
Aircraft Noise Generation and Assessment

Section 5-Overall Vehicle System Noise, Part d-Sonic Boom

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Abstract There has been a renewed interest globally in civil supersonic overland flight that has fostered numerous research and technology development activities. It is now possible to design a low-boom aircraft with a carefully tailored vehicle shape that controls the far field pressures and minimizes sonic booms on the ground. This section will describe recent international advances and cooperative research in sonic boom design, propagation modeling, and human subjective response in preparation of potential international rule changes that will permit civil supersonic flight over land.

Keywords sonic boom · supersonic aircraft

Nomenclature

C_v^2	Turbulence structure parameter for velocity fluctuations
C_T^2	Turbulence structure parameter for temperature fluctuations
PL	Stevens Mark VII Perceived Level [dB] [1]
$ASEL$	A-weighted Sound Exposure Level [dB] [2, 3]
$BSEL$	B-weighted Sound Exposure Level [dB] [2, 3]
$CSEL$	C-weighted Sound Exposure Level [dB] [2, 3]
$DSEL$	D-weighted Sound Exposure Level [dB] [2, 3]
$ESEL$	E-weighted Sound Exposure Level [dB] [2, 3]
$ISBAP$	Indoor Sonic Boom Annoyance Predictor [dB] [4]

Acronym

ABBA	Airborne Blimp Boom Acquisition System
ADS-B	Automatic Dependent Surveillance - Broadcast
AFRC	Armstrong Flight Research Center
AIAA	American Institute of Aeronautics and Astronautics

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ASCENT	Aviation Sustainability Center - FAA Center of Excellence for Alternative Jet Fuels & Environment
BASS	Boom Amplitude and Shape Sensor
CFD	Computational Fluid Dynamics
CISBoomDA	Cockpit Interactive Sonic Boom Display Avionics
cRIO	National Instruments CompactRIO
D-SEND	Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom
DARPA	Defense Advanced Research Projects Agency (United States)
DFRC	Dryden Flight Research Center
FAA	Federal Aviation Administration (United States)
FaINT	Farfield Investigation of No-boom Thresholds
FIR	Finite Impulse Response filters
GIS	Graphical Information System
HSCT	High Speed Civil Transport
HSR	High Speed Research
ICAO	International Civil Aviation Organization
IER	Interior Effects Room
JAXA	Japan Aerospace eXploration Agency
LBFD	Low Boom Flight Demonstration
L/D	Aircraft lift to drag ratio
MDAO	Multidisciplinary Design Analysis and Optimization
NASA	National Aeronautics and Space Administration (United States)
N+2	Small airliner concept (2nd generation supersonic airplane)
QueSST	Quiet SuperSonic Technology aircraft
SBUDAS	Sonic Boom Unattended Data Acquisition System
SCAMP	Superboom Caustic Analysis and Measurement Program
SSBD	Shaped Sonic Boom Demonstrator
SSBJ	SuperSonic Business Jet
SST	SuperSonic Transport
TOGW	Takeoff Gross Weight
WSPR	Waveform and Sonicboom Perception and Response program
WSPRRR	Waveform and Sonicboom Perception and Response Risk Reduction program

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1 Introduction

We are on the verge of a renewal of civil supersonic overland flight, and while the sonic booms that occur when aircraft travel at speeds greater than the speed of sound are still considered an environmental challenge, the most significant barriers are the regulations barring supersonic flight over land and the creation of objectionable sonic booms. Regulatory bodies such as the FAA and ICAO have indicated that they will consider a rule change driven by improved technology and industry interest, as long as “no unacceptable situation for the public is created by sonic boom from supersonic aircraft in commercial service” [5]. Furthermore, ICAO has continued its efforts toward the development of supersonic aircraft noise standards, including determining sonic boom measurement techniques, selection of suitable metrics, and flight test procedures for supersonic overland noise certification [6].

In a book presenting a comprehensive review of sonic boom by Maglieri et al. [7, p. 514], the authors presented their perspective on the outlook for civilian supersonic overland flight based on six decades of sonic boom mitigation research. They highlighted four key technical issues needing resolution, including:

1. Will overflown communities find the magnitude of low-boom shaped cruise signatures acceptable?
2. Can the magnitude and extent of the transition focus boom footprint be minimized to allow supersonic overland operations?
3. Are low-boom shaped signatures less influenced by the atmosphere?
4. Can low-boom shaped cruise signatures possibly damage ground structures or create undesired building vibration or rattle?

In light of the regulatory activities and time lines and the industry response, we offer an additional technical issue:

5. Will the acoustic sounds generated from non-low-boom aircraft operating over land at slightly supersonic and below Mach cut-off conditions be acceptable to the public?

This chapter will describe recent international sonic boom research and advances made toward answering these questions.

In the United States, the National Aeronautics and Space Administration (NASA) is leading the technology and science development in three areas: low-boom aircraft design, understanding community response to sonic booms, and gathering the scientific data to support a noise-based certification rule. In Asia, the Japan Aerospace Exploration Agency (JAXA) has made significant advancements in flight validation of shaped booms as well as in human perception studies in the laboratory. In Europe and Russia, several multi-partner research programs have investigated numerical and laboratory-scale experimental simulations that have led to new validated tools for sonic boom propagation modeling [8,9,10,11]. Studies with these tools have contributed to the understanding of complex propagation effects on sonic booms.

In the last two decades, significant milestones have been met in the critical technology of integrated low boom aircraft design. The DARPA/NASA Shaped Sonic Boom Demonstrator (SSBD) aircraft flight on Aug. 27, 2003 proved in flight that changing a supersonic aircraft’s shape would alter the near field pressure distribution, and the shaping would persist through propagation to the ground in a real atmosphere [12,13].

Subsequent research including the Gulfstream QuietSpikeTM [14] and the JAXA Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom (D-SEND) [15] have also demonstrated in flight the effectiveness of aircraft design to create shaped sonic booms. Additional wind tunnel testing by various aerospace companies has endeavored to fine tune low-boom optimization tools, propagation modeling techniques, and supersonic configuration designs.

Critical research has been conducted in the area of sonic boom modeling, including low boom design, propagation of sonic booms through focal zones, and atmospheric turbulence. Experimental testing has also gathered data to facilitate code validation and improvement of modeling at or near sonic boom lateral and Mach cut-off and for the propagation of booms in and around structures. Additional validated methodologies are needed to determine human responses to indoor and outdoor sonic boom noise, survey tools, and community testing protocols.

These technical successes have spawned a renewed interest by regulatory agencies worldwide in reevaluating current rules barring supersonic overland flight and potentially opening the door for quiet supersonic overland flight. Lockheed Martin has designed for NASA a subscale Quiet SuperSonic Technology (QueSST) aircraft that can be used to gather human subjective response data to low-amplitude sonic booms. If funded and built, this experimental plane (X-plane) will be flown in a future NASA Low Boom Flight Demonstration (LBFD) program, operating over communities to gather necessary quiet overland supersonic flight dose-response data for ICAO. Many years of preparations, including multiple NASA sponsored programs exploring techniques for conducting community response testing, are laying the groundwork for eventual LBFD community testing.

Subsequent sections describe the state-of-the-art advances in supersonic aircraft design, sonic boom propagation modeling, and community subjective research that are providing confidence to the regulatory agencies that the technologies are ready to demonstrate acceptable low boom signatures that will help facilitate a new era in civil supersonic overland flight.

2 Supersonic Aircraft Design

Since Al George and Richard Seebass conceived the concept of sonic boom minimization in the late 1960s [16,17,18], aircraft designers have been advancing the process for supersonic aircraft low boom design. Current technology includes sophisticated multidisciplinary design analysis and optimization (MDAO) techniques fully integrated with computational fluid dynamics (CFD) modeling, which can be used to drive the configuration design toward idealized, trim-feasible low-boom targets while allowing for realistic airframe/engine/control surface integration. There have been a multitude of designs and wind tunnel validation tests in recent years. A series of low boom design and validation activities for over-wing engine placement [19], inlet design [20,21] and highly tailored shaping have greatly improved and increased confidence in CFD technology¹ [22,23,24]. The MDAO methodology [25] is applicable to configurations with a large fineness ratio, uses a surrogate equivalent area lift distribution, and assumes the pitching moment is dominated by the lifting force. The adjoint-based design optimization process has also improved and been applied to multiple azimuths to minimize sonic boom loudness levels across the full carpet of a NASA low-boom vehicle [26]. This has been accomplished by coupling the adjoint methodology with the sonic boom propagation code sBoom [27,28] that takes into account atmospheric losses due to nonlinearity, molecular relaxation, and thermoviscous absorption.

