off the façade being tested (based upon modeling and calculations made). This reflection phenomenon, with respect to exterior flyover measurements, should be investigated in more detail so the corrections can be standardized and codified.

4.10.3 Interior Loudspeaker

The research team found that the interior loudspeaker measurements resulted in systematically high NLR values. Based on additional measurements conducted after the initial round of field measurements, the research team applied a 5-dB correction to the interior loudspeaker NLRs. This correction is based upon reverberant noise build-up measured inside of the room. However, this correction is not codified in any standards, nor are any other aspects of the interior loudspeaker measurements (e.g., position of the receive microphone on the outside of the building).

Further research should be conducted to standardize the interior loudspeaker measurement method so that results can be comparable to the exterior loudspeaker and flyover measurement methods.

4.10.4 Sound Intensity

Prominent on this list of future research is the use of an indoor loudspeaker with measurements made outdoors, since this offers so many clear advantages, such as there being no problem with neighbors, no problem with microphone placement (at least for intensity), good signal-to-noise ratio, and the smallest uncertainty. Some of the research questions would be:

1. Where and how should the indoor sound in the source room be measured?
2. Where and how should the outdoor sound be measured?
   a. Should a wall be divided into its elements, i.e., the windows, doors, and regular wall considered all separate, or as the total combined partition?

[NOTE: The above task 2.a is the same for both sound intensity and the interior loudspeaker described just above. These two methods depart in terms of the outdoor measurements. The intensity will be measured on or just beyond the surface of the wall to measure the power flowing from the reverberant room. For the interior loudspeaker measurements using pressure (microphones), one needs one or more microphones at some "free field" or pressure-doubling positions to measure just the integrated power flowing from the test room.]

b. Develop methods and procedures to measure the power flowing through the wall surface.
c. Improvements to the intensity meter are detailed in Section 4.7.5.4. These include:
    a. One mandatory software requirement for making unambiguous measurements of power flow through a surface is that there be a single defining vector for each element that represents the average of all the vectors through that element, that all the elements be independent and not overlapping, and that the sum of the elements equals the area of the surface under test.
    b. The second mandatory software requirement is that all overlap must be avoided. One cannot tolerate a situation where there is overlap between two or more elements, and the sum of elements must cover the entire wall under test.
    c. Several small hardware changes.
    d. Several major enhancements that would be "nice to have."

4.10.5 Field Measurement Uncertainty

Another research need is data that can better quantify measured field uncertainties. For example, the research team suggests herein that the tolerance on positioning a repeat measurement to the original measurements is unknown. Data are needed to answer this multifaceted question. The term multifaceted is used because the comparison can be the same technicians and equipment doing the same measurements in the same room twice, or it could be as varied as different people from a different company with different equipment and no knowledge of the placement of the equipment by the previous company. The research team proposed that the emphasis would be on the simplest situation since most often, the same company and people make the before and after measurements in the same house. The goal would be to understand the variation in results based primarily on the tolerance of the equipment placement and perhaps some second-order factors. This testing would provide a better understanding of the tolerance of repeatability under the most careful methods and conditions.

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Thomas, Ashwin, E. Ryherd, T. Bowling, and J. Irizarry. 2014. "Simulated and Laboratory Models of Aircraft Sound Transmission." *The Journal of the Acoustical Society of America*, Volume 135, Issue 4.

Trans Systems Corporation in association with Wyle Laboratories. 1977. Study of Soundproofing Public Buildings Near Airports. Washington, D.C.: Federal Aviation Administration, Office of Environmental Quality, Arlington, VA.

Vermeir, G., G. Geentjens, and W. Bruyninckx. 2004. "Measurement and Calculation Experience on Facade Sound Insulation." *INTER-NOISE and NOISE-CON* Congress and Conference Proceedings, InterNoise04, pp. 1–685, pp. 444–451(8), Prague, Czech Republic.

Definitions

A-Weighted Sound Level: A standard frequency weighting that filters the microphone signal in a manner that compares relative loudness of various sounds. A-weighting is standardized by ANSI. A 10-dB increase in sound level is generally perceived to be approximately twice as loud. All noise data in this report are A-weighted.

Community Noise Equivalent Level (CNEL): A metric used by the state of California for the 24-hour A-weighted average noise level. The CNEL accounts for the increased sensitivity of people to noise during the evening and nighttime hours. From 7 pm to 10 pm, sound levels are penalized by 5 dB; from 10 pm to 7 am, sound levels are penalized by 10 dB.

Day–Night Average Noise Level (DNL): A metric established by the U.S. EPA to describe the average day–night level with a 10 dB penalty applied to noise occurring during the nighttime hours (10 pm to 7 am) to account for the increased sensitivity of people during sleeping hours.

Decibel (dB): A logarithmic unit used in acoustics to describe the magnitude of a sound with respect to a reference sound level. The term "sound level," "noise level" and "SPL" all imply a standardized reference level near the threshold of human hearing (0 decibels).

Hertz (Hz): The rate or frequency of air pressure fluctuations called sound. One hertz is equivalent to one complete cycle of pressure variation per second. One kilohertz (kHz) is 1,000 cycles per second.

Noise Reduction Coefficient (NRC): A measure of the acoustical absorption performance of a material, calculated by averaging its sound absorption coefficients at 250, 500, 1000 and 2000 Hz, expressed to the nearest integral multiple of 0.05.

Octave band: An octave band is a frequency band where the highest frequency is twice the lowest frequency. For example, an octave filter with a center frequency of 1 kHz has a lower frequency of 707 Hz and an upper frequency of 1.414 kHz.

OITC: Outdoor-indoor transmission class as outlined in ASTM E1332. The OITC spectrum (curve) is based upon an average of aircraft takeoff, train, and vehicular noise sources.

Resonance: A resonance occurs at a certain frequency when the system response at that frequency is significantly higher than at other frequencies. It is somewhat like the squeal heard when a microphone is brought too close to a loudspeaker. In a room, one way to create resonances is for the distance between two parallel walls to be half the wavelength or integer multiples of the wavelength of the sound.

Sound Transmission Class (STC): The sound transmission class is a single number rating describing the attenuation of sound through building partitions. Sound attenuation properties called TL are measured at a minimum of 16 continuous frequency bandwidths in one-third octaves, primarily through the speech range. The STC rating is derived by fitting a standard curve to the measured data as prescribed by ASTM Standard E413.

Spatial Average: Spatial Average refers to the act of manually moving the microphone in front of the façade so as to measure the sound field across the plane of the building façade (i.e., at all points).

