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

The Pennsylvania State University
Purdue University

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- FAA Award Number: 13-C-AJFE-PSU, Amendment 49
- Period of Performance: May 31, 2019 to October 31, 2020
- Task(s):
  1. Assess uncertainty in aircraft noise events, examining the BANOERAC and similar data sets
  2. Assess uncertainty in realistic noise source models in ANOPP

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- PI(s): Kai Ming Li, Professor of Mechanical Engineering
- FAA Award Number: 13-C-AJFE-PU, Amendment 31
- Period of Performance: May 31, 2019 to May 31, 2020
- Task:
  3. Validate the noise model capabilities of the FAA Aviation Environmental Design Tool (AEDT) by comparing numerical results with field data and quantify uncertainties of both model prediction and measurement in trying to predict aircraft noise (or pattern of change) in the real world

Project Funding Level
FAA funding to Penn State in 2019–2020 is $170K. FAA funding to Purdue in 2019–2020 is $85K.

Airbus has committed in-kind cost share for both Penn State and Purdue regarding the SILENCE(R) data set, and this in-kind cost share is currently in process, awaiting a non-disclosure agreement. The point of contact for this cost sharing is Pierre Lempereur, pierre.lempereur@airbus.com.

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The BANOERAC (background noise level and noise levels from en route aircraft) data were provided to Penn State and Purdue by the European Union Aviation Safety Agency via a special licensing agreement, with the assistance of ANOTEC Engineering S.L. This in-kind data contribution is greatly appreciated.

Project Overview
The ASCENT R&D portfolio is designed to assist the Federal Aviation Authority (FAA) in meeting the overarching environmental performance goal for the Next Generation Transportation System (NextGen) to attain environmental protection that allows sustained aviation growth. This task is part of the aviation modeling and analysis task of the ASCENT R&D portfolio, with the goal to improve the accuracy of the FAA’s environmental modeling tools. This project is providing data and methods to improve aircraft weight and take-off thrust modeling capabilities within the FAA Aviation Environmental Design Tool (AEDT). Furthermore, atmospheric conditions and ground properties have significant impacts on accurate predictions of aircraft noise. The accuracy of these inputs is critical for the predictions. 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 developed and enhanced to account for the effects of meteorological conditions, atmospheric absorption, and the Doppler effect due to source motions on the propagation of aircraft noise. The purpose of this project is to understand and quantify uncertainty in the prediction of noise propagation of aircraft.

ASCENT Project 40 is developing numerical methods that could later be used in FAA tools to predict aircraft noise. The current proposal addresses an improved approach to extend the uncertainty quantification methods of Wilson et al. (2014) and other algorithms. Realistic aircraft trajectories and meteorology in the atmosphere are being used to predict aircraft flyover noise levels. The results will be compared with field data already acquired in DISCOVER-AQ Acoustics, the Vancouver Airport Authority, BANOERAC, and SILENCE(R) databases. In addition, uncertainties on geometric locations of source and receivers, effective surface impedance and ground topography, and source motion have been incorporated in this year of effort.

If successful, the outcomes of ASCENT Project 40 will lead to the development of improved methodologies that could be implemented in FAA tools to predict aircraft noise in the presence of real-world weather. By having faster predictions and predictions verified with field data, the project will help to improve confidence when making decisions regarding aircraft noise, such as choosing sites for new runways and implementing new landing approach and take-off patterns over populated areas. The project team has identified key drivers for quantifying uncertainties in predicting aircraft noise. To assess these uncertainties, an integrated approach will be used to understand uncertainties in (a) the aircraft state and resulting noise levels and directivity (source); (b) the atmospheric and meteorological conditions (propagation); and (c) the ground impedance and terrain model (receiver). This integrated approach will include all predominant uncertainties between the source and receiver. One of the main motivations of the current project is to guide these recent advancements to reach a research readiness level that leads to possible implementation in AEDT in the future.

This research will enhance the accuracy of AEDT through improved aircraft noise propagation modeling. This improvement is needed to support the evaluation and development of aircraft flight routes and procedures that could reduce community noise. These improvements will also facilitate the implementation of NextGen by improved characterization of the efficiency benefits it would deliver. If this research is not performed, the accuracy of the noise prediction tool may not be representative of real-world operations and would thus affect studies used by airport authorities.
Also, in 2019, a collaborative initiative with National Aviation University of Ukraine was continued and close cooperation with Georgia Tech on ASCENT Project 43 was initiated.