A Gulfstream assessment of the economic viability of a supersonic business jet (SSBJ), including a determination that Gulfstream IV and Gulfstream V aircraft operations spend only 25% of the flight time over water, led to the conclusion that sonic boom suppression technology coupled with regulatory changes are key to the success of a small civil supersonic aircraft [29]. To explore sonic boom suppression, a multistage extendable aircraft nose that retracts into the forward fuselage, called the QuietSpikeTM, was developed by Gulfstream [30]. This concept allows tailoring of the shape of the ground boom signature while allowing greater flexibility in the

¹ This section covers the nexus of supersonic CFD modeling from the perspective of sonic boom modeling and does not attempt to fully document the critical CFD modeling research that has enabled low-boom design.

aircraft design, overcoming one of the significant low-boom design challenges of allowing sufficient fuselage volume. The concept works by carefully tailoring the pressure distribution along the nose of the aircraft via creation of a sequence of weak shocks that propagate parallel to one another, without coalescing into a classic (loud) N-wave. This QuietSpikeTM has been tested and proven successful both in the wind tunnel and in flight (Figure 1) using a modified NASA F-15B [14].



Fig. 1 Gulfstream QuietSpikeTM in flight [NASA image].

In February 2016 NASA announced that it had selected Lockheed Martin Skunk Works to design a supersonic X-plane with low-boom features to launch the QueSST program [31]. This Mach 1.4 aircraft design (Figure 2), featuring a single-engine design and a delta wing, would be proposed as a platform for testing whether the reduced acoustic signature, expected to have a Perceived Level (PL) [1] of approximately 75 dB, is acceptable to the public.



Fig. 2 NASA QueSST vehicle concept designed by Lockheed Martin [NASA image].

While research for low-boom aircraft designs is advancing, there are a number of non-low-boom efforts [32,33] exploring the possibility of alternative designs to address concerns that

regulatory changes needed for civil supersonic overland flight will not be enacted quickly enough. These non-low-boom efforts are instead exploring the possibility of exclusive overwater supersonic flight operations, dual-point designs (subsonic overland and supersonic overwater flight), or Mach cut-off transonic flight (flying above Mach 1 but below the sound speed at the ground) [32,34] by leveraging natural supersonic laminar flow technology [35,36], state-of-the-art engines, and advanced composite materials. In the past, the potential performance tradeoffs between takeoff gross weight (TOGW) and range for increasingly stringent low-boom requirements were also a concern. As shown in Figure 3 [37, p. 36], subsonic and supersonic aircraft with no boom requirements allow for a wide range of potential airplane TOGW for a given range. As sonic boom requirements are introduced and made more stringent, TOGW is increased, and the result is a reduced design space with range limitations. However, more recent designs utilizing MDAO techniques² have achieved boom reductions with smaller performance penalties and increasing gains in Lift to Drag ratio (L/D). As shown in Figure 4, the L/D is increased for shaped vehicles in the commercial transport category with larger takeoff gross weights (N+2 and HSC/T designs) [38].

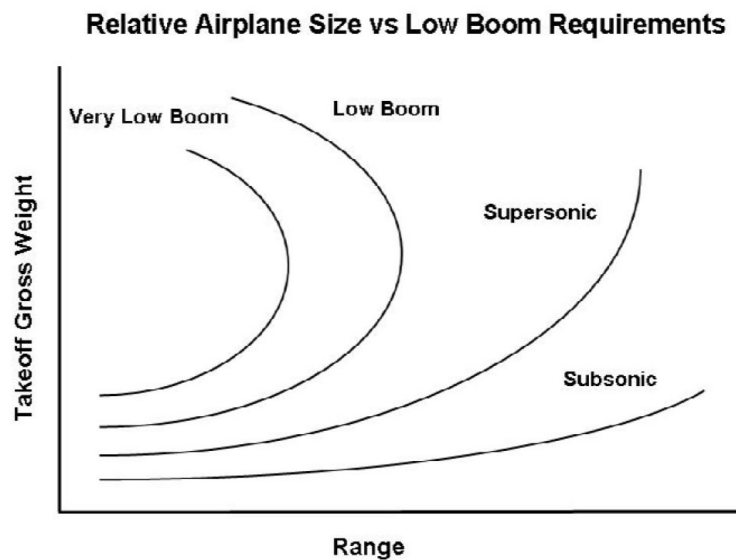


Fig. 3 Notional design space for TOGW versus range for various different aircraft types [37, p. 36]. Satisfactory designs lie anywhere in the area to the left of a given curve.

Mach cut-off takes advantage of the temperature gradient of the atmosphere to refract the sonic rays upward [7, p. 7]. Thus, the sonic boom never reaches the ground. This phenomenon is independent of aircraft configuration and allows boomless flight up to a local Mach number of 1.15 in an ideal, standard atmosphere [39], but the actual Mach number will vary in real atmospheres. Mach cut-off is seen by some manufacturers, such as Aerion, as a relatively low risk way to operate a first-generation civil supersonic aircraft over land. It offers an approximately 120 knot, or 23%, speed advantage over the fastest current business jets. At the same time, it avoids the many risks of low-boom designs. Since the sonic boom does not reach the ground, there is reduced probability of the public being disturbed by sonic boom, though it should be

² This N+2 design study included low-boom concepts that reflect supersonic airplanes two generations into the future, which at that time were estimated to have an entry into service date of 2018-2020.

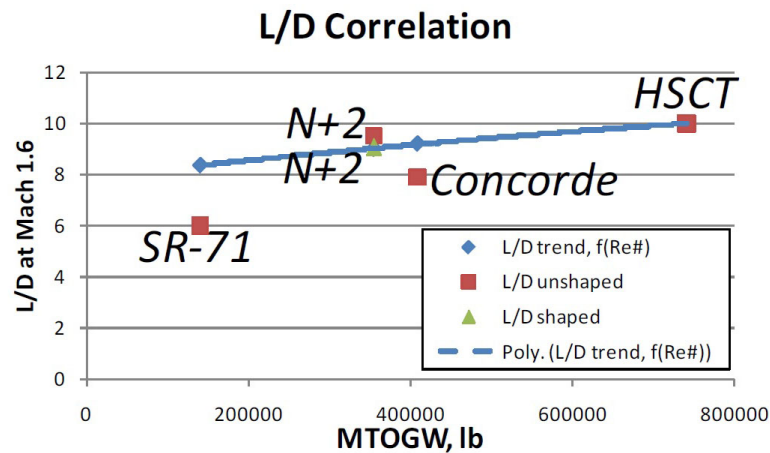


Fig. 4 Best trend of L/D correlation with MTOGW compared to various vehicles [38].

noted that evanescent waves beyond cut-off can create audible signals. With Mach cut-off, the vehicle may be optimized for minimum drag, while a low-boom design may result in a nonoptimal volume distribution that potentially increases wave drag.

The biggest potential pitfall of Mach cut-off is the risk of accidentally exceeding the cut-off speed and putting a focused sonic boom on the ground. Aerion considers this risk to be manageable with modern flight computers and weather data. In fact, the FAA conducted a successful Mach cut-off flight demonstration in 1977, using the standard weather reports, forecasts, and computers of the day, though the experiment was conducted such that the effects of headwinds and tailwinds on Mach cut-off were not tested [40]. The FAA has recently funded Mach cut-off research through the ASCENT Center of Excellence. NASA has also recently studied Mach cut-off and evanescent waves as part of the Farfield Investigation of No-boom Thresholds (FaINT) program [41] and in the Low Boom/No Boom flight test [42]. More information on Mach cut-off research is included in Section 3.3.

A number of investigations into the feasibility of the various low-boom and alternative concepts have explored the different business cases in terms of time savings, productivity, and marketability [29, 43]. The potential for supersonic overland operations was found to result in a 50-60% mission block time savings over comparable subsonic operations [44] while operating at Mach cut-off flight resulted in an average 27%-47% speed benefit over subsonic aircraft operating at Mach 0.85 [45]. Analysis of operational flight detours for different regulatory rules found a 10% distance penalty over unrestricted great circle route distances when optimistic³ supersonic flight routing is considered [44].

