

Cartesian Mesh Simulations for the Third AIAA Sonic Boom Prediction Workshop

Wade M. Spurlock*

Science and Technology Corporation, Moffett Field, CA 94035

Michael J. Aftosmis[†] and Marian Nemec[‡]

NASA Ames Research Center, Moffett Field, CA 94035

Simulation results are presented for all cases from the Third AIAA Sonic Boom Prediction Workshop. An inviscid, embedded-boundary Cartesian-mesh flow solver is used in conjunction with adjoint-based mesh adaptation to compute nearfield pressure signatures. Specialized techniques are applied to maximize accuracy and minimize cost on Cartesian meshes. The Richardson-based error estimate highlights regions of the signatures most sensitive to mesh refinement. Timing results and coarse, medium, and fine mesh sizes for nearfield cases demonstrate that the parallel decomposition approach is efficient in both computational time and wall-clock. Pressure signals are propagated to the ground using an augmented Burgers' equation solver to predict boom carpets. Ground signatures and loudness metrics are presented for a standard atmosphere as well as more realistic atmospheric profiles, which affect overall noise levels and can significantly widen the boom carpet. Mesh convergence studies show that high sampling frequencies, around 500 kHz, are required for propagation, and the sampling frequency increases at large off-track angles with longer acoustic ray paths and propagation times. The numerical methods yield accurate results for predicting low sonic boom signatures while being among the least computationally expensive of the workshop.

Nomenclature

$[a, b]$	= Interval notation for the region $a \leq x \leq b$ inclusive
x	= Longitudinal axis along flight path
R	= Radial distance from flight path
ϕ	= Azimuth around flight path, on-track at $\phi = 0^\circ$
L	= Reference length for propagation
M	= Mach number
μ	= Mach angle
P	= Pressure
T	= Temperature
h	= Altitude
Re_x	= Reynolds number per unit length
ΔP	= Overpressure, $(P - P_\infty)$

Subscripts

$(\cdot)_\infty$	= Freestream condition
$(\cdot)_t$	= Stagnation quantity
$(\cdot)_b$	= Value at computational domain boundary

Acronyms & Abbreviations

SBPW	= Sonic Boom Prediction Workshop
CFD	= Computational Fluid Dynamics
LBFD	= Low Boom Flight Demonstrator
c608	= LBFD design iteration, Nearfield Case II

*Research Scientist/Engineer, Computational Aerosciences Branch, wade.m.spurlock@nasa.gov, Member AIAA

[†]Aerospace Engineer, Computational Aerosciences Branch, michael.aftosmis@nasa.gov, Associate Fellow AIAA

[‡]Aerospace Engineer, Computational Aerosciences Branch, marian.nemec@nasa.gov, Member AIAA

c609	=	LBFD design iteration, Propagation Case II
ECS	=	Environmental Control System, outflow boundaries on c608 and c609
C25P	=	NASA Concept 25 Powered, Propagation Case I
ASEL	=	A-weighted Sound Exposure Level, units dB[A]
BSEL	=	B-weighted Sound Exposure Level, units dB[B]
CSEL	=	C-weighted Sound Exposure Level, units dB[C]
PLdB	=	Perceived Level of noise
sBOOM	=	NASA advanced Sonic Boom propagation tool
LCASB	=	NASA Loudness Code for Asymmetric Sonic Booms

I. Introduction

SUPERSONIC flight was first achieved over seventy years ago [1] but remains elusive for everyday travel due to high costs and loud sonic booms underneath the aircraft. Recent technological developments and commercial interest in overland supersonic flight have led to over a decade of research in sonic boom prediction and quieter supersonic aircraft designs. Improvements in sonic boom analysis methodology have been garnered in part by four workshops: NASA Fundamental Aeronautics Program Sonic Boom Prediction Workshop in 2008 [2] and the First, Second, and Third AIAA Sonic Boom Prediction Workshops in 2014 (SBPW1 [3]), 2017 (SBPW2 [4, 5]), and 2020 (SBPW3), respectively. These workshops bring together participants with many different approaches and simulation tools to compare results and identify challenges for further research.

The general approach to predicting sonic booms on the ground separates the problem into a nearfield portion and a propagation portion, as depicted in Fig. 1. Pressure waves near the aircraft are highly three-dimensional and are affected by local induced flow and pressure gradients. Due to the presence of aircraft geometry, propulsion systems, and nonlinear flow features, computational fluid dynamics (CFD) is the preferred method for *nearfield* simulation. As shocks and expansion waves travel farther from the aircraft, flowfield disturbances and azimuthal gradients become small enough that the pressure signals can be considered to propagate along independent radial paths. Simulating *propagation* involves modeling the evolution of these acoustic waves through the atmosphere along separate ray paths, some of which eventually reach the ground.

The third AIAA Sonic Boom Prediction Workshop (SBPW3) provides challenging benchmarks that represent current state-of-the-art low-boom designs. As supersonic aircraft designs become quieter, both the nearfield and propagation parts of ground noise prediction are more challenging. In nearfield CFD, the nearfield pressure signal is extracted several body lengths away from the aircraft. Coalescence of many flow features and smaller pressure disturbances are more sensitive to dissipation and require more mesh resolution. Just a few body lengths away from a low-boom aircraft, pressure disturbances are around three orders of magnitude smaller than ambient absolute pressure. Correctly predicting pressure to within a fraction of a percent at distances several hundred feet away from the aircraft requires accurate numerical schemes and proper mesh resolution.

Low-boom aircraft also require more numerical accuracy in the farfield propagation calculation. Pressure signals dissipate and spread, reaching the ground at disturbance amplitudes roughly five orders of magnitude smaller than sea-level pressure. Furthermore, since ground noise is calculated on a logarithmic scale in decibels, the same incremental pressure error will have a larger effect on low-noise signals than it would on high noise levels. All of these factors make boom prediction more challenging, and we must actually be *more* accurate on current low-boom designs, around 75 PLdB, than was necessary for earlier designs, which were over 90 PLdB just ten years ago.

This paper presents results for the nearfield workshop cases using an embedded-boundary Cartesian mesh approach with automatic control of discretization error through output-based mesh adaptation. Propagation calculations are

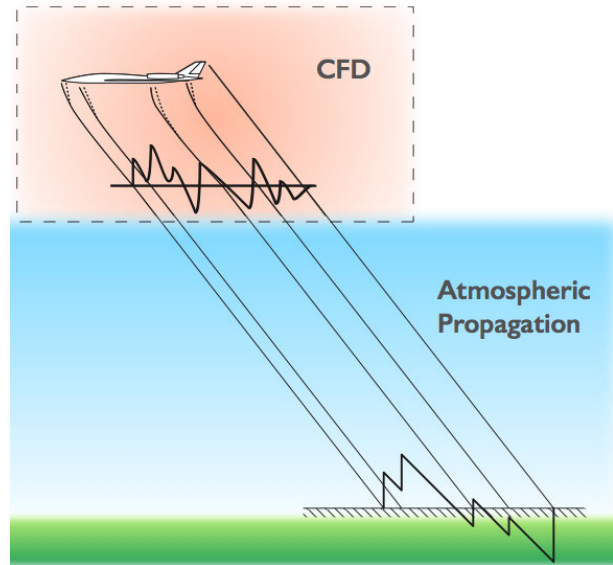


Fig. 1 Sonic boom prediction separated into nearfield CFD and farfield atmospheric propagation.

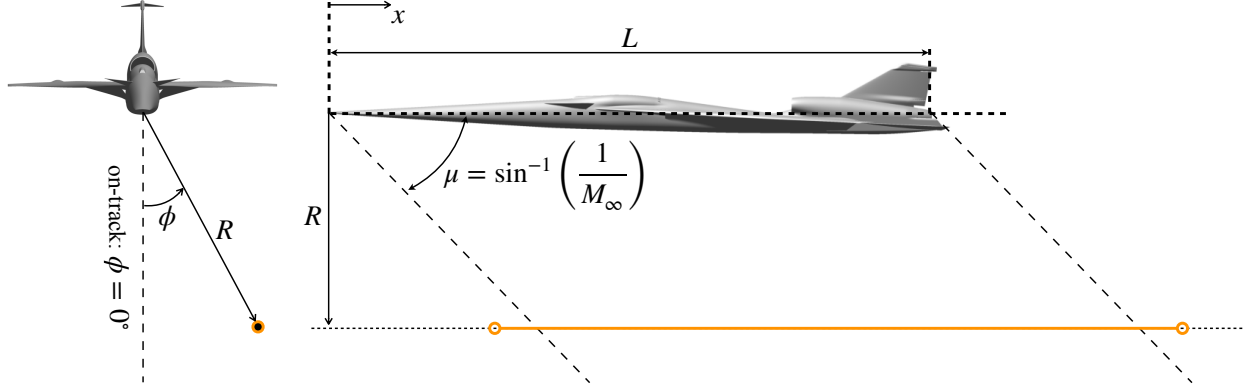


Fig. 2 Freestream-aligned cylindrical coordinate system and sign convention for nearfield line sensors (orange).

performed with sBOOM, NASA’s advanced Sonic Boom propagation tool, and are focused on mesh convergence of the ground signature and noise metrics. The nearfield CFD approach and results are presented in Section II, followed by propagation cases in Section III. The nearfield Biconvex case highlights shock-plume interaction and was originally designed and performed as a wind tunnel test at NASA Ames Research Center; the c608 case is a complex, full-aircraft geometry that is a modified version of an earlier design iteration from the NASA Low-Boom Flight Demonstrator (LBFD) project. The first propagation case is the C25P low-boom powered model, which was analyzed in SBPW2; the second case is based on the recent C609 design from the LBFD project and is intended to be even quieter than the C25P. Both cases are propagated through two different prescribed atmospheres, one standard atmosphere and another with variations representative of a realistic atmospheric profile.

II. Nearfield CFD

SBPW3 presents two nearfield CFD cases: a shock-plume interaction and a complex, full-aircraft geometry with multiple inflow and outflow boundary conditions. The Biconvex case is based on previous NASA wind tunnel tests [6–8] and CFD analysis [9, 10]. Not coincidentally, the orientation of the wing and nozzle is representative of control surfaces and engine exhaust plumes at the aft end of an aircraft. The c608 case is based on one of the latest cutting-edge low-boom aircraft designs from NASA’s LBFD project. In addition to complex geometry and flow features, capturing the nearfield pressure signal at a radial distance of three body lengths beneath the aircraft makes this case computationally challenging.

Figure 2 shows a cylindrical coordinate system around the aircraft. The origin is at the aircraft nose, with the longitudinal axis, x , parallel to freestream flow. Line sensors are prescribed by radial distance, R , away from and azimuthal angle, ϕ , rotating around the longitudinal axis. Directly underneath the aircraft is referred to as "on-track" and $\phi = 0^\circ$. Aircraft length, L , is typically used as a reference to describe pressure signals at multiple body-lengths away from the aircraft. Shocks and expansions coalesce and propagate away from the aircraft at the Mach angle, μ , forming a Mach cone around the body in three dimensions. We place line sensors starting just ahead of the Mach cone to ensure that the initial peak is captured. Note that in this nearfield sign convention, the off-track angle ϕ is positive around the aircraft left side; this is opposite of the propagation sign convention seen later in Figs. 21 and 28.

In the next section, we give an overview of our methodology and previous developments. Results are presented in Section II.B, with Biconvex Case I in II.B.1, c608 Case II in II.B.2, and finally a tabulation of the computational costs and hardware used in II.B.3. Section II.C contains a discussion of nearfield results.

A. Cart3D Methodology

Cart3D is a robust geometry, mesh generation, and flow solver package that solves the Euler equations on a multilevel Cartesian mesh with embedded cut-cell boundaries [11]. Depicted in Fig. 3, the computational mesh is divided into

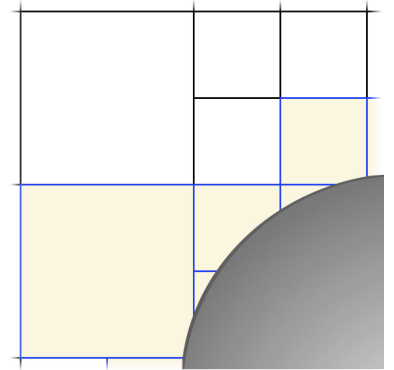


Fig. 3 Multilevel Cartesian mesh in two dimensions with a cut-cell boundary.

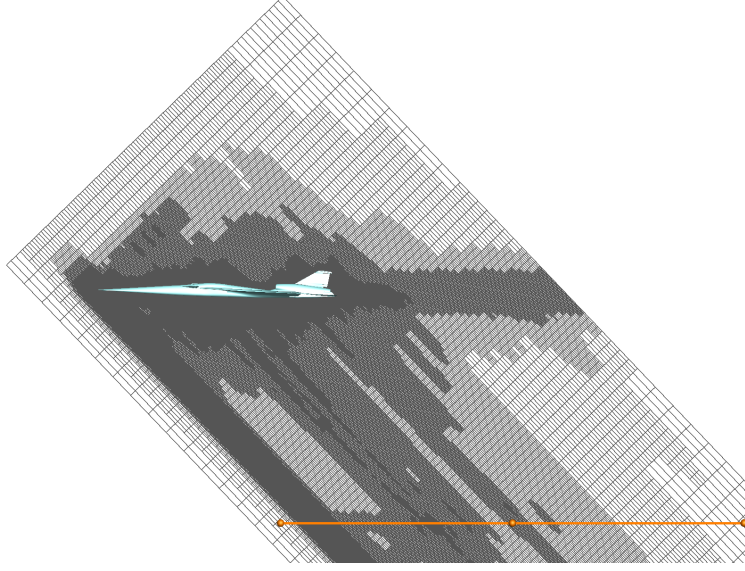


Fig. 4 Mach-aligned mesh rotation for c608 on coarse-level adapted grid, $\phi = 0^\circ$. Line sensor at $R/L = 1$ shown in orange.

