Propulsion Airframe Aeroacoustics and Aircraft System Noise Flight Research Test: NASA Overview

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Motivations and the formulation of the objectives are described for an ambitious flight research test conducted in collaboration between NASA and The Boeing Company. The Propulsion Airframe Aeroacoustics and Aircraft System Noise Flight Research Test was executed by the Boeing ecoDemonstrator Program with an Etihad Airways Boeing 787-10 aircraft. Five key technical approaches are described that were used to accomplish the more unconventional and challenging objectives of the research. In addition to the modern technology of the 787, these include evaluating multiple acoustic shielding and reflection effects using both the wing and fuselage in straight flight and banking flight paths, hardwalling the aft duct liner, and utilizing an extensive instrumentation array both on the ground and on the aircraft. The research level version of NASA's aircraft system noise prediction capability including a new acoustic scattering method were used to confirm the technical approaches and provide guidance for the detailed design of instrumentation and flight test plans. Initial comparisons are shown of flight test data to predictions using the research level of NASA's Aircraft Noise Prediction Program. Significant prediction challenges are revealed when compared to these high-quality data, while major progress is shown both in the measurement and the prediction of propulsion airframe aeroacoustic effects in flight. This comparison marks the first rigorous validation with modern flight test data and establishes a basis to further understand and quantify the state of NASA's current capability and to develop improvements in the fidelity of aircraft system noise predictions. The context of multiple coordinated companion research papers is described as well as future plans for the continued analysis of these flight research data.

I. Introduction

The NASA Aeronautics Research Mission Directorate has continually worked over several decades to improve the capabilities and the fidelity of aircraft system noise prediction through sustained NASA internal research and a wide range of partnerships. The applications range from current subsonic commercial aircraft to future advanced aircraft concepts and technologies (Refs. [1]-[10]). These capabilities have been developed through a broad spectrum of theoretical, computational, experimental, and validation efforts (Refs. [11]-[13]). Despite these extensive and long-term efforts, flight data on a relevant modern commercial transport have been lacking due to the many obstacles for an effort of this large scale and scope. However, full-scale, high-quality flight data are critical to many aspects of NASA's aircraft noise capabilities. This type of information is critical to perform the first rigorous assessment of the current state of NASA's internal research level aircraft system level tool, the Aircraft NOise Prediction Program (ANOPP-Research). ANOPP-Research is different from the released version of ANOPP in that ANOPP-Research has the newest methods under development and testing. Flight data are also essential to enable future improvements in prediction capabilities and to the development of increasingly advanced noise reduction technologies and approaches. Therefore, to address this long-standing and critical gap, NASA's Advanced Air Transport Technology (AATT) Project funded an ambitious acoustic flight research effort, the Propulsion Airframe Aeroacoustics and Aircraft System Noise (PAA & ASN) Flight Research Test.

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Many flights tests with acoustic objectives have been performed in the past, most often for the purpose of testing specific noise reduction technologies (Refs. [14], [15]). What is new about the current research is the specific focus on the total aircraft system noise, the Propulsion Airframe Aeroacoustic (PAA) integration effects, and the noise components utilizing an innovative flight test design with what is quite possibly the most extensive instrumentation assembled to date for an acoustic flight test.

The formulation of the objectives for this flight research began in late 2015 with engineers influenced greatly by the extensive experience with aircraft system noise and the integral role PAA has in the system noise results of a portfolio of advanced aircraft for the Environmentally Responsible Aviation Project of NASA. To study the PAA effects of a conventional aircraft in flight and to do so in a way that was applicable also to unconventional aircraft posed many technical challenges. Approaches were postulated and investigated over many months. A pivotal technical interchange meeting with Boeing instrumentation and acoustics specialists took place while at the AIAA/CEAS Aeroacoustics Conference in Lyon, France, confirming approaches for measuring the azimuthal directivity. Numerous technical interchanges and predictions took place over the next three years to plan the many complicated and interrelated aspects of a test that could ultimately accomplish the objectives. The technical work proceeded in parallel with project advocacy. To answer key technical and programmatic issues, a specific feasibility study task was performed in 2018. In May 2019, the collaboration with Boeing was formalized with a flight test contract award. Final test design, detailed instrumentation design, and test planning continued over more than a year in close collaboration between NASA and Boeing. This included moving the planned flight test site to the Glasgow Industrial Airport near Glasgow, Montana. This was done for several reasons, including maximizing the productivity of what would be a very limited number of available flight test days. On July 20, 2020, the partnership between Boeing and Etihad Airways was announced for the test aircraft. In August, the newly manufactured Etihad Airways 787-10 aircraft was flown from North Charleston, South Carolina, to the Boeing Flight Test Center at Boeing Field in Seattle, Washington. There the aircraft underwent more than a week of preparation for the test campaign before being flown to Glasgow, Montana. Between August 25 and September 1 of 2020, the Boeing ecoDemonstrator Program successfully executed the NASA PAA & ASN Flight Research Test. A photograph of the flight test site with the aircraft executing a banking maneuver test condition over the ground instrumentation is shown in Fig. 1.

II. Summary of Related Papers

This paper is a part of a group of papers to be presented at the 28th AIAA/CEAS Aeroacoustics Conference, and all focused on the NASA/Boeing PAA & ASN Flight Research Test. Therefore, it is important to briefly describe the focus of each.

This NASA overview paper is accompanied by a Boeing-led overview paper (Ref. [16]) that focuses on the flight test execution, the design of the extensive instrumentation package required to produce the high-quality, high-resolution data, test procedures, and some key results from the community noise microphone measurements. These two full papers provide a complete overview of the comprehensive research designed into this flight test and the following papers address in-depth analyses and methods.

The third paper focuses on the prediction of the airframe noise components using the next generation NASA airframe noise system level methods and comparison with these airframe noise data from the Boeing 787-10 (Ref. [17]). Fan acoustic flight effects are the subject of the fourth paper and include the impact of engine power condition, flight speed on fan noise, and comparisons with the prediction using ANOPP-Research methods (Ref. [18]). As part of developing new capabilities for ANOPP-Research, new shielding and scattering prediction methods have been developed. The Propulsion Airframe Aeroacoustics Shielding Attenuation (PAAShA) method for shielding prediction has been systematically validated and accepted for publication earlier this year (Ref. [19]). The more general and capable Propulsion Airframe Aeroacoustics Scattering (PAASc) method is the fifth paper presented at this conference and focuses on the theoretical development of a new system level, midfidelity method to predict PAA effects from acoustic scattering (Ref. [20]). This newly developed prediction method was crucial in the design of this test and a method that will be used in the continuing work with these data in studying the PAA effects included with this aircraft configuration and test matrix.

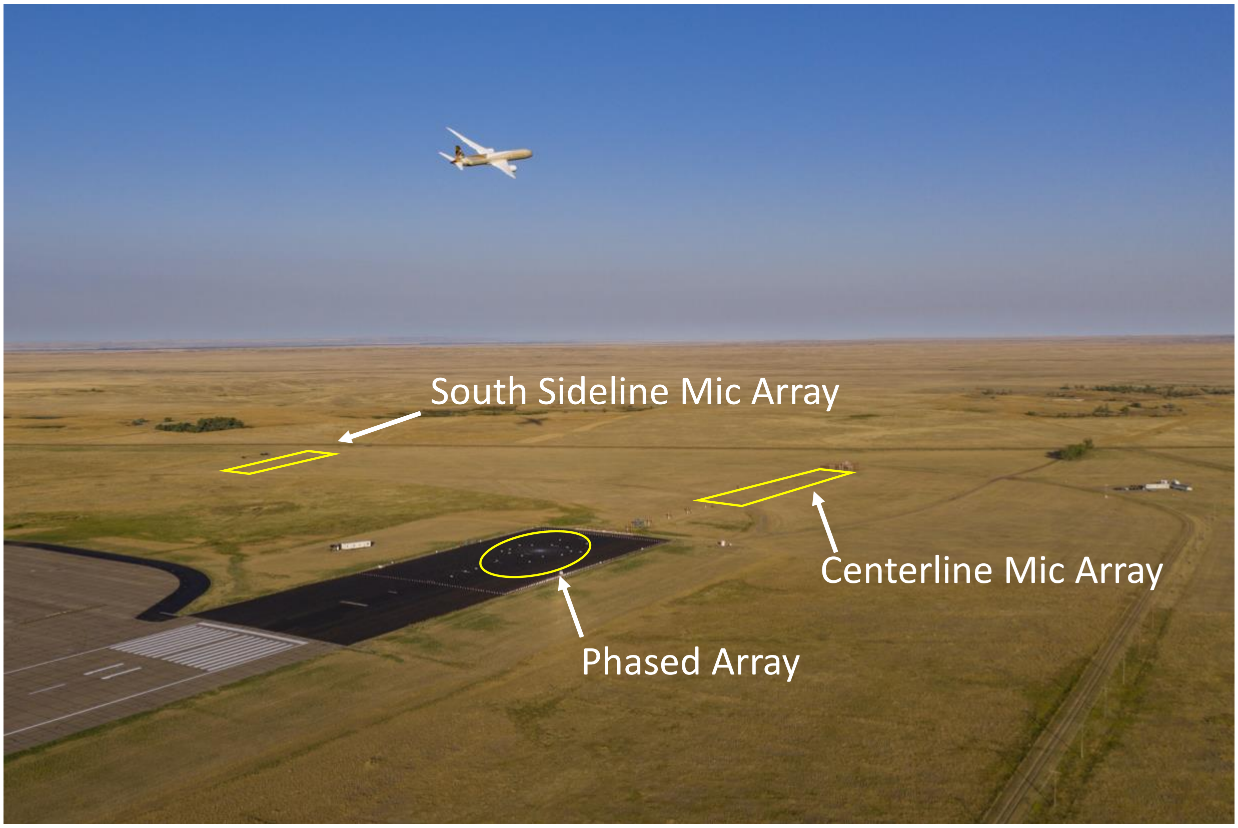


Fig. 1 Test site near Glasgow, Montana, with Etihad Airways 787-10 aircraft banking over the ground instrumentation. For reference, only the South Sideline, Centerline, and Phased Array are identified. The North Sideline microphone array is not shown. Photo Credit: The Boeing Company.

