Project 045 Takeoff/Climb Analysis to Support AEDT Aircraft Performance Model (APM) Development

Georgia Institute of Technology

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University Participants

Georgia Institute of Technology (GT)

- PIs: Prof. Dimitri Mavris, Dr. Michelle R. Kirby (Co-PI)
- FAA Award Number: 13-C-AJFE-GIT, Amendment 020, 035, 43, and 46
- Period of Performance: August 15, 2016 to March 28, 2019
- Tasks:
  - Task 1: Noise abatement departure profiles (NADP) library investigation.
  - Task 2: Arrival profile modeling.
  - Task 3: Integrated impact assessment of inaccuracies from thrust, weight, procedures, and noise-power-distance (NPD) curves.

Project Funding Level

FAA provided $175,000 in funding. Georgia Tech is providing $175,000 in matching funds. Cost share details are as follows: GT has agreed to a total of $175,000 in matching funds. This total includes salaries for the project director; research engineers; graduate research assistants; and computing, financial, and administrative support, including meeting arrangements. The institute has also agreed to provide tuition remission for the students, paid for by state funds.

Investigation Team

- Prof. Dimitri Mavris, Principal Investigator, Georgia Institute of Technology
- Dr. Michelle Kirby, Co-Investigator, Georgia Institute of Technology
- Dr. Yongchang Li, Research Faculty, Georgia Institute of Technology
- Dr. Tejas Puranik, Research Faculty, Georgia Institute of Technology
- Dr. Don Lim, Research Faculty, Georgia Institute of Technology
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- Ana Gabrielian, Graduate Student, Georgia Institute of Technology (Task 2)
- Loren Isakson, Graduate Student, Georgia Institute of Technology (Task 1)

Project Overview

Accurate modeling of aircraft performance is a key factor in estimating aircraft noise, emissions, and fuel burn. Within the Aviation Environmental Design Tool (AEDT), many assumptions are made for aircraft performance modeling with respect to aircraft weight and departure procedure, coupled with aircraft departure typically being modeled by assuming that full rated takeoff power/thrust is used. As operations around airports continue to evolve, there is a need to examine those assumptions and to improve the modeling accuracy with flight data. In recent years, flight data are increasingly being used to enhance models and bring model estimation even closer to reality. Research is needed to build on prior work with a view to develop a robust set of recommendations for improved estimation processes for takeoff weight, reduced thrust takeoffs, and departure profiles within AEDT.

Task 1 – NADP Library Investigation

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Objective

Previous research efforts under Project 45 led to the development of the NADP Library, a set of noise abatement departure profiles (NADPs) that are defined as procedural profiles in AEDT. The library is generic and can be applied to any aircraft or airport. Each such profile is based on the combination of three parameters: thrust cutback, initial acceleration, and final acceleration. The NADP Library contains 19 base profiles which can expand based on alternate weight and reduced thrust variants. The objective of this task is to recommend a subset of these 19 profiles for implementation in AEDT.

Research Approach

There are six NADP-1 profiles and 13 NADP-2 profiles defined in the library. Even more modeling options are possible when the possibilities of alternate weight and reduced thrust are considered. Including such a high number of profiles as modeling options in future versions of AEDT is undesirable. Therefore, a grouping of profiles within NADP Library is required so that a subset of these 19 profiles can be selected. A single profile within each group can then be chosen to represent all other profiles within the group. The overall process is summarized by Figure 1.

The 2019 ASCENT Annual Report describes in detail the process created for the downsizing and the computation of similarity metrics between different profiles. Similarity metrics are calculated using performance, fuel burn, emissions, and noise reports for each profile at various stage lengths. Similarity metrics are a pair-wise measure of how “close” two profiles are in their environmental impact. All similarity metrics were normalized to be on the same relative scale.

Once noise metrics have been obtained, they are used as inputs to the clustering algorithm which groups similar profiles together. Three clustering algorithms are implemented using the “sklearn.cluster” Python library: K-means, Hierarchical, and DBSCAN. Table 1 shows the results obtained from two of these algorithms on the alternate weight version of the NADP-2 part of the NADP Library. The table entries represent the cluster label, i.e., all profiles labeled as 1 in a column belong to cluster 1. Note that different metrics and different algorithms result in different cluster assignments. Therefore, a consensus clustering algorithm was utilized to obtain final cluster assignments.

