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Analytical Approach for Quantifying Noise from Advanced Operational Procedures

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This paper presents a method and initial results for improving the fidelity, accuracy, and utility of noise analysis techniques for environmental review of advanced operational procedures. Such procedures may have the potential to reduce aircraft noise through spatial management (noise-preferred routes, track dispersion or concentration) or specially-designed noise abatement flight procedures. Such procedures incorporate a combination of modified speed targets, vertical profiles, and/or flap and landing gear configuration schedules. Traditional noise analysis techniques cannot capture the details of such procedures. Older generations of jet engines produced significantly more noise than current-generation products. Therefore, the assumption that jet noise dominates aerodynamic sources may have been reasonable for previous generations of modeling [1]. However, for new advanced approach and departure procedures, aerodynamic noise reduction may constitute a significant portion of potential benefits. This effect is not captured using current noise-power-distance (NPD) methods as implemented in industry-standard models such as the Aviation Environmental Design Tool (AEDT). An alternative physics-based modeling approach has been developed to capture higher-fidelity noise impacts. This tool has been used to evaluate several candidate operational procedures for noise impact. Single-flight results are also combined using a novel rapid modeling approach to obtain integrated noise exposure contours and other metrics of interest at an airport and system level.

I. INTRODUCTION

Next-generation flight procedures are a key component of air traffic management modernization efforts in the United States [2] and Europe [3]. Specifically, performance-based navigation (PBN) is intended to play a key role in streamlining navigation standards and procedures to improve capacity, efficiency, and safety in the future ATM system. PBN allows greater potential flexibility in terms of lateral and vertical routing, speed control, and procedural design flexibility. The noise impacts of PBN and other advanced operational procedures have been investigated in several specific contexts (for example, [1], [4]–[10]), but work remains to model and mitigate noise implications arising from new procedures.

Operational procedures refer to the manner in which an aircraft is flown or operated in any phase of flight. Precise definition of a procedure includes the latitude, longitude, speed, thrust, altitude, and configuration of an aircraft as a function of time throughout a given phase of flight. Depending on the type of analysis, this definition may be limited to the approach, departure, cruise, or other phases of flight. Advanced operational procedures are those that use modern technology and procedures (infrastructure, avionics, and air traffic control) to control speed, thrust, ground track, and other variables in a manner that would not be possible in traditional operations. Examples include PBN procedures with required navigation performance (RNP) and precise speed scheduling for efficiency and noise.

The development of advanced flight operations has been driven by several main factors:

- Evolving airport traffic levels and utilization strategies change the environmental impact of air transportation. These changes can impact noise, emissions, air quality, and climate, motivating the exploration of operational mitigations through advanced procedures.
- Airport throughput may be increased based on airspace and procedural design. Adoption of advanced procedures may increase runway and airspace capacity in constrained areas.
- Airlines may achieve economic advantages from advanced operating procedures, including reduced fuel cost and flight times.
- Policy makers can modernize infrastructure through adoption of new technologies in day-to-day operations.

Although advanced operating procedures exist in all phases of flight, the focus of this project is on proposed advanced procedures for arrivals and departures within the terminal area of an airport. Examples include continuous descent arrivals, delayed deceleration approaches, steep approaches, and high-precision performance-based navigation (PBN) approach and departure procedures including Area Navigation (RNAV) and Required Navigation Performance (RNP). These procedures have the possibility to alter the noise footprint near airports relative to current operations due to:

- Changes in aircraft speed profiles on approach or departure, with a corresponding increase or decrease in aerodynamic noise;
- Changes in aircraft thrust profiles due to configuration changes, acceleration schedules, or speed targets, with a corresponding increase or decrease in engine noise;
- Changed aircraft configuration, such as flap settings and landing gear extension, with a corresponding change in aerodynamic noise generation;
- Concentration or dispersal of aircraft operations on set RNP tracks or procedural profiles.