III. Motivations for this Flight Research

A. ANOPP

In 1973, a focused aircraft system noise prediction activity was established at the NASA Langley Research Center. The mission was to develop a state-of-the-art method for predicting aircraft noise for a range of aircraft types from in-service aircraft to future concept aircraft. As described by Raney et al. (Ref. [21]), the two major goals were to predict effective perceived noise level (EPNL) to within ±1.5 dB and to establish the relationships of noise to the design and operation of aircraft in order that aircraft noise constraints could be incorporated into the preliminary design process.

This effort resulted in the creation of the NASA Aircraft NOise Prediction Program (ANOPP). The theoretical foundation of the ANOPP prediction process is described in the original publication (Ref. [22]). Sustained development has continued since that time with a constantly evolving scope of the aircraft concept types and technologies to consider. One of the key needs from inception was the need for NASA to have a credible means of quantifying the expected benefit of NASA's noise reduction technology developments. This need continues to exist in NASA Aeronautics as much as it did at the inception of ANOPP. Over five decades ANOPP has been used for many purposes by hundreds of users from other government organizations, NASA contractors, industry, and academia.

One of the first major applications of ANOPP in the 1970s was to support the Supersonic Cruise Research project. For decades now, most applications have been to subsonic transport aircraft, again for in-service aircraft as well as to the study of future aircraft concepts in support of NASA's research to develop noise reduction technology and advanced low noise configurations.

Over the past five decades, all aspects of aircraft noise research, including measurement technology, computing power, understanding of acoustic physics, and aircraft design and technology, have undergone significant changes. Nevertheless, it remains a grand challenge to develop robust, accurate, physics-based prediction methods to meet the most stringent requirements of aircraft system noise and to develop efficient noise reduction technologies. This most stringent requirement is for accuracy, a total turnaround time (not including the initial setup process) on the order of a less than a day so as to be useable in design and optimization cycles, and with sufficiently resolved parameters and results so as to be useful to provide design guidance.

B. Initial ANOPP Validation Studies

Since inception, ANOPP methods have often been developed and assessed largely with scale model wind tunnel and laboratory test data. Assessments with flight test data have been more infrequent due to the challenges in obtaining all the necessary information. In the late 1970s, NASA conducted a major validation study with comparisons of predictions with flyover noise for a range of commercial aircraft. A summary of the validation effort and results were presented in Raney et al. in 1981 (Ref. [21]).

For the McDonnell-Douglas DC-9, the manufacturer provided flight test noise levels, flight path information and aircraft data. The flight tests were conducted with hardwall engine ducts (no attenuation from acoustic liners). Pratt & Whitney provided the engine data. In terms of EPNL, ANOPP underpredicted the data by 1-2 EPNdB. At angles of peak noise, ANOPP's underprediction was 3-5 dB, perceived noise level, lower than data.

For the DC-10 aircraft, McDonnell-Douglas submitted comparisons of their predictions with ANOPP to flight test data for six flyovers ranging from approach to full power takeoff. In this case, data were collected with engine duct liner treatment, which was also included in the predictions by assuming that the liner eliminated fan tones. Comparisons showed that high frequency fan noise was overpredicted and jet noise was consistently underpredicted. On an EPNL basis, ANOPP overpredicted from 0.4 to 3.1 EPNdB with an average overprediction of 1.3 EPNdB for the six flyovers considered.

For the L-1011 aircraft, the Lockheed-California Company performed the ANOPP predictions and compared with six flyover test cases ranging from 60 to 100 percent engine power settings. Even when predictions were revised to eliminate fan combination tones (buzzsaw noise), the takeoff noise was overpredicted in the forward quadrant. For low power settings without supersonic fan tip speeds, ANOPP predicted L-1011 flyover noise quite well.

The flight test by The Boeing Company used a 747-100 with Pratt & Whitney JT9D engines with hardwall ducts (Ref. [23]). The flight test conditions ranged from 75.4 to 98.8% of the rated engine speed (rpm) all with 20° flaps and landing gear retracted. The flight paths were level at heights of 400 ft over 12 ground plane microphones. Boeing performed the ANOPP predictions and comparisons with the data. Boeing summarized the PNLT results for 90% and higher engine corrected speeds as overprediction in the forward arc of about 9 dB (due to buzzsaw noise) and underprediction in the aft arc by about 9 dB (likely due to jet noise). At approach power (75.4% corrected rpm) the PNLT was underpredicted by about 9 dB for all angles between 80° and 160°.

Even with these large ANOPP under and overpredictions noted by Boeing compared to the 747-100 flyover data, on an EPNL basis, the prediction was within 1 EPNdB of the measured value at high power. As noted, this was a mere coincidence because of the offsetting of the overprediction in forward angles by underprediction in the aft angles. At approach power, ANOPP underpredicted the data by about 5 EPNdB. It is interesting to note that the Boeing test configurations were selected with gear up and minimum flap of 20° to intentionally reduce airframe noise. As a result, no conclusions were drawn on the prediction accuracy for airframe noise components.

This first comprehensive NASA validation of ANOPP in 1981 concluded that the results were encouraging although prediction methods for fan noise and jet noise must be improved. Regarding fan noise, significant issues were noted related to buzzsaw noise and static-to-flight transformation. The importance of accurate prediction of duct liner attenuation for those cases that included a lined engine duct was also noted. Flight effects of jet noise were also noted as a likely source of prediction error.

It is essential to view in retrospect the results of this first NASA validation of ANOPP in the context of the aircraft technology, understanding of the physics of acoustics, measurement technology, and prediction methodologies. A few key observations are discussed briefly.

- The aircraft system noise of the aircraft studied was influenced heavily by the engine noise characteristics of fan pressure ratios of about 1.7-1.9 and bypass ratios of about 1.7 to 5. As a result, fan and jet noise heavily dominated the measured noise and prediction challenges. It is an understatement to say that modern aircraft and engines have greatly changed. Acoustically, the sum of all the technology changes amount to about 40 dB cumulative reduction based on certification noise.
- The Boeing report in particular notes the necessity and challenges of separating sources in the flight test data, foreshadowing the development and wide use in aircraft acoustics of techniques such as microphone phased arrays.
- The ultimate objective of ANOPP to accurately predict full-scale aircraft noise was clear as was, therefore, the necessity of comparison with flight test data which motivated this initial validation effort. The deficiencies in prediction noted likely issues with the flight effects and static-to-flight transformation.

- Interestingly, the commercial aircraft used in the study were also notably of three different aircraft configurations: the tail mounted DC-9, two different trijets (DC-10 and L1011), and the quad jet engine-under-wing B747. However, in final report of the study, there is no mention of the role of PAA integration effects that are, in fact, different among these aircraft configurations. Also, there was no mention of the need to predict them. These observations emphasize the importance of the initiative of the past two decades to focus on PAA effects, among other needed improvements in ANOPP methods.

In the intervening decades, the connection to flight testing was somewhat diminished. There were certainly several key NASA flight tests for noise reduction technology, particularly in the early 2000s. However, because of the objectives and the associated information limitations, these were not generally suitable for system noise studies. There was at least one effort in the early 2000s for a dedicated system noise flight test, however, it was not realized.

C. ANOPP-Research

From the beginning of ANOPP, there was a recognition of the need for and an emphasis on the development of new prediction methods in efforts to improve the accuracy of prediction and to extend prediction capabilities as technology advanced over the decades. In addition, beginning in the 2000s, ANOPP2 was created with the goals of providing a modern programming structure with greater efficiency, flexibility, and more capabilities (Ref. [24]).

For the past two decades both ANOPP and ANOPP2 have continued to be developed in coordination. NASA best practice for predicting a fixed wing aircraft is to use ANOPP together with ANOPP2 in order to take advantage of user interfaces, utilities, and efficiency of ANOPP2 while all the methods for noise sources are still a part of ANOPP.

The improved prediction capability in ANOPP has focused on the challenges presented by changing technologies of modern and future subsonic transport aircraft and noise reduction technology. In addition, NASA's ambitious system level metrics require advanced aircraft concepts and technologies that create additional prediction challenges. Low pressure ratio fan noise, duct liner attenuation, core noise, airframe noise, and PAA effects all represent much needed improved prediction methods for the future NASA aircraft system noise capability. In addition, these improvements ideally should be more physics-based to include details of the aircraft system and to enable a more direct linkage to preliminary design and optimization.

In recent years, ANOPP-Research has been a NASA internal version of ANOPP differentiated from the ANOPP version that is released to US users. The purpose of ANOPP-Research has been to deploy the best capabilities available for NASA system noise studies and also to gain experience with new methods under development. ANOPP-Research utilizes unique experimental information, prediction and experimental experience, and new research level prediction methods under development. ANOPP-Research has been used extensively in the past decade on many of NASA's system noise studies (Refs. [1]-[10]). As part of ANOPP-Research, there has been significant progress in the development of new methods for PAA effects and for airframe noise that will be used in this research.

Figure 2 provides an overview of the prediction process and the elements of ANOPP-Research. The elements of an aircraft noise prediction are noise sources, PAA effects, and noise reduction technologies (if any). These prediction elements are performed in ANOPP-Research with a variety of methods including: 1) from data-based process using the PAA & ASN team databases or as provided by collaborations with partners, 2) a dedicated research level prediction method, or 3) a custom modification such as how some airframe technologies are modeled with the Guo airframe methods. The major elements in ANOPP-Research will be described in Section VII. The definition of the aircraft, engine, and flight path must all be provided to the prediction process from external sources, either predictions or measured data. For this case, the aircraft definition and flight path were both provided to the prediction process as will be described in Section VII. Finally, the noise metrics are calculated.