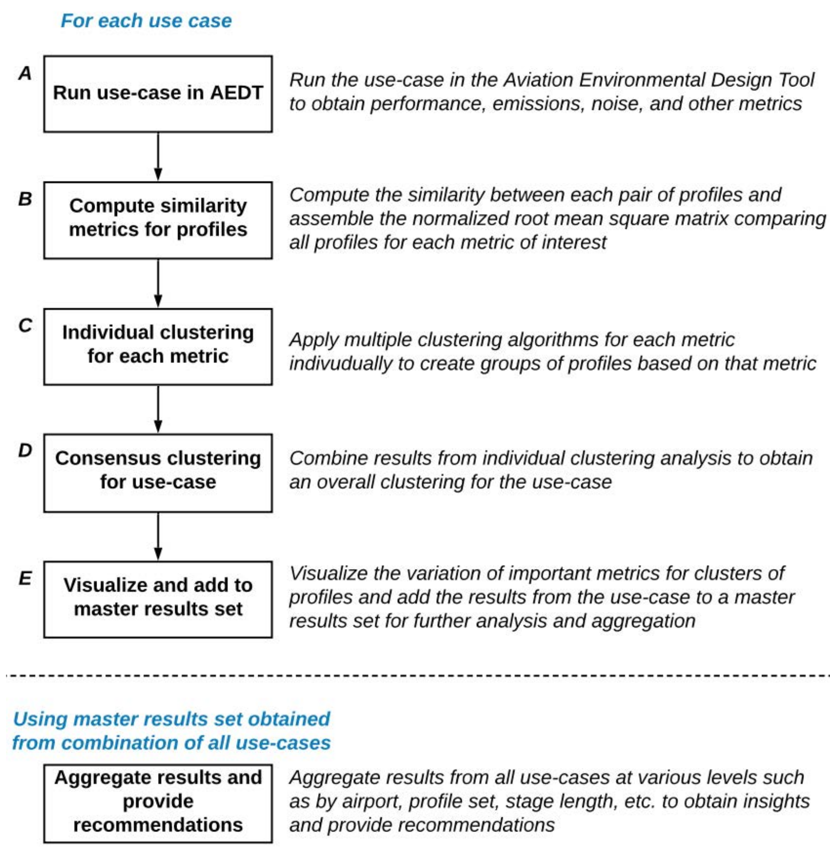


Figure 1. Overall clustering process for NADP Library.

Table 1. Sample results from clustering algorithms

	Algorithm 1: K Means			**Algorithm 2: DBSCAN**		
	Noise SEL	**Nox**	**Fuel Burn**	**Noise SEL**	**Nox**	**Fuel Burn**
NADP2_1_AW-3	2	2	1	2	2	2
NADP2_2_AW-3	2	1	2	2	1	1
NADP2_3_AW-3	2	1	2	2	1	1
NADP2_4_AW-3	2	2	1	2	2	2
NADP2_5_AW-3	2	2	1	2	2	2
NADP2_6_AW-3	2	2	1	2	2	2
NADP2_7_AW-3	1	1	2	1	1	1
NADP2_8_AW-3	1	2	1	1	2	2
NADP2_9_AW-3	1	2	1	1	2	2
NADP2_12_AW-3	1	2	1	1	2	2
NADP2_11_AW-3	1	1	2	1	1	1
NADP2_12_AW-3	1	2	1	1	2	2
NADP2_13_AW-3	1	1	2	1	1	1

The “goodness” of clusters is evaluated using a silhouette score. This score is used to judge the efficacy of a clustering algorithm on the given set of similarity metrics. When the number of desired clusters is not fixed, this score can also help determine the optimal number of clusters. A comparison of silhouette scores is shown in Table 2.

Table 2. Comparison of silhouette scores for NADP-1 profiles flown by Airbus A320 at Hartsfield–Jackson Atlanta International Airport

	K-Means Algorithm				DBSCAN Algorithm			
	SEL	**Emissions NO_x**	**Fuel Burn**	**LA_{max}**	**SEL**	**Emissions NO_x**	**Fuel Burn**	**LA_{max}**
NADP1_1-1	0	1	0	0	1	0	0	0
NADP1_2-1	1	1	0	0	0	0	0	0
NADP1_3-1	1	0	1	0	0	1	1	0
NADP1_4-1	1	1	0	0	0	0	0	0
NADP1_6-1	1	0	1	0	0	1	1	0
NADP1_7-1	2	0	1	1	1	1	1	1
Silhouette Score	0.28	0.79	0.79	0.42	0.27	0.79	0.79	0.42

3 clusters, poor score

2 clusters

2 clusters, better score

The final step for recommendation is to compare the clustered profiles with real-world flight operation data. For this task, flight operations quality assurance (FOQA) data was used as the validation data. FOQA data was grouped in accordance with the AEDT simulation results based on aircraft type and airport. Flight trajectories in each such group were condensed into a "median" FOQA profile. This median profile was then modeled in AEDT and compared to the modeled NADP profiles to identify the NADP profile which best represented the FOQA data.

In conclusion, the NADP-1_1 and NADP-2_11 profiles were found to consistently represent real world operations across a variety of aircraft types and airports. Hence, these profiles were recommended for implementation in AEDT.

Milestone

The objective of this task was to provide recommendations for the implementation of NADPs in AEDT, which has been accomplished.

Major Accomplishments

- Developed clustering process to perform down-selection of the NADP Library,
- Provided recommendations for additional departure profile options in AEDT to better represent real-world operations.

Publications

Ameya Behere, Loren Isakson, Tejas G. Puranik, Yongchang Li, Michelle Kirby, and Dimitri Mavris, Aircraft Landing and Takeoff Operations Clustering for Efficient Environmental Impact Assessment. AIAA AVIATION 2020 FORUM. June 2020, https://doi.org/10.2514/6.2020-2583

Outreach Efforts

Bi-weekly calls with the FAA, Volpe, and ATAC. Bi-annual ASCENT meetings.

Awards

None

Student Involvement

Ameya Behere and Loren Isakson, Graduate Research Assistants, Georgia Institute of Technology

Plans for Next Period

This Task is now complete.

