Project 057 Support for Supersonic Aircraft En-Route Noise Efforts in ICAO CAEP

The Pennsylvania State University

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- P.I.: Professor Victor W. Sparrow
- FAA Award Number: 13-C-AJFE-PSU Amendments 55, 77, 86, 100, 115, 117, 122, and 127
- Period of Performance: February 5, 2020, to September 14, 2026
- Tasks:
  1. Procedures for sonic boom certification
  2. Assessing secondary sonic boom propagation
  3. Investigating seismic networks for measuring sonic booms

Project Funding Level

This project focuses on multiple tasks at Penn State and its subcontractors Farmingdale State University and RAC Consulting, LLC. The Federal Aviation Administration (FAA) funding to Penn State in 2025 was $400,000. Matching funds are expected to meet cost sharing on all tasks. In 2024, the FAA granted Penn State's request for reduced cost sharing to 25% of the total project costs. In-kind contributions have been pledged by Boom Supersonic ($120,000), Exosonic ($220,000 in 2024; however, Exosonic is ceasing operations, so this cost share is uncertain at the time of this writing), Gulfstream ($250,000), and Pivotal Supersonics (previously known as Global SST; $75,000).

Task 3, investigating seismic networks, is fully funded by the FAA in 2025. It should be noted that this task was initiated in 2023 and 2024 by the Project P.I. using funds from the United Technologies Corporation Professorship within the Penn State College of Engineering. Additionally, Task 3 start up support in previous years is gratefully acknowledged.

Investigation Team

The Pennsylvania State University

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Joshua Kapcsos, (Acoustics graduate research assistant), Task 1
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Gulfstream (industrial partner)
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Project Overview

Passenger aircraft development is on the verge of a true revolution. Companies such as Boom Supersonic, Gulfstream Aerospace Corporation, Lockheed Martin, Pivotal Supersonics, and others are reaching the point at which they can build and deliver to users aircraft capable of flying supersonically in an environmentally responsible way. This development will allow for decreased air transportation travel times, to the great benefit of society.

New supersonic aircraft must be certified as being sufficiently quiet to not excessively disturb the public. Preparation for such a certification process has been ongoing for several years in the FAA Office of Environment and Energy (AEE). Working with its international partners in the International Civil Aviation Organizations (ICAO)'s Committee for Aviation Environmental Protection (CAEP), the FAA has been laying the groundwork for certification standards. The FAA's efforts have been supported by both universities and other governmental agencies. Specifically, Penn State has supported the FAA/AEE through Projects 008 and 024 in the PARTNER Center of Excellence (COE) and more recently in ASCENT Projects 007, 041, and 042. Summaries of these research efforts can be found on the website ascent.aero. To date, a group of six candidate metrics for en route supersonic certification have been agreed upon in the CAEP's Working Group 1 (WG1) (Noise Technical) Supersonic Task Group (SSTG). Multiple schemes for certification have been generated. Several schemes have been eliminated from further consideration, and others are currently being evaluated for possible implementation. Procedures have been proposed for acquiring and processing ground measurement of the en route supersonic noise, but all possibilities remain under discussion. The extent to which atmospheric conditions will affect the measurements, and the requirements and roles of numerical simulations of the noise propagating from the aircraft to the ground are being considered. One particularly challenging aspect is the influence of the atmosphere in distorting the acoustic pressure signatures, owing to atmospheric turbulence, and the subsequent effects on the metric values. These gaps are only several of those that must be filled.

All these topics are being worked on, in a stepwise manner, in the FAA and in WG1's SSTG. Efforts in the completed ASCENT Project 041 have been aimed at supporting the FAA with technical expertise in the development of the certification procedures and gaining an initial understanding of secondary sonic booms. Secondary sonic booms, also known as over-the-top sonic booms, are the sound energy that travels upward at heights above the aircraft cruise altitude and lands at distant locations. Secondary sonic booms are the reason why the Concorde[1] was requested to transition from supersonic to subsonic speeds at substantial distances before entering the continental United States airspace. ASCENT Project 041 ended in early 2021, and ASCENT Project 057 is now in its sixth year. However, much work remains to be done, and efforts lasting several more years will be required to advance certification standards for supersonic aircraft.

In 2026 and beyond, continued support for supersonic aircraft noise efforts will be necessary for the FAA and its international partners to fill technical solution gaps and continue progressing toward certification procedures. Although other universities and industries will continue their focus on aircraft design and landing and takeoff studies, continued work on en route supersonic noise issues will be essential, because these issues remain the greatest barrier to the use of environmentally responsible supersonic aircraft. ASCENT Project 057 will support the ongoing activities in ICAO CAEP and their WG1 (Technical Noise), with a focus on establishing supersonic aircraft en route procedures and metrics for noise certification standards, and to support the interface with the ICAO Air Navigation Commission to address related noise issues.

In the 2020 through 2026 project period, the emphasis will be on continuing the research support for supersonic aircraft en route procedures, including the utilization of an agreed-upon reference-day atmosphere, the establishment of techniques for incorporating measurement data and simulations into a draft certification procedure, and the consideration

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[1] The Concorde was a specifically designed aircraft for supersonic flight.

of off-design flight speed sonic booms, such as focus booms and acceleration booms. Support will also be provided for a more comprehensive analysis of the National Aeronautics and Space Administration (NASA) SonicBAT dataset and efforts in developing methods to remove the effects of atmospheric turbulence on measured acoustic pressure waveforms to support certification. The research in 2020 through 2026 will also need to consolidate and process the results of research from previous years on the topic of secondary sonic booms as a potential noise issue for the initial supersonic airplanes. This material will be of particular interest to ICAO's Air Navigation Commission because it could affect the operation of supersonic aircraft in the near term.

Task 1 – Procedures for Sonic Boom Certification

The Pennsylvania State University
RAC Consulting, LLC

Objectives

ASCENT Project 057 is a transition from ASCENT Project 041, *Identification of Noise Acceptance Onset for Noise Certification Standards of Supersonic Airplanes.* As national aviation authorities move toward developing noise certification standards for low-boom supersonic airplanes, several research gaps exist in areas including signature fidelity, metrics, metrics sensitivity to real-world atmospheric effects, and adjustments for reference conditions. The objective of Task 1 is to support the FAA in the development of technical standards for civil supersonic aircraft under the ICAO CAEP. This effort provides the FAA with technical noise expertise regarding the development of noise certification standards for future civil supersonic passenger aircraft, primarily in the area of en route noise (sonic boom) minimization and/or abatement.

Task 1 in ASCENT Project 057 focuses on research initiatives necessary to develop an overland supersonic en route noise certification standard. The objective is to improve the turbulence model in nonlinear propagation code KZKFourier by introducing atmospheric profiling and more realistic buoyancy- and shear-induced vector turbulence models. Additional work focuses on providing direct research support for ICAO/CAEP/WG1's SSTG and Procedures subgroup (PrSG) meetings and discussions.

