Project 004(A) Estimation of Noise Level Reduction

Georgia Institute of Technology and University of Nebraska - Lincoln

Project Lead Investigator

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University Participants

Georgia Institute of Technology (GT)

- P.I.(s): Kenneth Cunefare, Professor of Mechanical Engineering
  Javier Irizarry, Associate Professor of Building Construction
- FAA Award Number: 13-C-AJFE-GIT-005
- Period of Performance: 8/16/2014 – 2/29/2016
- Task(s):
  1. Conduct Field NLR Study
     1A: Test House Construction, Iterations, and Deconstruction (Lead = Irizarry)
     1B: Acoustic NLR Measurements (Lead = Cunefare)
  2. Evaluate NLR Estimation Approaches
     2A: Analyze Differences in Field-Measured NLR Iterations (Lead = Cunefare)
     2B: Compare Field Measurements and Model Simulations
  3. Synthesize Findings & Future Steps (Lead = Cunefare)
  4. Collaborations
  5. Travel Associated with the Project

University of Nebraska – Lincoln (UNL)

- P.I.(s): Erica Ryherd, Associate Professor of Architectural Engineering
- FAA Award Number: 13-C-AJFE-GIT-005
- Period of Performance: 8/16/2014 – 8/15/2015
- Task(s):
  1. Conduct Field NLR Study
     1A: Test House Construction, Iterations, and Deconstruction
     1B: Acoustic NLR Measurements
  2. Evaluate NLR Estimation Approaches
     2A: Analyze Differences in Field-Measured NLR Iterations
     2B: Compare Field Measurements and Model Simulations (Lead = Ryherd)
  3. Synthesize Findings & Future Steps
  4. Collaborations (Lead = Ryherd)
  5. Travel Associated with the Project (Lead = Ryherd)

Project Funding Level

$90,000	FAA
$90,000	Matching; Source: GT (86%) and UNL (14%)

Investigation Team

GT is the lead institution. Dr. Ken Cunefare serves as the GT PI and is the technical lead on engineering acoustics aspects of the project, including the NLR measurement tasks. He is assisted by René Robért, a graduate research assistant who is completing his master's thesis on this project. Dr. Javier Irizarry is the Project Co-PI from Georgia Tech serves as the technical lead on the building construction aspects of the project, including the test house construction tasks. He is assisted by students in the GT Building Construction Program.

UNL is a subcontracted institution. Dr. Erica Ryherd serves as the overall project coordinator and the technical lead on architectural acoustics aspects of the project, including the modeling task. She is assisted on the modeling task by Hyun Hong, a graduate research assistant.

Project Overview

Increasing trends towards urbanization have led to increased exposure to transportation noise. Airport sound insulation programs have grown extensively over the last several decades as many homeowners have found aircraft noise to be unacceptably disruptive [1,2]. Building envelopes act as filters to reduce noise, with noise level reduction (NLR) being a fundamental measure of outdoor-to-indoor sound reduction. Accurately estimating aircraft NLR is particularly challenging because the sound source is dynamic – the source location, directivity, and noise spectrum change continually relative to the building façade. There currently exist several methods to estimate aircraft NLR, including field measurements (e.g., in existing homes near airports), experimental measurements (e.g., test constructions in controlled laboratory settings), and simulations (e.g., using computer models). Studies are needed that directly compare the various approaches and evaluate their merits and limitations. This project rigorously evaluates a range of NLR estimation approaches in order to provide guidance to industry practitioners and standards developers.

The specific goal of Project 4A is to better understand and improve the outdoor loudspeaker methods of estimating the noise level reduction (NLR) performance of buildings exposed to aircraft noise. Measurements and modeling have been conducted on a test house located outdoors with a loudspeaker placed at an array of spatial positions to simulate angular coverage of real aircraft flyover in both vertical and lateral directions. Results are being used to evaluate and compare various NLR estimating approaches.

The following tasks are included to accomplish the project goals:

- Task 1: Conduct Field NLR Study
  - 1A: Test House Construction, Iterations, and Deconstruction
  - 1B: Acoustic NLR Measurements
- Task 2: Evaluate NLR Estimation Approaches
  - 2A: Analyze Differences in Field-Measured NLR Iterations
  - 2B: Compare Field Measurements and Model Simulations
- Task 3: Synthesize Findings & Future Steps
- Task 4: Collaborations
- Task 5: Travel Associated with the Project

Task 1: Conduct Field NLR Study

Georgia Institute of Technology

Objective(s)

The overall objective of Task 1 was to directly collect new NLR data via outdoor field measurements. Subtasks included:

- 1A: Test House Construction, Iterations, and Deconstruction
- 1B: Acoustic NLR Measurements

Research Approach

Introduction

There currently exist several methods to estimate NLR. The investigators gained extensive experience in NLR research through FAA PARTNER Project 38, "Sound Transmission Indoors – Study of Whole Houses" (a.k.a. P38). P38 formed the basis for this current NLR Project 4A [3-9]. Additionally, over 50 published articles, textbooks, and technical reports were compiled as part of P38 and were used in the planning of this project. Finally, the team collaborated with industry practitioners from Landrum & Brown to gain feedback on the merits and limitations of existing NLR estimation approaches and this research project specifically.

Methodology

Task 1A: Test House Construction, Iterations, and Deconstruction
A test house was constructed to allow for direct measurement of NLR outdoors under semi-controlled conditions. Subtasks included securing and preparing a construction site, estimating construction materials, material procurement, material delivery, student training, test house construction, and test house iterations.