Task 2 – NextGen Arrival Profile Modeling

Georgia Institute of Technology

Objective

Previous research has extensively investigated the difference between departure procedures in AEDT and the actual departure procedures observed by using data types such as radar data, FOQA data, and airline and airport documentation, thus resulting in a library of departure procedures. Under Task 2, a similar study will take place for arrival procedures. The use of FOQA data from one airline will be utilized to assess the accuracy of AEDT arrival procedures for 14 airframes. The FOQA data will be used to find different arrival characteristics such as level off altitude, velocity, gear setting, and flap setting. These different characteristics will then be compared to what is currently prescribed in AEDT. If a significant difference is found, new arrival profiles will be proposed. In essence, this will result in arrival procedures in AEDT that better capture existing operations as observed in data gathered via aircraft flight logs.

Research Approach

Methods to model advanced NextGen profiles in AEDT were developed through recent research conducted for Airport Cooperative Research Program (ACRP) 02-55. The final deliverables for ACRP 02-55 included a report and technical guidance for selecting appropriate aircraft approach and departure profiles, which are available to the public. The GT team has conducted a thorough review of the work conducted in ACRP 02-55 and has created an actionable plan to incorporate the findings.

The ACRP 02-55 objective was to capture and represent arrival procedures used in the real world. This was done by creating additional standard or default procedures that are not currently within AEDT. The researchers working on this study had access to Performance Data Analysis and Reporting System (PDARS) data for more than 274,000 arrival procedures. The data was taken from 30 airports throughout the United States for 68 different aircraft types. From this, the flights were grouped according to the level off length, level off altitude and aircraft class. An example of this grouping would be "A-LJ-1-3000-40to49-5to14." This signifies an approach operation for a large jet with a stage length of 1, which has a level off at 3,000 ft, for a distance between 40 and 49 nmi, ending with 5 to 14 nmi from the airport. The flights were then modeled to fly out of one airport, Hartsfield-Jackson Atlanta International Airport (KATL), to make the trajectories comparable. Level off "bins" for flights were created every 1,000 ft.

An averaged trajectory for these grouped flights was then created and compared to their analogous baseline trajectories, which were STANDARD AEDT approach procedures found in AEDT2a. The method used to average the flights was not explicitly defined within the airport. A trajectory score was computed for the average trajectories of the different groups with the following formula:

$$TrajScore = \frac{\sum_{i=1}^{N} \left| H_{avg,i} - H_{BL,i} \right|}{N}$$

where H_{avg} is the altitude from the averaged trajectory and H_{BL} is the altitude of the baseline from AEDT. These were then normalized to the number of samples taken. Samples were taken for every nautical mile in ground track distance. After the grouping process and the calculation of trajectory scores, the worst six profiles for six aircraft classes were chosen to create AEDT procedures by using AEDT's altitude controls functionality. Then 36 approach profiles were generated for six different aircraft classes.

This document was helpful in providing a method to group different flight trajectories. The GT team will create their own algorithm for averaging a particular group of flights according to characteristics that will be discussed later. The averaging and grouping findings will then be compared to the findings in the ACRP 02-55 document to assess whether there is a correlation between the two.

A similar study will be conducted by the GT team with a new set of airline data acquired from one airline. FOQA data from more than 16,000 flights and 14 airframes will be used to assemble visualizations next to existing standard profiles in AEDT. This data includes information regarding aircraft altitude, ground track distance, thrust, velocity, gear position, flap position, etc. The aircraft state information available may bring to light more details that PDARS data is incapable of revealing. Popular arrival settings for each of the previously described parameters will be heavily inspected to find common departure modes. The following aircraft are in the dataset with operations at 71 airports across North and Central America.

- Boeing 717-200

- Boeing 737-700, 800, 900
- Boeing 757-200, 300
- Boeing 777-200LR, 200ER
- McDonnell Douglas 90
- Airbus 319-100, 320-200, 321-200
- Airbus 330-200, 300

A systematic parsing of the data is conducted because it includes the entire flight trajectory from taxi and takeoff to landing and taxi again. For the purposes of this task, the GT team will be investigating only the altitude from 6,000 ft until touchdown because this is the same altitude range that AEDT uses in its definition of approach. In addition, arrival profiles are categorized as a continuous descent approach (CDA) or a level off approach. A subroutine in Python is utilized to categorize trajectories based on distinguishable factors in each trajectory. A level off is detected for a particular flight segment when one of the two following criteria are met: either a calculated glide slope of less than 0.6° is found while performing a rolling average over two time steps ahead and behind the current altitude sample point, or the altitude up to three time steps ahead is within 30 ft of the current altitude. The second criterion sufficiently catches level offs with turbulent perturbations that exceed glide slope tolerance. On the other hand, the first criterion captures rare cases where the descent gradient is extremely shallow for a noticeable period and is more accurately categorized as a level-off. One time-step equates to about 0.1-0.3 nmi and decrease with a reduction in speed which progresses during the descent. There are still occasional “gray line” cases when detecting level offs at low altitudes, but that has been minimized through tuning of tolerances. An example would be a brief level off segment while an aircraft is getting established on vertical guidance provided by an instrument landing system. This brief level off detection is ignored when categorizing. Lastly, any level off detected below 1000 ft or above 5200 ft above ground level (AGL) is immediately discarded. Below 1000 ft, mostly noise is detected. Above 5200 ft, level offs are considered a part of the route, not the approach. These techniques overall proved useful and robust for the vast majority of arrival trajectories; however, the next logical step would make use of classification to categorize level offs versus CDAs.

