Project 040 Quantifying Uncertainties in Predicting Aircraft Noise in Real-world Scenarios

Pennsylvania State University
Purdue University

Project Lead Investigator

Victor W. Sparrow
Director and Professor of Acoustics
Graduate Program in Acoustics
Penn State
201 Applied Science Bldg.
University Park, PA 16802
+1 (814) 865-6364
vws1@psu.edu

University Participants

Pennsylvania State University

- P.I.: Victor W. Sparrow, Professor of Acoustics
- Co-PI: Philip J. Morris, Boeing/A.D. Welliver Professor of Aerospace Engineering
- FAA Award Number: 13-C-AJFE-PSU, amendment 023.
- Period of Performance: June 28, 2016 to December 31, 2017.
- Task(s):
    1. Assess meteorological and acoustic measurement data sets for noise propagation model validation
    2. Assess influence of aircraft noise sources on uncertainty in noise modeling
    3. Assess overall modeling uncertainty for aircraft noise prediction
    4. Assess usefulness of SILENCE-R dataset

Purdue University

- P.I.(s): Kai Ming Li, Professor of Mechanical Engineering
- FAA Award Number: 13-C-AJFE-PU, amendment 14
- Period of Performance: August 1, 2016 – December 31, 2017
    5. Assess DISCOVER-AQ Acoustics data for model validation
    6. Assess the uncertainty due to the ground effect and source directivity for en-route aircraft

Project Funding Level

FAA funding to Penn State in 2016-2017 is $128K. FAA funding to Purdue in 2016-2017 is $90K.

In-kind cost sharing from Vancouver Airport Authority was recently received for ASCENT Project 5, and additional cost sharing is likely in Project 40. The point of contact for this cost sharing is Mark Cheng, mark_cheng@yvr.ca . Project support is in the form of aircraft noise and trajectory data, meteorology data, and consulting on those datasets.

Additional cost sharing from ANOTEC Engineering, Motril, Spain is likely in the future for ASCENT Project 40 regarding the BANOERAC data set. The point of contact for this cost sharing is Nico van Oosten, nico@anotecengineering.com .

Further cost sharing from National Aviation University of Ukraine (and Airbus) is possible in the future for ASCENT Project 40 regarding the SILENCE-R data set. The point of contact for this cost sharing is Sasha Zaporozhets, zap@nau.edu.ua .

Investigation Team

Penn State

Victor W. Sparrow (PI)
Philip J. Morris (Co-PI)
Graduate Research Assistant Manasi Biwalkar (measurement data sets for noise propagation model validation)

Purdue

Kai Ming Li (PI)
Graduate Research Assistant Yiming Wang (moving source investigation)

Project Overview

To assess the uncertainties in aircraft noise prediction, an integrated approach will be used to understand uncertainties in the aircraft state and resulting noise levels and directivity (source), the atmospheric and meteorological conditions (propagation), and ground impedance and terrain model (receiver). This approach will include all predominant uncertainties between source and receiver. The primary focus in the current year is in validating the propagation uncertainty. In addition, a new collaborative initiative with National Aviation University of Ukraine is underway.

As the tasks in this project all began in late summer 2016, reporting will be provided for tasks 1-4 of Penn State and tasks 5-6 of Purdue collectively instead of separately.

Task 1 "Assess meteorological and acoustic measurement data sets for noise propagation model validation"

Task 2 "Assess influence of aircraft noise sources on uncertainty in noise modeling"

Task 3 "Assess overall modeling uncertainty for aircraft noise prediction"

Task 4 "Assess usefulness of SILENCE-R dataset"

The Pennsylvania State University

Objective(s)

This research seeks to not only to validate current FAA/Volpe noise modeling capabilities by comparing with measurement data, but also to quantify uncertainties of both model prediction and measurement in trying to predict aircraft noise (or patterns or changes) in real world situations, particularly when meteorological conditions over various different time periods may affect prediction output. The research will (1) review and analyze available field measurement data for patterns that are influenced by the (change of) meteorological conditions; (2) identify sets of field data for specific scenarios that contain proper parameters/quality input values to validate the enhanced modeling capabilities; (3) use the enhanced modeling capabilities to understand the patterns identified in the field measurement data that are influenced by the (change of) meteorological conditions and (4) quantify uncertainties in predicting aircraft noise in real-world situations. In addition, a new collaborative initiative on aircraft noise propagation model validation will be begin with National Aviation University, Kiev, Ukraine.