The test house was a single-room structure of approximately 90 ft^2. It was constructed to be typical of the mixed-humid climate region in Atlanta, GA [10,11]. The test house consisted of the wall and roof materials shown in Table 1 below. There was a single hung vinyl window. Figure 1 shows the schematics of the design constructed. Figure 2 shows an exterior image of the finished test house. Approval was secured from the GT College of Architecture and GT Facilities Group to build the test house on the GT campus in an open green space. The house was located as far as possible from adjacent buildings. Students from the GT College of Architecture and Building Construction Program assisted in the actual construction, with oversight from Dr. Javier Irizarry. Some materials were reused from P38, such as roof trusses and windows. Other materials which were not salvageable from P38, such as insulation, we procured as new materials. Two construction iterations were implemented: a) window type, and b) window condition. For the window type iteration, two windows with differing acoustical performance were measured (STC 25 and STC 31). For the window condition iteration, three positions were measured (closed, ½ open, and fully open). The test house was deconstructed after acoustic NLR measurements (Task 1B) were completed.

Table 1: Exterior wall and roof materials used in the test house

	Exterior ⟶				**Interior**	
	1	**2**	**3**	**4**	**5**	**6**
Walls	Fiber-cement siding (7/16”)	Oriented Strand Board (OSB; 7/16”)	2x4 wood framing @ 24” on center	3 ½” lay-in fiberglass cavity insul (R-13)	½” gypsum board	
Roof	Asphalt shingles	Roofing felt	Oriented Strand Board (OSB; 7/16”)	Raised-heel wood truss framing	6 ¼” lay-in fiberglass cavity insul (R-19)	½” gypsum board

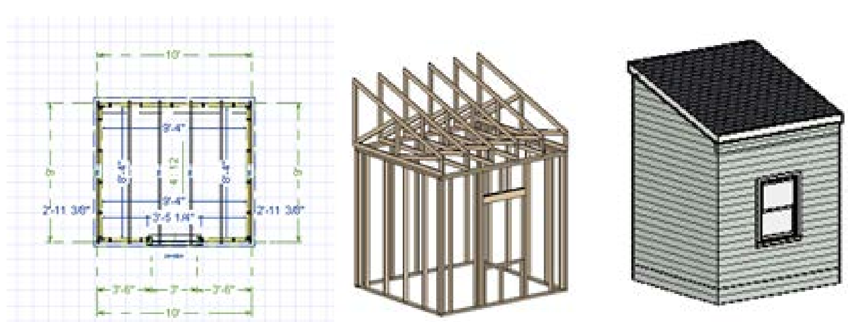

Figure 1: Test house design drawings

Figure 2: Exterior view of the completed test house

Task 1B: Acoustic NLR Measurements

NLR was directly measured in accordance with industry best practices and ASTM E966 [12, 13]. ASTM E966 details standard methods of measuring NLR that are utilized by many industry practitioners and also in accordance with algorithms used in commonly-used NLR modeling software such as IBANA-Calc. To summarize, a loudspeaker was located outside of the test house playing pink noise, a standard noise reduction measurement signal. Sensors located both inside and outside the test house captured NLR performance data. Three instrumentation iterations were implemented: a) source vertical location, b) source horizontal location, and c) sensor location.

The vertical and horizontal location iterations were included to investigate an array of spatial positions that simulate angular coverage of real aircraft flyover in both vertical and lateral directions. Two mounting methods were used to achieve a range of vertical locations: i) tripod mounting (3.4' and 7'), and ii) lift mounting (15', 20', and 30'). The range of horizontal angles was achieved by moving the source along fixed radial and linear increments. Figure 3 and Figure 4 show examples of vertical and horizontal iterations.

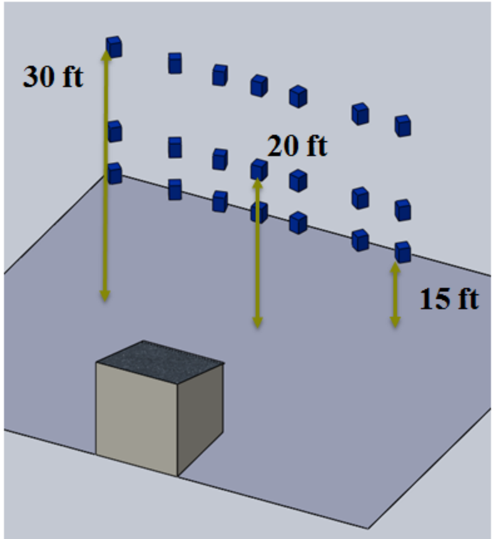

Figure 3: Example vertical iterations of the source used in the acoustic NLR measurements. The figure depicts 15', 20', and 30' lift locations as shown from the rear of the test house.