Preprocessed data is then entered into visualization software. This software allows users to easily manipulate the data to see trends; an example is shown in Figure 2. An overview is provided on entire FOQA datasets at all airports for all airframes. Below, the size of the circle represents the number of data points at each airport, varying between approximately 5 and 2500. The color gradient represents the proportion of flights that are determined to be level offs at that respective airport, with nonlevel offs automatically categorized as CDAs. Immediately, it is noticeable that level offs are less common in the southwest portion of the United States. On the east coast, the opposite is true and most likely can be attributed to traffic congestion up and down the coast. Currently, standard profile runs for KATL, Denver International Airport (KDEN), and San Francisco International Airport (KSFO) are in the database so comparisons can be made along those lines. These airports, in addition to McCarran International Airport (KLAS), John F. Kennedy International Airport (KJFK), and Salt Lake City International Airport (KSLC), appear to be the most prominent in the United States in terms of operations according to the figure.

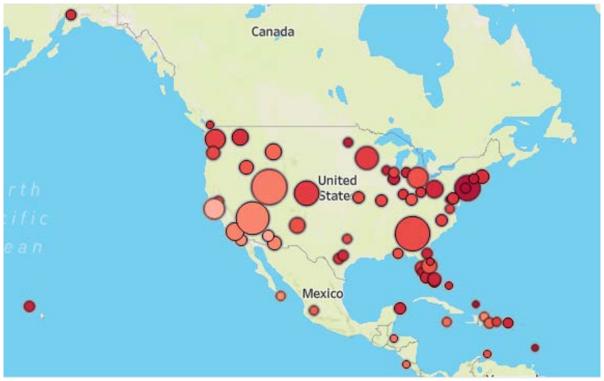


Figure 2. Percentage level offs detected at each airport in FOQA dataset.

The following process can be employed at any airport using the constructed dashboard. Selecting KATL for examination in Figure 3 alongside the default AEDT profiles, for the aircraft mentioned above, it is observed that AEDT profiles are either a CDA or a level off at 3000 ft AGL, with slight variation in level off segment distance. Fairly large discrepancies are immediately apparent between modeled AEDT profiles and FOQA data with respect to thrust. Thrust is underpredicted at distances greater than 10 nmi from touchdown. This difference is evident with all aircraft. The same can be said regarding airspeed. Airspeed changes in real aircraft appear to less abrupt between 15 and five nmi from touchdown.

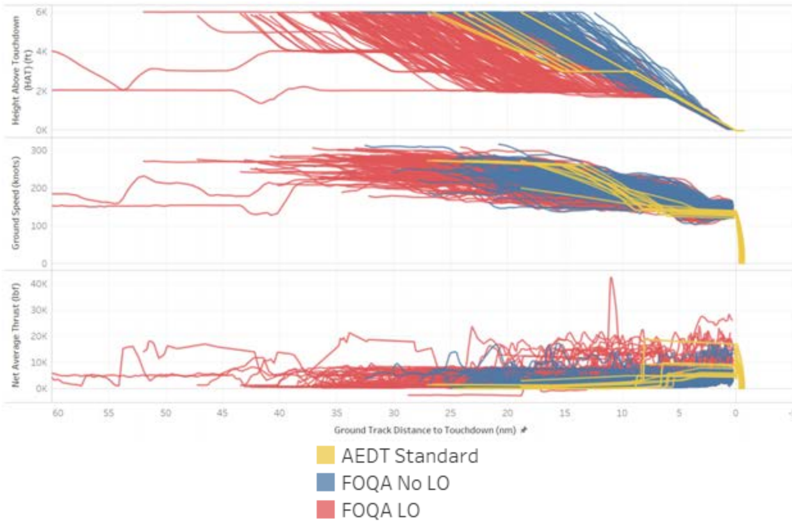


Figure 3. AEDT standard profiles next to FOQA data at KATL.

As shown in Figure 4(a), it is recommended that a CDA and level off profile be available for every type of aircraft. There is a relatively consistent proportion of level offs regardless of aircraft type at KATL. Level off proportions are less dependent on aircraft type and are airport-specific due to airspace, traffic, and obstacles. This assumption can be made after viewing the same breakdown performed at KJFK in Figure 4(b), which proves to consist almost entirely of level offs. However, on the whole, there are a significant number of airports with trends similar to KATL as shown by the final aircraft breakdown across all 71 airports in Figure 5.