APPENDIX A

Sound Intensity Measured Frequency Spectra

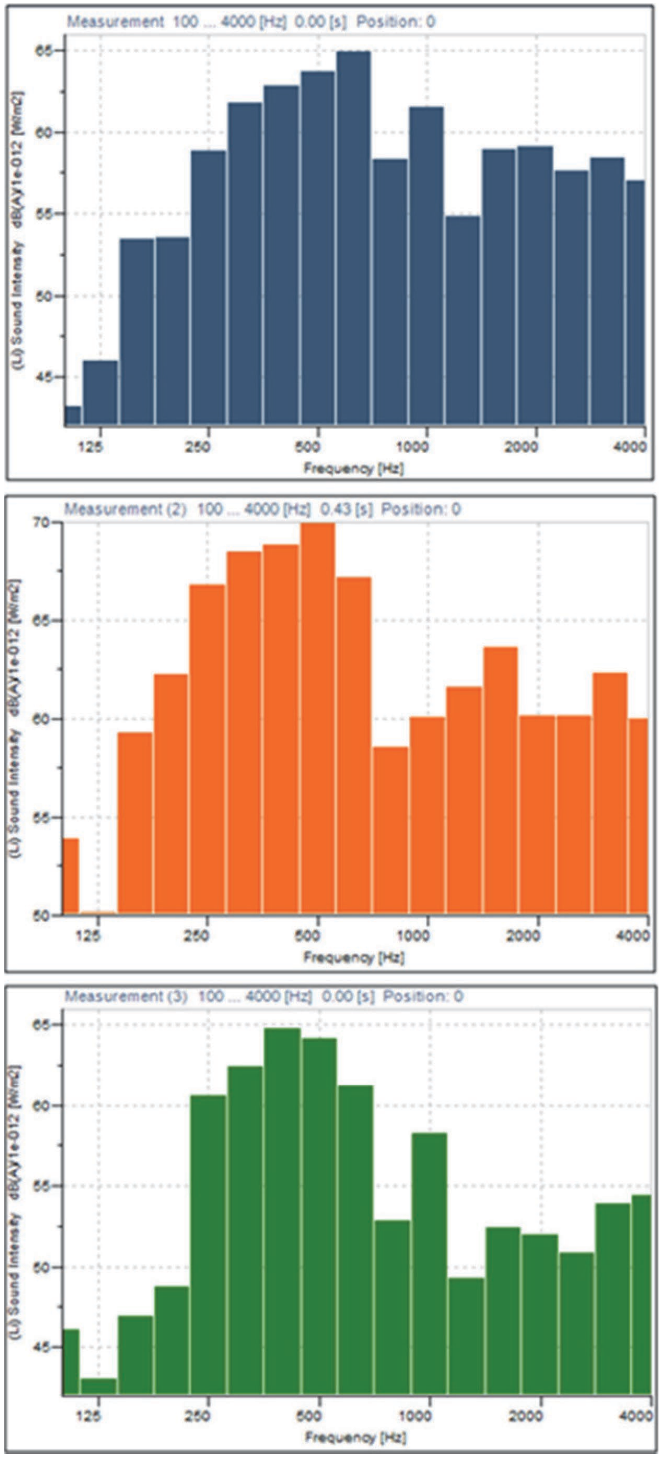

Figure A-1. Corresponding spectra for each of the three measurements shown in Figure 4-18.

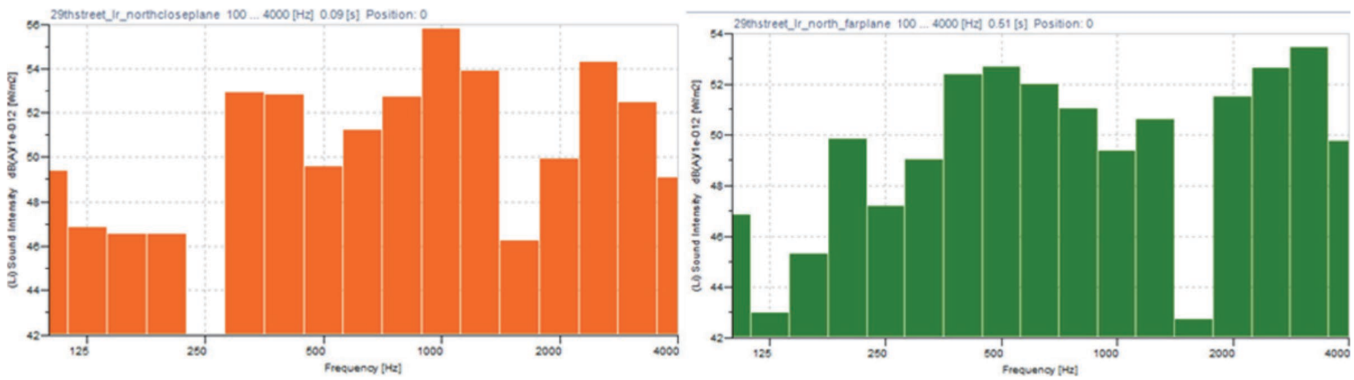

Figure A-2. San Diego #1 spectra.