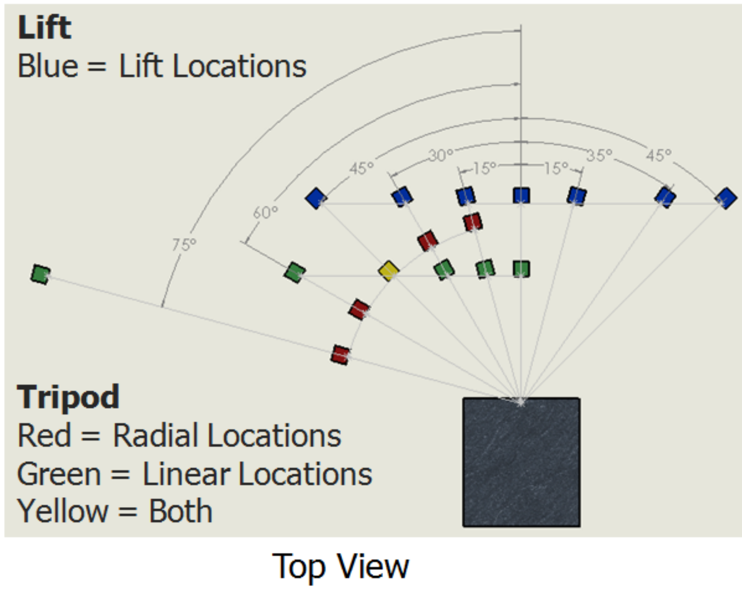

Figure 4: Example horizontal iterations of the source used in the acoustic NLR measurements. The figure depicts the lift (blue) and tripod (red, green, and yellow) locations as shown from above the test house.

Three sensor locations were included: i) fixed near, ii) fixed flush, and iii) moving. The ASTM standard contains procedures in adjusting noise depending on the placements of exterior microphones, including the fixed flush and fixed near methods. In the fixed near method, microphones are placed at a distance from the exterior façade surface, as shown in Figure 5. In the fixed flush method, microphones are located flush to the exterior façade surface, as shown in Figure 6. In both fixed near and fixed flush methods, interior microphones are located approximately 0.5m from the interior surface.