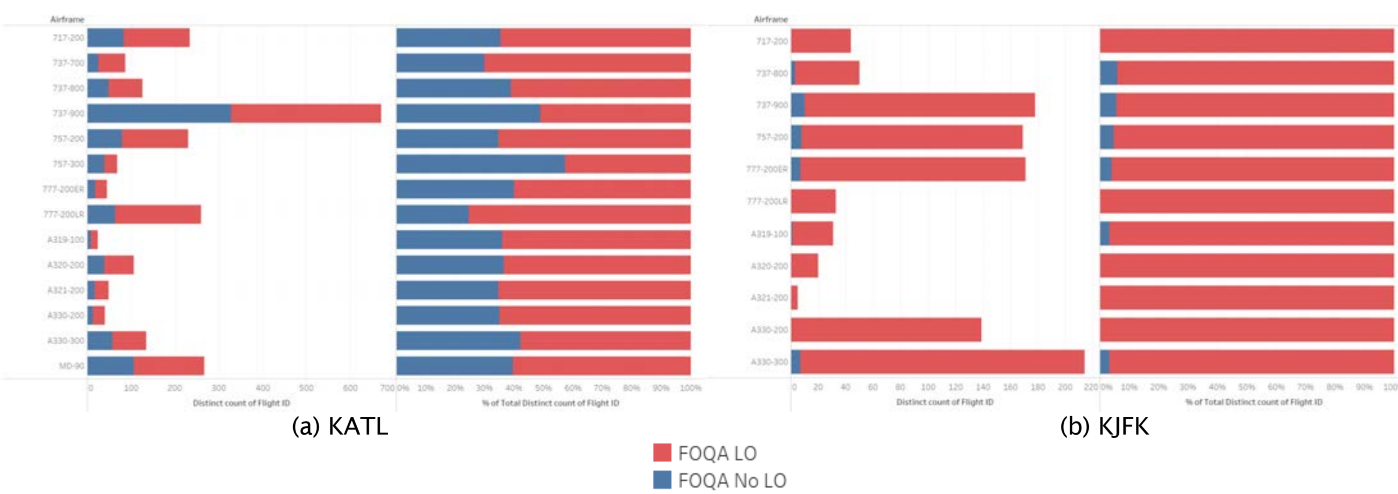


Figure 4. Level off percentage breakdown by aircraft at specific airports.

Distinct count of flight ID is simply the number of unique flights counted in each respective category, with red and blue representing level offs and CDAs, respectively. This color scheme is consistent throughout the report in accordance with the legend in Figure 3. On the right-hand side of each image, the relative proportion or percentage is shown of the counting performed on the left-hand side. Clearly, the number of wide body arrivals, currently solely modeled in AEDT using level offs, is significantly less. However, CDAs are still seen 20% to 30% of the time.

Figure 5. Level off percentage breakdown by aircraft including all 71 airports in the database.

In summary, it is recommended that all aircraft with a single arrival profile in AEDT have both a CDA and level off defined. Addressing discrepancies in thrust and speed may be prioritized as needed. However, noise prediction quality may degrade beyond 10 nmi. Effects of thrust underprediction and speed overprediction do act in opposition of each other. These effects, although possibly negligible, together may mask the issue at long distances and high altitudes.

The next portion of this section seeks to recommended altitudes and distances for level off arrival profiles in AEDT. There are a number of ways this can be done with varying fidelity. The best solution would be to examine every airport individually, but that is impractical, especially with a handful of airports dominating the dataset. Therefore, prominent airports will be selected. These airports, generally located near metropolitan areas, will also capture where the greatest concern is regarding noise. A recommendation made with respect to these airports will likely sufficiently reflect more remote regions in the vicinity, sometimes in the same airspace. The following airports are selected for this subset for their prominence in Figure 2 and for the reasons put forth in this paragraph.

- KATL
- KDEN
- KSFO
- KJFK
- KLAS
- KSLC

In Figure 6, a detailed visual analysis is conducted on the airport subset including trajectory, level off altitude, thrust setting, airspeed, and level off distance. Once popular altitudes are determined, additional filters will be applied to pinpoint distance. At this point, level off distance is somewhat nonsensical because it counts distances at all level off altitudes. Note that a miniscule proportion of level offs occur below 2000 ft height above touchdown (HAT); however, they are not interpreted as a traditional level off profile but rather a temporary level off assigned to intercept vertical guidance. In decreasing popularity, altitudes of approximately 2000 ft, 3000 ft, 4000 ft, and 5000 ft appear. The peak level off altitude at 5000 ft primarily belongs to approaches at KSLC and does not entirely represent a national trend. The noise between dominant altitudes is largely due to KDEN, which seems to have consistent separation of 1000 ft between popular level off altitudes. However, these altitudes are also consistently 200-300 ft lower on average. Hence, premature peaks are shown before 2000 ft, 3000 ft, 4000 ft, and 5000 ft.

