Reduction of Aircraft Noise Uncertainty for a Notional Supersonic Business Jet

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NASA supported a study by the International Civil Aviation Organization on the environmental impact of adding supersonic aircraft to the existing global fleet by designing a notional 55-tonne supersonic business jet. The aircraft is referred to as the Supersonic Technology Concept Aeroplane (STCA) and has been used in a multitude of studies over the past few years. One of the many studies on this aircraft was the noise produced by the STCA during landing and take-off (LTO) operations. The LTO noise for the STCA was assessed using contemporary noise prediction tools that have been primarily developed for and utilized by subsonic aircraft, resulting in a high level of uncertainty for the STCA noise predictions. NASA has recently been conducting research and developing tools to reduce the uncertainty for airport noise predictions of supersonic aircraft. The initial focus of the uncertainty reduction was on the jet and inlet-radiated fan noise produced by supersonic engine systems since these sources are dominant during take-off and landing operations for supersonic jets. The results of these efforts are discussed and applied to the STCA model to update the airport noise predictions and associated uncertainty metrics. It is shown that by using new noise source prediction models, the overall system-level cumulative noise uncertainty of the study vehicle is reduced from a standard deviation of 7.8 EPNdB to 2.0 EPNdB.

I. Introduction

Over the past several years, multiple companies were developing supersonic aircraft for commercial transport. Restarting the commercial supersonic transport industry after the Concorde retired in 2003 is no small task, and many obstacles must be overcome for this budding industry to succeed. One of these obstacles is a regulatory hurdle, that no airport noise certification rule was in place to tell them how quiet supersonic aircraft must be in landing and takeoff (LTO) operations. The current Federal Aviation Administration (FAA) and International Civil Aviation Organization (ICAO) regulations specifically omitted supersonic aircraft beside the Concorde. Without requirements in the noise certification regulations there exists considerable risk in developing a supersonic aircraft. An aircraft would not be allowed to fly if regulations were put in place at a lower noise level than the aircraft could achieve during LTO operations. Since engineering considerations for low LTO noise levels are generally opposed to those for range or payload, it is important to know the noise targets as the designer strives to maximize profitability of the aircraft. To create an optimal supersonic aircraft design, the LTO noise regulations and the expected noise levels of the vehicle are crucial to understand.

The process for creating the necessary noise regulations for supersonic aircraft has also faced its own hurdles. Historically, noise regulations are established using international consensus based on technical data from existing aircraft. Without existing commercial supersonic aircraft to establish the attainable trade between economic benefit, mission performance, and environmental impact, regulators did not have sufficient data needed to establish noise rules. Nevertheless, on March 2020, the FAA filed a Notice of Proposed Rule Making for small commercial supersonic aircraft [1]. This Notice was based heavily on low-fidelity studies of business-class supersonic aircraft, primarily from NASA but approved by industry advisors. Further progress in establishing supersonic noise regulations will require international collaboration and more information of increasing credibility around the performance and noise of potential supersonic aircraft concepts.

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A key study vehicle being used in international deliberations, the Supersonic Technology Concept Aeroplane (STCA), used empirical noise prediction methods from NASA's Aircraft Noise Prediction Program (ANOPP) program, itself a product of decades of research into noise of conventional, primarily subsonic, aircraft. NASA had shown that, when applied to conventional aircraft such as the Boeing 737-800, the system prediction tools used in the STCA study matched well with published certification noise levels. However, technical experts had some trepidation surrounding the assumptions and extrapolations being used to apply the tools to the STCA, which has several supersonic-specific features. Furthermore, there was no way to establish the uncertainty of the projected noise levels. Again, lacking the traditional noise databases typically used to establish accuracy of the empirical noise models there was concern about the accuracy of the estimates being used to establish noise policies.

These concerns were the motivation for the NASA's Prediction Uncertainty Reduction (PUR) Technical Challenge as formulated in 2019-2020 and officially established by the Advanced Air Vehicles Program in January 2021. The technical challenge objectives were as follows:

- Assess accuracy of models being used to predict LTO noise in international studies of commercial supersonic aircraft.
- Extend noise models to cover features and flow regimes relevant to supersonic aircraft and provide uncertainty metrics for these models.

The work presented in this study aims to address both objectives with a focus on the uncertainty of the noise prediction tools as they relate to supersonic aircraft and the efforts performed to reduce this uncertainty.

II. Initial Assessment of STCA Aircraft Noise

The baseline LTO noise assessment for the Prediction Uncertainty Reduction Technical Challenge was selected to be that of the NASA-developed 55-tonne Supersonic Technology Concept Aeroplane. The STCA is a notional research aircraft created to perform investigative studies and provide information to ICAO's Committee on Aviation Environmental Protection (CAEP) to assist in future regulation efforts for supersonic aircraft. The 55t (121k lb) STCA is an eight-passenger trijet aircraft that is intended to be representative of early-entry supersonic business jets in development by industry. The aircraft was designed for Mach 1.4 supersonic cruise over-water with a range of 4243 nmi. The 55t STCA is not intended to be a low-boom aircraft and only operates at supersonic conditions overwater. A summary of the aircraft characteristics is shown in Table 1. A model of the STCA aircraft is shown in Fig. 1.

Table 1 55t STCA trijet characteristics.

Max takeoff weight, klb	121
Passengers	8
Cruise Mach	1.4
Engines (x3)	CFM56-derived
Overall length, ft	135
Span, ft	67
Wing reference area, ft$_2$	1619
Wing aspect ratio	2.7
Wing taper ratio	0.09
Wing loading, lb/ft2	74
Wing fuel, klb	24
Fuselage fuel, klb	36
Fuel fraction	0.50

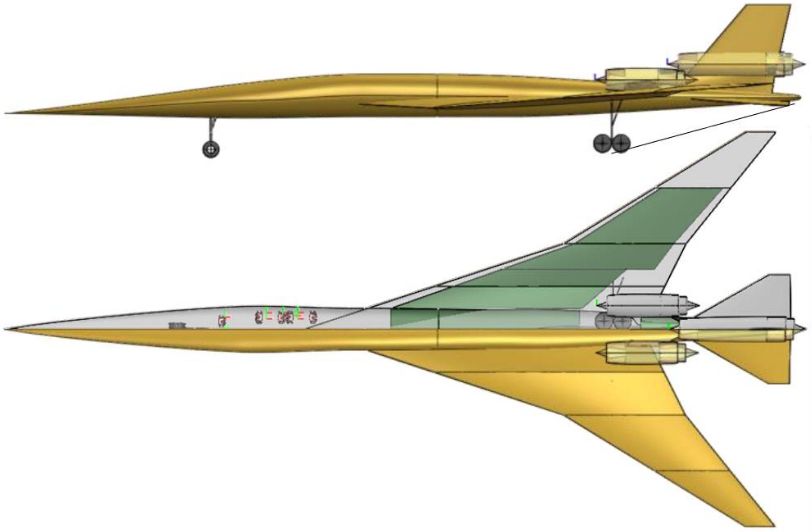


Fig. 1 55t STCA trijet aircraft concept (over-wing nacelles) [11].

The reference STCA aircraft has three over-wing mounted CFM56-7B-derived engines that were analytically redesigned using the Numerical Propulsion System Simulation (NPSS) software [2], [3]. The redesign of the engine for supersonic applications includes a higher pressure-ratio single-stage fan on the low-pressure spool, that operates at peak efficiency at a pressure ratio of 2.2. The engine redesign also features an internally mixed flow with a single-stream convergent-divergent plug nozzle. The center body plug and nozzle throat are fixed while the divergent flaps are variable. Table 2 summarizes the engine performance characteristics at relevant conditions for both cruise performance and LTO acoustic performance. Fig. 2 depicts models of the CFM56-7B engine and the notional modified supersonic variant for the STCA.

Table 2 Engine performance summary for the 55t STCA trijet engine.

	M1.4, 50kft, ISA	**M0.25, sea level, ISA+27°F**	**Sea level static, ISA+27°F**
Net thrust, lb/engine	3,330	14,140	16,620
Specific fuel consumption, lb/hr/lb	0.943	0.588	0.479
Bypass ratio	2.9	2.9	3.0
Burner temperature, °R	3300	3150	3130
Turbine inlet temperature, °R	3180	3040	3020
Compressor exit temperature, °R	1450	1440	1430
Overall pressure ratio	22	21	21
Fan pressure ratio	2.0	1.9	1.9
Compressor pressure ratio	11.2	11.1	11.2
Extraction ratio	1.1	1.1	1.1
Nozzle pressure ratio	5.9	1.9	1.8

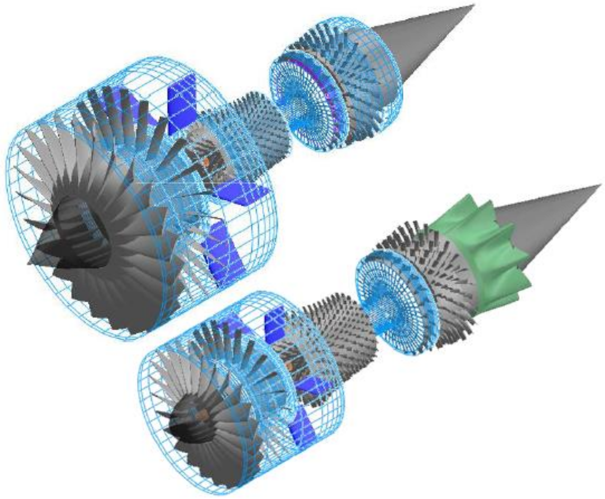


Fig. 2 Engine models of the CFM56-7B (top) and notional modified supersonic variant (bottom) [11].