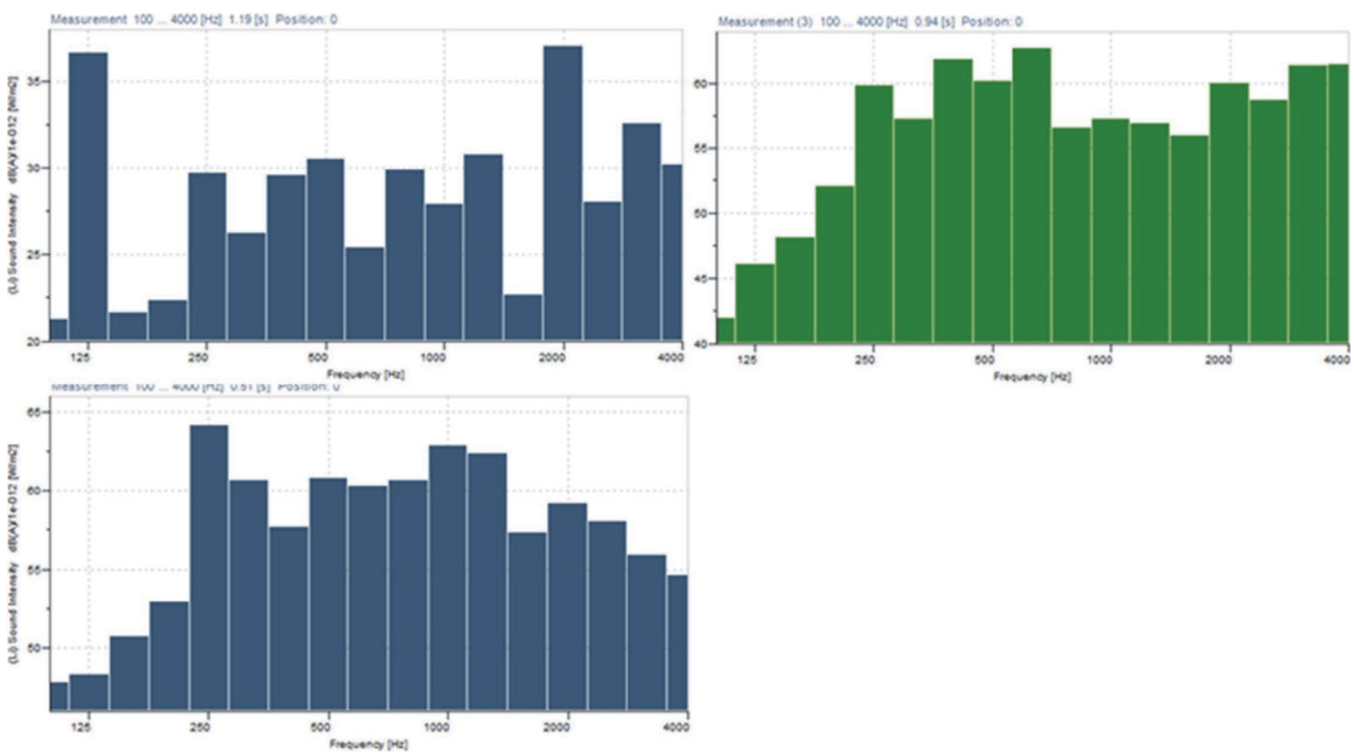

Figure A-3. San Diego #4 spectra.

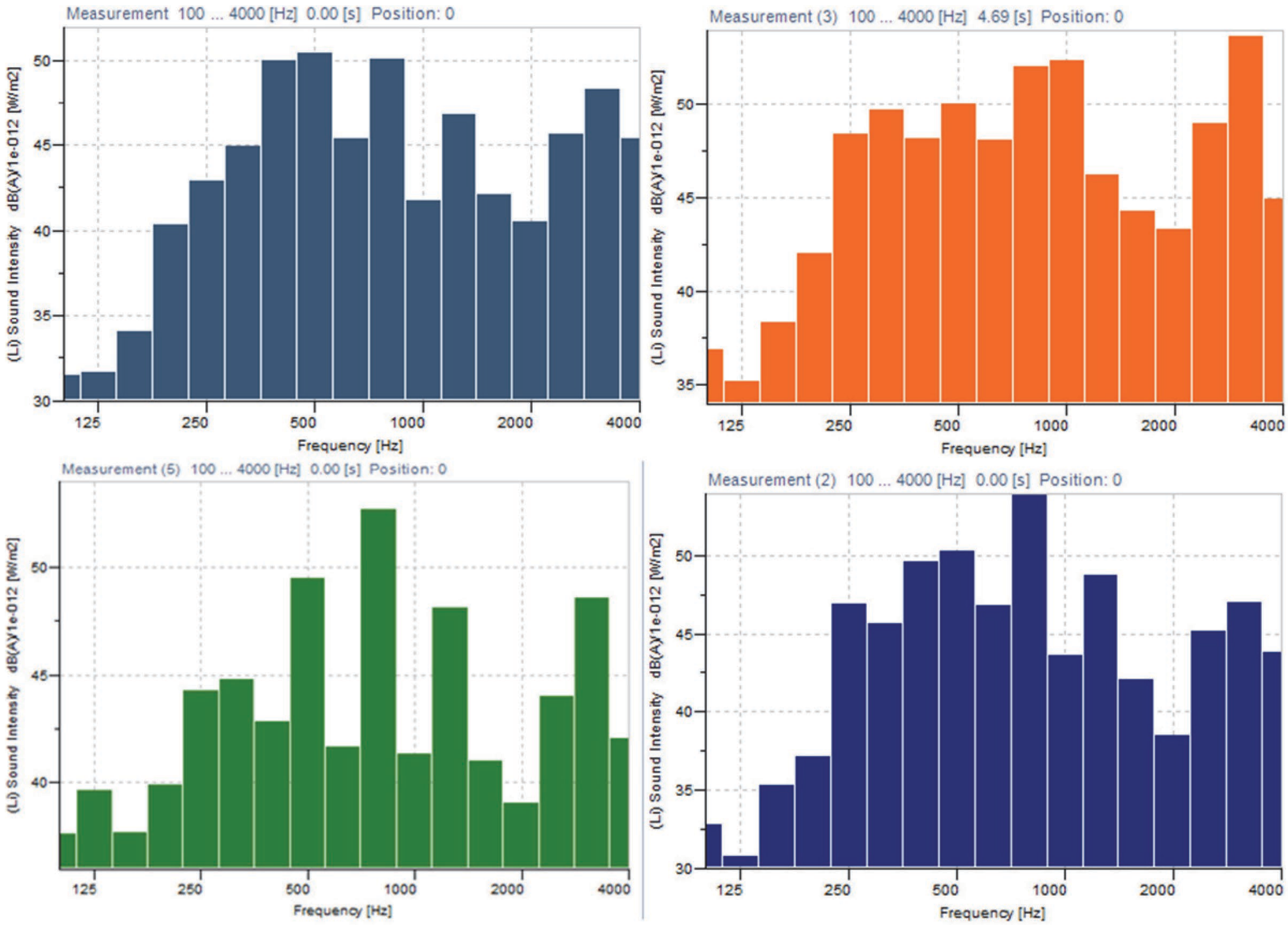

Figure A-4. San Diego #5 spectra.

APPENDIX B

Sound Intensity: Vector Output Compared to Screen Output

The sound intensity instrument with visualization used in this study has two forms of output, the sound power portrayed on the screen and the vector output in a spreadsheet table. The output to the screen, as stated in Chapter 4, is the sum of the powers of all the vectors that go through the area selected by the user for the screen display, each vector being a separate estimate of the power flow. So, the average power flow is the sum divided by the number of vectors. The effect of this operation can be different than one might expect. For example, if one scans a high intensity area that may be half the total area and then displays the data on the screen using that same area as the area for scanning, one would get a sound power. If one had the screen display for the entire area, double the scanning area, the screen would display a sound power that is 3 dB higher. That is, the machine is taking the power in the defined area that the measurement was made in and treating that as an estimate of the intensity of any bigger area the user selects. Likewise, if one scans a low intensity half and then has a screen display for the whole area the output would be much lower than the true power. So the power displayed on the screen really comes from estimates of the intensity times the area. The only way the research team found to regularize this was to take the screen display based on the entire area of the wall. Then all the measurements are normalized to the same area and all the measurement episodes are each an estimate of the power flow.