3 Sonic Boom Modeling

Sonic boom theoretical research of the 1950s and 1960s has resulted in numerous practical sonic boom propagation models with varying degrees of fidelity and capability. These tools are needed both for aircraft design and to assess operational impacts. They will also serve a critical role in sonic boom certification procedures. The atmosphere surrounding the aircraft plays an important role in the determination of the location and the characteristics of the sonic boom that reaches

³ Optimistic supersonic flight routing allows supersonic flight over sparsely populated areas and keeps a minimum 50 km distance from shorelines and permanent settlements.

the ground. In the lateral direction, the rays emanating from the aircraft travel directly toward the ground creating the primary boom carpet. Other rays, either initiating at higher azimuths relative to the vehicle or which reflect or refract and travel upward and then back down to the ground form the secondary carpet (Figure 5). Due to the long propagation distances and the resulting reductions in sonic boom overpressure levels as well as rounding of the signature, the secondary sonic boom carpet is not anticipated to be an issue; however, secondary booms may need to be evaluated as part of the regulatory process.

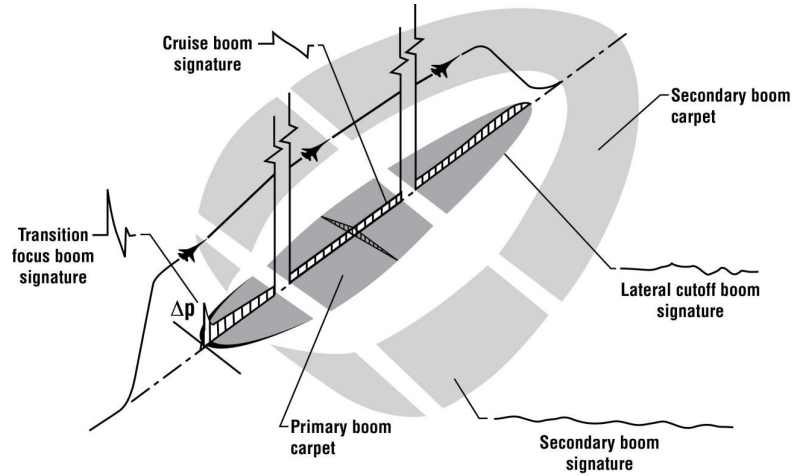


Fig. 5 Schematic of sonic boom ground footprint [7, p. 8].

In addition to basic ray path computation and signature evolution and aging, some advanced features needed for current research include the ability to model maneuvering flights in arbitrary atmospheres with winds, signatures in focal zones and under cut-off conditions, over-the-top booms, molecular relaxation, turbulence, and underwater propagation. Notable models for prediction of the sonic boom propagation from the aircraft to the ground include ARAP [46, 47, 48], BANGV [49, 50, 51], GACBOOM [52], LMBoom [53, 54], MDBoom [55, 56], PCBoom [57, 58], sBOOM [27], SHOCKN [59, 60, 61], THOR [62], TRAPS [63], Xnoise [64], and ZEPHYRUS [65, 66]. Current research activities are looking to extend and validate these models, including investigating propagation into focal zones, turbulence modeling, lateral and Mach cut-off, structural response to sonic booms, and diffraction around structures. Recent progress in these research areas is described below.

3.1 Focused Boom Modeling

Geometrical acoustics can be used to define the domains of primary and secondary sonic booms as illustrated in Figure 5. However, ray theory is inadequate for prediction of acoustic signatures in many areas of interest, such as at caustics (see Figure 6) or in the shadow zone (see Figure 7). These regions occur not only for steady flight in the domains between primary and secondary boom carpets (Figure 5), but also under maneuvering flight conditions such as accelerations or dive maneuvers (Figure 7). Additional models are required to predict the acoustic waves that will penetrate into these regions from conventional and low-boom supersonic flight vehicles. One approach for calculation of booms inside the shadow zone using a numerical time-domain

formulation to estimate nonlinear effects [67,68] was developed based on a generalized unsteady Tricomi equation [69]; this was further improved with the addition of effects due to molecular relaxation [70,71].

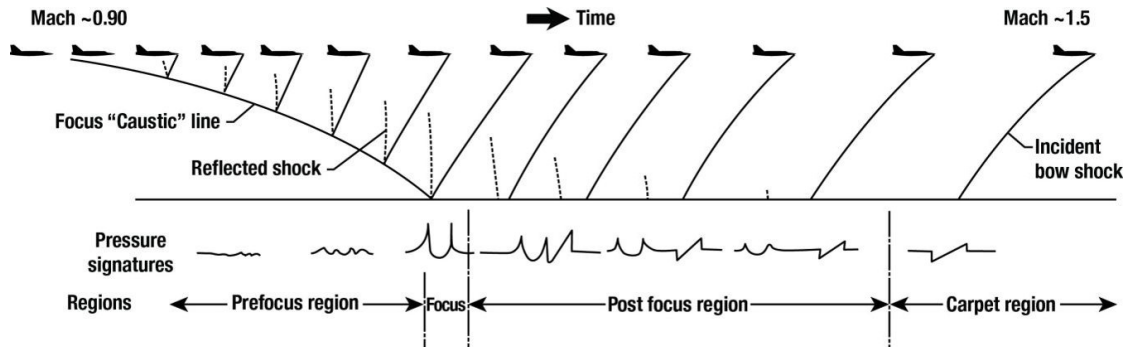


Fig. 6 Focal zone regions and pressure signatures for an aircraft in transition flight from subsonic to supersonic speeds [7, p. 79].

NASA conducted the Superboom Caustic Analysis and Measurement Program (SCAMP) to develop and validate analytical models for sonic boom signatures in and around focal zones using flight test measurements with a conventional N-wave aircraft. Focal zones are expected to occur during aircraft transition from subsonic to supersonic flight, as shown in Figures 6 and 7. Maneuvers during the flight test spanned a range of caustic curvatures in order to provide a variety of conditions for code validation. The SCAMP experiment was designed to capture concurrent F-18B on-board flight instrumentation data, high-fidelity ground-based and airborne acoustic data, and surface upper-air meteorological data.

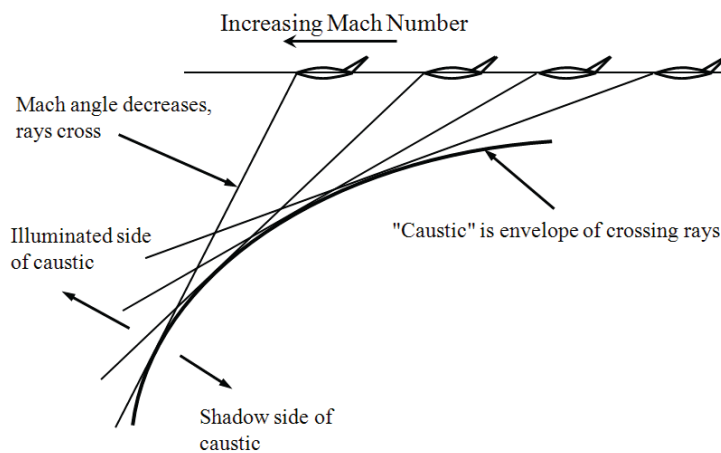


Fig. 7 Ray diagram of focusing caused by acceleration to supersonic speed [72, p. 12].

Close coordination with NASA AFRC (DFRC at the time) resulted in the development of new experimental instrumentation and techniques to facilitate the SCAMP flight-test execution, including the development of an F-18B Mach rate cockpit display, TG-14 powered glider in-flight

sonic boom acoustic measurement instrumentation, and software for near real-time way-point computation accounting for local atmospheric conditions.

A successful experimental flight and acoustic measurement test was executed in May 2011 with a team including industry, academia, and government organizations. Thirteen F-18B flights were conducted during 5 flying days over a 2-week period. A densely populated 3,048 m long ground acoustic array with 38 m microphone spacing was designed to capture pre-focus, focus, and post-focus regions. The ground-based acoustic array was placed in a nominally east-west orientation in the remote Cuddeback lakebed region, north of Edwards Air Force Base, California. The SCAMP flight tests successfully captured 70 boom events, with 61 focus passes and nine calibration passes. Seventeen of the focus passes and three of the calibration passes were laterally offset, with the others being centerline flights. Airborne incoming sonic boom wave measurements were measured by the TG-14 for ten of the F-18B flight passes including one maximum focus signature, several N-U combinations, several overlapped N-U signatures, and several evanescent waves. A greater understanding of the evolution of these signatures within the sonic boom carpet, as well as how to control placement of the focus boom, was obtained from this field measurement effort.