Research Approach

Background

The KZKFourier propagation code is an augmentation of the Burgers equation into a Khokhlov–Zabolotskaya–Kuznetsov (KZK) propagation equation to include nonlinearity, diffraction, and absorption in directional sound beams, to simulate wind and temperature fluctuation effects of the atmospheric boundary layer (ABL), according to the Ostashev and Wilson (2015) model. During the 2019–2020 academic year, PCBoom 6.7.1.1 and KZKFourier were used above and within the atmospheric boundary layer, respectively, to simulate turbulence effects of atmospheric boundary layer heights of 268.2, 411.4, and 1026.7 m, corresponding to SonicBAT Flight 5 conditions. Information regarding this endeavor appears in the 2020 report for ASCENT Project 057. After propagating shaped boom signatures through 10 randomly generated atmospheres, the data were shared with the WG1/SSTG/PrSG, in which zero-padding and spiking artifacts were discovered near the beginnings and ends of certain ground signatures; the plots shown in the 2020 report did not span the entire retarded time domain of the ground waveform data. These artifacts were corrected in the 2020–2021 academic year, as described in the 2021 report for ASCENT Project 057. In the 2021–2022 academic year, Penn State expanded the shaped boom database to 20 realizations at NASA's request, conducted a parameter check on KZKFourier for boundary layer thicknesses, freezing temperatures, and turbulence parameters, conducted a grid refinement study on KZKFourier, and initiated a reference-day crosscheck with international members of the CAEP's WG1 (Noise Technical); these milestones are described in the 2022 report for ASCENT Project 057. The 2023 report for ASCENT Project 057 reviews an extension of the reference-day crosscheck to evaluate participant noise metrics, an investigation of the numerical interpolation methods of the KZKFourier solution, and the introduction of atmospheric profiling in KZKFourier, in which humidity was profiled in the molecular relaxation module for the first time. The 2024 report for ASCENT Project 057 highlights the initial research into introducing a ground-blocking methodology into KZKFourier, which was fully implemented in 2025.

It is important to include the effects of a realistic atmospheric profile during supersonic aircraft noise simulation. Atmospheric variables such as humidity, pressure, density, and temperature realistically vary by altitude. NASA requested Penn State investigate improving the atmospheric turbulence model in KZKFourier, which models the primary supersonic noise carpet with atmospheric turbulence included. The two types of vector turbulence modeled in KZKFourier are shear-induced vector turbulence and buoyancy-induced vector turbulence, and as height-dependent ground blocking affects buoyancy, improving the modeling of both types of vector turbulence were the focus of the current project period.

Buoyancy-Induced Vector Turbulence Improvement

The original released version of KZKFourier does not consider the effect of the ground on the turbulent eddies in the atmospheric boundary layer; in reality, the proximity of the eddies to the ground affects their shape, as an eddy cannot penetrate the ground. While KZKFourier considers scalar (temperature) and both shear- and buoyancy-induced vector (wind) turbulence, height-dependent ground blocking affects only the buoyancy-induced vector turbulence. At the 186th meeting of the Acoustical Society of America in May 2024, Dr. D. Keith Wilson presented an equation (Wilson et al., 2024) to implement ground blocking by applying natural exponential factors to a two-dimensional cross spectrum (ϕ_{33}) between propagation heights, z_1 and z_2, and wavenumbers, κ_1 and κ_2 as follows:

$$\hat{\phi}_{33} = (\kappa_1, \kappa_2; z_1, z_2) = \phi_{33}(\kappa_1, \kappa_2; z_2 - z_1) - \phi_{33}^{*}(\kappa_1, \kappa_2; z_1)e^{-\kappa_\perp z_2} - \phi_{33}(\kappa_1, \kappa_2; z_2)e^{-\kappa_\perp z_1} + \phi_{33}(\kappa_1, \kappa_2; 0)e^{-\kappa_\perp (z_1 + z_2)} \qquad \text{(Eq. 1)}$$

Because KZKFourier uses a three-dimensional (3D) turbulence spectrum (E) as prescribed in *Acoustics in Moving Inhomogeneous Media* (Ostashev & Wilson, 2015) and not a two-dimensional (2D) cross spectrum as Wilson's ground blocking method requires, KZKFourier has now been modified to conciliate with the above exponential factors. Cotté and Blanc-Benon (2007) refer to a doctoral dissertation by Chevret (1994) that suggests the conversion factor from a 3D to 2D spectrum is $2\pi\kappa$. As shown in Figure 1, this conversion factor results in a spectrum that is similar to Wilson's 2D cross spectrum and factor of $4\pi\kappa^4/(\kappa_1^2 + \kappa_2^2)$ that returns E from a cross spectrum. Penn State has consequently used these conversion factors to modify the KZKFourier spectrum and implement the ground-blocking methodology in the C++ code.

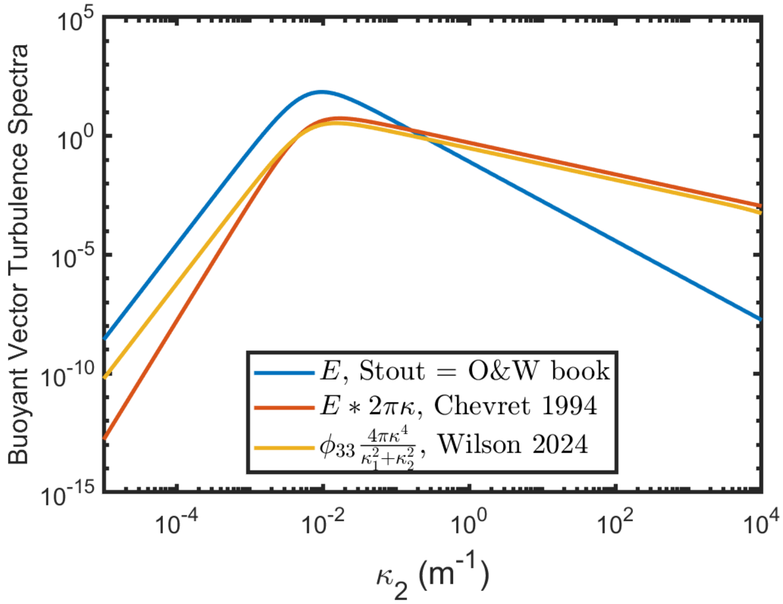

Figure 1. Buoyant vector turbulence spectra as it appears in three-dimensional E in KZKFourier, as multiplied by Chevret conversion factor to two-dimensional (2D), and as compared to a 2D cross spectrum ϕ_{33}.

PCBoom was used to propagate a C609 shaped boom, an early model of the NASA X-59 demonstrator, from a cruise altitude of 54 kilofeet to the top of the ABL, and the results were then fed into KZKFourier with and without ground blocking. After propagating the C609 shaped boom in KZKFourier through 1026.7 m and 268.224 m ABL heights with SonicBAT Flight 5 turbulence conditions, subtle differences were found in ground waveform distribution, but there was no difference to a hundredth of a decibel when comparing the ground-blocked results to the original unblocked results in average Perceived Level (PLdB) or Indoor Sonic Boom Annoyance Predictor (ISBAP) sound metrics. This may be due in part to the reliance of these metrics on overall waveform shape, which did not drastically change with the inclusion of ground blocking. Additionally, at low wavenumbers, shear turbulence contributes to part of the total vector spectra affected by ground blocking, so ground blocking may be made insignificant by the shear vector turbulence effects during the addition of the buoyant and shear spectra for a total vector turbulence spectrum. Ultimately, ground blocking, which is greatest near the surface, affects only a very small portion of this scenario's total propagation from 54 kilofeet. These results were presented at NOISE-CON 2025 in Stowe, Vermont, and were subsequently published in the *Noise Control Engineering Journal* paper "Developments on ground blocking implementation in turbulence tool for sonic boom propagation" (Kapcsos & Sparrow, 2025).

Shear-Induced Vector Turbulence Improvement

While investigating the ground blocking implementation of buoyancy-induced vector turbulence, Dr. D. Keith Wilson brought to Penn State's attention that the original simplified distribution of shear-induced vector turbulence in KZKFourier that grows with increasing height is not realistic. To rectify this, KZKFourier needs to demarcate different regions of turbulence within the atmospheric boundary layer. Particularly, the surface layer needs to be considered, defined as the lower tenth of the ABL, which comes from the Monin-Obukhov length where buoyant production of turbulence meets shear production of turbulence; that is, with respect to vector turbulence, shear should dominate within the surface layer, and buoyancy should dominate above it. KZKFourier uses turbulent length scales based on Monin-Obukhov Similarity Theory (MOST), so the changes needed to make the surface layer more realistic can be applied to the code. After first trying a simple exponential decay of the shear spectrum itself above the surface layer as was presented in the Spring 2025 Noise and Operations Meeting, Penn State began to investigate the physical behavior of the parameters that determine the shear spectrum. The meteorological turbulence value that prescribes the variance of shear-induced vector turbulence σ_s is friction velocity u_* as $\sigma_s^2 = 3.0u_*^2$. Friction velocity is constant in the original version of KZKFourier, which is not realistic, allowing shear to grow with increasing height in the ABL and preventing buoyancy from dominating above the surface layer. More realistically, Garrat (1992) defines surface friction velocity u_{*_0} as

$$u_{*_0}^2 = -(\overline{u'w'})_0 \qquad \text{(Eq. 2)}$$

Here, mean field velocity components $\bar{u}$ and $\bar{w}$ are in the x and vertical directions, respectively, and the covariance $\overline{u'w'}$ is related to the turbulent flux of momentum. According to Wyngaard (2010), "$\overline{uw}$ decreases linearly to zero at the ABL top" in the convective boundary layer. The behavior of u_* should, therefore, be the square root of a linear decrease to zero with increasing height to the top of the ABL.