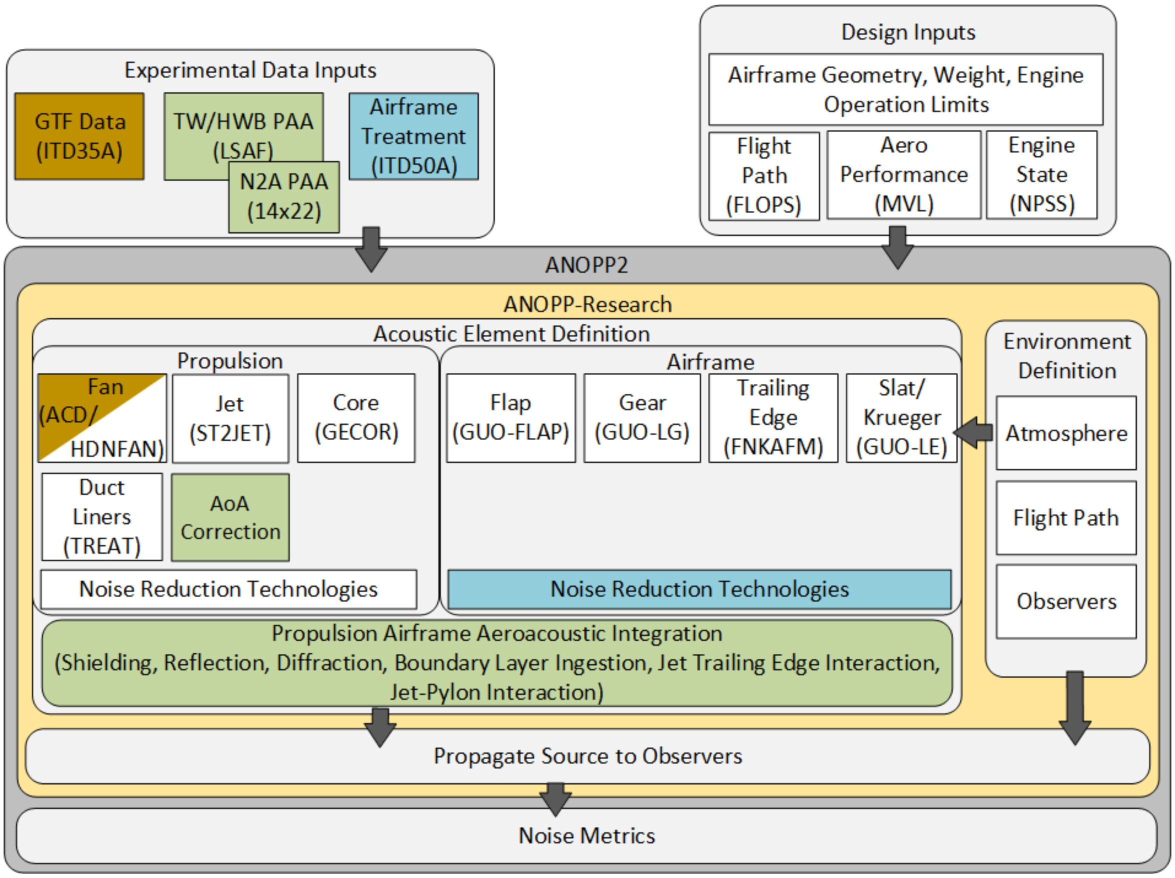


Fig. 2 Schematic of major elements of ANOPP-Research and the overall system noise prediction process.

D. PAA and ASN

PAA effects are the interactions from integration of the propulsion and airframe and include both the acoustic and flow interactions. Shielding, reflection, and diffraction are acoustic scattering interactions and are a function of how the aircraft configuration integrates the propulsion system with the airframe. Acoustic scattering is influenced by flowfield direction and shear layer characteristics. Acoustic scattering is significantly influenced by the characteristics of the engine noise sources including spectral content, distribution, and directivity. Airframe edge geometry details, control surfaces, and flight parameters can also influence the magnitude and directivity of the PAA effects. A useful, initial classification of PAA effects was made in Ref [1] based on this approach and has been an effective framework.

In comparison, aircraft system noise is defined as the total system noise of the aircraft and is the sum of all contributing noise elements including noise sources and PAA interactions. Additional interactions can occur such as airframe-to-airframe interactions (e.g., gear wake interacting with a high-lift flap).

PAA is a physical and integral aspect of aircraft system noise. Understanding and predicting the PAA effects is essential to the pursuit of higher fidelity, more realistic, and accurate predictions of system noise. This is equally true for today's aircraft as well as for future, unconventional aircraft, and even more so for low noise aircraft. In legacy prediction approaches, the PAA effects, if they were considered, were often lumped in with the prediction of the source or were added ex post facto as a system correction or an installation factor. However, when PAA effects are understood and predicted explicitly, the system noise prediction becomes higher fidelity, with dependency on the source directivity characteristics, design parameters such as wing dihedral, operational dependent parameters such as angle-of-attack, and other parameters of interest. As a result, there are many valuable implications of developing more physics-based PAA prediction methods. One of the important implications is to expand the scope of possible noise reduction concepts (Refs. [1]-[9]). Other implications include more accurate ground noise contours, for example (Ref. [25]).

PAA integration effects have been shown in previous research (Refs. [4]-[9]) to be the single largest differentiator in the system noise of future advanced aircraft configurations that use otherwise equivalent technology. To demonstrate and quantify the total effect of PAA possible from configuration change, an engine-under-wing, a midfuselage nacelle (MFN) and a hybrid wing body aircraft (HWB) were analyzed. The portfolio was conceptually designed with the same technology assumptions and mission requirements (Ref. [26]). The noise analysis showed a total difference just from the PAA effect of 10.7 EPNdB cumulative (Ref. [8]). That is, a noise increase for the engine-under-wing of 4.3 EPNdB cumulative to a noise reduction of 6.4 EPNdB cumulative for the HWB with shielding of both forward- and aft- radiated engine sources. The MFN configuration reduces the reflection effect and has some shielding (by both wing and fuselage) and as a result has a net 4.2 EPNdB cumulative noise reduction, in between the engine-under-wing and the HWB. The MFN with its favorable PAA characteristics can achieve an 8.5 EPNdB cumulative noise reduction entirely due to configuration change (from the engine-under-wing) within the basically tube-and-wing architecture (Ref. [6]).

With the combination of a configuration with favorable PAA effects and a full portfolio of noise reduction technologies, including several PAA technologies and design refinements to increase shielding effectiveness, the HWB was predicted to reach a total system noise of 43.9 EPNdB below Stage 5 (Ref. [5]). Notably, this study provided an example for future aircraft that PAA noise reduction technologies could increase the already favorable total PAA effect of the HWB by increasing shielding effectiveness; that is, more noise reduction for the same relative placement of the engine noise source to the shielding airframe. This level of 43.9 EPNdB is almost sufficient to reach NASA's most ambitious noise goal for 2035 and beyond, a goal determined to be sufficient to reduce population exposed to objectionable noise by a factor of ten (Ref. [27]).

These wide-ranging motivations outlined in the prior sections translated into the overarching long-term goals to improve many aspects of the fundamental understanding of aircraft noise including PAA integration effects, to validate NASA's system noise assessment tools more completely, to enable the development of new system level prediction capabilities, and to enable new noise reduction technologies and operational procedures. These long-term goals for NASA then translated into more specific objectives for the test. These required a full-scale, modern transport aircraft most representative of design trends into the future, and for this, the Boeing 787-10 is most suitable. Meeting the objectives also required including in the test design aspects to investigate PAA integration effects, flight effects, and operational aspects. These objectives will be discussed in the next section.

IV. Objectives and Technical Challenges

The objectives at a high level can be summarized by the two complex topics of PAA and Aircraft System Noise. The PAA objective is to accurately measure and understand PAA effects both specific to the modern engine-under-wing configuration, the 787-10 in this case, and more generally applicable to the wider range of PAA effects that are inherent to unconventional aircraft that are a part of NASA research. This results in multiple challenges that will be discussed below. Similarly, the Aircraft System Noise objective is broad and multifaceted, more specifically to provide high-quality, high-resolution flight data of total aircraft noise and the major noise elements, and also to understand flight effects and operational features. Longer term, the sum of the accomplished objectives is to provide improved understanding, a basis to evaluate ANOPP, and to develop improved prediction methods in the future.

These two objectives obviously result in developing many, interrelated lower level objectives that contribute to both high-level objectives. Some of the interrelated lower level objectives can be briefly listed as characterizing: reflection by wing (as a function of powerline and high lift deflection and then with different fan noise characteristics), shielding by the wing, shielding to the far field by the fuselage, azimuthal directivity, engine powerline, aft duct liner effectiveness, all airframe components and interactions, operational maneuvers (e.g., banking and spoiler deployment), and flight effects. These lower level objectives can also be seen as specific technical challenges that become the basis for requirements on aircraft configurations, test matrix points, and instrumentation.

The classical method of experimentally quantifying a PAA effect is to measure the noise source isolated and then again integrated with the airframe. The difference is the net PAA effect. If the isolated and integrated tests include simulated flight (e.g., wind tunnel flow) then the PAA effect includes both acoustic scattering and flow interactions. For a full-scale aircraft this can almost be achieved if the test campaign includes a static engine test in conjunction with a flight test, as was done with QTD2 (Refs. [14], [28]). Obviously, this adds even more cost and logistic challenges and was simply out of the question for this test from the beginning. Therefore, a significant challenge was how to measure PAA effects of the engine noise elements with only the aircraft in flight?

A major PAA effect for the engine-under-wing aircraft is from the reflection of the fan, jet, and core noise sources from the wing. This reflection can be modified by high-lift system deflection, aircraft attitude, aircraft speed, and engine power condition. With the objective to study the PAA effects of full-scale aircraft including flight effects and to be more generally applicable, then another significant technical challenge was how to include shielding and diffraction?

Azimuthal directivity has always been a key to PAA effects, in particular due to the strong directivity effects that can occur with both shielding and reflection. As a result, measuring azimuthal directivity accurately is important to both Aircraft System Noise and PAA objectives. A great deal of the azimuthal directivity on an engine-under-wing aircraft comes from the engine noise sources reflecting from the fuselage, wing, and high-lift devices when deflected. Ground far-field microphones can measure azimuthal directivity if arrayed on both sides of the aircraft at increasing distances. However, attenuation with distance will soon diminish the signal-to-noise ratio and, in addition, the azimuthal range will be relatively limited to about ±50°. Therefore, another key technical challenge was to measure an increased range of azimuthal directivity with sufficient signal-to-noise.

Azimuthal directivity is not only essential to PAA effects, but it could also be important to increasing the fidelity of the noise source models themselves and in combination, to improve the prediction of the ground footprints including when the aircraft is maneuvering as part of takeoff and landing. In these ways, azimuthal directivity requirements contribute to achieving the highest quality, high-resolution dataset possible that would provide the best characterization of the total aircraft system noise.

V. Key Enabling Technical Approaches

The accomplishment of the objectives of this flight research depended on five key enabling technical approaches to ensure successful research. These five will be discussed briefly.