Cartesian hexahedral cells with a layer of cut cells that intersect the body surface geometry, which is in the form a watertight surface triangulation with outward-pointing normals. Component tagging allows geometric manipulations, specification of boundary conditions, and post-processing forces and moments.

The van Leer flux-splitting approach [12] is used along with a cell-centered, second-order finite volume method and a weak imposition of boundary conditions. Steady-state Euler equations are solved using a five-stage Runge-Kutta scheme with local time stepping and multigrid acceleration. Computational efficiency is increased via parallel computing by performing domain decomposition using space-filling curves [13].

A unique feature of the Cart3D package is its fully integrated and automatic control of discretization error through output-based mesh adaptation using adjoint-weighted residuals [14]. Boom prediction makes use of off-body pressure signals, which can be tailored in the output functional through use of a local weighting function along the line sensor, $w(s)$, to emphasize certain parts of the pressure signals [15]. Equation 1 contains the scalar output functional, J , formed by integrating the weighted squared pressure disturbance over the length of a line sensor.

$$J = \int_0^l w(s) \left(\frac{P(s) - P_\infty}{P_\infty} \right)^2 ds \quad (1)$$

Cells can be stretched to an aspect ratio in the propagation and spanwise directions. Initial meshing refinement and subsequent adaptation always subdivides cells isotropically. Improved propulsive boundary conditions [16] have been implemented with accompanying functionals for the adjoint problem [17]. We used Cart3D version 1.5.5.3 to perform our nearfield CFD simulations for SBPW3.

Previous Cart3D development has established best practices for accurate and efficient boom prediction simulations. The Mach-aligned mesh rotation approach [18] yielded very good results for the 2008 NASA boom prediction workshop [19]. Aligning the Cartesian grid with the Mach angle more accurately captures pressure disturbances extending away from the aircraft and also allows some stretching in the propagation direction, which helps reduce the overall grid size. Figure 4 shows an example of Mach-aligned mesh rotation, with 4:1 aspect ratio stretching in the propagation direction and a coarse-level adapted grid to visualize some of the mesh adaptation patterns developing.

Work for SBPW1 and SBPW2 showed that aligning the mesh to the off-track angle also benefits both accuracy and efficiency [15, 19, 20]. The conceptual idea is actually the same as what is typically done in wind tunnels – pressure sensors remain fixed and the model is rotated about the longitudinal axis to capture different off-track angles. Figure 5 shows the geometry rotated to align an azimuthal off-track angle in the Cartesian mesh xz -plane of signal propagation. This approach decomposes the nearfield CFD setup into multiple independent simulations that can be run simultaneously. Advantages of this technique include good mesh alignment for each off-track angle, mesh adaptation for each individual simulation, and the ability to run cases simultaneously. Due to pressure signal decay radially outward, line sensors farther from the aircraft are given additional weighting in the objective function.

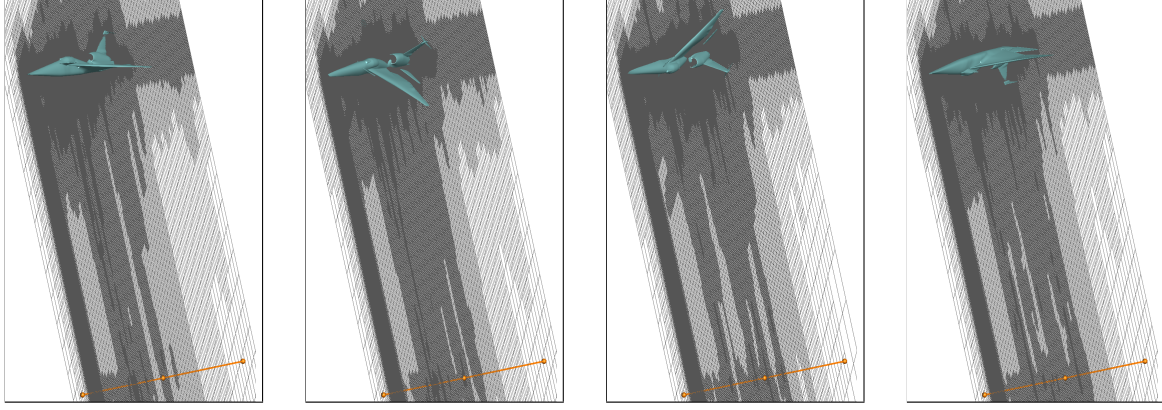


Fig. 5 Model rotation to align azimuth with Cartesian grid. From left to right: $\phi = 0^\circ$, $\phi = 50^\circ$, $\phi = 120^\circ$, $\phi = 180^\circ$. c608 shown with coarse-level adapted grid from each separate off-track angle run.

B. Results

1. Case I: Biconvex Airfoil Shock-Plume Interaction

The first case is shock-plume interaction with a biconvex airfoil near a supersonic exhaust plume. The model's forebody is a slender sphere-cone that reaches a constant cross-section before tapering slightly to the edge of the nozzle. A thin, swept strut supports the forebody and biconvex airfoil that generates the shock. In the physical wind tunnel model, the strut also contained plumbing to feed high pressure air to the nozzle; in CFD analysis, we specify the plenum conditions as total pressure and total temperature ratios at a boundary condition face ahead of the converging-diverging nozzle. The conditions in Table 1 are specified for this simulation, although note that we do not use freestream temperature and Reynolds number for solving the Euler equations.

We constructed the surface triangulation from workshop-provided STP and IGS geometry files. Where possible, we made a diagonalized structured grid for the revolved features (forebody, nozzle) and for the roughly rectangular airfoils (strut, biconvex shock generator). Other areas that were purely planar (plenum inflow face, wing end planes) or irregularly shaped (corners, fillets) were filled in with unstructured grid. The body is symmetric but is mirrored to create a full-span geometry in order to rotate to off-track azimuth angles in our split-and-align approach.

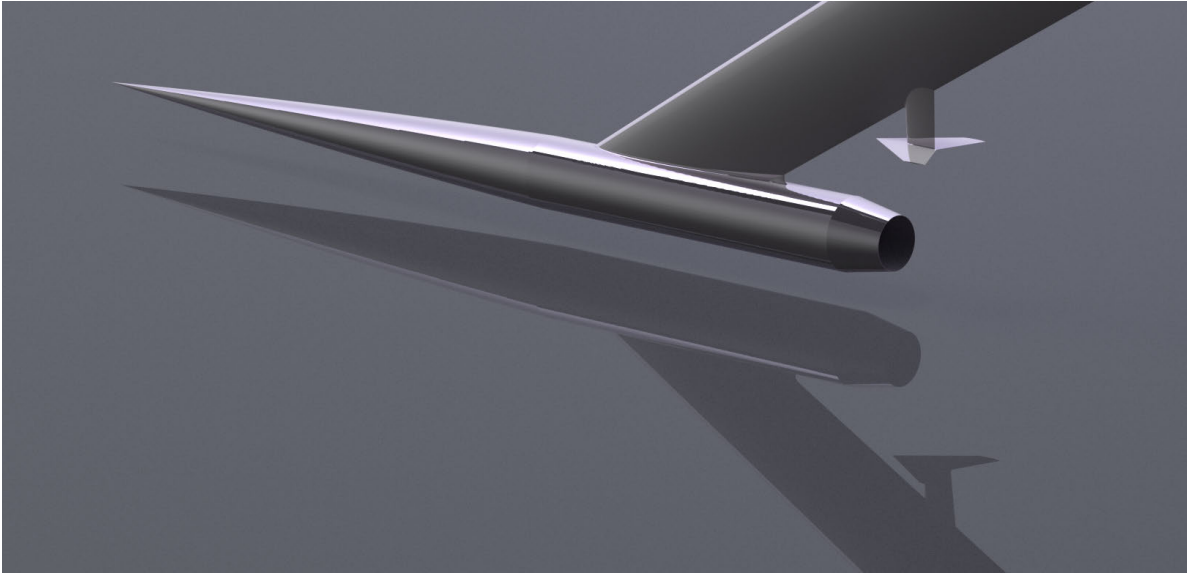


Fig. 6 Geometry for biconvex airfoil shock-plume interaction case.

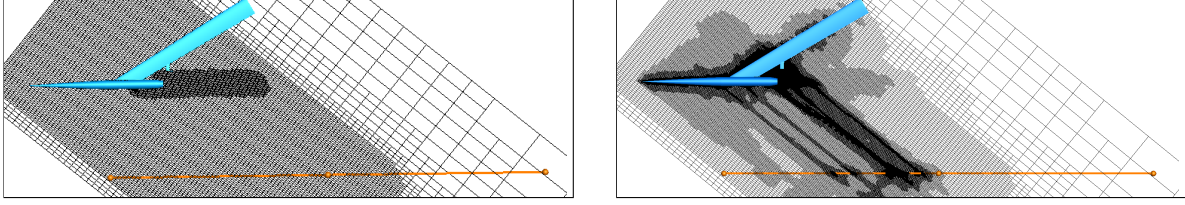


Fig. 7 Initial mesh $\sim 330k$ cells (left) and coarse-level adapted mesh $\sim 4.5M$ cells (right) for Biconvex case $\phi = 0^\circ$.

Table 1 Operating conditions for Case I: Biconvex

Quantity	Value	Description
M_∞	1.6	Freestream Mach number
P_t/P_∞	8.0	Plenum stagnation to freestream static pressure ratio
T_t/T_∞	1.768	Plenum stagnation to freestream static temperature ratio
T_∞	374 °R	Freestream static temperature, degrees Rankine
Re_x	376850 / in	Reynolds number per inch
R	15 in (0.38 m)	Radial distance for pressure signal extraction

Results are required at a radial distance of 15 inches from the body and at three azimuths, $\phi = \{0^\circ, 15^\circ, 30^\circ\}$. Figure 7 shows an example of our mesh adaptation results for the $\phi = 0^\circ$ run. To improve efficiency, we set up the initial mesh with a few pre-specified refinement regions to help capture plumes, small geometric features, and inflow/outflow boundaries early in the mesh adaptation process. The coarse-level mesh is obtained after five adaptation cycles; note that we have placed more weighting on the pressure signal in the shock-plume interaction region compared to the forward half of the forebody, and the weighting drops to zero farther aft to ignore the unwanted effects of the finite-span strut behind the biconvex airfoil.

Figure 8 shows a slice through the domain for $\phi = 0^\circ$, with contours of non-dimensional density. Although the geometry seems relatively simple, the flowfield shows the complicated interactions of the supersonic exhaust plume and shock structures. The fine-grid pressure signals from $R = 15$ inches at all three azimuths are shown in Fig. 9, with a transparent slice through the flowfield and geometry ($\phi = 0^\circ$) as a reference for roughly where the signal originated on the body. Some three-dimensional effects are apparent, especially at $\phi = 30^\circ$, due to the strut shock and expansion that wrap around the forebody as well as the finite-span biconvex shock generator.

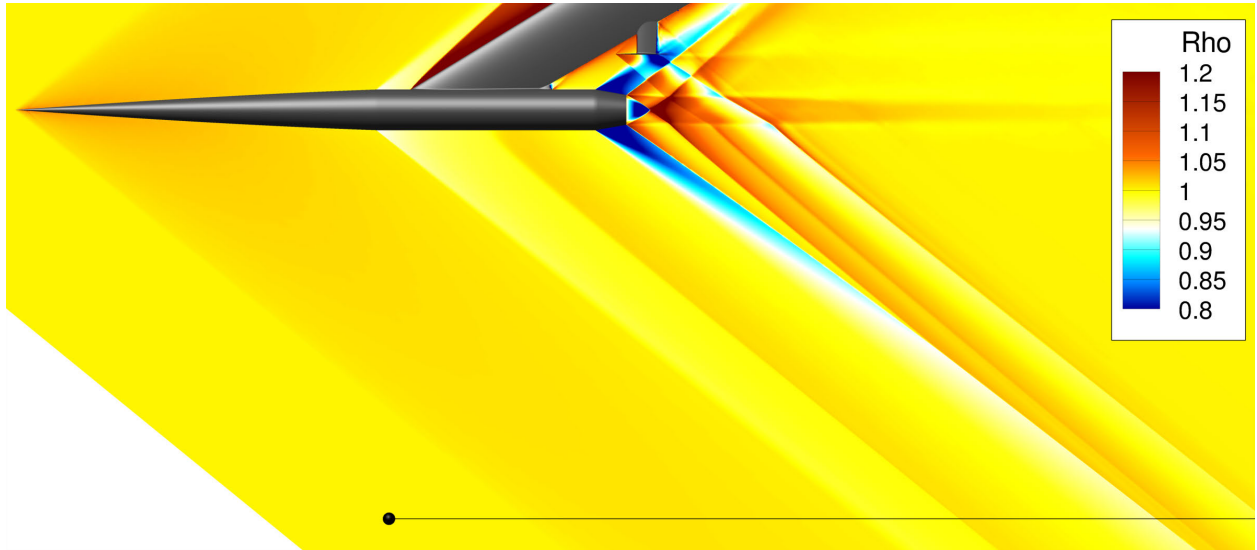


Fig. 8 Biconvex shock-plume interaction flowfield at azimuth $\phi = 0^\circ$. Contours are non-dimensional density, and line sensor at $R = 15$ in indicates where pressure signal is extracted.