Inexplicably, the same vectors take on a new dimension when output in the spreadsheet table. The vectors in the spreadsheet table have units of energy, joules. Each vector is a separate estimate of the energy during a measurement episode. The vectors are normalized such that the area under consideration is the entire party wall defined by the user, not any subset. To get the power flowing through the wall one must divide by the number of vectors, since each is a separate estimate, and also divide by the time duration of the measurement episode to convert from joules to watts. Table 4-19 in Chapter 4 shows these power calculations for the five *out to in* and the first of the three *in to out* episodes at the Champaign, IL, residence. Table B-1, in its last column, for reference, contains the power estimates from the display given in Table 4-19. When one adds the five *out to in* power measurements from the screen display, and adds the same five for the vector calculation, the average is the same. The small scatter from one case to the other is believed to be the difference in the total area between what one can control on the screen and what one can select using a mouse. In summary, the screen display is calculating power from intensity times the area, and the vector output is calculating power from joules divided by time.

Table B-1. Comparison of vector outputs.

Position measured	Episode	Time data collected (hr:min; PM)	Number of vectors, *N*	Measurement episode duration		Sum of vector energy estimates Joules (dB)	10*log(*N*) (dB)	10*log(s) (dB)	Average power Watts (dB)	Power from Table 4.19 Watts (dB)	Difference Watts (dB)
				(min:s)	(s)						
Inside	1	4:24	1,242	2:54	174	93.5	30.9	22.4	40.2	41.2	-1.0
	2	4:58	1,896	3:37	217	92.6	32.8	23.4	36.4	38.9	-2.5
	3	5:08	1,966	3:51	231	89.6	32.9	23.6	33.0	31.0	2.0
	4	5:22	1,437	2:28	148	89.5	31.6	21.7	36.2	35.6	0.6
	5	5:52	1,540	2:33	153	95.8	31.9	21.8	42.1	41.1	1.0
						Average difference (Watts)					**0.0**
Outside	1	7:11	1,687	2:47	167	106.4	32.3	22.2	51.9	50.6	1.3
	2	7:20	1,034	1:38	98	not available	30.1	19.9	not available	55.7	not available
	3	7:27	1,642	2:51	171	not available	32.2	22.3	not available	51.5	not available

APPENDIX C

Research Review

As a part of the research project, the research team reviewed various documents related to this study. The following summarizes the findings.

Table C-1. National and international standards.

Document Title	Quantities and procedures for description and measurement of environmental sound, Part 1: Basic quantities and procedures
Publication	ANSI/ASA S12.9-2013/Part 1
Date	June 1, 1993
Summary of Content	This standard defines the basic metrics (quantities) that can be used separately or in combination for the description of community sound and describes basic procedures for measurement of the quantities. The scope of this standard encompasses all types of environmental sounds, separately or in combination, that contribute to the total sound at a site. Defined are consistent metrics for physical quantities that may be used to measure and assess environmental sound. This standard does not specify limits for environmental sounds or recommend measurement locations or durations. This standard is applicable to the description and measurement of community sound for purposes of land use planning, environmental assessment, and noise control.
Relevance to this study	Essentially, the ACRP Project 02-51 aircraft measurements and classic TL measurements are made in accordance with the procedures of clause .2.1 and in particular, sub-clauses (a), (b), and (d). These procedures are only partially relevant to the intensity measurements.
Conclusions/findings/guidance related to this study	NA
In agreement with this study's findings?	NA

(continued on next page)

Table C-1. (Continued).

Document Title	Quantities and procedures for description and measurement of environmental sound, Part 3: Short-term measurements with an observer present
Publication	ANSI/ASA S12.9-2013/Part 3
Date	June 1, 1993
Summary of Content	This standard includes the measurement, with an observer present, of quantities such as equivalent-continuous SPL or sound exposure from a specific source or sources at a specified location. These measurements require several minutes to several hours to perform; they take less than one day to perform. Measurements may be obtained with a standard frequency weighting, may be frequency filtered in a defined manner, or may be frequency filtered by octave band or fractional octave band filters. This standard specifies procedures to effectively eliminate, to the extent possible, the contributions of extraneous background sound from the source-specific measurements. Measurement procedures in this standard require the presence of an instrument operator and are not applicable to measurements by unattended instruments.
Relevance to this study	Essentially, this study's classic TL measurements (using a loudspeaker) are made in accordance with the procedures of S12.9 Part 3.
Conclusions/findings/guidance related to this study	It is to be expected that something so precise as measurement of the TL of rooms in houses to in situ aircraft noise will not directly mesh with general environmental noise measurements.
In agreement with this study's findings?	NA

Document Title	ASTM E 966: Standard Guide for Field Measurements of Airborne Sound Attenuation of Building Facades and Facade Elements
Publication	ASTM Standards E966-2010
Date	2010
Summary of Content	A 15-page standard providing methods to measure the sound isolation of a room from outdoor sound, and to evaluate the sound transmission or apparent sound transmission through a particular façade of the room or an element of that façade such as a window or door.
Relevance to this study	Acoustical measurement techniques are described and discussed.
Conclusions/findings/guidance related to this study	Specific procedures are described in detail.
In agreement with this study's findings?	This standard addresses the major issues, such as angle of incidence, in the measurement techniques. It is state-of-the art for the time of publication.

Table C-1. (Continued).

Document Title	Determination of sound power levels of noise sources using sound intensity — Part 1: Measurement at discrete points
Publication	ISO 9614-1 1993-06-01
Date	June 1, 1993
Summary of Content	This standard is for the measurement of the sound power emitted by some machinery or device. This document introduces various quality indicators and the 3 grades of measurement: precisiongrade, engineering grade, survey grade. This Part 1 is for measurements at discrete points. The indicators deal with such topics as background noise: is it quiet enough? Source variation: is it stable enough? Is it regular enough? Etc.
Relevance to this study	The quality grading system and the corresponding indicators are relevant but not particularly illuminating in the context of this study. This study's source, pink noise, is by definition stable and regular, the background was very quiet so there could be no highly directional extraneous sources. The method of Part 1, discrete measurement points is not relevant to our measurements.
Conclusions/findings/guidance related to this study	None
In agreement with this study's findings?	NA

Document Title	Determination of sound power levels of noise sources using sound intensity — Part 2: Measurement by scanning
Publication	ISO 9614-1 1996-08-01
Date	August 1, 1996
Summary of Content	This standard, like Part 1, is for the measurement oft he sound power emitted by some machinery or device. This document introduces various quality indicators and the 3 grades of measurement: Precision grade, engineering grade, survey grade. This Part 2 is for measurement by scanning. The indicators deal with such topics as background noise; is it quiet enough? Source variation; is it stable enough? Is it regular enough? Etc.
Relevance to this study	The quality grading system and the corresponding indicators are relevant but not particularly illuminating in the context of this study. This study's source, pink noise, is by definition stable and regular, the background was very quiet so there could be no highly directional extraneous sources. The method of Part 2, measurement by scanning is relevant to our measurements
Conclusions/findings/guidance related to this study	The research team is meeting the precision requirements and scanning substantially as recommended.
In agreement with this study's findings?	NA

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Table C-1. (Continued).