As seen in the revision of the shear spectrum in Figure 2, applying the square root of a linear decay with increasing height to friction velocity u_* in KZKFourier results in the eventual decay to zero of the shear turbulence spectrum at the top of the ABL, as the decay of u_* with increasing height eventually counteracts the growth of the shear length scale. For a C609 shaped boom in KZKFourier, less overall shear turbulence generally results in slightly increased average sound metrics, as less overall shear turbulence occurs with decayed friction velocity, smaller ABL heights, and lower turbulence strength. In the case of SonicBAT Flight 5 turbulence conditions and a 1026.7 m ABL, the average metrics increased on the order of approx. a tenth of a decibel when friction velocity decay was included in the code. However, large ABL heights with high turbulence can result in slightly decreased average sound metrics when friction velocity decay is included. The larger the ABL height and the stronger the shear turbulence strength, the more important it is to realistically decay friction velocity.

An additional work item in Task 1 is to more fully understand the role of background noise in potentially contaminating the recordings of en route supersonic signatures that will likely be one input to a certification procedure for supersonic flight. Those efforts regarding background noise processing are underway and will be reported upon in the next project period.

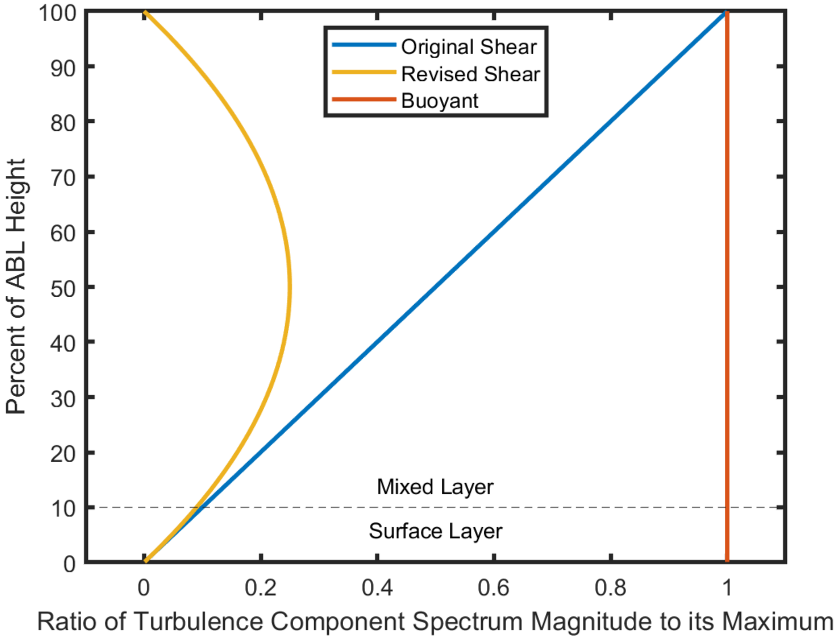

Figure 2. Shear vector turbulence spectra magnitude before and after applying the square root of a linear decay to friction velocity. Rather than growing with height, the revised shear vector turbulence begins to decay and reaches zero at the top of the atmospheric boundary layer.

Direct Support for CAEP/WG1 meetings

CAEP's WG1 on aircraft noise (technical) is responsible for aviation noise standards and recommended practices. ASCENT Project 057 research deliverables support WG1's SSTG tasks for supersonic en route/sonic boom noise standards. As described in the overview section, the SSTG's Procedures Subgroup concentrates on evaluating and implementing candidate noise certification schemes under consideration by WG1, supported by two smaller ad hoc groups. A Test Procedures ad hoc group (TPahg) is working to draft a set of proposed test procedures in concert with the Data Processing ad hoc group (DPahg) tasked to mature text for applying the candidate schemes. While much of the discussion and/or detailed results cannot be recorded due to the confidential nature of the ICAO-CAEP work, these paragraphs capture the essence of activities supporting the research.

During the current reporting period, teleconference coordination continued in the above-listed groups. RACC facilitated 10 virtual meetings in the fourth quarter of 2024, including a two-day virtual SSTG workshop in December 2024. Workshop topics centered around ongoing tasking and interface with the NASA Quesst project on its upcoming Phase 2 acoustic validation testing, a topic discussed over the most recent WG1 meetings. Data from Phase 2 are anticipated to be useful in evaluating the proposed test procedures and candidate noise certification schemes.

Early 2025 included a few teleconference meetings in preparation for the CAEP/13 meeting held in February. To date this year, RACC coordinated nearly 40 virtual meetings amongst the various groups in addition to supporting one virtual and two in-person WG1 meetings. During the second quarter 2025 (2Q25), in-person travel was accomplished to facilitate the SSTG session at WG1-1 in Aachen, Germany. The meeting included five technical papers covering research updates from the US, Europe, and Japan as well as progress reports and planning over the next 12 to 24 months. Research support into inflight and ground measurement techniques for low noise supersonic flight operations remains a priority topic, currently focused on the steady-state cruise flight condition as a starting point.

In addition to teleconference meetings, the third and fourth quarters included participation, both virtually and in person, for the WG1-2 and WG1-3 meetings to support SSTG sessions and facilitate ongoing discussion of key topics. Six technical papers were reviewed during the virtual WG1-2 and four papers at the in-person WG1-3 held in Phoenix, Arizona.

Unfortunately, NASA updates for WG1-3 were absent due to the United States government shutdown and employee furlough; however, a key event reported was the successful first flight of the X-59 research aircraft on October 28, 2025, just after the project period described here (see Figure 3). Another important note was the Japan Aerospace Exploration Agency (JAXA) Re-BooT flight research project update aimed at taking place in 2028. (ref. www.aero.jaxa.jp).

Figure 3. NASA X-59 First Flight (credit: www.lockheedmartin.com)

In addition to coordinating SSTG and its associated tasking, supersonic industry projects are monitored in support of ASCENT Project 057. During March 2024, Boom Supersonic conducted the first flight of its XB-1 flight test aircraft and continued to expand the flight envelope throughout the year (see Figure 4). In early 2025, the company conducted two supersonic test flights using the XB-1, one in January and the second in February before concluding its flight program and retiring the test aircraft. The flights consisted of multiple test points at flight speeds above Mach 1, demonstrating supersonic flight capability.

Figure 4. Boom Supersonic XB-1 (credit: www.boomsupersonic.com)

Milestones

- Made significant progress in improving the turbulence model in KZKFourier, beginning with the inclusion of uniform humidity profiling in its molecular relaxation module, a ground-blocking methodology to improve buoyancy-induced vector turbulence modeling, and currently a friction velocity decay to improve shear-induced vector turbulence modeling.

- Improved the realism of all vector turbulence components in KZKFourier, as the only types of vector turbulence in KZKFourier are buoyancy- and shear-induced.

Major Accomplishments

Considering the ground effects in buoyancy-induced vector turbulence spectra and surface layer behavior in shear-induced vector turbulence spectra will lead to more accurate sound metrics and annoyance predictions for NASA when they make comparisons to the data that will be obtained during the upcoming supersonic flights of their X-59 Quesst[1] aircraft.

