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Comparison of different measurement technologies for the in-flight assessment of radiated acoustic intensity

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1. INTRODUCTION

In an aircraft cabin during flight, there are numerous acoustic sources that radiate into the interior space producing a very complex sound field. To apply noise control treatment effectively, these noise sources must be identified, quantified and ranked. One approach for assessing these sources is an array of microphones and either near-field acoustical holography (NAH) or inverse boundary element method (IBEM) processing techniques that are used to reconstruct the sound field in the vicinity of the array. However, backside contamination and other flanking noise can corrupt the measurement of a source of interest, rendering a measurement result that may mislead the noise control engineer. Thus, NASA, The Naval Research Lab, and Boeing are pursuing an investigation of how best to use NAH and IBEM methods to make quality array measurement of noise sources in an aircraft cabin during flight.

A series of tests was planned and conducted in the Interior Noise Test Facility at Boeing Field, on the NASA Aries 757 flight research aircraft, and in the Structural Acoustic Loads and Transmission Facility at NASA Langley Research Center. These tests were designed to answer several questions concerning the use of array methods in flight. One focus of the tests was determining whether and to what extent array methods could be used to identify the effects of an acoustical treatment applied to a limited portion of an aircraft fuselage. Another focus of the tests was to verify that the arrays could be used to localize and quantify a known source purposely placed in front of the arrays. Thus the issues related to backside sources and flanking paths present in the complicated sound field were addressed during these tests. These issues were addressed through the use of reference transducers, both accelerometers mounted to the fuselage and microphones in the cabin, that were used to correlate the pressure holograms¹ measured by the microphone arrays using either SVD methods¹ or partial coherence methods². This correlation analysis accepts only energy that is coherent with the sources sensed by the reference transducers, allowing a noise control engineer to only identify and study those vibratory sources of interest. The remainder of this paper will present a detailed description of the test setups that were used in this test sequence and typical results of the NAH/IBEM analysis used to reconstruct the sound fields. Also, a comparison of data obtained in the laboratory environments and during flights of the 757 aircraft will be made.

2. INSTRUMENTATION AND ACOUSTIC TREATMENT DESCRIPTIONS

The primary instrumentation that was used during the tests in this effort was

- A spherical NAH¹ array (Fig. 1a) developed by Williams of the NRL
- A conformal NAH array (Fig. 1b) developed by Sklanka et. al. of Boeing
- An array of two microphone intensity probes (Fig. 1c)
- Several reference accelerometers mounted to the fuselage skin

The microphone arrays were centered on a window in the 757 test section in both the axial and circumferential direction (Fig. 2a). The spherical array consisted of 50 microphones arranged on a spherical surface that was 15.75 inches in diameter (Fig. 1a). When installed in the 757 test sections, the center of the sphere was spaced 16.25 inches horizontally off the center of the window and 37 inches off of the floor. The conformal array consisted of 120 microphones arranged with 12 mics axially and 10 mics circumferentially (Fig. 1b). The spacing in the axial and circumferential direction was 2 inches and 3 inches respectively and the conformal surface was offset 6 inches from the fuselage skin. The spacing of the mics in both the spherical and conformal arrays was suitable for analysis of the sound field up to a frequency of approximately 1,500 Hz. The measurement aperture of the conformal array was sufficient to overlap the ring frames on either side of the window by roughly 1 inch and cover the frame bays both above and below the window (Figs. 1b and 2a). During the laboratory tests in the INTF, 5 accelerometers were glued to the fuselage skin in front of the microphone arrays for use as reference transducers. During the test flight, 44 reference accelerometers were glued to the fuselage skin in front of the microphone arrays and 12 reference microphones were placed throughout the cabin.

The standard trim panels applied to the aircraft fuselage were removed from four frame bays in the test section (Fig. 2) and several simple treatments were applied to the fuselage and tested. The treatments studied were a 3 inch thick bat of “A” type yellow aircraft fiberglass, a 3 inch thick bat of “I” type gray aircraft fiberglass, and 1.0 lb/ft² mass fabric trim panel. All of the treatment configurations tested are listed in Table 1; however, only a subset of these data will be presented in this paper. The insertion loss of the treatments was measured with the different measurement techniques^{3,4} to determine the ability of the microphone arrays to measure changes in the sound power radiated from the sidewall under various treatment conditions and excitation mechanisms. In all, these treatments were studied while applied to four different fuselage test articles, two were in laboratory environments and two were sidewall sections of a flight test aircraft.