Task 1 - Assess Uncertainty in Aircraft Noise Events, Examining the BANOERAC and Similar Data Sets
Pennsylvania State University

Task 2 - Assess Uncertainty in Realistic Noise Source Models in ANOPP
Pennsylvania State University

Objectives
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.

Research Approach
Overview of the BANOERAC data
BANOERAC was a project initiated by the European Union Aviation Safety Agency in 2009 (ANOTEC Consulting S.L., 2009). The project had two main goals, the first of which was to prepare maps for Europe showing background noise levels. The calculation method relied on the population density to determine background noise levels, based on earlier work by Stiftelsen for industriell og teknisk forskning (SINTEF; Trondheim, Norway). The measurements of background noise and en route aircraft noise were conducted in Spain (see Figure 1). The first part of the BANOERAC study focused on correcting the SINTEF model for extremely low population density areas by taking background noise measurements (this is not the focus of the analysis presented here). The second part of the study involved measurements of en route aircraft noise, which were conducted from February to July 2009 (covering both winter and summer seasons). Data collection was spread over 20 days in the six-month period. The measured data included time histories of aircraft tracking data and noise measurement data (third-octave levels) from two microphones (one placed 1.2 m above the ground, the second inverted and placed on a flat plate on the ground). The locations of the noise monitors can be seen in Figure 1. Meteorological data from a ground meteorological station (time synchronized with the noise monitors) and seven distant sounding stations (seven Spanish airports shown by blue circles in Figure 1) are also provided.

Limitations of the available meteorological data
The data from the ground meteorological system (placed on a 1.8-m-high mast at the noise measurement site) consist of temperature, relative humidity, wind speed, wind direction, and atmospheric pressure. Although the data are synchronized in time with noise measurement data, they provide information at only one physical location (i.e., not along a vertical profile).

The data from the seven meteorological sounding stations do provide vertical profiles of the meteorological variable but the data are available for every 12 hr (and not synchronized with the noise events). In addition, the sounding stations are far away from the noise measurement sites, making the former unusable for inclusion in the acoustic propagation calculations.
A brief overview of the data handling process
In total, the dataset included 1,056 aircraft events. Events that were reported to be contaminated (by noise from helicopters, general aviation, motorized vehicles, wind, birds, and other natural sources) were removed, and only events that had audible commercial aircraft noise were selected. This reduced the number of events to 537. To this point, only the information reported in the BANOERAC report (ANOTEC Consulting S.L., 2009) was utilized for the data filtering process. All data from the 537 events were visualized to inspect the quality, the results of which are summarized in Table 1. The aim of this exercise was to understand the fleet mix of the usable data. Table 1 shows that the types of aircraft commonly found in U.S. airports are well represented. As can be seen in the last row, of 537 events that were considered uncontaminated (i.e., that only included noise from commercial aircrafts), only 68 events were useful for validating existing noise modeling capabilities.
Table 1. Number of aircraft events not contaminated by nonaircraft noise sources according to the BANOERAC report (shown in black) and number of aircraft events possibly useful for validation (based on a preliminary visual inspection performed by Penn State and subject to change) (shown in blue).