NASA used several conceptual design tools to synthesize and assess the notional STCA model. A solid modeling tool [4] is used to define the outer mold lines of the airplane, to guide interior packaging, and to estimate internal fuel volume. The model also informs component weight and vehicle aerodynamic analyses. Lift-dependent drags, lift-independent drags, and wave drags are calculated by the methods described in Refs. [5], [6]. A weight estimate of the STCA wing is made using physics-based factors based on its gross geometry, while weight estimates of other major structures and systems are made using statistical-empirical relations. The airframe weight estimation methods are discussed in [7]. The mission performance assessment of the STCA was done using NASA's Flight Optimization System (FLOPS) [8]. All LTO noise predictions for the STCA are made using NASA's ANOPP [9], [10]. An in-depth description of the development of the 55t STCA model can be found in [11].

For the PUR technical challenge, the reference 55t STCA was modified to move the over-wing mounted engines to underneath the wing, a configuration more commonly proposed. This modification was also made to remove the uncertainty associated with noise-shielding effects and to isolate the source-noise uncertainty for fan inlet radiated noise as much as possible. A depiction of this variant is shown in Fig. 3. For the baseline noise assessments of the STCA, the existing internal source-noise modules of ANOPP were used without modification aside from the fan noise source and the airframe noise source. The fan source-noise predictions include acoustic treatment suppression based on empirical methods in [12] for both the inlet-radiated and discharge-radiated fan noise. The airframe noise predictions are initially calculated using ANOPP's Fink airframe noise prediction method [13] and then adjusted based on acoustic testing of the high-speed civil transport (HSCT) airframe in 1996 [14].

Currently, there is discussion amongst regulation authorities to permit future supersonic aircraft to utilize Variable Noise Reduction Systems (VNRS) during takeoff and landing operations to reduce the amount of airport noise generated by these aircraft. VNRS are automatic changes allowed during the operation of the aircraft to abate noise without the intervention of the flight crew. Examples of VNRS include programmed thrust lapse and programmed high-lift devices. However, to focus the uncertainty assessments on source-noise predictions, all evaluations of the STCA LTO noise for this effort are conducted with an assumed, fixed VNRS take-off trajectory deployed. A standard landing trajectory for noise certification was used, without any VNRS, in accordance with the requirements for subsonic transports in 3.6.2 of [15]. The VNRS parameters used for the STCA analysis include a 10% thrust derate at takeoff, a thrust programmed lapse rate (PLR) of 10% after clearing the 35 ft obstacle, and an in-air acceleration to V2+35kts. Atmospheric absorption, ground reflections and lateral attenuation effects are included in the LTO noise assessments according to methods described in [16].

Fig. 3 Under-wing engine STCA variant used for PUR Technical Challenge.

The aircraft system-level uncertainty assessments for the technical challenge are conducted relative to the LTO noise certification metric regulated by the FAA and ICAO: Effective Perceive Noise Level (EPNL). The cumulative EPNL is used as an aggregate metric of separate EPNL calculations occurring at three noise monitor locations: Lateral, Flyover, and Approach as defined in Fig. 4. Instantaneous Sound Pressure Levels (SPLs) are determined throughout the operational trajectory and converted to Perceived Noise Levels (PNLs) using a noy table to account for human annoyance. The PNLs are then corrected for tonal content and differences to Tone-Corrected Perceived Noise Levels (PNLTs). The maximum PNLT is determined and the PNLTs within a 10dB difference of that maximum (commonly called the 10dB down period) are then used for the EPNL calculation, accounting for the duration of the 10dB down period [15].

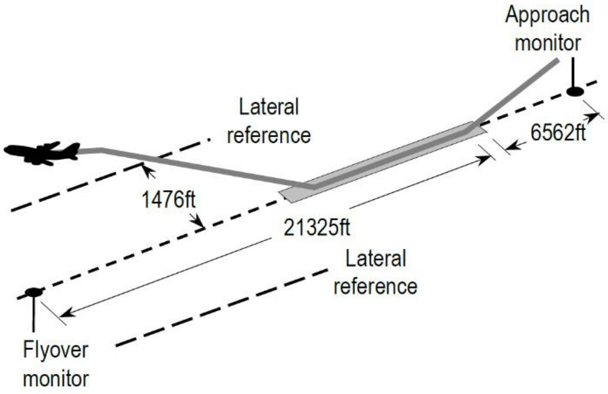


Fig. 4 Noise certification monitor arrangement relative to takeoff and landing flight paths.

The benchmark LTO noise assessment of the baseline STCA model resulted in a cumulative EPNL of 280.1 EPNdB. A breakdown of the individual noise sources and their contributing noise levels is shown in Fig. 5. These results show that the jet-noise component is very dominant relative to other noise sources at the lateral and flyover noise monitors, which is expected for a supersonic aircraft with low bypass ratio engines and high nozzle exit velocities. At the approach noise-monitor the dominant noise sources are the jet noise, fan inlet noise, and fan exit noise. In fact, the fan inlet tonal noise is equivalent in EPNL contribution to the jet noise for approach. As a result of this analysis, the technical challenge investigators focused the uncertainty reduction efforts on the jet-noise source and fan inlet radiated noise source. It was decided not to include the aft fan noise sources, core noise source, and airframe noise sources in the initial uncertainty reduction efforts due to their lessor contributions to the airport LTO EPNLs. Additionally, there are currently fewer datasets and studies available to use in uncertainty reduction efforts for these ancillary noise sources, but they should be considered for future studies to improve the overall LTO EPNL uncertainty for supersonic aircraft. It should also be noted that the relative importance of each noise-source component is based on the configuration, size, and capabilities of the STCA vehicle and could be different for other supersonic aircraft concepts. To have a comparison point to the STCA model, a similar benchmark LTO noise assessment was performed using a 737-800/CFM56-7B aircraft model. The 737-800 assessment resulted in a cumulative EPNL of 278.9 EPNdB. A breakdown of the individual noise sources is shown in Fig. 6.

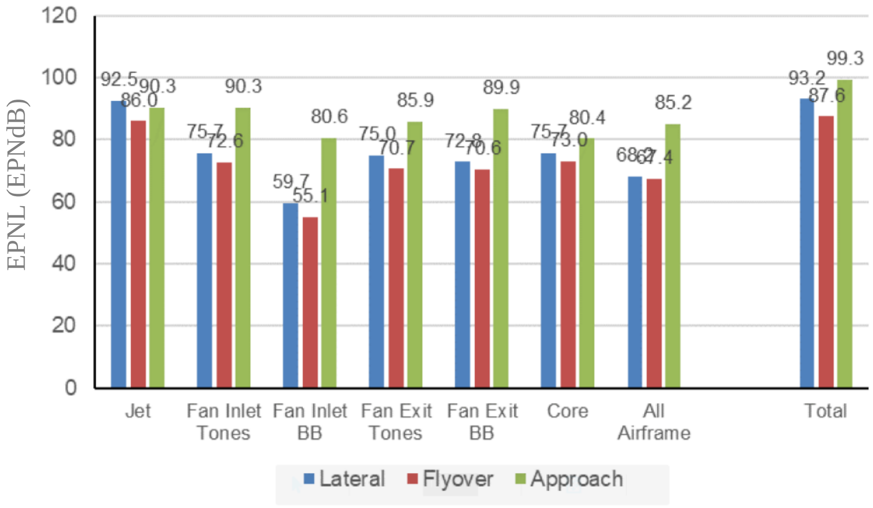


Fig. 5 Benchmark component noise prediction of STCA underwing engine variant.

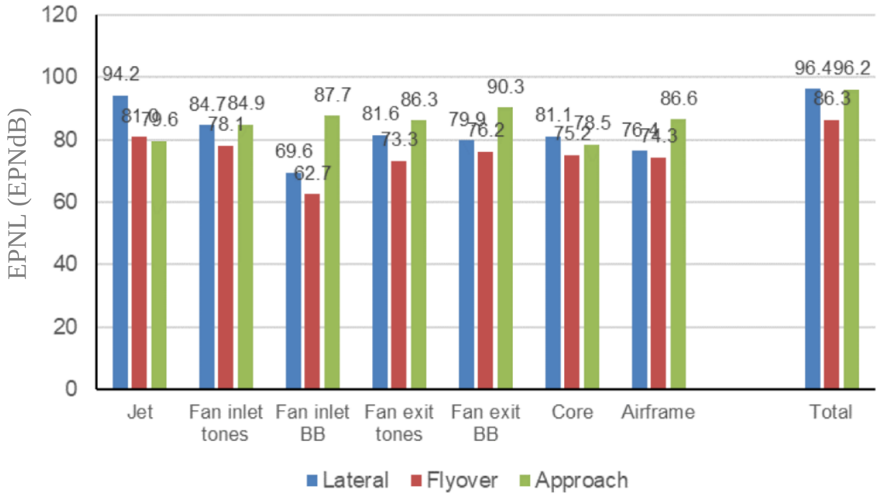


Fig. 6 Benchmark component noise prediction of 737-800 / CFM56-7B model.