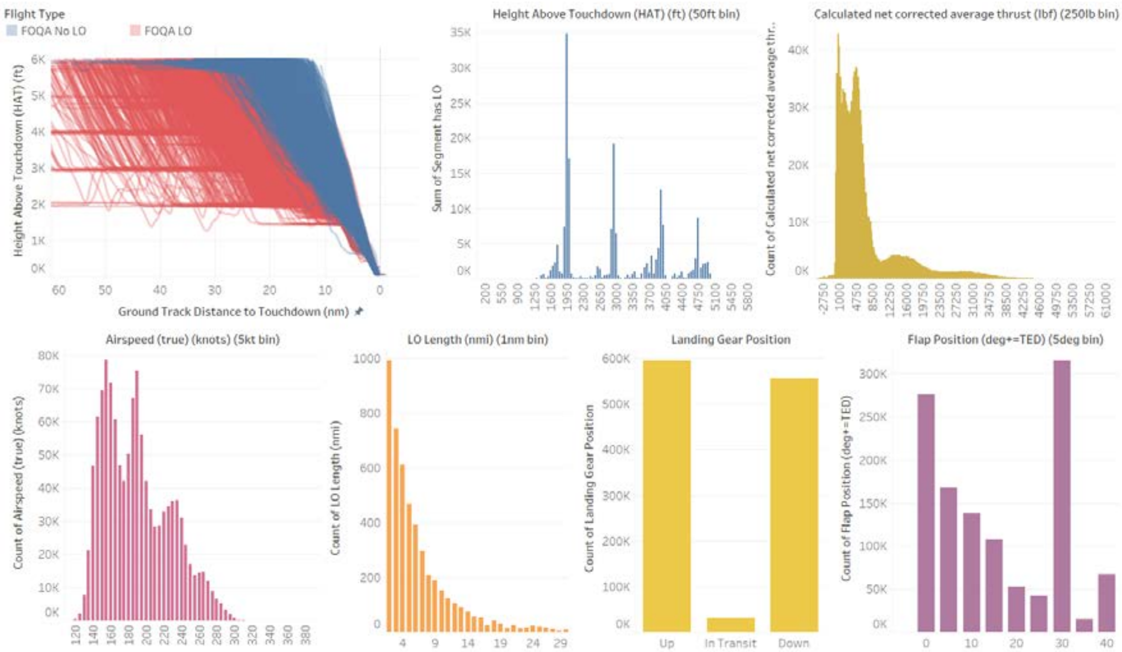


Figure 6. Level off analysis of airport subset.

On average, it can be shown that this trend holds for all other airports in the database. In Figure 7, the total count of level off altitudes is shown. A case can be made to discard 5000 ft as a level off to model due to the inconsistency. This altitude also appears to be associated with a select few airports such as KSLC. Altitudes of 2000 ft, 3000 ft, and 4000 ft remain in order of popularity. To address any uncertainty, level offs at 2000 ft do appear legitimate according to Figure 8 trajectories. The airport subset assumption holds quite well.

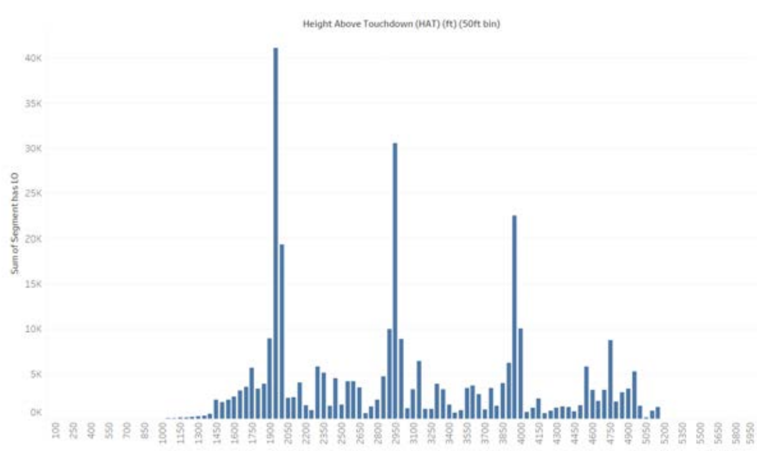
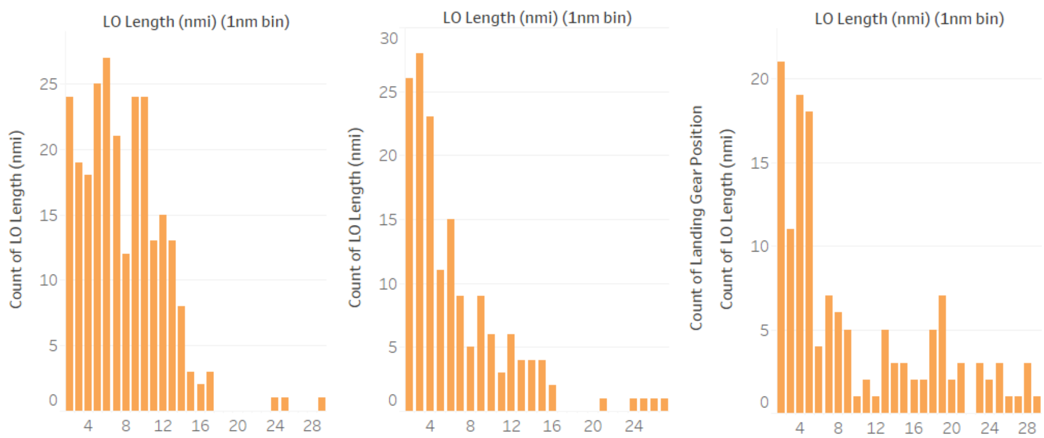


Figure 7. Level off altitude count for all aircraft at all 71 airports in the database.

Therefore, this technique is extended to level off distance. Thus, not only is better clarity observed when looking at the subset with respect to level off distance, but it validates previous and future analyses conducted at these airports. Level off distance is especially noisy when viewing all airports at the same time, masking any observable trend. The airport subset is selected and all datapoints outside of a centered 20 ft interval of the selected level off altitude are filtered out. Below in Figure 8, level off distances are examined. Stringent filtering is required to observe any trend beyond the previously observed simplistic trend of the shortest distance being most common in Figure 6.



(a) Level off 2000±20 ft (b) Level off 3000±20 ft (c) Level off 4000±20 ft

Figure 8. Level off distance examined at each level off altitude.