A. Boeing 787 Aircraft

For the future, low-noise advanced concepts that NASA is focused on, airframe noise sources, in particular those from the leading edge high-lift device and from the landing gear, have also been shown to be important noise sources at multiple conditions. Advanced aircraft concepts with different configurations and new airframe technology are currently being explored as part of NASA's ambitious sustainable aircraft technology research (Ref. [9]). For example, the Transonic Truss-Braced Wing (TTBW) concept has a high aspect ratio wing as well as a strut, making it possible for the trailing edge noise source to become more of an important airframe noise source. For these airframe technology reasons, the Boeing 787-10 airframe technology is among the most advanced of in-service aircraft and, therefore, most appropriate to use to evaluate the next generation airframe system noise prediction tools that have been developed (Ref. [17], [29]). Equally important is that the GEnx1B engine is among the most modern engines in service and, together with the nacelle liner technology, also represents the best choice of in-service propulsion systems to measure and to use in the unique experiments of this research. For these and other reasons, from the beginning of formulating this research, the Boeing 787 was the preferred choice for the test aircraft and is the first key enabling technical approach.

B. PAA In-Flight

There were many ideas considered over the years for how to study shielding by a full-scale aircraft in flight. Aircraft with tail mounted engines have been used in flight tests previously and could be considered (Ref. [30]). Rare or military aircraft that do have over-body mounted engines could be considered. Even instrumentation mounted on a chase aircraft was a possibility. Another approach that was used previously could be enhanced: two large towers with mounted microphones and the aircraft flying between the towers (Ref. [31]). These ideas and others were all considered in the early formulation of this current research. However, these previous approaches had significant drawbacks and were ultimately deemed unsuitable to accomplish all objectives. Furthermore, to meet all the objectives and use the most modern commercial transport available, the challenge quickly became how could PAA effects such as shielding and reflection be studied on a Boeing 787 configuration. With this challenge narrowed to this harder problem, the second key idea, which motivated the approach chosen to meet the PAA challenge was to use the wing as a shielding airframe with microphones on the fuselage above the wing. Figure 3 shows the view angle of microphones placed on the fuselage above the wing, demonstrating the wing as an effective shielding airframe for the propulsion noise sources below the wing.

Fig. 3 View from above the wing of a Boeing 787-10 showing the wing as shielding engine noise by the leading edge (left) and aft-radiated engine noise by the trailing edge with flaps deflected (right). Photo Credit: Russell H. Thomas.

Starting with this idea of installing microphones on the fuselage to study full-scale PAA effects, the newly developed NASA PAAShA and PAASc acoustic scattering methods (Refs. [19], [20]) were essential to evaluating the effects that could be measured in this approach. The predictions contributed to establishing the location of microphone arrays on the aircraft. Ultimately, the NASA predictions were useful for designing multiple approaches to the PAA challenge. The scattering of engine noise sources was predicted during the design and planning of the test, including both scattering to the fuselage as well as to the ground, which will be described below.

Scattering prediction of fan noise to the fuselage is a function of forward and aft-radiated fan noise source location, directivity, and frequency. For the purpose of determining the feasibility of the over-wing array to be able to measure the shielded aft fan noise signal, the predictions needed to determine the attenuation in the over-wing area. For the purpose of locating the axial and over-wing arrays, the predictions needed to show the distribution of the scattered field from fully insonified to the shadow zone.

For the pretest studies, both fan and jet sources were predicted. A generic airframe geometry was used that was similar enough to the 787-10 to be applicable and yet simplified for ease and efficiency. For the purposes of demonstration, only the fan noise predictions are shown for a frequency of 1000 Hz. The fan noise was modeled by two concentric rings of monopole sources to provide a suitable distribution, either over the inlet plane of the nacelle or the nozzle exit plane for aft fan noise. In addition, the sources have an expected fan noise directivity applied, either a directivity for inlet radiation or a directivity for aft radiation. Figure 4 shows the prediction of the scattered inlet and the scattered aft fan noise. The predicted attenuation patterns show a basic similarity in the regions forward, over, and aft of the wing; however, the attenuation levels can be different by approximately 10 dB at specific points. Shielding of aft fan noise was identified as the primary objective because the source is in a reasonable relative position. The region directly over the wing is the key region for shielding by the wing of aft-radiated noise. The prediction shows the potential for up to 25 dB of attenuation.

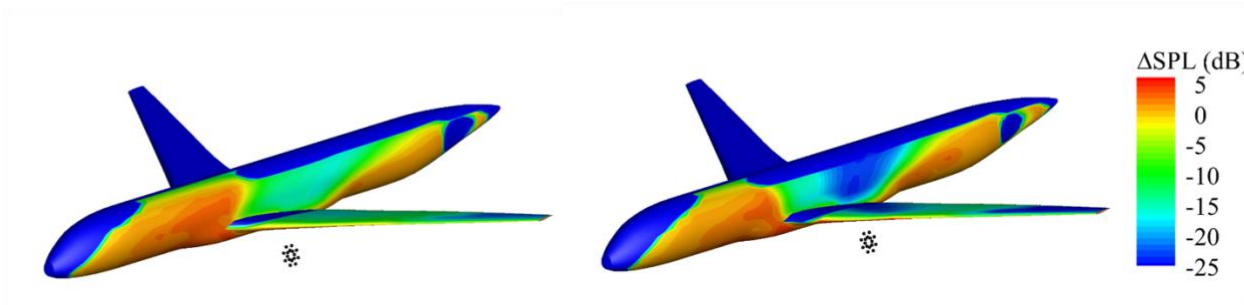


Fig. 4 Predicted scattering attenuation to the airframe of modeled inlet fan noise (left) and modeled aft fan noise (right) for 1000 Hz only.

The prediction was also done for total fan noise, with both inlet and aft sources, to predict what would be measured without the ability to separate forward- and aft-radiated fan noise. The predicted attenuation is shown in Fig. 5 and indicates sufficient attenuation to make shielding measurement feasible if an over-wing array is placed on the fuselage in the deep blue region in Fig. 5. The prediction also gives guidance on location of microphones on the fuselage forward and aft of the wing. Of course, to complete the feasibility of measurement, the turbulent boundary layer (TBL) noise and the effect of propagation of the fan noise through the TBL also had to be assessed. This will be shown in future publications.

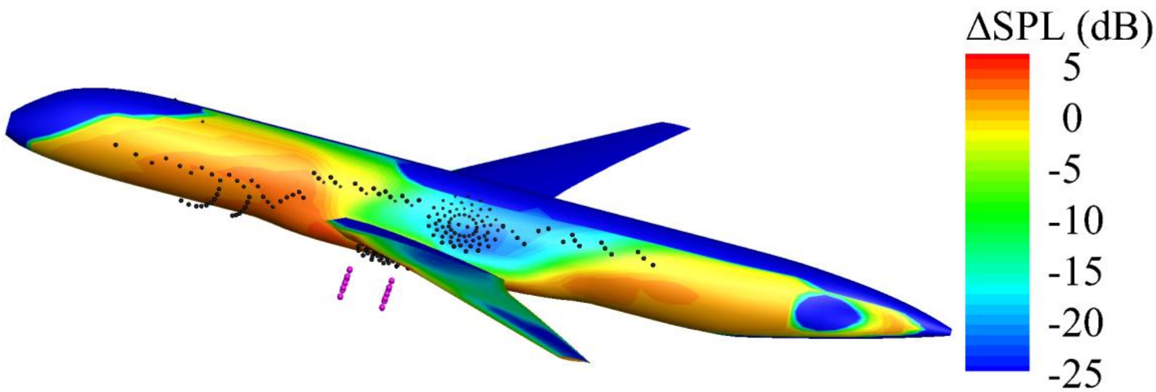


Fig. 5 Predicted scattered attenuation to the airframe from modeled total fan noise for 1000 Hz. Locations of the inlet source and aft source distributions are shown below and ahead of the wing leading edge. Approximate locations of the fuselage mounted microphone locations are also shown (black dots).

Figure 6 shows the final result of combining the NASA technical approach and prediction work and the Boeing experience and instrumentation expertise to turn this key enabling idea into the finished on-aircraft instrumentation to address the PAA challenge. The instrumentation was arranged in four arrays, once again enabling the accomplishment of multiple objectives. The four arrays are the axial array (along the fuselage length), the circumferential array (forward of the wing), the over-wing array, and the under-wing array.

The purpose of the axial array, combined with the over-wing array, was to measure all three regions of fan-radiated noise, namely the direct insonified region, the diffracted and transition regions from the leading and trailing edges, and the shielded (shadow) region directly above the wing. These arrays should measure the full distribution of forward-radiated and aft-radiated fan noise as scattered by the wing. Engine power and high-lift deflection could also augment this study with additional parameters that can impact the scattering. These predictions will also be shown in the future.

The circumferential array is forward of the wing to measure the forward fan-radiated sound field. This can provide a measure of the peak radiation angle of inlet fan noise as well as general directivity. However, by making the array around the circumference, this array can also measure the incidence field for the diffraction around the fuselage and to the far field. This created the possibility of a shielding experiment to the far field and will be discussed below.

The under-wing array is intended to measure the direct field of the engine providing source definition of the aft fan and jet sources. These measurements will be used as input to the shielding attenuation determination from the other arrays above the wing. Finally, the under-wing array may provide some quantification of the reflected level and primary reflection locations.

Fig. 6 Test aircraft outfitted with fuselage mounted microphones in four arrays: Over-wing, Under-wing, Axial, and Circumferential. Photo Credit: The Boeing Company.

C. Aircraft Maneuvers - Banking

A banking maneuver was introduced as a multipurpose test matrix element that was the third key enabling technical approach. First, as shown in Fig. 1, the banking increased the azimuthal directivity angle that the ground microphones viewed while keeping the propagation distance equivalent to that of a straight flyover. Second, the banking maneuver also created shielding by the fuselage to the ground microphones below and on the opposite side of the fuselage from the engine at power (also shown in Fig. 1). Third, the banking maneuver is of interest in and of itself because it is common in operations, and these data will enable evaluating prediction capabilities.

The design of the banking maneuver involved new prediction capability. With the ground microphone layout set by the ±1476 ft spacing of the two sideline arrays on either side of the runway centerline, all the remaining test variables must be considered in order to maximize potential for success, primarily allowable altitude and bank angle. The aircraft provided a limit to the banking angle that would be allowed, considering that the altitude was low and only one engine was at high power. Within these constraints, geometry determines what bank angle the engine on the far side of the fuselage would be shielded by the fuselage to the sideline microphones on the unpowered side of the aircraft. However, predictions would be valuable to determine the effect of diffraction and whether sufficient attenuation could be expected to make measurement feasible at the sideline microphones. For this task, the previously mentioned new NASA method were pressed into service. The new method has been developed into two separate but related codes, PAAShA (Ref. [19]) and PAASc (Ref. [20]). The prediction that is shown in Fig. 5 is now propagated to the far field in order to find the attenuation at the sideline microphone as a function of aircraft bank angle.