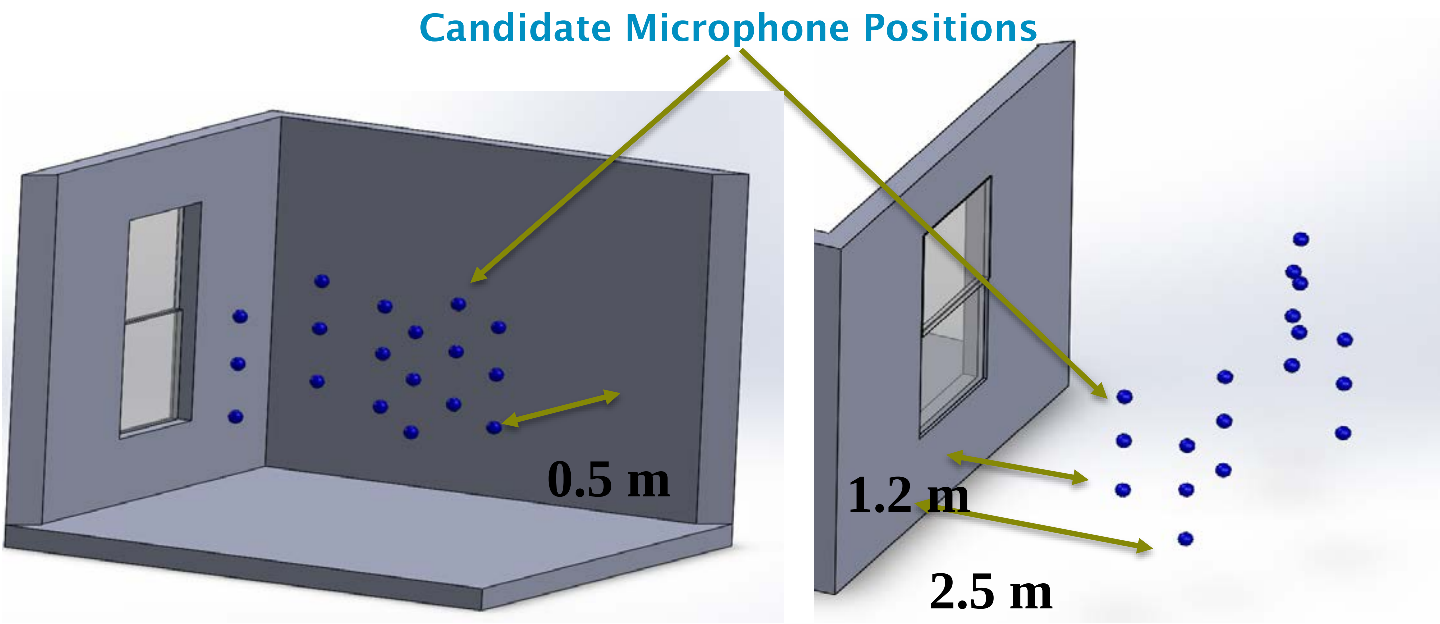

Figure 5: Fixed near microphone positions used in the acoustic NLR measurements

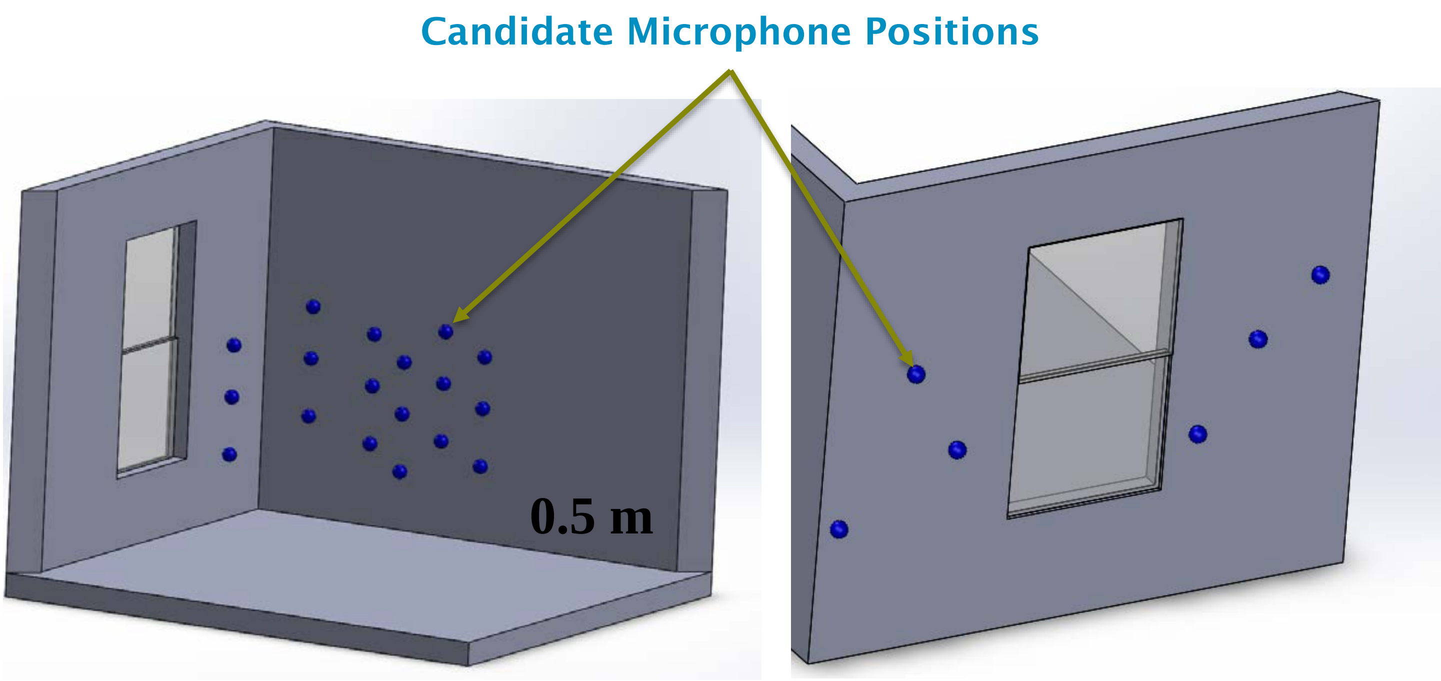

Figure 6: Fixed flush microphone positions used in the acoustic NLR measurements

The moving method was identified as one commonly used by industry practitioners. Guidance was provided by Landrum & Brown on appropriate implementation of this method. In the moving method, the microphone is dynamically swept along a path, as shown in Figure 7.

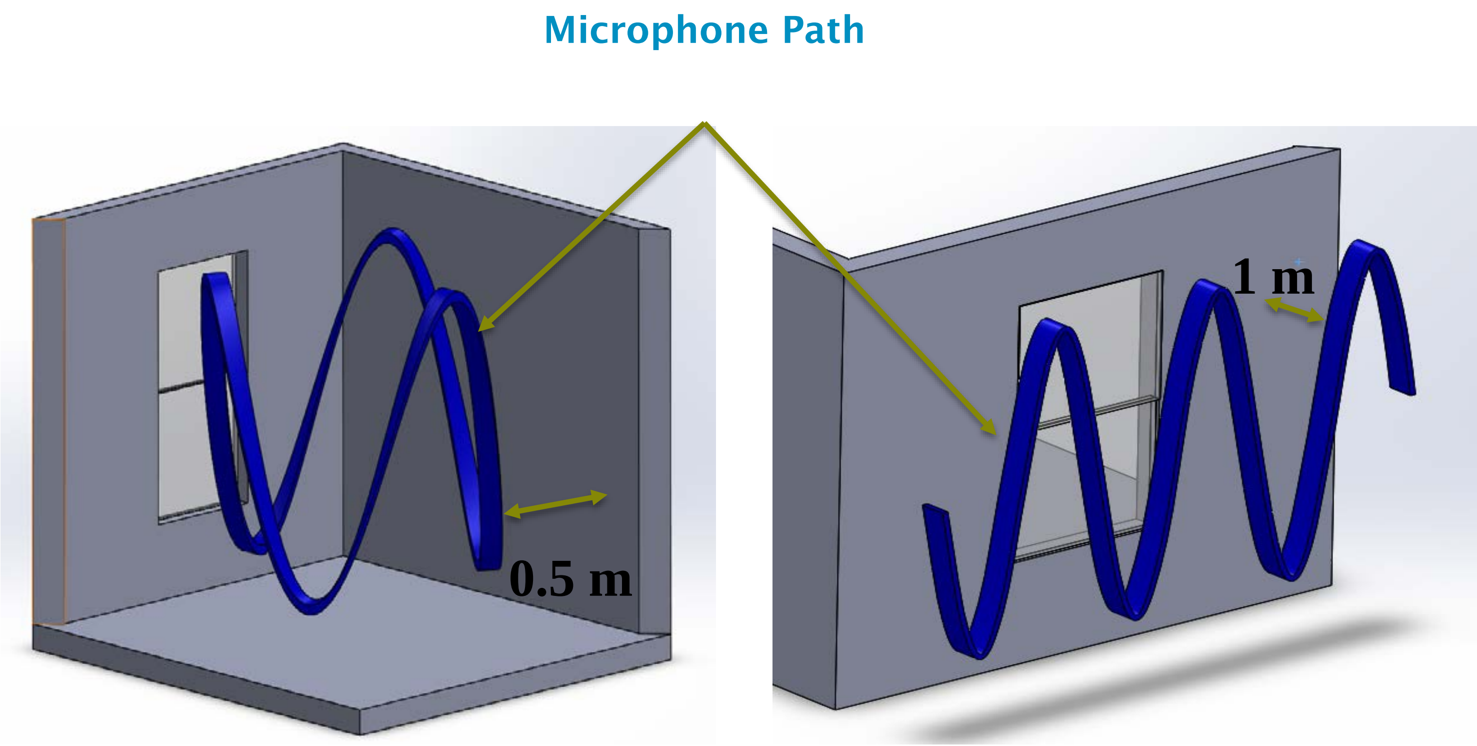

Figure 7: Moving microphone method used in the acoustic NLR measurements

Milestone(s)

Tasks 1A and 1B are complete, with major accomplishments described below.