Outliers in the figure above could be holding patterns or other anomalies. Still, no clear trend is observable, so level off distance recommendations remain inconclusive according to Figure 8. It is recommended that the manufacturer-supplied level off distance be utilized. Level offs modeled for the aircraft above in AEDT currently are around six nmi. This is actually a nice median in the figure above. If any adjustment is to be made, it would be to shorten the level off distance.

Final recommendations for level off altitude are summarized in Table 3. Note that existing profiles have either a CDA or a level off at 3000 ft. Profiles that already exist are marked with an “X”, whereas profiles that would be inserted are numbered in order of significance with "1" as the highest priority. Much of the older aircraft already have CDAs, while the newer aircraft have level offs at 3000 ft. All Airbus aircraft have only level offs defined when about 40% of approaches actually use CDAs. That is one of the more significant discrepancies.

With these recommendations in order, future work would involve incorporating threaded track data from radar to confirm these findings. Further analysis can be done on level off distance if required.

Table 3. Aircraft AEDT profile recommendations.

Aircraft	CDA	LO 2000	LO 3000	LO 4000
B717-200	X	1	2	3
B737-700	X	1	2	3
B737-800	1	2	X	3
B737-900	1	2	X	3
B757-200	X	1	2	3
B757-300	1	2	X	3
B777-200ER	1	2	X	3
B777-200LR	1	2	X	3
MD-90	X	1	2	3
A319-100	1	2	X	3
A320-200	1	2	X	3
A321-200	1	2	X	3
A330-200	1	2	X	3
A330-300	1	2	X	3

Milestone

The objective of this Task is to provide insight as to how accurately the current AEDT approach profile represents the performance of real-world flight trajectories, and if the AEDT approach profiles are not accurate, to propose new profiles for use.

Major Accomplishments

- Obtained real-world FOQA performance data from airline partner for 14 airframes,
- Created a parsing algorithm which observes only the approach phase of flight.
- Created an algorithm which detects a level segment during the approach phase,
- Used this algorithm to create a detailed statistical analysis of the FOQA data in order to observe common approach procedural patterns

Publications

None

Outreach Efforts

Bi-weekly calls with the FAA, Volpe, and ATAC. Bi-annual ASCENT meetings.

Awards

None

Student Involvement

Ana Gabrielian and Loren Isakson, Graduate Research Assistants, Georgia Institute of Technology

Plans for Next Period

- This Task is being continued in ASCENT 54

Task 3 – Integrated Impact Assessment of Inaccuracies from Thrust, Weight, Procedures, and NPD Curves

Georgia Institute of Technology

Objective

Assess the total impact of proposed improvement in accuracy in modeling assumptions from thrust, weight, procedures, and NPD curves in AEDT versus real-world settings. The final comparisons will be among standard baseline AEDT modeling assumptions, improved AEDT modeling assumptions (based on real-world data), and actual real-world noise contours.

Research Approach

The overall research approach is presented in Figure 9. The focus of this Task was the departure phase of flight. Detailed information about the processing of FOQA data, the determination of departure modes, and the creation of new NPDs and fixed-point profiles can be found in the 2019 ASCENT 45 Annual Report.

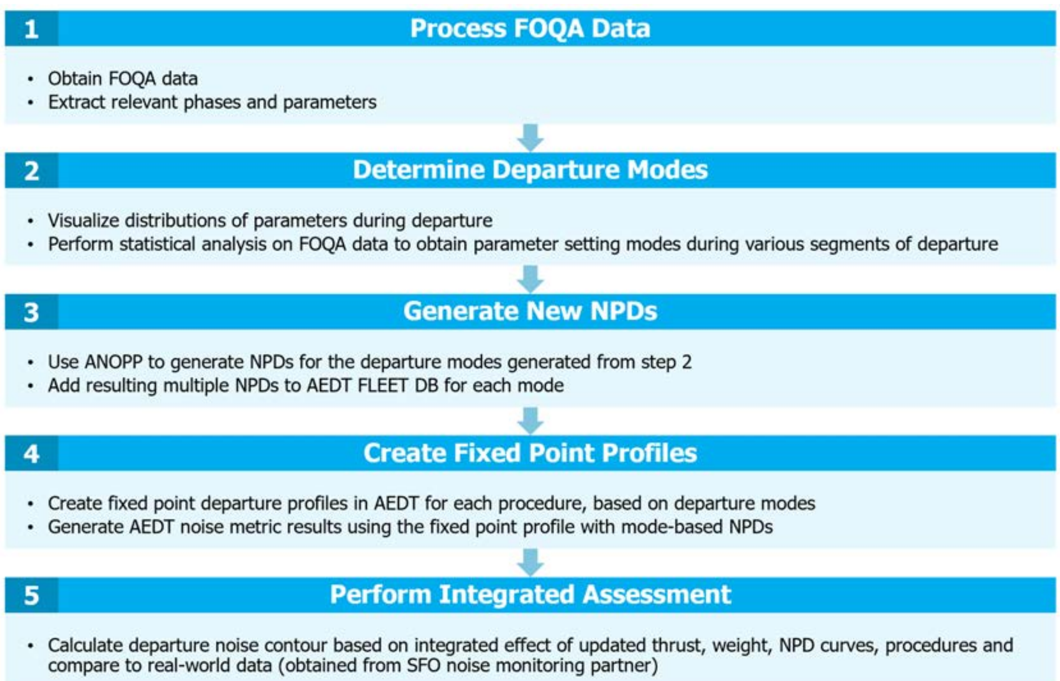


Figure 9. Task 3 research approach.