After the benchmark EPNL numbers were generated for both the STCA model and the conventional 737-800 model, an uncertainty assessment for each vehicle was performed. Since the fan inlet noise and jet noise were determined to be the focus of the technical challenge, these noise sources were included as normal distributions in the system uncertainty assessments (SUA). The term "system" in this context is defined as the entire aircraft system to include both engine and airframe noise sources. The benchmark values for both aircraft models were determined through a deterministic model, where the inputs to the system noise model are fixed values generating unique source-noise spectra for each noise component (see Fig. 7). This deterministic approach generates a single fixed output noise value for each model, represented by the cumulative EPNL. For the SUA, a stochastic modeling approach was used. This entails creating a randomized probability distribution function (PDF) for the three noise-source components subject to uncertainty: jet noise, fan inlet tone noise, and fan inlet broadband noise. The PDFs for these noise sources are described using a standard deviation and offset from the mean value to create a normal distribution. The noise sources not included in the current uncertainty efforts (aft-radiated fan noise, core noise, airframe noise, and gear noise) are modeled deterministically. Therefore, the resulting output of the stochastic model are EPNL noise sensitivities that capture the uncertainty ***only*** from the fan inlet-radiated noise and jet noise (see Fig. 7).

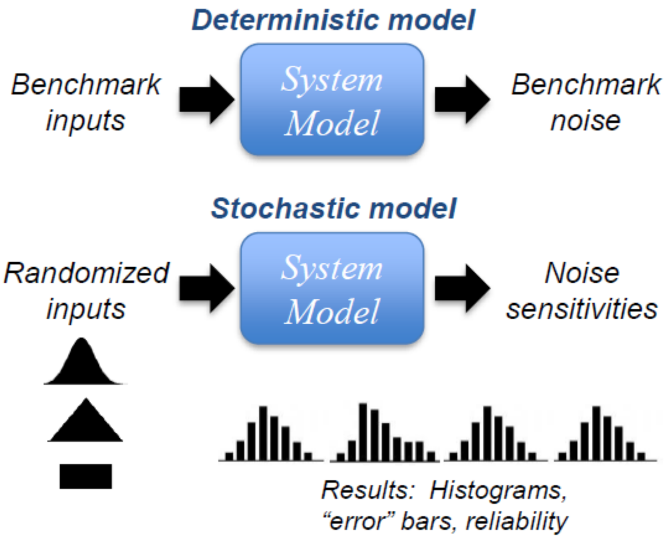


Fig. 7 Deterministic vs stochastic modeling methodology.

The output of the SUA is described as a mean EPNL value with a corresponding standard deviation. The SUA of the 737-800 model resulted in a mean value of 276.1 EPNdB with a standard deviation of 1.5 EPNdB. The initial SUA of the STCA model resulted in a mean value of 279.7 EPNdB with a standard deviation of 7.8 EPNdB, which is 6.3 EPNdB greater than the standard deviation of the conventional subsonic aircraft. The primary goal of the technical challenge was to reduce this standard deviation value for the STCA by 5 EPNdB to bring the uncertainty associated with modeling supersonic jet noise and fan inlet noise closer to the subsonic uncertainty value. Further details describing the initial SUAs for both models, including the input distributions, used can be found in [17].

III. Enhanced Source Noise Models for Supersonic Aircraft Designs

The effort to reduce the uncertainty associated with airport noise predictions of supersonic aircraft began by addressing the differences between conventional subsonic aircraft engines and engines being considered for supersonic applications. Two primary differences when considering the jet noise and inlet-radiated fan noise are in the configuration of the engine system. First, supersonic engines being investigated usually contain a mixed-flow nozzle with variable nozzle area devices, such as a plug, which is different from the modern conventional design of high bypass ratio engines which have a dual stream jet. Second, the fan of supersonic engines needs to produce high pressure ratios, which means these engines will most likely need multi-stage fans to meet performance requirements. The current modules in ANOPP for both jet and fan source noise predictions are based on historical empirical models that may not capture the nuances of these supersonic engine features sufficiently, thus leading to a high level of modeling epistemic uncertainty. Epistemic uncertainty is defined as uncertainty due to lack of knowledge in a system. This can be further classified into two kinds of epistemic uncertainty for this problem – uncertainty due to the source models themselves and underlying equations, and uncertainty due to lack of certainty of the inputs to the models. This effort was focused on reducing the uncertainty due to source models themselves, and does not address the potential uncertainty found in all conceptual design tools: how uncertain are the inputs? The following sub-sections discuss the creation of two new source noise modeling capabilities developed for this effort targeting jet and inlet-radiated fan noise, and their associated uncertainty.

A. Jet Noise

The primary need for a new empirical model for jet noise was that publicly available models did not capture noise sources related to internal lobed mixers. They also did not capture the impact of an external plug. Prior to the beginning of the PUR technical challenge a test program was created and partially executed that produced data for a single lobed mixer with variations in the external plug, the length of the nozzle, and whether the plug was external or internal. This test was called Plug20 and was invaluable for validating Large Eddy Simulations (LES) and to show that the most important attribute acoustically wasn't the external plug, but the lobed mixer.

Although the LES tool to be used in the Tech Challenge was validated for single stream nozzles over a wide range of hot and cold flows, with and without flight, it did not reproduce the noise data from the Plug20 test. More specifically, it did not have the internal noise source that was characteristic of the Plug20 and other tests with internally mixed exhaust systems. In the absence of noise data from LES, it was required to turn to historical data of internal lobed mixers. While these geometries did not have an external plug, they did have several variations on mixer geometry and some variation on nozzle length.

The historical data sets used came from jet noise tests conducted in collaboration with Allison Engines and then Rolls Royce Liberty Works in 1995 through 2006. The geometries of the tested nozzles are not generally publicly available, being a mix of proprietary and NASA owned geometries, but the acoustic data belongs to NASA. Much of the work had been presented by Rolls Royce authors in open publications [18], [19], [20], [21], [22], [23], where they carefully did not disclose all necessary information to reverse engineer the data. The mixers tested included variations in lobe count, lobe height, sidewall cutback, and two with alternate lobe tips clipped. The nozzles varied in length, relative to the mixer exit, from 0.5D to 1.25D, where D is the nozzle exit diameter. A total of 10 mixers and 3 nozzle lengths were included in the modeling effort.

Since the historical data sets seemed to capture the internal noise sources shown to be critical in the supersonic-relevant Plug20 test, it was decided to use them to create an acoustic model for internally mixed nozzle systems while the shortcomings of the LES tools were addressed. The derived empirical models were then applied to the Tech Challenge database, assuming that the internal mixer source was the main source of deviance found in the baseline uncertainty assessment.

1. Improved noise prediction method for single-stream jets

The current single-stream jet-noise models do not adequately predict single-stream scale-model data. These models are used in system-level studies, and the result is an unnecessarily large uncertainty for the jet-noise predictions. As a first step to improved jet-noise predictions, new empirical models [24] were developed from data acquired from the NASA Aero-Acoustic Propulsion Laboratory (AAPL). The models predict noise from single-stream jets at $1.5 \le \mathrm{NTR} \le 3.0$, $1.4 \le \mathrm{NPR} \le 1.8$, and $0.0 \le M_{fj} \le 3.0$, where M_{fj} is the flight-stream Mach number, and NTR and NPR are nozzle temperature and pressure ratio respectively. The spectra at different NPR were first collapsed at the same NTR, emission angle, and flight Mach number to master spectra after appropriate scaling by a power of the relative acoustic Mach number, which was computed from the difference in the jet and flight stream velocities and the ambient speed of sound. Peak shape functions were fit to the master spectra and the parameters for the functions were determined for static jets. Slight adjustments to some of the parameters were found to fit the master spectra for the jets with flight streams. The master spectra and the peak shape functions for an emission angle of 140° is shown in Fig. 8. More details can be found in ref. [24].

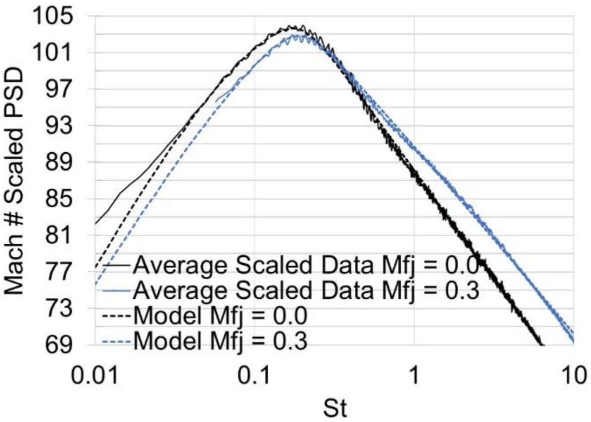


Fig. 8 The master spectra and empirical models for NTR = 2.5 and the indicated flight Mach numbers.