The large resulting database of sonic boom signatures and associated meteorological data was used to validate focal zone sonic boom prediction codes developed during the 27-month program: PCBoom, Lossy Nonlinear Tricomi Equation method (LNTE) [70,71], and the Nonlinear Progressive wave Equation (NPE) method [73,74]. PCBoom propagates the rays through the atmosphere and, in addition to legacy focus signature prediction based on the Gill-Seebass method, provides input source characteristics and propagation parameters to LNTE and NPE. LNTE, a Tricomi solver that incorporates atmospheric losses, computes the signature at the focus, and computes the signature in the vicinity of the focal zone, including the evanescent and post-focus zones.

The validated models were then applied to focus boom predictions from low-boom aircraft designs [72, pp. 150-185][75,76]. An example focal zone calculation using PCBoom/LNTE for a Gulfstream low-boom configuration is provided in Figure 8. The incoming and outgoing wavefronts are shown in the vicinity of the caustic, and the evanescent wave field at negative dimensionless distances is shown to quickly reduce to a very low level. The pressure signature extracted from the top of the LNTE computational domain (at dimensionless distance = 1) is shown in Figure 9 (no ground reflection included). One can see in Figure 9 that the multishock nature at the front and aft of the incoming waveform is not present in the outgoing wave from the caustic. Because the LNTE analysis method produces pressure-time signatures, auralization of the sonic boom noise [77] at and near the focusing caustic is also possible for low-boom vehicle designs. This has been demonstrated in the NASA Langley Interior Effects Room (IER) [78] as an example of the utility of LNTE for auditioning focus boom sounds from proposed vehicles that do not yet exist. In summary, the SCAMP program validated focal zone prediction techniques including ray tracing methodologies for predicting caustic curvatures and numerical techniques for determining sonic boom signatures in the focus, post-focus, and evanescent zones.

JAXA has also developed FFnoise for focus boom prediction by implementing the lossy NTE method in an efficient algorithm using a splitting scheme and a multigrid approach [79]. This tool has been applied to investigate the effect of aircraft shaping on the focus boom footprint extent, waveform pressures, and metric levels. It was found that aircraft shaping shows benefits for the focus area by reducing waveform pressures and metric levels, while also reducing the area of the focus footprint in the undertrack direction.

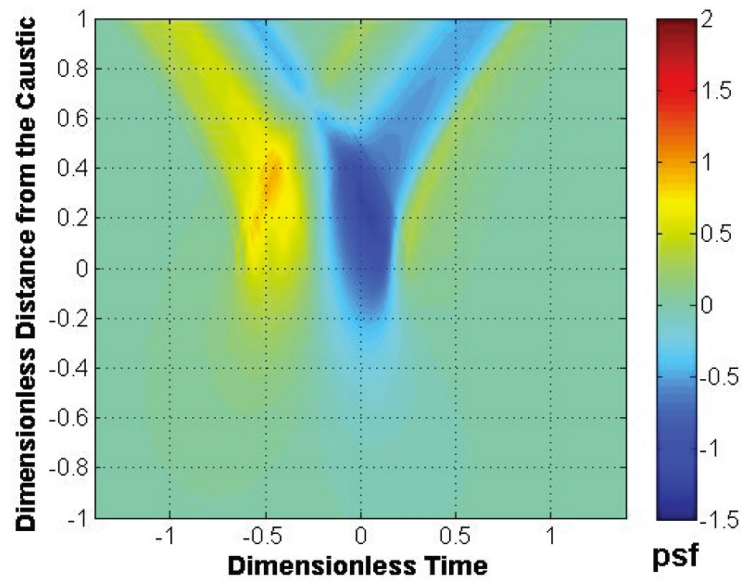


Fig. 8 Example focal zone calculation using PCBoom/LNTE for a Gulfstream low-boom configuration [72, p. 170].

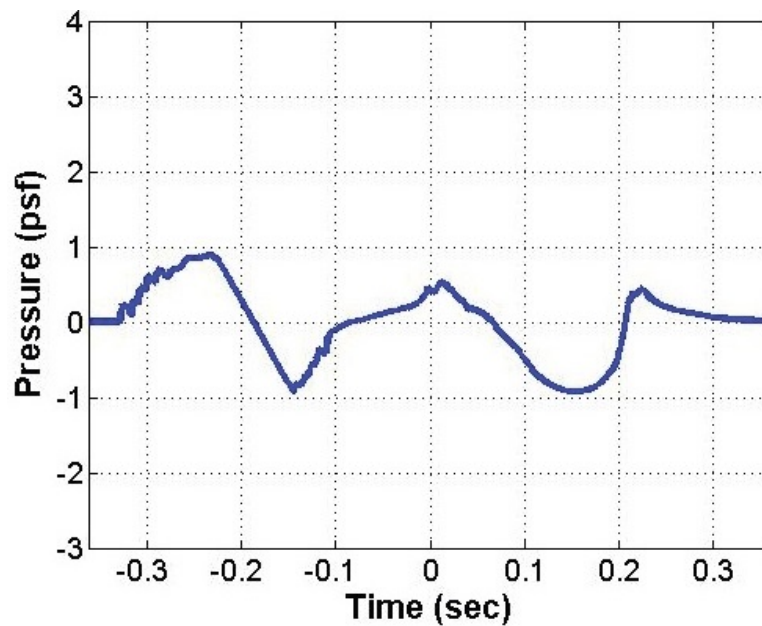


Fig. 9 Example of pressure signature extracted near the top of the LNTE computational domain for a Gulfstream low-boom configuration [72, p. 170].

3.2 Propagation Through Atmospheric Turbulence

As sonic booms propagate through the atmosphere, they can be affected by atmospheric turbulence, primarily resulting in signature distortion and a change in the peak overpressure. These

changes manifest themselves as rounded, peaked, or spiked signatures for which distortion probabilities of occurrence can be determined based on empirical data from N-wave vehicles and projected for shaped low-boom vehicles [7, pp. 53–54]. It was recognized by Plotkin [80], however, that a “definitive understanding of the mechanisms behind turbulent distortion will probably require numeric solutions.” In the last few decades, such numeric models of sonic boom propagation through turbulence have been developed [81, 82, 83]. Additional research has brought a statistical approach to turbulence modeling by developing and applying appropriate stochastic meteorological models for turbulence in the planetary boundary layer [84, 85] and ascertaining relevant turbulent scales for sonic boom propagation [86].

Scaled laboratory experiments have been conducted to measure turbulent propagation effects using spark-produced N-waves [87, 88, 89, 90]. Unique flight opportunities have provided small empirical datasets of propagation of shaped booms through turbulence during the Shaped Sonic Boom Demonstrator Test [91] and JAXA’s D-SEND tests [92]. Such datasets have been utilized to generate finite impulse response (FIR) filters to estimate atmospheric turbulence effects [93], which have applicability to specific turbulent realizations. The assumption is that the turbulence effects from the lower part of the atmosphere can be represented by a linear function applied to the sonic boom signal to estimate the signal distortion. These FIR filters are limited to the specific turbulence conditions captured in the data used to create the filters and are not applicable to the statistical approach mentioned above. To fill the need for robust validated tools for international regulatory decision making, applicable to a large variety of meteorological conditions, NASA is presently conducting a series of full-scale atmospheric experiments that will provide a critical dataset of sonic boom propagation through atmospheric turbulence. These studies are described below.

The NASA Sonic Booms in Atmospheric Turbulence (SonicBAT) program, led by KBRwyle with team members at The Pennsylvania State University (PSU), Boeing, Gulfstream, Eagle, Laboratoire de Mécanique des Fluides et d’Acoustique (LMFA), and Lockheed Martin has four objectives: a) developing a numeric turbulence model using the Khokhlov-Zabolotskaya-Kuznetsov (KZK) method [94] and a classic turbulence model, both capable of traditional and conceptual low-boom aircraft analysis, b) designing and executing flight experiments under a range of atmospheric conditions, c) using the measurement data to validate the codes using traditional booms in the presence of atmospheric turbulence, and d) applying the codes to estimate turbulence effects on the sonic booms from shaped boom aircraft designs.

The first set of flight tests was conducted in July 2016 at Edwards Air Force Base, California for continuity with the vast majority of prior sonic boom flight tests that have been conducted in that desert environment. Microphone data were recorded using modern digital instrumentation with concurrent measurement of atmospheric turbulence properties using GPSsonde balloons, Sonic Detection and Ranging (SODAR) acoustic sounders, and ultrasonic anemometers. Flight test booms generated by steady F-18B flights were N-waves, but data were collected in sufficient detail to serve as general model validation for developing additional FIR filters to represent the turbulence effects. An additional flight test in a hot and humid non-desert environment was conducted in Florida in August 2017.