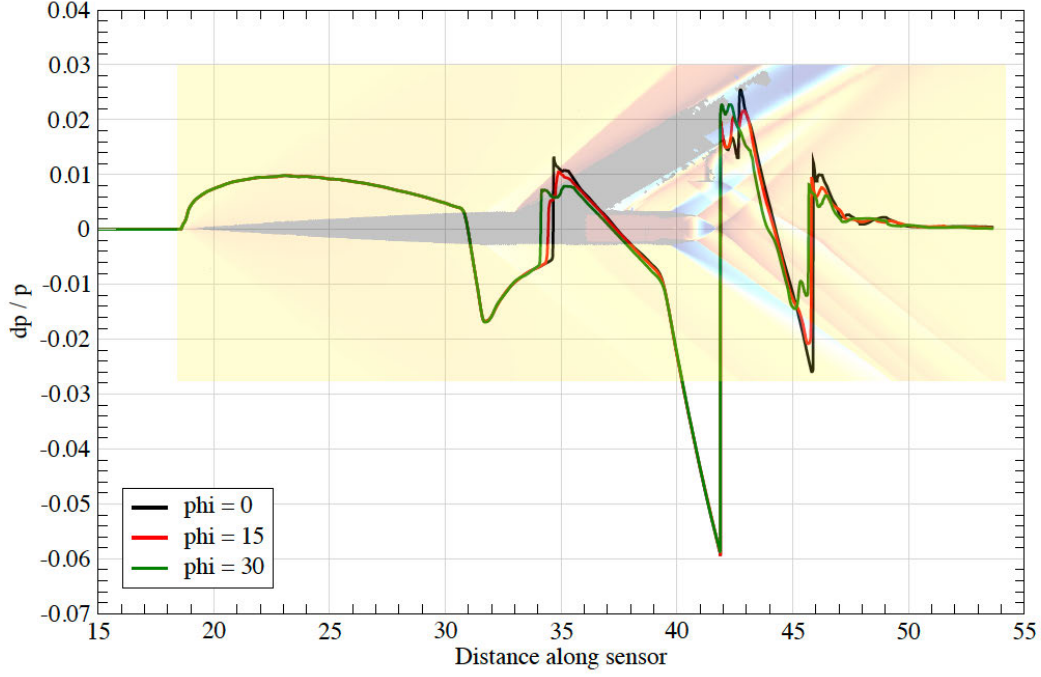


Fig. 9 Pressure signal on fine grids for $\phi = 0^\circ, 15^\circ, 30^\circ$, $R = 15$ in. Transparent slice through flowfield and geometry shown for reference of where flow features originate.

We examine iterative and mesh convergence for every run, with results from $\phi = 0^\circ$ in Fig. 10. Looking at iterative convergence on the left, the global numerical residual is reduced by 3–4 orders of magnitude for each adaptation cycle; each spike is the start of a run on a new mesh, with the initial mesh and seven adaptation cycles for a total of eight flow solutions. In the middle and right of Fig. 10, we see good mesh convergence of the objective function and adjoint-based error estimates. The objective function (middle) converges through the mesh adaptation process. Error bars on the objective function are also plotted in red on the right, along with incremental updates to the objective function and the adjoint-based error estimate; all of these quantities are becoming smaller as the grid is refined, indicating good mesh convergence.

Coarse, medium, and fine grid levels are taken from the final three mesh adaptation cycles (5, 6, and 7) and have roughly 4.5, 8.9, and 19.9 million cells, respectively. Pressure signal convergence on the three grids is shown in Fig. 11. For this case with relatively simple geometry and highly resolved mesh, there is very little difference among the solutions. Pressure signatures are converged very well over the forebody up to $x \sim 28$ in, and there are only slight differences farther aft in the shock-plume and wake regions. Figure 12 shows the pressure signal error estimate using a Richardson extrapolation technique [15, 20]. Overall, convergence of both pressure signatures and local error estimates is very good, but it is clear that the shock-plume interaction region is the most challenging with discontinuous shocks and coalescence of flow features.

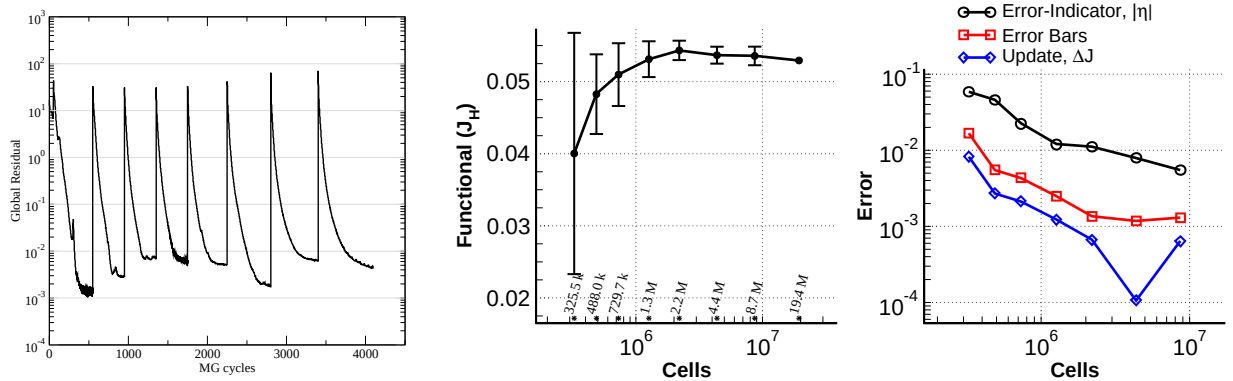


Fig. 10 Iterative and mesh convergence for Biconvex case at $\phi = 0^\circ$ run through seven mesh adaptation cycles. Left: Iterative convergence of residual with mesh refinement. Middle: Objective function history with mesh refinement. Right: Mesh convergence of objective function updates, error bars, and error estimate.

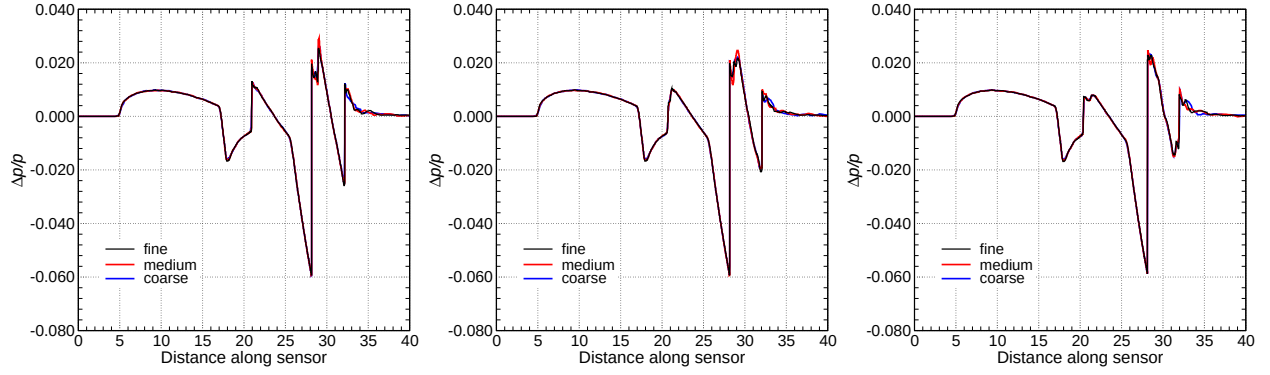


Fig. 11 Converging pressure signal solutions at $R = 15$ in on coarse, medium, fine grids for biconvex case run at $\phi = 0^\circ$ (left), $\phi = 15^\circ$ (middle), and $\phi = 30^\circ$ (right).

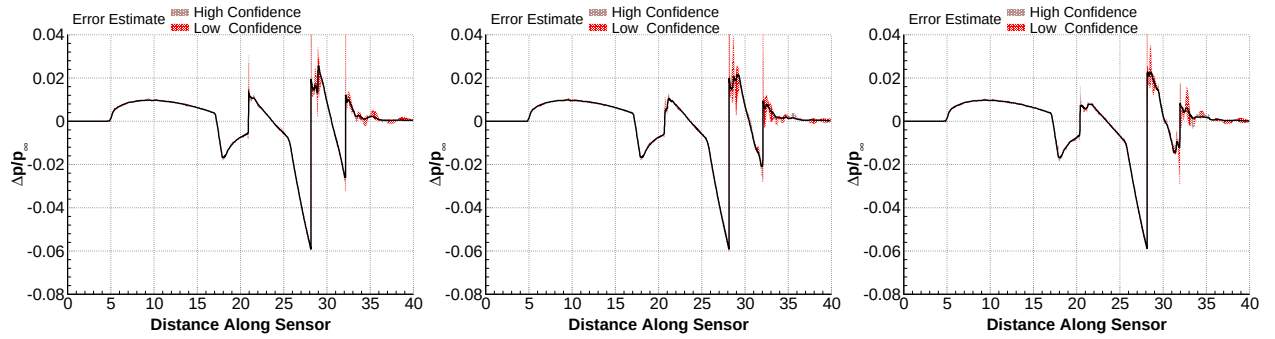


Fig. 12 Error estimate of pressure signals at $R = 15$ in for biconvex case run at $\phi = 0^\circ$ (left), $\phi = 15^\circ$ (middle), and $\phi = 30^\circ$ (right).

2. Case II: c608 Full Aircraft Geometry

The second nearfield CFD case comes from NASA's Low Boom Flight Demonstrator (LBFD) project and is a modified version of an earlier design iteration referred to as c608. Shown in Fig. 13, this is a challenging full aircraft case with complex geometry and multiple inflow/outflow boundary conditions. The geometry has a single engine at the aft end with boundary conditions at the fan face and nozzle; additionally, there is a "bypass vent" that exhausts around the lower half of the nozzle as well as small inboard inlets underneath the wing that take in air for the environmental control system (ECS). These features are small and thin, making them challenging to resolve and increasing both mesh size and computational cost.

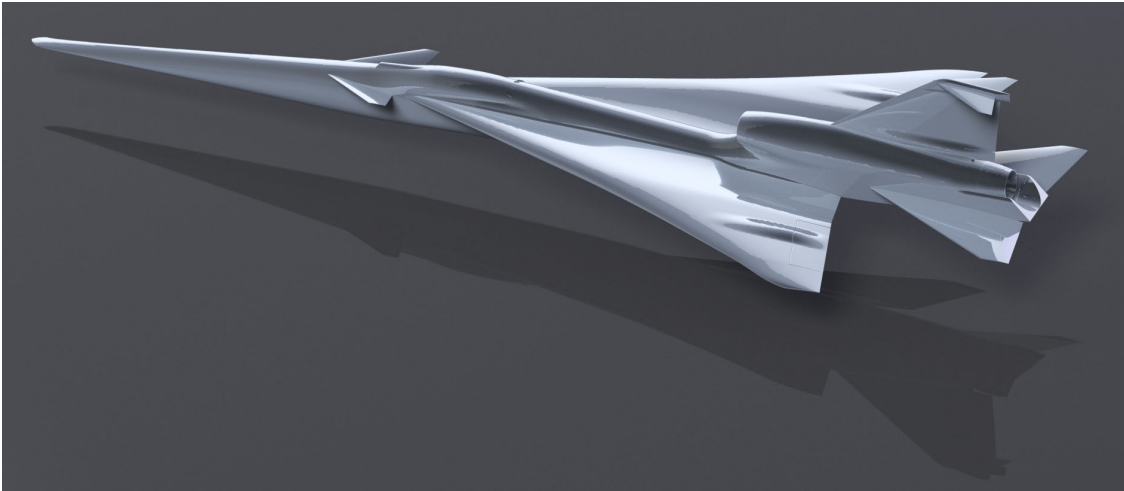


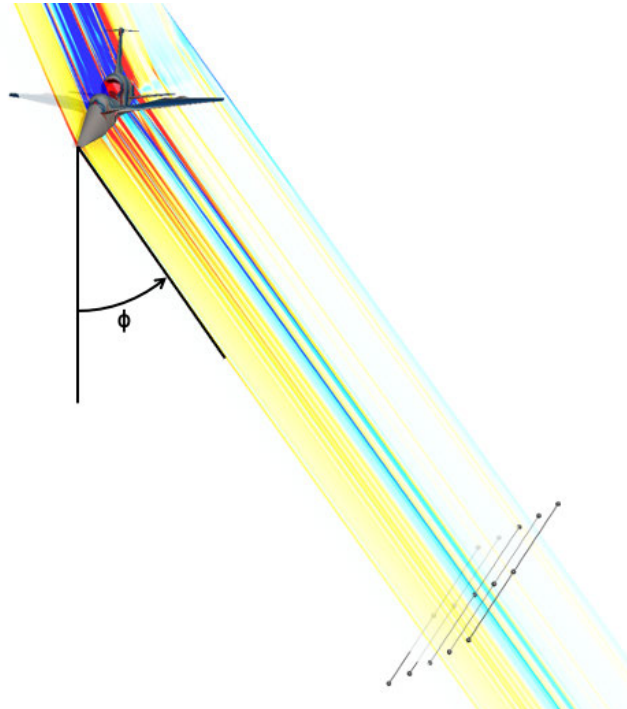
Fig. 13 Geometry for c608 full aircraft case.

Table 2 Operating conditions for Case II: c608

Quantity	Value	Description
M_∞	1.4	Freestream Mach number
P_t/P_∞	10.0	Engine plenum stagnation to freestream static pressure ratio
T_t/T_∞	7.0	Engine plenum stagnation to freestream static temperature ratio
P_t/P_∞	2.4	Bypass vent stagnation to freestream static pressure ratio
T_t/T_∞	2.0	Bypass vent stagnation to freestream static temperature ratio
T_∞	389.9 °R	Freestream static temperature, degrees Rankine
P_b/P_∞	2.75	Engine fan face back pressure to freestream static pressure ratio*
P_b/P_∞	2.60	ECS inlets back pressure to freestream static pressure ratio*
Re_x	109776 / in	Reynolds number per inch
h	53200 ft	Altitude, with US Standard Atmosphere (1976) conditions
L	1080 in	Body length, inches
R/L	3	Radial distance for pressure signal extraction

The operating conditions are given in Table 2. At the engine and ECS inlets, we use a back pressure outflow boundary condition in Cart3D. SBPW3 specifies local Mach numbers around 0.40 and 0.35 at the engine fan face and the ECS inlets, respectively. The workshop also suggested back pressure ratios P_b/P_∞ of 2.6 for the engine fan face and 1.4 for ECS inlet faces as a starting point for the boundary conditions. In a few iterations, we adjusted our inlet boundary condition pressure ratios to 2.75 for the engine fan face and 2.70 for the ECS inlets to achieve the desired Mach numbers at the outflow faces. These as-run boundary conditions are noted by a * in Table 2.

