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Preliminary AEDT Noise Model Validation using Real-World Data

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A focus on sustainability in aviation is required to mitigate the environmental impact of its growth. Modeling the environmental effects helps the aerospace community obtain quantitative data linked to aircraft emissions and noise. The Aviation Environmental Design Tool (AEDT) offers the capability to model aviation operations using data sources of differing fidelity and is used worldwide for quantifying emissions and noise impacts of such operations. As a result, validating the accuracy of AEDT is of vital importance for continuous sustainability efforts. This paper presents preliminary results of AEDT noise model validation at the San Francisco International Airport (SFO). The overall sensitivity of noise predictions to varying assumptions within AEDT is explored and quantified using a set of real-world flights modeled within it. This is achieved by utilizing routine Flight Operations Quality Assurance (FOQA) data records from airline operations, noise monitoring data from various stations around the SFO airport, and various weather data sources. The outcomes of this validation study are expected to benefit the developers of AEDT to produce a more accurate noise model.

I. Introduction and Background

There has been a growth of air passenger services over the last decade with a long-term average of over 5% in terms of revenue passenger kilometers (RPK) [1]. There is a recognized need across the aviation industry to monitor aviation's environmental impact as it continues to grow. Mitigation efforts in industry and academia include mitigating noise emissions by using high fidelity models that predict community noise. On the federal side, the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) have led the way towards environmental mitigation efforts by maximizing the economic advantages that can be achieved through higher efficiency and performance. Specifically, NASA's Environmentally Responsible Aviation (ERA) project has suggested goals through the *N*+ program [2] that plan to reduce aviation noise emissions in the years 2015, 2020, and 2025. The FAA's Aviation Environmental Design Tool (AEDT)** is one of the most advanced capabilities to model aircraft operations and compute the associated environmental metrics. Some of those metrics include emissions, noise, fuel consumption, and associated air quality consequences. Tools like AEDT are essential for environmental mitigation efforts in aerospace as it is able to provide quantitative meaning to a very large sustainability problem. In fact, AEDT will be the main resource used in this work.

The fidelity of AEDT is imperative for studies involving real-world data. There have been several previous efforts that studied the overall improvement of modeling procedures within AEDT and comparing AEDT capabilities with data from real-world operations. Noise Abatement Departure Procedures (NADPs) are often used when mitigating community noise. Lim et al. [3] utilized a set of 20 different NADP profiles that were sufficient for modeling various real-world operations. References [4–6] focused on quantifying the impact of those NADP profiles on noise modeling and identified the ones that were most representative. Additionally, AEDT has been used in developing alternate rapid noise modeling tools [7, 8], analyzing various mitigation strategies for the environmental impact of aviation [9], and a multitude of other noise quantification studies [10–12]. Other efforts worked with considerable amounts of data from real-world operations in order to produce reduced-order models that rapidly compute noise impacts [13]. AEDT has also been used to estimate the impact of average types of operations at numerous airports [14].

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Studies related to the validation of AEDT accuracy focused on the validation of AEDT's predecessor, the Integrated Noise Model (INM). These efforts focused on quantifying the level of agreement between INM model prediction and data recorded from actual operations. Page et al. [15] investigated a dataset from Denver International Airport (KDEN) in 1997 to discover how INM's modeling prediction accuracy varied with different thrust prediction methods. The main result of this study revealed that the manufacturer's F_n/δ curves – look-up values of normalized thrust while accounting for changes in density, were the most accurate. This information was used to improve the Noise Power Distance (NPD) curves used in INM from historical manufacturer data. In 2006, Forsyth and Follet [16] utilized the same 1997 KDEN dataset with a focus in updating INM's database emphasizing higher altitudes. As a result, spectral classes were established in order to correct the NPD information with respect to SAE AIR-1845 atmospheric absorption standards. Involving the same 1997 KDEN dataset, Plotkin et al. [17]studied the different options that could be used to further enhance INM's modeling capability by accounting for terrain and weather effects. These validation efforts on INM laid the groundwork and enabled future validation studies to improve the modeling accuracy of AEDT.

Since the FAA introduced AEDT in 2015, there have been several studies performed on it. Hobbs et al. [18] presented an implementable method that includes terrain with ground cover effects on noise propagation calculations by utilizing algorithms that were originally used in the Advanced Acoustic Model (AAM) [15]. This was found to improve noise propagation calculations when compared to empirical data from Portland International Airport (PDX), San Francisco International Airport (SFO), and Oakland International Airport (OAK). Downing et al. [19] explored a way to include man-made structural effects and varying terrain in AEDT's noise propagation calculations. Three different models were evaluated with respect to their ability to correctly predict the affect of aircraft noise that came from buildings and other barriers: Traffic Noise Model (TNM) [20], SoundPLAN 7.4 (which uses ISO 9613-2), and the National Cooperative Highway Research Program's Reflection Screening Tool. Utilizing data from Los Angeles International Airport (LAX) and Long Beach Airport (LGB), it was determined that the TNM was the best modeling option. This was due to the overall similarities and consistencies in its noise calculations when compared to AEDT's baseline calculations. Giladi and Menachi [21] developed a methodology to validate the AEDT noise model using published flight paths and Automatic Dependent Surveillance-Broadcast (ADS-B) data at three different locations. They found AEDT to underestimate actual noise levels based on a handful of operations. Following a similar methodology, Jackson et al. [22] developed an automated framework for modeling large datasets of real-world flight trajectories in AEDT using ADS-B data. Ref. [23] reports preliminary findings of that framework applied to over 86000 arrival operations at SFO for a couple of noise monitor locations. In a study using Flight Operations Quality Assurance (FOQA) data for AEDT noise model validation, Gabrielian et al. [24] presented an automated framework to model FOQA data as fixed-point profiles (FPPs) within AEDT. This was followed by an evaluation of AEDT's noise prediction capability while using high-fidelity weather data [25]. Shaw and Sparrow investigated acoustic impedance and atmospheric absorption using high-fidelity meteorological data to improve the AEDT noise model [26]. Further work on using appropriate averages based on inhomogeneous meteorological profiles instead of relying on homogeneous annual average weather to improve noise predictions is presently underway [27].

In previous work by the authors, a comparative assessment of AEDT's noise modeling assumptions using FOQA data was provided for operations at SFO [28]. In a parallel effort, work on improving substitution methodology for airframe-engine combinations without aircraft noise and performance (ANP) data is also underway to improve AEDT accuracy [29]. The present research intends to further the developments and findings of the SFO validation study by using FOQA data [27]. A large number of departure and arrival operations have been modeled in AEDT using the automated framework presented previously [24]. The comparison study presented here hopes to give insight into the modeling accuracy of AEDT under different modeling options; furthermore, it aims to provide insight on individual and aggregate noise prediction capability while considering various performance and flight operation parameters gathered from FOQA data. The remainder of this paper is structured as follows: Section II presents information on noise modeling data sources, various AEDT assumptions, and the development of this work's automation capabilities; Section III provides the results of the modeled bulk flight operations and associated individual or aggregate insights; Section IV concludes by discussing the various opportunities for future research.

II. Noise Modeling in AEDT

Procedures detailed in previous work provide the system-level noise modeling this work will follow [24, 28]. To this end, there are two important elements that the following subsections will discuss – A) The data sources that were utilized during modeling and B) The modeling assumptions and the modeling options available for each assumption.