It has been demonstrated by Blanc-Benon et al. that boom propagation modeling through turbulence is possible via geometrical acoustics and application of the KZK method [81]. Additional work has applied this method to propagation in a moving, random inhomogeneous medium [95]. An extension to a three-dimensional numerical sonic boom turbulence model has been developed at PSU using a KZK method. The propagation model includes convection, multidimensional diffraction, nonlinearity, and absorption effects. Turbulence is being represented by a Fourier modes model that can match the amplitude (turbulence structure constants C_v^2 and C_T^2) and scales of relevant conditions [86].

JAXA has been pursuing a supersonic research program focusing on sonic-boom reduction technology, including prediction tool development, since 2005 for future economically-viable and environmentally-friendly supersonic airliners. This research program has provided insight into sonic boom propagation through turbulence of value to the international community. In the program, a series of sonic boom measurement tests called D-SEND were conducted in order to demonstrate the persistence of boom shaping from the aircraft to the ground that was predicted for advanced low-boom design concepts [15]. After finishing its first phase of the axisymmetrical model drop tests (D-SEND#1) in 2011, its second phase (D-SEND#2) was conducted in 2015 in which an unmanned, non-powered scaled airplane was dropped from a stratospheric balloon to demonstrate concepts for shaping both front and aft parts of the sonic-boom signatures.

For these low-boom demonstration flight tests with scale model aircraft, JAXA developed an airborne sonic-boom measurement system named ABBA (Airborne Blimp Boom Acquisition) with tethered blimp and low-frequency microphones to attempt to capture the sonic boom signal above the turbulent boundary layer and to avoid ground reflection effects [96,97]. While the ABBA system worked very well in the D-SEND#1 drop test, measurements in D-SEND#2 were affected by atmospheric turbulence. Consequently, the test provided useful data for development of models for atmospheric turbulence effects on sonic booms. In D-SEND#1, two axisymmetrical scale models, named NWM (N-Wave Model) and LBM (Low-Boom Model), were dropped back to back from a stratospheric balloon and the sonic-booms generated from both models were measured with the ABBA system. The measured sonic boom signatures of the LBM showed flat-top type low-boom characteristics in the front part as designed while those of the NWM showed conventional N-shaped sonic boom pressure signatures as shown in Figure 10.

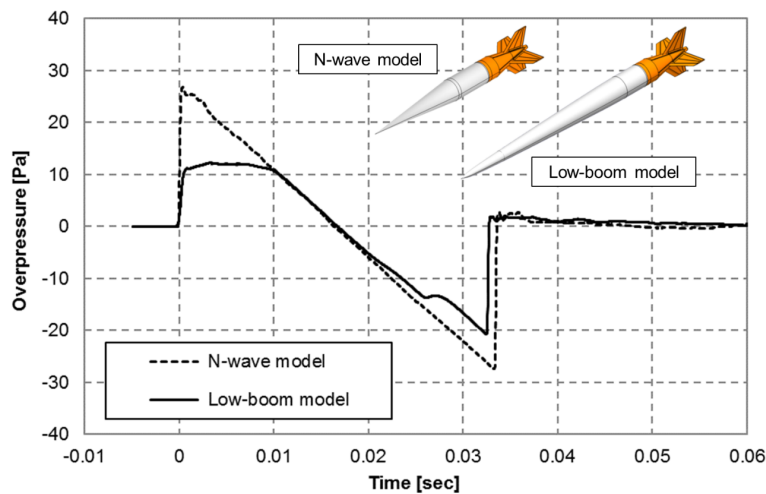


Fig. 10 Comparison of measured signals from JAXA D-SEND#1 N-wave model and Low-Boom Model. Used with permission from JAXA [98].

Although the same experimental system of a stratospheric balloon and the sonic-boom measurement system as in the D-SEND#1 drop tests were used in the D-SEND#2 flight test, the measured sonic-boom signatures were affected by the atmospheric turbulence even at the airborne microphone positions. JAXA developed a tool named “SPnoise” for analyzing the nonlinear acoustic wave propagation through inhomogeneous media [92]. The tool was applied to the D-SEND#2 drop test results together with the atmospheric turbulence characteristics on the test

day quantified with the meteorological data [99]. The analysis confirmed the presence of atmospheric turbulence effects on the measured low-boom pressure signatures as shown in Figure 11.

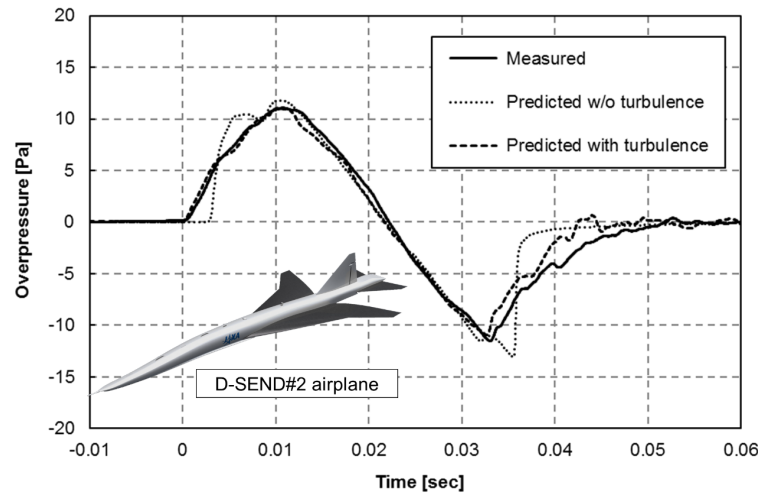


Fig. 11 Comparison of measured signal from JAXA D-SEND#2 experiment to predictions with and without atmospheric turbulence. Used with permission from JAXA [98].

3.3 Lateral and Mach Cut-off

NASA and several industry and academia partners have studied noise in the shadow zone, particularly noise at lateral and Mach cut-off conditions, as part of the Farfield Investigation of No-boom Thresholds (FaINT) program [41, 100]. As part of this study, a field test was conducted with an F-18 aircraft, utilizing a linear 60-microphone array with a length of approximately 2300 m, along with a 62-microphone spiral array over a diameter of approximately 600 m. In addition, a microphone system on a blimp was deployed to an altitude of approximately 900 m, and a microphone system on a TG-14 motor glider measured the sonic boom near the cut-off caustic or along the lateral cut-off ray ranging from about 900 to 1800 m above ground.

The resulting database can be used for further research on the Mach cut-off phenomenon and on noise in the shadow zone beyond lateral cut-off. Regarding Mach cut-off, the FaINT effort provided an empirical relationship between Mach cut-off flight conditions and shadow zone noise levels, an analysis of safe cut-off altitudes, and an analysis of the sensitivity of Mach cut-off to varying atmospheric conditions and realistic aircraft trajectory perturbations. Regarding lateral cut-off, the study measured sonic booms across the edge of carpet through the transition zone and into the shadow zone. It was found that significant noise levels can exist beyond the traditional carpet edge, so that an audible noise carpet can be defined. Comparisons between sonic boom measurements and numerical predictions show that predicted carpets are narrower than measured. Additionally, predictions often show complex focusing at the carpet edge that is not observed in the measured data, resulting in predicted levels that were higher than those measured near lateral cut-off. Finally, it is proposed that a different kind of metric be applied to the noise waveforms encountered in Mach cut-off and lateral cut-off regions since their extended

duration and low-frequency characteristics do not match the characteristics of a typical carpet sonic boom.

The FAA has recently been sponsoring Mach cut-off research as part of the ASCENT Center of Excellence [101]. Under Project 42, The Pennsylvania State University is developing improved sonic boom propagation algorithms that relax prior horizontally stratified wind limitations and incorporate vertical winds [102], while Georgia Tech is systematically exploring enabling technologies and atmospheric variability impacts on Mach cut-off flight [103]. Under the same project, University of Washington is exploring laboratory measurements of Mach cut-off that leverage biomedical research and instrumentation by utilizing gel layers to simulate a horizontally stratified atmosphere [104].