II. METHODOLOGY

Currently, the Aviation Environmental Design Tool (AEDT) is the primary tools used to evaluate new procedures and traffic intensity levels for calculating noise impact footprints near airports. AEDT noise calculations use Noise-Power-Distance (NPD) interpolation to calculate noise using engine data generated through flight test and/or analysis. A functional relationship between engine throttle setting and atmospheric slant distance yields noise estimates for locations on the surface. The frequency spectrum is obtained from a dataset of representative aircraft families at set power levels and aircraft configurations. This procedure results in a simple and computationally tractable noise estimation capability for engine noise sources only. Aerodynamic and procedural noise contributions are not fully incorporated into the model. For instance, aerodynamic noise is derived empirically for a reference speed of 160 knots. Any speed difference from this reference value results in potential inaccuracies in airframe noise estimates [11].

To address the limitations in the NPD-based noise modeling, higher-fidelity physics-based models can be used to capture various noise sources, shielding, and propagation. The outputs of such models can be used to directly calculate noise fields from an overflight or calculate higher-fidelity NPD data sets that better capture aircraft configuration, speed, and thrust levels of interest. The Aircraft Noise Prediction Program (ANOPP) is one model that can be used for this purpose. ANOPP is a NASA developed semi-empirical model that computes noise levels from the airframe and engine components (fan, core, jet, and turbine) at a user-defined observer grid for arbitrary flight procedures [12]. It also accounts for propagation through user-defined atmosphere and aircraft component shielding effects.

ANOPP was originally developed by NASA in the 1970s to provide predictive capabilities in individual aircraft studies and parametric multivariable environmental evaluations. The program was developed with a modular framework and open documentation to allow for interface development with other tools and objectives beyond single-procedure noise analysis. The tool calculates aggregate noise levels from the aircraft engines (fan, core, jet, and turbine noise) and the airframe for a user-defined three-dimensional observer grid. The tool is designed to evaluate noise for a single flight procedure. ANOPP also takes into account noise propagation through a user-defined atmosphere as well as aircraft shielding effects for higher-fidelity directivity analysis.

The methods used in ANOPP for noise computation are semi-empirical, based on historical noise data combined with physical noise models. These models have been improved over time, based on new full-scale and experimental data, but the fundamental noise source models are essentially unchanged. A series of modules take input on aircraft and engine parameters to generate cumulative noise projections for an aircraft configuration and flight procedure. Though ANOPP can provide meaningful noise predictions for conventional tube and wing aircraft configurations, its use for unconventional aircraft or unconventional procedures is challenging.

Aircraft and engine component geometry and performance parameters are also required for advanced procedural noise analysis with ANOPP. The Transport Aircraft System OPTimization (TASOPT) is being used to supply the performance parameters ANOPP requires. This tool jointly optimizes the airframe, engine, and full flight trajectory of a "tube and wing" transport aircraft using physics-based computations, and is therefore useful for predicting weight, aerodynamics and performance without the need for traditional empirical drag and weight prediction methods [13]. A tool to translate the performance outputs from TASOPT into inputs for ANOPP has been created as part of this research. The analysis architecture for the integrated TASOPT and ANOPP tool is summarized in Figure 1.

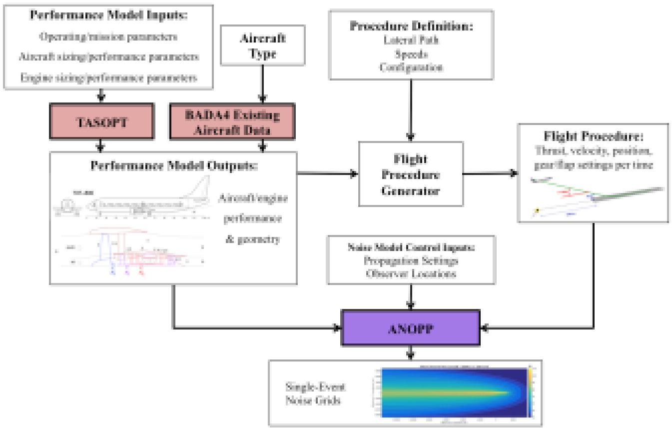

Figure 1. Integrated TASOPT and ANOPP analysis process to generate high fidelity approach and departure noise estimates

In order to obtain the flight profile data for ANOPP, a flight profile generator was created with the capability of computing the thrust profile from existing radar track data or for the generation of new profiles given a set of user specified segment requirements. The provided radar lateral track, altitude, and indicated airspeed of selected flights are processed through the procedure generator to compute the required thrust at each time stamp segment using a force balance model based on the velocity, altitude, acceleration, flight path angle, and configuration at that segment. If flap and gear configuration information is not available, the flap configuration changes are assumed governed by the weight and speed windows for the given aircraft type assuming the flap speed ranges given in public or airline-provided data sources.

