

Multiplanar Synthetic Arrays and Their Application to Full-Scale Landing Gear Noise Source Identification

Patricio A. Ravetta¹

AVEC Inc., Blacksburg, VA, 24060, USA

Mehdi R. Khorrami²

NASA Langley Research Center, Hampton, VA, 23681, USA

Benedikt König³ and Ehab Fares⁴

Dassault Systèmes Deutschland GmbH, D-70563, Stuttgart, Germany

Identification and quantification of noise sources generated by the landing gears of large civil transports are critical for the development of viable abatement technologies that can be applied locally to affect solely the source regions. Leveraging validated computational data sets obtained from airframe noise simulations of a full-scale B777-300ER aircraft, a framework based on multiplanar synthetic arrays was developed to examine landing gear sources. The position of the arrays relative to the aircraft nose or main landing gears, the number of microphones in each array, and their distribution pattern were judiciously selected to provide adequate spatial resolution of the sources in the primary flyover, sideline, and upstream directions while maintaining reasonable signal-to-noise ratio and beamwidth over a wide frequency range. Overall, seven synthetic arrays with 800 microphones each, for a total of 5,600 microphones, were used in the framework. Fully synchronous synthetic pressure records at each microphone location were obtained from the simulated data sets via a Ffowcs-Williams and Hawkings integral approach, with flow quantities on a permeable data surface enclosing the source regions used as input. Various applications of synthetic multiplanar arrays to acoustic data analysis are presented. The advantages of the framework in properly resolving and identifying the B777 landing gear sources is demonstrated by comparing three-dimensional source distribution maps with those obtained from a synthetic version of the ground-based microphone array used during flight tests of the same aircraft.

I. Introduction

The airframe is a significant contributor to the total noise generated by modern aircraft during approach and landing. The primary sources of airframe noise are the undercarriage and wing high-lift devices (slats and flaps) [1]. Contributions from the landing gear to the total airframe noise signature increase substantially for large, twin-aisle airliners [2-4] because of the extreme geometric complexity of the numerous subsystems involved. Proper resolution of gear sources is a prerequisite for accurately identifying the subcomponents that produce noise. Such knowledge is critical for the development of mitigation strategies that can be applied locally to the target area. During typical airframe noise flight tests, a phased microphone array deployed on the ground is used to determine the locations and strengths of the landing gear noise sources [4-6]. Due to large array sizes and relatively high altitudes of the test aircraft during flyby passes, the array is incapable of providing meaningful resolution at the subcomponent level. In some cases, even major nearby components, such as main landing gear and flaps, cannot be separated. This is par-

¹ Co-owner, Chief Research Engineer, Senior Member AIAA.

² Senior Scientist, Computational AeroSciences Branch, Associate Fellow AIAA.

³ Senior Specialist, SIMULIA Aerospace & Defense.

⁴ Director, Aerospace and Defense (currently with Geely Auto Technical, Deutschland, GmbH), Senior Member AIAA.

ticularly true in the direction normal to the ground. The availability of fully validated computational data from high-fidelity, full-scale airframe noise simulations affords us various unique advantages: we can move the array closer to the aircraft, reorient its direction, use multiple arrays simultaneously, and tailor the number of microphones and their pattern to achieve the desired resolution for the gear sources.

The present work was performed as part of the larger NASA-Boeing joint effort on airframe noise prediction designed to extend simulation-based methodology to the undercarriage and high-lift systems of full-scale, large civil transports. The collaboration was executed in successive steps whereby the complexity and relevance of the studied configuration to the full-scale, complete aircraft were gradually increased. During the latter stages of the joint effort, simulations of the full-scale, installed nose landing gear (NLG) of a B777-300ER aircraft in combination with a cruise wing were performed first [7], followed by simulations of a full-scale, complete B777-300ER with nose and main landing gears (MLG) deployed and wing high-lift devices either retracted or deployed [8]. Acoustic measurements acquired during the 2005 Quiet Technology Demonstrator II (QTD2) [4] flight test were used to validate the far-field noise spectra predicted by the full-scale simulations [9].

Leveraging the validated computational data sets, the present paper describes the development and evaluation of a multiplanar synthetic array framework for the identification of landing gear noise sources. Various applications of the framework to acoustic data analysis are presented. The advantages of the approach to the proper identification and quantification of B777 landing gear noise sources was demonstrated by comparing the computed integrated spectra and three-dimensional source distribution maps with those obtained from a synthetic realization of the ground-based microphone array used during the QTD2 flight test of the same aircraft.

II. Full-Scale Computational Data Sets

The computational data were generated during an extensive simulation campaign of the full-scale B777-300ER aircraft [7-8]. For validation purposes, multiple aircraft configurations were considered: a) NLG deployed with MLG and wing high-lift devices stowed (Fig. 1); b) NLG and MLG deployed with wing high-lift devices retracted (Fig. 2a); and c) NLG, MLG, and wing high-lift devices deployed (Fig. 2b). For simplification and consistency with related publications, these configurations are also referred to as “NLG-only”, “Config1”, and “Config2”, respectively. All simulations were performed using the lattice Boltzmann solver PowerFLOW® to capture time-dependent flow data. The computations were conducted at flight conditions and aircraft parameters that matched those recorded during the array flyover passes, except for Reynolds number (Re_c). The Re_c for all simulations was 20×10^6 , which is approximately 50% of the flight Re_c based on mean aerodynamic chord and aircraft speed of 86.89 m/s (168.9 kts) for Config2 and approximately 35% based on a speed of 117.87 m/s (229.8 kts) for NLG-only and Config1, as listed in Table 1. This Re_c is sufficiently high to produce far-field noise levels that are nearly equivalent, at a lower computational cost, to those obtained at full flight Re_c [9]. Simulations for the NLG-only configuration were performed first [7]. The forward location of the NLG, away from other airframe components, precludes interactions between the flow produced by this component and that from the main gear and/or high-lift devices [8]. As a result, the effectively isolated nose gear configuration shown in Fig. 1 enabled simulations at a very fine spatial resolution that would have been prohibitive if the MLG were also deployed. By performing the nose gear simulations at successively finer resolutions, we were able to ascertain the full effect of mesh granularity on predicted sound levels and frequency content of the far-field spectrum. This approach also helped develop a meshing strategy better suited to simulate the extremely challenging case of a large commercial aircraft in landing configuration.

Table 1. Flight conditions used for simulation of selected aircraft configurations.

Configuration	AoA	Mach	Speed (kts)	Re
NLG-only, Config1	6.5°	0.344	229.8	20×10^6
Config2	4.0°	0.254	168.9	20×10^6

The far-field pressure records at the microphones that comprised the arrays surrounding the landing gear were computed using a Ffowcs-Williams and Hawkins (FWH) integral approach [10], with flow quantities on a permeable data surface enclosing the noise sources of interest used as input. The synthetic microphone array pressure records contain 0.7 to 0.9 seconds of simulated physical time. Results for NLG-only were computed at four spatial resolutions referred to as “xcoarse” (short for extra coarse), “coarse”, “medium” and “fine”. As described in Ref. [8], medium resolution simulations for Config1 and Config2 were not yet complete when the NASA-Boeing joint effort ended. Therefore, results for configurations with the MLG deployed were only available in xcoarse and coarse

resolutions. A refinement factor of 1.5 in terms of minimum global voxel size was used between each resolution level. Note that, although the same resolution naming was used, the near-wall mesh size for NLG-only was slightly finer than that for the NLG in Config1 and Config2 simulations, resulting in a slight degradation in resolution of high frequency sound for the NLG in the latter two configurations. Full descriptions of the computational methodology, model geometries, and simulated data are provided in Refs. [7] and [8] for the isolated NLG and the aircraft with the MLG deployed, respectively.

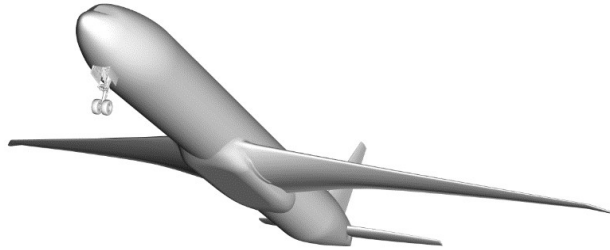


Fig. 1 Installed, isolated B777-300ER nose landing gear configuration (“NLG-only”), from Ref. [7].

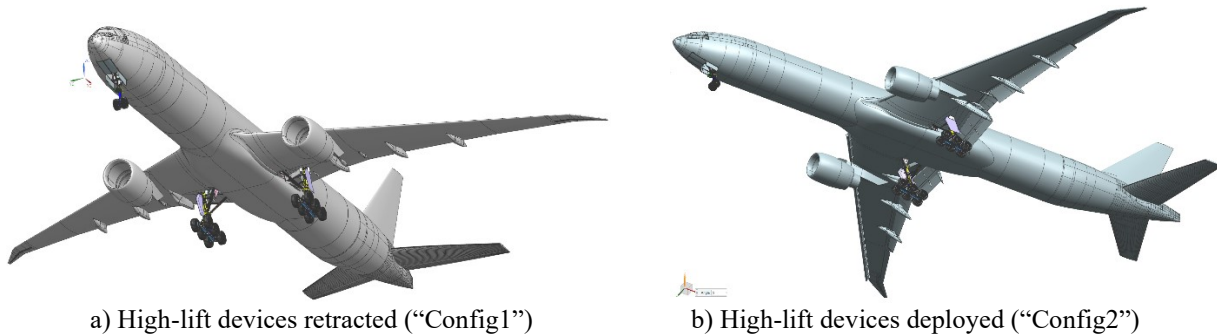


Fig. 2 Full-scale B777-300ER aircraft with nose and main landing gears deployed, from Ref. [8].

III. Multiplanar Synthetic Array Framework

The main goal of this work was to leverage results from existing simulations to quantify, at the subcomponent level, the dominant noise sources in both nose and main landing gears without including contributions from nearby sources, e.g., high-lift devices. This objective could be achieved with synthetic arrays judiciously placed in close proximity to the landing gears. The use of arrays smaller than those typically employed during flight tests, placed close to the components of interest, would allow a classification of sources at the subcomponent level, similar to what can be accomplished in a wind tunnel test of an isolated landing gear. Given the highly directional nature of the various landing gear noise sources and potential shielding effects typically observed in wind tunnel tests, we also sought to identify the dominant sources that radiate in the flyover, sideline, and forward (upstream) directions.

The approach consisted in developing a synthetic array with a high number of microphones to provide the desired spatial resolution and array signal-to-noise ratio (SNR) in the frequency range of interest. Replicas of this array were then positioned strategically to obtain the desired results for different directivities.

A. Synthetic Array Design

After multiple iterations, the final array design comprised three nested, multiarm spiral subarrays targeting different frequency ranges. The main parameters for each subarray are listed in Table 2. The outer diameter (OD) of the array was set to 8m – not too large relative to the NLG but still able to analyze very low frequencies. The figure of merit of each subarray and the combined array is 1 (no redundancy). The total number of microphones in the array was 800, including a reference microphone at the center of the array. The final design, with microphones color-coded according to subarray (as indicated in Table 2), and a schematic of the array relative to the NLG, are shown in Fig. 3.

Table 2 Array design parameters.

Sub-array	No. of mics.	No. of arms	Mics. per arm	ID [m]	OD [m]
Low Frequency (blue)	133	19	7	4.5	8
Mid Frequency (green)	207	23	9	2	5
High Frequency (red)	459	27	17	0.05	2.2
TOTAL	800*	*microphone added at the center of the array			

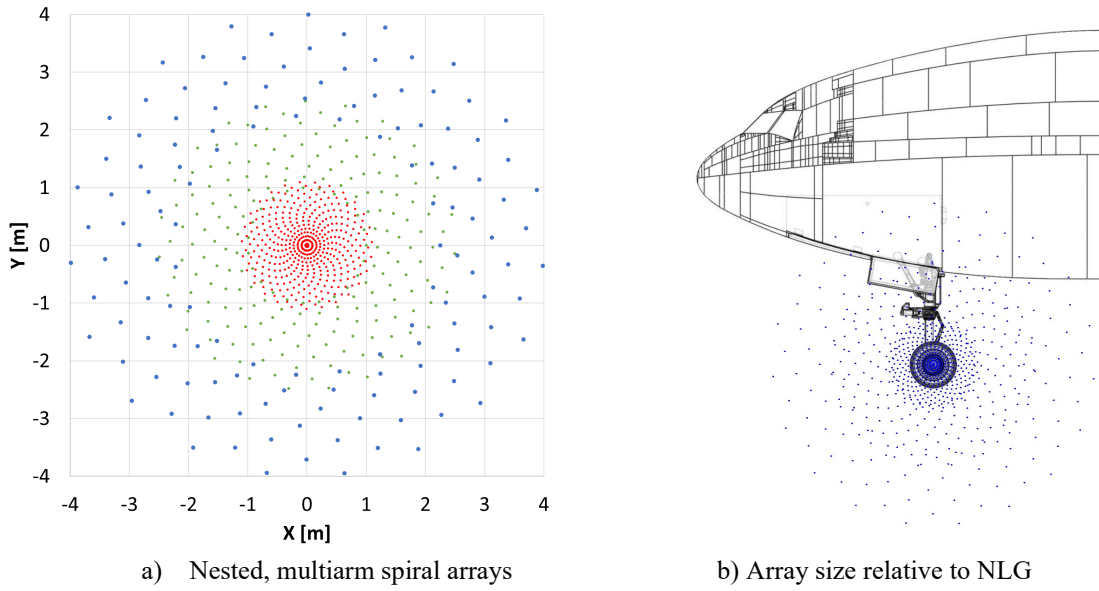


Fig. 3 Final array design.

A hyperbolic tangent-based shading algorithm, used previously in Ref. [11], was employed during beamforming to improve array resolution while preserving a good SNR for all frequencies of interest. To showcase array resolution relative to the NLG, beamwidth as a function of frequency is shown in Fig. 4 with shading (green line) and without shading (red line, reference). Also included in Fig. 4 are sample acoustic maps for a single source (point spread function, PSF) with a 3 dB cutoff for a few select frequencies. The SNR, beamwidth, and acoustic maps were obtained for a grid size (S) of 10 m by 10 m and a distance between source and array (L) of 6 m. Additional improvements in resolution, particularly below 1 kHz, were obtained from use of the CLEAN deconvolution algorithm [12]. With custom shading applied, the array SNR was at least 16 dB for the frequency range between 1.4 kHz and 10 kHz, and at least 10 dB at lower frequencies, as shown in Fig. 5. Sample acoustic maps with a 25 dB cutoff are also included in Fig. 5 to illustrate the impact of shading on the level and location of sidelobes.

Computation of synthetic pressure records at the microphone locations necessitated the arrays to be located outside of the permeable FWH surface. Although $L = 6$ m was desired, the shape and extent of the permeable data surface evolved as the simulation campaign progressed to accommodate more complex aircraft configurations. Distances between some arrays and the landing gear also increased during the process. Since the same array design was intended for all positions, the increased distances resulted in a modest degradation in array resolution relative to the values shown in Fig. 4.

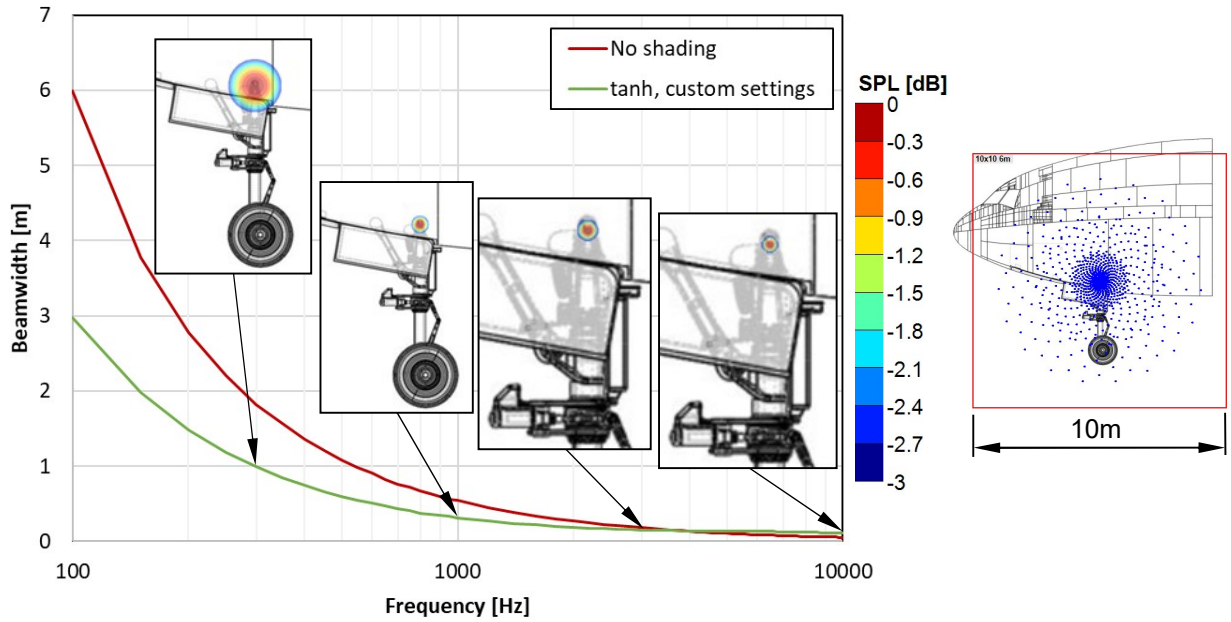


Fig. 4 Array resolution (beamwidth) as a function of frequency. Sample acoustic maps show beamwidth (PSF with 3 dB down) for a source 6 m from the array plane.

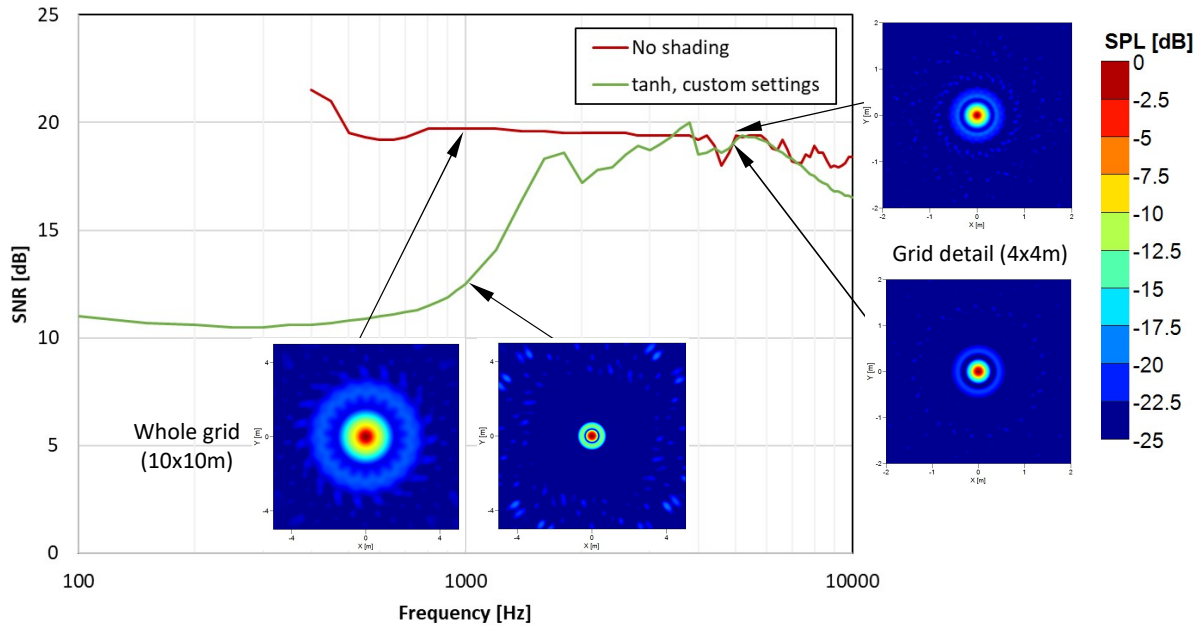


Fig. 5 Array signal-to-noise ratio (SNR) as a function of frequency. Sample acoustic maps show SNR (PSF with 25 dB down) for a source 6 m from the array plane.