A. Data Sources Utilized

When modeling noise, there are numerous data sources of different fidelity that can be used. Some examples include ground-based radar observations or data fusion into multiple aircraft sensors. Although there are many, this work will only utilize three applicable data sources –

1) **Flight Operational Quality Assurance (FOQA)** data consists of electronic flight data recorded by the airline operating the flight. FOQA systems record copious amounts of flight data at one recording per second, i.e. 1 Hz,. Of the various recorded parameters, this paper relates to the detailed time history of parameters such as weight, speed, thrust, altitude, configuration (flaps, gear), etc., which are included for each flight within the model in AEDT.
2) **Noise Monitoring Data** contains 5 key parameters: A unique flight ID, noise monitor locations, class of noise reading, Sound Exposure Level (SEL), and the maximum, A-weighted sound level (L_{max}) metrics of associated noise events. The flight ID and time of closest approach in the noise monitor data allows flights to be matched to the appropriate flight from FOQA data. The highest confidence noise readings from these noise monitors are used as a benchmark comparison for the noise results that are calculated by AEDT and discussed in following sections.
3) **Weather Data** is also used in AEDT's modeling capabilities utilizing various data sources. In this paper, the two weather data sources used are the standard airport weather and the automated surface observing system (ASOS) weather. Standard airport weather data is a stored database within AEDT that provides 10+ years of single year averages along with a rolling 10-year average for any given airport. The source for the standard airport weather data comes from the most recent data from the integrated surface database from the National Oceanic and Atmospheric Administration (NOAA). Additionally, ASOS weather data comes from various airport stations. A given station includes sensors to measure various weather parameters such as atmospheric temperature, humidity, dew point, precipitation, and wind speed.

The framework for modeling and automation developed in this paper is intended to be independent of the data source used with minimal modifications needed to incorporate other data sources. For the present work, FOQA data is used to model operations at SFO with noise monitoring readings obtained from the SFO airport noise program*.

B. Modeling Assumptions and AEDT Capabilities

AEDT presents users with a multitude of modeling options for critical assumptions pertaining to performance and noise. A matrix of alternatives for these options is shown in Tables 1 and 2. While there are a large number of possible modeling combinations, not all options are compatible. The limitations of these modeling options are noted while discussing the modeling assumptions individually.

Table 1 Modeling Options for Departure Operations [28]

Assumption	AEDT Default	Option 2	Option 3	Option 4	Option 5
Thrust	Full	FOQA	RT05	RT10	RT15
Weight	AEDT	FOQA	Alt Wt		
Ground Track	Airport Default	FOQA			
Procedure	Standard	FOQA	NADP1_1	NADP2_11	
Weather	AEDT Standard	FOQA	ASOS	High Fidelity	
Surface	Soft	Hard			
Terrain	Flat	Actual			
Flaps	AEDT	FOQA			
Gear	AEDT	FOQA			
NPDs	AEDT	NPD+C			

Under every assumption (row) of Tables 1 and 2, there are a number of settings available which can affect the performance and noise for each flight operation. Details can be found in previous work by the authors [24, 28] but are provided here again for completeness. For further details, readers are referred to the AEDT technical manual [30].

*https://webtrak.emsbk.com/sfo13

Table 2 Modeling Options for Arrival Operations [28]

Assumption	AEDT Default	Option 2	Option 3	Option 4
Thrust	Full[1]	FOQA		
Weight	AEDT	FOQA		
Ground Track	Airport Default	FOQA		
Procedure	Standard	FOQA		
Weather	AEDT Standard	FOQA	ASOS	High Fidelity
Surface	Soft	Hard		
Terrain	Flat	Actual		
Flaps	AEDT	FOQA		
Gear	AEDT	FOQA		
NPDs	AEDT	NPD+C		

[1] : AEDT Arrival thrust is derived from force balance.

1) **Thrust Settings**: Five options are utilized for modeling the thrust of departure operations in the present work. Apart from the default full thrust assumption, the true thrust value at different points along the departure or arrival is available from the FOQA data and can be used. The RT05, RT10, and RT15 procedures correspond to a 5, 10, 15% reduced thrust respectively during the takeoff procedure and are based on findings from literature [31].
2) **Procedure**: The FLEET database has two types of profiles that can be used: procedural profiles and fixed point profiles (FPPs). Procedural profiles define an aircraft's thrust, speed and trajectory in a series of steps. These include the standard, Noise Abatement Departure Procedures 1 and 2 (NADP1, NADP2). FPPs fully define the latitude, longitude, altitude of the aircraft as well as its thrust and speed from flight data.
3) **Weight**: Modified alternate weight procedures, generated based on prior research [31], are available within AEDT and can be combined with the standard or reduced thrust procedures. Alternatively, FOQA weight can be used for AEDT procedures. FOQA weight can also be used within AEDT while employing FPPs. However, weight does not affect noise computation for FPPs since all performance parameters, such as thrust, are already prescribed. The information regarding weight, thrust, and speed can be used in one FPP for each flight modeled.
4) **Ground Track**: The ground track is the latitude and longitude points on the ground of the aircraft during its flight. The default AEDT modeling for ground tracks are straight into the airport, parallel with whichever runway the aircraft is using upon arrival, or straight out of the airport upon departure. These default settings are likely to result in incorrect predictions when compared to real-world noise observations and are therefore not included in the current analysis. The FOQA ground track data is used in the present work which reflect the true flight paths into or leaving airports.
5) **Weather**: The default weather settings that are used in AEDT studies are located in the AIRPORT database. This includes Temperature, Relative Humidity, Wind Speed, Sea Level Pressure, and Dew Point which impacts the performance and acoustic calculations. The wind direction is always assumed to be a headwind direction. While AEDT has the capability to utilize high-fidelity weather data in multiple formats [25], the present work is limited to the default setting and ASOS weather data used alongside the standard departure profile.
6) **Surface and Terrain**: Within AEDT, there are hard and soft surface options that affect the ground attenuation in noise calculation. However, the surface is assumed to be soft for jet aircraft. Terrain elevation can also be included which affect noise propagation. In absence of terrain data, AEDT assumes a flat terrain. For the present work, AEDT default values of soft ground surface and flat terrain is used.
7) **Flaps and Landing Gear**: The flap and gear schedule for modeling in AEDT are provided with each of the procedures. For FOQA FPPs, AEDT infers a flap and gear schedule from the corresponding standard profile. However, unless the analysis is using NPD data with correction for configurations, the flap and gear configuration don't affect the calculated noise when using an FPP. The present work visualizes the errors in AEDT SEL predictions against FOQA flap and gear settings since these affect the real-world noise measured at monitoring stations.
8) **Noise Power Distance (NPD) Curves**: Noise calculations in AEDT rely on NPD curves derived from aircraft certification data. Noise levels are obtained as a function of observer distance via spherical spreading through a

standard atmosphere. Other correction factors are applied to obtain the desired sound field metrics at the location of the receiver. NPD + configuration (NPD+C) curves which may enable more accurate noise prediction due to aircraft configuration and speed changes are under research [32] and not included in the present work.

C. Compatibility of Settings

Modeling options chosen in this study include the procedures and profiles, thrust, and weight. However, not all of these options are compatible with one another. For instance, the FOQA FPPs are incompatible with reduced thrust or alternate weight settings. Likewise, the FOQA thrust values (prescribed to AEDT in pounds) cannot be used in a procedural profile. The procedural profile requires thrust type and step type definitions instead of actual thrust values. To this end, the thrust is calculated by AEDT instead of given as an input in the profile definition. Alternatively, arrivals have fewer combinations of modeling options. The only arrival profiles available are STANDARD and the FOQA FPP. Overall, the utilized combination of assumptions yields seven different jobs per noise metric for departures and two for arrivals. An additional set of standard departure profiles were run with ASOS weather data and are included in aggregate results.

D. Automation Capabilities

Running the different modeling assumptions on a large number of flights requires some form of an automation capability, which is developed in previous work [24] and summarized here for completeness. Automation is required for setting up the large combinations of settings within AEDT (pre-AEDT automation). It is also required for post-processing the results that are generated (post-AEDT automation). Pre-AEDT automation involves nine SQL automation scripts as shown in Figure 1. The user specifies the profiles to be modeled (either procedural or FPP) and the corresponding ground tracks. A combination matrix maps Profile IDs and Ground Track IDs together along with runway specifications to model the correct combinations from the matrix options in Tables 1 and 2. Once all studies are run within AEDT, the results, which include noise, emissions, and performance, are exported into csv files utilizing a batch report run tool. Finally, each case in the combination test matrix results in four reports that are processed using MATLAB and Python post-processing scripts.