To compute profile information for a user-defined profile, the user specifies a set of requirements to define a flight segment. These include thrust, configuration, velocity and acceleration, position, and flight path angle. Given enough defined requirements, the profile generator computes the remaining parameters not yet specified using the same model as in the case when flight radar tracks are given, including takeoff and landing rolls. This is repeated for any number of profile segments—the end parameters of the first defined segment become the initial parameters of the next segment. Figure 2 shows an example arrival trajectory with thrust calculated using this method.

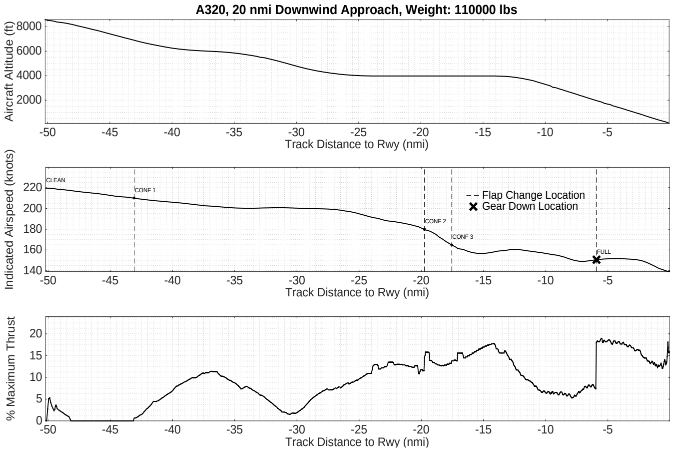

Figure 2. Flight Procedure Generator Sample Output

Combining these methods with data analysis techniques allow for the rapid calculation of airport-wide noise impacts. Radar trajectory data, such as data from Airport Surface Detection Equipment, Model X (ASDE-X), can be used to analyze all operations arriving or departing at a specified airport. From this data, several representative trajectories can be distilled to represent the overall system. Single event noise impacts can be calculated for each of these representative trajectories, and after performing a schedule analysis, the noise contribution of each representative can be scaled and summed to approximate the overall noise impact of the airport. An architecture diagram of this technique is shown in Figure 3.

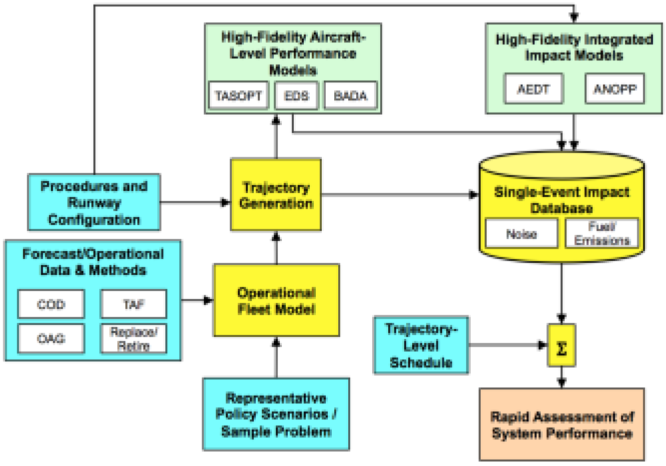

Figure 3. Rapid Noise Modeling Architecture

III. MODEL VALIDATION

Noise results from the noise modeling architecture were compared to existing Federal Aviation Administration noise certification data as initial validation of the method. The FAA reports the noise of civil aircraft at three specific observer locations with the aircraft flying three specific flight procedures. The details of the flight procedures and the observer locations are given in 14 CFR Part 36. In summary, each aircraft flies the procedures and effective perceived noise levels (EPNL) are recorded at the observer locations summarized in Figure 4 and Table 1 [14]. They include a flyover profile and observer directly under the departure flight path (flyover reference), an approach profile and observer directly under the approach path (approach reference), and a lateral profile and observer offset from the runway at the loudest point of the departure (lateral reference).