Publications

Peer-Review Journal Publication

Kapcsos, J. L., & Sparrow, V. W. (2025). Developments on ground blocking implementation in turbulence tool for sonic boom propagation. *Noise Control Engineering Journal, 73(3)*, 407-412. https://doi.org/10.3397/1/377331

Outreach Efforts

None.

Awards

Joshua Kapcsos received a Student Paper Competition award for the paper presentation, “Developments on ground blocking implementation in turbulence tool for sonic boom propagation” given at the NOISE-CON 2025 meeting in Stowe, Vermont, on June 9, 2025.

Student Involvement

Joshua Kapcsos was the Penn State graduate research assistant who worked on ASCENT Project 057 during the 2024–2025 academic year.

Plans for Next Period

- Continue developing atmospheric profiling schemes in KZKFourier for other atmospheric quantities (e.g., temperature). The revised buoyancy- and shear-induced vector turbulence spectra will be used in KZKFourier simulations of various turbulence strengths and boundary layer heights to aid in the development of standards for civil supersonic aircraft.

Special Acknowledgment

Penn State would like to thank Dr. D. Keith Wilson for his recommendations on appropriate models of turbulence in the atmospheric boundary layer.

References

Bradley, K. A., Hobbs, C. M., Wilmer, C. B., Sparrow, V. W., Stout, T. A., Morgenstern, J. M., Underwood, K. H., Maglieri, D. J., Cowart, R. A., Collmar, M. T., Shen, H., & Blanc-Benon, P. (2020). *Sonic booms in atmospheric turbulence (SonicBAT): The influence of turbulence on shaped sonic booms* (NASA/CR–2020–220509). National Aeronautics and Space Administration, Armstrong Flight Research Center, Edwards, California.

Chevret, P. (1994). *Simulation numérique des effets de la turbulence sur la propagation du son dans l’atmosphère* (Publication No. 94-18) [Doctoral dissertation, L’école Centrale de Lyon]. Centre Acoustique. https://acoustique.ec-lyon.fr/publi/chevret_thesis.pdf

Cotté, B., & Blanc-Benon, P. (2007). Estimates of the relevant turbulent scales for acoustic propagation in an upward refracting atmosphere. *Acta Acustica United with Acustica, 93*, 944-958.

Davidson, P. A. (2015). *Turbulence: An Introduction for Scientists and Engineers* (2nd ed.). Oxford University Press, Oxford, United Kingdom.

Garrat, J. R. (1992). *The Atmospheric Boundary Layer*. Cambridge University Press, Cambridge, United Kingdom.

Kapcsos, J. L., & Sparrow, V. W. (2023). Progress update on inclusion of atmospheric profiling for sonic boom propagation through turbulence. *The Journal of the Acoustical Society of America*, *154*(4_supplement), A148.

Loubeau, A., Doebler, W., Wilson, S. R., Ballard, K., Coen, P. G., Naka, Y., Sparrow, V. W., Kapcsos, J. L., Page, J. A., Downs, R. S., Lemaire, S., & Liu, S. R. (2021). Developing certification procedures for quiet supersonic aircraft using shaped sonic boom predictions through atmospheric turbulence. *The Journal of the Acoustical Society of America, 149*(4_supplement), A102.

Maglieri, D. J., Bobbitt, P. J., Plotkin, K. J., Shepherd, K. P., Coen, P. G., & Richwine, D. M. (2014). *Sonic Boom: Six Decades of Research* (NASA/SP-2014-622). National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia.

Ostashev, V. E., & Wilson, D. K. (2015). *Acoustics in moving inhomogeneous media* (2nd ed.). CRC Press, Boca Raton, Florida.

Ostashev, V. E., Wilson, D. K., & Hart, C. R. (2023). Influence of ground blocking on the acoustic phase variance in a turbulent atmosphere. *The Journal of the Acoustical Society of America, 154*, 346-360.

Stout, T. (2018). *Simulation of n-wave and shaped supersonic signature turbulent variations* [Doctoral dissertation, Pennsylvania State University]. Pennsylvania State University. https://etda.libraries.psu.edu/catalog/15959tqs5346

Wilson, D. K., Ostashev, V. E., Hart, C. R., & Kamrath, M. J. (2024). Verifying turbulence models in the atmospheric boundary layer by acoustical means. *The Journal of the Acoustical Society of America, 155*(3_supplement), A200.

Wyngaard, J. C. (2010). *Turbulence in the Atmosphere.* Cambridge University Press, Cambridge, United Kingdom.

Task 2 – Assessing Secondary Sonic Boom Propagation

The Pennsylvania State University
Farmingdale State College, State University of New York

Research Approach

As described in previous project reports secondary sonic booms are those sound events which can occur when either: (1) [Type I] the upward traveling portion of a sonic boom bends back toward the ground and eventually reaches the ground or (2) [Type II] when the primary (downward) traveling sonic boom reflects from the surface and then refracts in the upper atmosphere and makes its way back to the ground a second time. Secondary sonic booms do not occur all the time, only when there is a strong upper atmospheric wind to aid the sound getting back to the ground, far in front of the aircraft. Because of the really long propagation paths, most of the high frequency energy dissipates due to atmospheric absorption. Therefore, if secondary sonic booms are heard, they sound like a low-frequency rumble, somewhat similar to the sound of distant thunder. Nevertheless, it is known that secondary sonic booms from Concorde can produce annoyance, as was reported by Rickley and Pierce (1980).

In previous work in ASCENT Project 057, secondary sonic booms were modeled from flights approaching the United States coastlines and around Edwards Air Force Base (EAFB) in Edwards, California. Using NASA's PCBoom program seems to work effectively for this modeling purpose, although the research team does not yet have any experimental evidence validating the PCBoom secondary boom predictions for amplitude and duration of the sounds. In previous studies the project team has investigated the reflection of the Type II ground-reflected secondary booms as well as the origin of the long-durations of secondary sonic booms which are on the order of 10-30 s. Each of these studies are pieces of the puzzle for us to more fully understand how secondary sonic booms are generated, propagated, and received by communities.

In the current project period, the research team focused on understanding the atmospheric conditions that can result in a Mach cutoff condition yielding secondary sonic booms. This condition is primarily dependent on Mach number and the atmospheric conditions below the aircraft. The team looked to see if these two conditions could be combined to produce both secondary sonic booms and Mach cut off.

As an initial case the team selected a previously modeled condition that resulted in secondary sonic booms. This was a steady flight at Mach 1.2 with a heading of 251 degrees approaching the eastern coastline. The aircraft altitude was 55,000 ft and the team started with a weather profile for New York City from August 2018 (see Figure 5). The lower atmospheric winds were then modified to determine if there could be a Mach cutoff condition as well.

The described atmospheric conditions resulted in secondary sonic booms and a Mach cut off condition with only very small changes to the original profile (see Figure 6). For this condition, the primary boom rays turns about 550 ft above the ground, so no primary/direct sonic boom is heard on the ground.

The team is now carrying out a parametric study to determine what are the conditions when Mach cutoff flight can create secondary sonic booms. The parameters to be varied include flight speed and altitude as well as the wind profiles. The plan is that the team's preliminary results will be discussed at the December 2025 joint meeting of the Acoustical Society of America and the Acoustical Society of Japan.