3. BOEING INTERIOR NOISE TEST FACILITY (INTF)

The INTF at Boeing Field consists of a 58 ft by 41 ft by 31 ft anechoic chamber and a 35 ft by 29 ft by 22.8 ft reverberation chamber with a transmission loss window connecting these two rooms. A full-scale sidewall section of a 757 aircraft was mounted in the transmission loss window (Fig. 3). This permitted the study of the vibro-acoustic behavior of a typical 757 sidewall under ideal laboratory conditions that was compared to the behavior observed during flight of the 757 aircraft. During the INTF measurements, both point force and diffuse acoustic field excitations of the test section were used. For the case of the point force excitation, an impedance head was used to sense the acceleration and force at the drive point. The diffuse field excitation was produced by driving the reverberation room with speakers mounted to the walls (Fig. 3c). The arrays were installed in the test section (Fig. 3b) and the vibro-acoustic response of the treatment configurations (Table 1) was measured. All transducer channels were sampled simultaneously, at a sampling rate of 12,000 Hz. For each treatment configuration, time history data for each transducer was recorded for at least 5 minutes for both excitations. The radiated power was found using the various array processing methods^{1,2,3} for all of the treatment conditions and the insertion loss of the treatments was computed.

4. NASA ARIES 757 AIRCRAFT

The NASA Aries is a Boeing 757-200 series aircraft that is dedicated to flight test operations and is based at NASA Langley Research Center. The recent tests on this flying laboratory focused on the noise inside the aircraft cabin produced by pressure fluctuations on the outside surface of the fuselage, typically due to the turbulent boundary layer and excitation associated with the propulsor noise. The aircraft and array hardware are illustrated in Figs. 4 and 5. Most of the seats in the aircraft were removed for this flight test (Fig. 4b), which provided unobstructed experiment sections in both the forward and aft part of the cabin (Fig. 5a). The first experiment area was in the forward portion of the aircraft, at stations 480 through 560, where turbulent boundary layer (TBL) pressure fluctuations are a dominant source of sound. The second experiment area was in the aft of the aircraft, at stations 1380 through 1460, where both TBL and jet noise excitation of the fuselage are present. However, only results from the forward test section are presented

in this paper. For the various treatment configurations (Table 1), measurements were made with the arrays at these two experiment areas during separate flights. During each of the 18 flights that were made, the aircraft was flown off of the coast of South Carolina at a tightly controlled altitude and speed of 30,000 ft and 0.8 Mach for a straight and level flight condition with only minimal air turbulence allowed. To compute the insertion loss of the treatments, it was assumed that matching the altitude and air speed from flight to flight would provide consistency in the fuselage vibro-acoustic excitation levels. Thus, the insertion loss of a treatment was found by comparing the radiated sound power of the bare fuselage to the radiated sound power of the treated fuselage (Table 1). All transducer channels were sampled simultaneously, at a sampling rate of 12,000 Hz. For each treatment configuration, time history data for each transducer was recorded for 20 minutes during prescribed cruise conditions.

5. NASA STRUCTURAL ACOUSTIC LOADS AND TRANSMISSION (SALT) FACILITY

The SALT facility consists of a 15 ft by 25 ft by 31.6 ft anechoic chamber and a 14.75 ft by 21.3 ft by 31.2 ft reverberation chamber with a transmission loss window connecting these two rooms. A flat stiffened aluminum fuselage panel mounted in the transmission loss window is shown in Fig. 6. This panel was fabricated with the same ring frame-stringer geometry as a typical aircraft but is not identical to the construction of a 757 aircraft sidewall. The exposed area of the panel was 46 inches square and the panel was clamped in a steel frame in the transmission loss window. The skin is 0.050 inch thick aluminum, the frames are 2.25 inch deep by 0.050 inch thick aluminum S sections attached to the skin by 0.050 inch thick aluminum shear clips, and the longerons are 0.050 thick by 0.75 inch tall aluminum hat sections. The panel was driven by a diffuse acoustic field produced by exciting the reverberation chamber using an array of speakers mounted to the wall. An array of intensity probes was scanned in front of the test article to measure sound power transmitted through the panel into the anechoic room⁴. The transmission loss of the panel, both with and without treatment (Table 1), was found from the ratio of the transmitted and incident sound powers⁴. The insertion loss of each of the treatment configurations (Table 1) was found from the transmission loss data.