III. Results and Discussion

Detailed results for one departure and one arriving flight at KSFO are provided in this section. Additionally, those results are followed by aggregate AEDT prediction accuracy for hundreds of arrival and departure operations. While FOQA flight tracks and trajectories are expected to result in accurate AEDT noise predictions, other noise modeling options are also included in this validation exercise. A typical AEDT user may not have FOQA flight tracks and trajectories readily available. Therefore, investigating these modeling options and improving the overall fidelity of AEDT is important from a usability perspective.

A. Validation Data Overview

The following modeling framework is implemented on 140 arriving and 129 departing flights at San Francisco International Airport (KSFO) utilizing AEDT version 3c. In effort to anonymize the real-world flight details, these flights have been provided arbitrary flight IDs (GT-xxx). Figure 2 shows a map of the noise monitor locations with their respective monitors IDs around the SFO airport. The noise monitors that were triggered with the highest confidence and mapped to the corresponding flights are used as truth values when compared with AEDT predictions. Departure flights typically trigger multiple noise monitors while arrival flights typically trigger one or two monitors with some exceptions. Therefore, the 140 arrival flights resulted in a total of 179 flight-monitor pairs while the 129 departure flights resulted in a total of 437 flight-monitor pairs.

B. Identifying Outliers

During previous analyses, it became clear that there were many AEDT predicted SEL values that differed greatly from the actual SEL measurement. These outliers triggered a "deep dive" study to gain insight on flight characteristics that may explain the anomalous SEL predictions. It was important to investigate these outliers as they lead to erroneous results that are misleading when evaluating the accuracy of AEDT. The results of this study disclosed four rationales that affect the range of a SEL measurements and predictions.

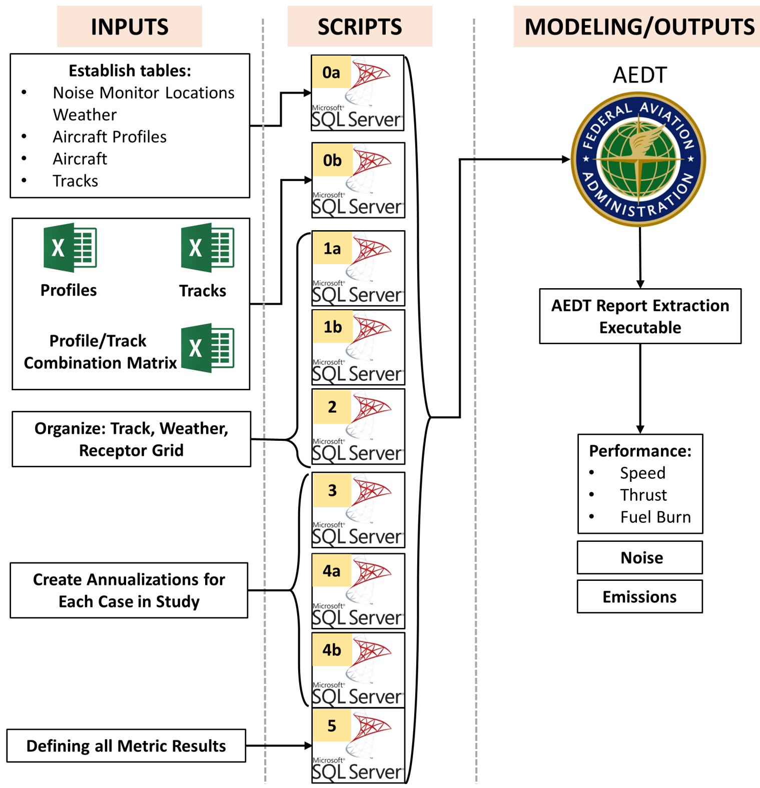

Fig. 1 Noise Modeling Process Automation Steps (Adapted from Ref. [24])

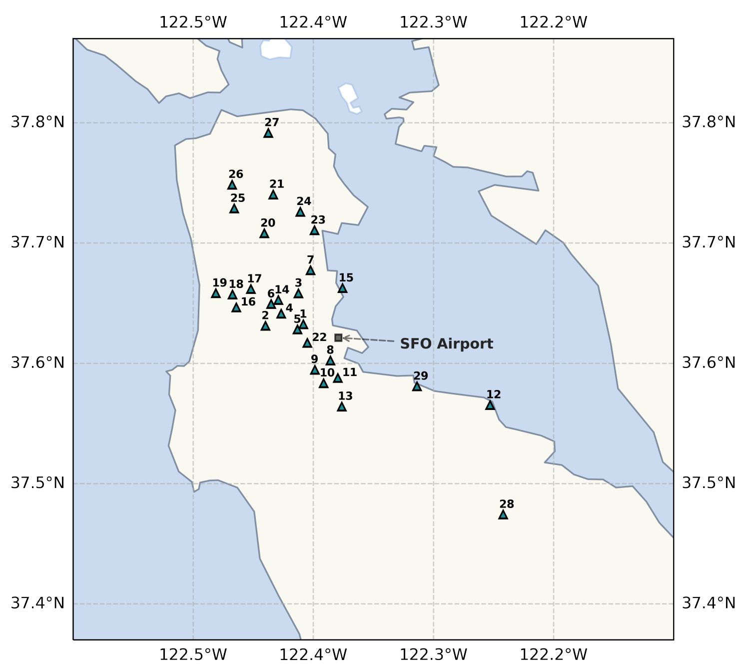

Fig. 2 Location of noise monitors around SFO

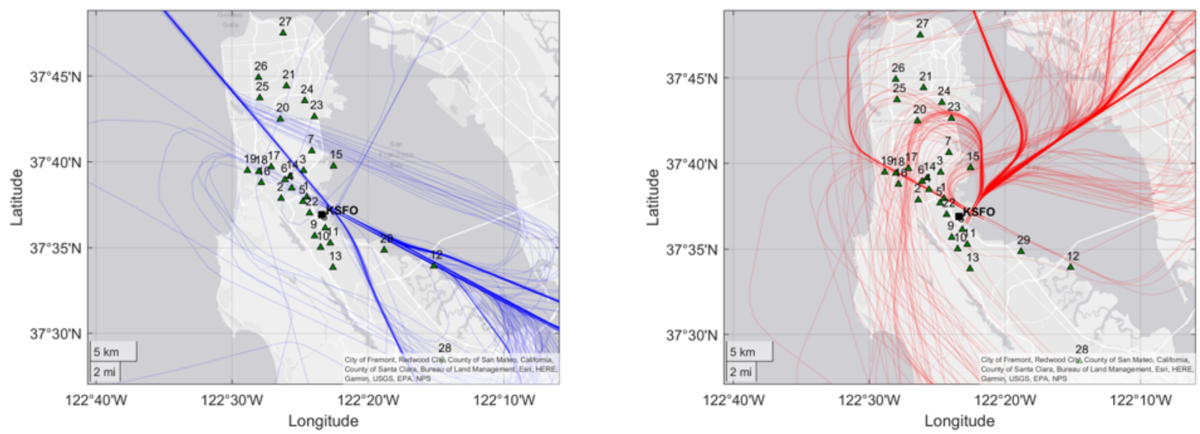

Fig. 3 Arrival (left) and departure (right) operations ground tracks at KSFO

Table 3 SFO Outlier Analysis

Operation	Flights	Noise Events	Notes
	140	179	Modeled in AEDT
		-44	Wind >10 knots or any precipitation
Arrivals		-36	Abnormal track correlations
		-15	Monitor 8
		-33	Slant distance >7,000 ft or misc.
	51	**51**	**Useful Total**
	129	437	Modeled in AEDT
		-213	Wind >10 knots or any precipitation
Departures		-37	Monitor 8
		-45	Slant distance >7,000 ft or misc.
	63	**142**	**Useful Total**

The first rationale involved weather related factors - (1) wind speed, and (2) precipitation. Subject matter expert feedback suggested that wind speeds greater than 10 knots or any precipitation can greatly affect noise monitor readings in a way that AEDT is not designed to account for. Therefore, any noise events with a wind above 10 knots or non-zero precipitation were excluded from the validation data. Second, there were many flights with ground tracks that were erroneously correlated with noise events. Most of these abnormal track correlations were attributed to go-arounds or approaches from the north-west that loop around to use runway 28. Such noise events were therefore excluded from the validation data. Third, out of the 29 noise monitors at KSFO, monitor 8 repeatedly showed high errors in SEL predictions. Further investigation determined that the location of monitor 8 was likely a big factor in these anomalous measurements. Monitor 8 is located directly next to a major highway near the San Francisco airport. Due to this consistent highway inference at this noise monitoring station, any noise event that triggered monitor 8 was excluded from the validation data as well. The last rationale from outlier analysis is related to slant distance, which is the distance between the aircraft and the noise monitor (illustrated in Figure 4). Slant distances over 10k ft were investigated to determine what threshold produced high SEL prediction errors. Noise events with higher slant distances have an increased possibility of inaccurate noise measurements or event correlation to flight due to uncontrollable factors like background noise levels. Additionally, 29 noise events with slant distances between 7k-10k ft were found to have elevation angles less than 1°. Since these are likely incorrect correlations between noise monitoring data and flight operations, they were dropped.