2. Improved noise prediction method for internally mixed exhaust systems

The modeling of the jet noise from internally mixed exhaust systems was based on historical concepts [25], but quantified using more modern methods and better prediction tools. Historically, the noise from internally mixed nozzles was divided into noise produced inside and outside the nozzle. The outside noise sources were thought to be the same as a single-stream, fully mixed jet, with some changes due to high-speed streaks where the internal mixing had been incomplete. The internal noise source was more of a mystery, often considered to be the noise of the internal shear layer but somehow amplified.

In the modeling approach used for PUR technical challenge, the first step was in validating an empirical noise code for hot single-stream jets in flight and seeing how much the noise of the internally mixed two-stream jet deviated from this. The code sjet, created by Khavaran and Bridges in 2005 [26], was found to give good agreement with the single-stream cases in the PUR uncertainty assessment dataset. When the historical dataset was compared to predictions of sjet, the deviation was found to correlate with mixer parameter of lobe height and with the velocity ratio of the two-stream flow. Creating a model for this correlation and adding it to the sjet prediction produced the empirical model sJetMod22, with a significant improvement in the ability to predict the PUR technical challenge uncertainty dataset.

The second step was to create a model for the internal noise. As described in [27], once the external jet noise source was clearly identified, the remaining noise was found to match several criteria that corroborated its internal origins. The source mechanism was not clear at first, and the next version, sJetMod23, made a very broad attempt at modeling this noise without good physical basis. The result was a strong improvement in ability to predict the TC uncertainty dataset, but did not seem applicable beyond the parameters of the historical database.

The third and final version of the empirical model, sJetMod24, resulted from insights gained from the ongoing LES runs, design efforts to create the next generation supersonic nozzle, and acoustic modal analysis of the nozzle system. Under the hypothesis that the internal noise was primarily caused by unsteady separation of the flow in the lobed mixers, triggered and organized by acoustic resonance in the nozzle, a more detailed, physics-based model was created for this noise source. The new model not only fit the range of parameters in the historical dataset, but also the Plug20 dataset representing exhaust systems for supersonic aircraft. The final improvement came from including a broadband shock noise model for exhaust flows with a pressure ratio above 1.9. While such high velocity jets are not likely to be able to meet noise requirements, they are included in the TC uncertainty analysis and need to be properly predicted when systems engineers push the engine performance boundaries. A full description of the model, including analytical expressions needed to encode it, are given in [28].

B. Jet Noise Uncertainty

Engine exhaust flow conditions of near term civil supersonic aircraft will likely follow conventional throttle conditions in their pressure and temperature relationships, but with nozzle pressure ratios possibly exceeding 2.0. For nozzle geometry, they might have internal plugs with flaps and seals to vary the nozzle areas for supersonic flight or they might have a translating external plug to make the area adjustments. They would most likely use an internal mixer and a common flow duct. The data set being used in the uncertainty assessment should cover this range of conditions and geometries. For external plug nozzles, the only noise data available was from the Plug20 test [29]. This test had an internal lobed mixer and included variations in plug and nozzle length. Thirty-two points covering throttle lines with 1.5 < NPR < 2.3 were included in the assessment exercises. For internal plug nozzles, the Plug20 test included just one internal plug configuration, but these 8 points were augmented by 45 data points from a test of a single stream nozzle which covered a range of flows and flight speeds representative of near-term supersonic aircraft. The combined range of flow conditions is shown in Fig. 9. An evolution of the improvement in jet source noise uncertainty over the course of the PUR technical challenge is shown in Table 3.

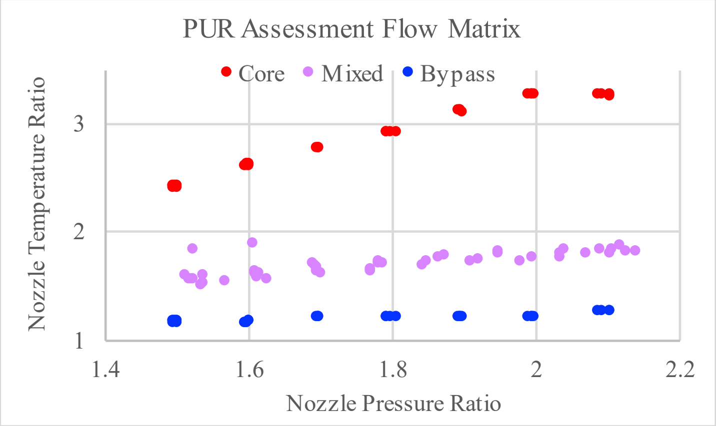


Fig. 9 Matrix of flow conditions contained in jet noise assessment database.

Table 3 Evolution of jet noise uncertainty metrics over technical challenge.

	SGLJET		sJetMod22		sJetMod23 (18Oct23)		sJetMod24 (09Apr24)	
Variable	Offset [dB]	Std. Dev. [dB]	Offset [dB]	Std. Dev. [dB]	Offset [dB]	Std. Dev. [dB]	Offset [dB]	Std. Dev. [dB]
Jet noise adjustment (lateral)	-1.68	3.85	1.50	1.13	-1.01	1	-0.67	0.75
Jet noise adjustment (flyover)	-1.47	2.92	1.17	1.13	-0.29	0.73	-0.23	0.34
Jet noise adjustment (approach)	-1.61	1.74	1.29	1.05	-0.45	0.78	-0.36	0.45

C. Inlet-Radiated Fan Noise

NASA's ANOPP software contains four empirical fan noise models based on the framework provided by Heidmann [31]. The models predict five sources: Inlet blade-passing and multiple pure tones, inlet broadband noise, aft blade-passing tones, and aft broadband noise. For the benchmark STCA assessment, the fan inlet noise was modeled following the recommendation of [32]. The inlet broadband noise was modeled using the GE Large Fan Model while the inlet tone noise was modeled using the AlliedSignal Small Fan Model [32]. All four Heidmann fan (HDNFAN) empirical models were developed for subsonic single-stage fans of various sizes, but none were based on data relevant to high-speed two-stage fans, which may be used by commercial supersonic aircraft being developed by industry.

In an effort to capture the noise from these two-stage fans, a fifth Heidmann fan empirical model was developed and is referred to as the HDNFAN-2S model. This model was developed using the same empirical model format as the other four Heidmann fan models but was creating using the high-speed two-stage fan experimental data from the 2002 Quiet Supersonic Platform (QSP) test [31],[33]. The resulting HDNFAN-2S model resulted in an improved error offset ('E' in Fig. 10) and standard deviation of the error ('S' in Fig. 10) when compared to the other Heidmann models. In Fig. 10, the error offset magnitude (left) and standard deviation of the error (right) are shown for HDNFAN methods 1-4 and the newly developed HDNFAN-2S method, labeled in green as "Method 5".

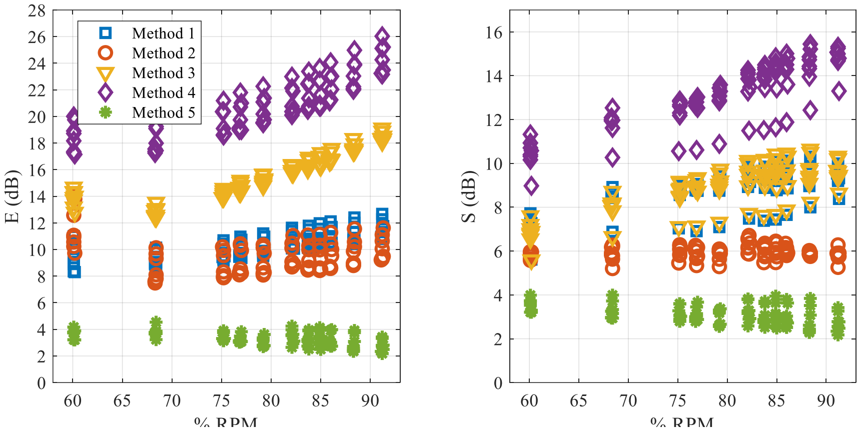


Fig. 10 Comparison of error and standard deviation of HDNFAN-2S, method 5, to original HDNFAN methods in predicting QSP dataset.

After utilizing the HDNFAN-2S model to predict the QSP experimental data points, it was observed that multiple data points were overpredicted. This was due to the variations in the QSP fan configurations tested; multiple configurations contained IGV/R1 spacer acoustic treatment and had a larger spacing between the rotor stages as shown in Table 4. A cross section of the QSP fan configurations for the "Baseline" configuration and the "Low Noise" configuration can be seen in Fig. 11, with the acoustic treatment highlighted in the yellow box.