B. Array Placement

The primary requirements for array placement were: i) arrays had to be placed outside the FWH permeable data surface, ii) noise emitted at 90° (overhead and sideline) was of main interest, and iii) the distance between source and each array should be similar to maintain a consistent array resolution in all directions. To obtain the noise emitted at 90° , the arrays for each landing gear were centered – after accounting for flow convection effects – at the corresponding gear axle.

To determine the effects of slat and flap deflection on landing gear noise sources, beamform maps and integrated spectra from all configurations must be compared directly. As displayed in Fig. 6, the permeable FWH surface for Config2 (Fig. 2b) is slightly larger than, and fully encloses, the data surface for Config1 (Fig. 2a). To simplify comparisons, all arrays were placed outside the larger permeable data surface. Final placement was not a major issue for the NLG arrays, requiring only slight movements (displacement and rotation) of the upstream array. However, for the MLG, the arrays had to be placed farther away than the distance for which they were originally designed (based on NLG-only simulations). The upstream array also had to be moved off-axis relative to the center of the MLG and rotated about two axes so that it would “point” toward the port MLG. Scaling each array to account for increased distance to the axle – a process that could require several iterations to satisfy the primary constraints – was not attempted. Thus, array resolution is slightly lower than that obtained with the NLG arrays, and emission angles are different than the preferred 90° after convection effects are included. The flyover MLG array is also included in Fig. 6. A depiction of the seven arrays used (3 for the NLG and 4 for the port MLG) is shown in Fig. 7. For conciseness, the arrays were named after the targeted landing gear (NLG or MLG) and their location: flyover (FO), sideline (SL), and upstream (US). The flyover array positioned between the two MLGs on the aircraft centerline will be referred to as flyover centered (FOC).

As indicated in Ref. [8], the permeable data surface for Config2 was too costly for use at spatial resolutions higher than xcoarse. Therefore, the permeable data surface devised for Config1 (shown in orange in Fig. 6) was used as the primary data surface for both configurations. For additional information on the impact of permeable data surface shape and extent, the reader is referred to Ref. [8].

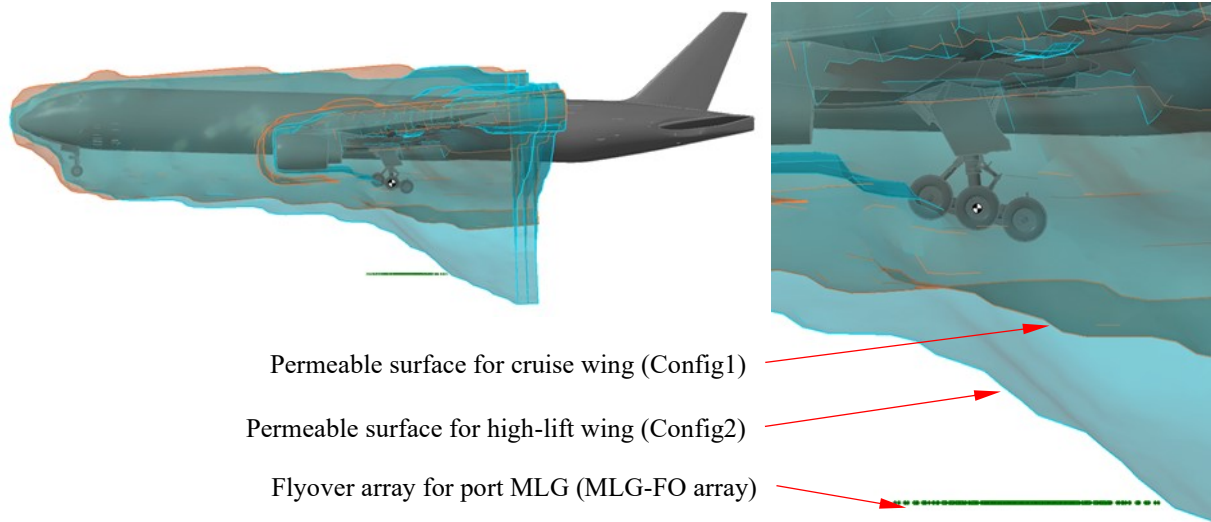


Fig. 6 Schematic of permeable data surfaces for Config1 (orange) and Config2 (light blue).

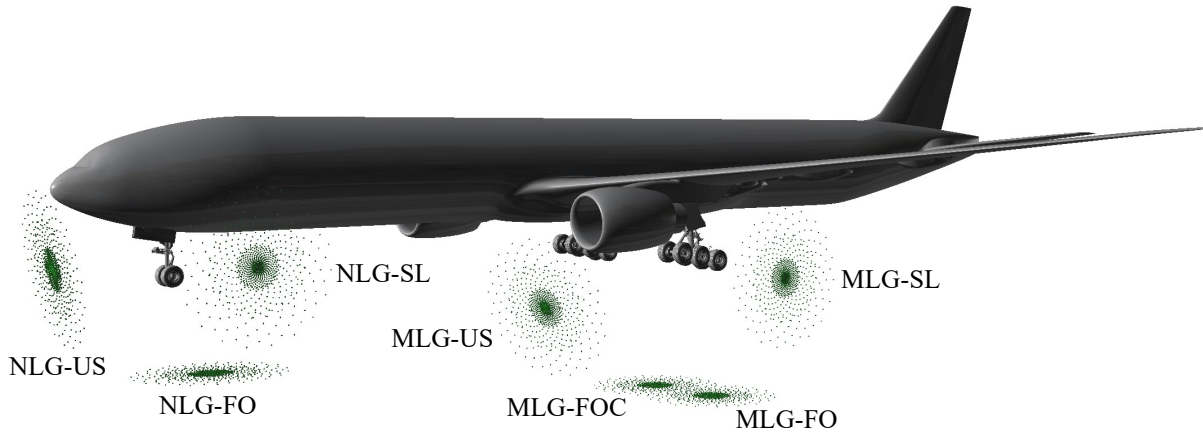


Fig. 7 Schematic of 7 synthetic arrays (5,600 microphones) designed for nose and port main landing gears.

C. Array Data Processing

Beamforming in the frequency domain was used to process the synthetic array data. Flow convection effects were included in the FWH propagation and beamforming process. Diagonal removal and array shading were used to improve the results [13]; beamforming results were post-processed using the CLEAN technique [12]. Acoustic maps were generated on a three-dimensional (3D) region surrounding each landing gear (nose or port main gear). For CLEAN to render accurate results, a grid that includes all noise sources in the flow field (the entire aircraft and the permeable data surface downstream of the wing) must be devised. Otherwise, CLEAN may produce inaccuracies and/or spurious sources. In the present case, the NLG and its close-up NLG arrays are so far from other components that no contamination from other sources was observed. However, even with the MLG arrays in close proximity of the port MLG, there are many other sources [8] that can impact the results (e.g., flaps, slats, flaperons, starboard MLG). Although a large grid encompassing the entire aircraft would have been ideal for CLEAN, such a choice would impose significant requirements in terms of computational resources and processing time. Therefore, after running conventional beamforming on different grids to determine the relative levels of other potential sources, two different 3D grids were defined: i) a high-lift (Config2) grid that encompasses the port MLG, the inboard section of the wing, and most of the left engine and its pylon; and ii) a cruise (Config1) grid that is similar to the high-lift one but excludes the slat region. Schematics of these two grids, superimposed on a low-fidelity model of the aircraft for visualization purposes, are shown in Fig. 8. The grid for the NLG is shown in Fig. 9.

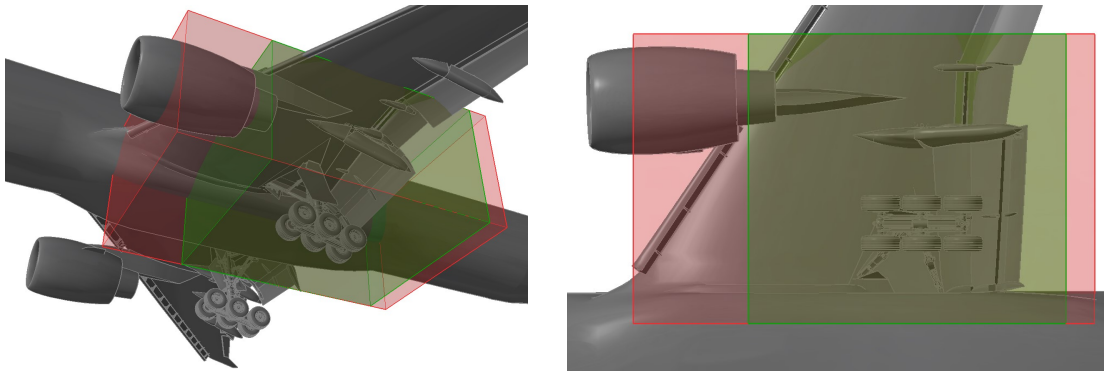


Fig. 8 Port MLG beamforming grids for Config1 (in green) and Config2 (in red).

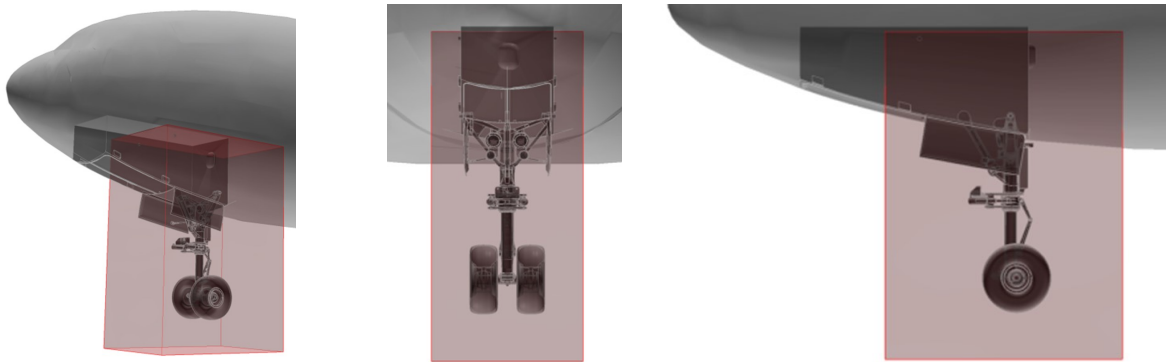


Fig. 9 NLG beamforming grid.

When deconvolving acoustic maps from conventional beamforming with the CLEAN algorithm, sources are often reduced to a few grid cells with nonzero values that could be in different planes of the 3D grid. Although their corresponding spectral values are accurate, these sources are difficult to visualize. Thus, CLEAN acoustic maps with an artificial resolution of 0.5 m were also generated for visualization purposes only. Sample acoustic maps showing both types of results (zero-resolution and custom-resolution) are shown in Fig. 10. This figure also includes isosurfaces of the CLEAN contour levels (Fig. 10d) that help visualize results from multiple planes by grouping them in a single map.

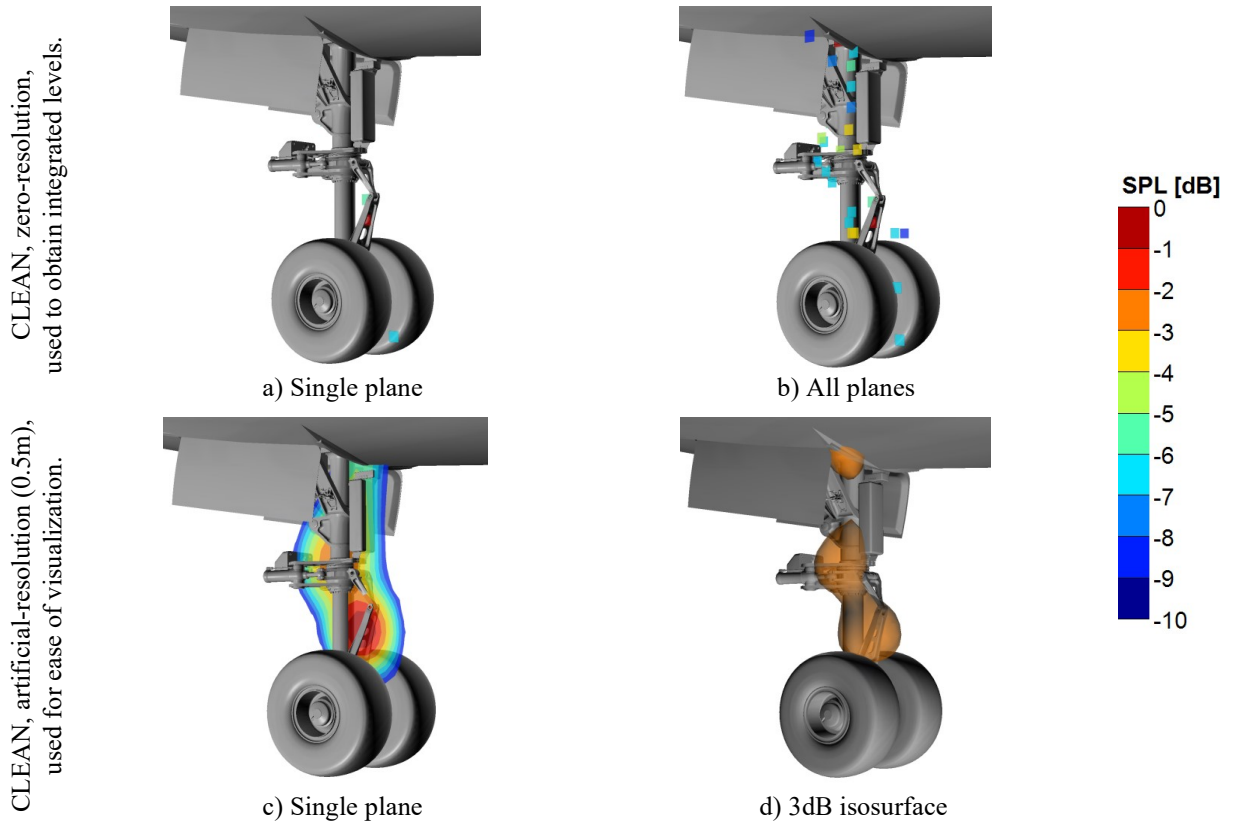


Fig. 10 Sample CLEAN acoustic maps for NLG at 1.6 kHz (1/12th octave band).

Tailored integration regions were defined to determine far-field noise contributions from subcomponents of the NLG. These regions are shown in Fig. 11. Similar regions were also defined originally to quantify the noise from subcomponents of the port MLG. Although the acoustic maps were very valuable in the noise source identification process, integration of various subcomponents could not be achieved at all frequencies with the same level of detail and accuracy as those obtained for the NLG. The reasons for this failure are mainly the complexity of the MLG geometry – which results in significant shielding effects – and the presence of dominant, non-gear related, airframe sources nearby, particularly for Config2. However, integration regions for the port MLG that still fulfilled the main goal of isolating landing gear noise from the rest of the aircraft were devised. These integration regions, “inboard leading edge” (IB-LE), “inboard flap” (IB-flap), and “inboard trailing edge” (IB-TE) are shown in Fig. 12. Note also in this figure that the IB-LE region includes the engine pylon. Due to the complexity of the geometry and software limitations in the definition of 3D integration regions, the integrated spectra for the port MLG in the high-lift wing configuration was obtained by subtracting from the full port MLG region (in red) the integrated levels for the inboard flap (that fully overlaps with the port MLG region, in yellow), referred to as “MLG (no IB flap)” in the spectral plots. With high-lift devices stowed (Config1), this subtraction was not strictly necessary, but the procedure, and hence naming, were maintained for consistency.

A 10 dB cutoff was used for integration of these subregions, while a 15 dB cutoff was used to obtain the levels for the “whole grid” region (shown in Figs. 8 and 9 for the NLG and MLG, respectively). The arrays, grids, and integration regions were automatically rotated within the software suite to account for the difference in angle of attack between Config1 and Config2 (see Table 1).

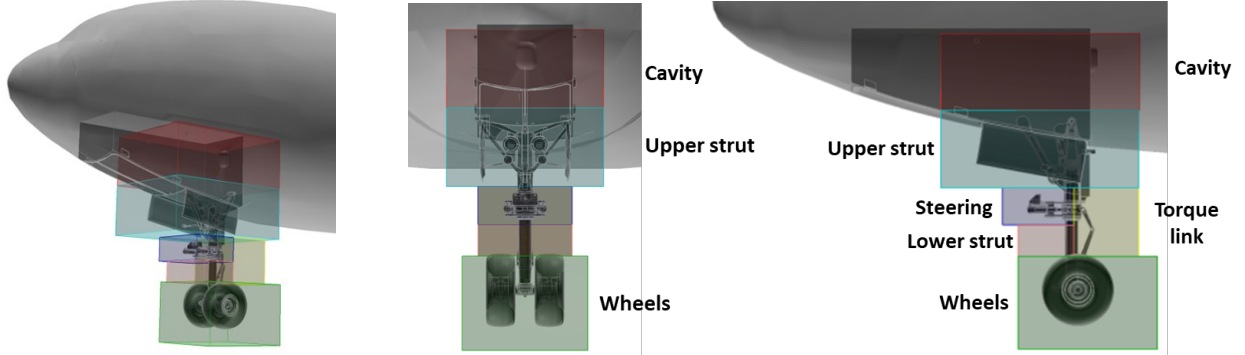


Fig. 11 Integration regions used to obtain noise spectra of NLG subcomponents.