6. RESULTS AND DISCUSSION

For diagnostic purposes during the flight test and the INTF test, a point source was created to verify the ability of the microphone arrays to localize a known source. A JBL compression driver model 2446H was connected to one end of a vinyl hose and the other end of the vinyl hose was placed at the center of the window in front of the microphone arrays (Fig. 7). During this diagnostic test, the JBL compression driver was excited by pseudo-random noise band limited from 500 to 1,500 Hz and the response of the arrays were measured along with this excitation signal. The pressure holograms were then correlated to this excitation signal and the sound field was reconstructed using NAH and IBEM. The results of this simple test are illustrated in Figs. 8 through 10. The spherical array responses and spherical NAH methods¹ were used to reconstruct the intensity field in a volume surrounding the spherical array (Fig. 8). It is clear that the source is radiating into the cabin from the position of the acoustic source exit at the center of the window (Fig. 8). The conformal and spherical array measurements were used with patch IBEM³ to reconstruct the intensity field on the surface of the fuselage skin (Figs. 9 and 10). These also clearly show the exit of the acoustic source at its location in the window. These data illustrate the usefulness of array methods and partial coherence or SVD analysis when trying to quantify a known source of interest inside the aircraft cabin. This can be very useful, for example, in studying HVAC noise.

As was outlined in Section 2, several treatments were applied to the aircraft fuselage and the arrays were used to measure the sound power transmitted through the test section with and without the treatments in place. In all, five treatment configurations (Table 1) were tested in four test sections (the forward and aft test sections of the NASA 757 Aries, the Boeing INTF 757 test section, and the SALT stiffened aluminum panel) using the spherical array, conformal array, and intensity probes. Thus, there is a database of 60 test conditions that can be analyzed using a variety of reconstruction methods. However, only a few conditions were analyzed for the results presented in this paper.

From the flight test, a sub-set of five reference accelerometers was used to correlate the array pressure measurements to the fuselage vibration in front of the arrays using a partial coherence approach².

This analysis results in five partial fields that are perfectly coherent to the respective accelerometer responses, having rejected the energy in the pressure measurement that is incoherent to these accelerometers. These coherent partial fields were then propagated to the treatment boundary using patch IBEM methods³, and the radiated intensity distribution and integrated sound power was computed for the different treatment configurations (Table 1). The insertion loss of the treatment was found as described in Sec. 4. For the results presented from the NASA SALT facility, the insertion loss of each treatment configuration (Table 1) was measured as described in Sec. 5.

The insertion loss measured in SALT using intensity probes is compared to the flight test insertion loss measured using both the conformal array and the intensity probe array for the “I” type fiberglass treatment (Fig. 11) and the “A” type fiberglass with mass fabric treatment (Fig. 12). From this comparison, good agreement is observed below 800 Hz for both treatment cases. However, during flight, the insertion loss of the AM treatment (Table 1) appears to plateau above roughly 800 Hz. This is believed to be the result of flanking energy that is coherent to the accelerometer vibration that was used to compute the insertion loss. It should be noted that the insertion loss measured by the intensity probe array during flight was in worse agreement with the expected insertion loss than was the conformal array result (Fig. 12). This suggests that during flight the microphone arrays may be less susceptible to extraneous noise than are the intensity probes.

7. CONCLUDING REMARKS

A series of tests, both laboratory and flight, were conducted by NASA, the NRL, and Boeing to assess the use of microphone array measurement techniques in studying the sound radiated into an aircraft cabin. The primary transmission path that was studied in this effort was sound in the cabin that is produced as a result of pressure fluctuations outside the aircraft transmitting through the fuselage. Several treatment configurations were used to identify how much of a change in radiated power can be detected by the array methods. It was shown that the microphone array measurements in flight are in close agreement with laboratory measurement for simple treatments that have insertion loss values up to roughly 30 dB. For insertion loss values greater than 30 dB, it is believed that coherent flanking noise was a problem during the flight tests because the expected insertion loss was significantly higher than was observed. It was also demonstrated, by the study of the point acoustic source, that array methods can be used to locate and quantify a known source during flight.

The content presented in this paper primarily serves to introduce the tests that were conducted and present typical results. In all, well over 500 GB of vibro-acoustic time history data was gathered during this test sequence. The response data collected during these tests will provide a significant database for ongoing analysis by the authors of this paper who look forward to future presentations of these data.

