Project 041 Identification of Noise Acceptance Onset for Noise Certification Standards of Supersonic Airplanes

The Pennsylvania State University

Project Lead Investigator

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University Participants

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- PI(s): Vic Sparrow, United Technologies Corporation Professor and Director, Graduate Program in Acoustics
- FAA Award Number: 13-C-AJFE-PSU Amendment 45
- Period of Performance: March 29, 2019 to August 29, 2020
- Tasks:
  1. Obtaining confidence in signatures, assessing metrics sensitivity, and adjusting for reference day conditions
  2. Assessing secondary sonic boom propagation

Queensborough Community College, City University of New York

- Co-Investigator: Kimberly A. Riegel, subrecipient to The Pennsylvania State University (Penn State)

Project Funding Level

This project supports the identification of noise acceptance onset for noise certification standards of supersonic airplanes through research conducted on multiple tasks at the Penn State University. The FAA funding to Penn State in 2019–2020 is $390,000. Matching funds are expected to meet cost share on both Tasks. Boom Supersonic has pledged $300,000, and Gulfstream has pledged $100,00.

Investigation Team

For 2019–2020, the investigation team includes:

- Victor W. Sparrow, PI (Task 1 and 2), The Pennsylvania State University
- Trevor Stout, postdoctoral scholar (Task 2), The Pennsylvania State University
- Lucas Wade, graduate research assistant (Task 1), The Pennsylvania State University
- Joshua Kapscos, graduate research assistant (Task 1), The Pennsylvania State University
- Juliet Page, coinvestigator, subrecipient to Penn State, Volpe – The National Transportation Systems Center
- Kimberly A. Riegel, coinvestigator, subrecipient to Penn State, Queensborough Community College, City University of New York
- Steve Ogg, et al., Boom Supersonic [industrial partner]
- Robbie Cowart, Joe Salamone, et al., Gulfstream [industrial partner]

Project Overview

FAA participation continues in International Civil Aviation Organization, Committee on Aviation Environmental Protection (ICAO CAEP) efforts to formulate a new civil, supersonic aircraft sonic boom (noise) certification standard. This research investigates elements related to the potential approval of supersonic flight over land for low boom aircraft. The efforts include investigating certification standards, assessing community noise impact, and developing methods to assess the public acceptability of low boom signatures. The proposed research will support NASA in the collaborative planning and execution of human response studies that gather the data to correlate human annoyance with low-level sonic boom noise. As the research progresses, this may involve the support of testing, data acquisition and analyses, field demonstrations, laboratory experiments, or theoretical studies, for example, see Maglieri et al. (2014).

Task 1 - Obtaining Confidence in Signatures, Assessing Metrics Sensitivity, and Adjusting for Reference Day Conditions

The Pennsylvania State University

Objective

As national aviation authorities move forward in 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. Research support is needed by FAA and international partners in these areas to progress toward standards.

The objective of this activity is to continue research at Penn State in the ASCENT Center of Excellence to complement the ongoing development of sonic boom standards within the Committee for Aviation Environmental Protection's (CAEP) Working Group 1 (Noise Technical), Supersonics Standards Task Group (SSTG). This research will ensure that the behavior of the sonic boom metrics considered in the SSTG discussions is well understood and will account for sonic boom variability effects, to move forward with sonic boom noise certification standard development and consideration of subsequent rulemaking.

Task 1 in ASCENT Project 41 focuses on several, but not all, research initiatives needed to move toward the development of a low-boom supersonic en-route noise certification standard.

Research Approach

Background

An ongoing effort of ASCENT Project 41 is determining the variability in sonic boom loudness level at the ground as a result of various atmospheric effects. Last year's report outlined a study of the effects of turbulence on sonic boom signatures, particularly how these effects might be isolated and removed from the signatures. Because turbulence is stochastic in nature, this is an important step in finding a more consistent baseline level for the purpose of supersonic aircraft certification.

Although turbulence is strongest in the lowest few kilometers of the atmosphere, heterogeneities in other atmospheric variables, including ambient pressure, temperature, relative humidity, and wind can have a significant impact on the level of the sonic boom over its entire propagation path. These quantities are thus of primary importance in the certification effort. Therefore, the focus of Project 41 Task 1 in 2018–2019 was to study the change in boom level that fluctuations in these quantities induce while also exercising the PCBoom sonic boom propagation software. According to the "reference day" certification method being explored by CAEP Working Group 1, all atmospheric variations were produced by altering a standard reference atmosphere.

The reference atmosphere in question uses mean temperature and pressure profiles taken from ICAO standard 7488/3 (or ISO 2533). Relative humidity is calculated from an equation given in Annex C of ISO 9613. No winds are present in the reference atmosphere. Plots of the pressures, temperatures, and relative humidities associated with the reference atmosphere are given below up to an altitude of 200 kft.