Figure 7 shows the computational model at a moment in time as the aircraft is flying level at 1000 ft altitude above the far field community noise microphones. The domain on the ground is 4000 ft by 4000 ft and encompasses both sideline arrays (indicated by the dashed lines). Just as in Fig. 5 and in the flight test, the test engine at high power is on the left side, and the engine on the opposite side is at flight idle. Figure 7 also shows the predicted levels on the ground, primarily a function of the reflection of the modeled total fan noise by the wing. The predicted level on the ground is shown in an absolute level in order to show asymmetry that is created by the fact that one engine is at high power and the other is at flight idle. If the reflection was not accounted for, the ground footprint would be predicted as symmetrical. The reflection is a function of the wing and fuselage three-dimensional shape including parameters such as wing dihedral angle. In this example, the high lift system is not deflected. In reality, the aircraft is flying past the community noise microphones creating a time integrated signal. A higher fidelity calculation was done at various times along the flight path; however, for the purpose of this paper, the prediction at the point with the aircraft directly over the microphones is sufficient for this demonstration.

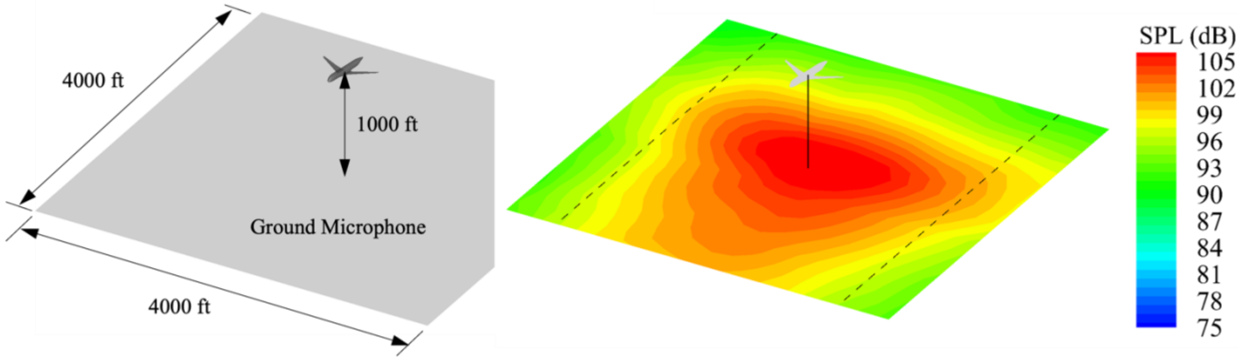


Fig. 7 Prediction of scattered total fan noise propagated to the ground plane. The aircraft left engine is at high power, the right engine at flight idle. The absolute level is representatively chosen and not associated with flight test data.

For the aircraft flying level at zero bank angle, the ground footprint is entirely from the modeled total fan noise, both direct and reflected contributions, the total PAA effect associated with fan noise for a conventional aircraft configuration. Again, in this special case, one engine is at high power and the other at flight idle power creating the side-to-side asymmetry. Figure 8 shows the PAASc prediction of the incident and reflected field on the underside of the aircraft showing the detailed origin of what manifests on the ground as the asymmetry in Fig. 7.

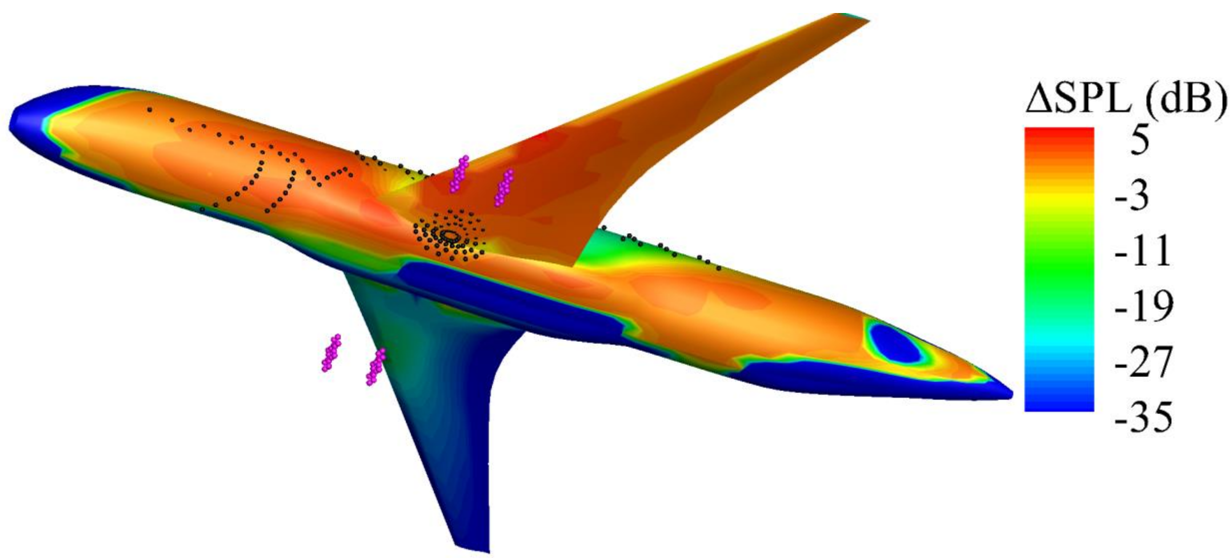


Fig. 8 Predicted scattered field on the underside of the generic aircraft body. The aircraft left engine is at high power, the right engine at flight idle. There is no absolute level on this figure.

The final step is to bank the aircraft with the wing tip (down) on the side with the engine at flight idle (unpowered side). This way the side with the engine at high power (powered side) becomes shielded by the fuselage to the community noise microphones in the far field. On the powered side and in the far field the microphones will continue to see the effect of the reflection, only with a slightly different directivity. This is shown in Fig. 9 for zero bank angle and also for 35° bank angle. In Fig. 9, the prediction is shown in a delta format because this effectively demonstrates the patterns predicted in the ground plane. The zero-bank angle case on the left of Fig. 9 is the same prediction as was shown on the right of Fig. 7. At zero bank angle, the sideline microphone on the unpowered side will just be on the edge of a noticeable attenuation. As bank angle increases the attenuation moves toward the centerline. At 35° of bank angle, 9.5 dB of attenuation is predicted as the aircraft crosses the center of the ground plane and, importantly, along much of the flight path as the aircraft traverses the domain. This simulation justified a possible experiment of shielding by the fuselage, and the 35° bank angle was chosen as the primary condition. This test condition was executed as designed in the test as described in Czech et al. (Ref. [16]). Clearly, this key technical approach was successful.

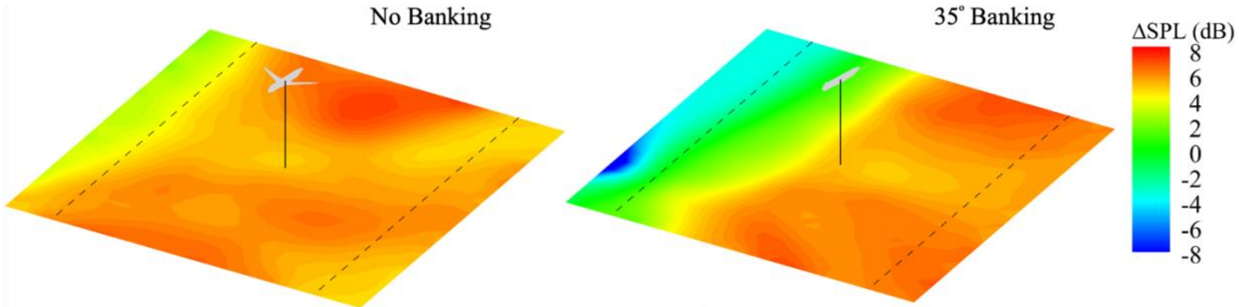


Fig. 9 Predicted attenuation in the ground plane for the aircraft flying level at zero-bank angle (left) and at 35 degrees of bank angle (right).

D. Hardwall Aft Duct

For another valuable approach, based on their previous experience, Boeing proposed hardwalling (by taping over) the liner in the aft bypass duct. Again, this achieved multiple purposes. First, it would provide an augmentation to the PAA objective by increasing the level of the aft-radiated fan noise and, therefore, the shielded noise measured by the over-wing array. This would increase the signal-to-noise ratio for aft fan noise received at the over-wing array, and it would also change the directivity of the aft fan noise. Second, the effectiveness of the production aft duct liner could be determined.

E. High Resolution Instrumentation

To contribute to a comprehensive and high-quality measurement and to enable the separation of individual noise sources the well-known instrumentation method is a microphone phased array. For the objectives of this research, the requirement was to assemble the most capable array that was possible with the Boeing resources. Details of the resulting 954 microphone array design and capabilities are found in Czech et al. (Ref. [16]).

Another valuable instrumentation system installed specifically for this research was the engine tachometer signal, also described in Czech et al. (Ref. [16]).

In sum, these five key approaches were designed into the test plan in an integrated approach that yielded more value. For example, this integrated approach provided multiple ways to address the key PAA technical challenge through different types of PAA effects and in several parts of the test matrix while also addressing many of the other related objectives. One advantage of this integrated approach is that the PAA effects studied are much more generally applicable compared to those expected just from an engine-under-wing configuration (reflection by the wing and fuselage to the ground below). Another advantage is that there are, in effect, multiple measurements, parameters, and types of scattering included in the acquired data that all contribute to improving the overall success and achieving the test objectives.

VI. Test Matrix

The test matrix was designed over a period of many months and balanced many factors including the fixed time for the test, which was set early in the process, efficient timing of the aircraft operation, weather and other contingencies, and, of course, the most efficient sequence of test conditions to accomplish all of the objectives. In total, the testing took place on five days out of eight sequential days. The test matrix was divided into four major sections.

Flights with the aft duct hardwalled (taped) were conducted first with conditions covering the full powerline. Given the integrated plan described above, these test conditions are used for multiple purposes including liner assessment and PAA effects.