Document Title	Acoustics: Determination and application of measurement uncertainties in building acoustics–Part 1: Sound Insulation
Publication	ISO 12999-1
Date	May 15, 2015
Summary of Content	This standard discusses how to calculate and quantify the measurement uncertainty (e.g., margin of error) of sound insulation measurements conducted in acoustical laboratories. Tables of standard uncertainties for different types of sound insulation measurements are provided.
Relevance to this study	While this study's sound insulation measurements were field measurements and not laboratory measurements, this document provides standard uncertainties for situations where a measurement is repeated using the same equipment and staff. The research team did repeat measurements in the field, so it would be reasonable to expect that the measurement uncertainty for this situation is the same as that encountered in the lab.
Conclusions/findings/guidance related to this study	The standard stipulates a 0.4 dB standard uncertainty for repeated measurements (same equipment and staff). The study's uncertainty was 0.4 dB for ground-level loudspeaker and 0 2 dB for elevated loudspeaker, so the results were in line with the ISO uncertainty.
In agreement with this study's findings?	Yes, the research team measured similar levels of uncertainty for repeated measurements as stipulated in the ISO document.

Document Title	Determination of sound power levels of noise sources using sound intensity— Part 3: Precision method for measurement by scanning
Publication	ISO 9614-3
Date	2002
Summary of Content	This standard, like Parts 1 and 2, is for the measurement of the sound power emitted by some machinery or device. The terminology in the first 2 parts was inconsistent and this Part 3 cleaned up these inconsistencies. It draws on the temporal variability and field non-uniformity, negative partial power indicators from Part 1 and concepts from Part 2 to create a coherent set of indicators.
Relevance to this study	Again, this quality grading system and corresponding indicators are relevant but not particularly illuminating in the context of this study. This study's source, pink noise, is by definition stable and regular, the background was very quiet so there could be no highly directional extraneous sources. The method of measurement by scanning is relevant to the research team's measurements.
Conclusions/findings/guidance related to this study	Again, the research team is meeting the precision requirements and scanning substantially as recommended.
In agreement with this study's findings?	NA

Table C-1. (Continued).

Document Title	Acoustics — Field measurement of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation
Publication	ISO 16283-1
Date	Feb. 15, 2014
Summary of Content	This 50-page standard specifies procedures to determine the airborne sound insulation between two rooms in a building using sound pressure measurements. These procedures are intended for room volumes in the range from 10 m^3 to 250 m^3 in the frequency range from 50 Hz to 5000 Hz. The test results can be used to quantify, assess and compare the airborne sound insulation in unfurnished or furnished rooms where the sound field may or may not approximate to a diffuse field. The measured airborne sound insulation is frequency-dependent and can be converted into a single number quantity to characterize the acoustic performance using the rating procedures in ISO 717-1.
Relevance to this study	Acoustical measurement techniques are described for internal room-to-room measurements, not for exterior measurements.
Conclusions/findings/guidance related to this study	Specific procedures are described in detail.
In agreement with this study's findings?	This standard addresses only interior noise reduction measurement. However, many of the techniques described and discussed are applicable to exterior measurement.

Table C-2. FAA documents.

Document Title	FAA Advisory Circular 150/5000-9A, Announcement of Availability Report No. DOT/FA7A/PP/92-5, Guidelines for the Sound Insulation of Residences Exposed to Aircraft Operations
Publication	FAA Advisory Circular 150/5000-9A
Date	July 02, 1993
Summary of Content	Announcement and inclusion of a 234-page report by Wyle Laboratories for the Naval Facilities Engineering Command, Guidelines for the Sound Insulation of Residences Exposed to Aircraft Operations, July 2, 1993.
Relevance to this study	Outlines the basic methods and procedures for sound insulation of residences used in most sound insulation projects.
Conclusions/findings/guidance related to this study	This is mostly a handbook guide for residential sound insulation. It does not rely on acoustical measurement but provides good general guidance for retrofit sound insulation treatment by home type and basic construction.
In agreement with this study's findings?	The research team agrees with most of the conclusions and recommendations if sound insulation is to be undertaken without the aid of acoustical measurements.

Table C-3. Research papers/reports.

Document Titles	*Measurements of the Sound Insulation of a Wood Frame House Exposed to Aircraft Noise* (IRC IR-831), Bradley et al., 2002. Interference Effects in Field Measurements of Airborne Sound Insulation of Building Facades. Berardi, U. *Noise Control Engineering Journal*, April 2011. The Position of the Instruments for the Sound Insulation Measurement of Building Facades: From ISO 140-5 to ISO 16283-3. Berardi, U. *Noise Control Engineering Journal*, February 2013. Sound Fields Near Exterior Building Surfaces. Quirt, J.D. *Journal of the Acoustical Society of America*. February, 1985.
Date	Multiple (see above)
Summary of Content	Berardi (2011, 2013), Bradley et al. (2002), and Quirt (1985) all have very similar content. Each is a theoretical analysis of potential geometric resonances. All use pure tone (single frequency) analyses. Quirt also provides a simple model to obtain these analyses for bands of noise. Figure 1 (after Berardi, 2011, Figure 4) is typical of these analyses. These dramatic dips and curves never occur in the real world when using bands of noise. The only dip that does normally occur is the broad ground dip. Even the broad ground dip is usually predicted to be deeper than is measured. Figure 2 (after Bradley et al., 2002, Figure 4) provides a good example of this phenomenon, and there are several other such examples in this report. Berardi (2013) and Bradley and Chu (2002) provide data upon which some inference as to the standard deviations can be made. In addition to ground dip, a second major problem is the mass-air-mass resonance (MAM) of double-glazed windows (Berardi 2013). This is probably the weakest link in the sound insulation of the wall and it will change with orientation. And the MAM frequency range pretty well coincides with ground dip. There also are effects from the angle the source makes with the house surface in question.
Relevance to this study	These topics, data, and results are all highly relevant to this study.
Conclusions/findings/guidance related to this study	Overall, in addition to the topics above, these papers discuss number and position of microphones for both interior and exterior measurements, scanning microphones, and the position(s) of the loudspeakers when used.
In agreement with this study's findings?	The research team agrees with many of the conclusions and recommendations but not all. For example, the research team would not recommend scanning microphones because there is no clear standard method of scanning.

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Table C-3. (Continued).