The pressure signal is required at $R/L = 3$ and at off-track angle increments every 2° from 0° to 180° . Note that we need only the half-cylinder due to symmetric geometry and boundary conditions. Using the split-and-align approach, which is shown in Fig. 14, we set up the simulations with separate meshes every 10° azimuthally, each with additional line sensors at $\pm 2^\circ$ and $\pm 4^\circ$ on either side of the centered off-track angle. This allows coverage of the entire 180° half-cylinder with 19 simulations that can be run simultaneously. Based on our previous work [15] for SBPW2, a spread of 4° on either side of the centered off-track angle is quite conservative.

**Fig. 14 Depiction of case run at off-track angle ϕ with additional line sensors at $\pm 2^\circ$ and $\pm 4^\circ$.**

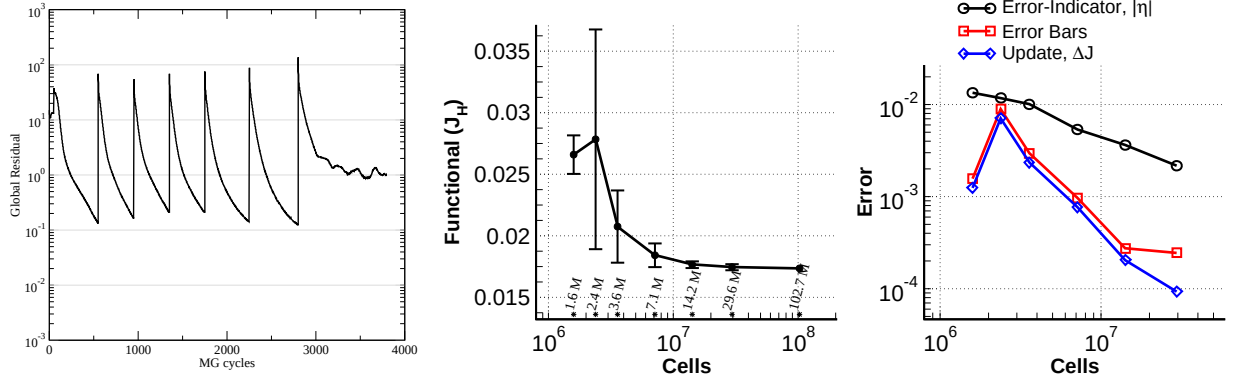


Fig. 15 Iterative and mesh convergence for c608 case at $\phi = 0^\circ$ run through six mesh adaptation cycles. Left: Iterative convergence of residual with mesh refinement. Middle: Objective function history with grid refinement. Right: Mesh convergence of objective function updates, error bars, and error estimate.

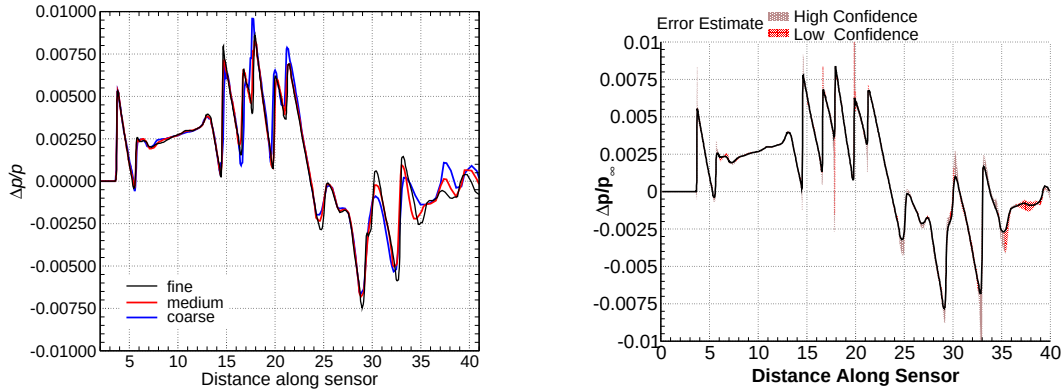


Fig. 16 Converging pressure signal solutions (left) and error estimate (right) on coarse, medium, fine grids for c608 case run at $\phi = 0^\circ$.

We ensure the quality of each simulation by checking iterative convergence of the numerical residual as well as mesh convergence of the objective function and adjoint-based error estimates, all shown in Fig. 15. Due to more complex geometry and initial coarse mesh, the functional may not be entirely monotonic; initially, small features are not well resolved and there is not enough mesh resolution for the signal to reach the farthest radial line sensors without excessive dissipation. After the first mesh adaptation or two, mesh resolution is sufficient to capture flow features out to the farthest radial line sensors, and we see asymptotic convergence and narrowing error bars. We submitted our coarse, medium, and fine workshop results from adapt cycles 3, 4, and 5, respectively. The fine grid mesh size and solution convergence are sufficient and are representative of high-quality but affordable production runs. We run an extra adaptation cycle and flow solution to ensure our simulations are fully converged, which would be good practice as a spot check when running several cases.

For the c608 cases, we see some differences in the converging pressure signal at $R/L = 3$ on coarse, medium, and fine grids, as shown on the left in Fig. 16. The aft half of the aircraft is especially complex, with multiple flow features coalescing as well as the T-tail shock-plume interaction. However, the difference between medium and fine grids is less than that between coarse and medium, indicating good convergence and verified by Richardson-based local error estimates shown on the right in Fig. 16.

Much of the effort in low-boom design is focused on the primary boom carpet underneath the aircraft, with nearfield pressure signals from off-track angles out to around $50 - 60^\circ$ propagating to the ground (see Section III for propagation results). However, some of the "sideways" and "over-the-top" signals can refract through the atmosphere and eventually reach the ground at very wide off-track distances to form a secondary boom carpet [1]. Over-the-top propagation paths are much longer, but if the nearfield signal has higher pressure amplitudes, secondary boom carpets can result in non-negligible noise levels at distances very far from the aircraft flight path (although likely not higher than the primary boom carpet noise). Secondary boom carpet propagation is not addressed in SBPW3, but we do present the pressure signal from the entire c608 nearfield half-cylinder here.

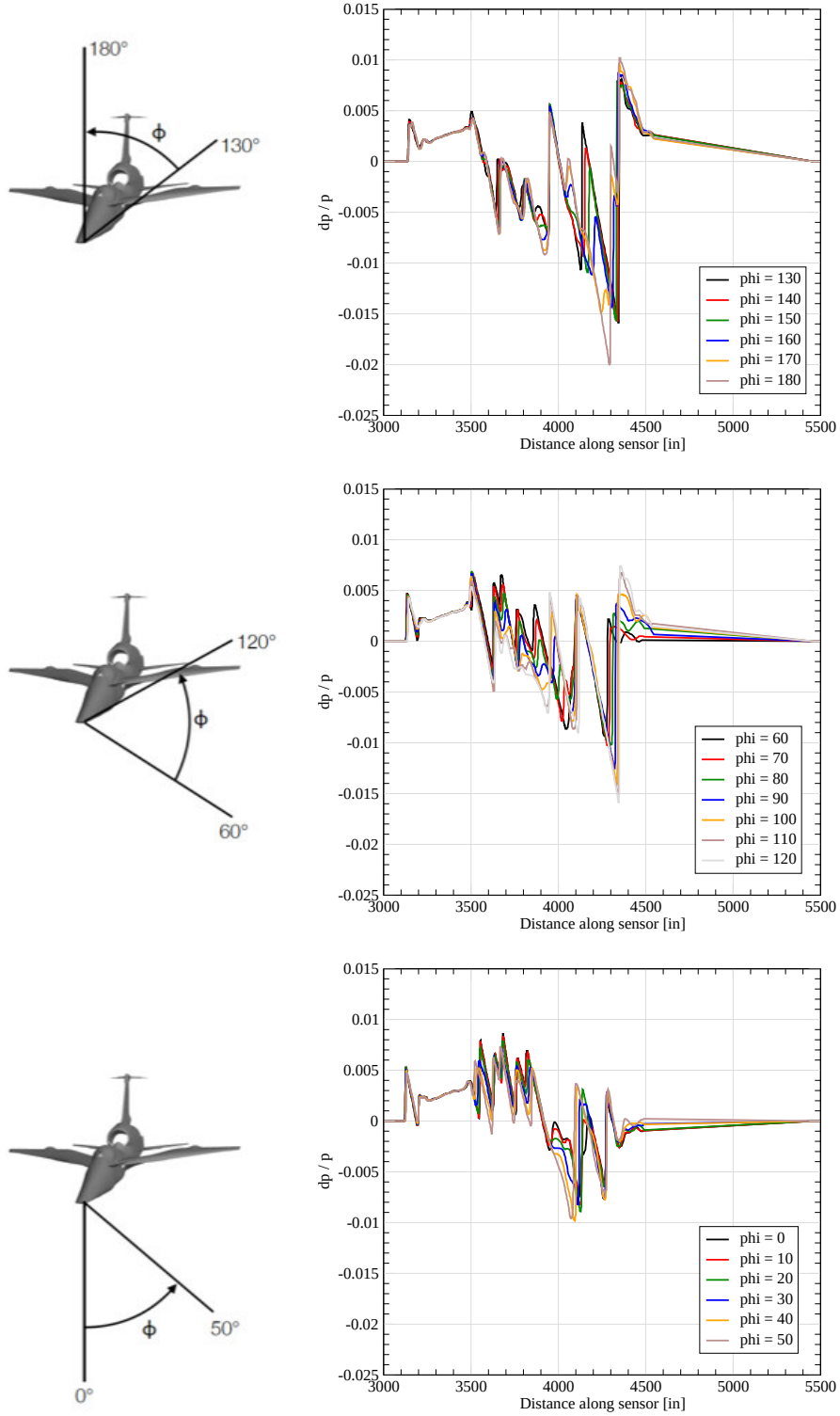


Fig. 17 c608 pressure signals grouped by off-track angles. Top: high ϕ above aircraft; Middle: mid ϕ to aircraft side; and Bottom: low ϕ underneath aircraft.

Figure 17 shows the pressure signal at off-track angles every 10° grouped by signals that are underneath, to the side, and over the top of the aircraft. It is interesting to see that the pressure signals underneath the aircraft have relatively small amplitudes of compression (positive $\Delta p/p_\infty$) and expansion (negative $\Delta p/p_\infty$) waves. While that is not exactly the same as the pressure coefficient over the surface of the aircraft, we would expect to see more expansion on the upper side in order for the aircraft to carry enough lift. Indeed, we do see larger amplitude pressure signals, mostly negative, for the large off-track angles above the aircraft, with a strong shock in the middle due to the nacelle inlet.

We also take the nearfield half-cylinder and "unroll" it to form a contour plot in the $x\phi$ -plane. Figure 18 contains contours of the pressure signal $\Delta p/p_\infty$ at $R/L = 3$. The colorbar is centered with yellow at $\Delta p/p_\infty = 0$ indicating freestream; any orange to red indicates positive $\Delta p/p_\infty$ compression waves, and green to blue is negative $\Delta p/p_\infty$ expansion waves. This figure contains results from every 2° off-track increment captured in the simulations. The split-and-align approach works very well and does not introduce any numerical artifacts; we see smooth azimuthal variations and no misaligned shocks.

We can see coalesced flow features changing along the off-track angle, with overall larger amplitudes and more expansion as we move to the aircraft side and top. The canard and front half of the wing create compression waves underneath the aircraft that spread into expansion waves over the top. The top-mounted nacelle's inlet shock at $x \sim 3960$ in stands out in the upper half of the cylinder but is shielded underneath by the wing; we can trace the sharp shock down from $\phi = 180^\circ$ to $\sim 90^\circ$ before it is weakened and replaced by expansion waves from the wing.

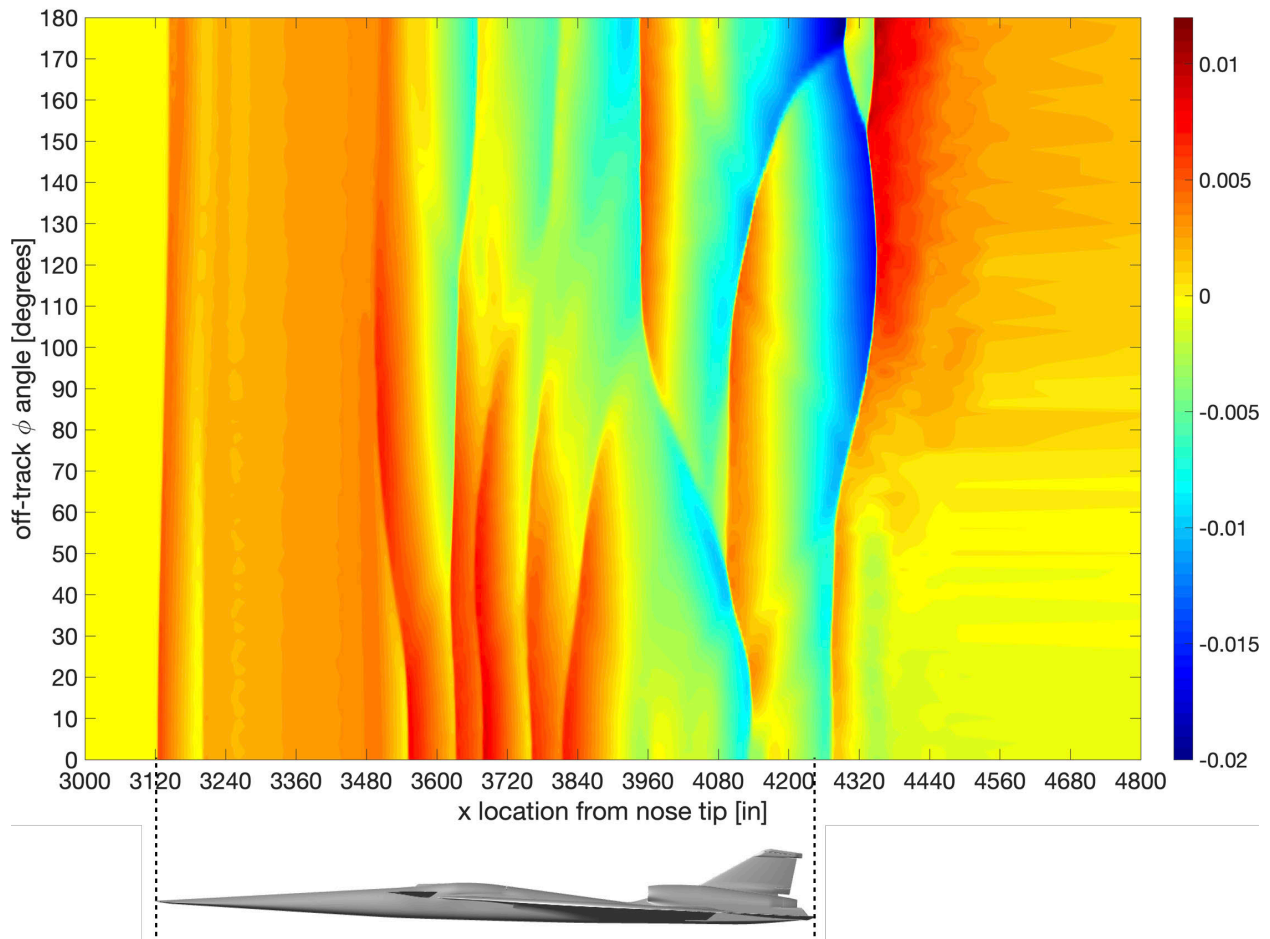


Fig. 18 c608 nearfield $R/L = 3$ pressure signal $\Delta p/p_\infty$ cylinder "unrolled" into planar contour plot. Geometry is shown to-scale for reference.