Research Approach

Introduction

It is a challenging task to include the influences of atmospheric conditions and ground properties for the prediction of aircraft noise. However the accuracy of these inputs are critical for the predictions. In the past three years, the research performed by Penn State and Purdue through FAA ASCENT Center research grants has informed FAA regarding the limitations of existing noise tools and helped advance the state-of-the-art in aircraft noise modeling. Appropriate models were enhanced and developed to account for the effects of meteorological conditions, atmospheric absorption, and the Doppler effect due to source motions on the propagation of aircraft noise. Field data obtained from Discover/AQ[1] are currently used to validate these numerical models. At the same time, Penn State and Purdue have also sought support from Vancouver Airport Authority[2] who has kept a comprehensive set of measured terminal area noise data around the Vancouver Airport. There are plans to use this database, and other databases, to improve the accuracy of the AEDT and quantify the sensitivities in the predicted noise levels due to the variation in atmospheric conditions and ground properties. It is possible that additional data available at National Aviation University of Ukraine may be helpful for the work. In Project 40 Penn State and Purdue will continue their efforts and extend them to quantify noise prediction uncertainties, now beginning to include the effects of the noise source.

Recent work at Penn State in ASCENT Project 5 has shown that the Discover/AQ Acoustics flight tracks can be read into AEDT 2b which will allow for direct comparisons between AEDT 2b noise calculations and the Discover/AQ measured noise data. Also in the last year the meteorological reanalysis data sets have been utilized to determine appropriate sound speed profiles. Profiles can be easily extracted for annual average atmospheric conditions, or for average profiles for shorter time periods. With this important atmospheric input, ray tracing has been used to assess the change in ground contours due to homeogeneous (AEDT 2b) versus linear and polynomial fit sound speed profiles. The new ASCENT Project 40 will take advantage of the new meteorological reanalysis data sets as one tool in the assessment of uncertainty in received sound levels due to aircraft noise.

Survey of available data sets

Almost all of the tasks in Project 40 involve a careful assessment of the available noise datasets that are candidates for validation of existing and future aircraft noise prediction tools. A short summary is available in Table 40.1 .

Table 40.1: Measurement datasets of interest for ASCENT Project 40.

Dataset	Focus	Owner	Potential Cost Share
Discover-AQ	Propeller aircraft	U.S. govt.	N
BANOERAC	Mostly jets en-route	EASA	Y
NINHA	Propeller aircraft en-route	EASA	Y
Vancouver, Canada Airport	Typical aircraft mix at large airport	Vancouver Airport	Y
SILENCE(R)	Airbus A320/A340	Xnoise/Airbus	Y
?			

It is clear that each dataset has its own focus. Ownership and cost share potential are also important regarding the administrative and financial ramifications of using each data set. Some specific information on the five datasets listed is now provided:

- Discover-AQ Acoustics
  Very high quality dataset

  - Propeller aircraft only
  - Includes detailed weather
- BANOERAC
  - “Background noise level and noise levels from en-route aircraft”
  - Owned by EASA, distributed by ANOTEC
  - Still unavailable as of December 2016
    - *Access agreement took much longer than expected*
    - *2nd round of negotiations commenced Summer 2016*
    - *Verbal agreements now completely in place, a signed agreement likely in early 2017.*
  - Extensive measurements of aircraft at various altitudes (incl. en-route) noise with
  - Ground noise data (both 1.2 m mic and inverted ground mic)
  - Aircraft slant distance and slant angle data at closest point of approach.
  - Full flight trajectory data can be processed (ANOTEC)
  - Distant weather data (balloon launches)
- NINHA
  - “Noise Impact of aircraft with Novel engine configurations in High Altitude operations”
  - Owned by EASA and X-Noise
    - *Unavailable: They are not yet ready to release to outsiders*
  - Project completed September 2013

  - Extensive noise prediction models in preparation for Counter Rotating Open Rotor (CROR) aircraft
  - Measurements with Airbus A440M (large military transport
- Vancouver Airport Authority airport noise
  - A non-U.S. airport, but easily accessible
  - Fleet mix similar to other large U.S. airports
  - Extensive measurements of aircraft terminal-area noise with
    - *Ground noise data*
    - *Radar tracking data (NAV Canada)*
    - *Local weather data*
  - Nondisclosure agreements signed between Penn State, Purdue, and Vancouver in June 2016
- SILENCE(R)
  - Brought to our attention by Sasha Zaporozhets, National Aviation University, Kiev, Ukraine
  - Airbus A320/A340 data
  - Just now learning about the unique features of this dataset

The Penn State team began working with the DISCOVER-AQ Acoustics data in the spring of 2016 to gain experience with it. Purdue University is now focusing on that data exclusively, so Penn State is now focused on using the other data sets.