The results of each exclusion criterion and the useful total noise events available for validation are outlined in Table 3. There were 140 arrival flights with 179 noise events and 129 departure flights with 437 noise events. Within the arrival flights' noise events, there were 44 events with wind speed above 10 knots or non-zero precipitation, 36 with

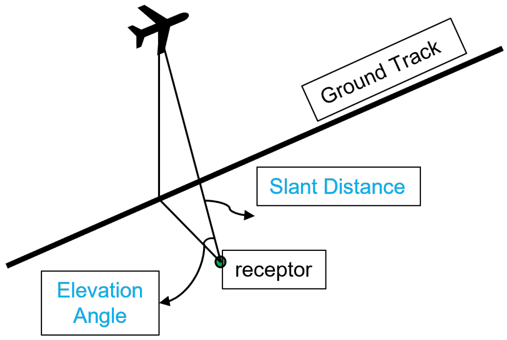

Fig. 4 Elevation Angle and Slant Distance at the Point of Closest Approach

an anomalous flight track, 15 triggering monitor 8, and 33 events with horizontal slant distances greater than 7,000 feet. All of these noise events were excluded from the validation data, leaving 51 noise events for 51 arrival flights. Unfortunately, all these useful arrival noise events were captured by just one noise monitor - monitor 12 (see Fig. 2). This has resulted in a limitation on the validation of noise due to arrival operations that will be addressed in future work. Within the departure flights' noise events, there were 213 events with wind speed above 10 knots or non-zero precipitation, 0 events with an anomalous flight track, 37 triggering monitor 8, and 45 events with horizontal slant distances greater than 7,000 feet. After exclusion, there are 142 noise events for 63 departure flights remaining. The individual flight modeling results are elaborated in the following subsection.

A ΔSEL metric is used to discuss the following results and is defined as AEDT prediction minus the real-world measurement. A negative ΔSEL therefore indicates an underprediction, while a positive value indicates an overprediction.

$$\Delta SEL = SEL_{AEDT} - SEL_{Measured} \tag{1}$$

C. Individual Flight Results

Although there are detailed performance and noise results available for all flights, only one departure and one arrival flight have been presented below that are a compendious representation of the results. Table 4 provides the AEDT airport weather parameters for the two flights of interest. AEDT airport weather models the flight using the average annual weather. This means that although our two study flights are not operating simultaneously, each respective model is using the same weather conditions because they operated in the same year.

Table 4 Airport weather conditions for the flights

Weather Option	Temp [F]	SLP [mb]	DP [F]	RH [%]	Wind Speed [kts]	Wind Dir [°]
AEDT Standard	61	1018.3	53.1	75.2	9	N/A

1. Flight Number: ***GT1015***

Flight GT1015 was a Boeing 737-800 with an origin-destination pair (OD Pair) of SFO-LAX. This makes the flight a stage length 1 departure, which will be discussed further in section III.D. The real-world FOQA data gives the gross takeoff weight as 145,591 lbs. Figure 5 displays the performance plots for flight GT1015. These plots were generated as a part of the post-processing automation discussed in section II.D. The aircraft performance, on the basis of procedural profiles, shows that the alternate weight reduced thrust profiles are shallower when compared to others. However, the FOQA FPP (actual flight) is the shallowest of them all. The ground track as well as the monitors that were triggered by this flight are presented in Figure 6.

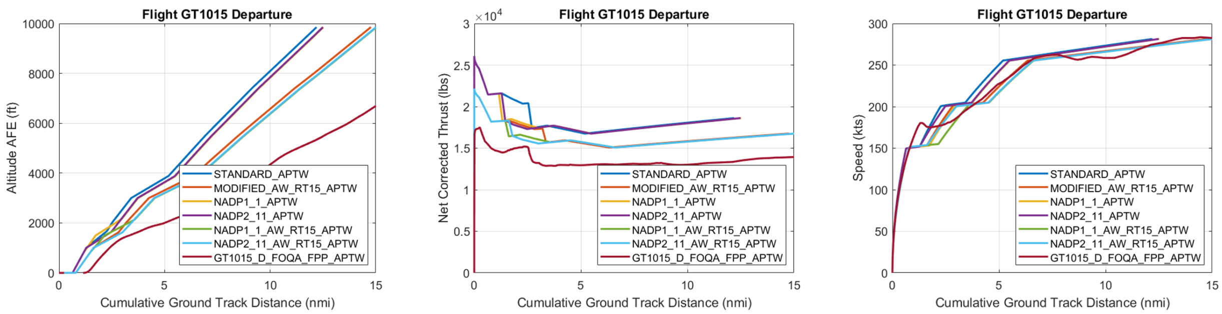

Fig. 5 Altitude, Thrust, and Ground Speed Performance for GT1015

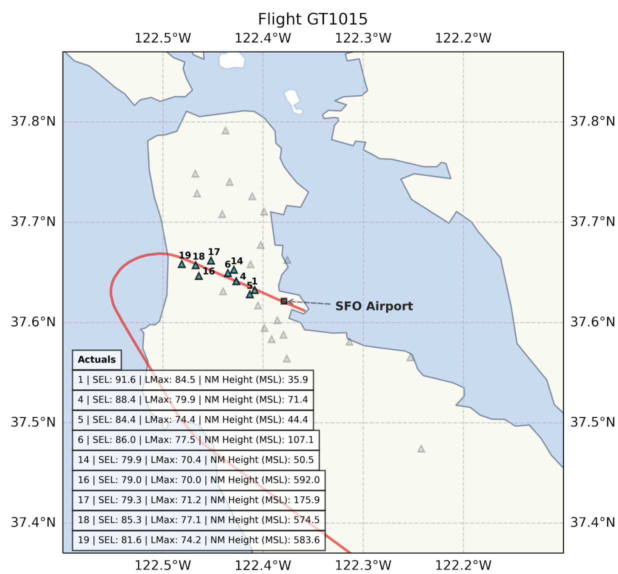

Fig. 6 Flight Trajectory and Monitors Triggered for GT1015

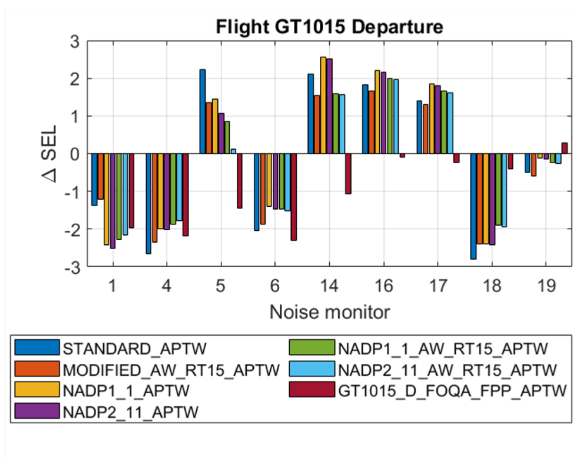

Fig. 7 AEDT predicted - actual noise results for GT1015

The noise comparison for flight GT1015 is given in Figure 7. This comparison shows both under predictions and over predictions of the noise created at each noise monitor locations. An interesting trend is observed when the noise monitor predictions are compared to the aircraft ground track and monitor locations from Fig. 6. Noise values at monitors 1, 4, 6, 18, and 19 tend to be underpredicted. These monitors are also very close to the flight's ground track. Alternatively, monitors 5, 14, 16, and 17 are all further away from the flight's ground track and tend to be overpredicted. Although these comparisons may not provide conclusive insights alone, they can be useful when aggregated across different flights and modeling assumptions.