Table 1. Description of FAA noise certification flight profiles

Procedure	**Speed (KIAS)**	**Configuration**	**Thrust**
Flyover	V2+10kt to V2+20kt	2nd Setting from clean	Max T/O to 300 m altitude, then reduced to maintain 4% climb gradient
Approach	Vref+10kt	Full flaps + landing gear	As required to maintain 3° glideslope
Lateral	V2+10kt to V2+20kt	2nd Setting from clean	Max T/O

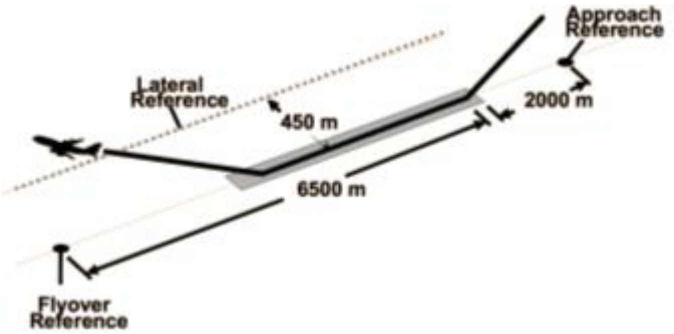

Figure 4. FAA Noise Certification Observer Locations

Six aircraft were modeled using the improved noise analysis method and the results are presented below. An agreement within -2.24 to 3.71 dB between the ANOPP noise results and the FAA data was found for each of these six aircraft and the three observer locations, with many of the measurements agreeing within 1 dB of the recorded value. Discussions with noise experts indicate that measured noise data can have a scatter of 15 dB [15]. In addition, aircraft flying noise certification test profiles do not always fly the procedures exactly as defined in 14 CFR Part 36. Thus these results are considered good agreement and thus are sufficient to warrant the use of the model.

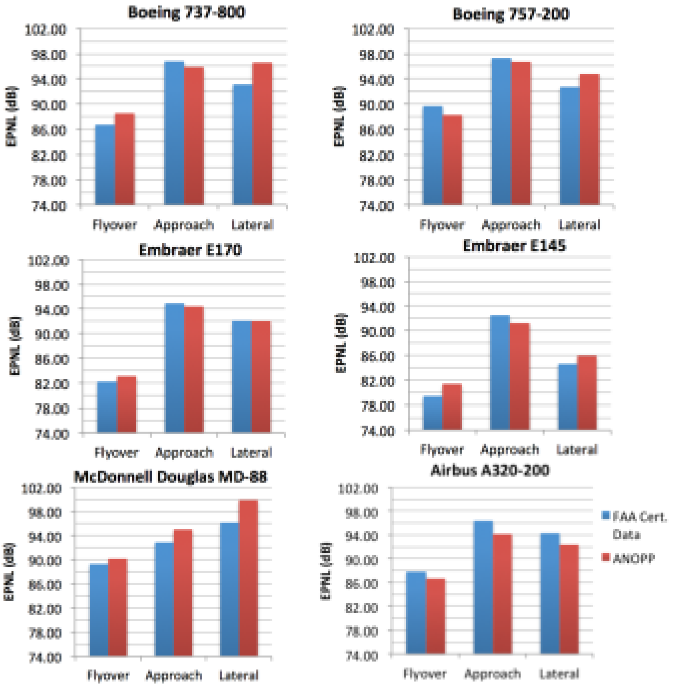

Figure 5. EPNL (dB) for several aircraft types computed in ANOPP and compared to FAA noise certification data

A validation of the noise modeling architecture's ability to assess noise from flight track radar data of existing flights was also done via a noise measurement campaign performed by MIT Lincoln Laboratory [15]. Three Brüel & Kjær Noise Sentinel monitor systems were placed at the noise monitor (NM) locations diagramed in Figure 6 to record noise data of flights on approach to Boston Logan Airport (KBOS) runways 22L/22R from November 13, 2015 to January 25, 2016. The location of the noise monitors was selected to capture phases of the approach farther from touchdown compared to typical permanent noise monitoring installations. In these locations (15 to 25 miles from touchdown), arriving aircraft were not fully configured for landing and had variable speed profiles. This distribution of speed provided a test case for the high-fidelity physics based aerodynamic noise modules in ANOPP. Flight track radar data was also recorded for each noise event.