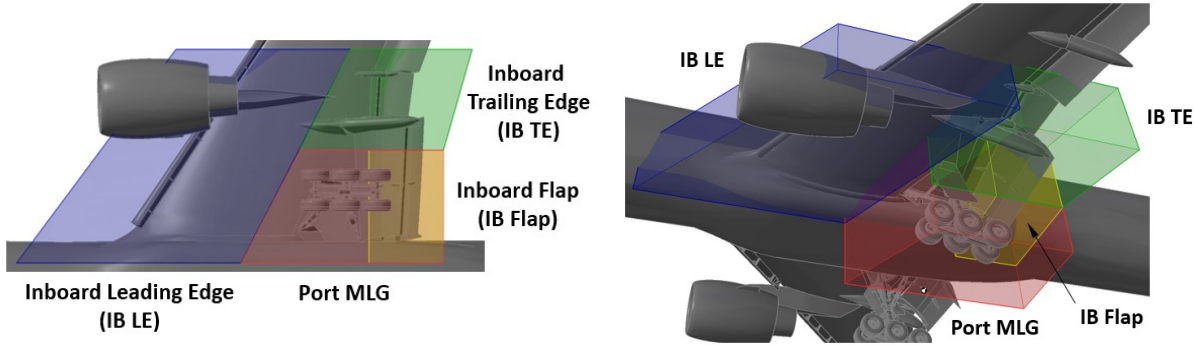


Fig. 12 Integration regions used to obtain noise spectra of port MLG and nearby high-lift devices.

IV. Applications of Multiplanar Arrays to Acoustic Data Analysis

The following subsections address common areas of consideration when studying synthetic array data. In subsection IV.A, results obtained from solid and permeable FWH data surfaces are compared to determine their merits and influence on average spectra, integrated spectra and acoustic maps. The impact of spatial resolution on simulated noise spectra is assessed in subsection IV.B. A breakdown of the contribution from subcomponents to the overall noise signature is presented in subsection IV.C. Finally, subsection IV.D provides a brief analysis of the tonal components observed from the coarse resolution simulation of Config2.

A. Solid versus Permeable FWH Data Surfaces

Our earlier study of the isolated 26%-scale, high-fidelity B777-200 MLG model [14] clearly demonstrated that, when using the FWH integral method [10] for noise prediction, data from permeable data surfaces must be used as input to obtain correct far-field noise signatures. This choice was further confirmed by the NLG study of Ref. [7] and by the extensive work of Spalart et al. [15] on various simpler test configurations. In these studies, the deficiencies of solid surface data were manifested in model configurations with prominent cavity noise or shielding effects. Therefore, most of the acoustic signals included in this study were obtained using a permeable FWH data surface. However, acoustic data were also obtained using the solid surface FWH approach from the medium resolution simulation of the NLG-only configuration. The availability of solid surface data for this configuration provided a unique opportunity to examine some of the differences inherent to the two approaches via application of the multiplanar array framework. A comparison of the results obtained from the two types of data surface is presented in this section. The spectral levels are given over a wide frequency range, up to 30 kHz, to show the full range of results from the solid surfaces. Recall that these surfaces reside in regions with very high temporal and spatial resolution that allow calculation of synthetic microphone records up to very high frequencies. As a result, the spectra obtained from solid surface data have a different frequency roll-off than corresponding permeable surface spectra. This trend can be seen in the average spectra⁵ of Fig. 13, where results for all three NLG arrays are shown for permeable (dashed lines) and solid (solid lines) FWH data surfaces. Except for some frequencies below 0.3 kHz, the spectral plots show

⁵ An average spectrum is the arithmetic mean of the acoustic pressures from all microphones in an array.

similar trends for all arrays: solid surfaces yield higher levels than the corresponding permeable surfaces. As expected, differences in sound level between the two types of surface increase with frequency. Also notice that below ~ 3 kHz the differences between solid and permeable surface results are relatively higher for the NLG-US array. The smallest relative differences between results from the two types of surface are observed for the NLG-SL array.

Spectral levels from integration of the whole NLG grid, shown in Fig. 14a, follow trends very similar to those seen for the average spectra of Fig. 13, thus corroborating observations from previous studies [7, 14, 15]. An advantage of using integrated spectra is that noise from sources other than the NLG can be excluded, even when the NLG is the only real source in the flow field. In this case, additional sources that are uncorrelated over the array (e.g., hydrodynamic and numerical noise) are also rejected. However, at higher frequencies, integrated spectra may show increased levels relative to those observed in the average spectra. This is because the acoustic sources at those frequencies are underresolved in the CFD simulation and generate spurious signals that contaminate the acoustic maps and hence the integrated spectra. Thus, validity of the integrated spectra should always be tied to an in-depth analysis of the acoustic maps (from beamforming and CLEAN) to ensure that the integration process is rendering levels that stem from physical sources.

Source distribution and relative levels among sources at a given frequency are also likely to be affected by the choice of FWH data surface. This is illustrated in Fig. 14b, where the integrated levels from solid and permeable data surfaces are shown for the NLG cavity, wheels, and whole NLG grid. As can be seen, differences in level between the two types of surface for the whole NLG grid below 2 kHz are mostly due to the cavity region. Above 2 kHz, solid surface results show similarly increased levels for the cavity and wheel regions relative to those from the permeable surface. Note, however, that medium resolution acoustic results from the permeable data surface indicated converged spectra for frequencies below ~ 4 kHz – above this frequency, results should be considered under-resolved and less accurate.

In the absence of quadrupole effects, one would expect the solid and permeable data surfaces to produce far-field spectra that are nearly the same for frequencies below 4 kHz, where convergence of permeable data surface results is assured. The overprediction of spectral levels by the solid surface observed in Fig. 14 is consistent with previous studies [14, 15] suggesting that solid surfaces do not render correct levels in the presence of cavities or when shielding effects are important. To illustrate the inadequacy of solid surface pressures as input for far-field noise prediction, sample sideline acoustic maps comparing the distribution of sources and their relative levels between solid and permeable data surface results are shown in Figs. 15 and 16 for different $1/12^{\text{th}}$ octave band frequencies. For comparison purposes, peak levels were set to the same value in the maps of Fig. 15. The solid surface results (Fig. 15a) show a source between the wheels that is not present in the permeable data surface results (Fig. 15b), as this source is shielded or does not propagate to the far field. Similarly, the isosurfaces of Fig. 16b (not normalized since the peak levels were almost identical) seem to indicate that sources between the wheels and inside the cavity are shielded. Clearly, this type of subcomponent analysis would not be possible with a ground-based array typical of a flight test setup, since the array size and relative distances result in poor resolution, particularly in the direction normal to the array.

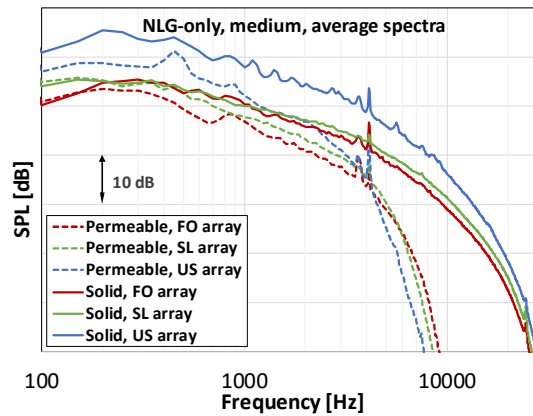
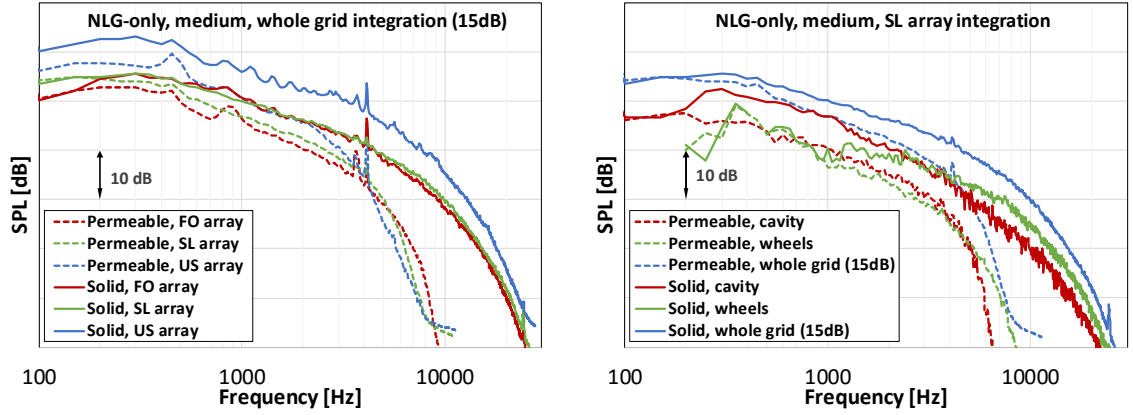


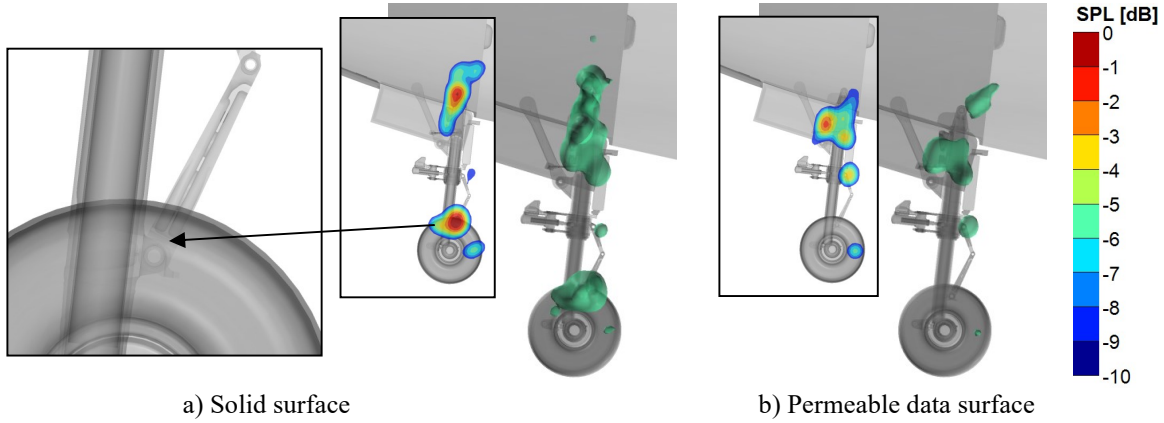
Fig. 13 Average spectra from solid and permeable FWH surfaces for medium resolution NLG-only simulation.



a) Whole NLG grid integration

b) Contribution of cavity and wheels, NLG SL array

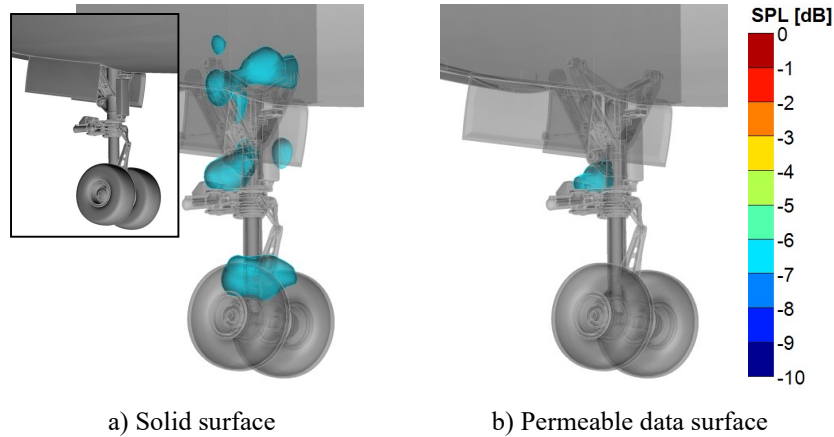
Fig. 14 Integrated spectra for NLG-only from solid and permeable FWH data surfaces.



a) Solid surface

b) Permeable data surface

Fig. 15 CLEAN isosurfaces (6 dB from peak level) and maps at 2 kHz (1/12th octave band) from SL array.



a) Solid surface

b) Permeable data surface

Fig. 16 CLEAN isosurfaces (7 dB from peak level) at 4.25 kHz (1/12th octave band) from sideline array.

B. Impact of Spatial Resolution on Simulated Noise Spectra

Simulations for Config1 and Config2 are available for xcoarse and coarse spatial resolutions only. This fact precludes a proper determination of the frequency at which coarse simulation results converged. However, synthetic array pressures for the NLG-only configuration are available from xcoarse, coarse, medium, and fine resolution

simulations [7]. Although these denominations do not correspond exactly to the same levels of resolution in each configuration, NLG-only results were used to infer the maximum frequency for which coarse results of Config1 converged. A convergence study for Config2 was not attempted because, as shown later, the coarse resolution spectra feature numerous prominent tones that complicate the task of determining spectral convergence.

Spatial resolution convergence of far-field spectra should not be determined solely from single-microphone or array average data because this information is insufficient to assess whether all aircraft sources are being resolved correctly in terms of location and frequency content. In the presence of complex geometries, an increase in spatial resolution is very likely to impact the relative contribution of major components to the overall noise signature – the spectrum of a particular component is likely to “converge faster” if the element has a simpler geometry, where sub-component interactions may not be prevalent. Based on trends observed in multiple studies, we have determined that integrated spectra for different components (e.g., nose or main landing gear, flap, wing leading edge) or even sub-components (e.g., nose gear wheels, strut or cavity) are more useful when trying to determine the frequency range for which overall noise results have converged. The following subsections discuss convergence at the component level for the NLG and the port MLG. The impact of spatial resolution on the spectra from subcomponents is exemplified in Section IV.B.1.

Acoustic maps show well-defined sources beyond the frequency for which solution convergence has been achieved in terms of integrated spectra. However, as frequency increases further, beamform acoustic maps start to deteriorate until they comprise mostly sidelobes. This typically leads to a change in the slope of the integration results relative to the average spectra, as observed around 8 kHz for the permeable data surface curves from the NLG-SL and NLG-US arrays in Fig. 14a when compared to those of Fig. 13. Most spectral data presented in the following sections are limited to frequencies below 5 kHz to reduce the computational time for CLEAN.

1. Isolated Nose Landing Gear (NLG-only)

NLG-only integrated spectra (for the whole NLG grid) from the flyover and sideline arrays are shown in Figs. 17a and 17b, respectively. Since the aircraft and flight conditions used in the simulations of NLG-only and Config1 were identical, as a reference, these figures also include corresponding integrated NLG spectra from Config1 (dashed lines). Observe from the figures that the NLG-only spectra from coarse resolution seem to have converged for frequencies below ~2.4 kHz. Therefore, full-aircraft noise levels obtained from a coarse resolution simulation should be fairly converged up to that frequency, while levels for higher frequencies would likely be underestimated due to insufficient grid resolution. The results in Fig. 17 also show that simulations at the “fine” resolution level would be needed to obtain converged results for frequencies up to ~5 kHz, a typical goal for airframe noise experiments. In Fig. 17, Config1 results from xcoarse and coarse grids show trends similar to those for NLG-only. Modest discrepancies in levels for the same “nominal” resolution are attributed to small differences in near-surface resolution.

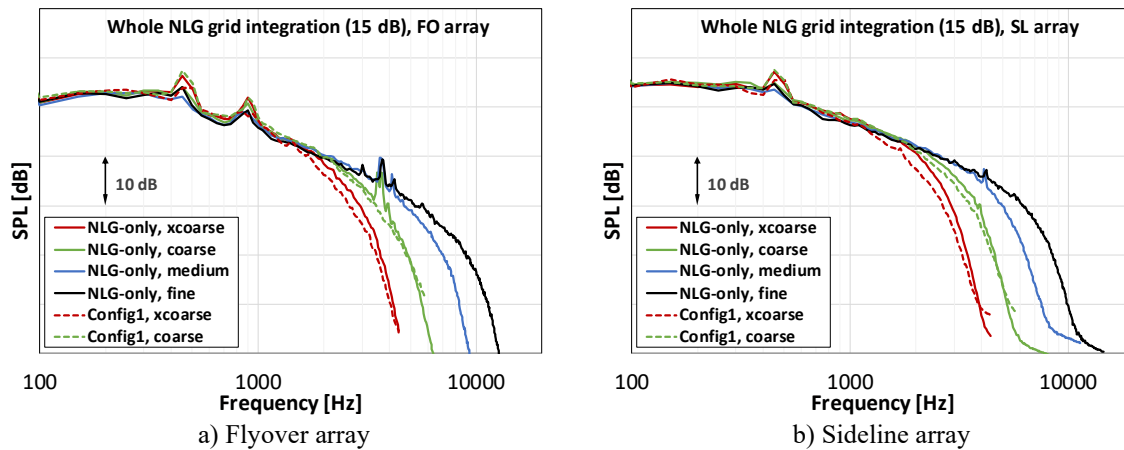


Fig. 17 Effect of spatial resolution on NLG integrated spectra for NLG-only simulation.

2. Cruise Wing Configuration with Landing Gear Deployed (Config1)

As stated previously, Config1 simulations were performed for xcoarse and coarse resolutions only. Figures 18 and 19 show comparisons of the average and integrated spectra, respectively. These figures include results at the

flyover and sideline arrays for the NLG and port MLG. Since the main goal of the present effort was to examine the noise produced by these components, integrated spectra for the corresponding gear regions were used to minimize contributions from other airframe noise sources. The impact of other sources on the flyover spectra becomes clear when comparing Figs. 18a and 19a. As expected, the difference between average and integrated spectra is more noticeable for the port MLG due to its closer proximity to other sources, in this case the starboard MLG and the engine pylons. Noise from the NLG is also expected to contribute to the average spectra of the MLG arrays, and vice versa.

Convergence of the Config1 NLG component with increased resolution, depicted in Fig. 19a, closely tracks that of the NLG-only spectra in Fig. 17a with xcoarse results having converged up to ~ 1.2 kHz. An increase in the level of tonal components around 0.45 kHz and 0.9 kHz is also observed for the NLG from coarse resolution data. With increased resolution, spectral levels associated with the MLG component begin to show differences around 0.7 kHz, a significantly lower frequency than the corresponding value for the NLG. Integrated spectra for the sideline (Fig. 19b) and upstream arrays (not shown here) of each landing gear depict similar convergence behavior to that observed from the flyover arrays. Note that the 0.9 kHz tone in the coarse NLG-FO spectra is not present in the sideline results, consistent with the spectral plots of NLG-only shown in Fig. 17. The flyover and sideline acoustic maps in Fig. 20 (using different ranges) clearly show a source between the wheels that is shielded when observed with the NLG-SL array.

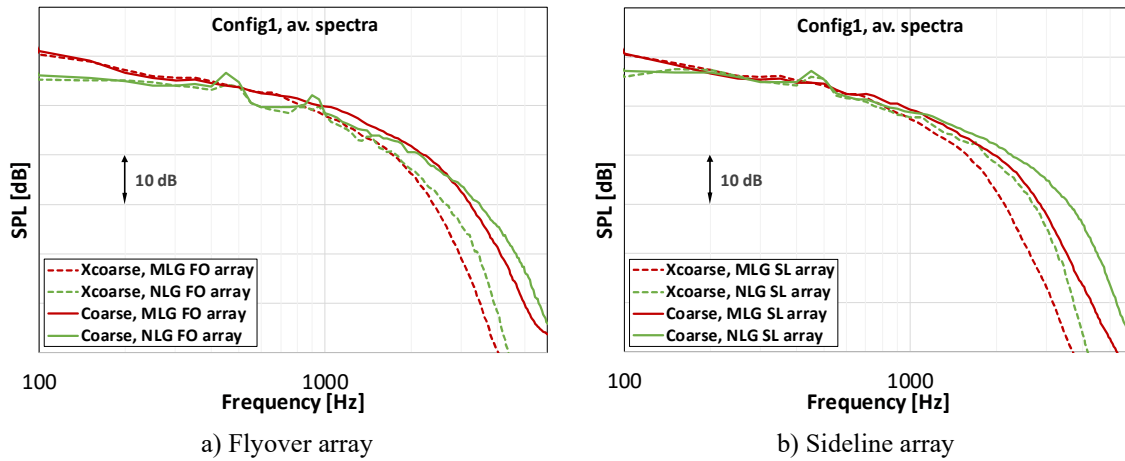


Fig. 18 Effect of spatial resolution on average spectra for Config1.