2. Flight Number: ***GT992***

GT992 was a Boeing 737-800 arriving flight with an OD pair of LAX-SFO and a gross weight at touchdown of 121,637 lbs. Figure 8 shows the ground track of the flight, where it flew overhead and triggered solely monitor 12. Figure 9 shows the performance plots for GT992 with the point of closest approach to monitor 12 shown by the dotted black line. The two major differences between STD_APTW and FOQA_FPP profile are the lower thrust and higher speed in the FOQA data as compared to AEDT standard profile assumptions near monitor 12. An interesting note is that the FOQA profile (actual flight) descended continuously and did not level off at 3,000 feet as apposed to the standard profile assumption.

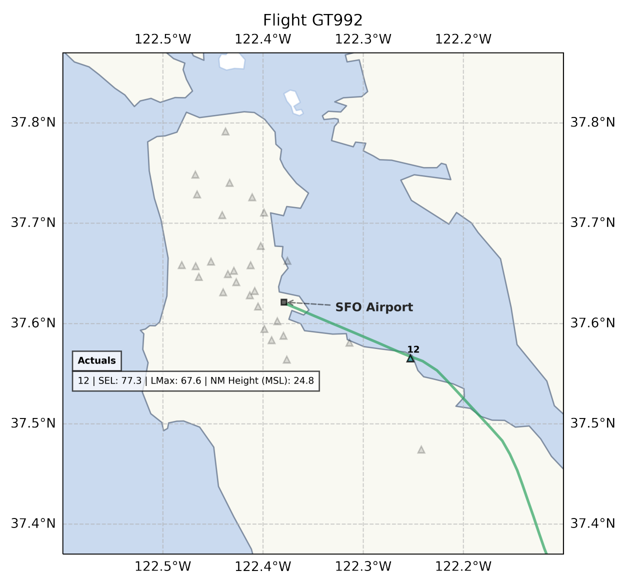

Fig. 8 Trajectory and Monitors Triggered for Flight GT 992.

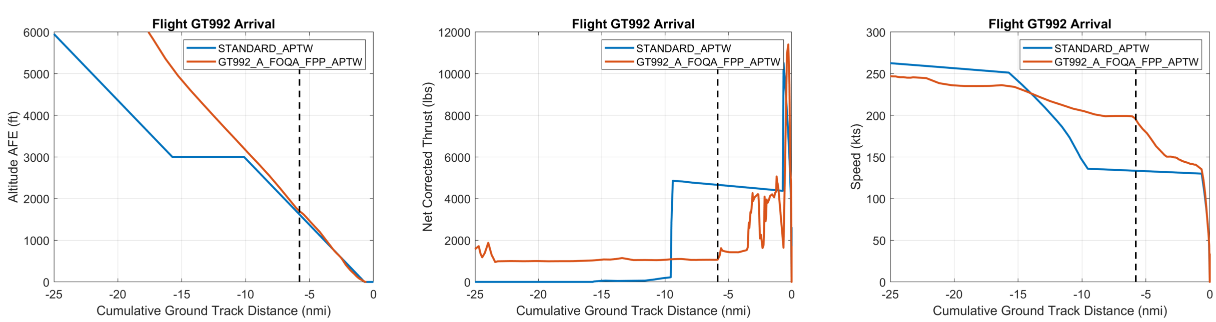

Fig. 9 Trajectory, Thrust, and Ground Speed Performance for Flight GT992.

Additionally, Figure 10 shows the difference between the AEDT prediction and the real-world noise monitor reading for the FOQA FPP and the standard profile. The FOQA FPP is an underprediction of the actual reading by approximately

1.5 dB while the standard profile is an overprediction by about 2.5 dB. As explained in the previous case, this single flight comparison does not provide conclusive insight alone but can be valuable in an aggregate analysis.

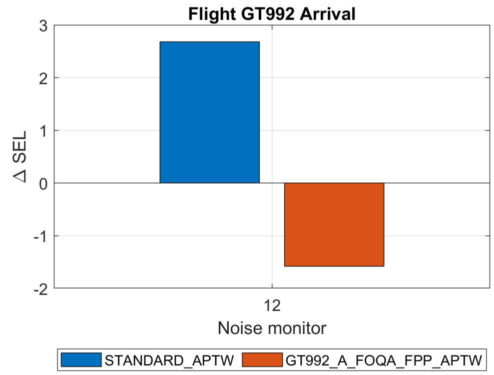

Fig. 10 AEDT predicted - actual noise results for GT992

D. Aggregate Flight Modeling Results

As shown previously, individual flights can be analyzed to compare the performance and noise prediction accuracy of the different modeling options within AEDT. However, to obtain more meaningful inferences, an aggregate, statistical analysis of all 114 flights and 193 noise events from Table 3 is carried out in this section. Specifically, all operations are aggregated for each profile rather than viewing one flight at a time,. For relevance, there are two separate aggregate categories, arrivals and departures. These results are further sliced by different data parameters that can only be available via the FOQA data, like landing gear and flap settings, takeoff and landing weights, elevation angles and slant distances, etc.

Some preliminary results for noise prediction error are shown in Figure 11. These box plots represent all ΔSEL (predicted - measured) values for both arriving and departing flights. The arrivals are modeled using 2 different profiles, Standard Profile with Average Airport Weather (STD_APTW) and FOQA Fixed Point Profile (FOQA_FPP). The departures are modeled using eight different profiles: Alternate Weight Reduced Thrust (AW_RT15), FOQA_FPP, Noise Abatement Departure Procedure Alternate Weight Reduced Thrust (NADP1_AW_RT_15), Noise Abatement Departure Procedure Alternate Weight Reduced Thrust (NADP2_AW_RT_15), NADP1, NADP2, STD_APTW, and Standard Procedure with Automated Surface Observing System (ASOS) Airport Weather (STD_ASOS). Ideally, this box plot would show a median of zero and a small spread, indicating minimal error between AEDT predictions of multiple operations and real-world data. All modeled departure profiles (D) show a median overprediction error of less than 1 dB. The FOQA profile has the tightest spread with the STD_ASOS profile being a close second. This indicates that these two profiles have the highest precision for departures. However, the NADP2_AW_RT_15 profile is the most accurate as its median is closest to zero. The arrival profiles (A) show a median underprediction error of around 2-3 dB. In addition, the STD_APTW profile has the tightest spread and has a median ΔSEL closest to zero, indicating the best precision and accuracy.

To understand these results in greater detail, more in-depth analyses with respect to various modeling parameters captured from real data are presented next. These include overhead vs. sideline, slant distance, landing gear configuration, flap position, airframe type, weight, and stage length. Figure 4 illustrates the definition of an aircraft's slant distance and elevation angle at the closest point of approach. These points are used to determine whether the noise event was an overhead trigger (elevation angle $\geq 50°$) or whether it was a sideline trigger (elevation angle $\leq 50°$). After making these classifications, the box plot in Figure 12 represents preliminary results based on whether the noise event was overhead or sideline. Median of arrival noise events suggests an underprediction for both classes while departure events' medians are overpredicted, with the FOQA profile showing a median ΔSEL closer to zero for sideline noise events with the smallest variation. Based on these results, it is observed that for overhead and sideline arrivals, the standard profile gives the most accurate noise prediction. For sideline departures, the FOQA profile shows the most accurate prediction while the STD_APTW and STD_ASOS profiles are the most accurate for overhead departures.