Document Title	*Policy, Engineering, Analysis, and Research Support (PEARS), Contract No. DTFAWA-11-D-00019, Study of Noise Level Reduction Variation,* Landrum and Brown, 2013
Publication	PEARS Contract No. DTFAWA-11-D-00019
Date	April 2013
Summary of Content	A 99-page report on the variation of NLR using the different testing methods, and the execution thereof. Testing methods and the elements of each are described. Parallel measurements are reported for the loudspeaker and flyover test methods on several homes, with the variation in NLR reported. Sources of error and discrepancy are discussed.
Relevance to this study	The entire report is extremely relevant to this study in that it deals with the same subject.
Conclusions/findings/guidance related to this study	An average 3 dB discrepancy is found for NLR results between the two test methods. Potential causes are outlined.
In agreement with this study's findings?	The research team agrees with the findings and the outline of possible sources of error and discrepancy between the test methods.

Document Title	*ACRP Report 89: Guidelines for Airport Sound Insulation Programs* (Payne et al. 2013)
Publication	*ACRP Report 89*
Date	2013
Summary of Content	A 313-page report outlining the recommended conduct of residential sound insulation projects conducted for the FAA. Topics include program development, community outreach, acoustical engineering, architectural treatment, historic structures, HVAC, "Green" initiatives, construction contracting, costs, and reporting and closeout.
Relevance to this study	Acoustical measurement techniques are described and discussed in the sections on acoustical engineering.
Conclusions/findings/guidance related to this study	Loudspeaker and flyover measurement techniques are described and discussed, outlining the various issues with each.
In agreement with this study's findings?	The research team agrees with the discussions on acoustical measurement and the various issues discussed for the different measurement techniques.

Table C-3. (Continued).

Document Title	Simulated and Laboratory Models of Aircraft Sound Transmission
Publication	Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) Presentation at Acoustical Society of America 2014 Spring Meeting in Providence, RI
Authors	Ashwin Thomas, Thomas Bowling, Erica Ryherd, Javier Irizarry
Date	May 8, 2014
Summary of Content	This presentation summarized the authors' work to validate computer model NLR predictions. Insul and IBANA-Calc software were analyzed, and six buildings (representing the six climate regions) were modeled. Results were compared to acoustical measurement results contained in the DOT-FAA-AEQ-77-9 study. Calculated NLR was typically within 1 dB of measured NLR. Georgia Tech then built a one room home in the lab to compare modeling results to laboratory gathered NLR data. Laboratory data was gathered using multiple source speaker, microphone positions, and façade construction (e.g., different window STC ratings).
Relevance to this study	The authors did some of the same tests (e.g., exterior loudspeaker) as performed in this study, although their measurements were conducted in a laboratory setting.
Conclusions/findings/guidance related to this study	Horizontal loudspeaker source angle of incidence affects measured noise reduction; correction factor should be used: $10 * LOG\left(\frac{S}{A}\right) + 10 * LOG(COS\Theta) + 6\ dB$
In agreement with this study's findings?	Yes, the research team found that angle of the incidence of the exterior loudspeaker affects the measured noise reduction.

Document Title	Aircraft Sound Transmission in Homes Categorized by Typical Construction Type
Publication	Paper submitted for 2014 Construction Research Congress
Authors	Ashwin Thomas, Daniel Castro, Rick Porter, Erica Ryherd, Javier Irizarry
Date	May 19, 2014
Summary of Content	This paper summarizes the authors' work to validate computer model NLR predictions. Insul and IBANA-Calc software was analyzed, and six buildings (representing the six climate regions) were modeled. Results were compared to acoustical measurement results contained in the DOT-FAA-AEQ-77-9 study. Calculated NLR was typically within 1 dB of measured NLR. Georgia Tech then built a 90 square foot room in their lab to compare modeling results to laboratory gathered NLR data. Laboratory data gathered using multiple source speaker, microphone positions, and façade construction (e.g., different window STC ratings) was measured.
Relevance to this study	The authors did some of the same tests (e.g., exterior loudspeaker) as performed in this study, although their measurements were conducted in a laboratory setting.
Conclusions/findings/guidance related to this study	Georgia Tech found that the modeling of noise reduction was within 1 dB of the measured noise reduction.
In agreement with this study's findings?	The research team found that acoustical modeling was within 1 to 2 dB of this study's measured noise reduction, so the results generally agree with this paper.

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Table C-3. (Continued).

Document Title	The Position of the Instruments for the Sound Insulation Measurement of Building Facades: From ISO 140-5 to ISO 16283-3
Publication	Noise Control Engineering Journal
Author(s)	Umberto Berardi
Date	January-February 2013
Summary of Content	This paper evaluates the effects of various outdoor, ground-level loudspeaker measurement techniques. Specifically, the author quantifies the different NLR values measured with various exterior and interior microphone positions and different loudspeaker positions/angles. The author also discusses the uncertainty present in measuring low frequency noise (50 Hz to 100 Hz) due to interference wave effects.
Relevance to this study	This paper goes into detail on the effect of loudspeaker and microphone position on NLR results, which this study also investigated.
Conclusions/findings/guidance related to this study	The loudspeaker's horizontal angle of incidence and microphone position affect the overall measured NLR.
In agreement with this study's findings?	Yes.

Document Title	Sound Insulation Measurements of Facades with Variable Microphone Positions
Publication	Inter-Noise 2011
Authors	Sigmund Olafsen
Date	September 4-7, 2011
Summary of Content	This paper evaluates interference effects of exterior loudspeaker measurements. The author quantifies loudspeaker noise levels measured at various distances from the façade (0.01 meter to 2 meters from the façade). Both theoretical and field measurement results are presented. Up to a 5-dB one-third octave band difference was measured between microphone positions.
Relevance to this study	This paper goes into detail on the effect of microphone position on NLR results, which the ACRP Project 02-51 study also investigated.
Conclusions/findings/guidance related to this study	The author found that there was little difference in uncertainty between a microphone placed flush on the façade versus a microphone located in front of the façade.
In agreement with this study's findings?	Not applicable. The research team did not directly evaluate the difference between a flush exterior microphone and a microphone located 1-2 meters from the façade.

Table C-3. (Continued).

Document Title	Relationship Between Air Infiltration and Acoustic Leakage of Building Enclosures
Publication	Argonne National Laboratory Presentation at Acoustical Society of America 2014 Spring Meeting in Providence, RI
Author(s)	Ralph Muehleisen, Eric Tatara, Brett Bethke
Date	May 8, 2014
Summary of Content	This presentation proposes a building infiltration evaluation method using a microphone array rather than the traditional method of using a blower door to pressurize a room. Due to patent laws, the authors do not provide many details on how the microphone array method works.
Relevance to this study	Air infiltration measurements and interior loudspeaker measurements were conducted as a part of this project's field research; the authors' proposed air infiltration evaluation method utilizes an interior loudspeaker and a microphone array.
Conclusions/findings/guidance related to this study	None.
In agreement with this study's findings?	Not applicable, there were no findings yet.