Major Accomplishments

In total, 197 construction and instrumentation iterations were measured, using a combination of the following iteration variables:

- Source vertical location
  - 3.4', 7', 15', 20', 30'
- Source horizontal location
  - 0°, ±15°, +30°, -35°, ±45°, +60°, +75°
- Sensor location
  - fixed near, fixed flush, moving
- Window type
  - STC 25, STC 31
- Window condition
  - closed, ½ open, fully open

Publications

Publications are summarized under Task 3.

Outreach Efforts
Outreach efforts are summarized under Task 3.

Awards
None

Student Involvement
Student involvement information is summarized under Task 3.

Plans for Next Period
Plans for the next period are summarized under Task 3.

Task 2: Evaluate NLR Estimation Approaches
Georgia Institute of Technology (Cunefare)

Objective(s)
The overall objective of Task 2 was to evaluate various NLR estimation approaches. Subtasks included:

- 2A: Analyze Differences in Field-Measured NLR Iterations
- 2B: Compare Field Measurements and Model Simulations

Research Approach
NLR estimation approaches were evaluated by: a) analyzing differences in field-measured NLR for the various construction and instrumentation iterations, and b) comparing a subset of the field-measured NLR to model simulations.

Methodology

Task 2A: Analyze Differences in Field-Measured NLR Iterations
The field-measured NLR results were compiled and analyzed using Excel software. Averages, confidence intervals, and graphical inspection techniques were used to compare results across various combinations of iterations.

Task 2B: Compare Field Measurements and Model Simulations
Model simulations were generated using IBANA-Calc software. IBANA-Calc was developed through the NRC's "Insulating Buildings Against Noise from Aircraft" project [14-16]. It is a software program designed to calculate the outdoor-to-indoor noise level reduction due to aircraft in whole-house construction scenarios. It was used extensively in PARTNER P38 [3-8].

In total, 27 iterations were modeled as shown in

Table 2, using a combination of the major measurement iterations described above.

Table 2: Iterations modeled in IBANA-Calc software

#	Sensor Location	Window STC	Window Condition	Source Horizontal Angle of Incidence	Source Vertical Height
33	Fixed Near	25	Closed	45°	3.4'
38	Fixed Flush	25	Closed	45°	3.4'
43	Moving	25	Closed	45°	3.4'
46	Fixed Near	25	Closed	15°	7'
48	Fixed Near	25	Closed	45°	7'
50	Fixed Near	25	Closed	75°	7'
51	Fixed Flush	25	Closed	15°	7'

53	Fixed Flush	25	Closed	45˚	7'
55	Fixed Flush	25	Closed	75˚	7'
56	Moving	25	Closed	15˚	7'
58	Moving	25	Closed	45˚	7'
60	Moving	25	Closed	75˚	7'
61	Moving	25	Half Open	45˚	3.4'
62	Moving	25	Open	45˚	3.4'
66	Moving	25	Closed	45˚	3.4'
71	Fixed Near	31	Closed	45˚	3.4'
76	Fixed Flush	31	Closed	45˚	3.4'
81	Moving	31	Closed	45˚	3.4'
99	Moving	31	Half Open	45˚	3.4'
100	Moving	31	Open	45˚	3.4'
104	Moving	31	Closed	45˚	3.4'
107	Fixed Near	25	Closed	45˚	15'
108	Fixed Flush	25	Closed	45˚	15'
109	Moving	25	Closed	45˚	15'
152	Fixed Near	25	Closed	45˚	30'
153	Fixed Flush	25	Closed	45˚	30'
154	Moving	25	Closed	45˚	30'

Milestone(s)
Tasks 2A and 2B are complete, with major accomplishments described below.

Major Accomplishments

Task 2A: Analyze Differences in Field-Measured NLR Iterations
Extensive analyses were conducted to analyze the differences in the 197 field-measured NLR iterations. Examples are shown below.

Repeatability and Reproducibility Analysis
An analysis of the repeatability and reproducibility of the three sensor iterations (fixed near, fixed flush, and moving) was conducted. The repeatability test compares the results of a single test configuration multiple times. It therefore reveals the within-test variability, or the ability of a specific test to be implemented multiple times with comparable results. The reproducibility test compares the results of different test configurations. It therefore reveals the between-test variability, or the ability for various test configurations (allowed within the standard) to yield comparable results.

Example repeatability and reproducibility test results are shown in Table 3. The moving method was found to have the most reproducible results.