ACKNOWLEDGMENTS

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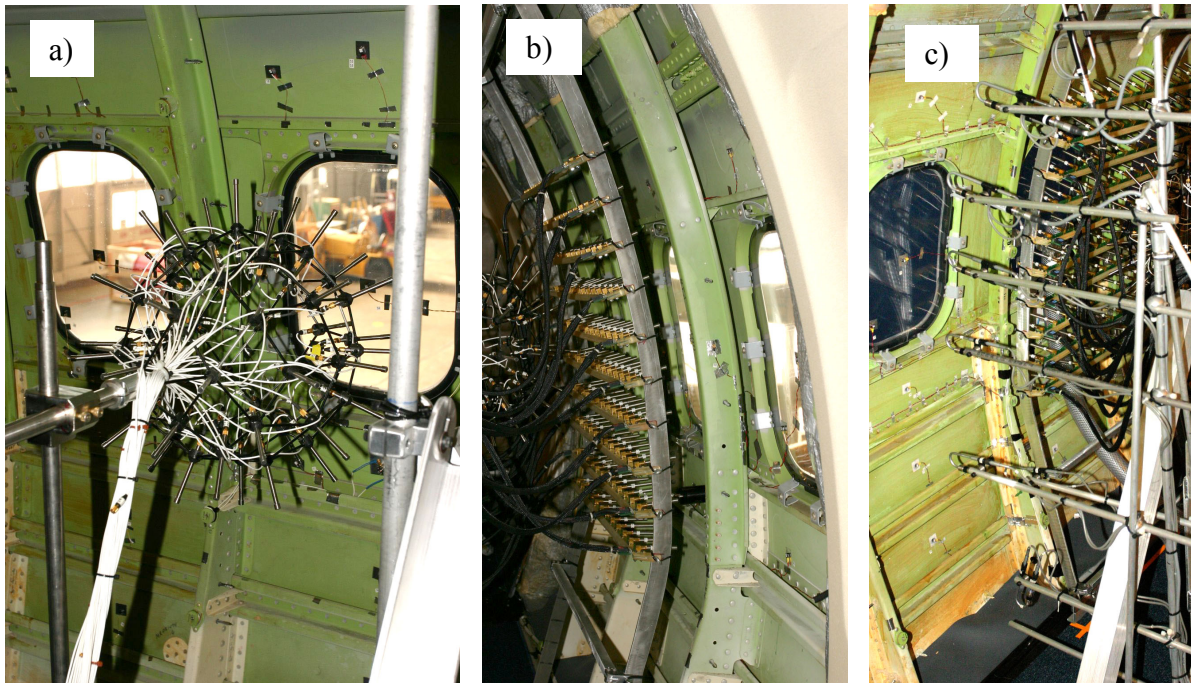


Fig. 1: Other transducers used during the test series; a) spherical NAH array, b) conformal NAH array, c) matched microphone pair intensity probe array.