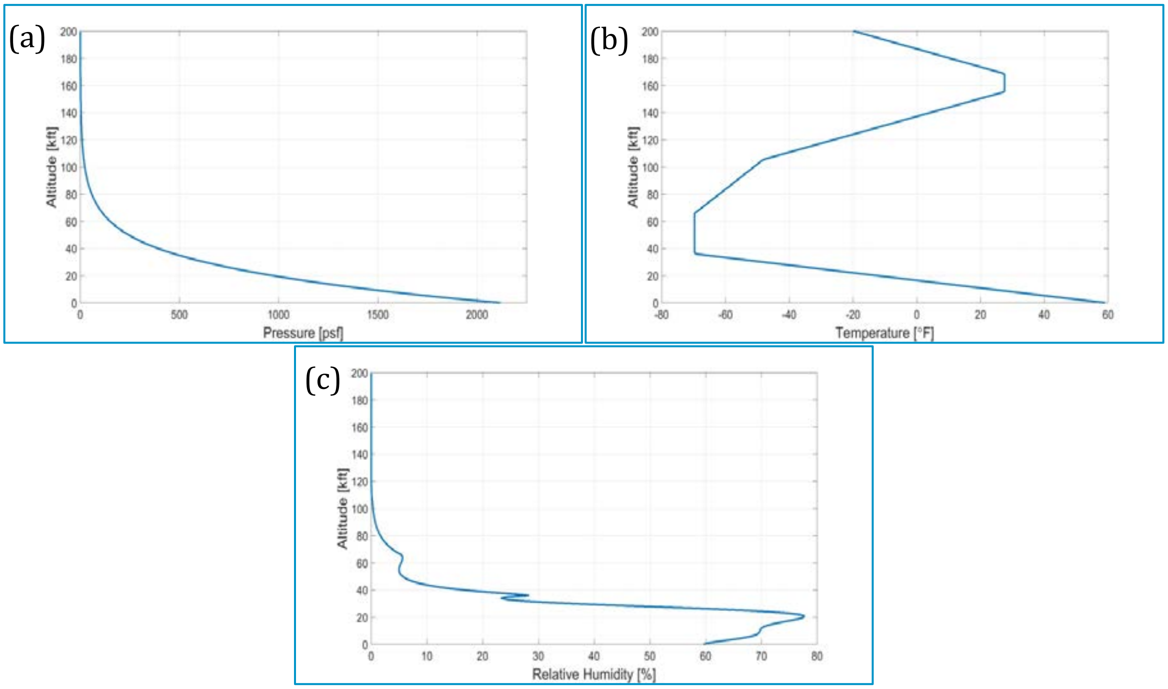

Figure 1. Plots of the reference atmosphere pressure in psf (a), temperature in °F (b), and relative humidity (c) up to 200 kft.

PCBoom 6.7b vs. 6.7.1.1
The work undertaken in 2018–2019 required heavy use of sonic boom propagation software. The chosen software, PCBoom, was developed by kbrWyle and is maintained in part by NASA. The latest version available to the public at the start of this work was 6.7b, which relied on a split-step pseudospectral numerical solution of an augmented Burgers' equation. An updated version, 6.7.1, was provided to Penn State in July of 2019, and a further revision, 6.7.1.1, was supplied in August 2019 (Lonzaga, 2019). The updated version involved a complete restructuring of the Burgers' solver and incorporated wind effects such as Doppler shift and convective amplification. Cases without winds did not change significantly, but any results for which wind was present needed to be redone after the update. The two versions are compared for a particular set of propagation cases in the "Linear Wind Profile" section below. All cases used as input a computational fluid dynamics simulated pressure signature for a Lockheed Martin LM-1021 concept low boom aircraft, which was a configuration provided in the 2nd AIAA Sonic Boom Prediction Workshop as well as the 6.7b installation of PCBoom as an example case. Only undertrack levels are reported.

Temperature smoothing
One of the first cases studied was a smoothing of the temperature profile in Figure 1. The justification for doing so is twofold. First, a real atmosphere will generally not have such a clear distinction (slope discontinuity) between the linear temperature lapse of the troposphere and the isothermal portion of the lower stratosphere. Instead, a real atmosphere will fluctuate about this idealized profile and have a smoother transition between the two regions. Therefore, it was of interest to determine how much of a change in sonic boom level this sort of smoothing would produce. Second, slope discontinuities can cause instability in some numerical methods. Thus, it was important to verify that PCBoom could properly handle such a discontinuity. The smoothed profile could be used as a comparative tool, because the two profiles would not be expected to produce wildly different results unless numerical instability were present. Of note, relative humidity is partially dependent on temperature, and therefore its profile needed to be altered appropriately. The smoothed case is plotted for both temperature and relative humidity in Figure 2 below.