Table 3: Example repeatability and reproducibility test results for the three sensor iterations (fixed near, fixed flush, and moving)

	NLR [dB]					
	Repeatability			Reproducibility		
	Fixed Near	Fixed Flush	Moving	Fixed Near	Fixed Flush	Moving

Set 1	17.3	17.9	16.3	16.8	16.2	16.3
Set 2	17.5	18.3	15.7	17.8	16.4	15.7
Set 3	17.6	18.4	16.8	16.1	17	16.8
Set 4	17.6	18.4	16.2	17.7	16.6	16.2
Set 5	17.3	18.2	16.4	18.2	16.2	16.4
Average	**17.5**	**18.3**	**16.4**	**17.5**	**16.6**	**16.4**
±95% Confidence Interval	**0.5**	**0.3**	**0.5**	**0.9**	**0.8**	**0.5**

Differences Across Iterations

Extensive analyses of the differences measured across the various construction and instrumentation iterations was conducted. Example results are shown in Figure 8, which shows NLR versus horizontal angle of incidence for two tripod heights (3.5’ and 7’) and three sensor iterations (fixed flush, fixed near, and moving). The horizontal angles are plotted on a range from 15° to 75° in 15° increments. These results are interpreted as showing that the measurements did not exhibit consistent angular dependency.

Additional example results are shown in Figure 9, which shows NLR versus horizontal angle of incidence for the three lift heights (15’, 20’, and 30’) and three sensor iterations (fixed flush, fixed near, and moving). The horizontal angles are plotted on a range from 45° to -45° in 15° increments. These results are interpreted as showing that the measurements did not exhibit symmetry.

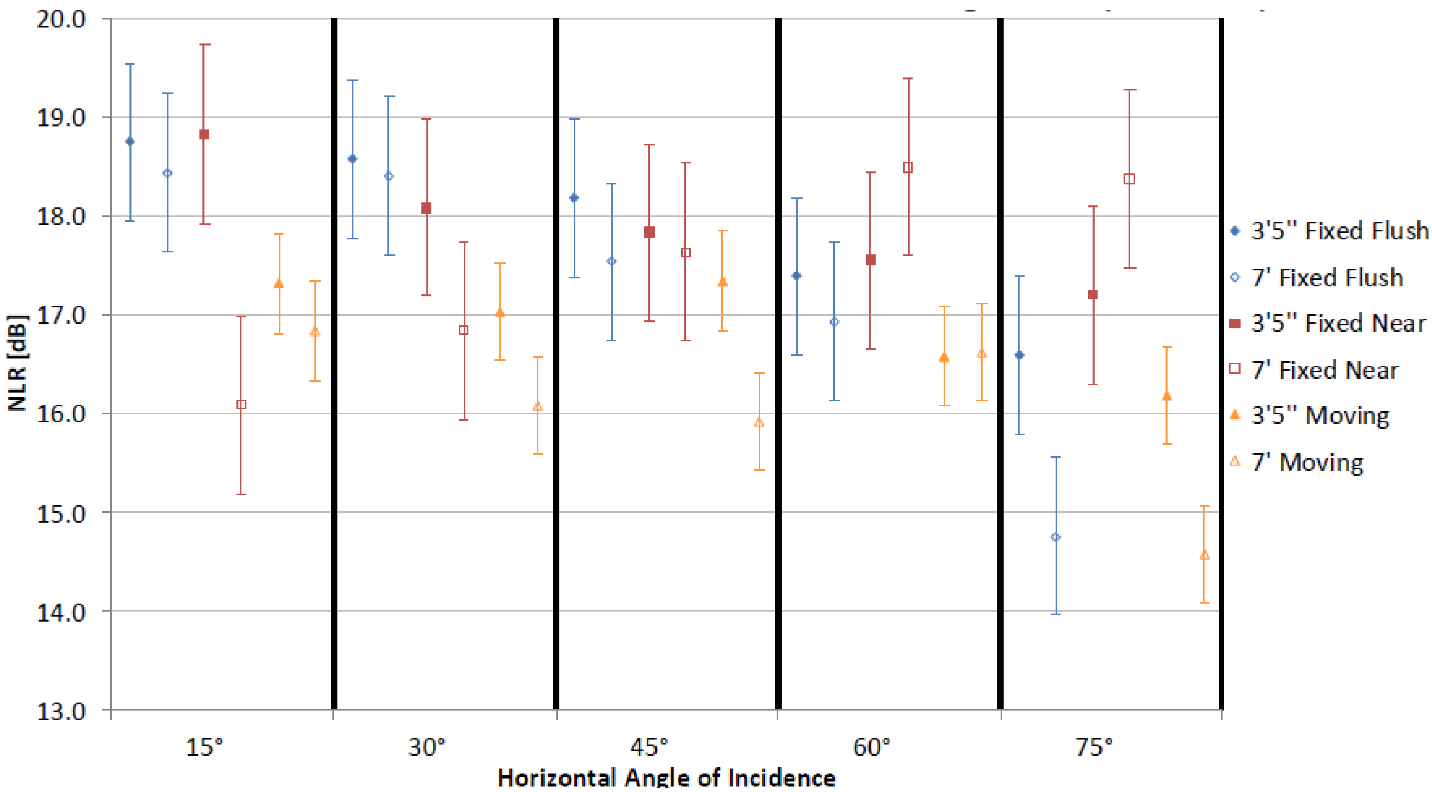

Figure 8: Example results of NLR (dB) versus horizontal angle of incidence for two tripod heights (3.5’ and 7’) and three sensor iterations (fixed flush, fixed near, and moving).