<table>
<thead>
<tr>
<th>Aircraft class</th>
<th>Aircraft model</th>
<th>Cruise</th>
<th>Descent</th>
<th>Climb</th>
<th>Total</th>
</tr>
</thead>
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<tr>
<td>Business jet</td>
<td>Beech 390</td>
<td>0 (0)</td>
<td>1 (0)</td>
<td>0 (0)</td>
<td>1 (0)</td>
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<td>Long-range quad</td>
<td>747-400</td>
<td>2 (0)</td>
<td>1 (1)</td>
<td>0 (0)</td>
<td>3 (1)</td>
</tr>
<tr>
<td></td>
<td>A-340-300</td>
<td>0 (0)</td>
<td>6 (1)</td>
<td>27 (7)</td>
<td>33 (8)</td>
</tr>
<tr>
<td></td>
<td>A-340-500</td>
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<td>0 (0)</td>
<td>0 (0)</td>
<td>2 (0)</td>
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<tr>
<td></td>
<td>A-340-600</td>
<td>0 (0)</td>
<td>5 (1)</td>
<td>8 (1)</td>
<td>13 (2)</td>
</tr>
<tr>
<td>Long-range twin</td>
<td>757-200</td>
<td>7 (1)</td>
<td>4 (1)</td>
<td>0 (0)</td>
<td>11 (2)</td>
</tr>
<tr>
<td></td>
<td>757-300</td>
<td>2 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>2 (0)</td>
</tr>
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<td>767-200</td>
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<td>2 (1)</td>
<td>0 (0)</td>
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<tr>
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<td>767-300</td>
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<td>1 (1)</td>
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<tr>
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<td>8 (3)</td>
<td>0 (0)</td>
<td>9 (3)</td>
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<tr>
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<td>A-330-200</td>
<td>2 (1)</td>
<td>10 (3)</td>
<td>3 (1)</td>
<td>15 (5)</td>
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<tr>
<td></td>
<td>A-330-300</td>
<td>9 (2)</td>
<td>1 (0)</td>
<td>1 (0)</td>
<td>11 (2)</td>
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<tr>
<td></td>
<td>A300F4 BELUGA</td>
<td>0 (0)</td>
<td>1 (1)</td>
<td>0 (0)</td>
<td>1 (1)</td>
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<tr>
<td>Medium-range (Gen 2)</td>
<td>737-300</td>
<td>19 (1)</td>
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<tr>
<td></td>
<td>737-400</td>
<td>4 (0)</td>
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<td>0 (0)</td>
<td>5 (0)</td>
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<tr>
<td></td>
<td>737-700</td>
<td>30 (3)</td>
<td>1 (0)</td>
<td>0 (0)</td>
<td>31 (3)</td>
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<td>737-800</td>
<td>68 (7)</td>
<td>15 (3)</td>
<td>11 (4)</td>
<td>94 (14)</td>
</tr>
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<td>A-318</td>
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<td>0 (0)</td>
<td>0 (0)</td>
<td>4 (0)</td>
</tr>
<tr>
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<td>A-319</td>
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<td>15 (2)</td>
<td>22 (0)</td>
<td>91 (6)</td>
</tr>
<tr>
<td></td>
<td>A-320</td>
<td>57 (4)</td>
<td>38 (5)</td>
<td>40 (5)</td>
<td>135 (14)</td>
</tr>
<tr>
<td></td>
<td>A-321</td>
<td>27 (1)</td>
<td>10 (1)</td>
<td>7 (1)</td>
<td>44 (3)</td>
</tr>
<tr>
<td>Regional jet (Gen 1)</td>
<td>F100</td>
<td>6 (0)</td>
<td>0 (0)</td>
<td>2 (0)</td>
<td>8 (0)</td>
</tr>
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<td>Total events</td>
<td></td>
<td>295 (24)</td>
<td>121 (25)</td>
<td>121 (19)</td>
<td>537 (68)</td>
</tr>
</tbody>
</table>

Visualization of a candidate event

After carefully reviewing the 68 selected events, we chose one event that had the least amount of nonaircraft noise for the preliminary investigation. The data for this event were recorded on the morning of March 10, 2009, and involved a Boeing 757-200 aircraft. The aircraft trajectory (Figure 2), the altitude time history (solid black line in Figure 4), and the noise monitor location were used to calculate the distance between the aircraft and the noise monitor (dashed blue line in Figure 4). Figure 3 shows the time history of third-octave band sound pressure levels (SPL) visualized with a colormap and the overall SPL (OASPL) with red lines. The BANOERAC project report mentions instances of contamination of noise data by insect noise (above 1 kHz). Hence, the OASPL is shown for 25 to 1000 Hz (dotted red line in Figure 3) and 25 to 4000 Hz (solid red line in Figure 3). For the event under consideration, there was virtually no difference between the two lines, implying that the dominant part of the sound energy is in frequency bands below the 1000-Hz third-octave band. Interference patterns (because of direct and ground-reflected sound energy) show up in the data measured by the microphone placed 1.2 m above the ground. Figure 5 shows the time history of the aircraft ground speed (aircraft slowing by about 190 km/hr) and a constant heading angle (which can be corroborated with the aircraft trajectory shown in Figure 2).
Next, the time history of the distance between the aircraft and the noise monitor was combined with the time history of third-octave SPLs, and the results are shown in Figure 6 (SPL vs. distance). For the 25- to 1600-Hz third-octave bands, the SPLs were lower when the aircraft was approaching the noise monitor than when it was going away from the noise monitor (for the same distance). For this event, the maximum geometric distance was about 12 km and the duration of the event was less than 90 s. This implies that changes in meteorological conditions (over the distance and duration involved) probably play an insignificant role when explaining the difference in levels for the same geometric distance. The two likely explanations are convective amplification and aircraft noise directivity.