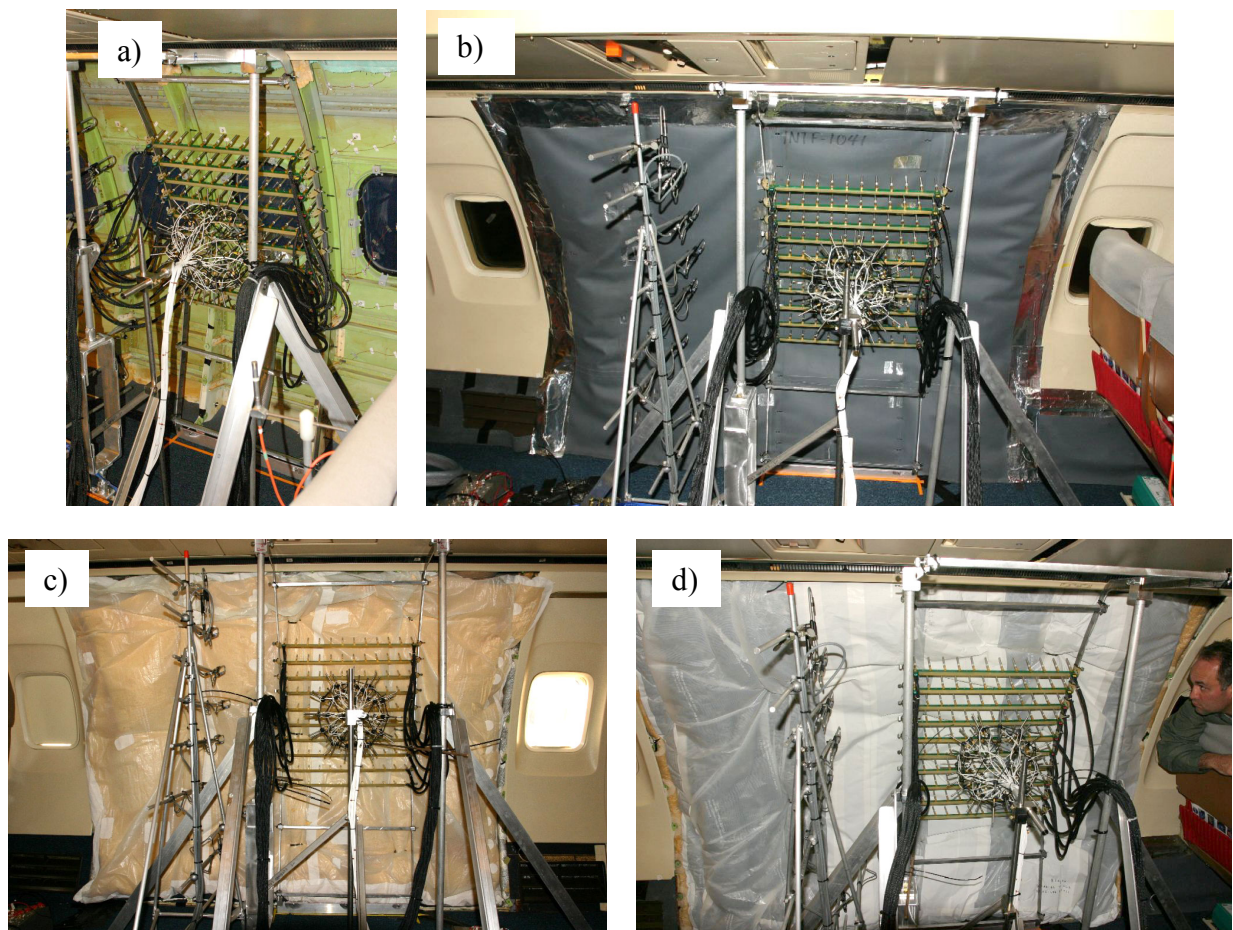


Fig. 2: Treatment configurations and array positions for the 757 flight test; a) bare fuselage, b) mass fabric, c) A-type fiberglass, d) I-type fiberglass.

Table 1: Treatment Configurations	Acronym
Bare fuselage panel, no treatment	B
Fuselage panel with mass fabric trim panel	M
Fuselage panel with "A" type fiberglass	A
Fuselage panel with "I" type fiberglass	I
Fuselage panel with mass fabric trim panel with "A" type fiberglass	AM
Fuselage panel with mass fabric trim panel with "I" type fiberglass	IM