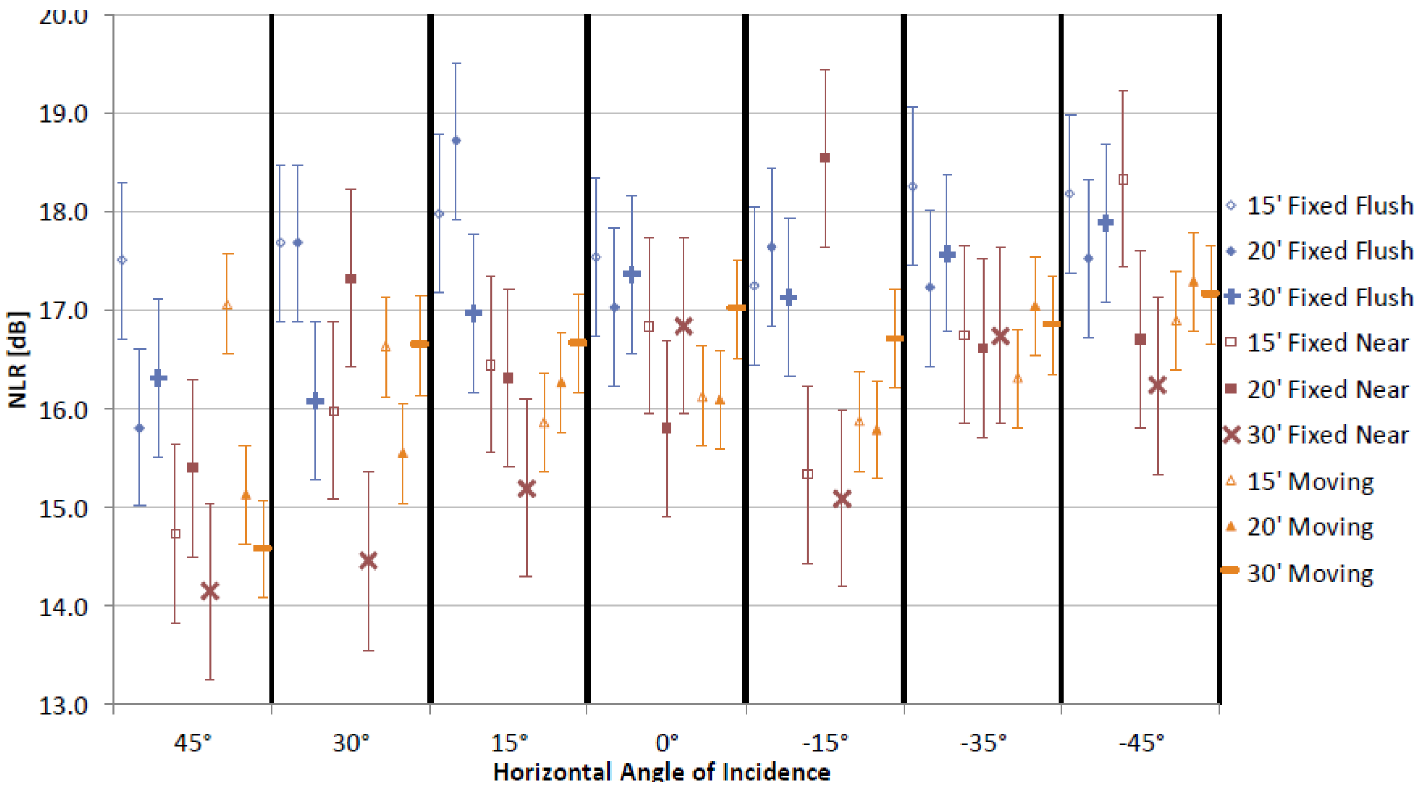

Figure 9: Example results of NLR (dB) versus horizontal angle of incidence for three lift heights (15', 20', and 30') and three sensor iterations (fixed flush, fixed near, and moving).

Task 2B: Compare Field Measurements and Model Simulations
A subset of 27 iterations were modeled in composite sound transmission software (IBANA-Calc) and compared to the field-measured results.

The difference between measured and modeled predictions was calculated using two measures: a) $|\Delta NR|$, and b) $|\Delta TL|$. Both measures were averages of the differences between measured and modeled predictions across the frequency range 315 – 5000 Hz. The $|\Delta NR|$ was a direct measure of the difference between measured and modeled results. The $|\Delta TL|$ was found by accounting for the horizontal angle of incidence. Results showed that the difference between measured and modeled was less than 3-5 dB for approximately 57% of the iterations ($|\Delta NR|$) and 83% of the iterations ($|\Delta TL|$) depending on the metric evaluated.

Publications
Publications are summarized under Task 3.

Outreach Efforts
Outreach efforts are summarized under Task 3.

Awards
None

Student Involvement
Student involvement information is summarized under Task 3.

Plans for Next Period
Plans for the next period are summarized under Task 3.

Task 3: Synthesize Findings and Future Steps
Georgia Institute of Technology (Cunefare)

Objective(s)
The objective of Task 3 is to synthesize findings from Tasks 1-2 and determine future steps.

Research Approach
A variety of NLR estimation approaches are being compared and evaluated. This includes identifying limitations of existing NLR methods and opportunities for improvements. Opportunities for future research are being identified.

Milestone(s)
The following tasks were undertaken and completed in the current project period:

- Task 1: Conduct Field NLR Study
  - 1A: Test House Construction, Iterations, and Deconstruction
  - 1B: Acoustic NLR Measurements
- Task 2: Evaluate NLR Estimation Approaches
  - 2A: Analyze Differences in Field-Measured NLR Iterations
  - 2B: Compare Field Measurements and Model Simulations

Task 3 is partially complete, with major accomplishments, publications, and outreach materials as described below.

Major Accomplishments
Results from Tasks 1-2 are being synthesized into several work products, some of which are complete and some of which are on-going.

Publications
Graduate student R. Robért is currently finishing his Master's Thesis on this project:

- R. Robért, "Measuring noise level reduction using an artificial noise source," M.S. Thesis to be presented to the Georgia Institute of Technology (expected: December 2015).