Figure 2. Time history of the aircraft trajectory.

Figure 3. Time history of third-octave SPLs and OASPL for microphone on the ground and microphone at 1.2 m height.
Figure 4. Time history of aircraft altitude and the slant distance between the aircraft (A/C) and the noise monitoring station (N.M.S.).

Figure 5. Time history of aircraft ground speed and aircraft heading angle.

Figure 6. Dependence of the third-octave SPL on the distance between the aircraft and the noise monitor.
Convective amplification

For a moving source, the effect of convection on the received SPL depends on the Mach number, $M$, and the emission angle (as shown in Figure 7). This effect can be calculated using Equation (40.1), where $n = 1$ for a monopole or dipole source and $n = 2$ for a quadrupole source (Ruijgrok, 1994). In general, aircraft noise can be represented using multipole expansion (i.e., as a combination of a monopole, a dipole, a quadrupole, and higher-order sources). For now, we will treat the aircraft as a monopole source.

\[
\text{Convective amplification} = -20(n + 1) \log (1 - M \cos \theta_{\text{emission}})
\]  

(40.1)

The Mach number needs to be calculated using the airspeed of the aircraft, but the available data are only for ground speed. The flight altitude for the event under consideration was about 4 km, where typical wind velocity could be as high as 100 km/hr. Because wind speed and wind direction information were not available, we considered three scenarios (i.e., no wind, aircraft flying downwind, and aircraft flying upwind) to assess the effect of wind on convective amplification. The results are shown in Figure 8. As can be seen, if wind speed and direction are not known, then the uncertainty in predicting convective amplification can be as high as 6 dB.

Figure 7. A schematic showing the emission angle and its relation to the aircraft and the receiver location.

Figure 8. Time history of the emission angle and convective amplification for three wind conditions.

Aircraft directivity

The main sources of aircraft noise are jet noise, fan and turbine noise, combustion chamber noise, and airframe noise (Zaporozhets et al., 2011). The overall directivity of aircraft noise depends on the relative strengths and directivities of each of these sources (which, in turn, can be functions of aircraft configuration, aircraft state, and engine power). For the event under consideration, as a first attempt at including aircraft directivity, we assumed that jet noise would be the dominant source; hence, the overall noise directivity would closely resemble jet noise directivity. The polar directivity pattern shown in Figure 10 was assumed to represent the overall aircraft noise directivity (ANOPP documentation, NASA).
For the event under consideration, the time history of the polar angle was calculated using the geometry shown in Figure 9.

**Figure 9.** A schematic showing the polar angle and its relation to the aircraft and the receiver location.

**Figure 10.** A typical directivity pattern associated with jet noise.

**Results and discussion**

In our first attempt at comparing measured data (Figure 6) with predictions, the 500-Hz third-octave band was chosen as a representative case. To calculate the acoustic absorption for the 500-Hz third-octave band (using ISO 9613-1 and SAE-ARP-5534), we assumed a temperature of 13 °C and relative humidity of 30% (these values are based on data measured at the ground meteorological station). Figure 11 shows the predicted normalized SPL and the three contributing factors: acoustic propagation and absorption, convective amplification, and jet noise directivity. The dashed and solid lines in Figure 11 correspond to the duration of the event when the aircraft is approaching and going away from the noise monitor, respectively. The effect of acoustic propagation in both cases is the same for the same distance (irrespective of whether the aircraft is approaching or going away). Convective amplification and jet noise directivity appear to be competing factors; that is, convective amplification results in higher levels when the aircraft is approaching the noise monitor and the contribution from jet noise directivity is lower for that part of the event (and vice versa when the aircraft is going away from the noise monitor). It is evident that the combined effect of the three factors results in qualitative agreement with the measured data (Figure 6).
Based on the preliminary analysis shown in this work, the following conclusions can be drawn:

1. To accurately predict aircraft noise, it is necessary to account for both convective amplification and aircraft directivity.
2. Source levels and directivity as a function of frequency are needed to explain the details of the received noise levels across all third-octave bands of interest.
3. Detailed information about aircraft state is required to predict the absolute source levels and the overall directivity.
4. Vertical profiles of meteorological variables are needed to correctly predict acoustic propagation and absorption effects.