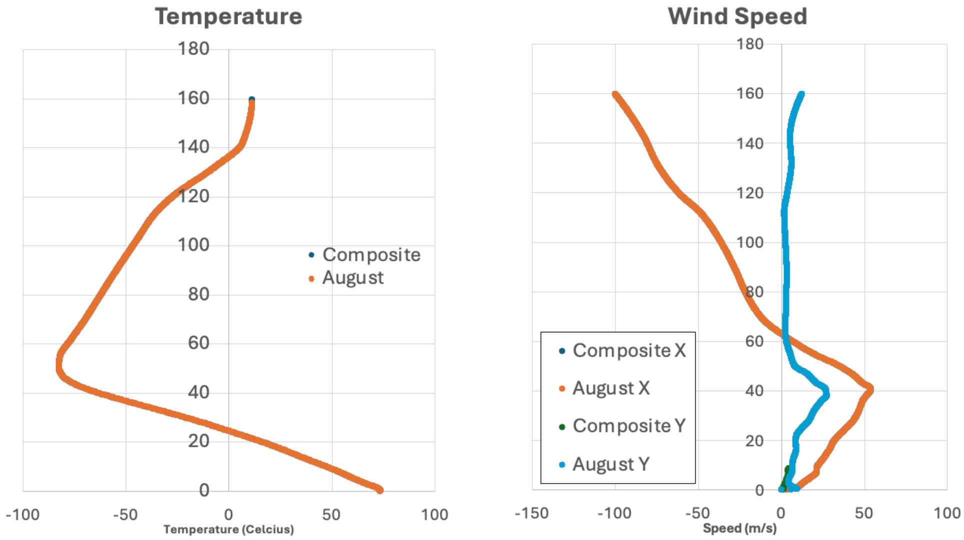

Figure 5. The atmospheric profiles result in both Mach cutoff and secondary sonic boom conditions compared to the unmodified August profiles.

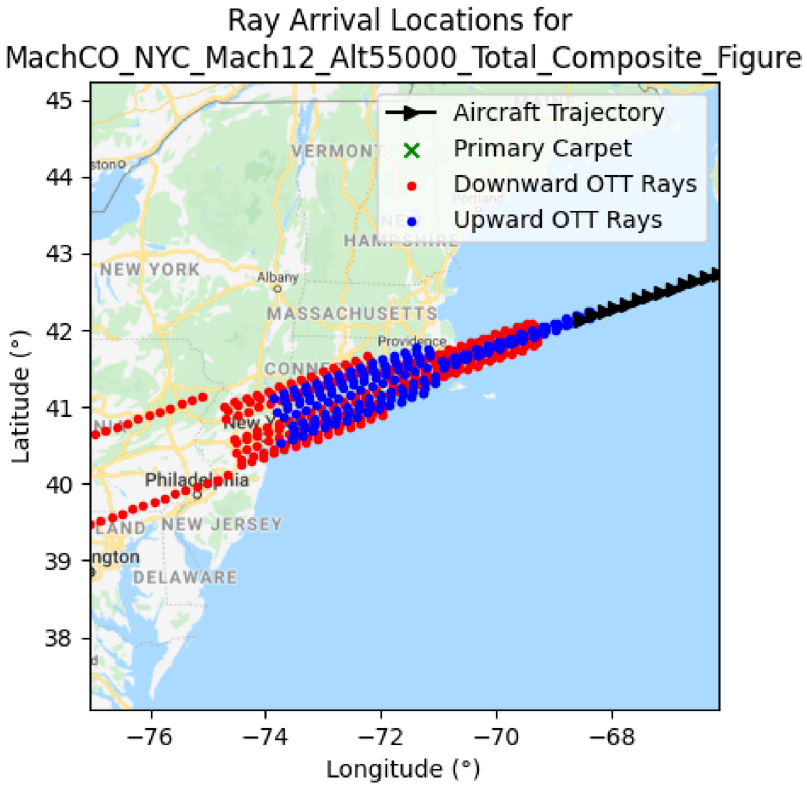

Figure 6. The resulting secondary sonic boom arrivals and no primary boom arrivals during an example Mach cutoff flight.

Milestone

N/A

Major Accomplishments

The project team has been shown that Mach cutoff flight can result in secondary sonic boom sounds, and our team believes that this is the first time that this has been demonstrated.

Publications

Conference Presentation

Sparrow, V. & Riegel, K. (2024, June 4-7). *Multipath interpretation of secondary sonic boom signatures* [Conference Presentation]. AIAA/CEAS Aeroacoustics Conference, Rome, Italy, AIAA-3187). https://doi.org/10.2514/6.2024-3187

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period

- Continue the work exploring the parameter space for the occurrence of secondary booms during Mach cutoff flight, and report upon in a peer-reviewed journal.
- Participate in measurements of the test flights of the X-59 Quesst aircraft. The team aims to better understand whether secondary sonic booms are produced by X-59.

References

Rickley, E. & Pierce, A. (1980). *Detection and assessment of secondary sonic booms in New England* (Report No. FAA-AEE-80-22). Defense Technical Aviation Center, Fort Belvoir, Virginia.

Sparrow, V., & Riegel, K. (2023, September 11-15). The role of topography for secondary sonic boom reflection. *Proceedings of the Forum Acusticum 2023 - 10th Convention of the European Acoustics Association, EAA 2023,* Torino, Italy, 2221-3767. https://appfa2023.silsystem.solutions/atti/000361.pdf

Sparrow, V., & Riegel, K. (2024, June 4-7). *Multipath interpretation of secondary sonic boom signatures* [Conference presentation]. 30th AIAA/CEAS Aeroacoustics Conference, Rome, Italy, AIAA-3187. https://doi.org/10.2514/6.2024-3187

Task 3 – Investigating seismic networks for measuring sonic booms

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Objective

The pressure signals from sonic booms, triggered by supersonic flights, will generate detectable ground motions along and across the land surface of the corresponding flight paths (Rickley & Pierce, 1980; Cates & Sturtevant, 2002). The long-range propagation of direct and indirect pressure wave signatures from the sonic booms is poorly understood due to the lack of precise sonic boom landing location predictions as well as better ground coverage of seismic stations which can detect the signals. The high-density seismic networks in southern California, which routinely detect sonic booms from supersonic flights (Cates & Sturtevant, 2002; Rathnayaka et al., 2023), provide a unique opportunity to study the areal extent of the boom signals and its' impact on U. S. population centers. In 2025, this work focused on investigating primary and secondary sonic boom signals recorded on seismic stations from four supersonic passes that occurred near EAFB, California, in 2005.

Research Approach

The sonic boom events used in this study were triggered on June 15, 2005, near EAFB, California, associated with the PARTNER (Partnership for AiR Transportation Noise and Emissions Reduction) Project 8 (LowBoom/NoBoom phase 1 project) field experiment (Sparrow, 2005). There were four supersonic passes, all of them were flown from east to west over EAFB at *M* = 1.3 or 1.4 at four different altitudes (9,753.6 m, 11,227.6 m, 12,192 m, and 13,716 m). The sonic booms were created by F-18 aircraft. The approximate event detection times correspond to 17 sonic boom events at a monitoring station (Latitude: 34.928, Longitude: -117.936) near EAFB (Table 1). The precise location and the time of boom initiations are not known. The sonic boom detection times, shown in Table 1, are from the PARTNER Project 8 annual report (Sparrow 2005).

Table 1. Summary of sonic booms detection time at the monitoring station, Edwards, California (Latitude: 34.928, Longitude: -117.936).