Vancouver Airport Authority Data analysis

At the beginning of ASCENT Project 40 Penn State begin looking at the Vancouver Airport Authority dataset in detail. Figure 40.1 shows an overhead view of the YVR airport and the noise monitors in the surrounding area. The work in Fall of 2016 has centered on understanding the Vancouver acoustics data, meteorology data, and radar data, and the work continues.

Uncertainty in aircraft source models

In order to evaluate aircraft noise propagation methods it is necessary to characterize the noise sources. This includes both the amplitude and the directivity. The latter is particularly important in the determination of the pressure time histories at ground observer locations. The noise directivity generated by a propeller-driven aircraft, as well as the tonal content in the spectra, is very different from those of a jet-powered aircraft. In order to interpret the noise data measured as part of the Discover-AQ Acoustics database, the noise directivity characteristics of a Lockheed P-3B aircraft have been estimated. The aircraft is powered by four Allison T56-A14 engines, each with a four-bladed 4.11 m diameter propeller. The directivity and the effects of forward flight were estimated based on fundamental propeller noise theory. This provided guidance to the modeling effort being undertaken at Purdue University.

FILE: NMT Locations – September 2015.ppt

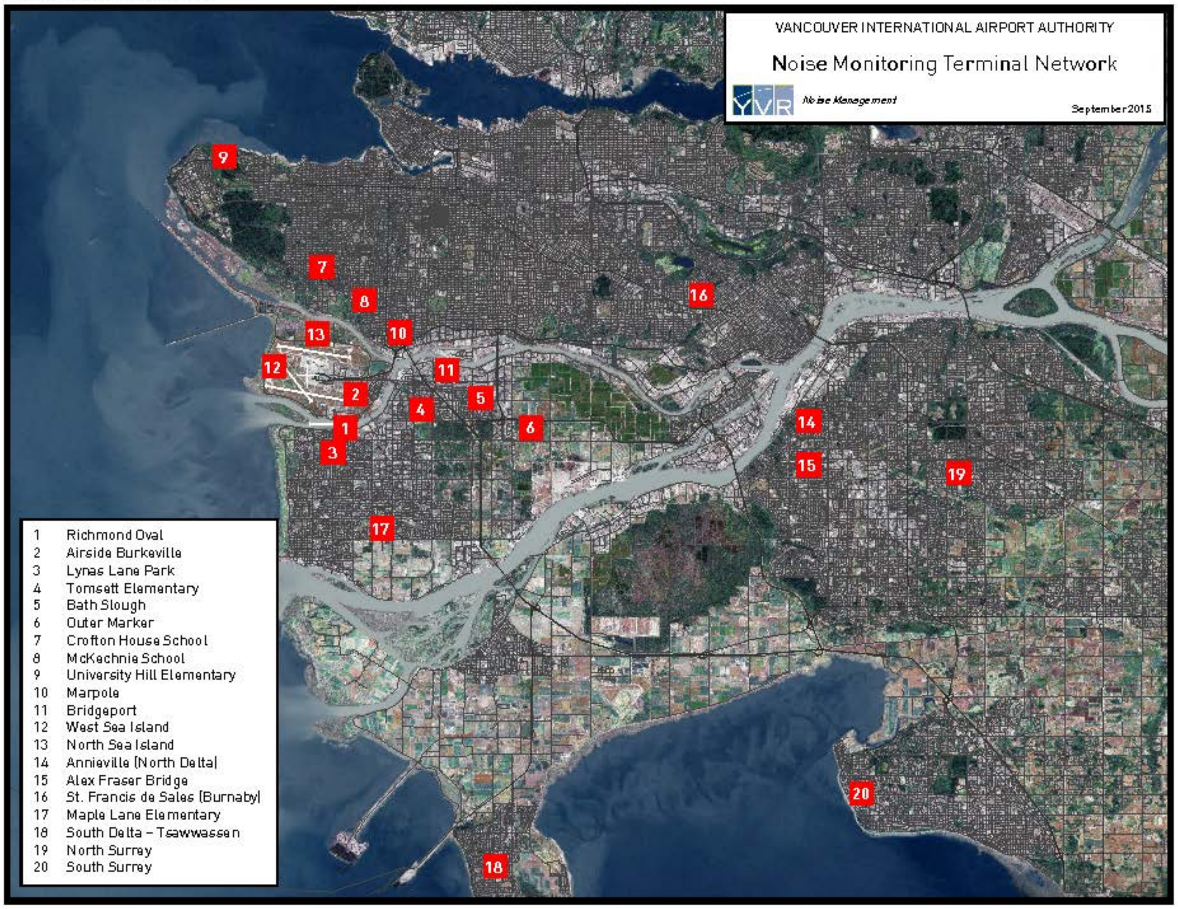

Figure 40.1: Overview of Vancouver International Airport and the surrounding noise monitors.