Table 4 QSP experimental fan configurations.

Config. #	IGV Count	IGV/R1 Spacing	IGV/R1 Spacer Treatment	R1/S1 Spacing	S1 Angle (deg.)	Acoustic Barrier Wall
1A	23	Nom.	N/A	Nom.	4.1	Orig.
2	23	Open	Hard Wall	Nom.	4.1	Orig.
3	23	Open	Treated	Nom.	4.1	Orig.
4	19	Open	Treated	Nom.	4.1	Orig.
5	19	Open	Hard Wall	Nom.	4.1	Orig.
9A	19	Open	Treated	Open	4.1	Extended
9S	19	Open	Treated	Open	- 3.0	Extended
11W	23	Nom.	N/A	Open	4.1	Extended

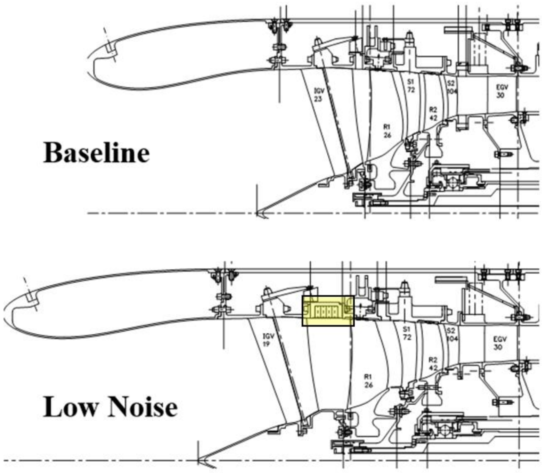


Fig. 11 Cross sections of QSP fan baseline and low noise configurations.

It was therefore determined that the new HDNFAN-2S model needed to incorporate the effects of acoustic treatment and rotor-stator spacing. To accomplish the former, a study was conducted to compare the application of the acoustic treatment models in ANOPP to the HDNFAN-2S model. ANOPP has two methods for predicting the acoustic attenuation of liners on fan noise: the Magliozzi method [34], and the GE method [12]. Both methods were coded into the HDNFAN-2S MATLAB model and the impact of the IGV/R1 spacer treatment was calculated and applied to the appropriate QSP configurations. A comparison of the impact on standard deviation of the fan inlet noise showed that the Magliozzi method increased the standard deviation by 0.4 EPNdB and the GE method reduced the standard deviation by 0.3 EPNdB. The GE method was adopted into the HDNFAN-2S model and was carried forward in the system assessments as the preferred treatment method.

A secondary study was performed to validate the correct implementation of the acoustic treatment model in the HDNFAN-2S. This was done by comparing the impact of various liner lengths and positioning (in the forward inlet of the IGV vs in-between the IGV / R1 rotor) based on calculations from the GE method (modeled in HDNFAN-2S) and Actran, as detailed in a companion paper by D. Stephens [35]. The comparison was done for the SuperFan inlet / fan model used in that study. The TREAT GE model seemed to underpredict the attenuation at approach condition, perform similarly at the flyover condition, and overpredict at the lateral (sideline) condition when compared to the Actran results. The decision was made to continue using the GE TREAT model in HDNFAN-2S model without any alterations based on the Actran results, since it captures the trend with liner length adequately and would be a more conservative approach to handling the impact of acoustic treatment.

The other crucial two-stage fan variation investigated that needed to be captured in the empirical fan model was the impact of the IGV/R1 spacing. To save weight in the engine system for supersonic aircraft, fan designers might be tempted to minimize the space between the IGV and R1 rotor. However, this could potentially cause an acoustic problem to arise as the strength of the fan harmonic tones generally increases as the spacing between the IGV/R1 is reduced. The QSP data set contained two different IGV/R1 spacings (see Fig. 11) and the HDNFAN-2S model was lacking a method to capture the acoustic impacts of the different spacings. Therefore, the goal was to provide a high-level impact of reducing spacing and capture an appropriate noise penalty for having tight IGV/R1 spacing in a two-stage fan.

As discussed in [35], the SuperFan geometry in that study was modified to capture the acoustic change caused by varying the IGV/R1 spacing using FINE/Turbo simulations. It should be noted that there were some combinations of spacing and power condition that exhibited unexpected trends, most likely due to non-optimal phasing of the wakes off the IGV into R1. These points were excluded from the empirical model since the goal of this effort was to capture high-level trends appropriate for usage during the conceptual design phase. Investigating these unusual points could be part of future work to enhance the current model further.

The empirical IGV/R1 model developed for HDNFAN-2S consists of nine different curves based on logarithmic functions of the form $\Delta PWL = A \times \ln(s^*) - B$, where s* is the normalized IGV/R1 spacing, and A and B are coefficients determined empirically from the simulation data. A separate equation was created for each power setting and harmonic value, and all nine are shown in Fig. 12. The approach condition (A) curves are shown in orange, the

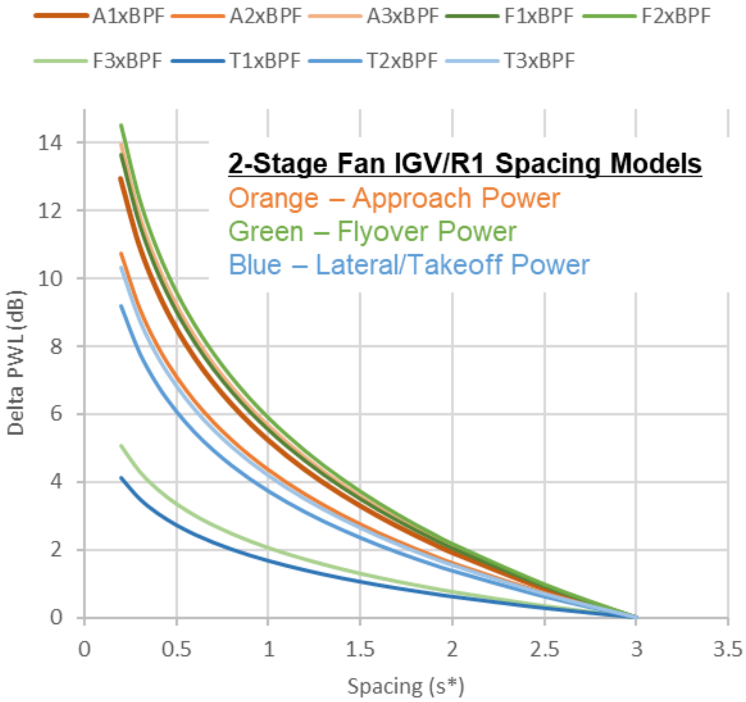


Fig. 12 **Two-stage fan IGV/R1 spacing models implemented into HDNFAN-2S.**

flyover condition (F) curves are shown in green, and the lateral/takeoff condition (T) curves are shown in blue. The delta in sound power level (PWL) is then applied to the appropriate tone harmonic sound power levels at the source prior to propagation of the fan noise. The appropriate range of IGV/R1 spacing values for use with these models is s*=0.2 to s*=3.0 and should not be used outside of this range. These empirical models were implemented into the HDNFAN-2S code and used for the final system uncertainty assessments.

Crucially, the fan noise simulations of various inlet design details, described in [35], showed that these details had effects on tone strength generally less than 2dB. This allowed such design features of supersonic fans to be ignored in the empirical modeling, since the impact was less than the current model uncertainty and thus simplifying the use of the models.

D. Inlet Radiated Fan Noise Uncertainty

The fan-noise component uncertainty of the system uncertainty assessment was determined through comparing the predictions of the two-stage fan empirical model (HDNFAN-2S) against available experimental datasets. Two datasets were utilized, the Quiet Supersonic Platform (QSP) dataset and the GE High-Speed Fan (GE HSF) dataset. The QSP data is from a two-stage fan tested with inlet guide vanes and was designed by Pratt & Whitney and tested in the GRC 9x15 LSWT in 2003. The GE HSF data is from experiments of a series of three single-stage fans and three stator sets designed and built by General Electric Aircraft Engines (GEAE) and tested as part of the NASA Advanced Subsonic Technology (AST) program in 1999. More details on these datasets and how they were used for the technical challenge can be found in [17] and [31]. The HDNFAN-2S model was used as the prediction tool for the QSP data (two-stage fan) and the original HDNFAN methods within ANOPP were used as the prediction tool for the GE HSF data (single-stage fan). The total inlet fan-source uncertainty was calculated by combining the results of both into a single standard deviation and offset value. A combined result from the GE HSF and QSP fan model was determined to be a reasonable method for an overall prediction uncertainty, since perhaps either a single or two-stage fan might be chosen as the final design for an efficient and quiet supersonic aircraft engine. The single stage fan is appropriate for lower supersonic Mach number applications, generally less than Mach 1.5.