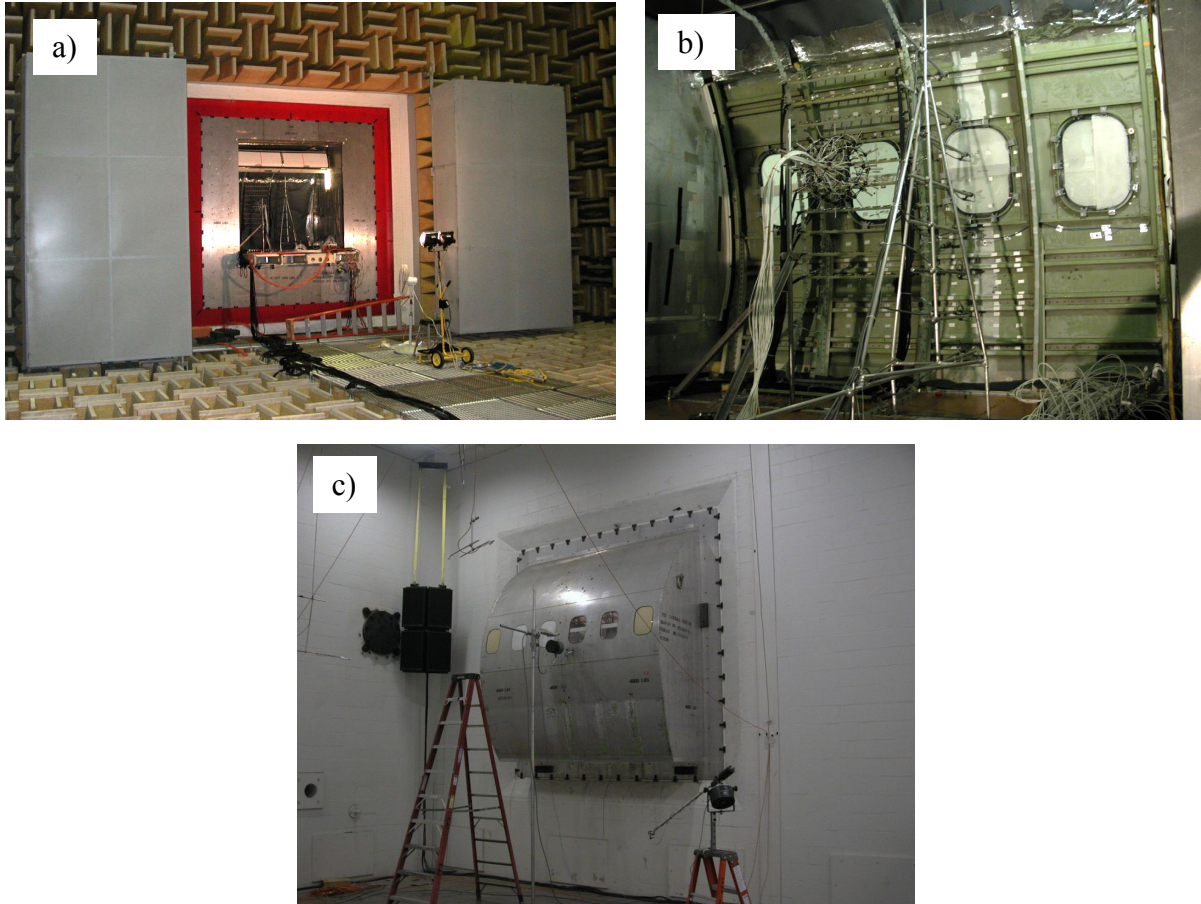


Fig. 3: 757 sidewall section installed in the Boeing INTF transmission loss window; a) the sidewall section from the anechoic side, b) close-up of the sidewall section showing the array locations, c) the sidewall section from the reverberation room.

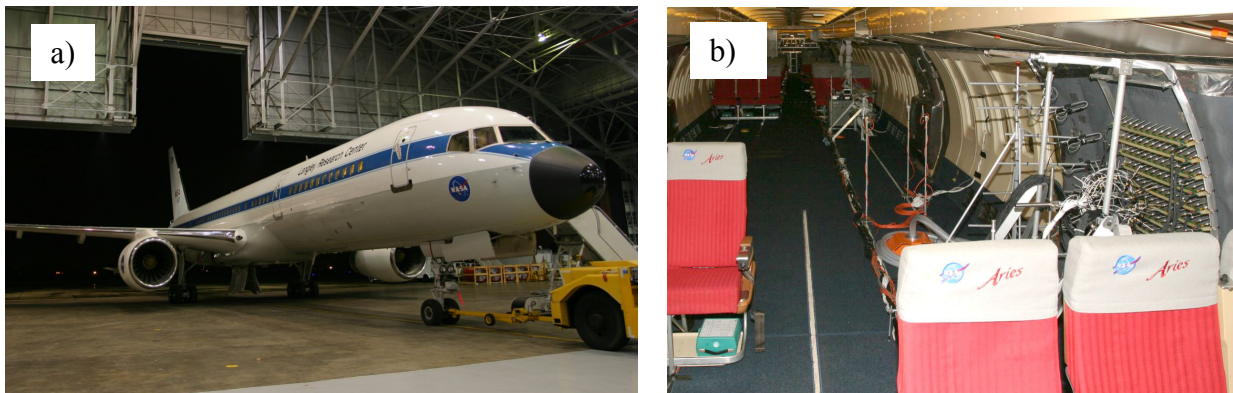


Fig. 4: NASA Aries 757 flight test setup; a) the aircraft and b) the cabin showing the array locations installed in the forward experiment section.

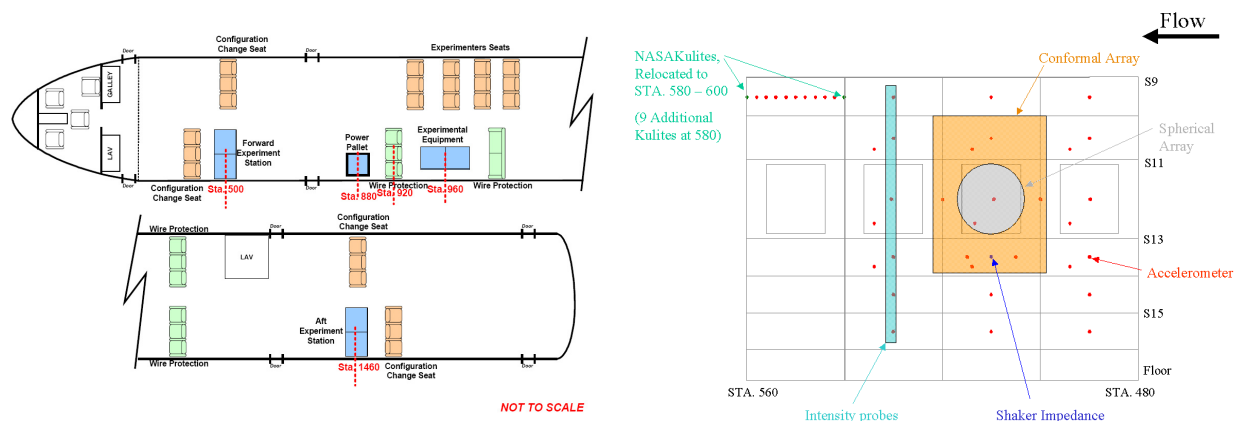


Fig. 5: NASA Aries 757 flight test; a) cabin layout illustrating the experiment section locations and b) forward experiment section transducer positions were accelerometer locations are identified by the red dots, the conformal array position is identified orange rectangle, the sphere position is identified by the gray circle, and the intensity probe array position is identified by the blue rectangle.