Airframe conditions were accomplished over a full day of testing and included conditions to allow separation of the major airframe components and interactions. In addition, special conditions included the spoiler deployment.

After the aft duct was returned to production condition, another day was flown for another full powerline. Again, these conditions are useful both for characterization of engine noise and for PAA effects.

The fourth major section was PAA Special Operations and included the test conditions with banking. Also included were test conditions featuring the aircraft flying straight but offset from the centerline of the ground microphones. This was another way of measuring the azimuthal directivity of the aircraft.

VII. Comparison of ANOPP-Research Predictions with Flight Data

An initial comparison of measured total aircraft noise with predictions is now shown. The purpose of this comparison is to quantify the accuracy of prediction for total aircraft noise using select test conditions that span the range of the typical aircraft low speed operation. Companion studies use specific test conditions to compare the prediction accuracy for the components of airframe noise (Ref. [17]) and for fan noise flight effects (Ref. [18]). Together the three provide a good overall initial assessment of the current status of ANOPP-Research.

These predictions will be with the best capabilities in ANOPP-Research, outlined in Fig. 2, that have been used in NASA's system noise studies in recent years and that are most applicable to a prediction of the 787-10. The following methods for fan source, jet source, and liner attenuation are the same as in ANOPP released version. For duct liner attenuation, the TREAT method (Ref. [32]) continues to be used but with the 10% correction factor used in previous studies as a way to account for the added effectiveness of current spliceless liner technology. The method of Stone et al. (Ref. [33]) is used for the jet source noise and the method of Krejsa et al. (Ref. [34]) is used for the fan source noise.

A major part of ANOPP-Research is the 3rd generation GUO airframe prediction methods for the gear, flap, and slat components. The Fink method continues to be used for the trailing edge source (Ref. [35]). Another major part of ANOPP-Research is the prediction of the PAA effects. In the future, acoustic scattering PAA effects will be able to be predicted using the new methods of PAAShA or PAASc; however, for this study the PAA scattering uses the method based on experimental data from the NASA/Boeing PAA series of experiments performed in the Boeing Low Speed Aeroacoustics Facility (LSAF) (Refs. [36]-[38]). For the 787-10, the following PAA effects are included.

- The reflection of fan inlet noise from the fuselage and the reflection of fan exhaust noise from the wing, flap, and fuselage are included. These effects have been predicted in ANOPP-Research for more than a decade using experimental data mentioned above. For fan noise reflection, a broadband source in a nacelle was used with a 777 airframe model.
- Reflections of the jet noise from the wing, flap, and fuselage are included. These effects were also predicted using data from the NASA/Boeing PAA series of experiments conducted with representative nozzle and jet conditions.
- The angle-of-attack effect on the jet is predicted using a NASA model based on data from the NASA/Boeing PAA series of experiments.

In general, most of the flight tests that are performed for noise reduction technology development or that are reported for certification purposes are of very limited use for system noise prediction method development or validation. This is for several reasons including the use of often much older technology aircraft or limited aircraft and acoustic data. Most lacking are often the adequate definition of the aircraft and engine parameters, geometry, and performance. These are critical to any aircraft system noise validation effort because these are the inputs to the prediction methods and having these well-defined removes what is often a large uncertainty. For this study, Boeing provided aircraft parameters and flight path information for each test condition. Boeing also provided geometry definition needed for the inputs to the ANOPP-Research prediction methods. For the engine, the flight data system provided the N1 (rotational speed of the fan) with the other engine parameters needed for prediction provided by Boeing based on their internal engine cycle model results for each test condition. No information was provided for the engine core, and therefore, core noise is not included in the predictions reported below.

The results are presented as the difference between ANOPP-Research prediction and measured data. A negative value represents underprediction relative to the measured data. For this first comparison, shown in Fig. 10, a high power condition with the production engine is chosen. The difference between the two figures being shown is solely the inclusion (left) or exclusion (right) of the fan combination tones in the prediction. For frequencies of 1000 Hz and below, the combination tones noticeably increase the overprediction by ANOPP-Research at the forward angle and at the overhead angle. Based on the parameters of the fan at the high power condition, the Krejsa fan source noise model includes the combination tones; however, for several reasons listed in the companion paper by Clark et al. (Ref. [18]), it is reasonable to proactively exclude the combination tones from the predictions presented later in this section. From a prediction method perspective, it can be either the fan source model or the liner attenuation model or both that are not adequately representing the physics of the GEnx engine combination tone source and propagation.

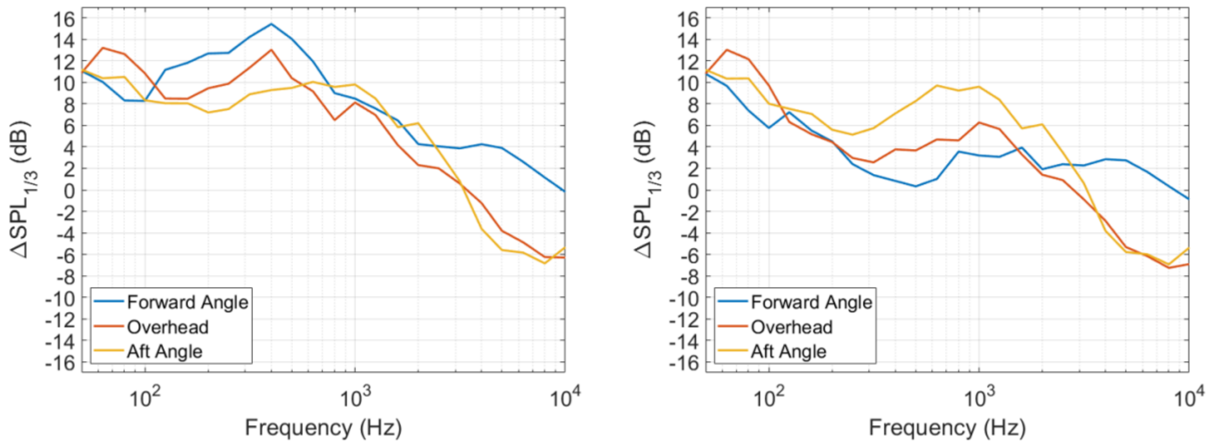


Fig. 10 Total aircraft ANOPP-Research prediction minus measured data for a high power condition production engine, including combination tones in the fan source noise prediction (left) and excluding the combination tones (right).

Even for a conventional aircraft, the PAA effect from acoustic scattering, primarily reflection in this case, has a significant effect both in magnitude and directivity. Since this is a key part of ANOPP-Research capability, the following predictions are made both with the PAA effect and without. Figure 11 shows the comparison at the flyover microphones, directly under the straight flight path, without PAA effects included in the prediction, (a), and with PAA effects, (b). Figures 11 (c) through (f) show the comparisons at the same condition except at the sideline microphones on the side of the aircraft with the engine at flight idle (unpowered) and then on the powered side, respectively. Without PAA effects, the comparisons generally show agreement within ±4 dB at the forward angle for the whole frequency range. This is the best comparison in Fig. 11. However, at both the overhead and aft angles there are trends of greater overpredictions at low frequencies and greater underpredictions at the high frequencies with the crossover approximately around 2-3 kHz.

When the predictions include PAA effects, (b), (d), and (f), generally the comparisons show even greater prediction errors. The trends are consistently large overpredictions at low frequencies and underprediction at high frequencies. Generally, the PAA effects add 1-2 dB over mid to high frequencies and often considerably more at the very low frequencies. Because jet-flap interaction is in the LSAF experimental data that the full-scale PAA effects are predicted from, it is a possibility that some of this large overprediction at the very low frequencies may stem from model-to-full-scale issues. This possibility and others will have to be investigated as the future work unfolds. However, because the flight experiment has PAA effects inherent, clearly including PAA effects results in the higher fidelity prediction. The differences between prediction and measured data demonstrates the true state of the prediction and points to prediction deficiencies in the key areas of fan source, liner attenuation, and the jet source. Of course, the prediction of the PAA effects could be improved in the future as described above, for example.

Figure 12, (a) through (f), shows the same pattern of comparisons with the only difference being for a mid-power engine condition. There are many high-level similarities between the comparisons at the high power and the mid power condition, including:

- inclusion of PAA effects adds 1-2 dB across the mid to high frequencies,
- for the forward angle, a consistent overprediction at all frequencies,
- the aft angle generally shows the largest prediction error for frequencies below 2-3 kHz and,
- for the overhead and aft angles, the trends are for overpredictions at low frequencies and underpredictions at the high frequencies with the crossover approximately around 3 kHz.

The final comparison is for a low power engine condition and again uses the same six plot format, with and without PAA effects in the prediction for each of the three ground microphone arrays, Fig. 13 (a) through (f). Several observations can be made.

- For this low engine power, the total aircraft noise would be expected to be mostly airframe dominant. This is confirmed in the comparison with and without PAA effects applied where the differences are smaller, at most 1 dB smaller, as compared to the 1-2 dB difference observed at higher power. The PAA effect is applied to the fan and jet sources; however, since their levels are so low there is much less impact at the total aircraft level.

- From 100 Hz to 1 kHz, over all angles, the trends of the comparison are generally consistent and within approximately ±4 dB,
- The larger differences in the comparisons occur at frequencies below 100 Hz and above 2 kHz, consistent over polar and azimuthal angles, and
- There is little difference between powered and unpowered sidelines, corresponding to less azimuthal directivity variation, as would be expected from total aircraft noise dominated by airframe system noise.

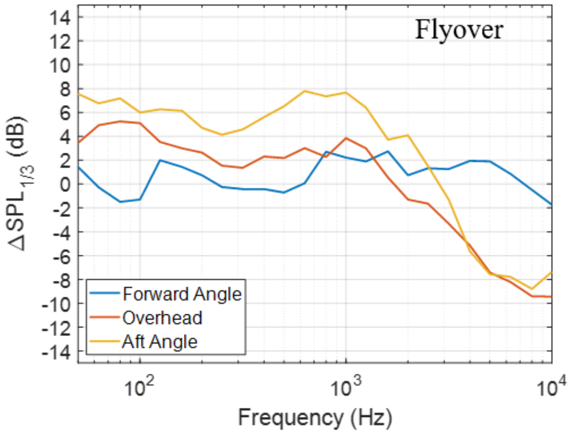
The predictions and measured data in Figs. 11 through 13 are compared quantitatively in Table 1, now on a relative EPNdB basis. For each engine power condition, the measured EPNL at the flyover array is used as a reference level so that the other values are negative or positive in comparison. The comparisons between prediction and measured levels follow many of the observations made earlier from the spectral comparisons.