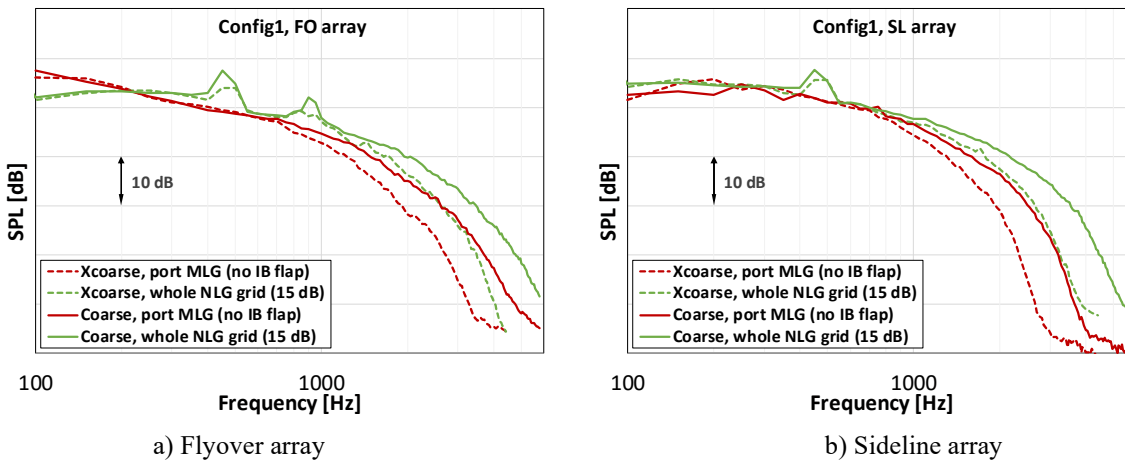


Fig. 19 Effect of spatial resolution on integrated spectra for Config1.

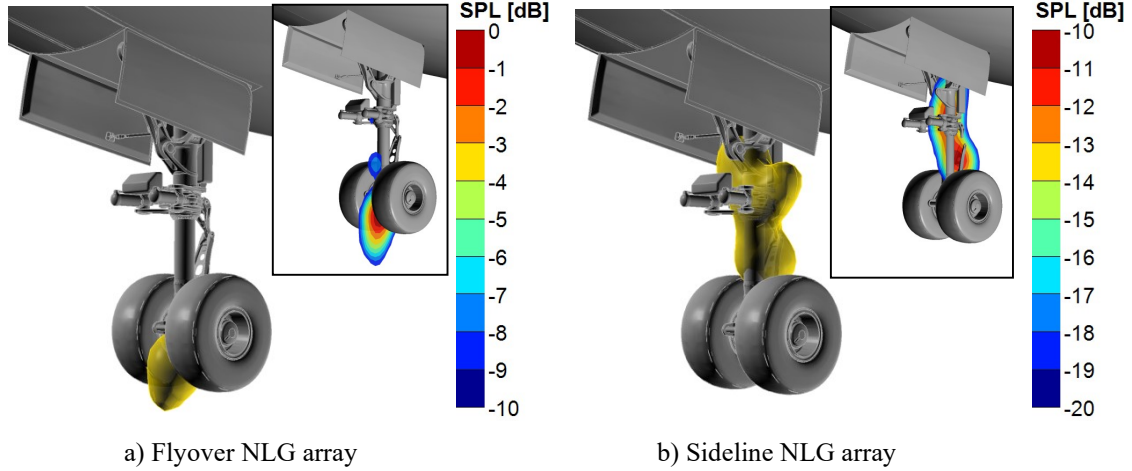


Fig. 20 CLEAN isosurfaces (4 dB) for 0.9 kHz.

C. Noise Contribution from Different Sources

We wanted to establish an effective approach for the accurate breakdown of total noise levels from the landing gear into the contributions from its subcomponents, as commonly done during wind tunnel tests of an isolated landing gear. This type of analysis is very useful during development, implementation, and optimization of locally applied noise abatement devices. However, due to the large difference in relative distances between each noise source and the center of the array, contributions to the overall noise levels could be easily skewed by putting too much emphasis on components closer to the array. This error would also be manifested as overestimates of the noise reduction potential of devices installed on these components.

In order to obtain results comparable to a flight test setup, we believe that near-field noise levels from each subcomponent (or at least each major component) measured at any of the synthetic arrays defined in Fig. 7 (“wind tunnel” array) should be extrapolated and their contributions added at the desired observer location. In the present analysis, this was achieved by normalizing subcomponent levels to a distance of 120 m (“flight test” array), typical of an approach altitude used during aircraft noise certification. The total noise spectrum (referred to as “sum” in the figures) was obtained by adding the noise from all components or subcomponents after extrapolation to the chosen observer distance.

We provide an example to illustrate the potential difference in relative component levels without and with extrapolation to a location on the ground 120 m away. Based on the distance between the center of each region and the center of the NLG-FO array, noise from the NLG upper strut/doors and NLG wheels regions requires sound pressure level corrections of about -27.1 and -32.8 dB, respectively, when normalized to 120m. This indicates that the contribution from the upper strut would be significantly more important when observed with the “flight test” array than with a “wind tunnel” array. Fig. 21 shows spectra for the NLG subcomponents as well as the total NLG noise (sum of all NLG subcomponents described in Section III.C.). In this figure, levels normalized to 120m (at the “flight test” array, in solid lines) clearly show that uncorrected levels (at the “wind tunnel” array, in dashed lines) underestimate the contribution of sources in the upper strut region. Note that, strictly speaking, a component in the upper strut region would also be farther away from a ground observer than the wheel axle, in this case about 2m based on the center of their corresponding integration regions. Therefore, an “error” of less than 0.2 dB is introduced by not accounting for the 2 m separation. However, this error is significantly smaller than the 5.7 dB (32.8 minus 27.1) that would be introduced by not applying any corrections. Source-to-observer distance correction is a built-in feature of AVEC’s phased array software [16]. Thus, the process of obtaining corrected results for several arrays, regions and configurations is greatly simplified.

Accounting for the aircraft path during a flight test (including deviations from the nominal path) would require additional directivity information to correctly obtain the far-field levels from wind tunnel-like results. That is, simply using extrapolated flyover array results from a wind tunnel setup may not accurately represent flight test conditions. However, since the same simulations were used to generate the acoustic data for both scenarios (“wind tunnel” and “flight test”), we had a unique opportunity to directly compare output from the two types of array setup and the

farfield noise results obtained with them. Examples comparing results from all the synthetic arrays implemented in this work and the synthetic flight test array of Ref. [8] are presented in Section V.

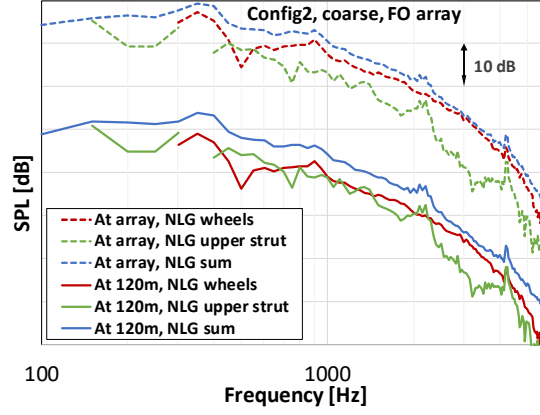


Fig. 21 Integrated array levels for two NLG subcomponents and total NLG noise, coarse results for Config2.

1. Nose Landing Gear

All subcomponent spectral levels shown in this section have been normalized to a distance of 120 m. The sum was then obtained by adding the contributions from all subcomponents using the corresponding corrected levels. We note that some subcomponents may show “missing” spectral values. This simply indicates that, within the subcomponent’s integration region, the CLEAN maps are “empty” (zero energy). Since NLG sources of Config1 and Config2 are insufficiently resolved above ~ 2.4 kHz for coarse resolution simulations, integrated levels above this frequency are considered to be less accurate.

Results for Config1 are presented in Figs. 22a through 22c for the flyover, sideline and upstream arrays, respectively. These results show clear differences regarding the subcomponents that produce dominant sources in each radiation direction. For instance, the NLG-FO array (Fig. 22a) indicates that the wheels integration region – which contains the wheels and a host of other complex structures, such as the toe bar and axle, that produce high amplitude noise [7] – generates dominant sources for most frequencies, while the NLG-SL array (Fig. 22b) shows the upper strut region as dominant.

We stated earlier that increasing spatial resolution not only changes frequency content, but it may also change the relative contribution of each subcomponent. To illustrate this point, Fig. 23 shows the breakdown obtained from the xcoarse and fine grid simulations of the NLG-only configuration from the sideline array. When compared to the coarse resolution results in Fig. 22b, it is clear that the relative contribution of components in the upper strut region and cavity increases with resolution. Since NLG-only results are available at four different resolutions, it is also informative to compare the source distribution in the acoustic maps. This is illustrated in Fig. 24 with CLEAN maps obtained at 1.18 kHz, a frequency for which the integrated spectra indicate converged levels at all four resolutions. As can be seen in these maps, the location and level of the dominant source (upper strut) do not change significantly (peak levels in all maps are within 0.4 dB). However, the relative strength and location of sources between the wheels and near the torque link do change.

Figure 25 shows the subcomponent breakdown of the NLG noise for Config2 (same ordinate scale as in Fig. 23). Besides the difference in actual levels caused by the different aircraft speeds in each configuration, observe that the relative contribution from each subcomponent to the total noise has also changed. For instance, the wheels region in the NLG-FO results and the upper strut in the NLG-SL results are not as dominant as noted for Config1. This is to be expected, considering that the noise generation mechanism for each subcomponent is unlikely to be the same, and therefore their levels may not scale in the same manner with flow speed.

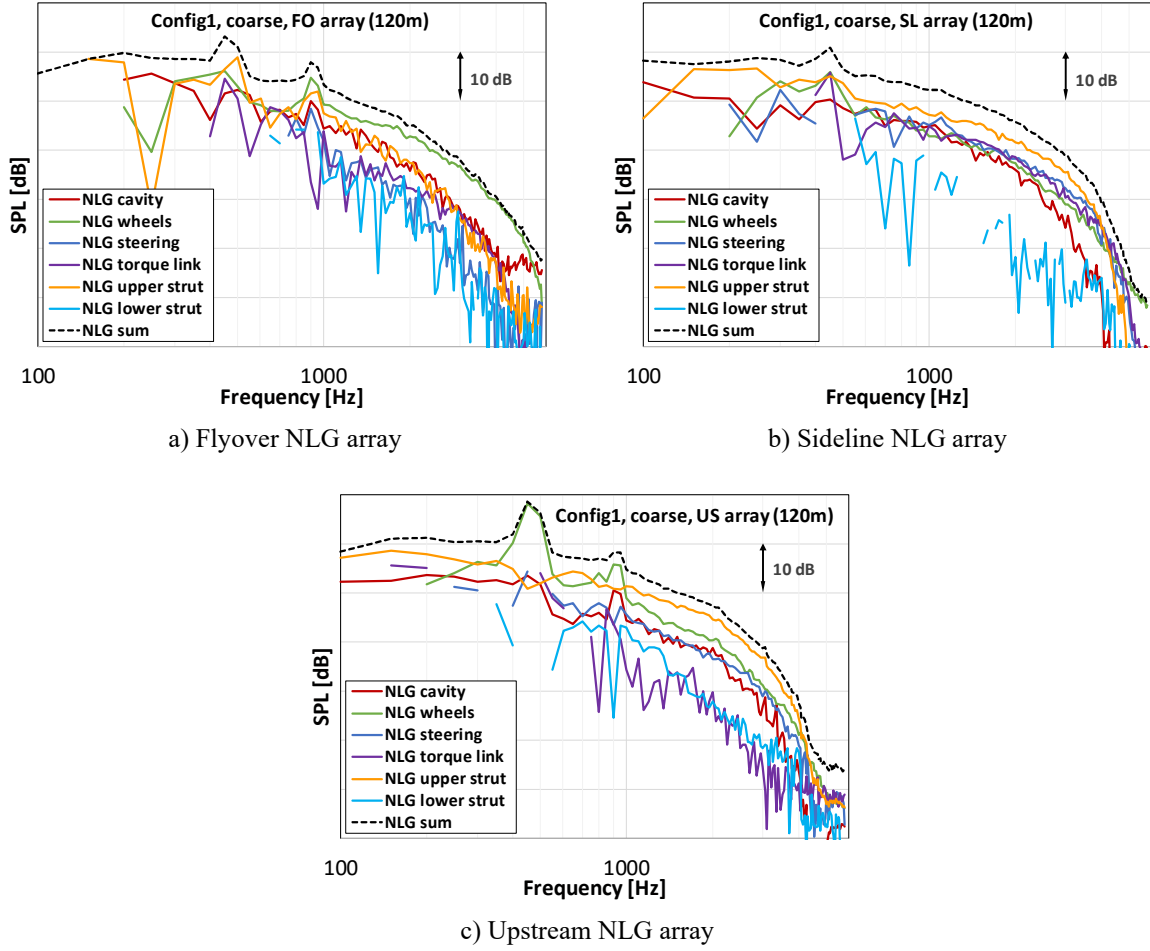


Fig. 22 Breakdown of Config1 noise into NLG subcomponents for coarse resolution.

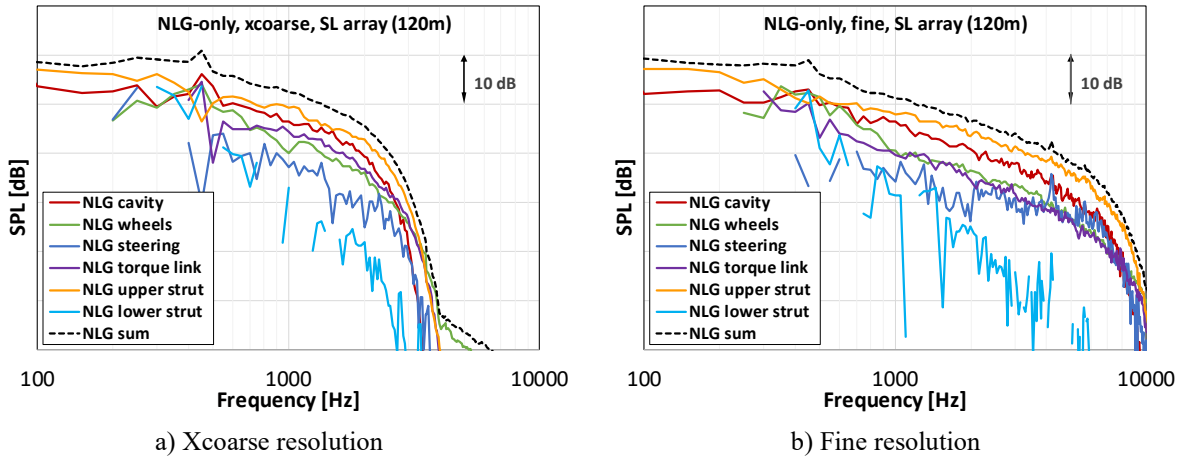


Fig. 23 Breakdown of sideline NLG-only noise into NLG subcomponents.

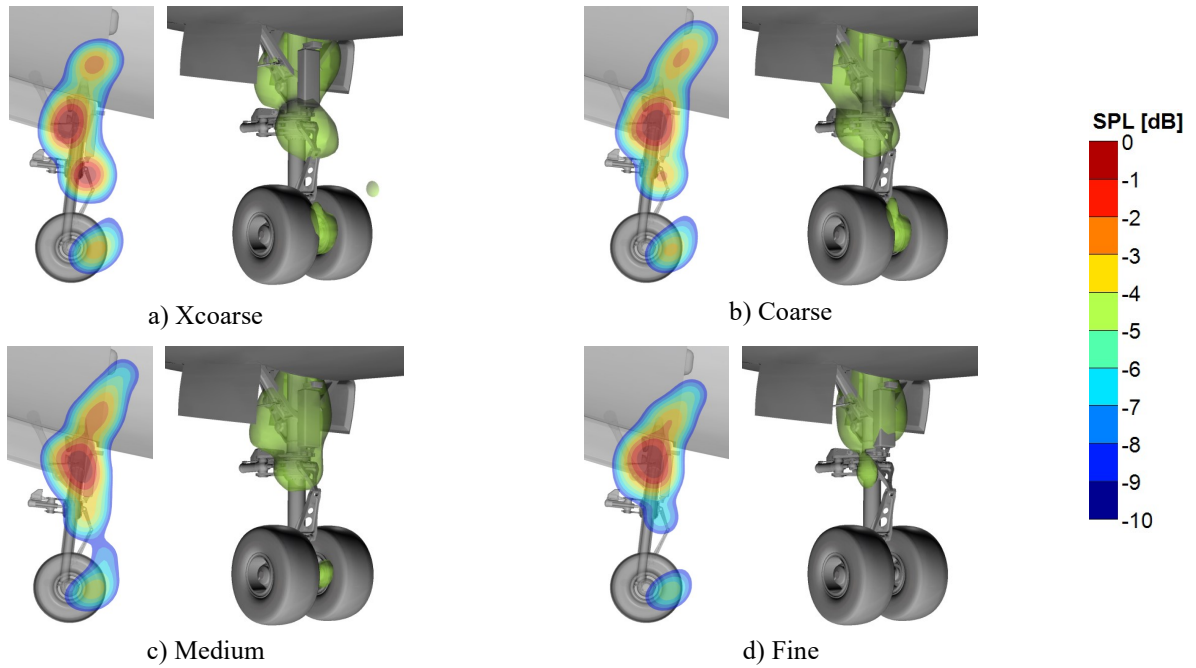


Fig. 24 Sideline CLEAN acoustic maps (plane at aircraft centerline) and 5 dB isosurfaces (1.18 kHz, 1/12th octave band) for NLG-only configuration with different resolutions.