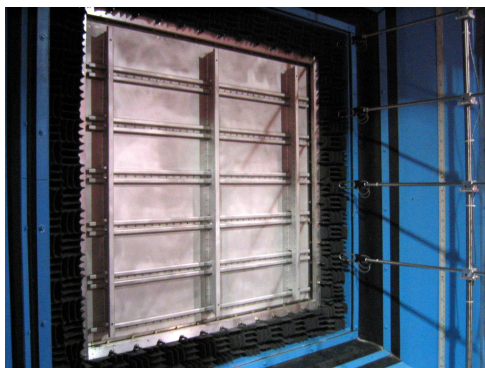


Fig. 6: Flat stiffened aluminum panel tested in the Structural Acoustic Loads and Transmission facility at NASA Langley Research Center.

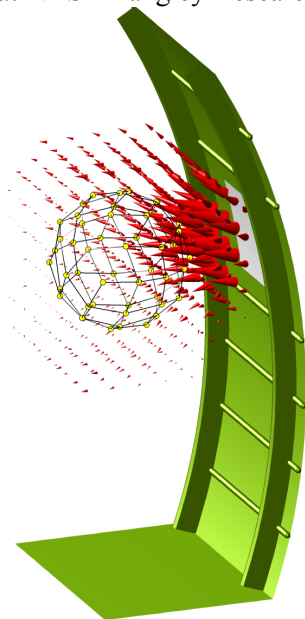


Fig. 8: Spherical NAH result with the acoustic source placed in the window.

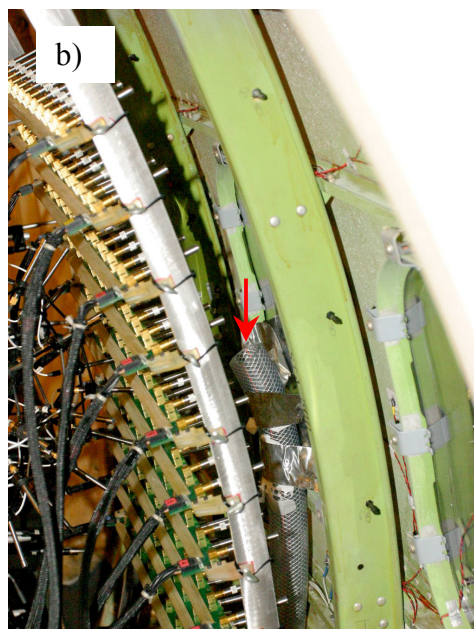
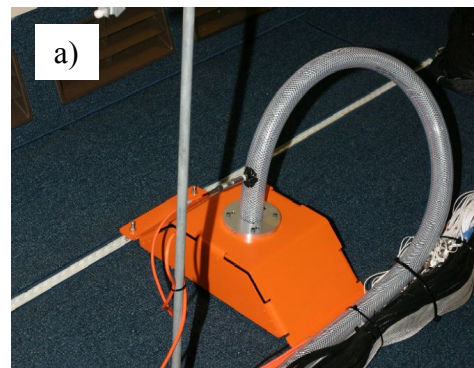


Fig. 7: Acoustic source (exit indicated by the red arrow) placed at the center of the window to provide a known point source; a) the acoustic driver and b) termination behind the arrays.