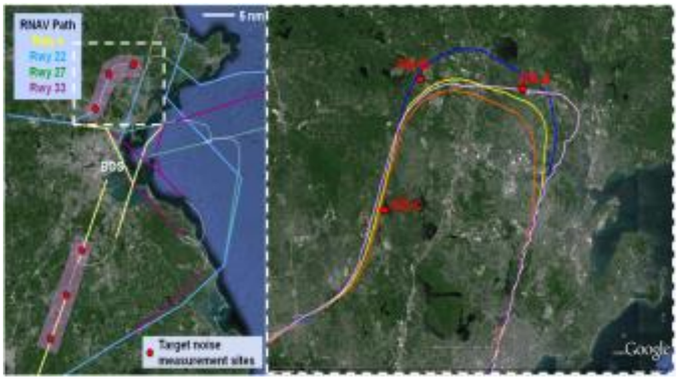

Figure 6. Noise monitor locations for empirical study of approach noise at Boston Logan Airport

With the noise measurement data obtained, the improved noise modeling approach was then used to model example flights from the radar track data analysis in order to validate how well modeled results agree with the measured noise data. For two aircraft types, the A320 and B737, example flights from the BOS noise measurement campaign were chosen based on their average speeds and the number of noise monitors the aircraft flew over. Four flights were chosen that followed a large fraction of the QUABN3 RNAV approach procedure seen in Figure 6 and flew over at least two noise monitors.

The lateral track, altitude and indicated airspeed of the selected flights were processed through the model in order to develop noise contours. The computed values of LA_{max} from the noise contours as the aircraft passes over each noise monitor are shown in Table 2. Those values are compared with the measured values recorded by the noise monitors. Comparison between the measured and modeled LA_{max} data at these locations are within 7 dBA agreement across all cases.

LA_{max} (dBA)	NM (A)		NM (B)		NM (C)		Difference (Measured minus Modeled)		
	Measured	Modeled	Measured	Modeled	Measured	Modeled	NM(A)	NM(B)	NM(C)
A320 Flight 1	-	-	62.38	57.33	60.95	56.57	-	5.05	4.38
A320 Flight 2	61.85	63.97	-	-	54.27	57.65	-2.12	-	-3.38
B738 Flight 1	-	-	59.10	57.76	60.70	55.64	-	1.34	5.06
B738 Flight 2	69.02	62.35	66.50	62.30	60.08	58.89	6.67	4.2	1.19

Table 2: Comparison of Measured and Modeled LA_{max}(dBA)

IV. RESULTS

A. *Sample Analysis of an Advanced Operational Flight Procedure*

The utility of the noise modeling architecture to assess the noise impacts of a user-designed single event advanced operational procedure is shown in the example below.

The example demonstrated is the noise impacts of variation in transition height of an aircraft performing a 2-segment steep approach. Here a Boeing 752 on a strait-in approach was modeled using the noise modeling architecture. The aircraft was modeled with the flight profile generator at a constant landing airspeed and landing configuration initially flying level at 5000 ft. The aircraft then begins a steep descent by reducing the thrust to idle, and the flight angle is determined by the aircraft's drag characteristics. Where the aircraft begins the descent is calculated such that the aircraft intercepts with the 3° ILS glideslope at transition locations 1000ft to 2000ft. At the transition locations, the aircraft maintains a 3° descent to the runway. The resulting flight profiles are shown in Figure 7, along with a baseline 3° continuous descent approach.

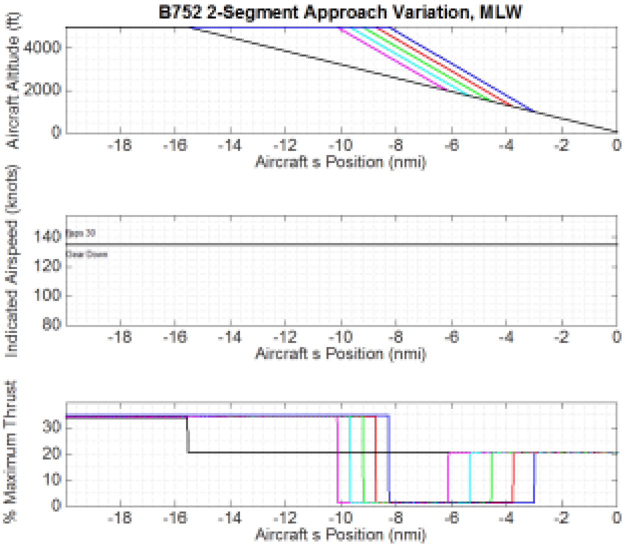

Figure 7. Flight profile definitions for a Boeing 757-200 on a 2-segment steep approach with parametric transition height