In order to visualize the results from the integrated impact assessment, a dashboard was created in Tableau. A sample view of the input side of the dashboard is shown in Figure 10. A breakdown of all 88 flights shown in this sample view is described in Table 4. The dashboard is useful in visualizing both the vertical profile and the ground track of the aircraft, in addition to the noise sensor locations. Many filters are available to isolate different flights based on airframe type, noise monitors triggered by the flight, etc. Each of the 88 flights shown in the sample view represents a real-world FOQA flight which has been modeled in AEDT and has linked noise validation data from the KSFO noise monitoring program.

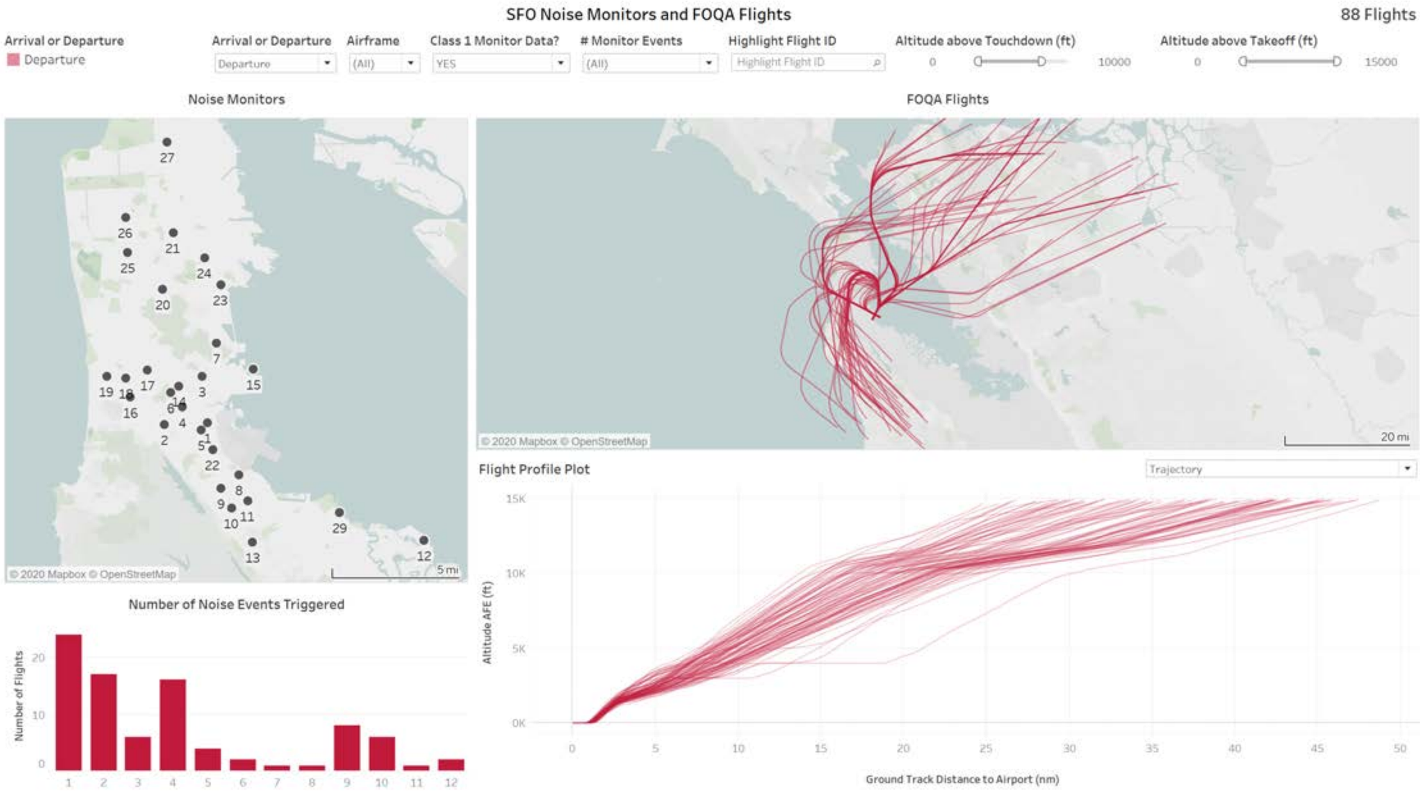


Figure 10. Sample view of input section of dashboard.

Table 4. Number of flights by aircraft type for input dashboard

FOQA Aircraft	AEDT Aircraft	# Flights
737-800	737-800	21
737-900ER	737-800	59
757-200	757-300	3
757-300	757-300	4
A320-200	A320-211	1

Additional progress on this task is covered in the ASCENT Project 62 “Noise Model Validation for AEDT” 2020 Annual Report.

Milestones
None

Major Accomplishments
- Created visualization dashboards and statistical analysis codes to visualize validation flights and their associated noise data,

Publications
None

Outreach Efforts
Bi-weekly calls with the FAA, Volpe, and ATAC. Bi-annual ASCENT meetings.

Awards
N/A

Student Involvement
Dylan Monteiro, Graduate Research Assistant, Georgia Institute of Technology

Plans for Next Period
Further efforts on this task are covered under ASCENT Project 62 "Noise Model Validation for AEDT".