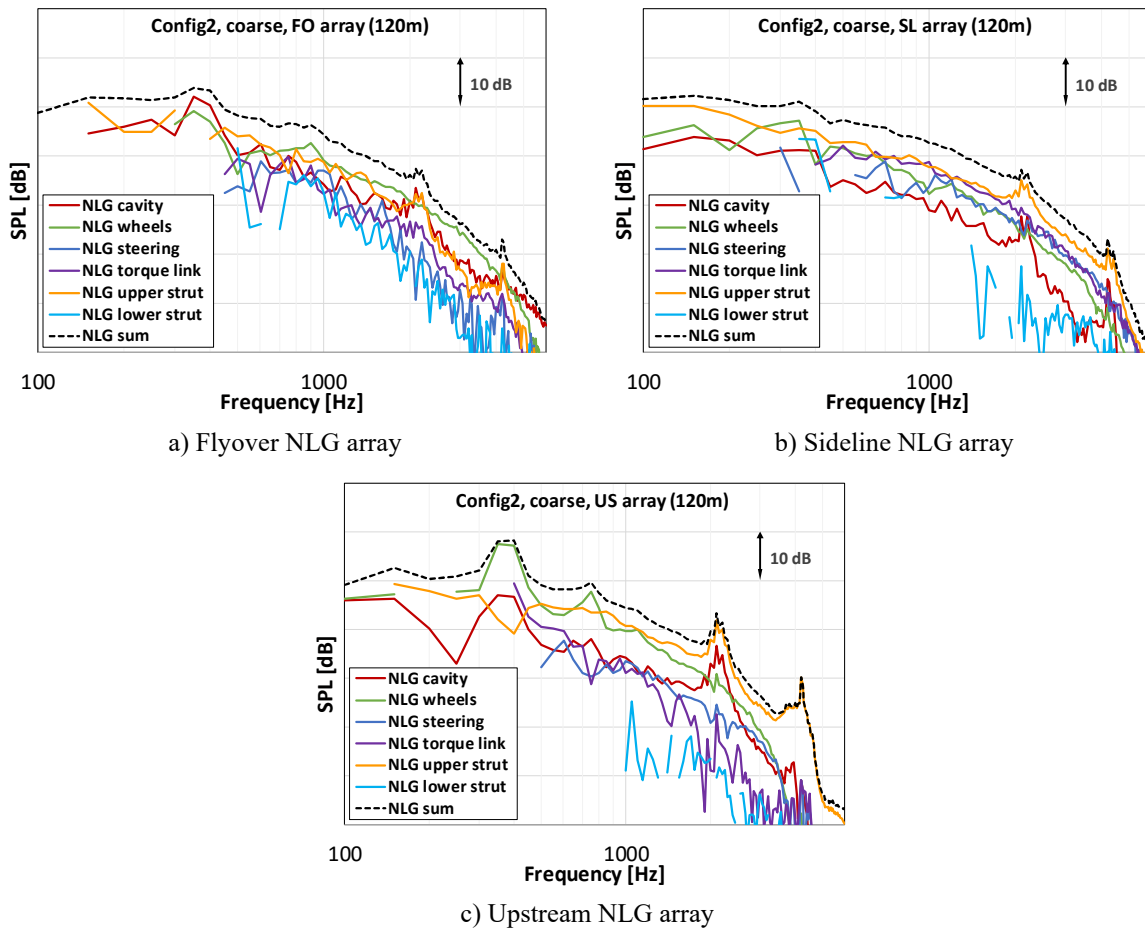


Fig. 25 Breakdown of Config2 noise into NLG subcomponents for coarse resolution.

2. Port MLG, High-lift Wing Configuration (Config2)

As described in Section III.C, the MLG noise spectra could not be broken down accurately into contributions from smaller subcomponents because of additional dominant airframe noise sources within close proximity of the MLG (particularly for Config2) and significant shielding from different MLG subcomponents (door, truck). When combined with the inherently lower resolution in the direction normal to the array, these two factors can introduce inaccuracies in the spatial location of the sources within the 3D grid, making them appear as if they were suspended in “space”. Additionally, with significant downwash from deployment of high-lift devices (Config2), the local flow upstream of the MLG is highly complex with rapid variations in all directions [8]. As a result, the assumption of uniform flow between the permeable data surface and the US array, invoked in the FWH formulation to generate the synthetic pressure records, may be inappropriate. If so, the resulting degradation in phase information and loss of correlation caused by violation of this assumption may have significantly lowered the effectiveness of the US array in identifying the MLG noise sources. Despite these challenges, relative to the results from the “flight-test” ground array, we were able to more accurately separate MLG noise from that produced by nearby high-lift sources and to better pinpoint the location of the main gear sources at the subcomponent level.

As in previous sections, levels presented here were normalized to a distance of 120 m. Subtraction of inboard flap noise from the MLG spectra was performed after applying the distance correction to both regions separately. Given the large size of the MLG and its relative distance to each array, we expect this approach to include residual inaccuracies when compared to the results that would be obtained if MLG noise could be accurately broken down into its subcomponents, as was done for the NLG. However, at this stage, the results presented in this section are considered the most accurate obtainable.

To illustrate the impact of the distance correction on the relative noise levels between the MLG and high-lift devices, Fig. 26a shows the spectra of different components as measured at the MLG-FO array while Fig. 26b shows the corresponding levels extrapolated to a distance of 120 m. Both figures depict prominent tones emitted by the MLG. The tonal components for Config2 are addressed in Section IV.D. Again, the sum was obtained by adding the contribution of each element after extrapolating the levels to 120m. For simplicity, noise components from the inboard flap and inboard trailing edge regions (see Fig. 12) were added and their sum is presented in this section as a single region identified as “IB TE/flap (sum)”. The results in Fig. 26 clearly indicate that the contribution of the MLG to total noise is less significant when the levels at a ground observer 120 m away are considered. Note that, except for the inboard leading-edge region, the spectral shape of other regions can change (between Figs. 26a and 26b) because they include an additional operation, i.e., subtraction or sum of multiple regions. Although the changes are very minor for the flyover results, they will become more evident for the sideline spectra presented next.

Integrated spectra at the array and at 120 m from the sideline array are shown for the same components in Figs. 27a and 27b, respectively. In this case, the IB flap region is farther away from the sideline array than the IB TE region (see Fig. 12). Therefore, the changes in spectral shape for the “IB/TE flap (sum)” region between both figures are more noticeable than those observed for the flyover array. However, changes in relative levels between the MLG and IB LE regions are less pronounced.

The flyover and sideline results shown in Figs. 26 and 27 indicate that the flaps are the dominant sources in the far field. In the absence of tonal components for the MLG, flyover levels for sources in the IB LE region (port side inboard slats and engine pylon) would be comparable to those of the port MLG. Also, based on sideline results, the port IB LE would be louder than the MLG above ~ 1.2 kHz. We must emphasize that an in-depth analysis of the synthetic noise sources associated with the high-lift devices was neither the goal nor was it attempted here, since the simulated slat and flap brackets were scaled up from a 26%-scale wind tunnel model of the aircraft [8] and, as such, do not correspond to the actual components flown during the flight tests described in Ref. [4]. Therefore, the contributions from high-lift devices relative to the landing gear would likely change if their true, full-scale bracket geometries were included in the simulations.

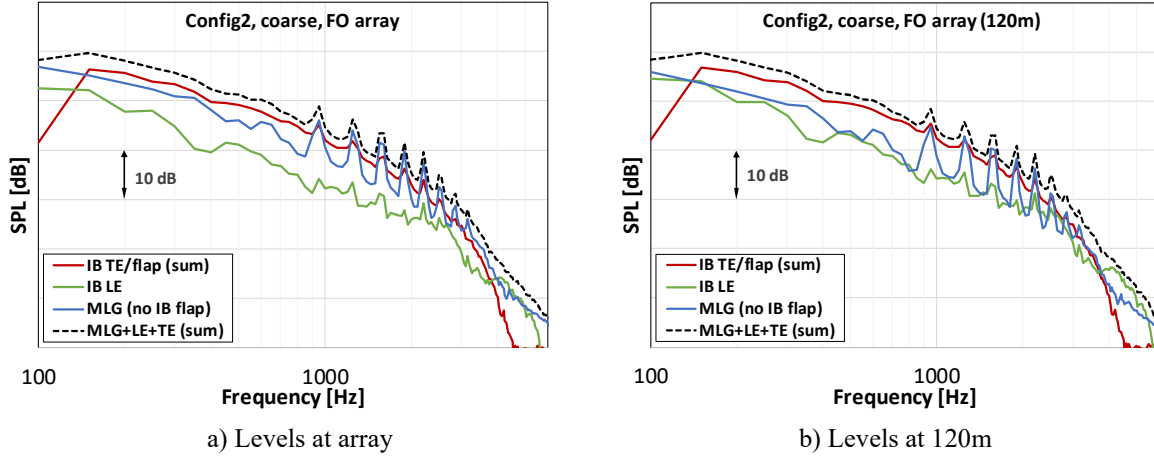


Fig. 26 Contribution from major components to flyover noise for coarse resolution Config2.

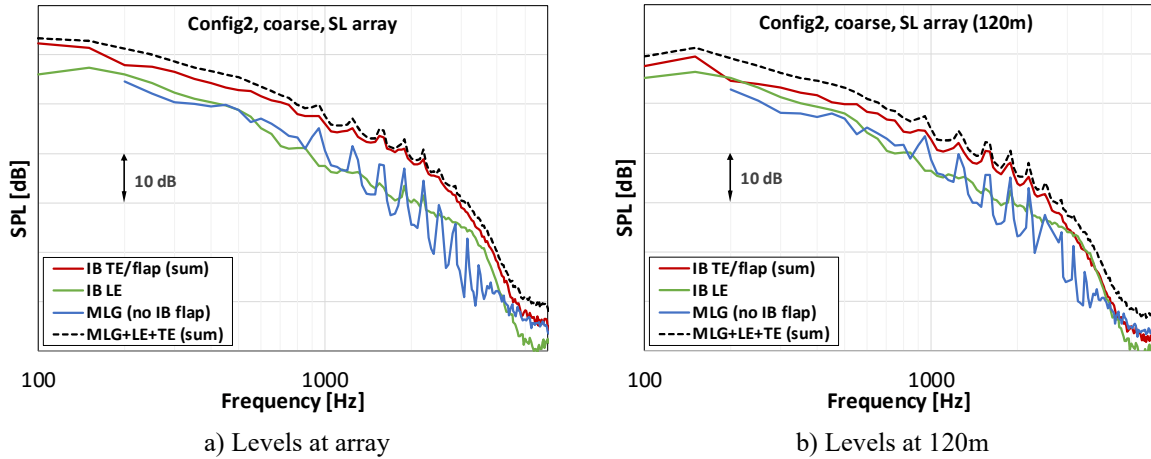


Fig. 27 Contribution from major components to sideline noise for coarse resolution Config2.

D. Brief Analysis of Tonal Components in Config2

As seen in Section IV.C.2, coarse resolution results for Config2 showed multiple tones in the integrated spectra for the port MLG. These tones, which first became evident during analysis of simulated pressure records for the flight test array [8], are not as prominent in single or average microphone spectra because several other sources are present at the same frequencies. To illustrate this, sample average and integrated spectra for the flyover and sideline arrays are shown in Figs. 28a and 28b, respectively. These figures include integration results for the port MLG and the whole MLG grid, as well as average spectra (dashed black lines). Note that the differences between the “MLG (no IB flap)” spectra and those from integration of the whole MLG grid are caused by the presence of other sources outside the port MLG, such as flaps, engine pylon, and wing leading edge. Also, differences between spectra from whole grid integration and that from averaging are due to sources outside the port MLG/flap grid (shown in Fig. 8) – all components in the outboard region of the port wing, the nose gear, and the entire starboard side of the aircraft.

Based on examination of MLG surface pressure fluctuations (around 0.9 kHz and 1.8 kHz) and synthetic array data, the source of some of these tones was traced to a pin attaching the hydraulic cylinder to the main strut, shown in Fig. 29. A simple analysis using the pin geometry and the speed of sound to determine the fundamental resonance frequency for an unflanged open-open pipe with end correction [17] resulted in a frequency of 322.6 Hz, which is very close to the fundamental frequency of ~314 Hz observed in the array results. The small difference in frequency could be associated with the presence of a bolt across the aft opening (see Fig. 29b) or with a chamfer in the geometry of the pin hole that may affect the actual location of the antinode in the openings. Although this fundamental frequency matches most harmonics seen in the spectra, further analysis of the geometry [8] and acoustic maps re-

vealed sources at other pins with similar geometries and hence harmonic frequencies that would coincide with those shown in Fig. 28.

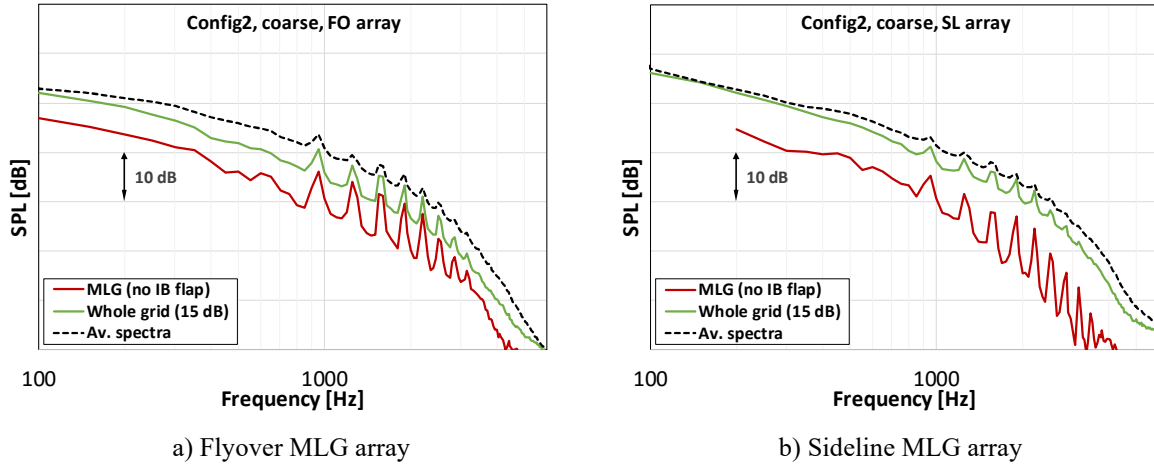


Fig. 28 Comparison of relative levels between integrated spectra for port MLG and whole MLG/flap grid to average spectra of all microphones in the array.

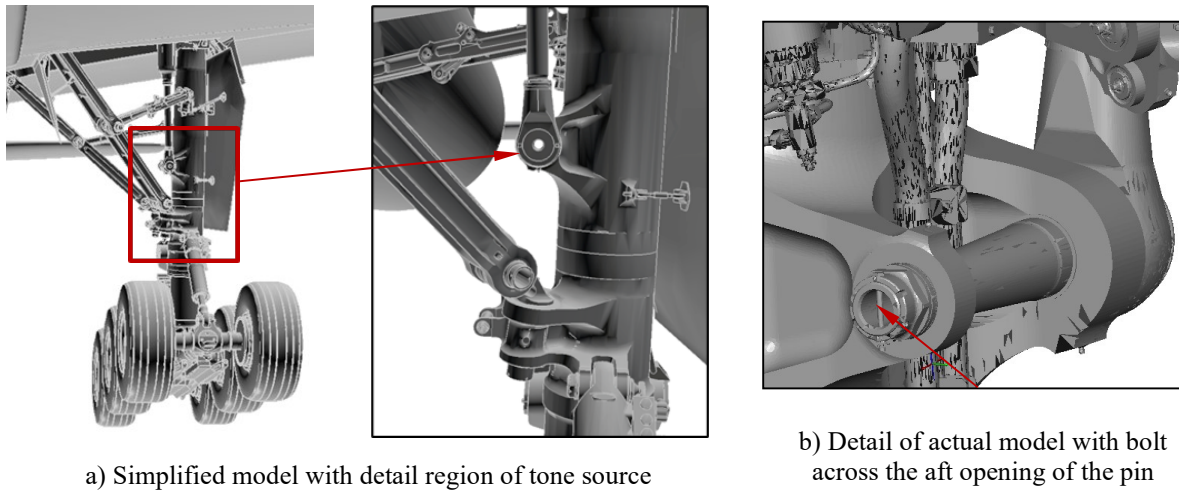


Fig. 29 Port MLG CAD geometry.

V. Advantages of Multiplanar Arrays: A Comparison to Synthetic Flight-test Results

As demonstrated throughout this paper, placement of synthetic arrays in close proximity of the landing gear affords us the ability to identify and quantify the major gear sources down to the subcomponent level. The availability of validated, high-fidelity computational data provides a unique opportunity to determine how source identification and noise levels measured close to the model (similar to a wind tunnel setup) compare to those measured with ground-based arrays used in flight-test environments and, in the process, showcase the advantages of the present approach. To this end, data on the same permeable surfaces were used to generate synthetic pressure records for the multiplanar arrays around each landing gear and the QTD2 flight test array [4]. In Ref. [8], QTD2 synthetic microphone records were obtained with the aircraft position laterally offset from the center of the ground array to emulate the offset measured for actual aircraft flyover passes performed during the test, as shown in Fig. 30a for Config1. Other synthetic QTD2 array results included in this section were obtained with the aircraft flight path aligned with the array center, as depicted in Fig. 30b. In order to show the correct emission angle, the schematics in Fig. 30 display the relative locations after accounting for flow convection, with the MLG directly above the array center (90° emission angle). Note that, consequently, the emission angle for the NLG is larger than 90° .

Acoustic maps and integrated spectra for the NLG and port MLG obtained with the multiplanar and QTD2 arrays are compared in this section. As done previously, the spectra have been normalized to a distance of 120 m. Processing of multi-planar and QTD2 array data sets was performed with the same software package and algorithms. The extent of the grid (2D plane) and integration regions used to obtain the QTD2 integrated spectra, reproduced from Ref. [8], are shown in Fig. 31. Given the large size of the MLG and the relatively poor resolution of typical flight-test arrays in the vertical direction, acoustic maps are subject to parallax effects that may affect the position of the sources in the map. That is, sources may appear slightly off their actual location because the 2D grid plane does not intersect their exact positions in the vertical direction. Note also that the impact of this effect is different for each array location shown in Fig. 30. To overcome this issue, two different grids, referred to as “gear plane” and “wing plane”, were defined and are shown in Fig. 32, also from Ref. [8]. This reference includes a discussion on the impact of grid position on integrated results for the flight test array.

Note that the resolution of the QTD2 array precludes the accurate removal of potential contributions from the inboard flaps to the MLG. However, analysis of the acoustic maps revealed that removing the noise generated at the junction between the inboard flaps and the fuselage was possible and should improve the accuracy of the integrated spectra for the MLG. Therefore, following an approach similar to that used for the multiplanar arrays, the MLG noise from the QTD2 array was obtained by removing the contribution from the regions labeled as “IB flap” in Fig. 31 from the corresponding MLG regions.