APPENDIX D

Computation of Uncertainty

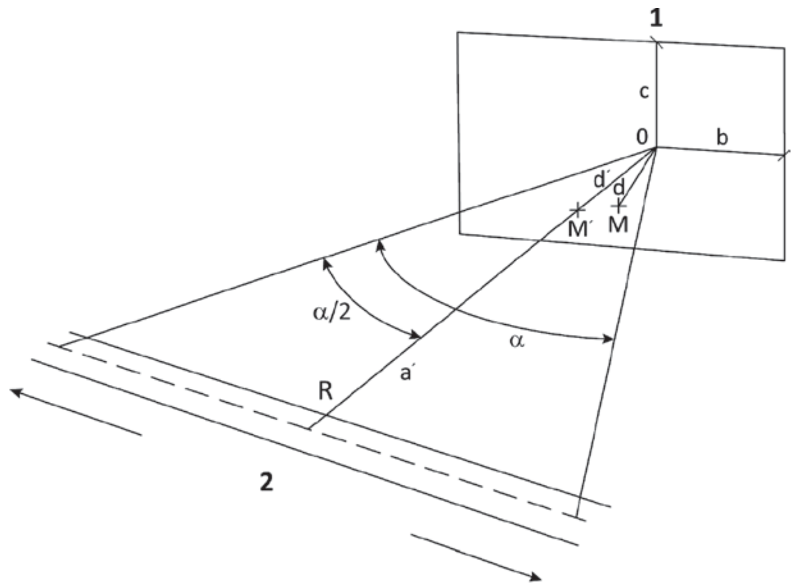
Current Loudspeaker Practice

The basic uncertainty outlined in ISO 1996-2 is for a single source and single receiver measurement. In the study herein, this would be one aircraft flyover or one loudspeaker test. To reduce the uncertainty in the source or receiver regions, one can replicate the test or otherwise increase the quantity of data, such as by adding additional microphones or sweeping through an area. In the case of loudspeakers, one can increase the number of loudspeaker positions. For current practice, people have been using the +2-dB source (exterior) measurement position, measuring 1 m–2 m from the façade, for virtually every measurement predicated on the use of an outdoor loudspeaker. Also, many have been sweeping a large area of the wall or roof under test of the building's surface. It appears that this sweeping is equivalent to using about three or four fixed-position microphones. However, the swept measurements can approach a distance of 30 cm (~1 foot) from the wall, which is considerably closer to the wall than the +2 dB region. A reverberant build-up of 5 dB at the wall surface and 2 dB at 1.5 m (5 ft.) from the wall is assumed. This suggests a build-up of 4.5 dB at 0.25 m (10 in.) from the wall and 4 dB at 0.5 m (1.6 ft.) from the wall, which is in agreement with existing standards. Even if one wants to get only A-weighted data, there are three criteria that must be met in order to use the +2 dB (1 m to 2 m) position. Although the two general methods (outdoor loudspeaker and flyover) each meet two of the three criteria required for use of A-weighting at the +2 dB position, neither meets all three. Thus, the use of the +2 dB position is deprecated for all TL measurements that do not utilize sweeping,

The three criteria are essentially (1) the wall be big enough in extent from the point, **O**, where a line normal (perpendicular) to the wall goes through the point representing the microphone position. This perpendicular distance is termed **d**. The shorter of the distances from point **O** to the two vertical wall edges is distance **b**. The shorter of the distances from point **O** to the two horizontal wall edges is distance **c**. The requirements for this criterion are that **b** > **4d**, and **c** > **2d**. For most houses, the largest **d** can be is 0.5 m. See Figure D-1 for a graphic representation (from ISO 1996-2).

The second criterion is for balance between the incident and reflected waves and essentially requires that **d** ≤ **0.05a**, where **a** is the perpendicular distance from the loudspeaker to the wall. When one measures along a perpendicular to a house wall, the distance is 10 m and the corresponding requirement is **d < 0.5m**, again, purely by chance.

The third criterion, that the measurement be in the +2 dB (1 m–2 m) region and not too near the wall, requires that **d** > **1 m**, which is clearly impossible. But it is possible to add a number between 2 and 5 dB depending on the distance **d**. The +5 dB value is currently recommended, but the "correct value" could be 3.5 or 4.5 dB. It is not unlikely that the uncertainty to this +4 dB offset is 0.5 dB.



Key

1	building façade or other reflecting surface
2	extended source
O	point on the reflecting surface in front of which the microphone is mounted
M	microphone position
R	point where the ray from O meets the center line of the road
RO	dividing line of the angle *α* in two halves
α	angle of view of road/rail on one side of the normal seen from O
M'	equivalent microphone position on the line RO
d	perpendicular distance from the microphone position to the reflecting surface, O
d'	distance OM'
a'	distance OR
b,*c*	distances to the edges of the reflecting surfaces

Figure D-1. Microphone position geometry.

Current Flyover Measurements

For flyover measurements, each aircraft measured represents an independent trial. Especially on takeoff, each aircraft that flies by does so at a different climb profile and with some lateral dispersion. This is equivalent to having the measurement microphones move around during the measurement. All three of these positions, in many cases, will suffer from nearby reflecting structures. Because many other factors affect the received sound, +3 dB is being used for the basic location uncertainty.

Although +3 dB is the basic airplane fly-by uncertainty, independent replications reduce that uncertainty. If one has *n* independent measurements, then the effective uncertainty for the average of *n* samples is approximately the basic uncertainty divided by the square root of $(n - 1)$. The problem is that it is not known *a priori* what size *n* will be for any given measurement or to what degree the samples will be independent. So, to be conservative, assume only 26 samples; exactly 26 were selected so that the square root of $(n - 1)$ is 5, and then divide that 5 by 2 because degree of independence for the 26 samples is not known. So for current practice, the outdoor flyover measurements for a set of data have a value of 3 dB/2.5 = 1.2 dB for the location factor to the measurement uncertainty.

For loudspeaker measurements that use fixed positions, these must be flush-mounted wall positions. However, there is a current practice of using a swept microphone, especially when two people replicate the basic swept-microphone measurement, each using his/her own sweeping technique.

For the loudspeaker method, the position of the loudspeaker itself becomes a source of additional uncertainty. In particular, if the structure under test has insulated windows (dual glazed) of the type MAM, these may produce resonances that are dependent on the angle of incidence. This source of uncertainty is unrelated to other factors, and therefore will be added in as an independent source of uncertainty. This source of uncertainty is due to the change of TL of the window with angle of incidence, independent of ground dip (sound reflected off the ground). This factor is 1 dB when MAM windows are present and 0 when they are absent.