A new insight that this EPNdB quantification illuminates are aspects of the PAA effect in the measured data and validation of ANOPP-Research prediction. Starting with the low power condition, the measured data show a 0.9 dB difference between the two sideline measurements. At mid power and high power, the differences are 2.0 and 1.1 dB, respectively. Note that the measured value on the powered side is always louder. Because the distance from the engine at power to each sideline is essentially the same, this observation demonstrates the reflection is a measurable and significant PAA effect for an engine-under-wing aircraft. If predictions are done without PAA effects, as shown in Table 1, the results at both sidelines are equal and do not trend with the measurements. The physically correct prediction must include PAA effects and, in this case, using the LSAF data-based approach, ANOPP-Research accurately predicts the correct trends and reasonable agreement in magnitude, although this is certainly an area for future improved accuracy.

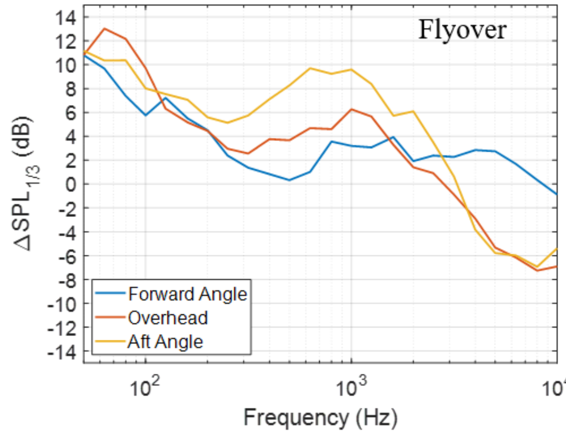
When the aircraft is banked by 35 degrees, both shielding and reflection become significant effects predicted as described in Section V.C. Figure 9 shows the prediction where the PAA effects are predicted from the physics-based geometric acoustics method PAASc rather than from the LSAF PAA data-based approach. Figure 9 has the prediction both for a straight level flight condition and for a 35° banking maneuver. The difference between the two sideline microphone arrays when the aircraft is banking is 9.5 dB at 1000 Hz. This compares with a measured value, at 1000 Hz, of approximately 10 dB as shown in Fig. 16 of Czech et al. (Ref. [16]). Together, these comparisons between the measured effects and both the LSAF PAA data-based approach and the PAASc code demonstrates excellent initial validation of the ANOPP-Research predictions for full-scale, in-flight PAA effects of acoustic scattering.

Table 1. Relative EPNL dB levels of ANOPP-Research predictions compared to measured data for three microphone linear arrays at three engine power conditions. For each power condition, the measured level at flyover is used as the reference for comparison.

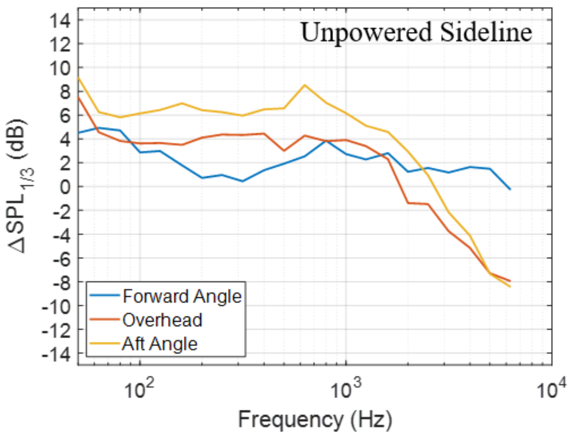
	Low Power			Mid Power			High Power		
	Prediction		Measured	Prediction		Measured	Prediction		Measured
	PAA	No PAA		PAA	No PAA		PAA	No PAA	
Unpowered Side	-12.3	-12.7	-11.7	-2.9	-4.2	-8.7	-1.9	-3.1	-7.3
Flyover	-2.6	-3.3	0.0	+4.3	+2.5	0.0	+5.0	+3.2	0.0
Powered Side	-12.0	-12.6	-10.8	-2	-4.2	-6.7	-0.9	-3.1	-6.2



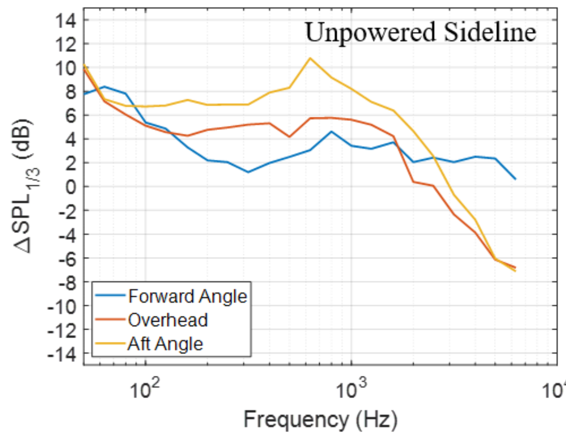
(a) Prediction without PAA



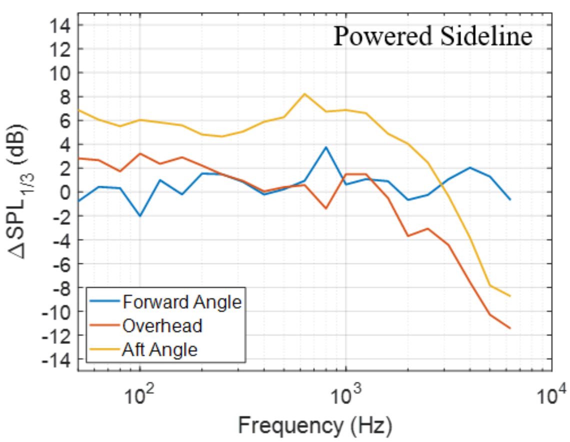
(b) Prediction with PAA



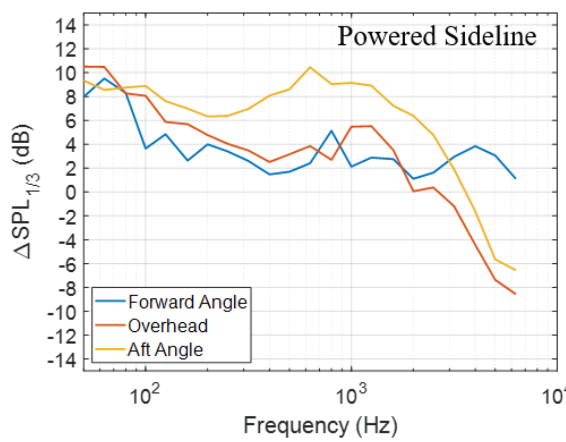
(c) Prediction without PAA



(d) Prediction with PAA



(e) Prediction without PAA



(f) Prediction with PAA

Fig. 11 Total aircraft ANOPP-Research prediction minus measured data for a high power condition (production engine).