Outreach Efforts
The team shared results of P4A at an Acoustical Society of America Conference:

- R. Robért, K. Cunefare, E. Ryherd, J. Irizarry (2015) "Reproducibility and repeatability of measuring Noise Level Reduction using an artificial noise source," *169th meeting of the Acoustical Society of America*, Pittsburgh, PA.

The following activities and work products were used to foster collaboration and solicit feedback:

- Held periodic telecons with collaborators and FAA Program Manager
- Submitted monthly briefs to collaborators and FAA Program Manager
- Submitted Quarterly Reports through KSN site

Awards
None

Student Involvement
Two primary graduate students assisted in this project. Multiple students from the GT College of Architecture and Building Construction Program assisted in the test house construction.

René Robért is the lead graduate research assistant on this project. He has been involved in almost all aspects of the work. He conducted all of the field NLR measurements and is responsible for analyzing the differences in field-measured NLR results. René is on track to graduate with his Master's Degree in Mechanical Engineering from GT in December 2015. His Master's Thesis will focus on this project and will be submitted to the FAA upon completion.

Hyun Hong is a graduate research assistant who contributed to a portion of the project. He was involved in Task 3B: Compare Field Measurements and Model Simulations. He was responsible for generating the models in IBANA-Calc and comparing the results to René's field measured data. Hyun is on track to graduate with his PhD in Architectural Engineering from UNL in December 2015. His dissertation is on a separate project on reflection density in interior room acoustic simulations.

Plans for Next Period

Additional synthesis of the results from Tasks 1-2 is currently underway.

The team plans to present results of P4A at an upcoming Acoustical Society of America Conference:

- R. Robért, K. Cunefare, E. Ryherd, J. Irizarry (2015) "Measuring noise level reduction using an artificial noise source," *170th meeting of the Acoustical Society of America*, Jacksonville, FL (invited).

Final project deliverables will be submitted to the FAA by the project close-out date (2/29/2016).

Task 4: Collaborations

University of Nebraska – Lincoln (Ryherd)

Objective(s)

The objective of Task 4 is to collaborate with others from ASCENT and industry to strengthen the overall project.

Research Approach

The GT Team collaborated with the University of Washington (UW), the Pennsylvania State University (PSU), and Landrum & Brown on various aspects of the project.

Milestone(s)

Task 4 is complete, with major accomplishments described below.

Major Accomplishments

The team collaborated with The University of Washington (UW) on their ASCENT Project 4B. The goal of their project was to investigate a new, phased array microphone method to measure NLR. Several telecons were held to share information and exchange ideas on Project 4A and 4B. Participants included:

- K. Cunefare, J. Irizarry, R. Robért (GT)
- E. Ryherd (UNL)
- R. Doughtery and M. Kurosaka (UW)
- V. Sparrow (PSU)
- H. He (FAA)

In addition to the periodic telecons, all members listed above were copied on the monthly briefs submitted to the FAA.

The team also collaborated with Landrum & Brown on Project 4A as described earlier. This included a site visit by Landrum & Brown to the GT test house in December 2014.

Publications

Publications are summarized under Task 3.

Outreach Efforts

Outreach efforts are summarized under Task 3.

Awards
None

Student Involvement
Student involvement information is summarized under Task 3.

Plans for Next Period
The team will continue to collaborate with others from ASCENT and industry as appropriate, including but not limited to UW, PSU, and Landrum & Brown. Remaining work products will be shared with collaborators, including but not limited to monthly briefs, project summary reports, ASCENT materials, and R. Robért's thesis.

Task 5: Travel Associated with the Project
Lead: University of Nebraska – Lincoln (Ryherd)

Objective(s)
The objective of Task 5 is to conduct appropriate travel associated with the project to foster collaboration, feedback, and information dissemination.

Research Approach
Attend Annual Board Meetings and other meetings/conferences related to the project as appropriate.

Milestone(s)
Task 5 is complete, with major accomplishments described below.

Major Accomplishments
The team participated in the two bi-annual ASCENT meeting during the project period. The team prepared slides which were presented by E. Ryherd and feedback was solicited from the ASCENT attendees. This included:

- ASCENT Fall 2014 Advisory Committee Meeting; October 2014; Alexandria, VA
- ASCENT Winter 2015 Advisory Committee Meeting; March 2015; Alexandria, VA

E. Ryherd also attended the Noise Meetings that occurred adjacent to the Advisory Board Meetings. This included:

- Noise Roadmap Meeting; March 2015; Alexandria, VA

The Advisory Committee and other attendees at these meetings provided many useful suggestions and comments that were incorporated into the project. These discussions helped facilitate current and future directions of P4A.

Additionally, project funds, cost-share, and other funds were used to partially support travel to professional conferences. At these conferences, the team met internally and attended technical lectures related to P4A, including noise, architectural acoustics.

- 168th Meeting of the Acoustical Society of America; October 2014; Indianapolis, IN
- 169th Meeting of the Acoustical Society of America; May 2015; Pittsburgh, PA

Publications
Publications are summarized under Task 3.

Outreach Efforts
Outreach efforts are summarized under Task 3.

Awards
None

Student Involvement
Student involvement information is summarized under Task 3.

Plans for Next Period
The team will participate in the next bi-annual ASCENT meeting. The team has prepared slides which will be presented by R. Robért and feedback will be solicited from the ASCENT attendees.

- ASCENT Fall 2015 Advisory Committee Meeting; October 2015; Seattle, WA

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