**Initial efforts on Aircraft Noise Prediction Program (ANOPP) prediction for source models**

Preliminary noise propagation predictions have shown the importance of using a realistic noise source directivity when interpreting the ground-based measurements. To provide such a noise source description, the NASA Aircraft Noise Prediction Program (ANOPP2) is being used. Selected information from the BANOERAC dataset is being used to identify the aircraft and engine type and the flight conditions. An example is shown in Table 2. In this case, the aircraft is descending. Based on the aircraft location and the rate of descent, a reasonable estimate can be made of the aircraft’s destination, flap settings, and weight (information that is not included in the dataset). The information in the table was provided to colleagues at Georgia Tech, who provided an initial input script for ANOPP2. This script enables the aircraft noise source to be characterized and the information is provided to the propagation prediction team. The basic script is also used to make noise predictions at the observer location for comparison with those determined when a realistic atmosphere is included. In addition, the variation in the noise source calculation caused by changes to the assumed aircraft state can be quantified.
Table 2. Example flight information from BANOERAC dataset.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Descent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft model</td>
<td>Boeing 737-800</td>
</tr>
<tr>
<td>Engine model</td>
<td>(2x) CFMI CFM56-7B26</td>
</tr>
<tr>
<td>Mean ground speed (ft/s)</td>
<td>562.1</td>
</tr>
<tr>
<td>Mean rate of descent (ft/s)</td>
<td>26.3</td>
</tr>
<tr>
<td>Mean altitude (ft)</td>
<td>17,448</td>
</tr>
<tr>
<td>Weight at event time (lbs)</td>
<td>139,205</td>
</tr>
</tbody>
</table>

Milestone(s)
The raw data from the BANOERAC dataset has been parsed and visualized to identify aircraft noise events that might be useful to validate existing noise modeling capabilities. Preliminary analysis of a candidate event has been completed to guide future efforts.

Major Accomplishments
For accurate aircraft noise predictions, we have demonstrated the importance of high-speed source motion (convective amplification) and source directivity. Qualitative agreement has been achieved between predicted and measured aircraft noise from a real-world database.

Publications
N/A

Outreach Efforts
N/A

Awards
None.

Student Involvement
Graduate research assistant Harshal P. Patankar has been the primary person working on this task. An undergraduate student, Stephen Willoughby, has also been contributing. Neither student has graduated at this time.

Plans for Next Period
1. Penn State plans to look closely at the effects of aircraft state (to predict source levels and directivity) and propagation on the received noise levels.
2. Penn State previously showed that the overall approach of Wilson et al. (2014) could be adapted to the aircraft noise prediction problem (Patankar & Sparrow, 2018; Patankar & Sparrow, 2019). This approach will be extended by using a 2-dimensional ray tracing model to comment on the uncertainty in predictions caused by the lack of or insufficient meteorological conditions.

References

**Task 3 - Validate the Noise Model Capabilities of AEDT by Comparing Numerical Results with Field Data and Quantify Uncertainties of Both Model Prediction and Measurement in Trying to Predict Aircraft Noise (or Pattern of Change) in the Real World**

**Objectives**
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 due to source motion (source), the atmospheric and meteorological conditions (propagation), and ground impedance and the terrain model (receiver). This approach will include all predominant uncertainties between the source and receiver.

**Research Approach**
**Background**
The Purdue research team has been working extensively on the DISCOVER-AQ dataset in the past two years. The full details of the scope of the DISCOVER-AQ acoustic research effort and its measured results can be found in Boeker et al. (2015). In summary, NASA conducted a series of acoustic measurements near Houston, Texas, in September 2013. The aim of these acoustic measurements was to measure in situ acoustic level data from two aircraft operating with controlled flight paths, in which the corresponding acoustic, meteorological, aircraft position, and performance data were recorded. This combined dataset was designed to provide a comprehensive validation of various modeling of noise levels from a flyover aircraft. The receivers were located in areas with relatively low ambient noise levels and minimal outside transportation noise sources and at a variety of distances and elevation angles from the nominal aircraft flight paths.