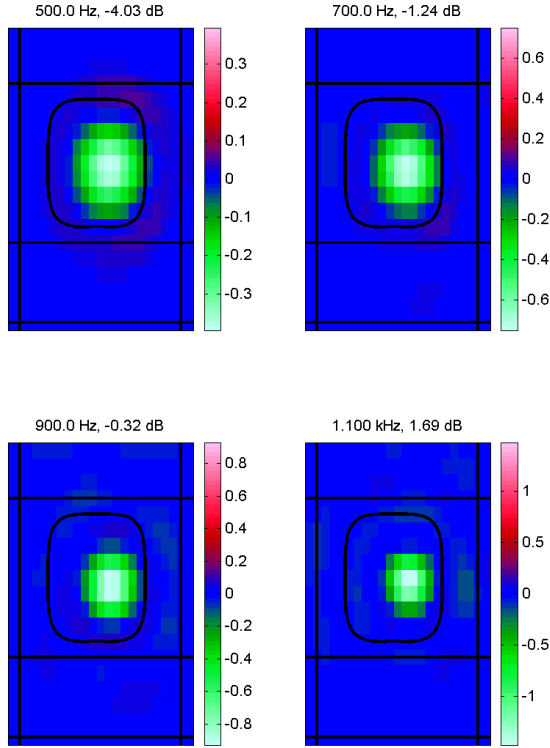


Fig. 9: Reconstruction of the acoustic source at four frequencies using the conformal array and IBEM methods.

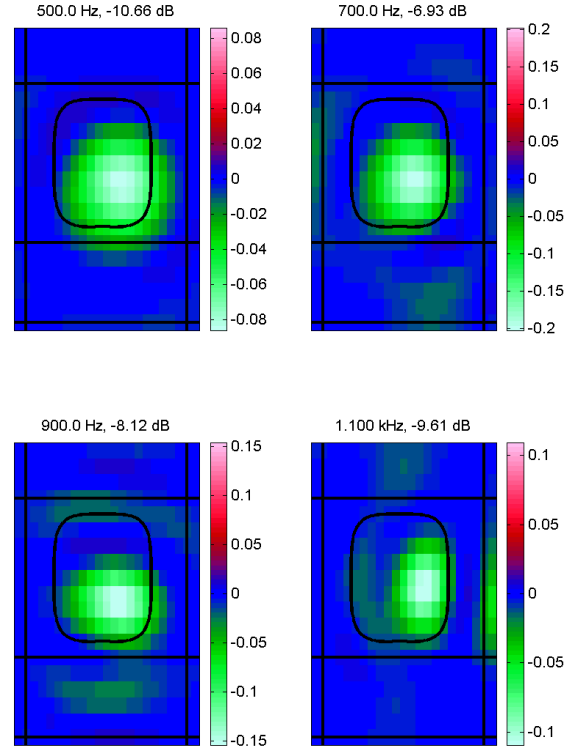


Fig. 10: Reconstruction of the acoustic source at four frequencies using the spherical array and IBEM methods.

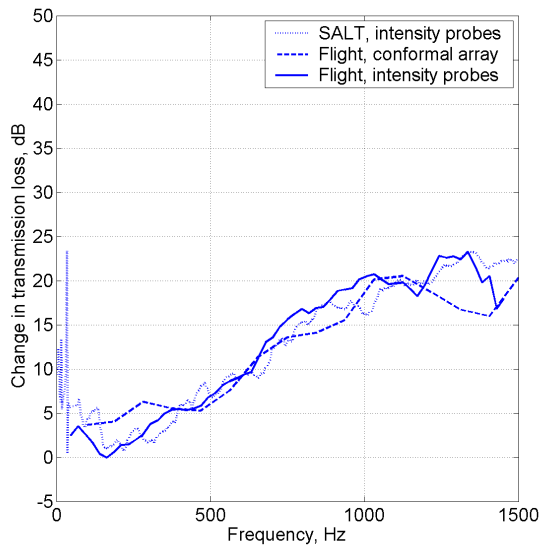


Fig. 11: Comparison of the insertion loss of the "T" type fiberglass treatment measured in the SALT facility and in flight on the 757.

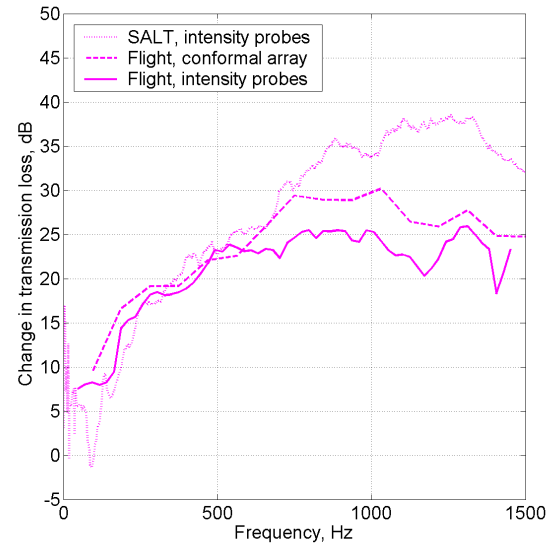


Fig. 12: Comparison of the insertion loss of the "A" type fiberglass with mass fabric treatment measured in the SALT facility and in flight on the 757.