Boom ID	Pass Number	Mach Number (*M*)	Altitude (km)	Date	Event detection time (Coordinated Universal time-UTC)
1	1	1.3	9.7536	06/15/2005	13:13:37
2	1	1.4	11.228	06/15/2005	13:22:20*
3	1	1.4	12.192	06/15/2005	13:32:49
4	1	1.4	13.716	06/15/2005	13:41:42
5	2	1.3	9.7536	06/15/2005	13:49:08
6	2	1.4	11.228	06/15/2005	13:57:00*
7	2	1.4	12.192	06/15/2005	14:07:12
8	2	1.4	13.716	06/15/2005	14:17:51
9	2	1.4	11.228	06/15/2005	14:25:35
10	3	1.3	9.7536	06/15/2005	14:33:00
11	3	1.4	11.228	06/15/2005	14:40:20
12	3	1.4	12.192	06/15/2005	14:47:24
13	3	1.4	13.716	06/15/2005	14:57:00*
14	4	1.3	9.7536	06/15/2005	15:27:00
15	4	1.4	11.228	06/15/2005	15:37:00
16	4	1.4	12.192	06/15/2005	15:47:00
17	4	1.33	13.716	06/15/2005	15:54:00

*Detection time estimated based on seismic observations

Data and Methods

The seismic stations used in this study consist of 254 surface receivers which belong to the Northern California Seismic Network (NC), the Southern California Seismic Network (CI) and the US Transportable Array (TA) (Figure 7). All the stations consist of either single or three-component broadband seismometers with sample rates of 40 to 100 samples/s. Only vertical component ground motion data are used in this study. The seismic data used were provided by the Seismological facility for the Advancement of Geoscience (SAGE; https://ds.iris.edu/mda/), Northern California Earthquake Data Center (NCEDC; https://service.ncedc.org/fdsnws/dataselect/1/), and Southern California Earthquake Data Center (SCEDC; https://scedc.caltech.edu/data/waveform.html).

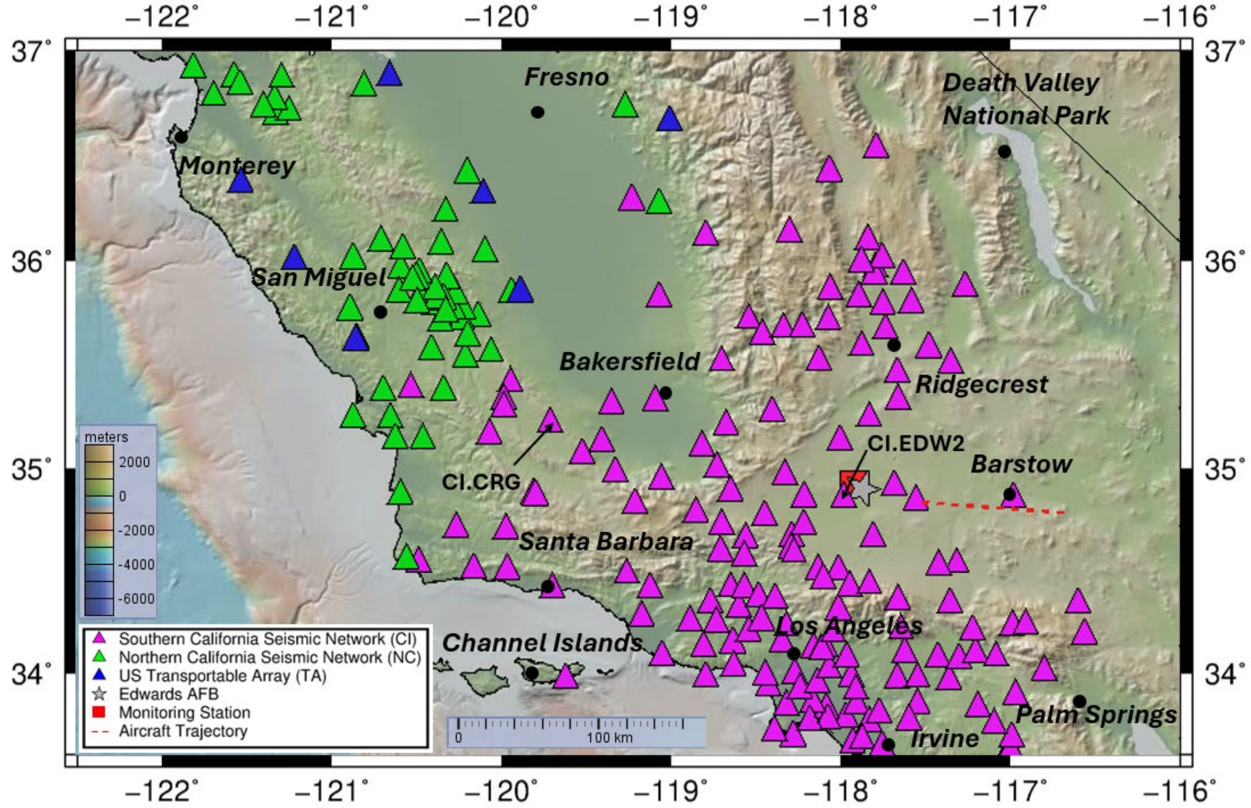


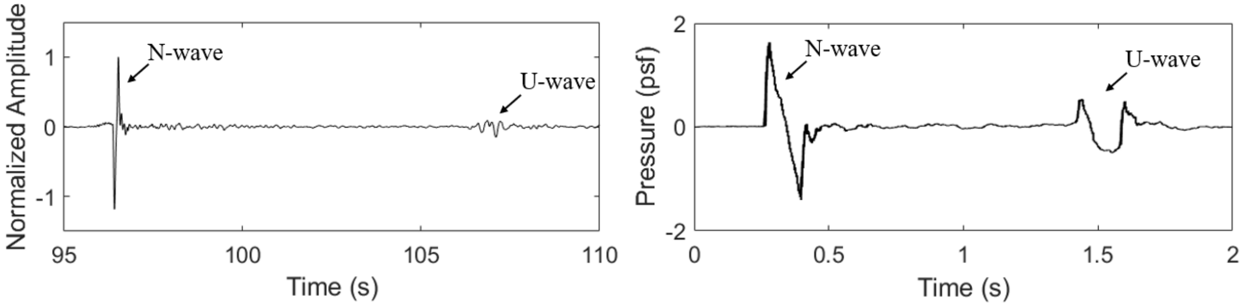
Figure 7. The distribution of seismic stations used in this study. The magenta, green and blue triangles represent instruments from the Southern California Seismic Network (CI), the Northern California Seismic Network (NC), and the US Transportable Array (TA), respectively. The gray star and red square show the locations of the Edwards Air Force Base and nearby sonic boom monitoring station, respectively. The red dashed line represents F-18 aircraft flight trajectories.

Instrument responses were deconvolved from the vertical ground velocity seismograms prior to converting them to ground displacement. The displacement seismograms for all boom events were windowed to begin 0 s prior to and few hundreds of seconds after the event time at the monitoring station (Table 1), ensuring recording of both the primary or secondary boom waves at all distance ranges. The windowed seismograms were then demeaned, detrended and tapered, and finally filtered at 1-20 Hz with four-pole two-pass Butterworth bandpass filters.

Using the seismograms, the primary and secondary boom events were detected through manual identification. For primary boom detection, event identification was performed by inspecting the seismograms for N-type wave signatures followed by a U-shaped wave, as illustrated in Figure 8a, at seismic stations located within a radius of ~ 100 km from EAFB where the primary carpet for the boom events is predicted to be seen. For secondary boom carpet detection, several template waveforms were chosen based on the infrasound microphone records published by Rickley and Pierce (1980) (type I and type II waves, Figure 8d). We then manually searched for secondary booms by visually comparing the template waveforms with seismograms for seismic stations located greater than 60 km from EAFB showing both type I and type II waves.