For the initial STCA benchmark system uncertainty assessment, the inlet fan-noise source uncertainty was calculated based on using the internal ANOPP HDNFAN methods for both the single-stage and two-stage fan predictions prior to the development of the HDNFAN-2S model. These predictions were compared to the experimental values and the standard deviation and offset metrics were calculated for both broadband fan noise and tonal fan noise. Furthermore, the uncertainty metrics were separated based on flight condition (approach, flyover, lateral) to retain as much detail in the uncertainty as possible. The difference between predicted EPNL and experimental EPNL (dEPNL = predicted – experimental) is shown in Fig. 13 for the various flight conditions and fan-noise components.

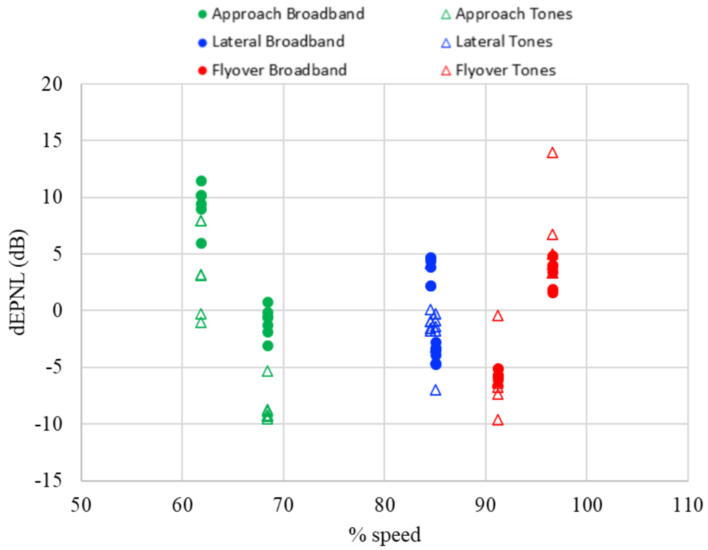


Fig. 13 Comparison of broadband (circle) and tone (triangle) dEPNL between model and test data for inlet fan-noise; initial benchmark uncertainty assessment.

Throughout the technical challenge, two interim updates (in October 2022 and October 2023) and a final update (in April 2024) of the SUA were performed and incorporated updated inlet fan-source noise uncertainty metrics based on the empirical modeling improvements in the previous sections. The evolution of the inlet fan source noise uncertainty metrics can be seen in Table 5.

Table 5 Evolution of inlet-radiated fan noise uncertainty metrics over technical challenge.

Variable	SUA Benchmark: May21		SUA Update I: Oct22		SUA Update II: Oct23		SUA Final Update: Apr24	
	Std.Dev.	Offset	Std.Dev.	Offset	Std.Dev.	Offset	Std.Dev.	Offset
Fan inlet tone (lateral)	7.13	0.49	6.82	0.00	6.19	0.49	4.36	2.67
Fan inlet tone (flyover)	2.55	1.52	3.41	2.06	3.42	2.57	2.72	0.33
Fan inlet tone (approach)	9.46	0.30	5.21	-4.38	5.54	-3.97	1.91	-1.14
Fan inlet BB (lateral)	4.71	1.48	2.03	-1.42	2.52	-0.96	2.06	-0.46
Fan inlet BB (flyover)	3.96	0.28	1.66	-2.28	2.13	-1.83	1.68	-1.26
Fan inlet BB (approach)	3.50	-1.11	2.76	-2.64	2.99	-2.20	2.62	-1.14

The first SUA update in October 2022 included the newly developed HDNFAN-2S empirical model for predicting the two-stage fan noise. The second SUA update in October 2023 included improvements to the HDNFAN-2S model by including the impact of acoustic treatment based on the GE TREAT method found in ANOPP. The final SUA assessment in April 2024 included the IGV/R1 spacing model in the HDNFAN-2S model and updated predictions for the single-stage GE HSF data that included the impact of swept rotors and swept / leaned stators. Updates for the single-stage predictions was done to reduce the total fan noise uncertainty metrics by implementing the effects of rotor / stator sweep and lean as discussed in [36]. It was found that the internal ANOPP HDNFAN methods do not account for rotor / stator sweep and lean and the GE HSF acoustic tests were done for various sweep and lean configurations. To capture the acoustic changes from the various configurations tested, a series of sweep and lean deltas, taken from

[15], were applied to the fan source spectra. This process helped align the single-stage fan predictions to the GE HSF experimental data. It is noted that this is a potential knowledge gap in predicting fan noise (for both subsonic and supersonic fans) at the conceptual level and could be investigated further in the future. The final SUA dEPNL values for the inlet fan noise source are shown in Fig. 14. Comparing to Fig. 13, a substantial improvement in predicting inlet fan noise was achieved over the course of the technical challenge. The new empirical models to predict inlet fan noise show great promise in capturing the noise from fans designed for supersonic applications.

IV. Updated Assessment of STCA Aircraft Noise and Uncertainty

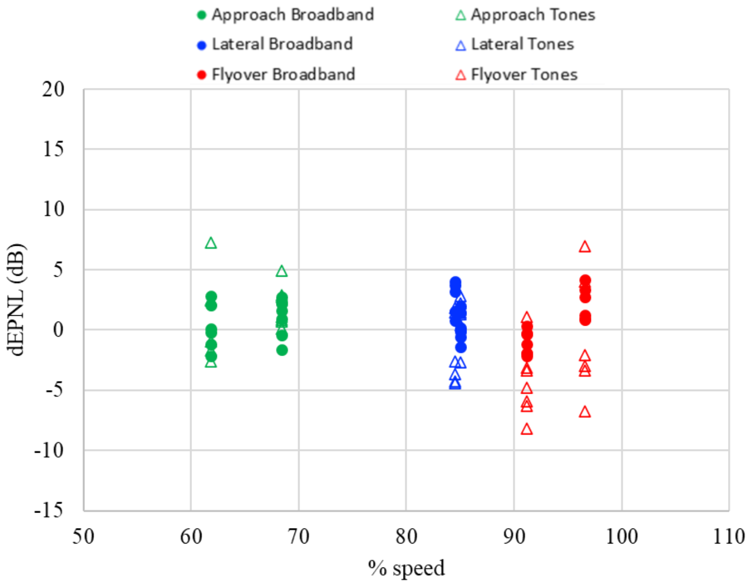


Fig. 14 Comparison of broadband (circle) and tone (triangle) dEPNL between model and test data for inlet fan-noise; final uncertainty assessment.

A PUR progress indicator for the STCA system uncertainty assessments was tracked throughout the course of the technical challenge to monitor the progress in reducing the STCA aircraft system-level uncertainty. The metric used in tracking the total aircraft noise uncertainty was the standard deviation of the LTO cumulative EPNL. The cumulative EPNL is a summation of the EPNL at the three observer locations for aircraft noise certification, approach, flyover, and lateral. The initial benchmark uncertainty assessments for the conventional subsonic 737-800 model and the STCA model, preformed in May 2021, resulted in a cumulative EPNL standard deviation of 1.5 EPNdB and 7.8 EPNdB respectively. The goal of the technical challenge was to reduce the STCA EPNL standard deviation by 5EPNdB by the end of the period of performance. Intermediate updates to the SUA were performed over the course of the technical challenge and incrementally incorporated improvements to the jet and fan source noise empirical models based on the research of the investigative team.

The first SUA update occurred in October of 2022 and included significant updates to both the fan and jet empirical models. The jet noise empirical model (sJetMod) was developed to predict jet noise from internally mixed, external plug nozzles, not present in existing jet-source noise models. The initial two-stage fan empirical model, HDNFAN-2S, was developed and utilized in the first SUA update instead of the heritage ANOPP HDNFAN models. The major changes in the empirical predictions of jet and fan noise resulted in a large reduction in aircraft system-level uncertainty, reducing the 7.8 EPNdB standard deviation to 3.4 EPNdB (a 4.4 EPNdB reduction from the benchmark value). The second SUA update occurred in October of 2023 and included substantial improvements to the jet and fan empirical models. The jet empirical model updates included updates based on the information gained from the LES analyses of the plug nozzle experimental designs, focused primarily on changes to plug-dependence in the sJetMod model. The fan empirical model updates included the addition of an acoustic treatment model, based on the ANOPP GE TREAT method, to capture the impact of liner attenuation on the two-stage fan noise source. These incremental improvements to the empirical models resulted in a SUA standard deviation value of 2.9 EPNdB (a 4.9 EPNdB reduction from the benchmark value).

The final SUA occurred in April of 2024 and is the cumulation of all the improvements made to the jet and fan empirical models over the course of the technical challenges. Improvements to empirical jet noise model from SUA update 2 included a two-component model based on new understandings of noise source mechanisms, guided by jet LES analyses that captured more details of the internal mixer impact on jet noise. The jet model also included a new spectral model of internal noise sources coupling with nozzle duct modes for internal mixers and plug geometries. Improvements to the empirical fan noise model from SUA update 2 included the inclusion of a IGV / R1 spacing model based on the SuperFan simulations. The final SUA resulted in a final EPNL standard deviation value of 2.0 EPNdB (a 5.8 EPNdB reduction from the benchmark value). This exceeded the PUR technical challenge goal by 0.8 EPNdB. The final SUA Monte Carlo analysis used to generate the standard deviation metric consisted of 10,000 cases, and the convergence of the statistical metrics is shown in Fig. 15. The resulting probability distribution function of the STCA Cumulative EPNL is shown in Fig. 16. A tracking of the PUR progress indicator relative to the goal over the course of the technical challenge is shown in Fig. 17.