The resulting L_{max} (dB) contours for these flight profiles are shown in figure 7. Compared to the baseline 3° profile, the 2-segment steep approach profiles result in a in L_{max} around the region of idle thrust between about -10 nmi and -4 nmi from touchdown. While there exists operational and technological barriers for the real implementation of steep approaches, this example demonstrates the utility of the noise modeling architecture to assess a user-defined advanced operational flight procedure.

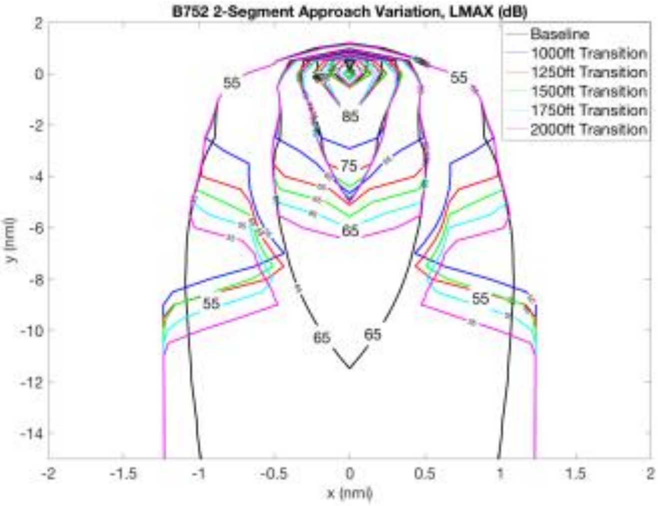

Figure 8. Change in Lmax (dB) Contour of a Boeing 757-200 on a 2-Segment Approach with Transition Height

B. *Rapid Noise Modeling Results*

Washington National Airport (DCA) was selected as a sample case for full airport noise analysis due to its complex, highly localized airspace. These complexities are a good test for the tool, as simplified modeling techniques such as a straight-in, straight-out assumption for arrivals and departures would lead to highly inaccurate results.

First, ASDE-X data for 20 days over the course of 2015 and 2016 was analyzed to determine the ground tracks of representative trajectories. For this case, RNAV routes were chosen as representative trajectories. If all aircraft flew RNAV routes into and out of DCA, this approximation would yield highly accurate results, while for existing operations it remains a useful approximation for a medium fidelity estimate of airport noise. Trajectories were filtered to find flights flying the RNAV routes. Then, for each RNAV routes, the ground track of the single trajectory closest to the root-mean-square average position was selected as the ground track of the representative trajectory. This process is shown in Figure 9 for DCA departures over the selected 20 days.

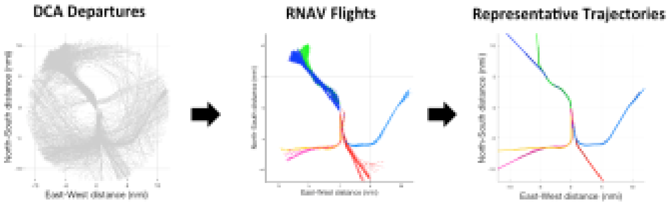

Figure 9. All DCA departure routes (left), ground tracks of flights that flew RNAV routes (center), and selected representative ground tracks (right).

The selected arrival and departure representative ground tracks are shown overlaid on a map of the area in Figure 10.