(a) Primary boom record (Seismic signal)

(b) Primary boom record (Acoustic signal)



(c) Ground-wave + Secondary boom record (Seismic signal)

(d) Ground-wave + Secondary boom record (Acoustic signal)

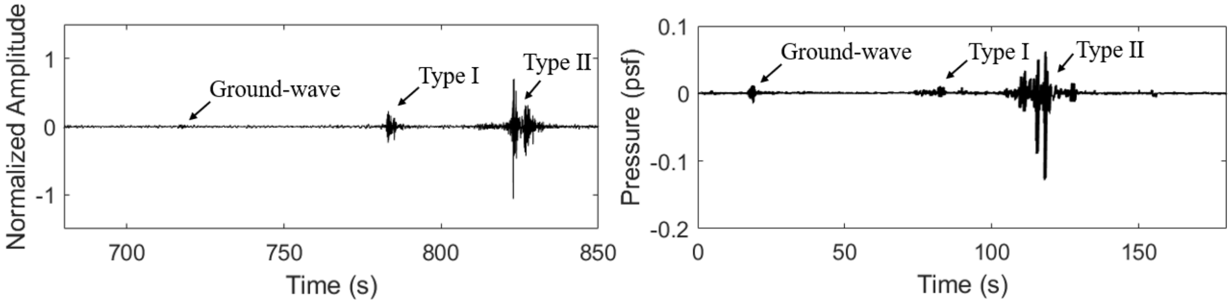


Figure 8. Primary (a,b) and secondary (c,d) sonic boom waves shown on displacement seismograms (left panel) and microphone records (right panel). (Left) The top (a) and bottom (c) seismograms are from boom number 3 recorded on station CI.EDW2 and boom number 4 recorded on station CI.CRG, respectively. Seismic station locations are shown in Figure 7. The starting time (i.e., 0 s) of each window corresponds to each of the sonic boom event detection times at the monitoring station. The waveforms are filtered at 1-20 Hz. Right: The top (b) and bottom (d) pressure traces are modified from the PARTNER project 8 annual report (Sparrow 2005) and Rickley and Pierce (1980), respectively.

Results

Seismograms illustrating primary and secondary sonic boom signatures are from the third boom event's first pass are shown in Figure 9 and Figure 10. It should be noted that the exact event origin time and location are not known, and so we have assumed all the events initiated near EAFB. Therefore, some arrivals plotted on Figure 9 and Figure 10 may show earlier or later arrivals than the minimum or maximum effective sound speeds of 0.2 km/s or 0.4 km/s, respectively. For all passes (Table 1), we note that primary and secondary boom signals are captured by the seismometers at distances up to ~55 km and ~100 - 250 km from EAFB, respectively. We further note that type II secondary sonic boom waves typically arrive about 30 to 50 s after the type I wave (Figure 10). Figure 11 shows the locations of stations that recorded primary and secondary booms for events 14-18 (Table 1), illustrating the spatial coverage of our results across southern California.

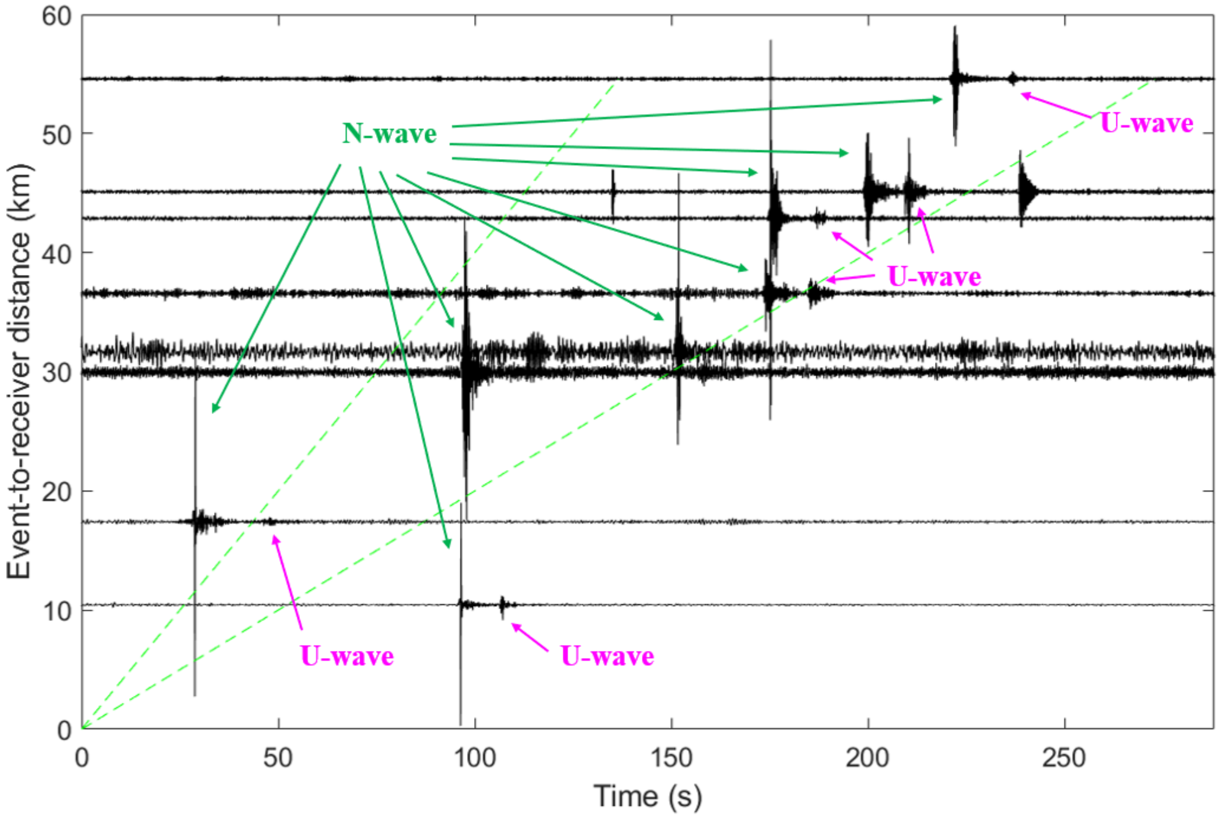


Figure 9. Displacement seismograms from seismic stations for the third boom event during first flight pass (Table 1) showing N and U-type waves (primary boom). Zero time corresponds to the sonic boom detection time at the monitoring station, and the green dashed lines shows velocities of 0.2 km/s to 0.4 km/s used to help identify primary sonic boom arrivals. The seismograms are filttered from 1 to 20 Hz.