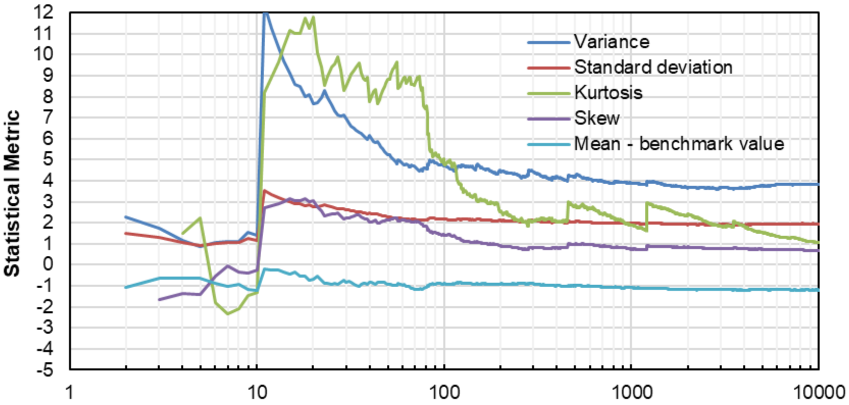


Fig. 15 Final STCA SUA Monte Carlo statistical metrics.

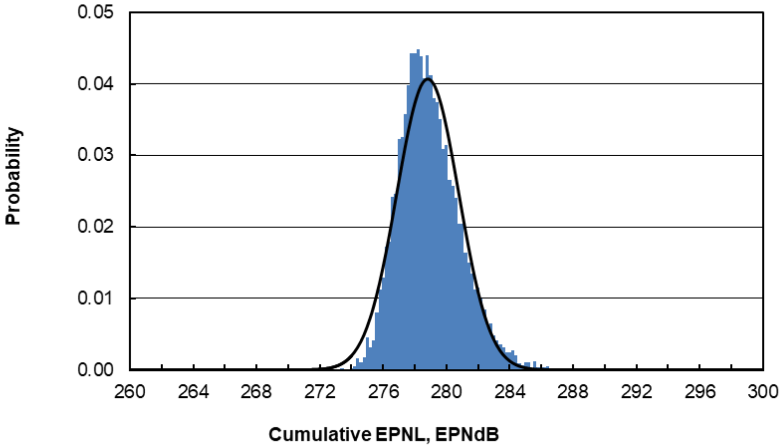


Fig. 16 Final STCA SUA probability distribution function resulting from the Monte Carlo Analysis.

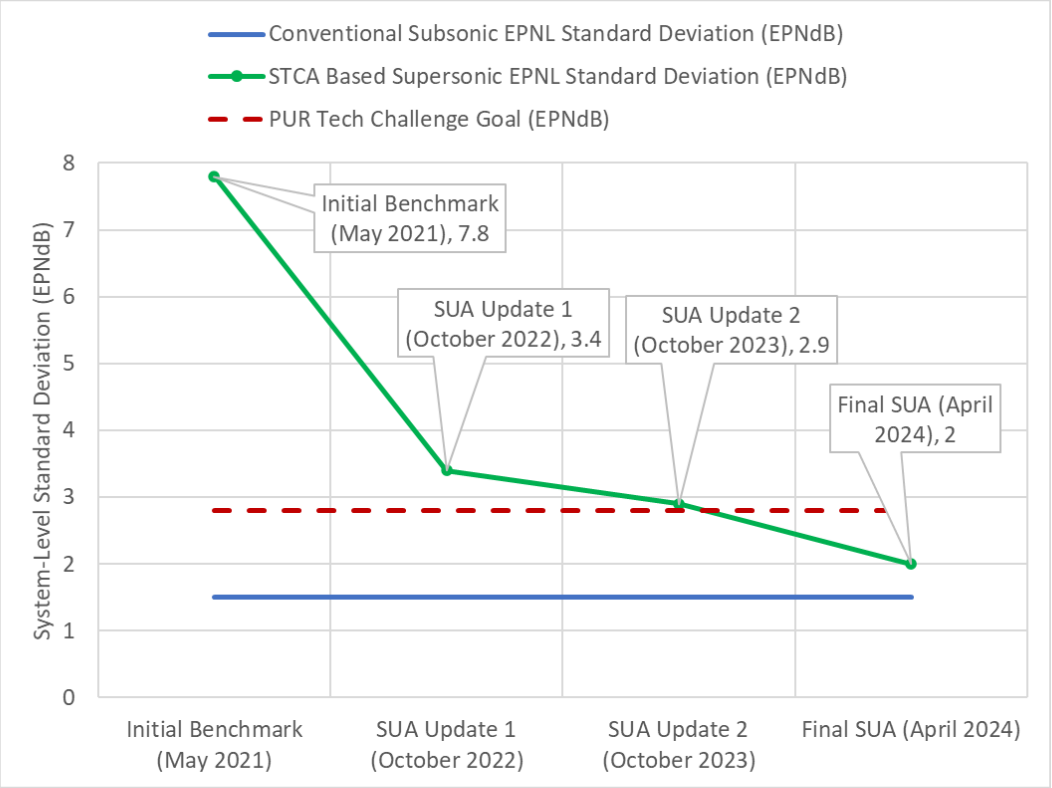


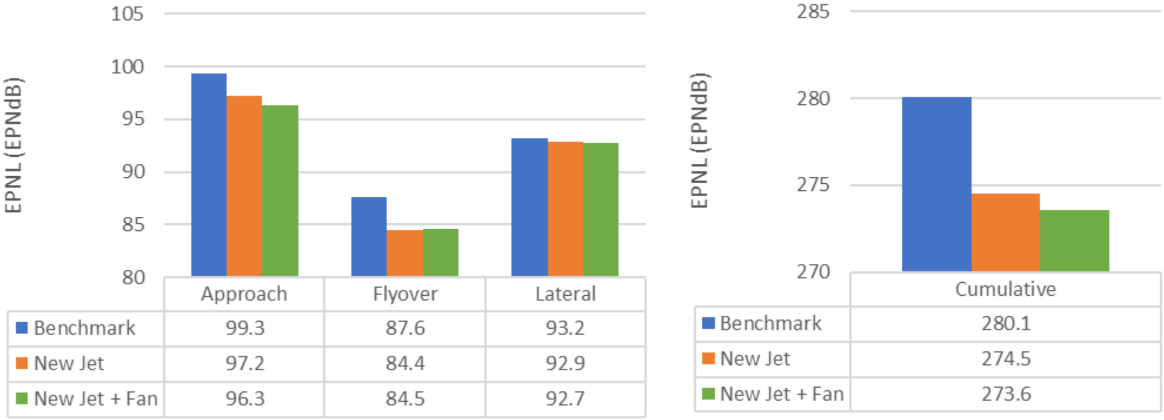
Fig. 17 Evolution of the PUR progress indicator relative to the technical challenge goal.

The final effort of this study was to re-benchmark the 55t STCA model utilizing the newly developed supersonic jet and inlet-radiated fan source noise models to produce new airport noise level predictions. This was accomplished through incorporating the new source models in the ANOPP system-level model. Since the initial STCA engine model had a single-stage fan design, a new two-stage engine model was developed to use the new inlet-radiated fan noise source model. The new two-stage variant of the engine was altered to include a second fan stage and the subsequent geometry and operational changes while maintaining the same thermodynamic cycle and thrust capabilities at LTO conditions. This method of updating the engine was done to isolate the potential acoustic impact of moving from a single-stage configuration to a two-stage configuration, but in practice the engine would need to be re-designed to account for all stages of flight and other system level design considerations. A cross-section of the two-stage engine variant is shown in Fig. 18.

Fig. 18 Cross-section of two-stage engine variant for the STCA model.

The updated STCA model was then run through system-level noise analyses using ANOPP and the new jet and fan source models. This was performed using a two-step process of incorporating the new jet source noise model alone first, to isolate the impact of the jet source noise improvements on the overall EPNLs. This was followed by adding on the new inlet-radiated fan noise model to achieve the combined improvements on the overall uncertainties. The results of the three observer EPNLs for the under-wing STCA variant with the two-stage engine is shown in Fig. 19

a). The new jet noise model (sJetMod24) significantly reduced the predicted noise levels at approach (-2.1 EPNdB) and flyover (-3.2 EPNdB), while only slightly reducing the predicted noise level at the lateral condition (-0.3 EPNdB). This implies that at higher engine power conditions, the previous heritage ANOPP modules were aligned more with the test data used to develop the new jet noise model and were overpredicting the jet noise at lower engine power settings. The impact of the new inlet-radiated fan noise source model resulted in a reduction of the observer noise levels at the approach (-0.9 EPNdB) and lateral (-0.2 EPNdB) locations while producing an increase in the noise level at the flyover condition (+0.1 EPNdB). The impact of the new source models on the cumulative EPNL levels are shown in Fig. 19 b). The inclusion of the new source noise models developed under the PUR technical challenge reduced the nominal cumulative EPNL prediction of the STCA from 280.1 EPNL with a standard deviation of 7.8 EPNdB, down to a value of 273.6 EPNdB with a standard deviation of 2.0 EPNdB. A reduction of 6.5 EPNdB in the nominal prediction value and a reduction of 5.8 EPNdB in the uncertainty associated with that nominal value was achieved.