3.4 Structural Modeling

Since people spend most of their time indoors, it is important to understand the indoor sonic boom exposure and variations expected across different structures. Field studies of the vibro-acoustic response of buildings and of diffraction around buildings have been conducted by NASA with military aircraft [105, 106, 107], and there are plans to supplement this work with measurements using a low-boom demonstration aircraft. However, these studies are limited to particular aircraft and select communities. To inform standards development, modeling is needed to quantify the expected variation in indoor sonic boom exposure within the same community, across different communities, and due to overflight of a variety of low-boom vehicles. This will aid in estimating the range and bias in subjective response that may be expected in communities due to changes in exposure from aircraft other than the LBFD aircraft and also differences in response in communities that are not overflowed during LBFD tests.

A model of structural response and interior acoustics was developed by Burdisso et al. [108, 109] using a transient modal interaction model and taking advantage of a diffraction model for exterior loading [110]. This model was modified by Klos to improve results at higher frequencies, at least up to 150 Hz, especially for partitions with only one sheathing surface, such as a floor [111]. Exercising the model has yielded indoor acoustics and vibration results that have been used to estimate exposure across notional communities [112] and to determine input parameters for subjective studies [113].

A more complex sonic boom transmission model was developed by Kim and Sparrow using a finite-element method with detailed partition models [114]. The detailed model agreed well with experimental data gathered by NASA, albeit at a high computational cost. Exterior pressure loading on buildings due to sonic booms was investigated by Cho [115] and Riegel [116], resulting in a hybrid model that combines a three-dimensional finite-difference time-domain (FDTD) model, including diffraction, for low frequencies with a high-frequency ray tracing model. In addition, Cho described a building spiking effect due to frequency-dependent diffraction and reflection that leads to amplification of the front and tail shocks [117].

More recent studies at NASA of diffraction of sonic booms around buildings in urban environments have led to the implementation of an efficient frequency-domain boundary-element method to predict the total surface pressure, including diffraction [118]. Removing the influence of incident and reflected images reveals the diffraction surface pressure for analysis. Preliminary results confirm that the significance of diffraction decreases with increasing frequency. Building surface pressures and sidewalk pressures have been computed for example urban layouts [119], with significantly less computational expense and a wider frequency range of applicability than previous methods [110, 120].

3.5 Cooperative International Sonic Boom Modeling Activities

The AIAA hosted its first Sonic Boom Prediction Workshop in January 2014 to assess the state of the art for predicting near field sonic boom signatures using CFD [121]. Nineteen participants took part in the prediction calculations for an axisymmetric body and a delta wing configuration using a variety of grids; an optional case was also included of a wind tunnel model with fuselage, wing, tail, flow-through nacelles, and blade sting. Results showed much less variation for the simple cases as compared to the optional full configuration, and areas for further work were identified, including configurations with lower loudness, propulsion effects, and standard grids.

This successful workshop led to the Second AIAA Sonic Boom Prediction Workshop, held in January 2017, which assessed the state of the art for predicting near field sonic boom signatures with CFD as well as propagation of near field signatures to the ground. With 18 participants overall representing five countries, the first day of this expanded workshop included near field calculations for a set of four configurations that were designed to produce similar signatures with a range of simulation complexity. These configurations included an axisymmetric equivalent area model, a simple wing-body configuration, an aircraft concept design with flow-through nacelle, and finally the same aircraft concept design with propulsion boundary conditions. With a predicted ground signature PL of approximately 78 dB, these configurations were considerably quieter than the cases from the first workshop. Analyses showed that variation in results increased with configuration complexity, and that variations were greatest in the aft portion of the signature [122]. The second day concentrated on comparisons of ground boom predictions for two shaped boom configurations and explored the effect of the atmosphere on the evolution of the shaped sonic booms. In addition to standard atmosphere cases, measured atmospheres with winds were included. Analyses showed that results tended to match well across participants for the undertrack case, but discrepancies increased for off-track angles, particularly near lateral cut-offs. Issues with atmospheric pressure interpolation schemes, wind conventions, and PL calculations were revealed and identified for further clarification in the future. Analyses showed that realistic atmospheric profiles have a significant impact on the propagated signatures, carpet ranges, and loudness metrics, and analyses with a set of loudness metrics identified differences in metric sensitivity to atmospheric properties [123].

4 Sonic Boom Measurement and Avionics Instrumentation

The anticipated regulatory process and community testing using the NASA LBFD aircraft will both require ground-based acoustic measurement devices. Measurement protocols and instrumentation needs have been identified by the international regulatory community and are under refinement with each sonic boom test. Instrumentation techniques are also needed to aid in estimating sonic boom exposure across the community during the LBFD testing. Pilot awareness of the extent of, and levels within, the sonic boom footprint will aid in flight planning and situational awareness, not only for LBFD but also for future commercial operations. Recent progress in developing these supporting technologies are described in this section.

4.1 Sonic Boom Avionics Development

NASA has invested in the development of a cockpit display (Figure 12) with the ability to provide to pilots real-time feedback on the sonic boom footprints, expected to occur based on the current aircraft state, for the purpose of controlling exposure [124]. The software is coupled with a rapid propagation version of PCBoom called CISBoomDA (Cockpit Interactive Sonic Boom Display

Avionics) with GIS display. In 2015 and 2016, this technology was successfully demonstrated in a PC-based system in the back seat of a NASA F-18, and it is slated for testing during upcoming SonicBAT measurements in 2017. Integration with commercial flight management software and inclusion of a predictive element for flight planning of future aircraft trajectories by Rockwell Collins and Honeywell is currently under development [31] in order to support low boom community overflight research. Enhancements are also being added to provide Mach cut-off information to the pilot.

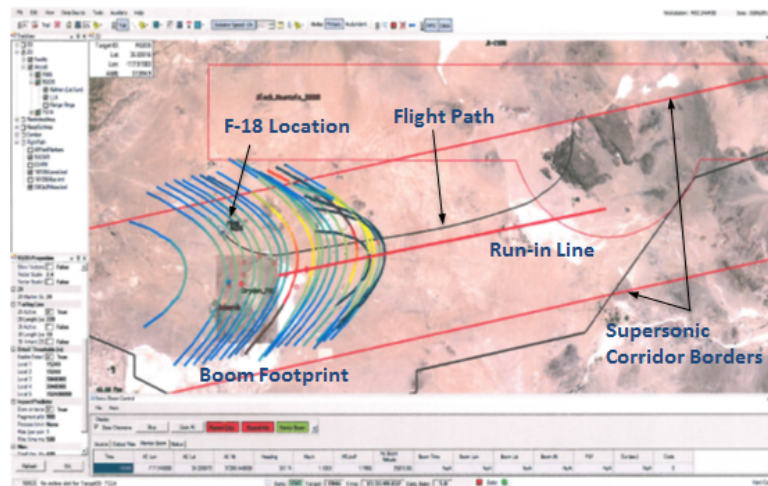


Fig. 12 Example screenshot of CISBoomDA program for providing pilots a display of real-time sonic boom footprints [NASA image].

4.2 Sonic Boom Measurements

The aircraft regulatory certification process will most likely rely on a blend of acoustic measurements and adjustments based on numerical predictions under reference day conditions. Development of the instrumentation hardware and measurement protocols is a necessary element to facilitate future civil supersonic overland flight. The upcoming experiments identified in this paper will help give a better understanding of the challenges of measuring sonic booms in realistic atmospheres, and will provide opportunities for fine-tuning potential sonic boom measurement and certification procedures.

A study has been conducted to estimate the number of microphones that would be required in an array to measure with a high degree of confidence the sonic boom from a steady supersonic flyover [125]. Using undertrack measurements from six steady and level supersonic passes from the SCAMP experiment, an analysis of 90% confidence intervals for different subsets of microphones revealed that between five and ten microphones would be needed for a 90% confidence interval of 2 to 4 dB. Inclusion of additional microphones did not significantly improve the confidence intervals. This conclusion was similar for different methods of selecting microphone measurements from the array and for analyses with five different noise metrics, including PL. Although there are limitations to the applicability of the data due to the small amount of data, linear array layout, and N-wave boom characteristics, this kind of analysis could be extended with other datasets to

help inform the development of accurate measurement procedures for en route noise certification of supersonic aircraft.