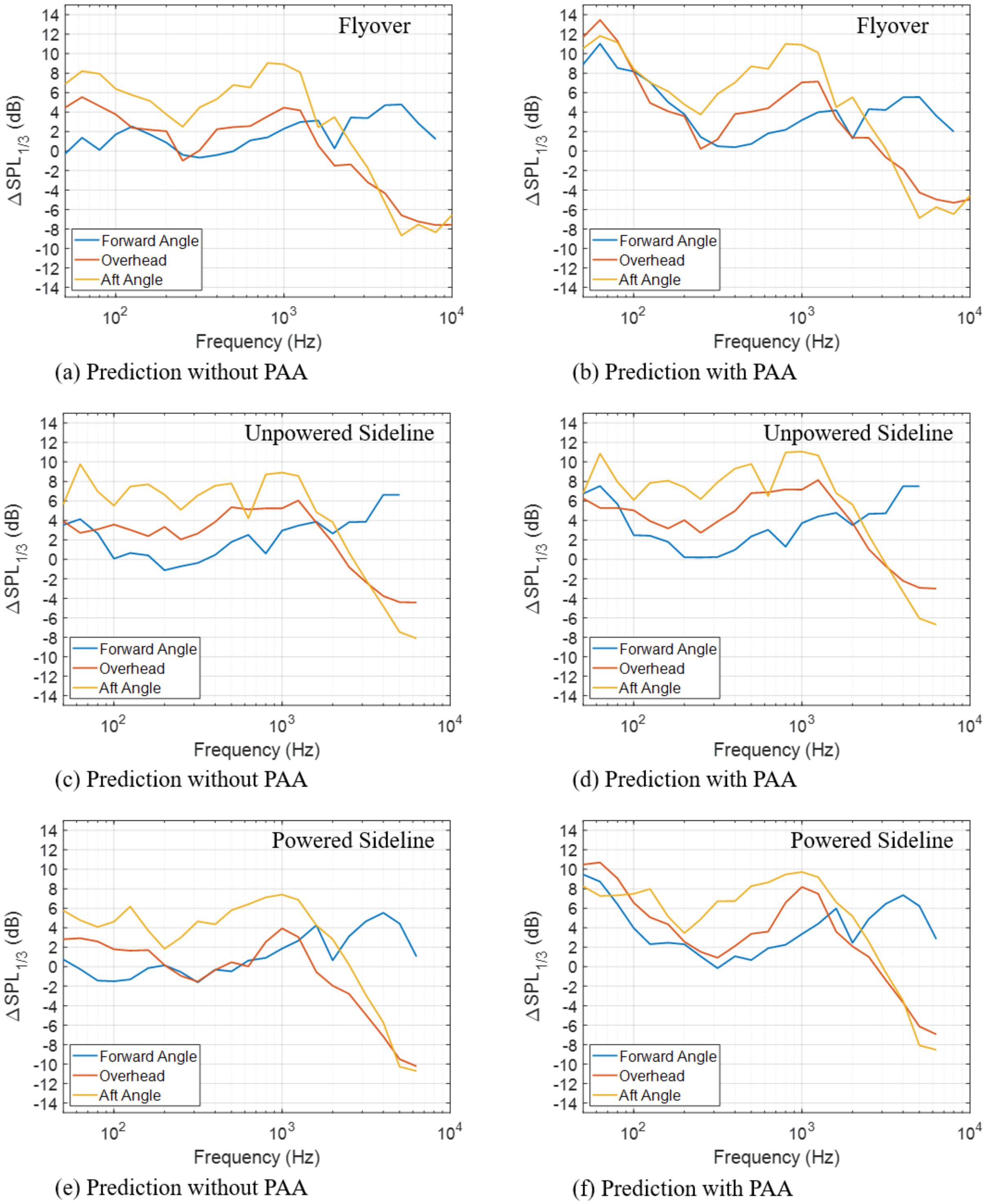
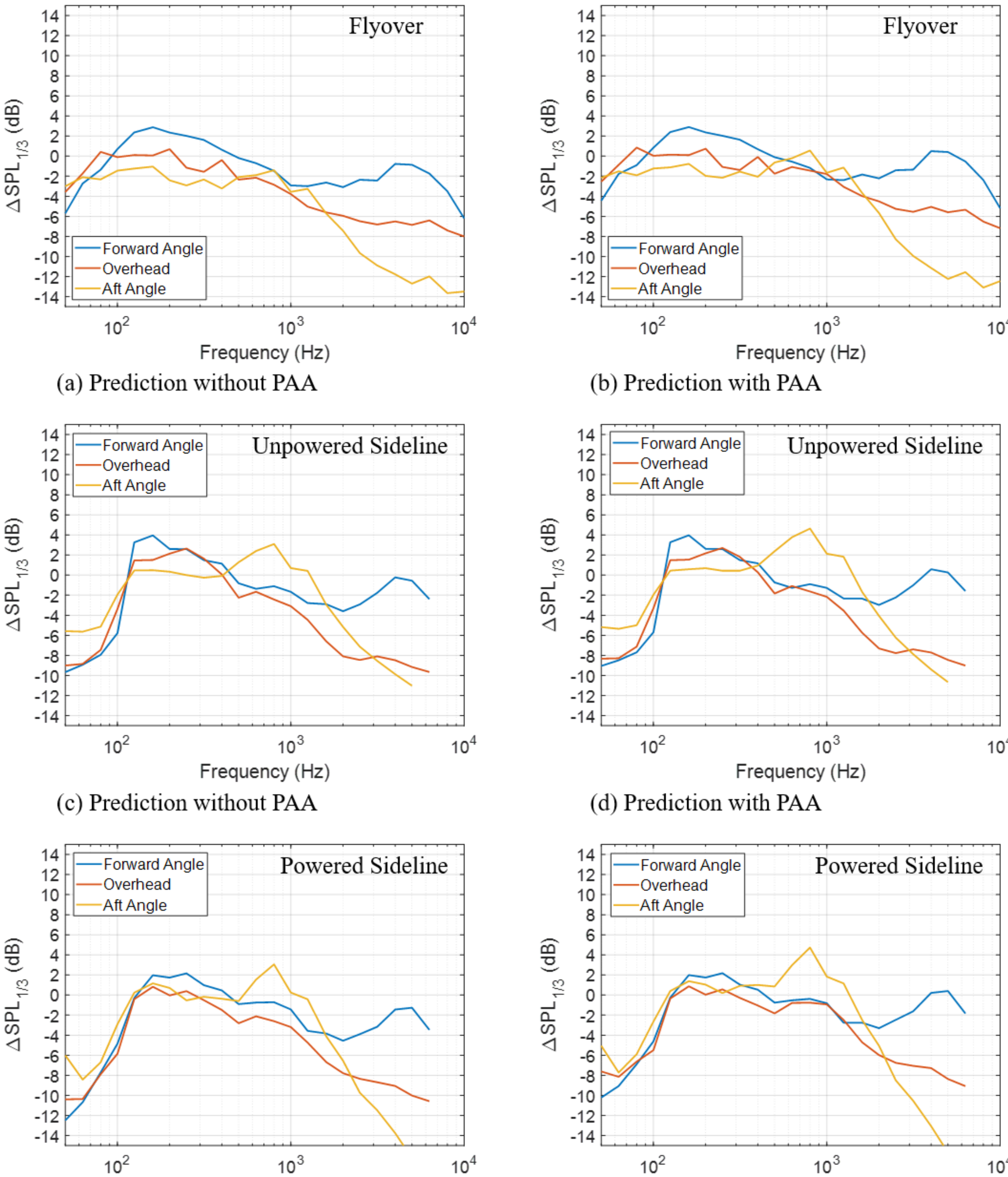


Fig. 12 Total aircraft ANOPP-Research prediction minus measured data for a mid power condition (production engine).



(a) Prediction without PAA

(b) Prediction with PAA

(c) Prediction without PAA

(d) Prediction with PAA

(e) Prediction without PAA

(f) Prediction with PAA

Fig. 13 Total aircraft ANOPP-Research prediction minus measured data for a low power condition (production engine).

VIII. Future Studies

This paper, together with the companion studies (Ref. [16]-[18]), represent an initial investigation with this high quality and high resolution flight research database. This research will continue well into the future in order to extract the full value of this flight test. The research will continue to be guided to achieve the following long-term objectives:

- understanding the full aircraft system noise and PAA effects as much as possible,
- more detailed evaluation and quantification of prediction deficiencies, improving predictions in the near future, and gaining insights to guide future modeling improvements,
- system noise predictions with greater fidelity to include more of the real effects of an aircraft in flight and,
- new, innovative noise reduction approaches resulting from deeper understanding and more capable, higher fidelity predictions. These approaches could include both technologies as well as operational aspects.

Results from two of the major instrumentation systems in the flight test have not been reported in this first series of studies. These two systems are the on-aircraft dynamic pressure sensor arrays and the ground microphone phased arrays. These will be used extensively in the next stages of this research as all data are utilized to analyze the results and reach the most rigorous conclusions. In addition, the new prediction methods that were just beginning to be used in the design of the flight test, PAAShA and PAASc, will also play a major role in the analysis of the PAA effects.

IX. Conclusions

To address long-standing needed improvements in a critical capability, NASA's Advanced Air Transport Technology (AATT) Project funded an ambitious aeroacoustic flight research effort, the Propulsion Airframe Aeroacoustics and Aircraft System Noise (PAA & ASN) Flight Research Test. The flight test was formulated in a highly collaborative process between the NASA and Boeing teams. The result was an extremely successful flight test conducted by the Boeing ecoDemonstrator 2020 program with an Etihad Airways 787-10 aircraft.

The major motivations that led to this PAA & ASN flight research have been outlined in this paper. Also described were key enabling technical approaches that established the basis for successful accomplishment of the challenging objectives. These five key technical approaches contributed to an innovative aeroacoustic flight research test. The Boeing 787 aircraft was preferred for its advanced technology and design features. The wing of the aircraft was used as a shield for microphone arrays above the wing relative to the engine noise sources below the wing. Additional types of PAA effects and operational objectives were studied by introducing a banking maneuver creating shielding by the fuselage to the ground below. The aft duct of the test engine was hardwalled (by taping the liner) in order to change the level, engine source ranking, and spectral content of aft fan noise to accomplish several objectives. Finally, to support all the objectives, the largest (known to the coauthors) array of ground and on-aircraft acoustic instrumentation was deployed for the test including a 954 microphone phased array, 216 on-aircraft dynamic pressure sensors, and 31 ground community noise microphones.

The resulting test plan was highly integrated so that each test condition and instrumentation system was contributing to multiple objectives. For example, the PAA high-level objective was accomplished with multiple types of PAA experiments that were integrated into the test that could be documented by multiple measurement systems. The Aircraft System Noise high-level objective was accomplished by the high quality and high-resolution instrumentation combined with an extensive set of flight test conditions.

This paper together with three complimentary papers (Refs. [16]-[18]) documents the description of the flight test planning, flight test execution, some initial results, and initial comparisons with the current predictions with the in-house version of NASA's ANOPP-Research code. Multiple PAA effects were measured including reflection to the ground and the azimuthal directivity introduced by this effect. Shielding by the fuselage while the aircraft is banking was measured, and results showed excellent agreement with pretest predictions with the new NASA PAASc method.

ANOPP has not been validated in a systematic way with flight test data in over 40 years. The initial comparisons of ANOPP-Research prediction for the total aircraft noise with measured data were the first performed and, by far, with the most detailed data ever available to NASA. While ANOPP has been updated most notably in the past 20 years, and several key new capabilities are now available in ANOPP-Research, aircraft technology has also changed greatly in the last 40 years, and at this point in time, the grand challenge of more physics-based prediction remains. Between the methods that have accumulated in ANOPP and the new tools for PAA and the Guo airframe methods in ANOPP-Research, many efforts have added more physics-based capability. Clearly, there have been great strides made in the direct prediction of PAA effects, specifically for the acoustic interaction effects of shielding, diffraction, and reflection. Also, the prediction of airframe noise sources, including airframe-to-airframe interactions, has made great advancement through the Guo airframe methods. However, the comparisons with data at the total aircraft level continue to show areas of much needed improvement. Combining results across the set of papers shows that prediction improvements are needed notably in fan source noise, liner attenuation, trailing edge, flap, and several additional PAA effects such as flow effects on scattering, jet-flap, and others.

This comprehensive flight test data of such high quality and resolution is already proving extremely valuable because the aircraft with all the real sources, geometry, PAA integration, and flight effects is the ultimate goal of this grand prediction challenge, and this dataset provides what has been lacking for decades. Of great value is being able to identify and quantify the prediction deficiencies, not just to guide, but to test, future modeling improvements. Understanding the current state of prediction is a great assist in the application of the current prediction capability until new improvements arrive.

Also notable is that with the scope of what was accomplished with this highly integrated PAA & ASN flight research, it has been demonstrated that acoustic flight research can, in fact, accomplish unique and comprehensive research objectives beyond just testing of noise reduction technologies. Acoustic flight research can be more directly relevant to application (as compared to wind tunnel research) for perhaps many more acoustic research topics than previously thought possible. Also, it is likely that time to application can be greatly shortened by accelerating research to flight. Acoustic flight research, similar to this model of PAA & ASN flight research, should become a more consistent tool in NASA's research portfolio.

Acknowledgments

The extraordinary support and funding of this research by the NASA Advanced Air Transport Technology Project is gratefully acknowledged. The exceptional efforts of The Boeing Company and the Boeing ecoDemonstrator Program are gratefully acknowledged in the execution of this challenging test under difficult circumstances. John Rawls and Stuart Pope, members of the Propulsion Airframe Aeroacoustics and Aircraft System Noise Team of the Aeroacoustics Branch, are also thanked for their support.

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