Uncertainty Analysis

The loudspeaker represents a large and somewhat distributed source as opposed to a microphone, which represents more nearly a one point source. For this reason, there is added uncertainty to the loudspeaker position. Largely, this latter position effect is seen in the variation of the well-known ground dip, which is basically a function of the loudspeaker and microphone heights, the distance from the loudspeaker to the wall, the measurement position on the wall, the acoustic impedance of the ground at the point of reflection, and the angle of reflection. From experience, the uncertainty to the ground dip is usually less than 1 dB, but the research team is using 1 dB to be conservative.

In addition to location, the other sources of uncertainty are the effect of background noise, instrument error, and the effects that meteorological conditions have on sound propagation. Loudspeaker testing is done with a loud source and high indoor levels compared to most neighborhood and household backgrounds, so the research team assigns an uncertainty of 0.3 dB to these. The flyovers may or may not be loud compared to the background either indoors or outdoors. If consultants are careful to ferret out questionable data, and maintain a 10 dB signal-to-noise ratio, then the uncertainty is 0.5 dB.

The instrument measurement uncertainty is given in ISO documents as 0.4 dB.

The uncertainty due to meteorological conditions, as with most of these factors, is a function of the precise testing conducted and the precise circumstances of the test. In the analysis being discussed in this section, relative measurements are contemplated. That is, for measurements such as those for pre- and post-construction, most of the meteorological effects will cancel out because the fundamental TL may remain almost the same (at least when measured in one-third octave bands). However, background noise effects and the amplitude of the test signal may change between tests.

Table D-2 provides the uncertainties for the current measurement methods for relative measurements both with and without windows that may exhibit MAM resonance.

Best Practice

For flyover measurements, the two changes the research team suggests are (1) to minimize net effects, the distance from the outdoor microphone(s) to the test room should be less than 5% of the nominal aircraft distance of closest approach and (2) heightened concern about the effects of nearby reflecting objects or structures with the rule that, when in doubt, one should use a ground-plane or surface-mounted microphone position, whichever is farther from grazing incidence.

For loudspeaker measurements, fixed-position outdoor microphones should be flush-mounted on the surface of the structure under test. The number of microphones needed is dependent on the number of loudspeaker positions chosen. Measuring with a fixed microphone, the emission from two different loudspeaker locations is, for statistical purposes, equivalent to measuring one loudspeaker location at two different microphone positions. So for the acoustic measurements, a team will be interested in the number of loudspeaker positions times the number of microphones in ascertaining the uncertainty. For best practice, a minimum of four positions/microphones is suggested. For example, this might be accomplished with two microphone positions and two other loudspeaker positions. The number of loudspeaker positions depends on the presence or absence of windows that exhibit MAM resonance, so making additional measurements at various angles of incidence is suggested. In the absence of variation with angle of incidence, one loudspeaker position is sufficient, but with resonances, at least four different loudspeaker positions are suggested; and it is still ideal to have two microphone positions for each façade. Table D-2 gives the best practice uncertainties for the aircraft method and for the loudspeaker method using two outdoor fixed-position microphones and four outdoor loudspeaker positions with windows that exhibit MAM resonance.

Just below these two cases are the best practice data for the loudspeaker method using the swept-microphone technique with two, 30-second sweep measurements made for each test, and with four outdoor loudspeaker positions with MAM windows on the façade. This method is included for accuracy (low uncertainty in the range from 1 to 1.25 dB) while still being fast and simple. The problem is that the measurements can be closer to the wall than 1 to 2 meters, and the sound level may be above the +2 dB level and closer to the +5 dB level. Using linear interpolation one can estimate the following:

Table D-1. Reverberant build-up at façade.

Wall Distance (m)	0	0.25	0.5	0.75	1.0	1.25	1.5
Level added (dB) – theoretical	6	5.5	5	4.5	4	3.5	3
Level added (dB) – real world	5	4.5	4	3.5	3	2.5	2

With respect to the table, a normal distribution with a mean of 0.5 m (1.6 ft.) and a standard deviation of 0.25 m (10 in.) should be close to the actual situation. This translates to a mean of 5 dB and a standard of 0.5 dB. Any systematic offset to the mean also should be less than 0.5 dB. What is needed is a study on the transition from the level on a test wall surface to its +2 dB distance.

In the near future, further development of intensity in conjunction with an indoor loudspeaker is suggested because of the many potential benefits that this TL measurement method could provide, including:

1. Unaffected by weather.
2. Unaffected by ground dip, MAM resonance or any other resonance effect.
3. Because of the short distances involved, it is unaffected by air absorption, relative humidity, ground absorption, and reflections from nearby structures.
4. Because of the high levels, it is usually unaffected by other environmental noises.
5. Because the acoustic signals of interest are confined to the test room itself and to the outdoor surfaces of the test room, there are minimal outdoor effects; the only two are wind on the microphone and precipitation.
6. Can find "hot spots" (on low TL building elements showing high noise transmission) to a resolution of about 10 cm (4 in.).
7. Elimination of logistical problems outdoors like: "Where can I fit in a loudspeaker?"
8. No noise problems with neighbors.
9. Because of all the problems other methods have that this method does not have, this method is likely the most accurate method.

The intensity method is listed on its own line in Table D-2.

Table D-2. Calculated measurement uncertainty.

Method	Field Meas. Margin of Error	Calculated Total Margin of Error	Outdoor Measurement Factors			Interior Measurement Factors			Meteor-ology	Ground Dip	MAM resonance
			Location	Ambient	Instrument	Location	Ambient	Instrument			
Existing Practice											
Aircraft flyover	± 1.9	**± 1.9**	1.2	0.5	0.4	0.4	0.5	0.4	1.0	0.5	
Speaker outside	± 1.8	**± 1.9**	1.3	0.3	0.4	0.4	0.3	0.4	0.5	0.3	1.0
Best Practice											
Aircraft flyover		**± 1.4**	0.2	0.5	0.4	0.2	0.5	0.4	1.0		
Speaker outside		**± 1.1**	0.2	0.3	0.4	0.2	0.5	0.4	0.5	0.2	0.5
Intensity		**± 0.9**	0.4	0.3	0.4	0.4	0.3	0.4			

Notes:

1 Flyover method: Assumes only aircraft with a 10 dB or higher signal-to-noise ratio used.

2 Loudspeaker: Assumes only data with a 10 dB or higher signal-to-noise ratio used.

3 Loudspeaker Best Practice: Assumes four loudspeaker positions, two surface-mounted microphones (exterior), and interior spatial average/manual scan.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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