Dose-response testing using the NASA low-boom flight demonstration aircraft will also require ground-based acoustic measurement devices coupled with numerical predictions to estimate sonic boom exposure across the community. The measurement systems need to capture the sonic boom waveform with enough fidelity, across the full range of frequencies from 1 Hz to approximately 10 kHz, to allow for assessing noise metrics over a large sonic boom footprint area that is predicted to be around 48 km wide. Remotely triggered Sonic Boom Unattended Data Acquisition Systems (SBUDAS) were developed by Gulfstream [126] and employed during the NASA WSPR program. The SBUDAS consist of a GPS time-synchronized digital data acquisition system built upon the National Instruments CompactRIO (cRIO) with network nodes, packaged in an environmental enclosure and capable of being deployed for extended periods of time. During the WSPR program the SBUDAS were operated using a manual trigger to capture planned low-amplitude booms while being left in auto-trigger mode with an amplitude threshold set at other times. Due to the small overpressures of low-amplitude booms, normal background noise in communities can cause false triggers and fill recording buffers, so an improved automated boom finder (ABF) methodology was developed. This algorithm leverages the triggering mechanism found in the NASA Boom Amplitude and Shape Sensor (BASS) recording system [13], coupled with a 4-10 Hz band pass filter to capture the dominant frequency range of most sonic booms as a two-step process. During the NASA WSPRRR program the SBUDAS systems were upgraded to include cellular modems to facilitate communications across a wide area and for near real-time feedback to allow adjustment of the flight plan for close agreement to target exposure/noise dosage levels for each day of flight testing.

5 Community Subjective Response Research

In support of the anticipated international regulatory activities for civil supersonic overland flight, a body of scientific data that correlates low boom noise with community subjective response will be needed. Existing knowledge of the impact of sonic booms on the community is based primarily on experiments conducted during the 1960s-1970s (Concorde and the U.S. Supersonic Transport (SST) Program) [127,128,129,130] and the 1990s (the NASA High Speed Research (HSR) Program) [131]. In the former work, it was concluded that high-amplitude sonic booms (Concorde sonic booms were approximately 2 psf) were clearly unacceptable to a large segment of the population. The resultant outcome is that civil supersonic overland flight has been prohibited in the United States since 1973 [14 CFR 91.817] and in Canada [Canadian Aviation Regulations SOR/96-433, 602.33], while the creation of sonic booms has been prohibited in Europe [Luftverkehrsordnung (LuftVO) 11a and 11b]. Prevention of an unacceptable situation for the public due to sonic booms from supersonic aircraft in commercial service has been adopted and continues to be reaffirmed by the ICAO [5]. Although much progress was made in modeling the sonic boom and understanding its effects during the HSR program, the boom levels achieved were still unacceptably loud.

Sonic boom subjective research is being conducted in order to provide data for the regulatory bodies. The research has included laboratory studies involving headphones and advanced simulator room testing with the ability to independently control vibration and rattle. This provides critical information about metric performance; however, ultimately subjective responses are needed from residents in their own homes. A number of “in situ” field tests have been conducted with supersonic aircraft and with people in their own homes in preparation for eventual testing

with a low-boom flight demonstration aircraft. These key areas of laboratory and simulator tests, vibration and rattle effects, and in situ testing, are described below.

5.1 Laboratory and Simulator Tests

Many studies have been conducted in laboratory sonic boom simulators to gain an understanding of the factors that contribute to human annoyance of sonic booms and how changes in the shape of the waveform affect annoyance (see Chapter 8 in Ref. [7]). A study on the effect of playback environment, using sonic booms recorded both outdoors and indoors, revealed that the listening environment was a significant factor in annoyance scores [132]. Indoor recordings presented in an indoor environment were found to be the most annoying.

Recent studies at NASA and JAXA have concentrated on human response in an indoor environment, where people spend most of their time and where annoyance tends to increase despite the decrease in signal energy as the boom transmits indoors. The boom may be accompanied by secondary contact-induced rattle noises and vibration, and these effects have been cited numerous times as potential causes for the increase in indoor annoyance. Indoor studies at NASA have been conducted over headphones as well as in the Interior Effects Room (IER) [78], an indoor sonic boom simulator that uses arrays of loudspeakers to simulate the sonic boom sounds by surrounding two outside walls of a structure made with typical American residential components and methods; the booms transmit through the structure to the inside, where test subjects are seated in a living room environment.

The IER studies have investigated the components of the waveform that affect annoyance and looked at the performance of different noise metrics in describing the annoyance [133,134]. The effect of aircraft size on annoyance to the resulting sonic booms has also been studied and found to be insignificant for booms of approximately the same PL presented alone without secondary indoor effects [135,4]. Thus the metric PL adequately accounts for the effect of aircraft size. This result adds credence to the plans of using a sub-scale demonstration aircraft to study community response to sonic booms by ensuring relevance between the sub-scale aircraft and potential future larger airliners.

Another study using Gulfstream's SASS II sonic boom simulator highlighted the challenges associated with human subject testing, including bias due to presenting participants with boom sounds over a wide dynamic range [136]. To minimize risk, having a large pool of subjects was recommended when deriving a relationship between expected low annoyance and noise of a low-boom aircraft in community studies. Mixed-fidelity noise measurement instrumentation was also recommended to reduce costs associated with measuring the sonic boom exposure across a community.

5.2 Vibration and Rattle Effects

Additional factors such as rattle and vibration effects have been studied separately, and a "penalty" has been derived that quantifies the increase in boom level that would cause the same increase in annoyance as that caused by these secondary factors. Preliminary estimates of rattle penalties range from 3 to 9 dB depending on the rattle sound, with rattles emanating from structural components of a house being more annoying than rattles from smaller objects [137,138,139]. In order to inform subjective investigations on vibration penalties, a numerical study was conducted to predict vibration levels in a notional community, with a wide range of structures and construction details [113]. From the resulting predicted distribution of vibration levels, the 84th and 99th percentile vibration levels were chosen to represent some of the higher

levels that might be expected and were then used in a subjective study. Vibration penalties found for the 84th and 99th percentile vibration levels varied from 0 to 8 dB for a selection of booms [140]; this is consistent with an earlier study that derived a vibration penalty of approximately 5 dB for a smaller range of vibration levels [141, 142]. The most recent IER study has returned to the question of aircraft size, with the addition of rattle sounds. These rattles were measured beforehand in the IER with sonic boom excitation of the structure with different windows installed and with suncatchers attached to the windows. This is the first time the rattle sound and playback level has been matched to the specific boom excitations, which varied in length, spectral content, and level. Preliminary results indicate rattle penalties on the same order as the previous studies. Future studies will attempt to generalize results to a variety of houses expected in communities.

JAXA has conducted several studies in their sonic boom simulator, using both an outdoor simulation configuration and an indoor simulation configuration by the installation of an interior window sash [143]. The small booth contains eight low-frequency and eight mid-frequency loudspeakers mounted on two walls to simulate the sonic boom sounds. As part of this research, JAXA has evaluated the performance of several different noise metrics for describing human perception of the sonic boom sounds. While some metrics such as maximum pressure, GSEL, and unweighted SEL did not perform well, most of the loudness metrics and other weighted SEL metrics were able to describe human loudness judgments in both indoor and outdoor settings.

An evaluation of noise metrics for describing human perception of sonic booms was performed in 2015 using a set of NASA and JAXA laboratory studies of indoor and outdoor human response [144]. Waveforms ranged from traditional N-waves with various shock shapes and rise times to predicted waveforms from designs of low-boom aircraft for a variety of aircraft sizes. From the initial 25 metrics considered, eight metrics were suggested for further study. A follow-on study was performed by NASA to include more laboratory study results, incorporating annoyance studies with secondary rattle and vibration effects [145]. This study followed a multiple-criteria decision process of a Pareto analysis paired with an analytic hierarchy process to more objectively evaluate the metric performance across the different experiments. This study resulted in a smaller set of five metrics: Perceived Level (PL), B-, D-, and E-weighted Sound Exposure Levels (BSEL, DSEL, and ESEL), and a hybrid metric model called the Indoor Sonic Boom Annoyance Predictor (ISBAP). The ISBAP metric was derived from earlier studies and includes a “heaviness” factor of low-frequency energy; the empirically-derived relationship is given as $ISBAP = PL + 0.4201(CSEL - ASEL)$ [4].

5.3 In Situ Testing

Sonic boom community response studies are a key to establishing new international rules for supersonic overland flight and sonic boom aircraft certification. To accomplish this, a low-boom flight demonstration aircraft is needed. In preparation for eventual community response testing a number of tests have been designed and conducted to research experimental methodologies including noise exposure design, sonic boom data acquisition, subjective data collection, and data analysis. One effort was conducted by NASA Langley Research Center, NASA Dryden Flight Research Center, and two contractor teams led by Wyle [146] and Fidell Associates [147].