Figure 10. Arrival and departure representative ground tracks for DCA

Once ground tracks were selected, vertical profiles were generated using the profile generation tool described above. All arrivals were assumed to fly an ICAO standard 3-degree glide slope approach. Departures were assumed to fly an ICAO standard departure, but takeoff and climb thrust settings were de-rated to match the climb rate of as-flown operations of the same aircraft type at DCA. An example of this vertical profile thrust matching is shown in Figure 11

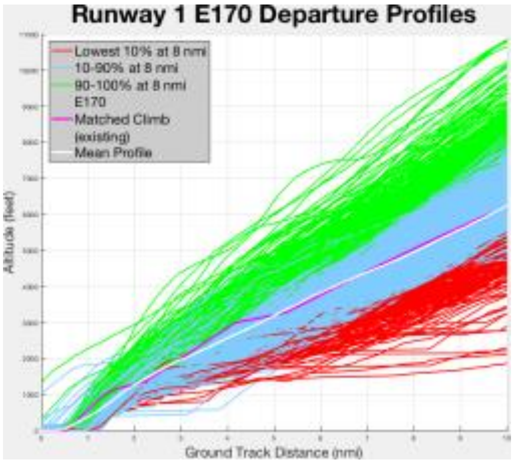

Figure 11. Representative trajectory profile for E170 flights shown in magenta, flight closest to mean as-flown shown in white.

Given these representative trajectories, defined by the ground track and altitude profile, with thrust and speed calculated using the profile generation tool, the methodology described above was used to calculate noise impacts due to a single flight on each trajectory.

A 60x60 nautical mile X-Y grid was defined, and the desired noise metric was calculated at each point of the grid on one half nautical mile increments. For this example, single event noise was measured using Sound Exposure Level (SEL). Each one of these SEL grids was stored to create a database of SEL “building blocks” with which to calculate total airport noise. A sample SEL output contour is shown in Figure 7. Population data from the US Census Bureau is also processed into a gridded format that matches the noise results, allowing rapid evaluation of population exposure for a variety of metrics.

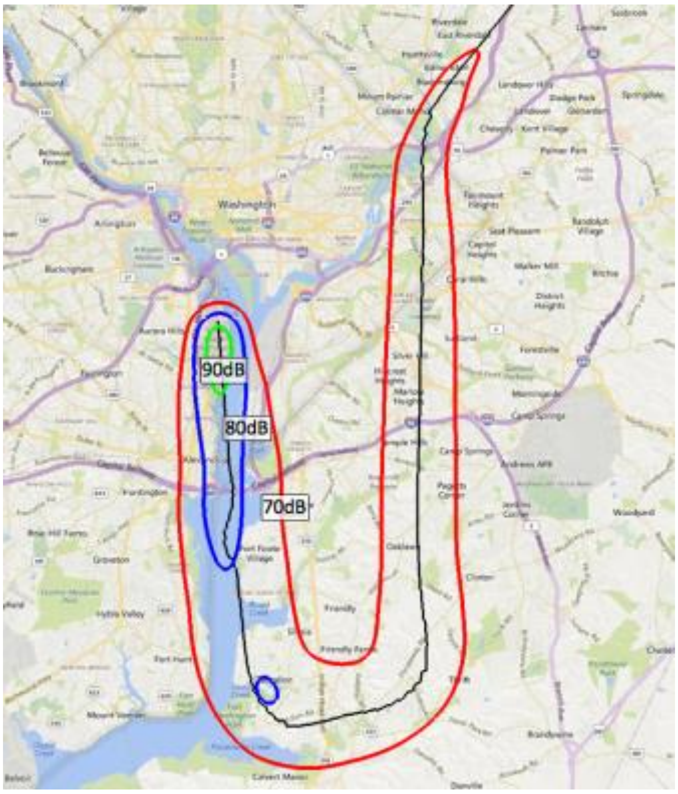

Figure 12. Sound Exposure Level (SEL) noise contour for a single A320 arrival calculated using the TASOPT-ANOPP model framework

With the database of single event impacts calculated, integrated metrics are calculated by summing single-event noise grids at each observer location. For example, the day-night average sound level (DNL or L_{DN}) can be calculated using the following equation:

$$L_{dn} = 10\log\left[\frac{1}{86{,}400}\left(\sum 10^{L_{ae,day}/10} + \sum 10^{\left(L_{ae,night}+10\right)/10}\right)\right]$$

The primary benefit of pre-computing SEL grids for a subset of operations is to reduce computation time requirements by not computing results for each flight individually. In order to reduce computational expense, all operations are binned into a subset of aircraft types chosen to be representative of the fleet in the analysis scenario. Each flight is then assigned to one of the subset of representative aircraft and profile definitions, allowing for summation to system-level impacts without computing SEL grids for each individual operation.