Milestone(s)

N/A

Major Accomplishments

None. Project started in August 2016.

Publications

None.

Outreach Efforts

None

Awards

None.

Student Involvement

Graduate Research Assistant Manasi Biwalkar has been the primary person working on this task. She is working toward a Summer 2017 graduation with her M.S. in Acoustics.

Plans for Next Period

Continue the work.

References

[1] E. Boeker, *et al.,* "Discover-AQ Acoustics Measurement and Data Report," DOT-VNTSC-FAA-15-09 (2015).
[2] M. Cheng, *et al.,* Vancouver Airport Authority [Private Communication] (2016).
[3] BANOERAC Project final report, Document ID PA074-5-0, ANOTEC Consulting S.L. (2009).
[4] Lopes, L. V. and Burley, C. L., "Design of the Next Generation Aircraft Noise Prediction Program: ANOPP2," AIAA Paper 2011-2854 (2011).
[5] D. K. Wilson, C. L. Pettit, V. E. Ostashev, and S. N Vecherin, "Description and quantification of uncertainty in outdoor sound propagation calculations," J. Acoust. Soc. Am. **136**(3) 1013-1028 (2014).

Task 5 "Assess DISCOVER-AQ Acoustics data for model validation" Task 6 "Assess the uncertainty due to the ground effect and source directivity for en-route aircraft"

Purdue University

Research Approach

FAA's Aviation Environmental Design Tool (AEDT) has now been used by the U.S. Aviation industry for conducting airport noise studies such as FAR part 150 studies and Environmental Impact Statements. In the calculation of lateral attenuation of aircraft noise, AEDT makes use of the standard[4] for modeling the sound absorption by a flat ground. Typically, the ground effect model is based on the well-known Weyl Van der Pol (WVDP) formula:[5]

$$p_{tot}(\vec{r}) = \frac{1}{4\pi}\left[\frac{e^{ik_0R_1}}{R_1} + Q\frac{e^{ik_0R_2}}{R_2}\right], \qquad (1)$$

where $\vec{r}$ is the source position, $k_0 = \omega / c_0$ is the reference wavenumber with ω being the angular frequency and c_0 being the sound speed in air. The parameters, R_1 and R_2 correspond to the respective path lengths of the direct and reflected waves. The spherical reflection coefficient, Q, is given by:

$$Q = V_P + (1 - V_P)F(w_\theta) \qquad (2)$$

where V_P is the plane wave reflection coefficient and F is the boundary loss factor with a complex argument known as the approximate numerical distance, w_θ. They are defined, respectively, by:

$$V_P = \frac{\cos\theta - \beta}{\cos\theta + \beta}, \qquad (3)$$

$$F(w_\theta) = 1 + i\sqrt{\pi}w_\theta e^{-w_\theta^2}\,\mathrm{erfc}(-iw_\theta), \qquad (4)$$

$$w_\theta = \sqrt{ikR_2/2}(\cos\theta + \beta), \qquad (5)$$

where θ is the incidence angle of the reflected wave and $\beta = 1/Z(f)$ is the specific normalized admittance of the ground surface and Z is its characteristic impedance and f is the frequency of the source. In the AEDT model, the Delaney and Bazley model[5] was used to calculate the characteristic impedance of the ground surface where

$$Z(f) = 1 + 9.08\left(f/\sigma\right)^{-0.75} + i11.9\left(f/\sigma\right)^{-0.73}, \qquad (6)$$

and σ is the effective flow resistivity of the ground surface which is expressed in cgs rayls. Typically, AEDT uses 150 cgs rayls for a soft ground and 20,000 cgs rayls for a hard ground. Numerical simulations have suggested that $\beta \to 0$ when σ = 20,000 cgs rayls. In this case, $V_p \to 1$, $F(w_\theta) \to 0$ and $Q \to 1$. Hence, Eq. (1) can be reduced simply to

$$p_{tot}(\vec{r}) = \frac{1}{4\pi}\left[\frac{e^{ik_0R_1}}{R_1} + \frac{e^{ik_0R_2}}{R_2}\right]. \qquad (7)$$

In addition, the ground can be treated as a locally reacting one when σ = 150 cgs rayls. Consequently, there is no need to calculate the complex wavenumber (*k*) of the ground surface as suggested by Fleming et al.[6] As a result, the Delaney and Bazley formula is typically not needed for calculating *k* in the ground effect model for the prediction of long-range outdoor sound propagation.