3. Computational Costs

Nearfield CFD simulations were done on the NASA Ames Electra cluster [21] using 1 Skylake node with two Intel Xeon Gold 6148 processors and a total of 40 cores for each separate azimuth run. Initial and adapted mesh sizes are shown in Table 3. For the biconvex case, initial grids are around 330k cells, and the coarse, medium, and fine adapted grids correspond to 5, 6, and 7 mesh adaptation cycles, respectively. For the more complex c608 geometry, initial grid size is 1.6M cells, and we run 3, 4, and 5 mesh adaptation cycles.

Table 3 Computational mesh sizes for final three adaptation levels, in millions of cells

Grid level	Biconvex	c608
Initial	0.33	1.6
Coarse	4.5	7.1
Medium	8.9	14.2
Fine	19.9	29.6

Computational costs are shown in Table 4. Fine grid flow solution time is listed separately from the adaptive meshing time, which includes all mesh generation as well as flow and adjoint solutions on coarser grids. Fine grid size, adaptive mesh time, and fine grid flow solution time are listed for a single off-track angle run; for total cpu-time, the wall-clock times are added together and multiplied by the number of separate off-track angle runs and 40 cores. However, utilizing the split-and-align approach, multiple off-track angle simulations are run simultaneously. Even for the c608 case, using 19 nodes and a total of 760 cores is easily possible on current supercomputers. Assuming all off-track runs are performed simultaneously, total wall time is only around 1 hr 12 min for the three Biconvex runs and 1 hr 53 min for nineteen c608 runs.

Table 4 Computational costs of nearfield CFD cases on NASA Electra cluster, 1 Skylake node with 40 cores

	Biconvex	c608
Fine grid size	19.9 M cells	29.6 M cells
Adaptive meshing wall time	32 min	53 min
Fine grid flow solution wall time	40 min	60 min
Independent off-track angle runs	3	19
Total computational time	144 cpu-hr	1431 cpu-hr
Total wall-clock time	72 min	113 min

C. Nearfield CFD Discussion

Shock-plume interaction remains challenging, and SBPW3 isolates this flow phenomenon in the Biconvex case. Even this seemingly simple setup has many complex flow features, with shocks and expansions coalescing as they propagate away from the body. We examine both iterative and mesh convergence as well as local error estimates of pressure signal outputs, confirming the accuracy of our results.

We then applied our methodology to the c608 case, a cutting-edge low-boom design with more complex geometry and inflow/outflow boundaries. Our results are accurate yet reasonably affordable, with fine-grid meshes of around 30 million cells for each of the nineteen separate azimuths. Decomposing the simulation this way also allows for comparisons among the azimuths and spot checks; we suggest running an additional adaptation cycle to confirm solution convergence. Also, we use the additional inflow/outflow boundaries to our advantage to ensure consistency among the separate runs – mass flow rates through the power boundaries varies by only a few percent among all the separate runs. A wide discrepancy would help identify a run that may not have converged or possibly an unstarted inlet. The overall aerodynamics are also consistent among the runs, with lift coefficients varying less than one percent and even drag coefficients within a few percent.

Low-boom designs make boom prediction even more challenging. As we see in these nearfield cases, shocks and expansions near the body are roughly the same order of magnitude as freestream, but only one body-length away in the biconvex case, pressure disturbances are already 1–2 orders of magnitude smaller. At $R/L = 3$ for c608, pressure

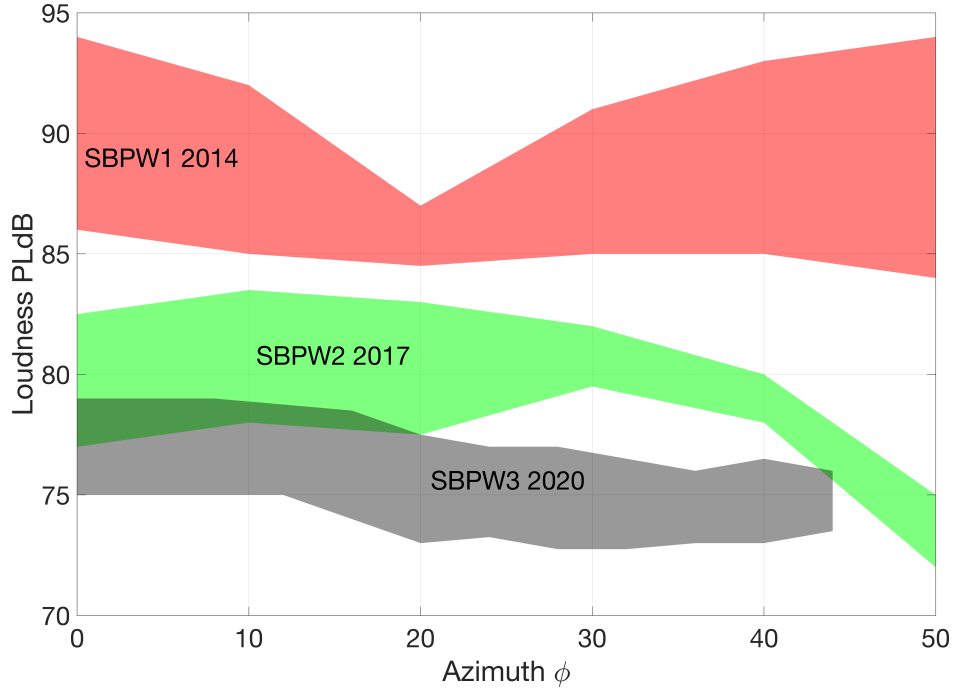


Fig. 19 Boom carpet comparison and low-boom design developments. Shaded regions cover the range of workshop participants’ results from SBPW1 (red, high), SBPW2 (green, middle), and SBPW3 (black, low).

disturbances are around 3 orders of magnitude less than ambient pressure. Despite this challenge, computational methods in the boom prediction community have improved, and the agreement among SBPW3 participants is better than ever [22]. The workshop organizers took participants’ nearfield signals and consistently propagated them to the ground. The shaded regions in Fig. 19 are based on the workshop summary and show the spread among participants generally shrinking even as designs have continued to become quieter.

III. Farfield Acoustic Propagation

The propagation workshop consisted of two cases that considered sonic booms from two supersonic full aircraft configurations in powered flight. For each of these, nearfield pressure signatures were provided to give all participants a consistent starting point. Participants were required to propagate these signals to the ground through prescribed atmospheric conditions, some of which include non-standard temperature, pressure, humidity, and wind profiles.

The first case considered propagation of nearfield pressure signals from the Concept 25P (C25P) aircraft from SBPW2. The C25P is a powered aircraft model designed for low sonic boom. Prescribed nearfield signatures were provided at all azimuths for the lower half-cylinder surrounding the aircraft, $\phi = [-90^\circ, 90^\circ]$. The second case is based on the c609 prototype for the X-59 Low Boom Flight Demonstrator (*LBFD*). This iteration of the LBFD contained some small design improvements over the c608 discussed in the nearfield results. With a ground noise target of 75 dB this model is expected to be ~5 dB quieter than the C25P under standard atmospheric conditions, potentially making this a more difficult case.

All of the results in this section used NASA’s advanced Sonic Boom propagation tool, sBOOM (v2.82) [23]. ASEL, CSEL, and PLdB noise metrics were computed with NASA’s Loudness Code for Asymmetric Sonic Booms, LCASB [24]. sBOOM solves a quasi-one-dimensional PDE via finite difference and is therefore subject to truncation error. Consequently, the accuracy of the propagated signal is directly influenced by the mesh spacing along the waveform. This discretized spacing is expressed as a sampling frequency (points per second of the ground signal). Mesh convergence studies spanning 100–1200 kHz were conducted for each case to determine resolution requirements for accurate propagation and noise metric computation.

Mesh convergence studies using v2.82 of sBOOM [23] revealed that the ASEL noise metric diverged at sampling frequencies higher than roughly 400 kHz, despite the fact that propagated ground signals demonstrated continued convergence.* After the workshop, we discovered that this version of sBOOM was using a single-step implementation of

*Note that BSEL and CSEL from sBOOM converged in our tests up to 1.2 MHz, and all LCASB noise metrics converged nicely.

the higher-order discrete-time filters, which are not always numerically well-behaved at higher sampling frequencies. A/B/C-SEL filters are 6th-, 5th-, and 4th-order, respectively; ASEL is the first filter to corrupt as sampling frequency increases, but BSEL and CSEL eventually show the same divergence. The second-order sections approach improves numerical stability, and it has now been implemented in a newer version of SBOOM (v 2.85) and tested up to 40 MHz with no numerical issues. We did not recompute workshop cases, however, and our SBPW3 results used SBOOM (v2.82) for propagation and BSEL noise. LCASB was used to compute ASEL, CSEL, and PLdB noise metrics.

A. CASE I: NASA Concept 25 with Powered Nacelle

The C25P is a variant of NASA's "Concept 25" with a powered nacelle. The model is largely similar to the flow-through version, but the fuselage and tail bulb have both undergone re-contouring as a result of design optimization with power [25]. Figure 20 shows a rendering of the vehicle with its single aft-mounted nacelle and spike nozzle. Propagation workshop participants were provided with nearfield signatures, $\Delta p/p_\infty$, for azimuths $\phi = [-90^\circ, 90^\circ]$ in 10° increments. These signatures correspond to flight conditions of Mach 1.6 at an altitude of 52 k ft (15760 m). The model has a reference length for propagation $L = 110$ ft (33.53 m), and the signatures were extracted at a distance $R/L = 3.0$, roughly 330 ft or 100 m from the flightpath.

Figure 21 shows plots of the the nearfield signatures provided by the workshop for azimuths in the range $\phi = [-50^\circ, 50^\circ]$. To aid in legibility, $\pm\phi$'s are color matched, and dashed lines denote the negative azimuths. A sketch on the left shows the sign convention for measuring azimuth angles with a nose-on view of the C25P. As in the earlier nearfield signatures, the expansion from the wing ($x \approx 60$ m) dominates the signature at all azimuths and constitutes the first zero crossing. Peak-to-peak variation of the pressure signature is comparable to that of the c608 in the nearfield section.

1. C25P: Propagation and Loudness

The nearfield pressure signals in Fig. 21 were propagated through both the standard and required atmospheres from an altitude of 52 k ft (15760 m) to the ground height of 866 ft (264.1 m). Before propagating all the nearfield signals, we conducted a mesh convergence study to determine appropriate sampling frequencies. Figure 22 shows mesh convergence of the on-track ground noise metrics. The plots show values of dB[B], dB[C], and PLdB in decibels as a function of sampling frequency. Major divisions on the ordinate of all three plots are set to 0.2 dB and are scaled consistently to facilitate cross comparison. These plots were generated for both on-track, $\phi = 0^\circ$, and off-track at $\phi = 30^\circ$. Mesh convergence of ASEL (not shown) was qualitatively similar to BSEL. These investigations indicated that sampling frequencies in the range of 500-800 kHz were sufficient to confine the effects of truncation error in the propagation to less than 0.05 dB in all the metrics. Since there is more accumulated truncation error on the longer ray paths at high azimuths, our propagation used sampling frequencies of 500 kHz at low azimuths ($|\phi| \leq 30^\circ$) and 800 kHz sampling farther out board ($|\phi| > 30^\circ$). For the inputs provided, 500 kHz sampling corresponds to ~ 140 k points along the signal.

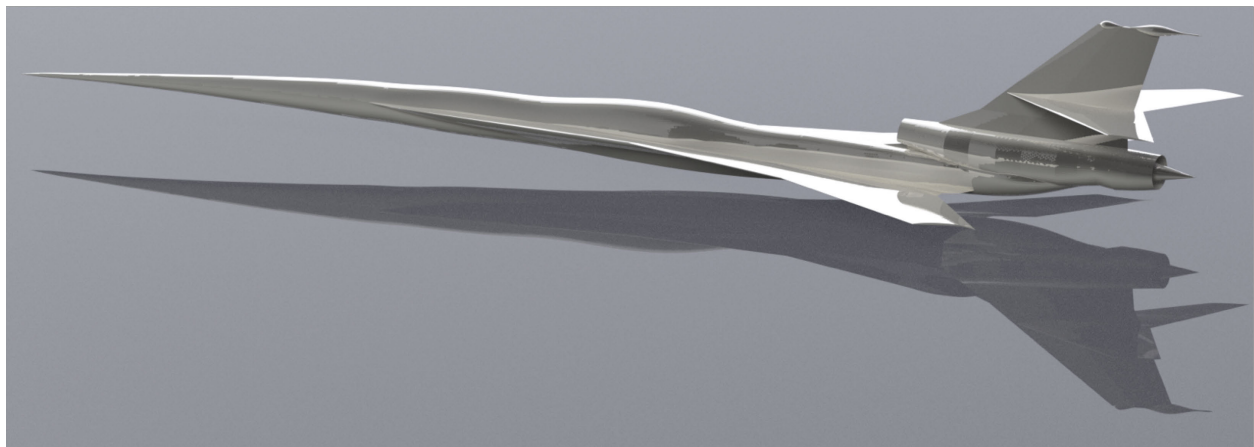


Fig. 20 NASA C25P powered low-boom aircraft configuration from the AIAA SBPW2 in 2018. The aft-mounted nacelle has a centerbody nozzle. Propagation Workshop Case I specifies easterly flight at Mach 1.6 and an altitude of 52 k ft (15760 m).