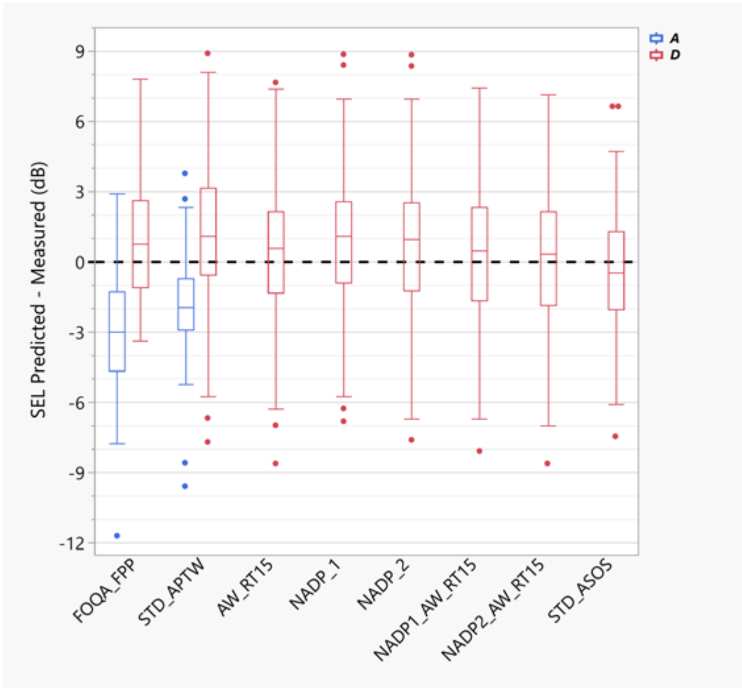

Fig. 11 Predicted - Measured SEL (dB) noise box plot for all noise events at all monitors split by Arrivals (A) and Departures (D)

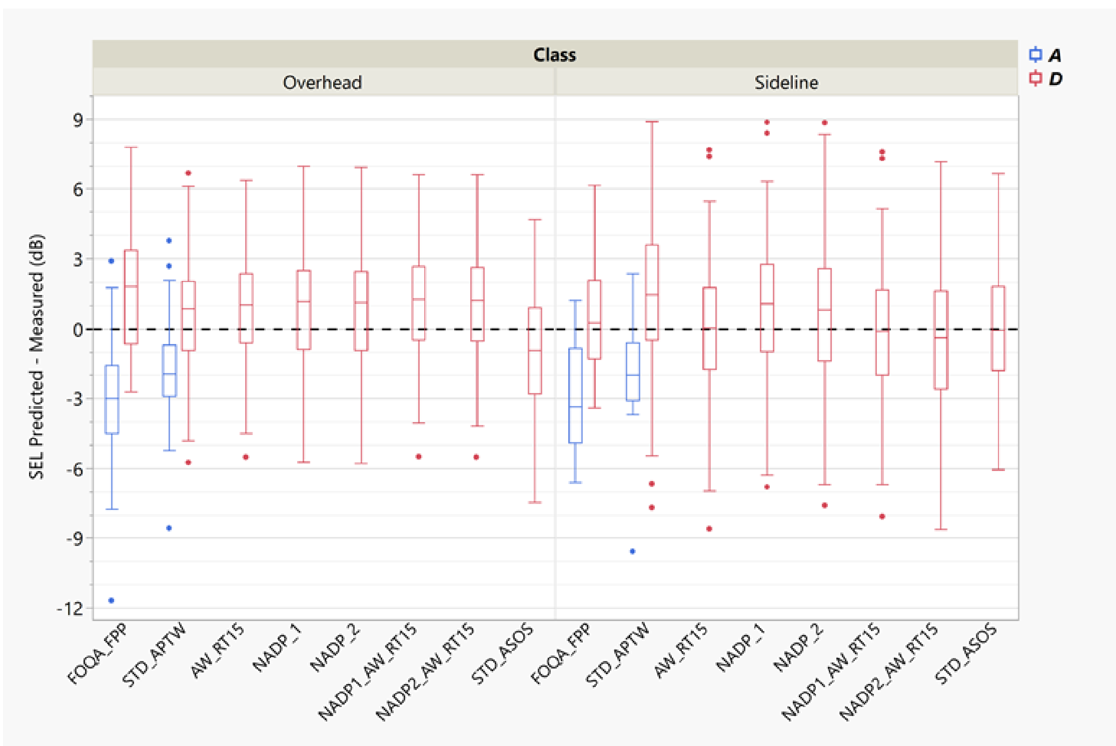

Fig. 12 Predicted - Measured SEL (dB) for overhead vs sideline noise events across all monitors

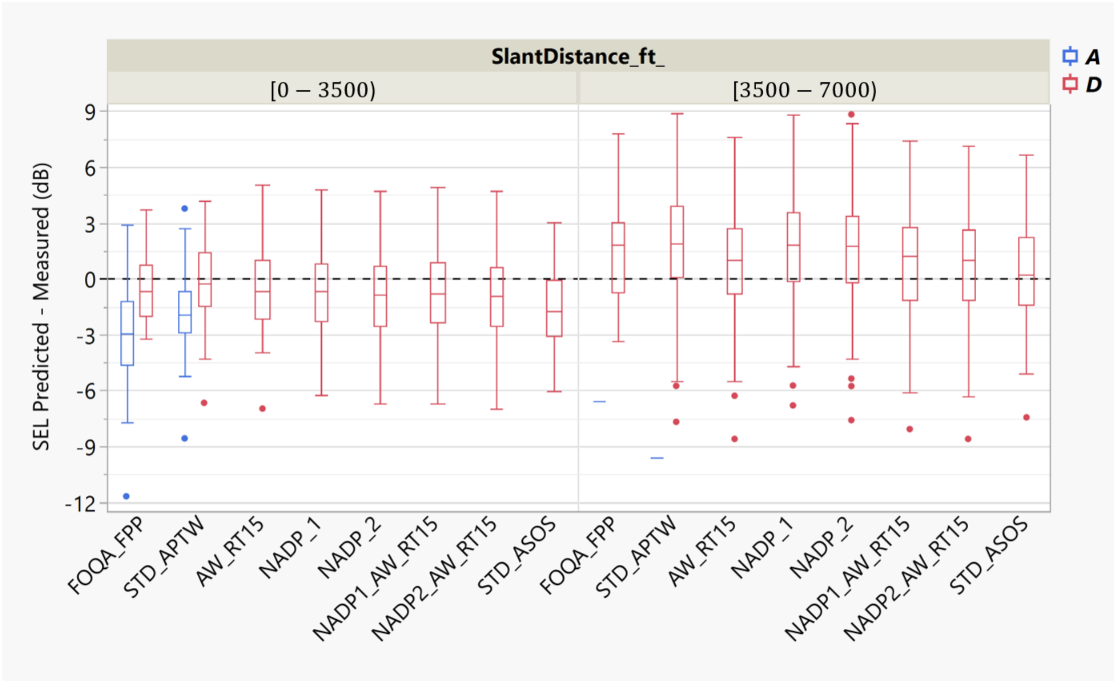

Fig. 13 Predicted - Measured SEL (dB) by slant distance across all monitors

In addition to overhead vs. sideline, slant distances were also explored for the same profiles. As discussed in section III.B, slant distances above 7,000 feet and elevation angles of less than 1° were removed from the results. Represented in Figure 13 are slant distances less than 3,500 ft (left) and between 3,500-7,000 feet (right). For slant distances less than 3,500 feet, there were a total of 51 arrival events and 45 departure noise events. The arrival events are underpredicted by about 3 dB. The departures events are predicting well, with a median ΔSEL between 0 and -1 dB. For slant distances in the second range, 3,500-7,000 feet, there are no arrivals, and all 97 departures are overpredicted by 0 to 2 dB depending on the modeling assumption used. Both ranges in this analysis reveal insight to noise prediction accuracy. The most accurate noise prediction is found in slant distances less than 3,500 ft. These observations will be used to understand why some AEDT predictions are not accurate and to help guide improvements to the AEDT noise modeling capability overall.

The next two parameters considered for these aggregate studies are landing gear configuration and flap position. Both these parameters are computed within AEDT according to a predetermined schedule. Note that noise prediction in AEDT using FPPs is not affected by FOQA flap or gear settings since we did not use NPD+C (see Table 1). The results discussed here utilize the real-world FOQA landing gear and flap settings of the aircraft at the closest point to noise monitors to explore whether modeling these settings might be important to improve AEDT noise predictions.