After an initial study, the Purdue team identified that the maneuvers of the Lockheed P-3B Orion (see Figure 12) contained the most relevant acoustic datasets for detail investigations. The Lockheed P-3B Orion is a four-engine turboprop aircraft with a maximum gross take-off weight of 135,000 lbs. The propeller blades were manufactured by Hamilton Standard. Each of the propeller blades was driven by an Allison T56-A-14 turboprop engine delivering 4,100 shp.

**Accomplishments in the past two years (2016–2018) of Project 40 at Purdue University**
A typical source spectrum of the noise radiated by the Lockheed P-3B Orion is shown in Figure 13a. For this type of turboprop aircraft, the low-frequency tonal components (below 200 Hz) dominate the sound fields, which is quite different from the noise spectrum of the Boeing 747-100 jet engine aircraft (Ahearn et al., 2017) shown in Figure 13b (see Figure 18b for the Lockheed F-22 jet engine noise spectrum). The low-frequency components are usually much lower for the noise radiated from jet engines. Hence, jet noise cannot propagate long range in the atmosphere because of high air absorption at mid- to high-frequency regimes. Compared with that of jet engines, noise radiated from turboprop engines can travel a
relatively longer distance to the ground because the rate of atmospheric absorption of sound is typically much smaller in this low-frequency regime. For ground-based receivers, the en route noise from a turboprop aircraft is likely more noticeable than that of a jet-driven aircraft.

![Image](90x472 to 325x642)

**Figure 13.** Typical noise spectra of two types of aircraft engines: (a) Lockheed P-3B Orion turboprop engine; and (b) Boeing 747-100 jet engine.

Using the available information, we could identify the flight trajectory of the test aircraft and the atmospheric sound speed profiles during the flight trials. With onboard noise monitoring equipment and ground-based microphones, we were able to extract the measured data and compare them with the predictions due to a flyover aircraft. According to the results, the assumption that the test aircraft can be modeled as an omnidirectional source is satisfactory only at higher frequencies (over about 300 Hz); use of the omnidirectional source model has become increasingly inadequate for source frequencies below 125 Hz.

The Purdue team has developed an empirical model to estimate the directivity patterns of the test aircraft. Figure 14 compares the predicted and measured time histories of a typical set of measured data with a source frequency of 63 Hz. The agreement between the measured results and predictions is reasonably good.
Figure 14. Comparison of measured and predicted time histories of A-weighted SPL of the test aircraft at a frequency of 63 Hz.

According to AEDT (Ahearn et al., 2017), attenuation ($\text{Att}$) due to an “acoustically soft” ground can be modeled using the following empirical formula:

$$\text{Att}(l_{\text{seg}}) = \begin{cases} 11.83 \times \left[ 1 - e^{-0.00274 l_{\text{seg}}} \right] & 0 \leq l_{\text{seg}} \leq 3000 \text{ ft} \\ 10.86 & l_{\text{seg}} > 3000 \text{ ft} \end{cases}$$

where $l_{\text{seg}}$ is the horizontal sideline distance measured from the aircraft flight path. The Purdue team has examined the uncertainties in the prediction of aircraft noise due to the ground effect according to the empirical formula. The ground effect of the predicted/measured sound fields is caused by interference of direct and reflected waves arriving at the receivers. The intrinsic variability in the predictions depends on a number of factors, including the source/receiver geometry, source frequency, atmospheric turbulence, acoustic characteristics of the ground surface, and terrain profile (Attenborough et al., 2007).

Figure 15 compares the predicted attenuation due to the ground effects for source frequencies of 250 and 500 Hz. The predicted attenuation according to the AEDT model is shown by the gold line. The predicted attenuation at different sideline distances is shown for snow-covered (blue) and grass-covered (red) ground with frequencies at 250 Hz (solid line) and 500 Hz (dashed line). The Delany-Bazley (D-B) model (Attenborough et al., 2007) was used to predict the effective impedance of the ground surface in Figure 15. In the D-B model, a single parameter known as “effective flow resistivity” is used to characterize the impedance of the ground surface. Parametric values of 20 and 250 kPa m s$^{-2}$ were used to model snow-covered ground and grassland. The source and receiver heights were 100 and 0 m above the ground, respectively, in the simulations shown in Figure 15. The total sound fields were computed by summing the direct and reflected waves coherently. We can see that the discrepancy in predicting attenuation can be as high as 6 dB between the AEDT and D-B models.
Figure 15. Comparison of AEDT ground model with a more precise ground impedance model.