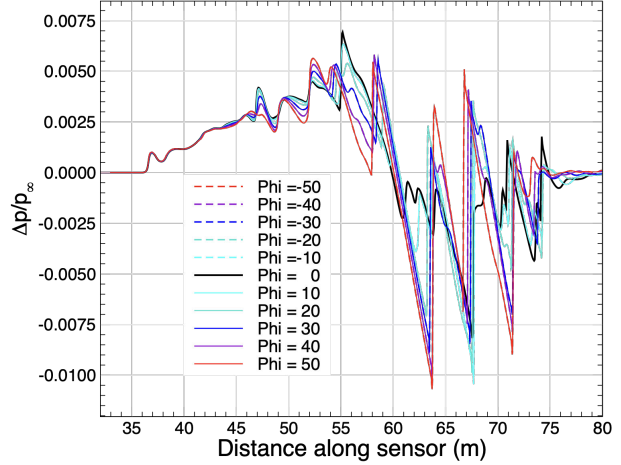
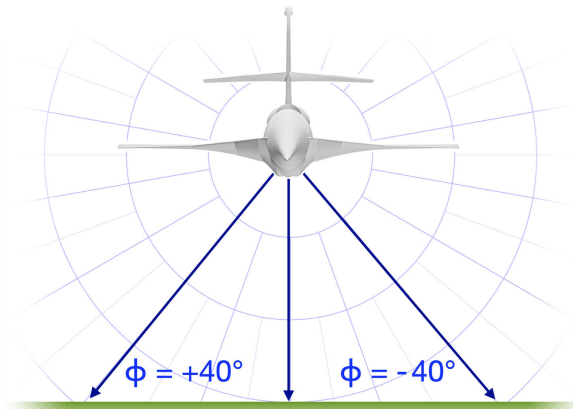


Fig. 21 Sign convention for azimuth, and nearfield pressure signatures, $\Delta p / p_{\infty}$, provided for the C25P. Signatures are shown for $\phi = [-50^{\circ}, 50^{\circ}]$ but were provided from $[-90^{\circ}, 90^{\circ}]$.

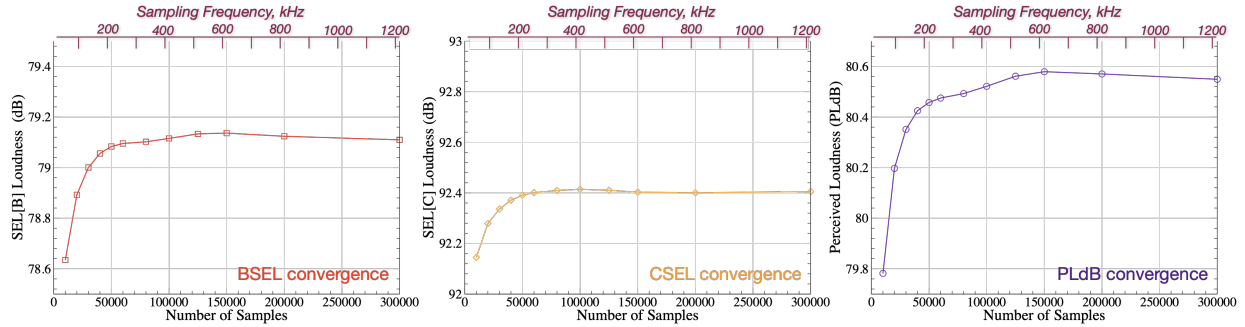


Fig. 22 Mesh convergence of BSEL, CSEL, and PLdB noise metrics as a function of sampling frequency for on-track signal propagation through the standard atmosphere from an altitude of 52 k ft (15760 m) to the ground height of 866 ft (264.1 m).

Figure 23 shows the ground signals for all azimuths after propagation through both the standard atmosphere (left) and required atmosphere (right). Azimuths in both plots are consistently colored and negative azimuths are indicated with dashed lines. In both plots, the black line indicates the on-track signal ($\phi = 0^{\circ}$). The required atmosphere for this case included profiles for crosswind, humidity, temperature and pressure. The meteorological conditions were chosen from the National Centers for Environmental Prediction (NCEP) Climate Forecast System[26] and correspond to a chilly day near State College, PA,[†] with moderate upper atmospheric winds. These winds become apparent in the ground signatures as they are responsible for the differences between corresponding $\pm\phi$'s, while both the nearfield signals and standard atmosphere ground signals are essentially symmetric.

Figure 24 shows the noise metrics for the C25P computed for the ground signals in Fig. 23. As with the ground signals, the standard atmosphere is shown at the left while the real atmosphere is to the right. The plots include the A/B/C-SEL and PLdB noise metrics as a function of azimuth for all the rays in the nearfield that reach the ground. The B-weighted loudness (BSEL) was computed internally by sBOOM, while all the others came from the FFT-based implementation in LCASB. Comparing the noise metrics for standard and real atmospheres, we notice immediately that the high-altitude winds and low humidity in the real atmosphere reduce peak loudness by ~ 4 dB[A], ~ 2.5 dB[B], ~ 2 dB[C] and ~ 4 PLdB. Although noise does indeed drop near the edges of the carpet, it is apparent that wider azimuthal ray paths reach the ground in the real atmosphere. In the standard atmosphere, peak loudness for this C25P variant is $\sim 30^{\circ}$ off track, and the B- and C-weighted noise metrics are only a few decibels below their on-track value very near the carpet edge.

[†]Private communication with S. Rallabhandi & W. Doeblér.

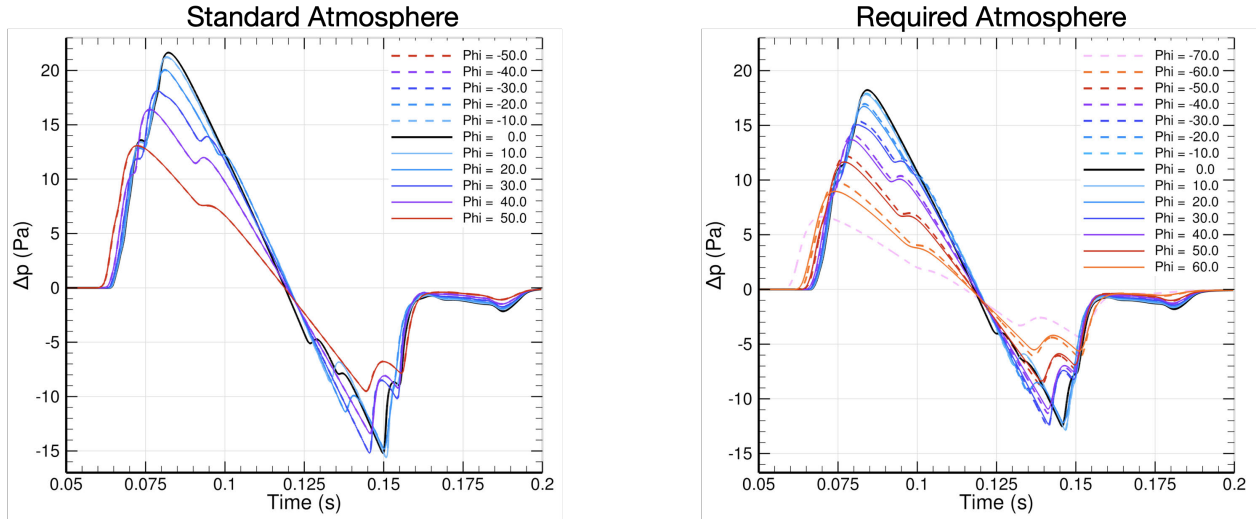


Fig. 23 Ground signals for the C25P after signal propagation through both the standard atmosphere (left) and required atmosphere (right) from an altitude of 52 k ft (15760 m) to the ground height of 866 ft (264.1 m) for all azimuths. Dashed lines show negative azimuths. The required atmosphere has specified profiles for crosswind, humidity, temperature, and pressure.

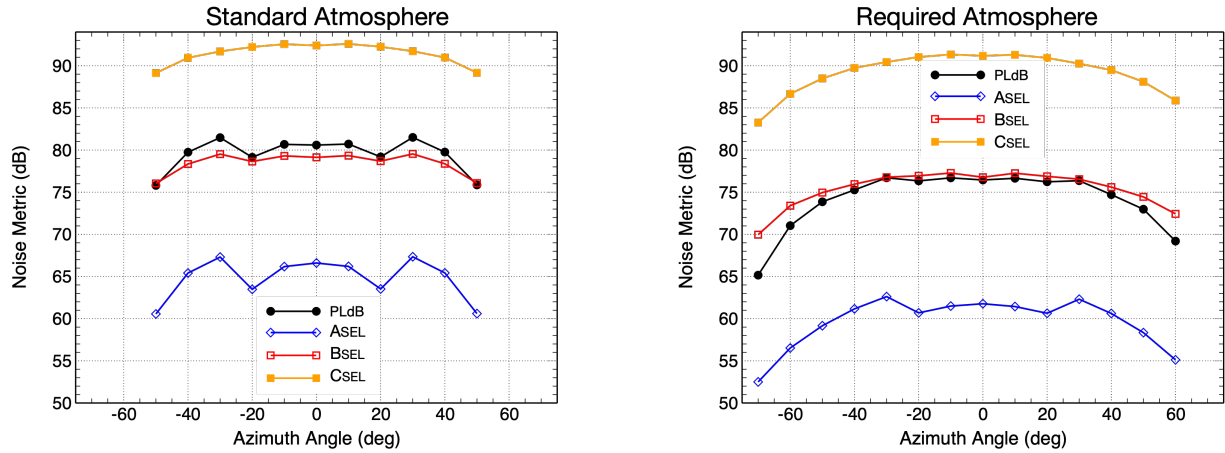


Fig. 24 Ground noise metrics for the C25P after signal propagation through both the standard atmosphere (left) and required atmosphere (right) from an altitude of 52 k ft (15760 m) as a function of azimuth.

2. C25P: Boom Carpet

Figure 25 shows a 3D view of the ray paths for azimuths for the prescribed atmosphere whose ground signatures and noise metrics were shown in the preceding two figures. The rays are colored and scaled by the local ray tube area as the sound refracts through the atmosphere. Note also that in this case the aircraft was headed due east (downrange), and the workshop prescribed sign convention measured negative crossrange to the north and positive crossrange to the south. The effect of the winds and thermal profile in the real atmosphere are evident on the ray paths. SBOOM computed propagation cut-off angles of $\phi = \pm 50.82^\circ$ for the standard atmosphere. With the high-altitude winds in this real atmosphere, the ray path cut-off angles opened up to $\phi = +69.1^\circ$ to the south and an incredibly wide $\phi = -78.4^\circ$ to the north. Even for the acoustic rays shown, those near the carpet edges travel more than twice as far as those near or on-track at low azimuth. This increased ray path distance and propagation time amplifies the effects of truncation error in the propagation calculation and motivated our use of higher sampling frequencies for signals traveling along these outboard rays. In fact, the rays shown in Fig. 25 only span the interval $\phi = [-70^\circ, +60^\circ]$ and signal cut-off is around 9° wider on each side. Travel time for the on-track ($\phi = 0^\circ$) ray was about a minute (~ 65 s) while it was over three minutes (188 s) for the outboard ray at -70° . Right at signal cut-off, the travel time balloons to 386 s on negative side at $\phi = -78.4^\circ$, and 284 s on the positive side, $\phi = 69.1^\circ$.

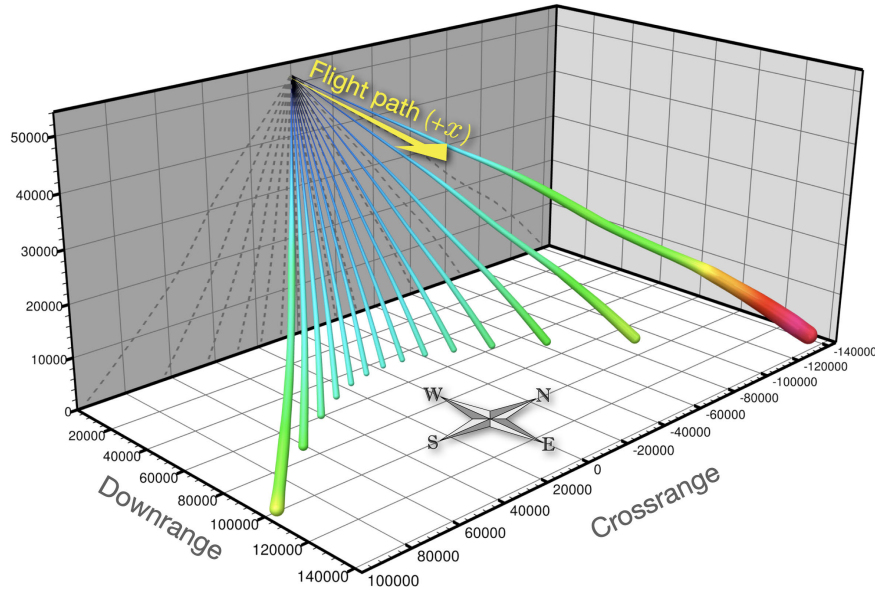


Fig. 25 Ray paths for C25P traveling at Mach 1.6 and an altitude of 52 k ft (15760 m) in the workshop provided atmosphere with crosswind, humidity, and temperature profiles. The ray paths are scaled and colored by ray tube area, and axes are labeled in feet.