In the present project, the Purdue team is examining the uncertainties in the prediction of aircraft noise due to the ground effect. In essence, the ground effect of the measured sound fields is caused by the interference of the direct and reflected waves arriving at the receivers. The intrinsic variability in the predictions depends on a host of factors including the source/receiver geometry, source frequency, atmospheric turbulence, acoustic characteristics of the ground surface, and, terrain profile.

At the first step, we shall quantify these uncertainties by considering a simple situation with the source placed above a hard ground. The impacts of the source and receiver locations on the accurate prediction of sound fields are investigated. The analysis will focus not only on the narrow band analysis but also on the simulations of one-third octave bands and the integrated A-weighted noise levels of the pass-by noise. In this initial study, we shall investigate the situations for an en-route aircraft or when the source is close to a hard ground modeling the situations of the take-off/landing of an aircraft.

Our next step involves the quantification of uncertainties for the aircraft operating above a locally reacting ground. The computational times can be minimized by assuming a homogeneous atmosphere and Eq. (1) is used in the numerical simulations for predicting the sound fields. The Delaney and Bazley model was used initially because the impedance can be characterized by a single parameter – σ, the effective flow resistivity of the ground surface. A sensitivity analysis can be conducted to investigate the effect of the 'errors' in both σ and the source/receiver geometry on the predicted sound fields. The experimental data (Discover-AQ and Vancouver Airport dataset) will be used to compare with the numerical simulations for quantifying the uncertainties.

In the recent study,[7] Hobbs has examined the possible incorporation of a mixed impedance ground model in AEDT. Hobbs has suggested the use of the National Land Cover Database (NLCD) to derive the information of the ground surface. Basically, NLCD has used satellite imagery (with a 30 m resolution) which provides useful classifications of land cover in the continental U.S. Potentially, this information may be used in conjunction with the National Elevation Data (NED) in AEDT for assessing the ground effects of the aircraft noise. For the current year, we propose to look into the uncertainties introduced by the presence of a mixed impedance ground in the prediction of aircraft noise.

The proposed tasks may lead to a better understanding of the uncertainties due to the ground effect, source/receiver geometry, and their interactions. Insights from the proposed work can be integrated into existing FAA noise modeling tools to handle more realistic propagation effects. Specifically, the Purdue team will focus on (a) the review of the Impact of ground effects, and (b) how the dataset can potentially be used to quantify the uncertainties in predicting noise around airports and the en-route aircraft noise.

The current project aims to quantify the uncertainties in predicting aircraft noise in real-world situations. In the current year, the proposed tasks for the Purdue team can be summarized as follows:

- Study the uncertainties in the predicted noise levels due to the geometric locations of the source and receiver,
- Investigate the 1-parameter ground impedance model on the ground effects of aircraft noise,
- Based on the input from the Penn State team, examine the effect of source directivity for the prediction of noise levels of en-route aircraft.
- Explore the impact of a mixed impedance ground on the uncertainties in the prediction of ground effects of aircraft noise.

Milestone(s)

N/A

Major Accomplishments

None. Project started in August 2016.

Publications

None.

Outreach Efforts

None

Awards

None.

Student Involvement

Graduate Research Assistant Yiming Wang has been the primary person working on this task.

Plans for Next Period

Continue the work.

References

[1] E. Boeker et al. Discover-AQ Acoustics Measurement and Data Report,"DOT-VNTSC-FAA-15-09 (2015).
[2] M. Cheng, *et al.,* Vancouver Airport Authority [Private Communication] (2016).
[3] BANOERAC Project final report, Document ID PA074-5-0, ANOTEC Consulting S.L. (2009).
[4] SAE-AIR-5662 "Method for Predicting Lateral Attenuation of Airplane Noise" (2012).
[5] K. Attenborough, K.M. Li, and K. Horoshenkov. *Predicting Outdoor Sound*. Taylor & Francis, 2007.
[6] C. G. Fleming, J. Burstein, A. S. Rapoza, D. A. Senzig, and J. M. Guilding. "Ground effects in FAA's integrated noise model," Noise Control Engineering Journal **48**, 16-24.
[7] C. Hobbs, Interim Report on ACRP 02-52: Improving AEDT noise modeling of ground surfaces (2016).