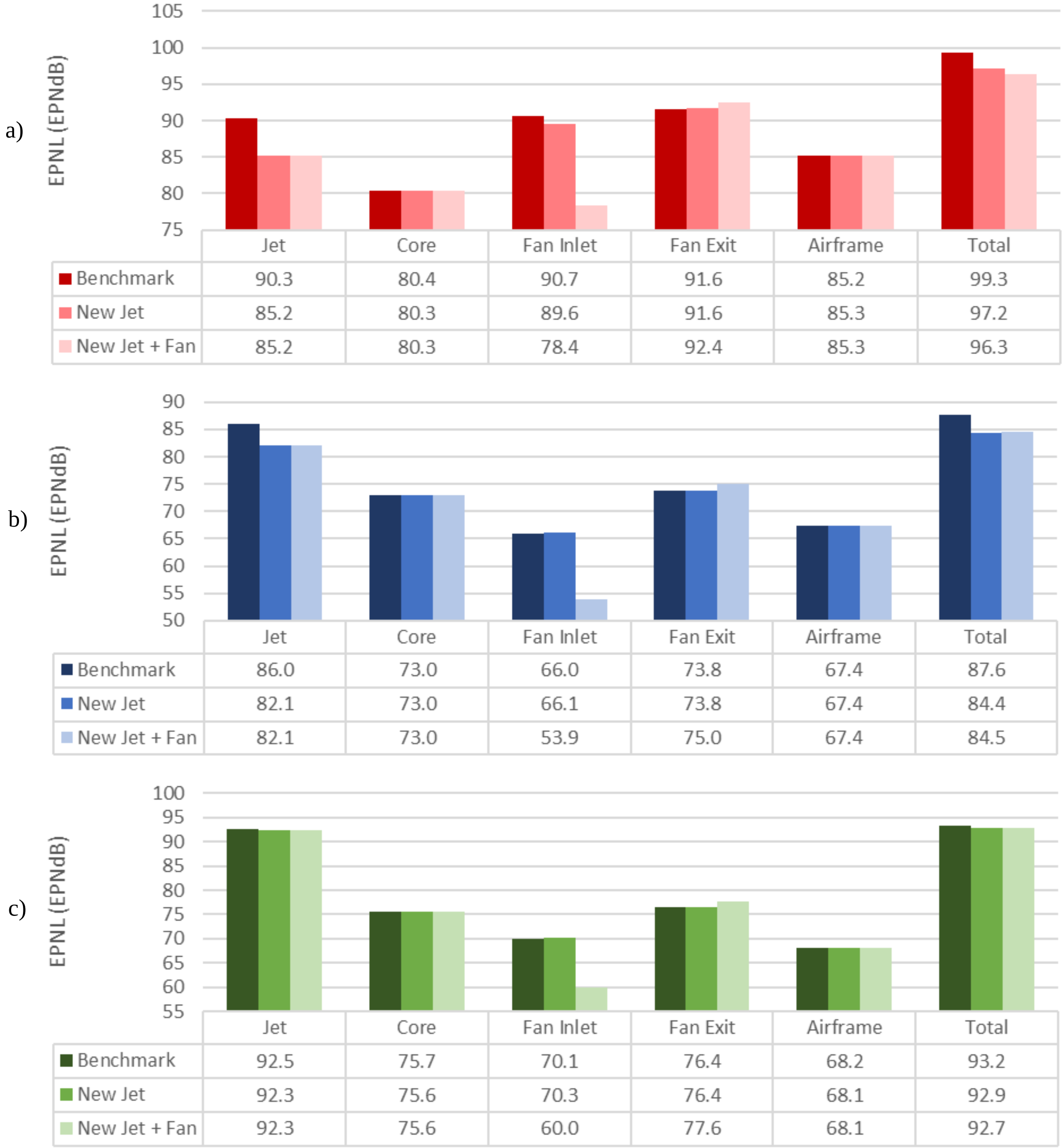


a) b)

Fig. 19 STCA noise prediction source model comparison at a) individual observers and b) cumulative levels.

To further investigate these trends a source noise breakdown was created to identify the contribution of each noise source on the total EPNL at each observer location. The source noise breakdowns can be seen in Fig. 20 for a) Approach, b) Flyover, and c) Lateral. The increase in noise at flyover due to the two-stage fan can be attributed to an increase in the aft-radiated fan noise. The inclusion of the new two-stage fan engine caused the aft fan noise levels to increase since the ANOPP internal HDNFAN methods were continued to be utilized in predicting that source. The higher rotational speed of the two-stage fan and the decrease in rotor-stator spacing relative to the single-stage engine resulted in ANOPP predicting an increase in aft fan noise. This resulted in a net increase in the total EPNL at flyover due to the inclusion of the two-stage fan engine, even though the inlet-radiated fan noise decreased significantly. The nuance in the relative strength of individual noise sources can be deceptive when looking at only the total noise levels and is why investigating a noise source breakdown is crucial in understanding the noise characteristic of a system-level analysis.

The results presented in this study reflect the 55t STCA configuration with under-wing mounted engines. This was done to identify and quantify the improvements achieved in inlet-radiated fan noise achieved over the course of the PUR technical challenge. The original 55t STCA variant with over-wing mounted engines was also assessed with the new jet and inlet-radiated fan source noise models and saw a smaller reduction in the overall cumulative EPNL values of only 4.3 EPNdB, relative to the 6.5 EPNdB seen by the under-wing variant. This is a result of the fan inlet noise being shielded by the wing surface and reducing the relative contribution of inlet-radiated fan noise to the overall noise levels.



	Jet	Core	Fan Inlet	Fan Exit	Airframe	Total
Benchmark	90.3	80.4	90.7	91.6	85.2	99.3
New Jet	85.2	80.3	89.6	91.6	85.3	97.2
New Jet + Fan	85.2	80.3	78.4	92.4	85.3	96.3

	Jet	Core	Fan Inlet	Fan Exit	Airframe	Total
Benchmark	86.0	73.0	66.0	73.8	67.4	87.6
New Jet	82.1	73.0	66.1	73.8	67.4	84.4
New Jet + Fan	82.1	73.0	53.9	75.0	67.4	84.5

	Jet	Core	Fan Inlet	Fan Exit	Airframe	Total
Benchmark	92.5	75.7	70.1	76.4	68.2	93.2
New Jet	92.3	75.6	70.3	76.4	68.1	92.9
New Jet + Fan	92.3	75.6	60.0	77.6	68.1	92.7

Fig. 20 STCA noise prediction model comparisons - source noise breakdowns for a) Approach, b) Flyover, and c) Lateral.

V. Conclusions and Future Work

An effort to reduce the uncertainty associated with the airport certification noise levels for commercial supersonic aircraft was presented in this paper. The work aimed to reduce the uncertainty associated with predicting both the jet source noise and inlet-radiated fan source noise for supersonic-relevant engine configurations and assess how reducing the uncertainty at the source level impacts the system-level uncertainty. New source noise models were developed for an engine system containing an internally mixed exhaust system with an external plug and a two-stage fan. These new source models for jet noise and inlet-radiated fan noise saw a significant reduction in prediction uncertainty when compared to previously obtained datasets. Utilizing the new source noise models at the STCA system-level analysis resulted in a reduction in the overall cumulative noise of 6.5 EPNdB and a reduction in uncertainty of 5.8 EPNdB relative to the benchmark analysis conducted using previous noise prediction methods.

Future work is needed to improve the uncertainty of commercial supersonic aircraft noise predictions. One area highlighted by the current work that needs additional research is the aft radiated fan noise for a two-stage fan with an internally mixed exhaust system. Presently, there are few if any publicly available studies investigating two-stage fan aft-radiated noise and the differences in the source strength relative to single-stage fans. There is also little information on how aft-radiating fan noise would propagate through an internally mixed exhaust system and interact with other noise sources present in the exhaust. Therefore, to further reduce the system-level uncertainty for the airport noise levels of supersonic aircraft, this should be a high priority for researchers to consider. Another consideration for future work expanding on the current study is to investigate different supersonic configurations other than the 55t STCA model. This model has served its purposes in assisting the FAA and ICAO perform exploratory studies, but industry, regulators and the research community would benefit from additional concepts with varying mission requirements to gain a better understanding of how changes in configuration impacts the expected noise levels of supersonic aircraft.

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