The Purdue team has conducted a detailed analysis on the overall uncertainties on the DISCOVER-AQ dataset. Figure 16 shows the improvement in prediction of the A-weighted SPL. The agreement between the field data and our current prediction scheme using an improved spherical directivity pattern (gold) was much better than that using the monopole model (red); that is, noise due to an omnidirectional source. The agreement was especially good in the location of the first peak.
Figure 16. Comparison of predicted and field data for the A-weighted SPL of a typical event.

Figure 17 shows that the prediction “errors” with the use of the source directivity model have been reduced. However, larger error still exists when the distance is short and the elevation angle small. Future work should focus on the analysis of ground effects because most measurement sites are located in the vicinities of forested grounds, which would change the measured sound and many aircraft paths are above water-covered regions.

Figure 17. Discrepancies between measurement data and predictions for a selected event.

In the past year, the Purdue team has also studied the effect of source motion on predicting the A-weighted noise levels of flyover aircraft. Again, the DISCOVER-AQ dataset was used for comparison with predicted results. Figure 18 shows that the A-weighted SPL due to the test aircraft (driven by turboprop engines) showed higher sensitivity to the Doppler effect than aircraft driven by jet engines.

Figure 18. Measured A-weighted SPL at different times of a flyover aircraft: (a) P3-B Orion (turboprop engines), and (b) F-22 (jet engine).
We also showed that predictions without the inclusion of Doppler effects usually underestimate the maximum A-weighted SPL for P-3B Orion test aircraft.

**Milestones and Major Accomplishments**

To complete the tasks for the current year, we launched an initial study to identify a set of relevant data in the DISCOVER-AQ report. Figure 19 shows detailed receiver locations and a three-dimensional view for a flight event near the airport of Conroe, Texas. There is one set of data for the level flight path before the spiral section and one set after the spiral maneuver. The measured noise data for the level flight before the spiral path had better signal-to-noise ratios because the flyover aircraft was operated at a lower elevation and, therefore, was much closer to the microphones mounted on the ground near the forest about 10 miles from Conroe airport. Hence, this set of data will be used in our work for the coming year. There are 11 groups of similar level flight tests with noise levels recorded by four to six receivers. Atmospheric profiles recorded by weather balloon will be used for comparisons with various numeric models.

![Figure 19. Flight path and receiver locations for level flight (events 279–284) in DISCOVER-AQ measurement results.](image)

**Publications**


**Outreach Efforts**

N/A

**Awards**

Graduate research assistant Yiming Wang received the Institute of Noise Control Engineering (INCE) Best Graduate Student Award, 2018.

**Student Involvement**

Graduate research assistant Yiming Wang has been the primary person working on this task.

**Plans for Next Period**

The Purdue team plans four tasks:

1. Assess the DISCOVER-AQ Acoustics datasets for use in validating noise tools (propagation).
2. Assess the influence of source (aircraft) motion on the accuracy in predicting en route aircraft noise (source).
3. Assess the impacts of geometric locations of source and receiver, the effective surface impedance, and the ground topography on the accurate prediction of aircraft noise (receiver).
4. Assess the overall uncertainty in the noise prediction (propagation + source + receiver) of flyover aircraft.
Three of these four tasks are being conducted in coordination with the Penn State team. The Purdue team will also focus on the use of DISCOVER-AQ datasets to investigate the influence of ground effects on predicting aircraft noise (Task C). Other Purdue efforts include the investigation of the Doppler effect on measured noise contents (for the shift in frequency and change in noise levels) for approaching and receding aircraft.

References
SILENCE(R) Consortium; a description of this research program can be found here: http://www.xnoise.eu/index.php?id=85 (Last Accessed 7/15/2017). The research program is under the administration of X-Noise, which is a collaborative network in the European Union specializing in aeroacoustics.