To determine the schedule and representative fleet for integrated metric calculation, analysis was done using the FAA’s Airport System Performance Metric (ASPM) database. A full year of operations at DCA were analyzed, and aircraft were binned into five representative types based on size, weight, passenger capacity, and airframe similarity. These numbers of arrivals and departures were then averaged to find an average day of representative flights. The annual arrival allocation by type at DCA for 2015 is shown in Table 2 [16].

Table 2. 2015 DCA Traffic Counts and Representative Type Assignments

Type Code	Annual Arrivals	Representative Type	Average Daily Arrivals
E170	28732	E170	132.4
E190	13399		
CRJ7	3734		
CRJ9	2455		
E135	222	E145	94.8
E145	2189		
E45X	1223		
CRJ2	28835		
DH8A	869		
DH8D	586		
GA T-Prop	370		
GA Turbine	290		
A319	16658	A320	65.9
A320	6419		
A321	985		
B733	193	B738	83.6
B737	15512		
B738	14684		
B739	117		
B752	814	B752	2.2
B712	378	MD88	16.6
MD82	22		
MD83	11		
MD88	2546		
MD90	3095		
Heli+Light GA	Omitted	Omitted	-
Total			395.4

Once the total number of arrivals and departures of each aircraft type was determined, flights were divided between the different representative arrival and departure routes. For this initial analysis, it was assumed that traffic was distributed equally between each route, but for future analysis an approach using an analysis of different runway configurations could add fidelity.

Given these assumptions, DNL contours were calculated. Overlaying these contours onto a map of population density, as shown in Figure 13, yields the overall population-based noise exposure impacts of the airport.

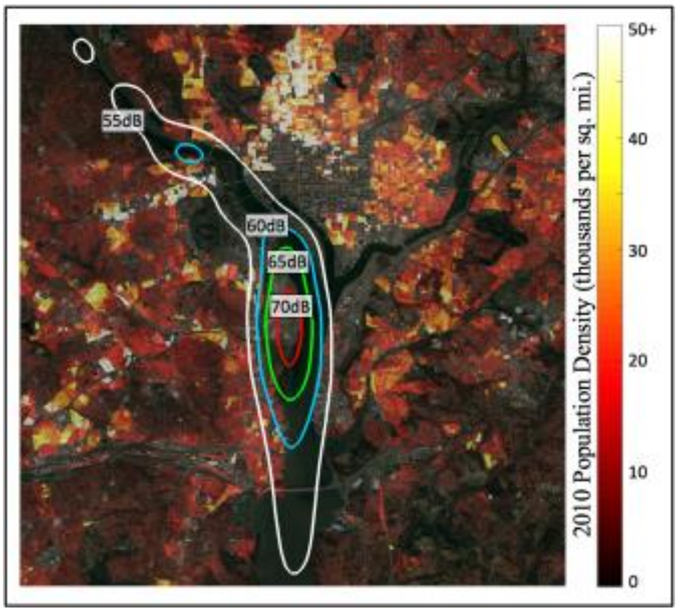

Figure 13. DCA noise contours overlaid on a population density map

V. CONCLUSION

The primary objective of this research program was to develop a novel analysis framework allowing for noise estimation for advanced operational procedures. By integrating aircraft design and performance calculations from TASOPT with high-fidelity noise modeling in ANOPP, a unique and flexible set of research questions can be addressed. This paper summarized process of developing the analysis architecture, validating the integrated TASOPT/ANOPP model using FAA certification data and empirical measurements, and modeling a candidate advanced operational procedure for potential noise impact over a distributed observer grid.

In addition, the gridded nature of the model outputs allows for rapid integration of results for airport-level integrated impact analysis (such as generating DNL contours or other metrics of interest). This method allows for potential future integration of advanced operational procedures into system-level environmental impact analyses at a higher fidelity than current models. For example, this architecture allows for detailed flight performance modeling and airframe noise estimation due to modified speed and configuration profiles on arrival and departure. Due to the flexibility of TASOPT as the source of aircraft performance estimates, noise calculations are also possible for a wide range of notional aircraft technologies and configurations.

The next phases of this research will include analysis of a broad portfolio of candidate advanced operational procedures for both arrival and departure flight phases. The model will be used to identify promising generic procedural concepts as well as procedures tailored for specific airports, runways, or aircraft types.

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