The *boom carpet* for a supersonic aircraft refers to the area between the positive and negative cut-off angles. Figure 26 shows this carpet for the C25P flying in both the standard and required atmospheres at the conditions discussed earlier. This plot is constructed by computing the intersection of the ray paths with the ground plane. All the computed intercepts are marked with symbols on the plot. The most apparent take-away is that the carpet for the real atmosphere is ~157 km wide while the carpet for the standard atmosphere is confined to only about 70 km. In examining Fig. 26 recall that the sign convention takes negative crossrange as north, and positive south. Rays from higher azimuths extend farther east, but take more time to get there. The ray intercept times are listed for a number of critical points on the curves, notably the on-track signal times (around 65 s in both atmospheres), the propagation times at signal cut-off, and the times for the highest azimuths of the ground signals plotted in Fig. 23. Since the acoustic speed scales with the square root of temperature, and the temperature differences are relatively small, propagation times for the sound to reach a given crossrange distance are similar in both atmospheres.

It is remarkable how the glancing rays near cut-off extend the carpet width so significantly for the required atmosphere. Shown in Fig. 26, the ray at $\phi = -70^\circ$ intercepts the ground 42.6 km north of the ground track, while the ray at signal cut-off (-78.4°) is at 91.5 km, formally extending the carpet more than twice as far to the north. Even in the standard atmosphere, the glancing cut-off ray at 50.8° intersects the ground a full 6 km outboard

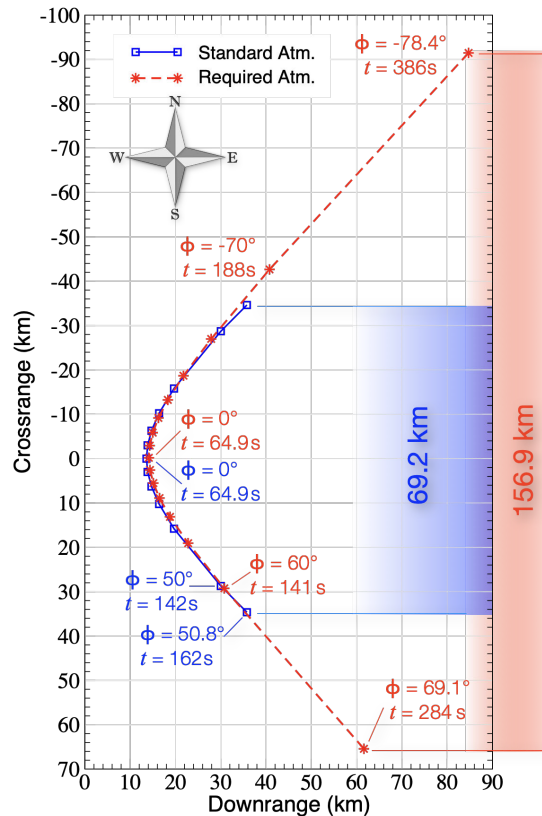


Fig. 26 Boom carpet for C25P traveling at Mach 1.6 and an altitude of 52 k ft (15760 m) in both the standard and required atmospheres. Ground elevation is 866 ft (264.1 m). The track width, measured cut-off to cut-off, is labeled for both atmospheres.

of the ray computed at $\phi = 50^\circ$ and increases the crossrange extent by 20%. Ground signals were not computed for the rays at cut-off – given their very long propagation times, around five times longer than on-track, mesh-converged propagation would require sampling frequencies much higher than even the 800 kHz used for the outboard rays. It is also worth noting that given the drop in sound exposure level already seen near the edges of Fig. 24, loudness this far out on the carpet is likely to be relatively low, making accurate propagation even more expensive due to the log scaling of the noise metrics.

B. CASE II: C609 Low-Boom Demonstrator

The c609 was a candidate design for NASA's Low-Boom Flight Demonstrator. Not surprisingly, this configuration followed, and is quite similar to, the c608 analyzed in the nearfield workshop. Superficially, the c609 has relocated environmental control system (ECS) vents and a re-contoured aft end. Figure 27 shows a rendering of the vehicle with its canards, full flying stabilator, t-tail, and single aft-mounted nacelle. Propagation workshop participants were provided with nearfield signatures, $\Delta p/p_\infty$, for azimuths from $\phi = [-60^\circ, 60^\circ]$ in 10° increments and extended out to $\phi = \pm 70^\circ$ in 2° increments. These signatures correspond to flight at Mach 1.4 at an altitude of 54 k ft (16.46 km) heading east with a ground elevation of 361 ft (110 m). The reference length for propagation was given as $L = 90$ ft (27.43 m), and the signatures were extracted at a distance $R/L = 3.0$, which is 270 ft (82.3 m) from the flightpath. The provided signatures were symmetric for positive and negative azimuths.

Figure 28 shows plots of the the nearfield signatures provided by the workshop for azimuths $\phi = [0^\circ, 70^\circ]$ in 10° increments. The on-track signature is plotted in black. The sign convention for azimuth is the same as in Case I. Qualitatively, the signatures are quite similar to the c608 examined in the nearfield workshop and the peak-to-peak variation of the pressure signature is also similar to that of the C25P discussed above.

1. c609: Propagation and Loudness

The provided nearfield pressure signals were propagated through both the standard and required atmospheres from an altitude of 54 k ft (16459 m) to a ground elevation of 361 ft (110 m). Similar to our approach for the C25P in Section III.A.1, we conducted mesh convergence studies to establish appropriate sampling frequencies. These investigations yielded similar results as for the C25P and indicated that sampling frequencies in the range of 500-800 kHz were sufficient. We again used sampling frequencies of 500 kHz at low azimuths ($|\phi| \leq 30^\circ$) and 800 kHz sampling farther out board ($|\phi| > 30^\circ$). On the c609 input signals, 500 kHz sampling corresponded to ~95 k points along the nearfield curves.

Figure 29 shows the ground signals for all azimuths after propagation through both the standard atmosphere (left) and required atmosphere (right). As before, we've consistently colored the azimuths in both plots and negative angles are indicated with dashed lines. The black line denotes the on-track signal ($\phi = 0^\circ$). The most striking feature of the comparison is the marked decrease in the amplitude of the waveforms in the real atmosphere. Peak-to-peak variation is down by about 25% (~8 Pa) due to the real atmosphere's profiles of crosswind, humidity, temperature and pressure. As before, the meteorological conditions were chosen from the NCEP Climate Forecast System[26] for a location near

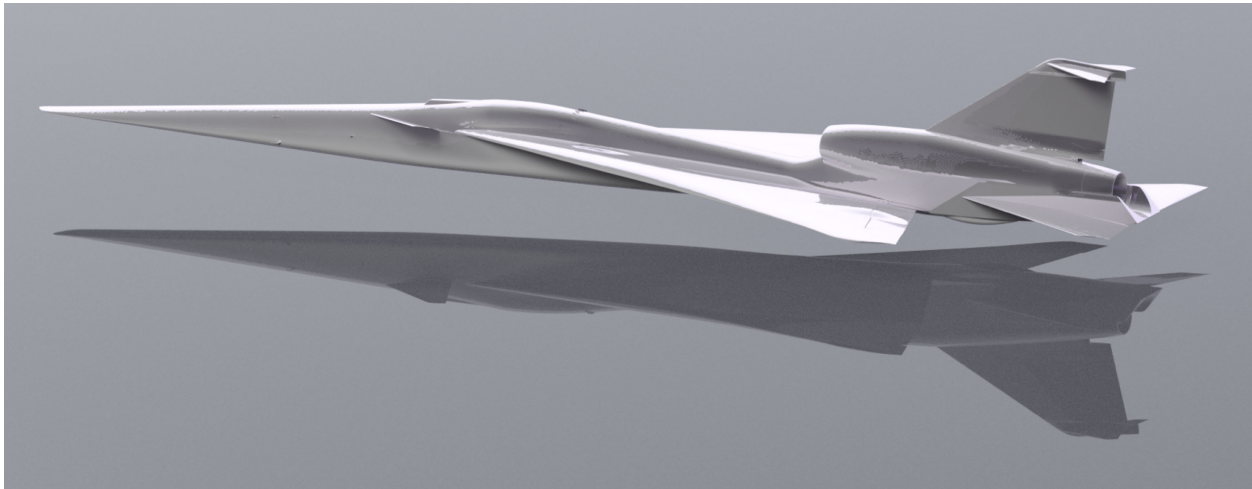


Fig. 27 c609 design iteration for the NASA Low-Boom Flight Demonstrator used for Case II of the Propagation Workshop. Flight conditions were prescribed at Mach 1.4 with an altitude of 54 k ft (16.46 km) flying east with a ground elevation of 361 ft (110 m).

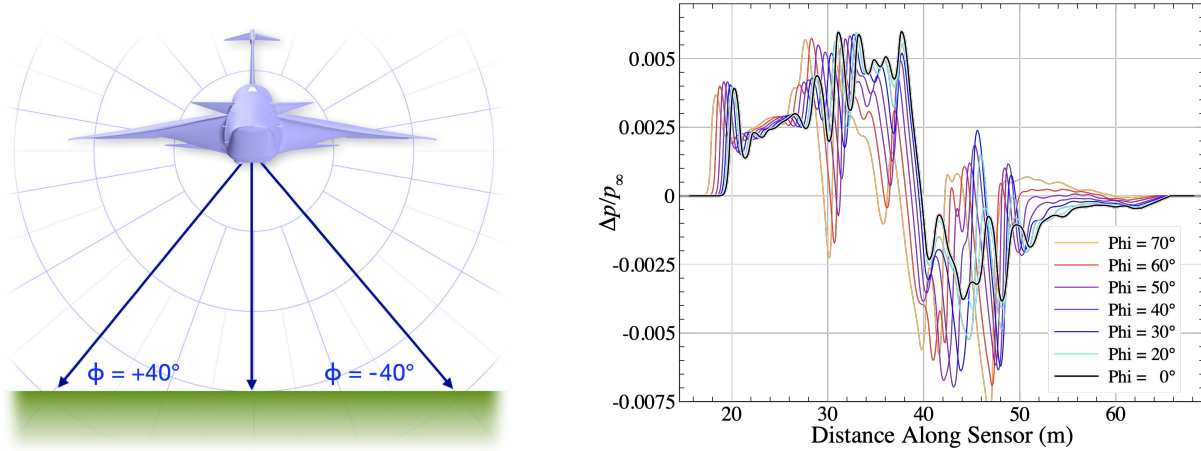


Fig. 28 Sign convention for azimuth, and nearfield pressure signatures, $\Delta p / p_{\infty}$, provided for the c609. Signatures were symmetric in $\pm\phi$ are shown for the interval $\phi = [0, 70^\circ]$ in 10° increments.

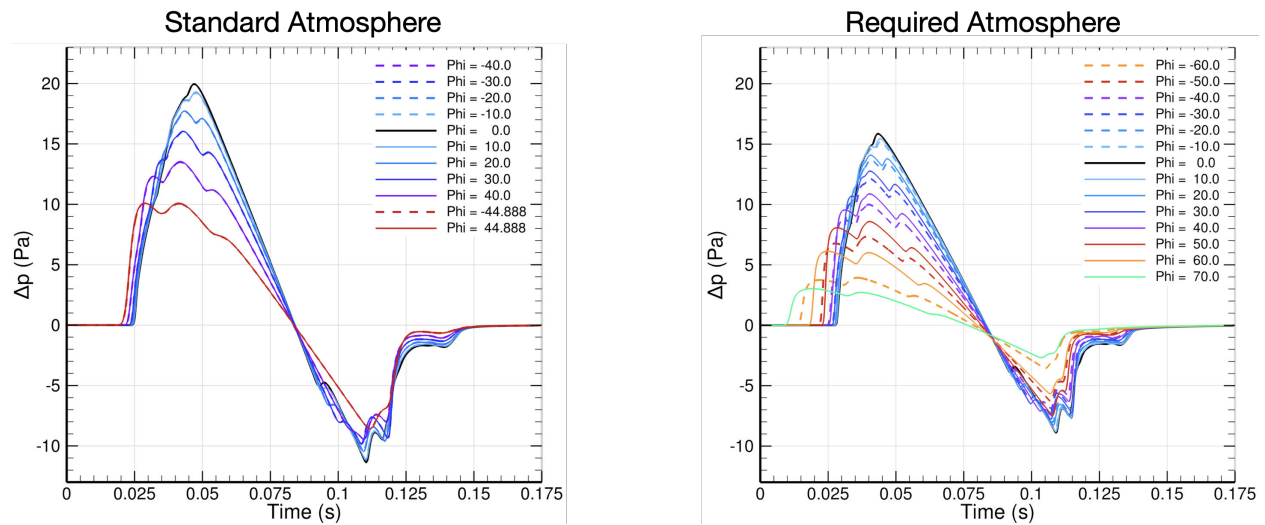


Fig. 29 Ground signals for the c609 after signal propagation through both the standard atmosphere (left) and required atmosphere (right) from an altitude of 54 k ft (16459 m) to a ground elevation of 361 ft (110 m). The required atmosphere has specified profiles for crosswind, humidity, temperature, and pressure.

State College, PA; this time, however, the profile corresponds to a day with moderate temperatures but extremely high humidity (~95%) near the ground. Winds were mild near the ground but stronger higher aloft, and once again differences between corresponding $\pm\phi$ ground signals in the required atmosphere are due to these wind profiles.