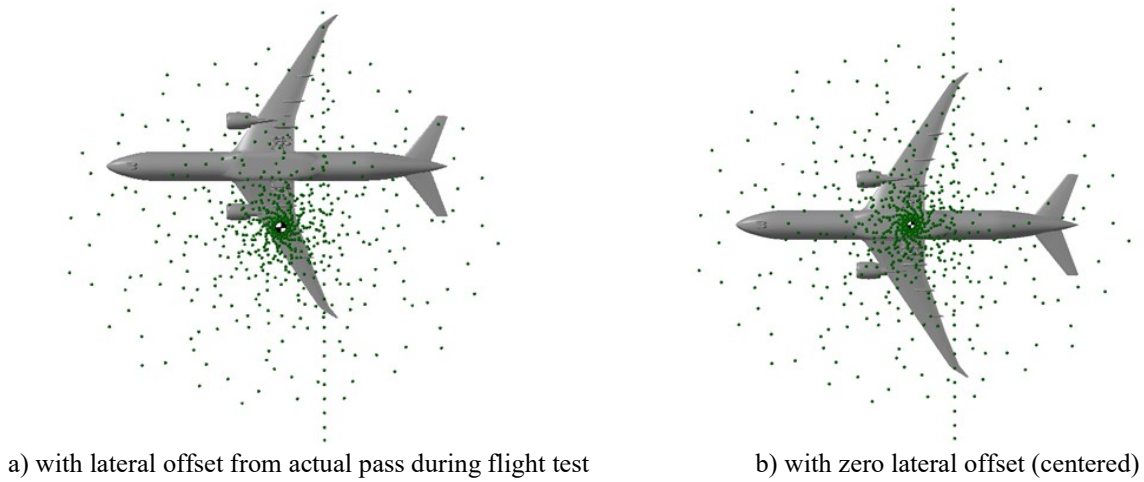


Fig. 30 Schematic of relative positions between array and aircraft for flight test simulations (accounting for flow convection).

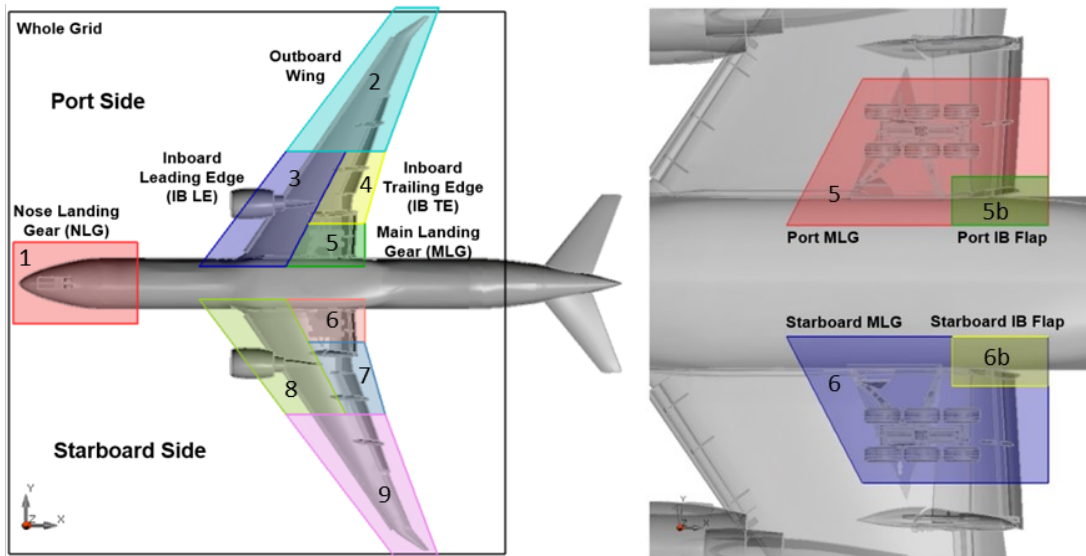


Fig. 31 Regions used to calculate QTD2 integrated far-field noise spectra, from Ref. [8].

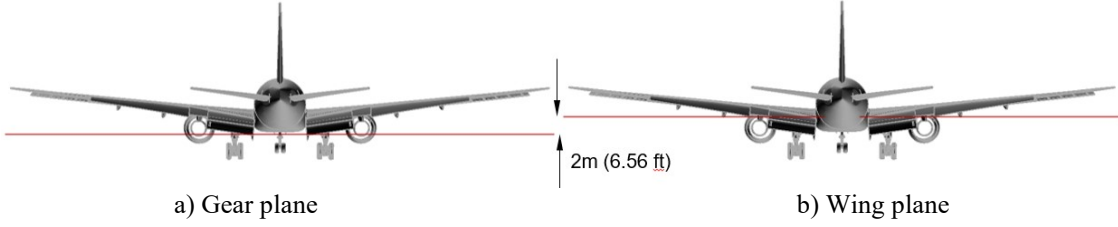


Fig. 32 Position and relative distance between scanning planes with aircraft in Config2, from Ref. [8].

A. Results for Config1 (Landing Gears Deployed, Hight-lift Devices Retracted)

For Config1, Fig. 33a compares the NLG (sum) integrated spectra from the multiplanar NLG arrays to the integrated spectrum obtained from synthetic QTD2 array data. Overall, the two array setups produce similar spectral shape and levels in the overhead direction. The most noticeable differences between the results from the NLG-FO and centered QTD2 arrays are observed in the tones at 0.45 kHz and 0.9 kHz. QTD2 array results with a lateral offset (not presented here) showed very similar levels for most of the NLG spectrum, but the 0.45 kHz tone was about 5dB quieter. Fig. 33a also shows small differences below 1.2 kHz, and between 2.2 kHz and 3 kHz. Although absolute levels above ~ 2.2 kHz should be viewed with caution due to insufficient spatial resolution, levels up to ~ 3.5 kHz can still be used to study the differences between the two array setups. Data processing below 0.3 kHz was challenging in the QTD2 setup because of ground array resolution and the presence of sources other than the NLG. Therefore, the integration results may be less accurate in the lower frequency range. In terms of noise directivity, the results from the NLG-US array clearly show higher relative levels for most frequencies below 2.7 kHz. This is consistent with results presented in Ref. [7] that indicate higher levels in the forward arc (50° to 70° emission angle) for the NLG-only configuration.

Config1 results for the port MLG are shown in Fig. 33b for all MLG arrays (including FOC) and the centered QTD2 array. Observe that there are noticeable differences in levels among the MLG arrays, indicating strong directivity effects. For instance, results from the MLG-FOC array are about 2dB louder than those from the MLG-FO array for most frequencies below 3 kHz. QTD2 results with the aircraft offset from the array centerline (not shown) suggested that the port MLG is louder than the starboard MLG for most frequencies, about 1 dB in the 400 Hz to 1.4 kHz range and between ~ 1 dB and 2.3 dB for most frequencies between 1.7 kHz and 3 kHz. Regardless of the variability in levels among MLG arrays, notice that, for most frequencies above 0.3 kHz, QTD2 levels are bound between those from the MLG-FO and MLG-FOC arrays. Keep in mind that MLG results above ~ 2 kHz are underresolved, while results beyond ~ 3.5 kHz are contaminated by spurious sources and should be ignored.

Sample acoustic maps from the QTD2 arrays and isosurfaces from the multiplanar arrays for a frequency of 0.85 kHz (in $1/12^{\text{th}}$ octave bands) are shown in Figs. 34 and 35, respectively.

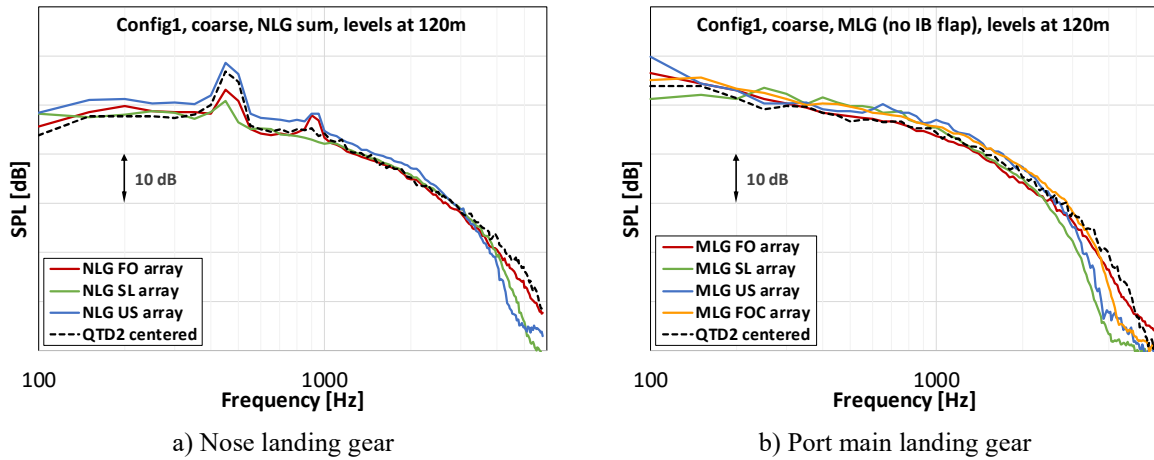


Fig. 33 Comparison of integrated levels for Config1 from different arrays (normalized to 120m).

Acoustic maps for a frequency of 0.85 kHz (in $1/12^{\text{th}}$ octave bands) with peak levels set to the same value are depicted for the centered QTD2 array in Fig. 34a and for the offset QTD2 array in Fig. 34b. These maps for the wing

plane show changes in the source distribution and peak levels. Although very informative, the maps only indicate that the MLG is a major noise source at this frequency and that the center wheel axle (or main strut) plus the aft side-brace may be the subcomponents generating most of the noise. In contrast, the isosurfaces of Fig. 35 (with different peak levels for each multiplanar array) demonstrate that sources can be clearly separated and assigned to the proper subcomponent generating the noise. Notice, though, that the source distribution seen with each MLG array changes drastically. This is caused by the radiation pattern of each source and by the shielding effects inherent in large complex structures such as the MLG. For instance, the MLG-FOC array clearly shows sources in the strut region (Fig. 35b) that are not visible to the MLG-FO array due to shielding by the truck and wheels (Fig. 35a). This behavior also explains why the integrated MLG-FOC levels are higher than those obtained from the MLG-FO array, as observed in Fig. 33b. The fact that the truck is closer to the MLG-FO array also plays a role in potentially hiding sources along the strut with similar or lower levels than those on the truck. Note also that the sideline results (Fig. 35c) show sources at the rear torque link and in the region between the wing and doors (main and trunnion). Furthermore, the peak level for the MLG-SL array is 3dB higher than the peak level for the MLG-FO array.

Results for 1.4 kHz are shown in Figs. 36 through 38. For visualization purposes, the peak levels in the QTD2 maps (located at the NLG) have been set to the same value. At this frequency, the centered QTD2 array maps for the gear plane (Fig. 36) showed sources downstream of the aft side brace while the offset array showed a source at the brace. Maps for a 2D plane closer to the wing (Fig. 37) could be used to better detect the correct location of the sources, but the location of the actual subcomponent responsible for the noise remains elusive. In contrast, the isosurfaces from the multiplanar arrays shown in Fig. 38 (with peak levels for MLG-FO array 1.7 dB higher) clearly point to sources in the cavity, aft brace, and around the wheel axles.

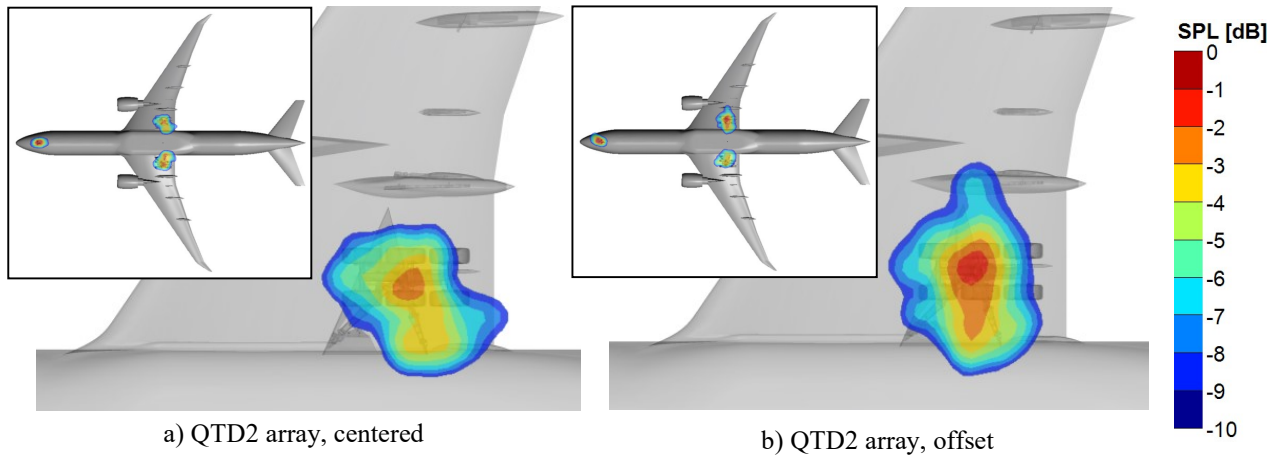


Fig. 34 Synthetic QTD2 array acoustic maps for 0.85 kHz (in 1/12th octave bands) from Config1 simulations. Maps for wing plane.

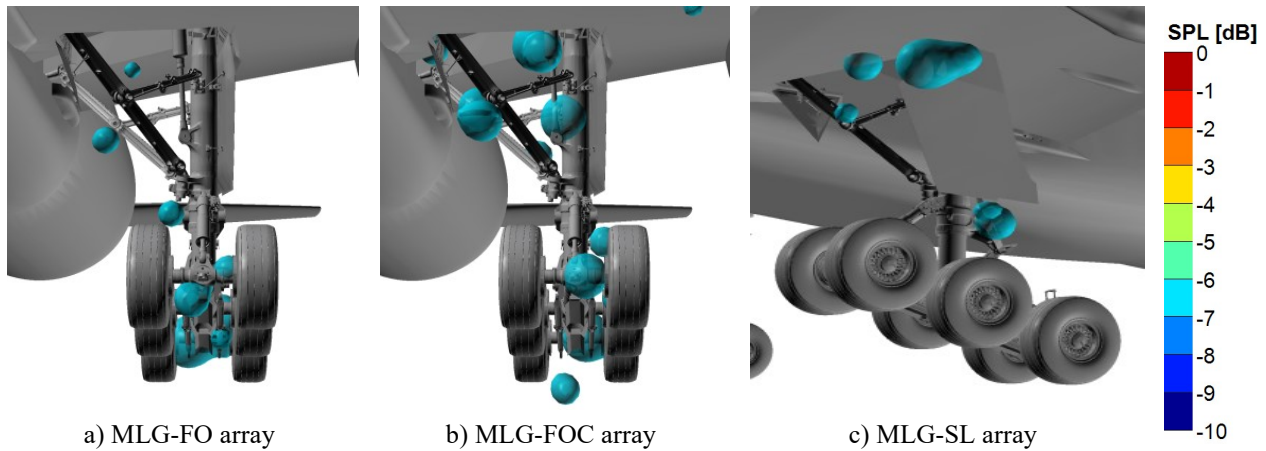


Fig. 35 CLEAN isosurfaces for 0.85 kHz (7 dB from peak, in 1/12th octave bands) from Config1 simulations.

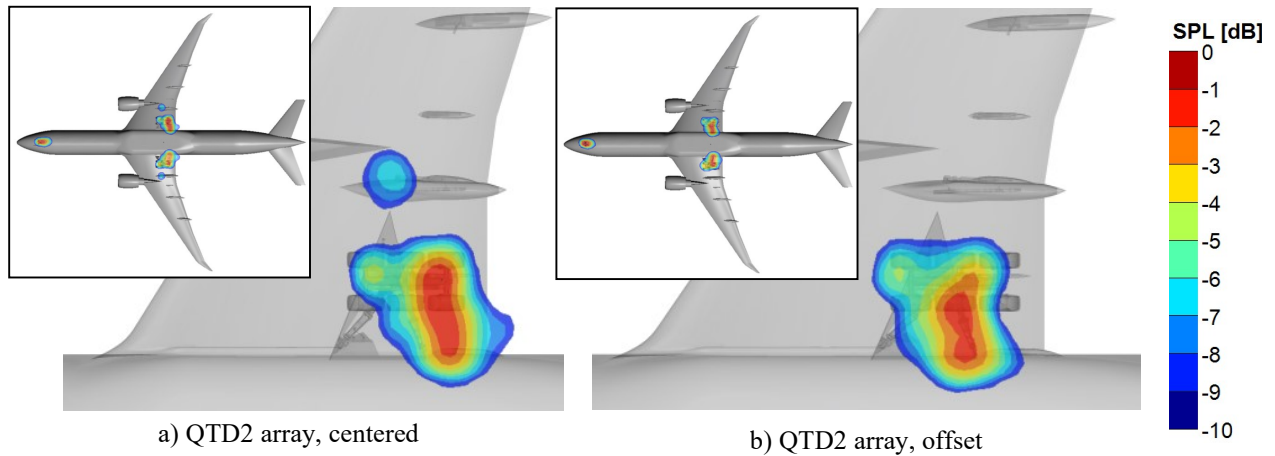


Fig. 36 Synthetic QTD2 array acoustic maps for 1.4 kHz (in 1/12th octave bands) from Config1 simulations. Maps for gear plane.

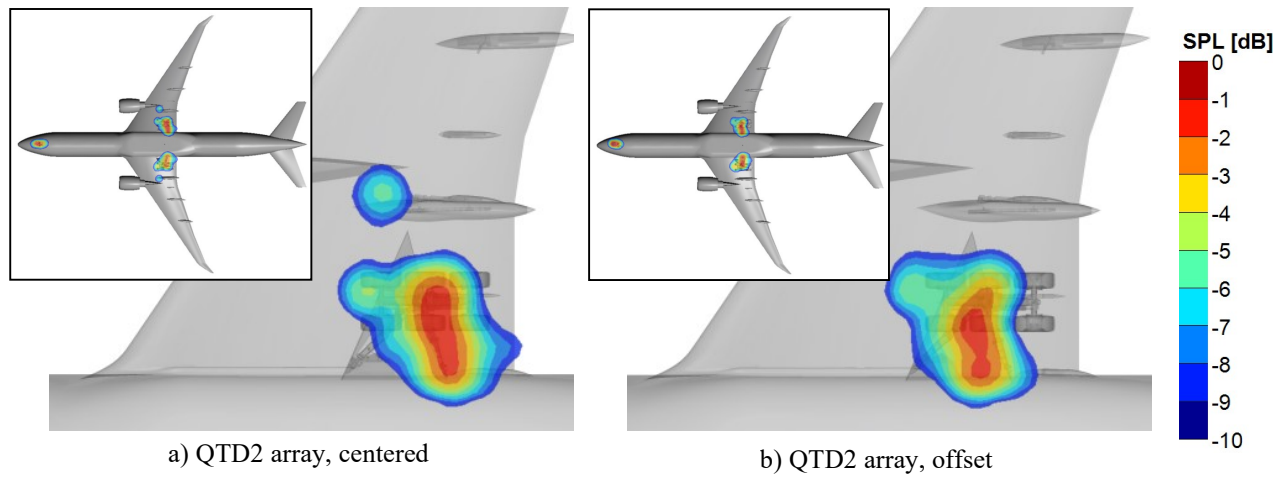


Fig. 37 Synthetic QTD2 array acoustic maps for 1.4 kHz (in 1/12th octave bands) from Config1 simulations. Maps for wing plane.