For landing gear configuration, an analysis on arrival flights only was done to determine the relationship between the position of an aircraft's landing gear and noise prediction accuracy. Departure flights are all modeled with a singular configuration (landing gear up) so they were excluded from the analysis. There are three basic configurations of landing gear in the FOQA data: 0 (gear up), 1 (gear in transit), and 2 (gear down). In Figure 14, the arrival profiles (FOQA_FPP and STD_APTW) are modeled to show the correlation between ΔSEL and landing gear position of the aircraft when it is closest to the noise monitors in their trajectories. In all three configurations (0, 1, and 2), the FOQA FPPs show a median underprediction of about 2-3 dB. When the landing gear is up, the standard profile has a median ΔSEL of zero but underpredicts by about 3 dB when the gear is in transit or down.

For flap position, Figure 15 shows the ΔSEL values for all operations by the FOQA flap position when the aircraft are closest to the noise monitors in their trajectories. Because the FOQA data often provides approximate decimal values instead of exact flap settings (e.g. 4.65°instead of 5°or 28.23°instead of 30°), the results are divided into the three bins shown. There were 115 departure noise events found with flap angles between [0°, 5°) at the time of triggering noise monitors. All profiles except the standard profile with ASOS weather are found to overpredict SEL values in that group. Between [5°,15°), the 22 departure noise events are generally underpredicted by 1 dB with the FOQA profile

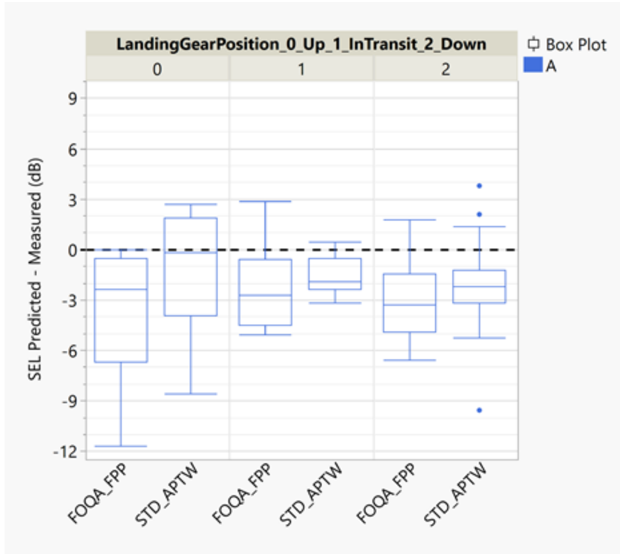

Fig. 14 Predicted - Measured SEL (dB) by landing gear position for all arrivals

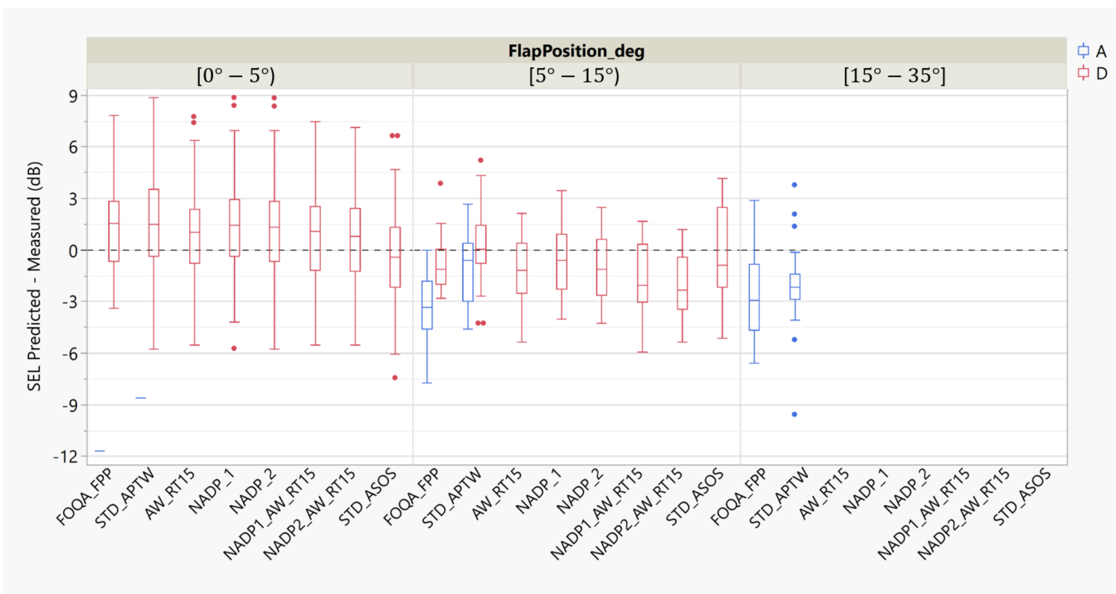

Fig. 15 Predicted - Measured SEL (dB) by flap positions for all noise events

having the least variability. The 14 arrival events in this group and another 36 arrival events with flap positions between [15°,35°) are both generally underpredicted by 2-3 dB. The distribution of SEL measurements from the noise monitors and AEDT predictions for FOQA_FPP and STD_APTW are provided by Fig. 16.

A brief data analysis was done with respect to various airframes and their weight assumptions. The various airframes included in this analysis are the 717-200, 737-800, 737-900, 757-200, 757-300, A319-100, and the A320-200. As shown in Figure 17, the 737 family is sufficiently represented and makes up most of the noise event population. Balancing the data for other airframes will be explored in future work for other airports and years of noise data. Figure 18 shows the weight error between AEDT assumptions and real-world FOQA operations by the stage length and airframe of interest. Weight error was calculated by differing AEDT predicted airframe weight with the actual FOQA airframe weight. It was determined that real-world operations are often heavier than AEDT standard assumptions. Specifically, FOQA weights are higher than AEDT standard predictions because the FOQA data provides actual load factors which are often

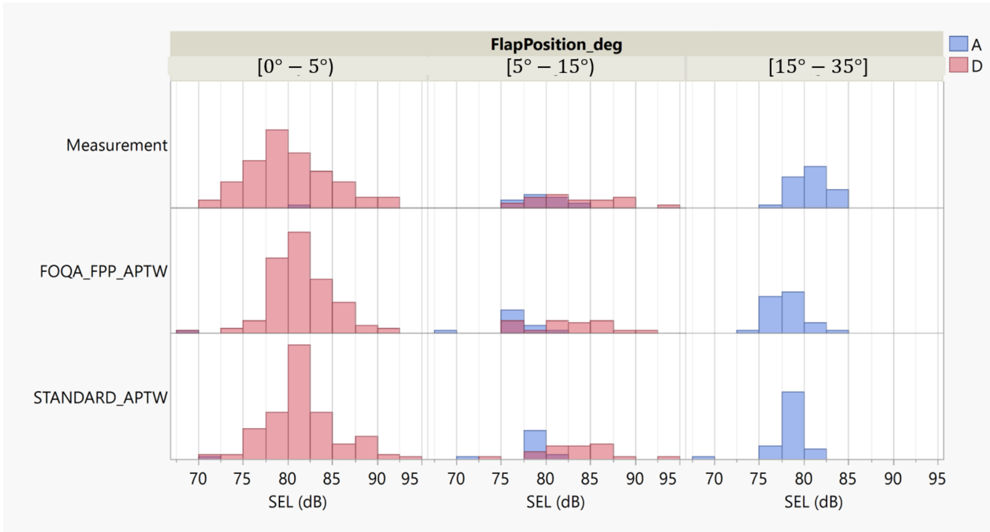

Fig. 16 SEL (dB) measured and predicted by FOQA_FPP and APTW_STD profiles for all noise events

higher than the assumed AEDT load factor of 65%. This corroborates prior studies which quantified this error and resulted in alternate weight modeling profiles [31].