Figure 30 shows the noise metrics for the c609 computed for the ground signals in Fig. 29. Loudness ratings for the standard atmosphere are shown at the left while those for the real atmosphere are to the right. The plots include the A/B/C-SEL and PLdB noise metrics as a function of azimuth for all the rays in the nearfield that reach the ground. The B-weighted loudness (BSEL) was computed by sBOOM, and the others came from LCASB. While naively one expects the decrease in amplitudes of ground signatures in Fig. 29 to decrease loudness, frequency content also plays an important role – humid air does not attenuate sound as well as drier air. In this case, the higher humidity of the real atmosphere ultimately has a stronger effect on ground noise. The real atmosphere is about the same or slightly louder (0–1 dB) than the standard atmosphere in most metrics across a broad range of azimuths.

Another striking feature in the azimuthal profiles of the noise metrics for the c609 is that they are surprisingly flat. While there are slight rises in loudness near $\pm 30^\circ$ for all metrics except CSEL, the profiles are otherwise generally flat. This is particularly interesting in the real atmosphere where the off-track booms at $\pm 50^\circ$ generate as much or more noise as on-track, again in all but CSEL. Outboard of $\pm 50^\circ$ there is a rapid roll-off to the edge of the carpet. We see similar behavior in the standard atmosphere, but here the profiles are symmetric and confined to a narrower range of azimuths; the decline at the carpet edge is even more abrupt, and loudness at carpet cut-off ($\pm 44.9^\circ$) is only a few decibels lower than on-track.

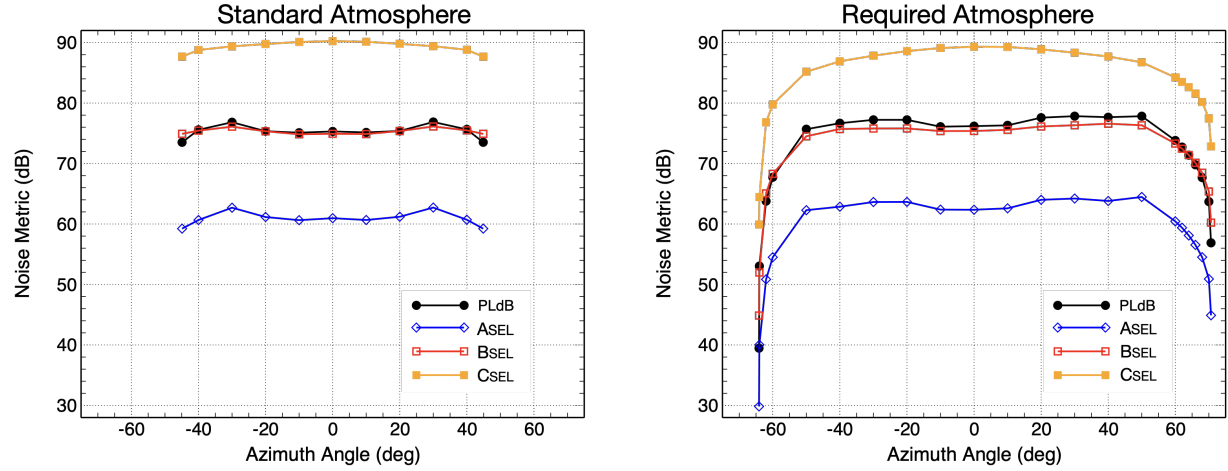


Fig. 30 Ground noise metrics for the c609 after signal propagation through both the standard atmosphere (left) and required atmosphere (right) for the ground signals in Fig. 29.

2. c609: Boom Carpet

Figure 31 shows a 3D view of the ray paths for azimuths for the prescribed atmosphere whose ground signatures and noise metrics were shown in the preceding two figures. As before, the rays are colored and scaled by the local ray tube area as the sound refracts through the atmosphere. The effect of the winds and thermal profile in the real atmosphere are evident on the ray paths. Rays are shown for azimuths from -64° on the north to $+70^\circ$ in the south. In this atmosphere, SBOOM again computed ultra-wide cut-off angles of $\phi = -64.1^\circ$ and $\phi = 70.6^\circ$, so the rays on either edge are within a fraction of a degree of the actual cut-off and are the most heavily impacted by wind and other atmospheric gradients. The necking down of the tubes is particularly interesting, since it is generally associated with an increase in the local amplitude of the signal. If a narrow section of the ray tube impacts the ground it will generally have a high sound pressure level, despite arriving several minutes after the aircraft has passed. For comparison, cut-off angles in the standard atmosphere were only $\pm 44.9^\circ$ and those rays impact the ground about 30 km (~ 100 k ft) off-track.

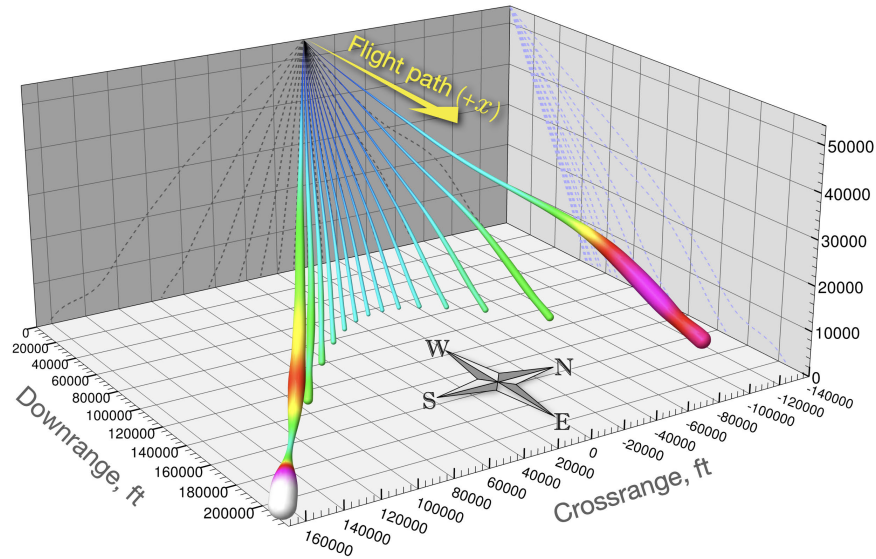


Fig. 31 Ray paths for c609 traveling east at Mach 1.4 and an altitude of 54 k ft (16459 m) in the workshop provided atmosphere with crosswind, humidity, and temperature profiles. Ray paths are shown for azimuths -64° to $+70^\circ$ and are scaled and colored by ray tube area.

Figure 32 shows this carpet for the c609 in both the standard and required atmospheres. Here again, the ultra-wide cut-offs for the required atmosphere result in a carpet that is nearly three times wider than the boom carpet in the standard atmosphere (162 km vs. 58.4 km, respectively). Intercept times for selected rays are listed on the curves. Since the Mach cone at $M_\infty = 1.4$ is wider than it was for the C25P at Mach 1.6, the acoustic rays all travel farther downrange before hitting the ground. As a result, we observe that the on-track signal now takes ~80 s as compared to just over a minute for the C25P. Near cut-off the travel time in the standard atmosphere is roughly three minutes (172 s) and over 8.5 mins for the north-most ray ($\phi = -64.1^\circ$) in the real atmosphere.

C. Farfield Propagation Discussion

Quieter designs continue to challenge the numerical accuracy not only for nearfield CFD solvers but also for farfield atmospheric propagation codes. Whether we are comparing different designs, operating conditions, or atmospheric profiles, small changes of only a few dB are important in low-boom aircraft. We must ensure that propagation calculations have converged well within the size of any differences that we are trying to predict. We focused on mesh convergence of the propagation calculation and ground noise metrics. This convergence study approach could also be applied to over-the-top propagation and secondary boom carpets, which have much longer ray paths and may prove to be computationally expensive.

Our mesh convergence studies in SBOOM indicated that sampling frequencies between 500–800 kHz were required to ensure that truncation error remained low and to guarantee loudness accuracy of within 0.05 dB in all noise metrics. This implies that significant oversampling of nearfield signals is required to control discretization error during signal propagation. This oversampling potentially introduces very high frequencies into the propagated signal; however, internal studies show minimal influence on ground noise metrics since high frequencies are heavily de-emphasized in the frequency response curves of the metrics.

Real atmospheric conditions and wind profiles generally, but not always, reduce ground noise. The real atmospheres for both SBPW3 cases also result in much wider boom carpets. Although the loudness does drop off near the edges of the boom carpet, ground noise can remain non-negligible for very wide crossrange distances.

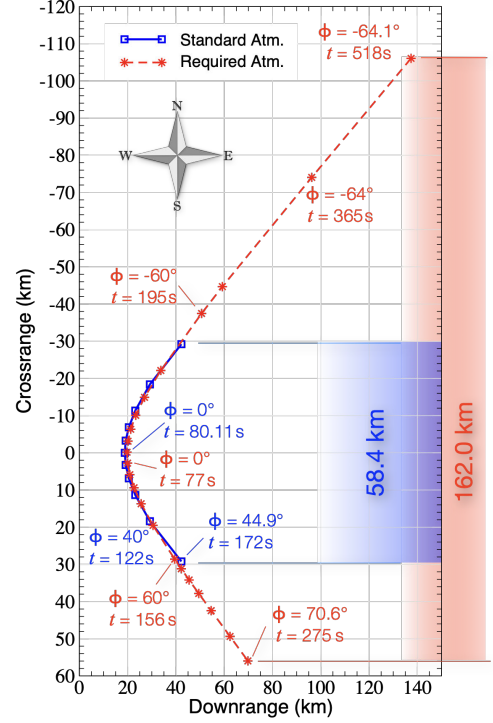


Fig. 32 Boom carpet for c609 traveling east at Mach 1.4 and an altitude of 54 k ft (16459 m) in both the standard and required atmospheres. Ground elevation is 361 ft (110 m). The track width, measured cut-off to cut-off, is labeled for both atmospheres.

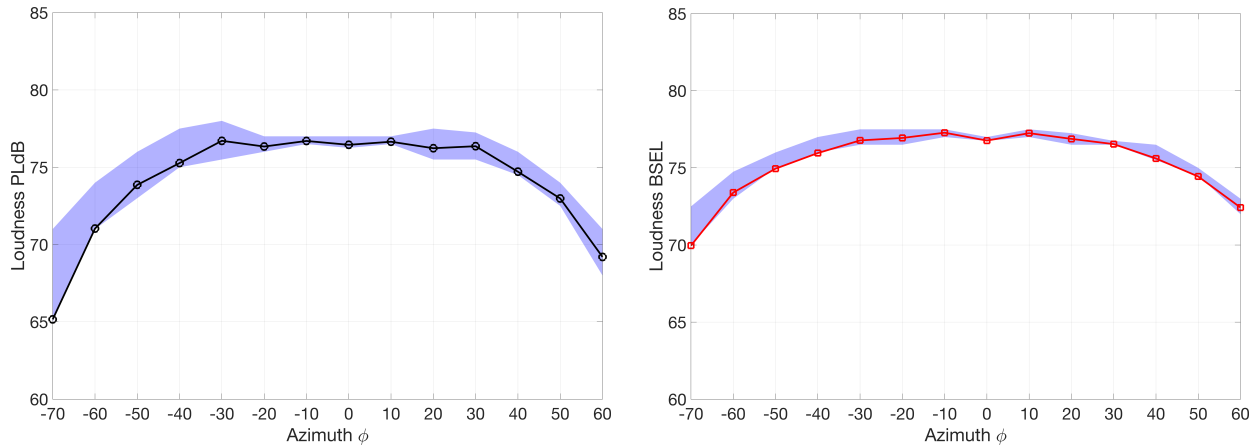


Fig. 33 Propagation results for SBPW3 Case I: C25P in required atmosphere. Shaded regions cover the range of participants' results, with our results denoted in black for PLdB (left) and in red for BSEL (right).

Figure 33 shows our PLdB and BSEL boom carpets presented earlier along with corresponding data from all SBPW3 participants compiled by workshop organizers [27]. Agreement is better closer to on-track, with an amazingly small spread in both metrics between $\phi = [-10^\circ, 10^\circ]$. The required atmosphere introduces some asymmetry in the propagation calculation, and it appears that ground noise prediction is more challenging at wider azimuths – this is not surprising considering the longer ray paths and increased sensitivity to discretization error discussed earlier.

IV. Summary

The Third Sonic Boom Prediction Workshop continued to advance the state-of-the-art in low-boom designs and analysis methods. Our work for nearfield CFD simulations focused on accuracy and efficiency by using a Cartesian Mach-aligned mesh, by decomposing the simulation into independent meshes rotated to align with the off-track angle, and by targeting an off-body pressure signal functional for adjoint-based mesh adaptation. Solving inviscid flow equations further reduces the computational cost while still accurately capturing supersonic flow features.

In examining the farfield propagation cases, our analysis focused on mesh convergence of the pressure signals and noise metrics at the ground. When attempting to determine atmospheric effects where a few decibels are important, we must have confidence that the propagation calculation has converged to within a fraction of a dB. For the two propagation cases, mesh convergence analysis indicated that sBOOM required a sampling frequency of at least 200 kHz and usually in the range of 500–800 kHz to ensure convergence of all ground noise metrics.

Our work demonstrates the importance of thorough mesh convergence studies for propagation calculations, since the number of discretization points impacts truncation error during the propagation steps as well as the noise filter calculation at the ground. The nature of the farfield acoustic propagation approach treats each ray path individually. Wider azimuths are particularly challenging, with propagation distances and times that are much longer before reaching the ground. Additionally, pressure signal amplitudes and noise levels are typically lower near the edges of the boom carpet. Higher sampling frequencies are needed for wider azimuths in order to reduce truncation error and obtain sufficiently converged solutions. This is especially true for windy atmospheres where acoustic ray paths and propagation times near the carpet edge may be 3–5 times longer than those on-track.

Acknowledgments

The authors thank the SBPW3 organizers for their efforts planning and holding the workshop, especially Melissa Carter, Mike Park, and Sriram Rallabhandi (NASA Langley Research Center). We also thank James Jensen (NASA Ames Research Center) for preparing the c608 surface triangulation. Computational resources were provided by NASA Advanced Supercomputing Division, and this work was supported by NASA ARMD Commercial Supersonic Technology (CST) project and NASA Ames Research Center contract NNA16BD60. Wade would like to thank STC for supporting his involvement and travel.

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