The NASA-sponsored Waveform and Sonic boom Perception and Response (WSPR) Program conducted in California in November 2011 was designed to test and demonstrate the applicability and effectiveness of techniques to gather data relating human subjective response to multiple low-amplitude sonic booms [146, 148]. It was a practice session for future wider scale testing of communities, eventually using a purpose-built low-boom demonstration aircraft. The WSPR

program addressed the following: design and development of an experimental design to expose people to low-amplitude sonic booms; development and implementation of methods for collecting acoustical measures of the sonic booms in the neighborhoods where people live; design and administration of social surveys to measure people's reactions to sonic booms; and assessment of the effectiveness of various elements of the experimental design and execution to inform future, wider-scale testing. The community was exposed to low-amplitude sonic booms created by NASA F-18 aircraft executing the low-boom dive maneuver [42], in addition to higher-amplitude booms created by normal Edwards Air Force Base operations. A power interpolation technique was developed to predict loudness metrics at the participant households based on a sparsely distributed microphone array.

The low-boom dive maneuver [42] involves executing a 53° inverted dive where the aircraft accelerates supersonically to Mach 1.1 and then pulls out above 30,000 ft. Approximately 20 nautical miles downrange from the aircraft dive location, very low overpressure booms of 0.1 psf are created, while a loud focal zone is created near the dive location. In the footprint area between the focal zone and the downrange cut-off, the dive maneuver produces egg- and crescent-shaped sonic boom contour isopemps. Due to the complex maneuver, two sonic boom signatures impact most observer locations. The influence of the local meteorological conditions has a striking effect on the sonic boom footprints, including the shape and location of the focal zone and the extent of the low-amplitude sonic boom carpet region.

The researchers of the WSPR project conducted an assessment of the suitability of using PCBoom in conjunction with the low-boom dive maneuver for the purposes of designing future sonic boom testing over large communities. A follow-on NASA risk reduction test denoted WSPR Risk Reduction (WSPRRR) that utilizes this approach is currently under way, and a community dose-response test is planned in the United States in late 2018 with a team of researchers from industry, academia, and government organizations.

As part of the site selection process for the NASA WSPRRR 2018 test, a statistical sonic boom analysis of the F-18 low-boom dive maneuver has been conducted [149] using PCBoom6 [58]. This analysis utilizes 10 years of historical seasonal meteorological data at potential test sites to ascertain the geometric extent of low-amplitude boom levels. This analysis helps to determine a flight path that minimizes the possibility of exposing the public to focused and high-amplitude sonic booms, while maximizing the probability that usable portions of the footprint coincide with the intended community testing area.

Figure 13 illustrates the PCBoom composite sonic boom overpressure predictions (psf) using historical upper air data (August-November, 2006-2016) at a coastal location in the United States with an F-18 low-boom dive trajectory, generated by computing the maximum predicted overpressure in each 610 m by 610 m (2000 ft) ground cell across all meteorological cases. The relationship between the maximum cell overpressure and the probability of the dive delivering a nonzero cell pressure was determined. The probability of the F-18 delivering a nonzero pressure in a given cell (Figure 14) was determined in order to gauge in which geometric areas participants should be solicited for dose-response testing, so as to maximize opportunity for garnering subjective response data while balancing sonic boom exposure levels. The greyed out region in Figure 14 represents those areas for which an overpressure of 0.75 psf or larger occurs 50% of the time and, therefore, must be placed over water or in uninhabited areas.

An additional NASA risk reduction effort is investigating random sampling methods for identifying the noise survey participants in a community, as well as interview methods for administering the noise survey in order to maximize response rates [150]. Recognizing the need for prompt single-event responses to the sonic booms, Fidell et al. propose investigating and comparing response rates for computer-assisted telephone interviewing with a live interviewer and interactive voice response interviewing led by a computer. Finally, an ADS-B-based, Internet-enabled flight

Composite sonic boom overpressures (2000 × 2000 ft cells)

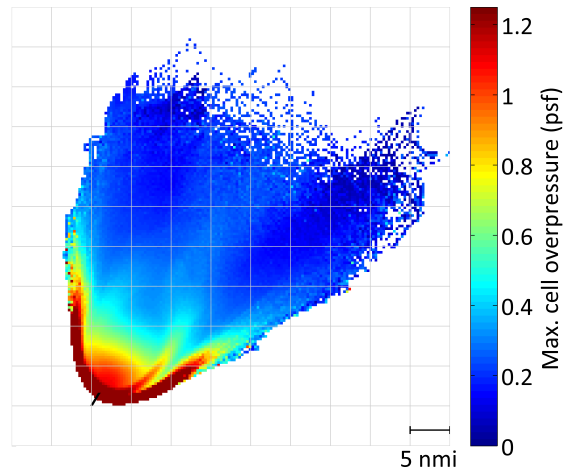


Fig. 13 PCBoom composite sonic boom overpressure predictions for an F-18 low-boom dive trajectory with historical upper air data from August to November 2006-2016 [149].

Probability of non-zero cell overpressure (2000 × 2000 ft cells)

With both color contours and contour lines (in white) representing probability of non-zero cell pressure, a sharp gradient from 80% to 20% is evident.

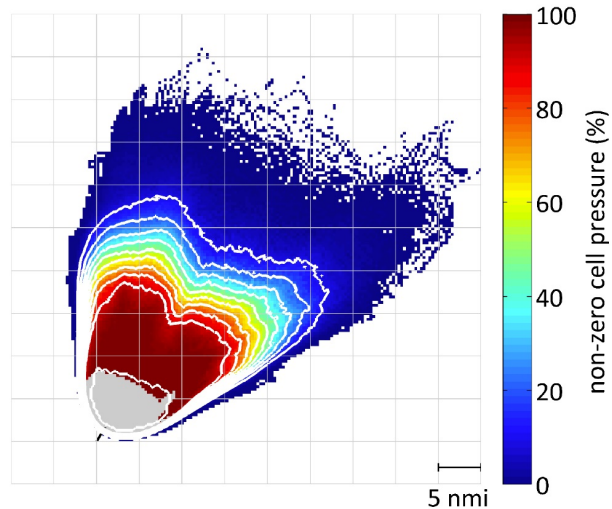


Fig. 14 Probability of nonzero cell overpressures for F-18 low-boom dive trajectory with historical upper air data from August to November 2006-2016 [149].

tracking system is being developed to trigger the interviews based on aircraft position to help address some of the challenges associated with collecting prompt responses to sonic boom events.

6 Sonic Boom Effects on Animals

There have not been any recent published studies on the effects of low booms on animals. From the many past studies reported on the effects of high-amplitude N-wave sonic booms on land and sea animals, the majority conclude that any effect is minimal. A review of these studies on farm animals, wildlife, and marine mammals is given by Maglieri et al. [7, pp. 376-382]. Given that the shaped low booms predicted for the proposed new generation of supersonic aircraft will be much quieter than conventional N-waves, it is expected that there should be minimal to no effect on animals.

7 Conclusions

Recent advances in sonic boom understanding, modeling, and enhanced design capabilities using modern computational techniques have served to rapidly advance technologies toward the possibility of future civil supersonic overland flight. Metrics to measure booms that are reflective of community acceptance have been developed and will continue to be tested with the planned NASA low boom flight demonstration aircraft. There are several active research programs addressing atmospheric propagation including the effects of turbulence, lateral cut-off, and Mach-cutoff flight. Computational modeling of sonic boom propagation under a variety of meteorological conditions has greatly improved our confidence in sonic boom tool suites, though work remains to address aspects of the sonic boom footprint in the region of lateral and Mach cut-off, and in the region due to secondary booms. Investigations of the complex interactions between low-boom shaped signatures and structures have contributed to our understanding of the indoor noise environment from sonic booms across a variety of structure types. These investigations have enabled subjective dose-response research in laboratory settings.

Collaborative sonic boom research efforts in Japan, the European Union, and Russia, along with the United States leadership in the development of a low boom flight demonstration aircraft will yield additional opportunities for providing confidence in supersonic aircraft technologies and data gathering necessary for international regulatory civil supersonic aviation decision making.

While the questions posed in the Introduction have not yet been fully answered, active and continuing sonic boom research over the last decade has not revealed any major technical impediments for low-boom flight and human subjective acceptability, so the outlook for supersonic overland commercial flight in the future remains promising.

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