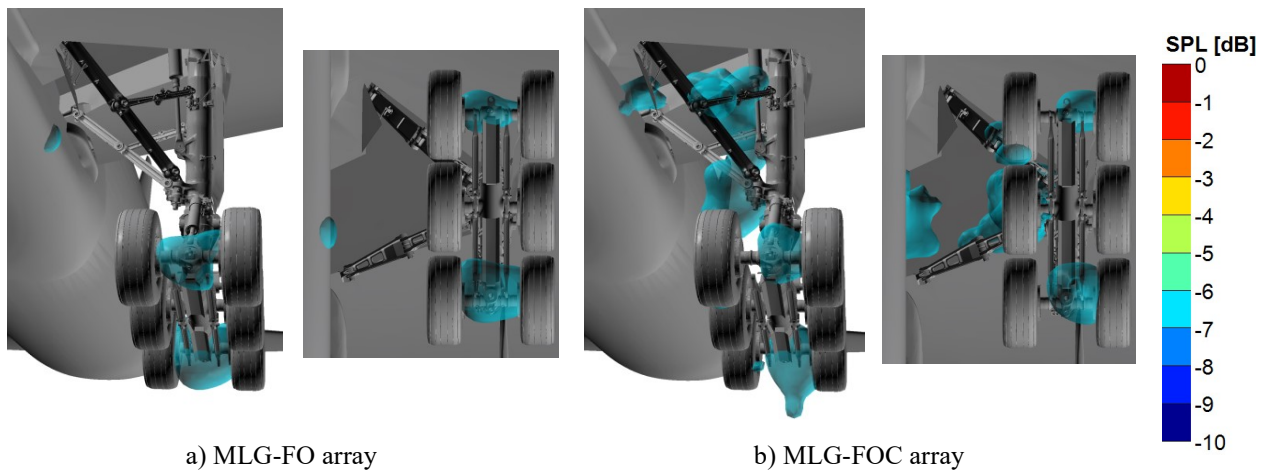


Fig. 38 CLEAN isosurfaces for 1.4 kHz (7 dB from peak, in 1/12th octave bands) from Config1 simulations.

B. Results for Config2 (Landing Gears and Hight-Lift Devices Deployed)

Integrated NLG and MLG spectra for Config2, normalized to 120 m, are presented in Figs. 39a and 39b, respectively. Observe in Fig. 39a that the noise levels obtained from the QTD2 array follow the NLG-FO array trends, except at the tone around 0.38 kHz. Despite the different flight conditions for Config1 and Config2 (see Table 1), it is clear from Fig. 39a that “new sources” have emerged around 0.75 kHz, 2.1 kHz, and 4.2 kHz for Config2, radiating mostly in the forward (upstream array) direction. Analysis of the acoustic maps showed that the haystacks around these frequencies are related to sources at the leading edge of the cavity doors, as indicated by the isosurfaces (with different peak level for each NLG array) presented in Fig. 40. These sources could not have been unequivocally identified with the ground-based QTD2 array. As can be observed in Fig. 41, maps obtained from the QTD2 array only show that strong sources appear upstream of the wheels, more noticeably at 4.25 kHz. Although this frequency is beyond the range for which spectral levels are converged, the acoustic maps can still be used to identify source locations up to the frequencies where spurious sources become overwhelming.

Integrated spectra for the port MLG are presented in Fig. 39b. Unlike the MLG results for Config1 (Fig. 33b), the QTD2 ground array shows levels that are significantly higher than those from the MLG-FO array. Although the QTD2 levels are comparable to those obtained from the MLG-FOC array, noticeable differences still exist between them. Observe that broadband noise levels obtained from the QTD2 array are higher than those for MLG-FOC at most frequencies below 2 kHz. Likely, this increase in MLG levels is related to sources in the flap (outside the IB flap region indicated in Fig. 31) that contaminate the integration results, to be discussed next. Differences between MLG-FO and MLG-FOC arrays are mostly due to shielding, as observed for Config1. Also notice the directivity of the tonal components, radiating more prominently in the upstream direction. This behavior is consistent with the streamwise orientation of the pins generating the noise, as mentioned in Section IV.D.

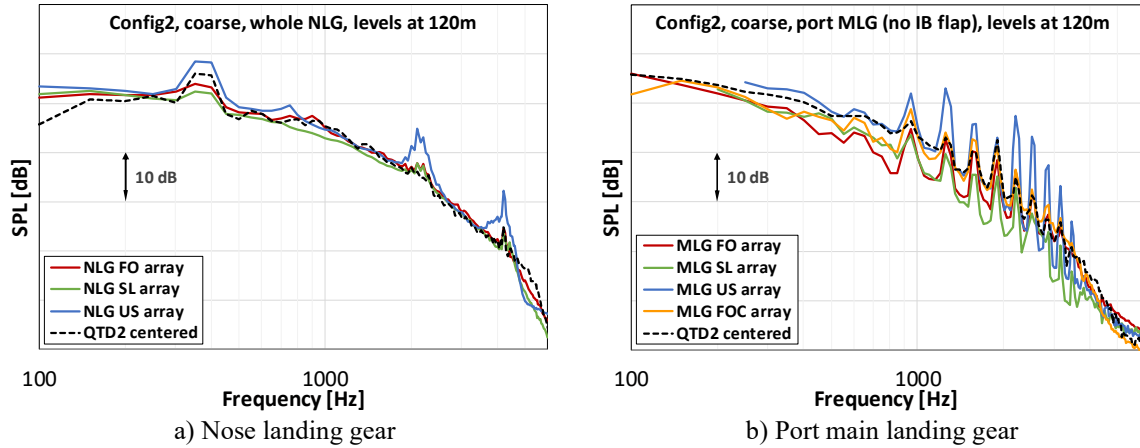


Fig. 39 Comparison of integrated levels for Config2 from different arrays.

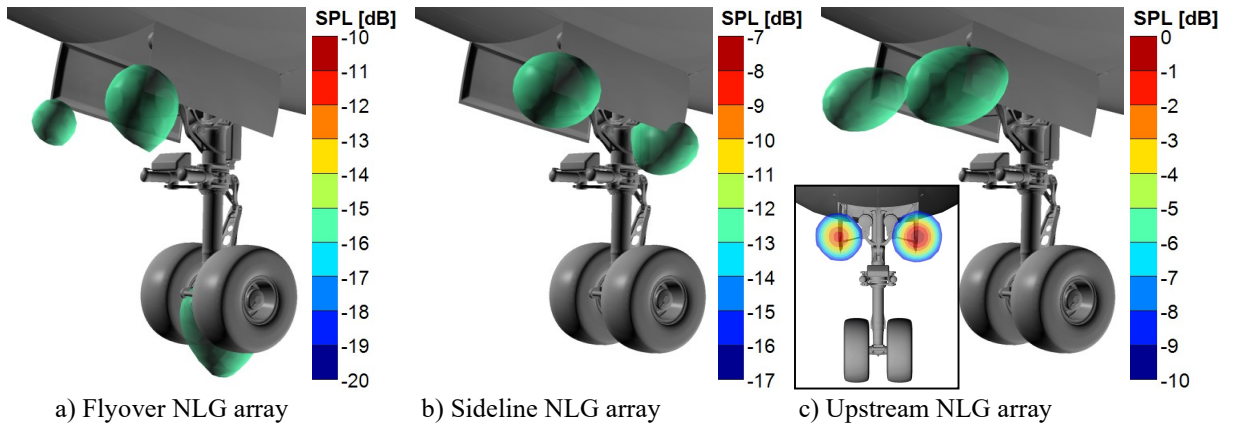


Fig. 40 CLEAN isosurfaces for 2.12 kHz (6dB from peak, in 1/12th octave bands) showing NLG door sources.

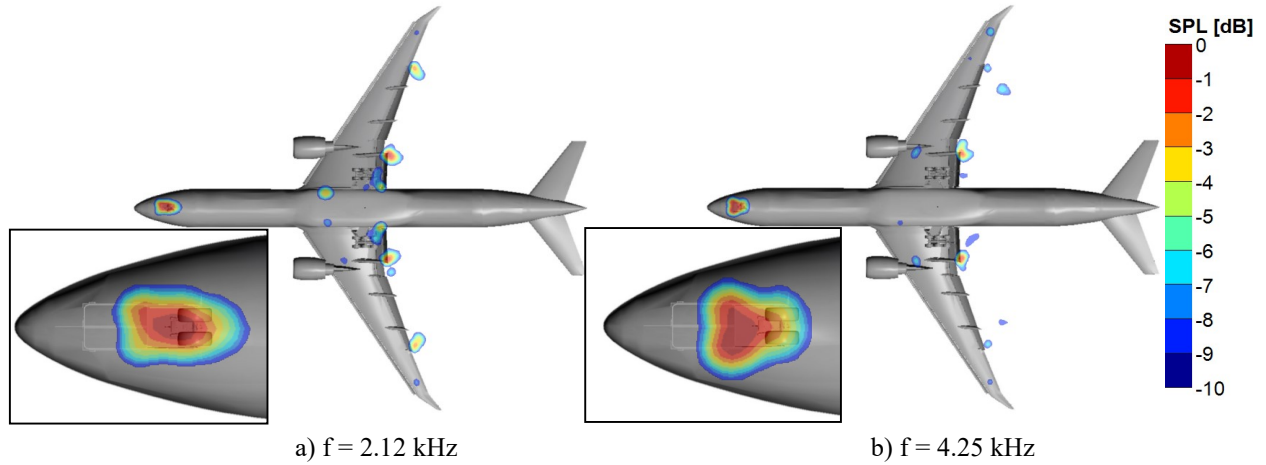


Fig. 41 QTD2 array acoustic maps (in $1/12^{\text{th}}$ octave bands) from Config2 simulations. Actual peak levels different for each frequency.

Sample CLEAN maps and isosurfaces for 0.8 kHz ($1/12^{\text{th}}$ octave band) are shown in Figs. 42 and 43 for the QTD2 and multiplanar arrays, respectively. For comparison purposes, the peak levels (located at the NLG) in the acoustic maps of Fig. 42 were set to the same values. A clear difference in the source distribution between the centered (Fig. 42a) and offset (Fig. 42b) QTD2 arrays can be observed. This directivity is consistent with the large difference in levels observed in Fig. 39b between the spectra for the MLG-FO and MLG-FOC arrays. Figure 43 shows the isosurfaces for the MLG-FO and MLG-SL arrays (peak levels are 5 dB higher for the latter). These maps and further analysis of the beamforming results show that no source is present in the aft region of the MLG truck, and that the source seen near the aft section of the truck in the QTD2 maps (Fig. 42) is actually due to the flap. This illustrates our stated conjecture that quantification of MLG noise from ground-based arrays, such as the QTD2, may be difficult due to contamination from sources in the flap area that cannot be accurately separated because of poor array resolution.

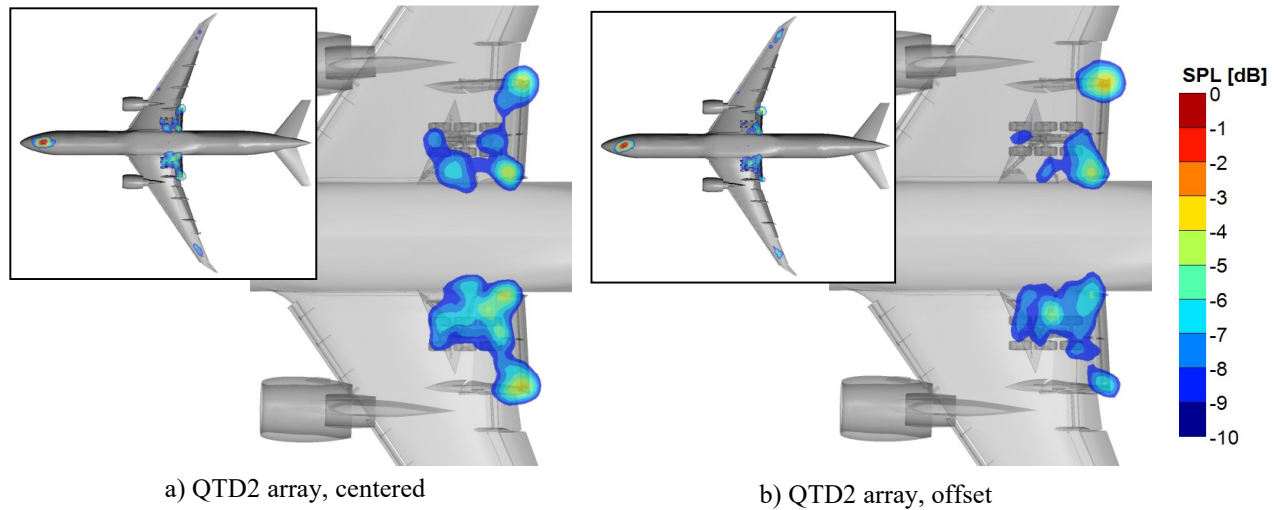


Fig. 42 Synthetic QTD2 array acoustic maps for 0.8 kHz (in $1/12^{\text{th}}$ octave bands) from Config2 simulations.

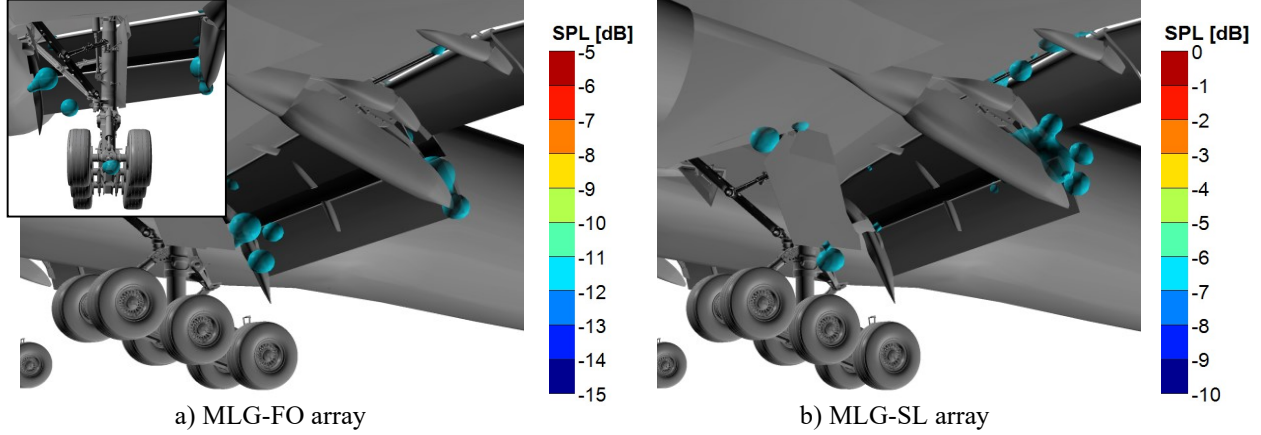


Fig. 43 CLEAN isosurfaces for 0.8 kHz (7 dB from peak, in 1/12th octave bands) from Config2 simulations.

The next set of examples showcasing the advantages of multiplanar arrays target several frequencies where prominent tones were observed. A comparison of CLEAN maps from both types of array setup is used to demonstrate the gains in source identification achieved with the present approach. The maps obtained from the QTD2 array are shown in Figs. 44 and 45 for 950 Hz and 1.9 kHz, respectively. For visualization purposes, the peak levels for the two maps in each figure were set to the same value. Notice that the results for the centered (Figs. 44a and 45a) and offset (Figs. 44b and 45b) QTD2 arrays show clear changes in source distribution, indicating highly directional sources consistent with the integrated spectra of Fig. 39b. As in previous examples, the exact location of these sources cannot be pinpointed using only QTD2 maps, even from grids at different locations in the vertical direction (not shown here). However, in conjunction with surface pressure fluctuations, acoustic maps from ground arrays can be used to assign the location of these sources to a particular component [8]. Alternatively, results from the multiplanar arrays at the same frequencies, shown in Figs. 46 and 47, can be used to clearly pinpoint the sources without resorting to time-consuming analyses of the surface pressure fluctuations. Note that the maps in Fig. 46 also show a source in the fuselage side of the cavity. Since the starboard MLG also generates high-amplitude tonal sources at the same frequencies, the isosurfaces in Fig. 47 also contain spurious sources below the MLG. This type of contamination of the CLEAN results can be minimized by using a 3D grid encompassing the entire aircraft. However, the computational cost to run CLEAN on such expansive grids would increase significantly.

The maps generated at 1.4 kHz shown in Figs. 48 and 49 were used to determine whether a source seen with the QTD2 array in the aft section of the truck is actually caused by the inboard flap, as suggested in Fig. 42. The fact that the source near the engine pylons appears to move when observed with the centered (Fig. 48a) and offset (Fig. 48b) QTD2 arrays suggested that these sources may be reflections of other sources. This suspicion was confirmed with the multiplanar array isosurfaces of Fig. 49, where no sources were found in these areas. A comparison of results at 1.4 kHz with those for Config1 at the same frequency (Figs. 36 through 38), reveals that the sources in the aft axle are less dominant for Config2. This change could be caused by the lower aircraft speed for Config2 and/or by significant alterations to the local flow approaching the MLG that result from deployment of high-lift devices in Config2.

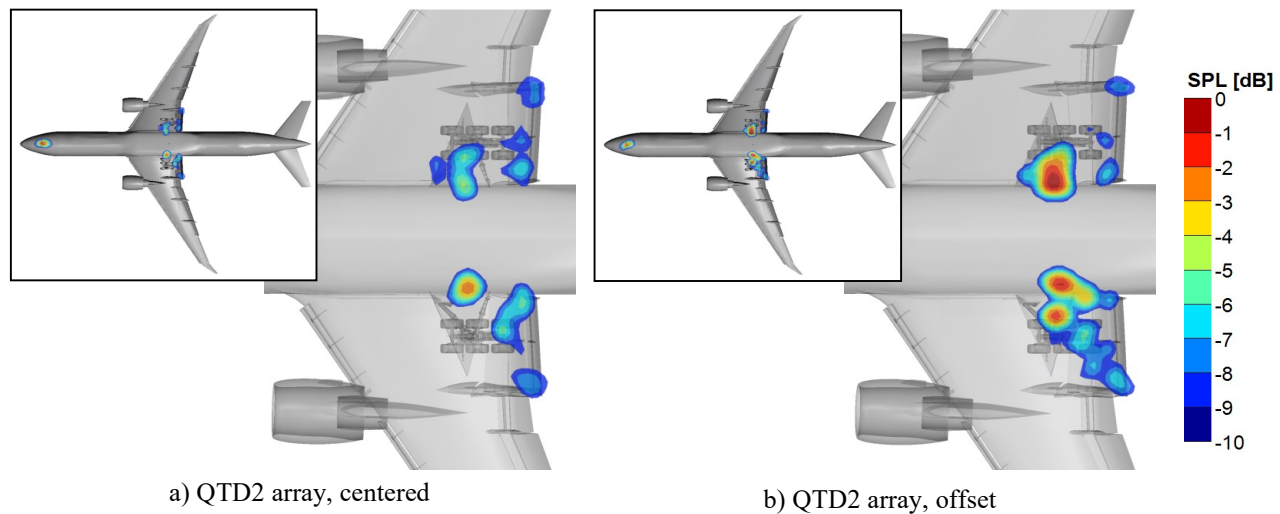


Fig. 44 Synthetic QTD2 array acoustic maps for 0.95 kHz (in 1/12th octave bands) from Config2 simulations.