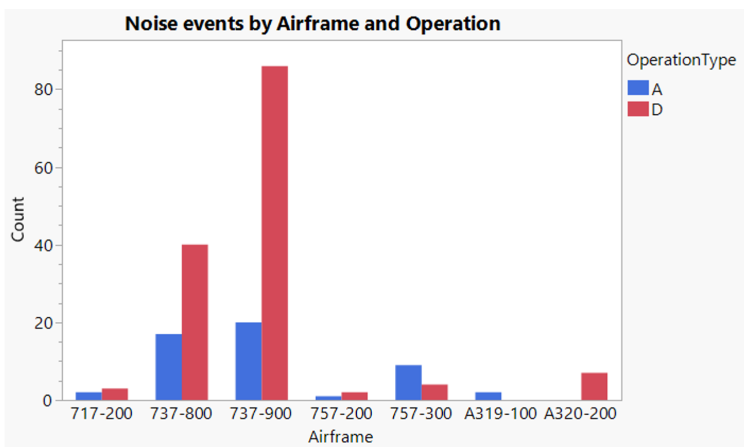

Fig. 17 Noise events by airframe type

Stage length is a term used to describe the length of a single flight leg (takeoff to landing). For the scope of this analysis, there are four stage lengths: 1, 2, 3, and 4. Stage length 1 is the shortest flight leg (less than 500 nautical miles (nmi)). Also, all arrivals in this analysis are assumed to have a stage length of 1 by AEDT. Furthermore, stage lengths 2, 3, and 4 are longer flight legs, ranging from 500 to 2,500 nmi. Using the same FOQA and procedural profiles as the previous analyses, arrivals and departures were studied to determine the relationship between stage length and SEL measurement. Figure 19 represents the ΔSEL values for departures and arrivals at various stage lengths. The total number of departure noise events in stage lengths 1, 2, 3, 4 were 72, 19, 5, and 43 respectively. All arrivals are modeled as stage length 1 and are therefore not of consequence in this case. For departures, median ΔSEL values for stage length 4 flights are close to zero. This is an interesting observation as Figure 18 shows the most weight error also coming from stage length 4 for the 737-900. Another observation for departures is shown in stage length 1, where the majority of the overprediction is happening. However, it is difficult to draw conclusions for stage lengths 2 and 3 due to limited sample sizes.

Fig. 18 Weight error by airframe type

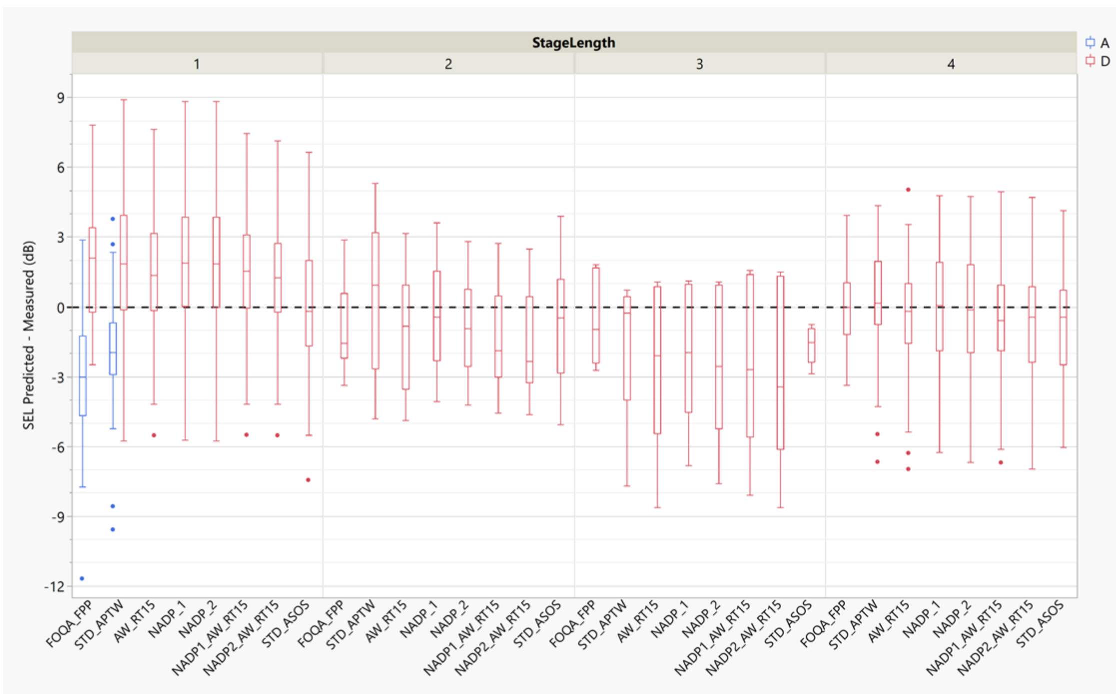

Fig. 19 Predicted - Measured SEL (dB) by stage length for all noise events

IV. Conclusion and Future Work

This work presented a framework that was structured and repeatable for AEDT noise model validation utilizing operational data from the real-world. Bulk flight operations at SFO were modeled in AEDT by utilizing pre-AEDT automation scripts, which resulted in 142 departure and 51 arrival high confidence noise events from 63 departure and 51 arrival operations. Additionally, the post-AEDT automation scripts enabled the fast post-processing of a large volume of output files resulting from the model in AEDT. These scripts also helped extract individual and aggregate noise comparison results that were used to make inferences about the most accurate modeling options in AEDT.

One departure and one arrival flight were analyzed in detail providing the ground tracks, performance plots, and the

AEDT noise prediction errors for different profiles. Aggregate results that were analyzed for departures and arrivals show that, generally speaking, the FOQA fixed point profile and standard profile were the most precise modeling option in AEDT. Both the FOQA and standard profile have small spreads and small median errors (± 2 dB) across all monitors. Variation due to factors like overhead vs. sideline noise events, slant distance, landing gear configuration, flap position, airframe type, weight, and stage length were also presented based on available FOQA data. AEDT was found to be most accurate in predicting SEL for slant distances of less than 3,500 feet, and for higher stage length (heavier) departures.

In conclusion, AEDT is designed to be accurate on average while modeling the sound exposure of operations over a long duration of time at a place of interest. The present preliminary results confirm that fact and show that AEDT has a median error of between 0-3 dB over hundreds of flights and noise events across different monitoring locations. While these results are important in validating AEDT, it is important to recognize the limitations of the results presented here. This study reports results from only one airport - SFO, with its varied geography and climate, for the year 2019, while matching FOQA flight data to airport noise monitoring SEL measurements. Furthermore, all available arrival validation data points were captured by just one monitor - monitor 12. This limited control over factors such as terrain, background levels, etc. for arrivals. While the authors have taken sufficient care in selecting noise events that meet stringent quality criteria to compare AEDT predictions with real-world operations, detailed noise time histories were not available for the year under consideration. Having these noise time histories would have improved the overall quality of many of the validation data points in this work. For future work, some of these limitations will be addressed. Results from a few additional airports are being processed for multiple years, which include noise time history data to improve the quality of data matching and comparison. This should provide sufficient results to generate confidence in AEDT's noise model for different weather and geographic conditions and for varied operations.

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16. Abstract

A focus on sustainability in aviation is required to mitigate the environmental impact of its growth. Modeling the environmental effects helps the aerospace community obtain quantitative data linked to aircraft emissions and noise. The Aviation Environmental Design Tool (AEDT) offers the capability to model aviation operations using data sources of differing fidelity and is used worldwide for quantifying emissions and noise impacts of such operations. As a result, validating the accuracy of AEDT is of vital importance for continuous sustainability efforts. This paper presents preliminary results of AEDT noise model validation at the San Francisco International Airport (SFO). The overall sensitivity of noise predictions to varying assumptions within AEDT is explored and quantified using a set of real-world flights modeled within it. This is achieved by utilizing routine Flight Operations Quality Assurance (FOQA) data records from airline operations, noise monitoring data from various stations around the SFO airport, and various weather data sources. The outcomes of this validation study are expected to benefit the developers of AEDT to produce a more accurate noise model

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