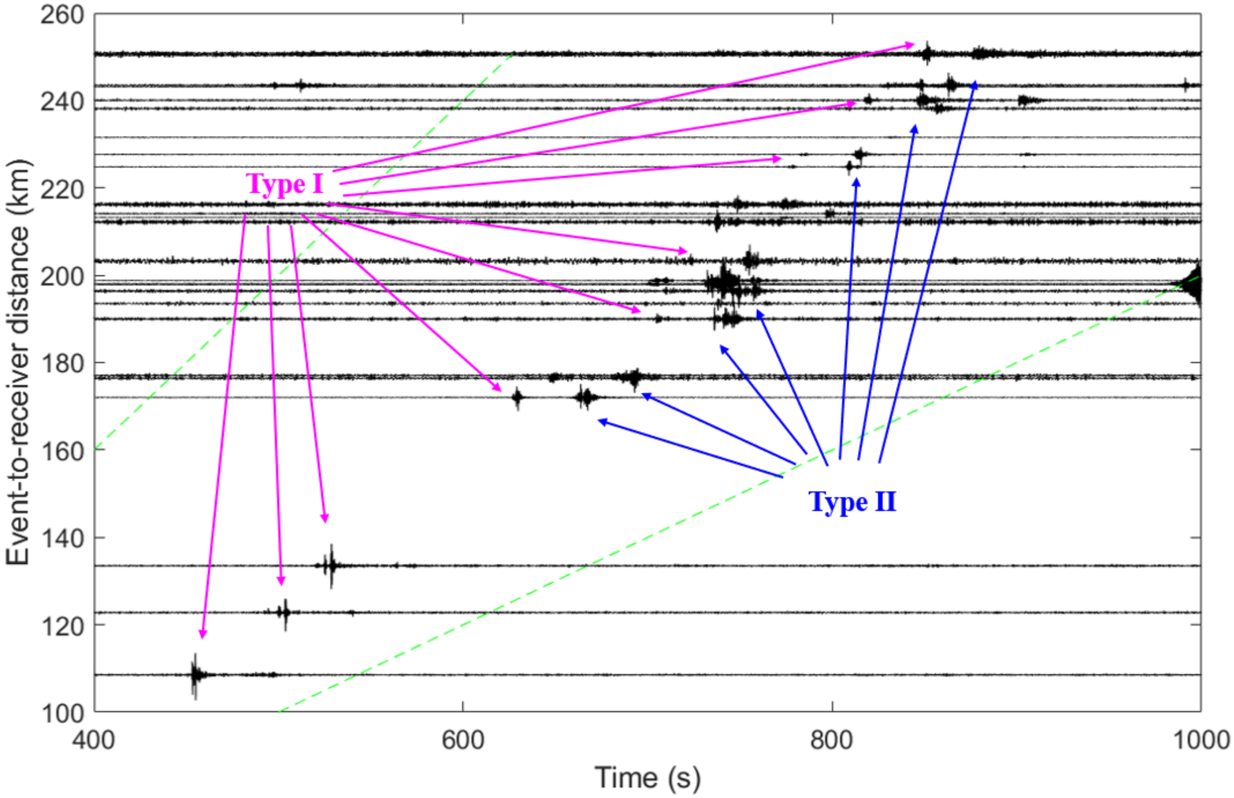
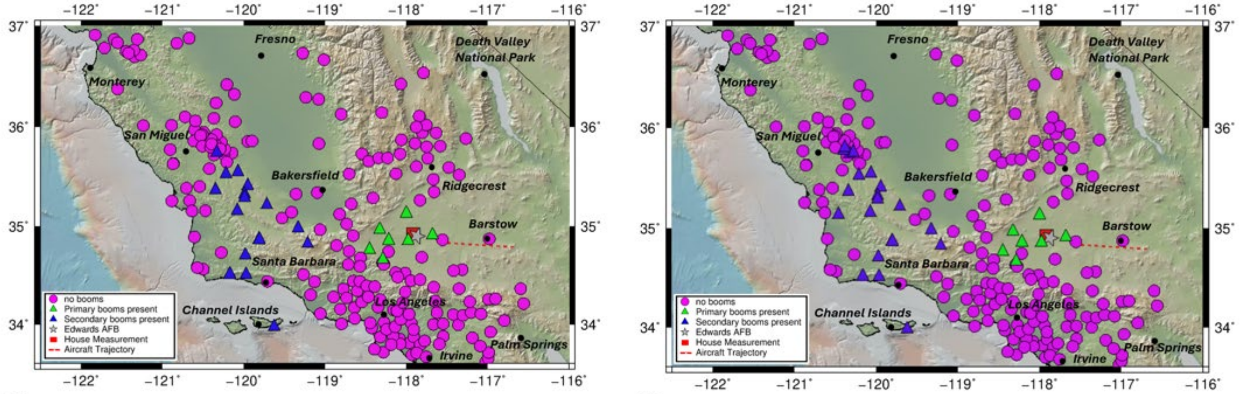


Figure 10. Displacement seismograms from seismic stations for the third boom event during the first flight pass (Table 1) showing type I and II waves (secondary boom). Zero time corresponds to the sonic boom detection time a the monitoring station, and the green dashed lines shows velocities of 0.2 km/s to 0.4 km/s used to help identify the boom arrivals. The seismograms are filtered from 1 to 20 Hz.

(a) Boom ID: 14 (b) Boom ID: 15



(c) Boom ID: 16 (d) Boom ID: 17

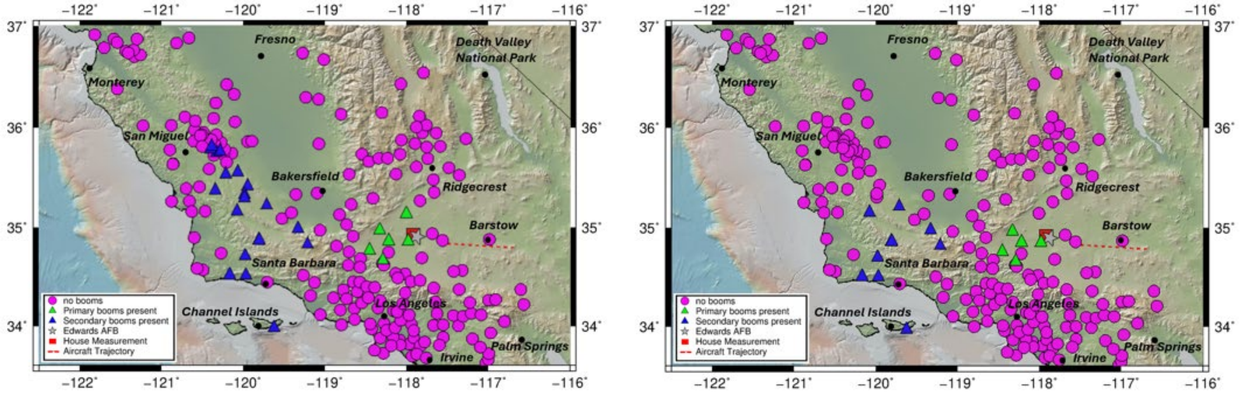


Figure 11. Maps showing primary and secondary boom event detections for boom events 14-17 (the fourth flight pass; Table 1). The green and blue triangles represent instruments with clearly recorded primary and secondary booms, respectively. The magenta circles show stations where the sonic booms were not clearly recorded. Other symbols are similar to Figure 7.

Summary

The goal of this work has been to explore the current capability of detecting primary and secondary sonic booms by seismic stations. The project is specifically aimed at identifying N-type and U-type waves from primary booms, and type I and type II waves from secondary booms recorded on seismic stations in southern California. The research team's results indicate that primary and secondary sonic booms were well recorded on seismic networks in 2005 in southern California over an area of ~ 5,000 km^2 and ~ 30,000 km^2, respectively. These results are consistent with findings previously reported by Cates and Sturtevant (2002) for primary booms. We also report the first seismic observations of secondary sonic booms. Thus, both primary and secondary sonic booms can be detected and classified using existing seismic networks.

Special Acknowledgments

The project team thanks NASA overall, particularly Edward Haering of the NASA Armstrong Flight Research Center, for providing flight info and tremendous support throughout this investigation.

Milestone

- Showed through the results of this study that seismic detection of primary and secondary booms from supersonic flights is possible using existing seismic networks.

Major Accomplishments

ASCENT Project 057 Task 3 extended knowledge of the recording capability of primary and secondary booms by existing seismic stations. The project can now continue identifying secondary booms to understand primary and secondary boom carpets.

Publications

Journal Publication of Presented Conference Abstract

Rathnayaka, S., Nyblade, A. A., Sparrow, V. W., & Riegel, K. A. (2023). Air show primary sonic boom across a Seismic network. *The Journal of the Acoustical Society of America, 154*(4). https://doi.org/10.1121/10.0023074

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period

- Continue to work on identifying signatures for primary and secondary sonic booms from various supersonic passes, an essential step toward assessing community impact.
- Identify if secondary booms can be detected as part of NASA's X-59 phase II flight tests.

References

Cates, J. E., & Sturtevant, B. (2002). Seismic detection of sonic booms. *The Journal of the Acoustical Society of America*, *111*(1), 614-628. https://doi.org/10.1121/1.1413754

Rathnayaka, S., Nyblade, A. A., Sparrow, V. W., & Riegel, K. (2023). Air show primary sonic booms across a seismic network. *The Journal of the Acoustical Society of America*, *154*(4_supplement), A147-A147. https://doi.org/10.1121/10.0023074

Rickley, E. J., & Pierce, A. D. (1980). *Detection and assessment of secondary sonic booms in New England* (FAA-AEE-80- 22) Federal Aviation Administration. https://rosap.ntl.bts.gov/view/dot/8970/dot_8970_DS1.pdf

Sparrow, V. W. (2005). PARTNER Project 8: Sonic boom mitigation. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings, NoiseCon05*, 267-274. https://ince.publisher.ingentaconnect.com/contentone/ince/incecp/2005/00002005/00000002/art00037#