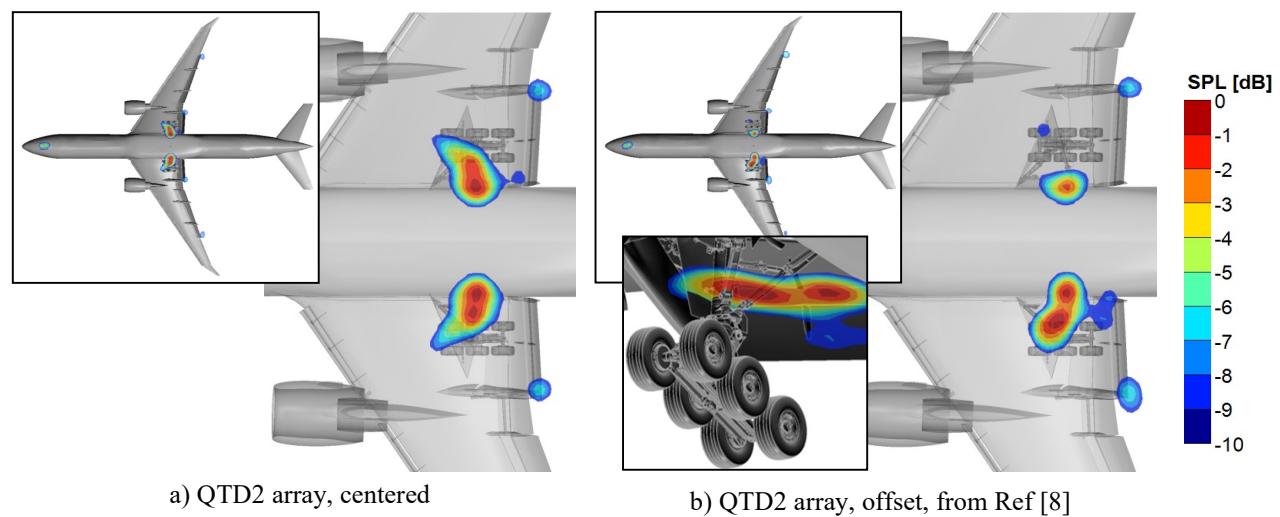


Fig. 45 Synthetic QTD2 array acoustic maps for 1.9 kHz (in 1/12th octave bands) from Config2 simulations.

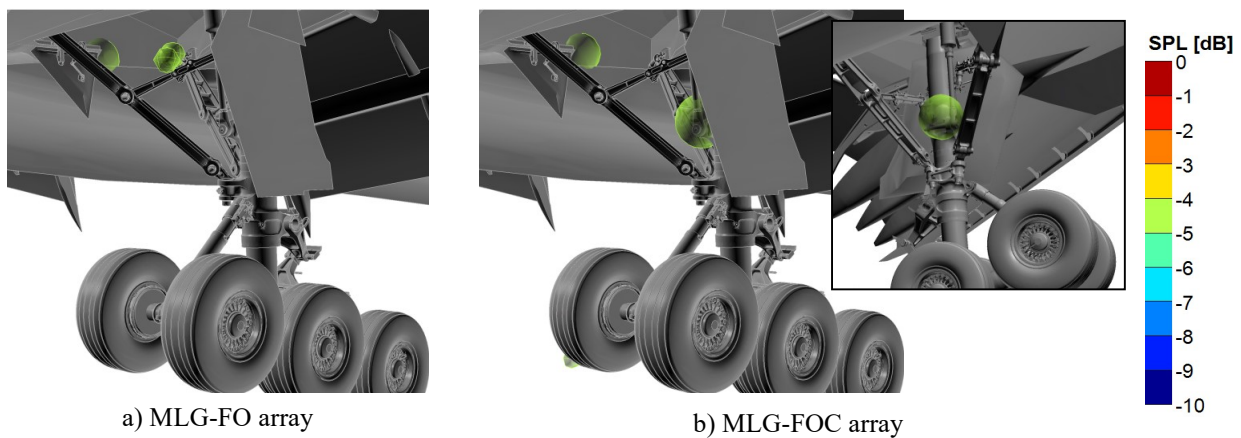


Fig. 46 CLEAN isosurfaces for 0.95 kHz (5 dB from peak, in 1/12th octave bands) from Config2 simulations. Actual peak levels are 1.5 dB higher for FOC array.

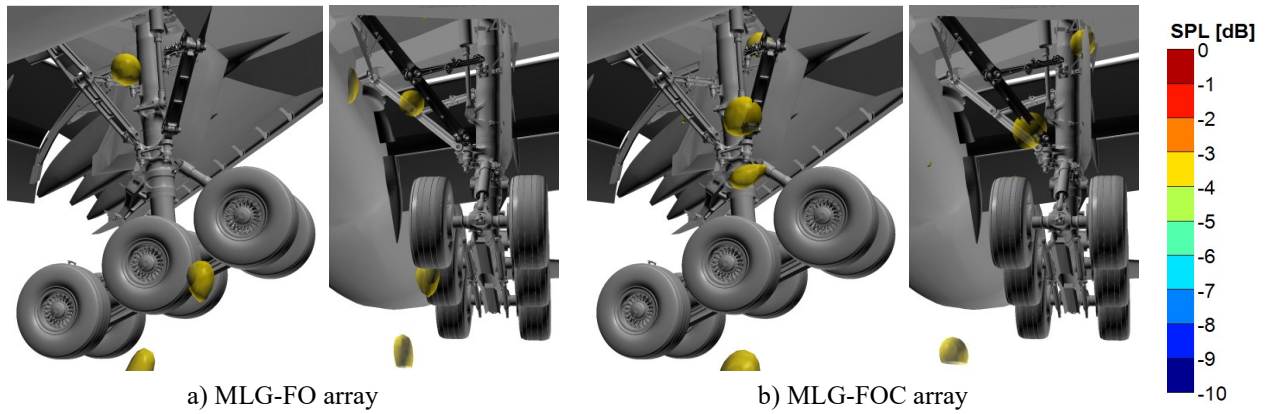


Fig. 47 CLEAN isosurfaces for 1.9 kHz (4 dB from peak, in 1/12th octave bands) from Config2 simulations. Actual peak levels are ~4 dB higher for MLG-FOC array.

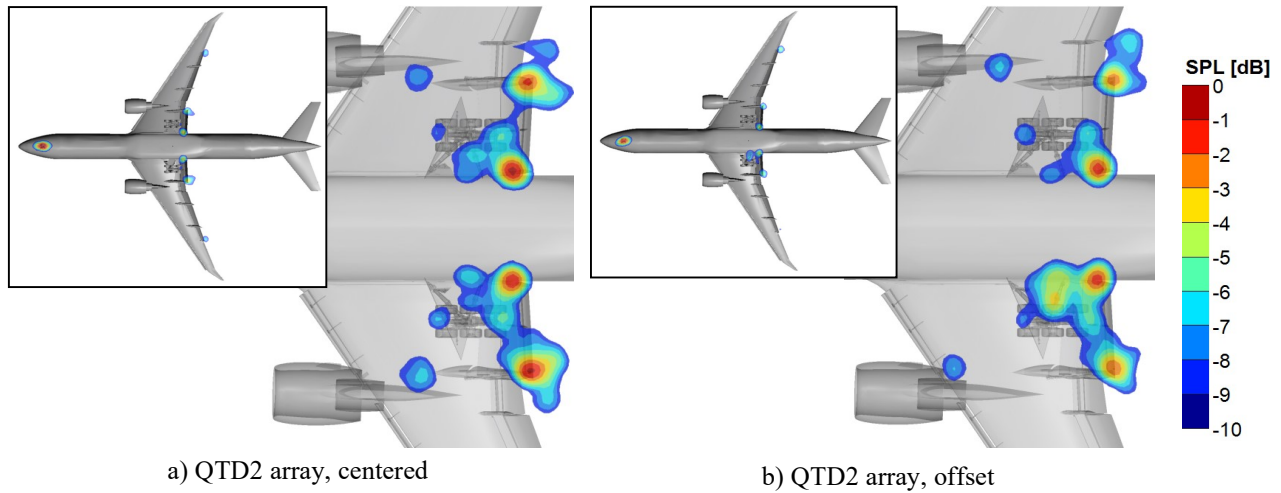


Fig. 48 Synthetic QTD2 array acoustic maps for 1.4 kHz (in 1/12th octave bands) from Config2 simulations. Levels in closeup views adjusted to show MLG sources (peak level located at NLG is 3dB higher in acoustic maps for full-aircraft).

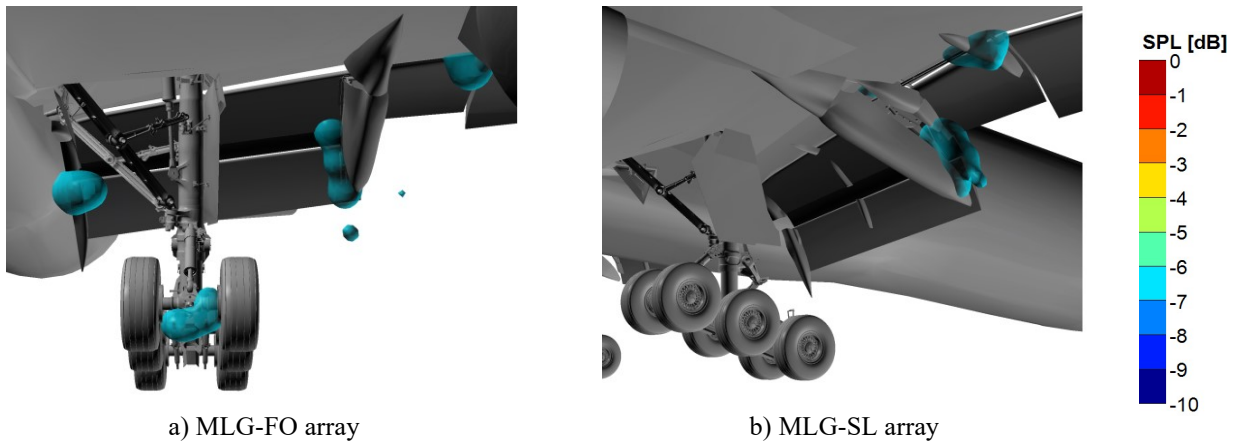


Fig. 49 CLEAN isosurfaces for 1.4 kHz (7 dB from peak, in 1/12th octave bands) from Config2 simulations. Actual peak levels are 6dB higher for MLG-SL array.

Finally, Figs. 50 and 51 depict results for 2.12 kHz, a frequency at the boundary of the range for which coarse results are considered to be converged. At this frequency, the maps of Fig. 50 – with peak levels set to the same values – show that the source distribution and relative levels change substantially between the centered (Fig. 50a) and offset (Fig. 50b) QTD2 arrays, particularly in the flap trailing edge region. Notice also the sources that appear to be near the fuselage/wing junction forward of the MLG. In contrast, the maps from the multiplanar arrays presented in Fig. 51 – with MLG-SL peak levels approximately 7 dB and 9 dB higher than those for the MLG-FO and MLG-FOC arrays, respectively – reveal no sources in this area. This suggests that the sources seen in the QTD2 maps are reflections of another source, likely that observed in the junction between the wing leading edge and the engine pylon. In addition, the MLG-FOC map (Fig. 51b) shows spurious sources along the boundary of the MLG grid (indicated with a dashed line). These are sidelobes of a dominant trailing edge source (situated around 75% span in Fig. 50) that also seems to be highly directional.

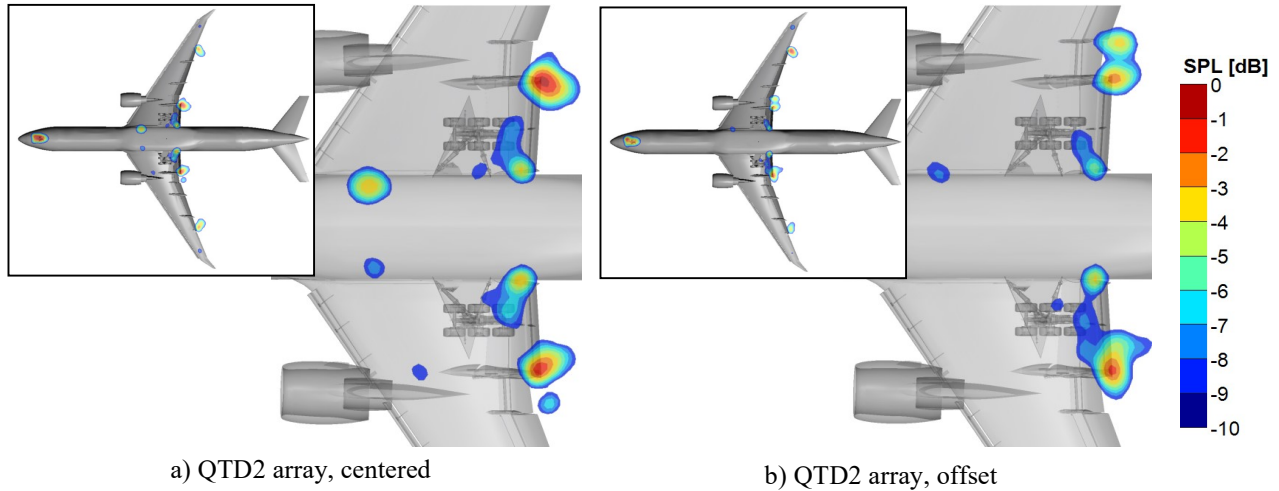


Fig. 50 Synthetic QTD2 array acoustic maps for 2.12 kHz (in $1/12^{\text{th}}$ octave bands) from Config2 simulations.

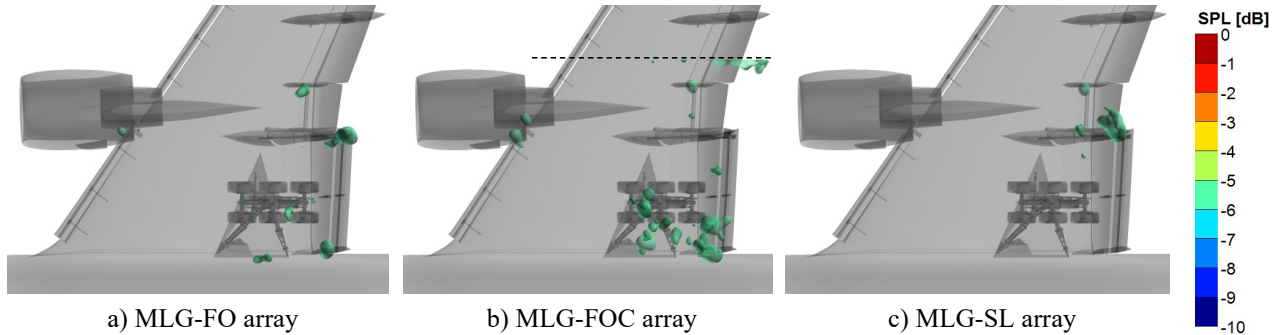


Fig. 51 CLEAN isosurfaces for 2.12 kHz (6 dB from peak, in $1/12^{\text{th}}$ octave bands) from Config2 simulations.

VI. Summary

A multiplanar synthetic array framework is proposed for the accurate identification and quantification of primary and secondary noise sources generated by the various subcomponents of aircraft landing gear. With high-fidelity airframe noise simulations of full-scale, complete aircraft becoming prevalent, the approach leverages the output of such computations to deliver better insights on the location and magnitude of gear sources and, thus, hasten the development of viable abatement technologies that can be tailored and applied locally to affect solely the source regions of interest.

As part of a NASA-Boeing effort to predict landing gear noise signatures of large civil transports, a comprehensive set of validated airframe noise simulations for a full-scale Boeing 777-300ER aircraft was generated and made

available for the present analysis. The simulations, conducted with the lattice-Boltzmann flow solver PowerFLOW®, comprised three configurations: a) full aircraft with nose landing gear deployed, and main landing gear and high-lift devices retracted (NLG-only); b) nose and main landing gears deployed with high-lift devices retracted (Config1); and c) landing gears deployed with high-lift devices deflected (landing configuration, Config2). A high-fidelity digital model of the aircraft with as-flown geometries for the nose and main landing gears was used in the simulations.

The work presented here was an attempt to leverage existing simulations to obtain information that cannot be gleaned from ground arrays used during flight tests. The main goal was to quantify landing gear noise at the sub-component level, including dominant radiation directions, while rejecting noise from nearby high-lift devices. To achieve this, a framework of multiplanar arrays located relatively close to the landing gears was developed to resemble a wind tunnel setup. The availability of high-fidelity simulations also provided a unique opportunity to directly compare results between the “flight test” and “wind tunnel” array setups, which is not possible in real-life experimental measurements.

To implement and assess the framework, a synthetic, 800-microphone array was designed and replicated at various locations around the nose and port main landing gears and oriented along the three primary propagation directions (flyover, sideline and upstream). Approximately 0.8 seconds of synthetic pressure records for 7 arrays and a total of 5,600 microphones were generated via a FWH integral approach with flow quantities on permeable data surfaces as input. Array integrated spectra for different aircraft components and their subcomponents were obtained using CLEAN beamform maps for 3D regions surrounding the nose landing gear, main landing gear, and high-lift devices in the inboard region of the port wing.

A spatial resolution analysis indicated that coarse resolution simulations provide converged integration results up to ~2 kHz. Although acoustic maps showed well-defined sources beyond these frequencies, their integrated levels are not considered accurate because sources are underresolved.

The impact of using solid surfaces in the FWH integral approach was studied using medium resolution simulations. The results confirm findings from previous studies indicating that solid surfaces do not render correct levels and source distributions in the presence of cavities, nor when shielding of noise among different components takes place.

Results from the multiplanar arrays were used to highlight the advantages of their implementation when compared to a flight-test array setup. These advantages include a very accurate localization of dominant noise sources, quantification of integrated spectra at the subcomponent level, and separation of landing gear noise from surrounding high-lift devices. The presence of tonal components in the MLG (pinpointed to pin holes in the strut and braces) complicated the analysis of coarse resolution results for Config2. At some frequencies, dominant noise sources within the high-lift devices – but external to the integration regions used to beamform – contaminated the results with spurious sources that CLEAN could not accurately recognize as sidelobes. Future work should look into expanding the 3D grid to include most of the aircraft and thus obtain more accurate CLEAN results.

We demonstrated that when simulation results are readily available, the methodology presented here can provide additional, in-depth acoustic information in a relatively inexpensive manner. Although results obtained with multiplanar arrays are not infallible, the approach can provide valuable insight into the noise generated at the subcomponent level that cannot be obtained with ground arrays.

Acknowledgments

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