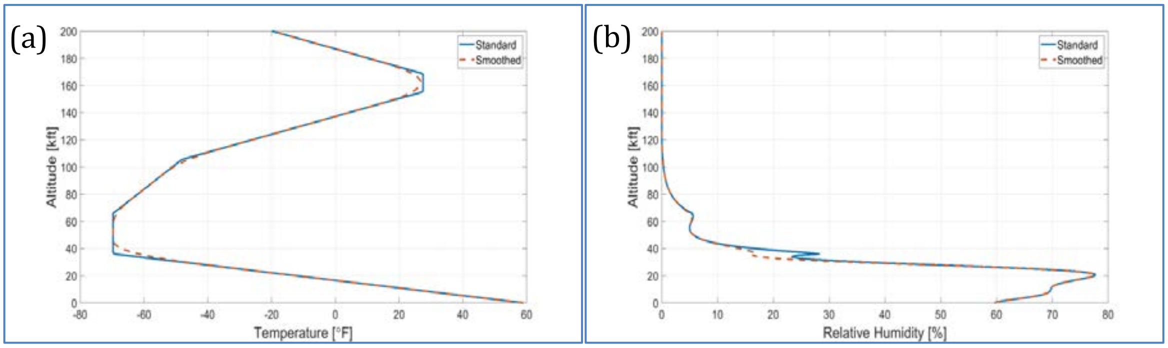

Figure 2. Smoothed temperature profile (a) and resulting relative humidity profile (b).

After propagation of the sonic booms to the ground in PCBoom, two key sonic boom metrics were computed, among others. Both the Steven's Mark VII Perceived Level (PL) and the Indoor Sonic Boom Annoyance Predictor (ISBAP) were calculated and are utilized below. The change in sonic boom level due to the smoothing was seen to be approximately 0.04 PLdB/0.04 dB ISBAP, thus confirming that PCBoom does not have any difficulty in processing the discontinuity, and small fluctuations about the mean profile produce correspondingly small fluctuations in boom level.

Shifts in molar concentrations of water vapor

Water vapor concentration is a key component in determining the extent of atmospheric absorption due to molecular relaxation. Because absorption limits waveform steepening and hastens amplitude decay, it is an important factor in determining overall boom loudness. Thus, the research team sought to observe the quantitative impact of water vapor concentration (or, loosely, relative humidity) on boom level. To do so, the molar concentration of water vapor was increased and then decreased by 25% relative to the reference profile, and the corresponding relative humidity was computed. The resulting curves are plotted in Figure 3.

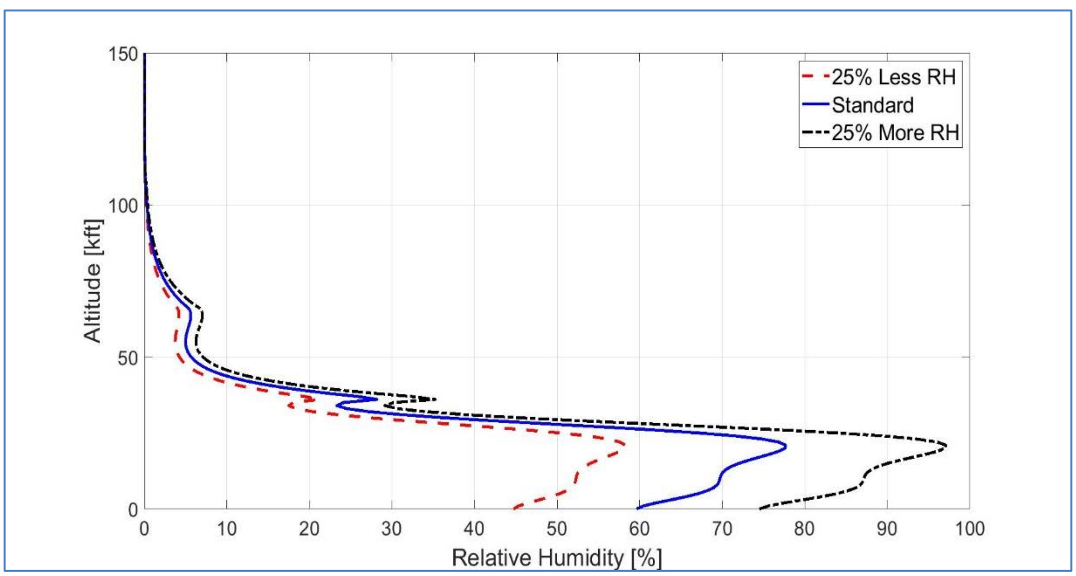

Figure 3. Relative humidity profile after increasing or decreasing the molar concentration of water vapor by ±25%.

Unexpectedly, this rather dramatic shift in water vapor concentration induced a maximum decrease (due to -25% shift) in PL of only approximately 0.9 dB and 0.6 dB for ISBAP, and a maximum increase (due to +25% shift) of only 0.5 PLdB and 0.35 dB ISBAP.

Linear wind profile

Because wind convects sound, it can have a marked impact on the propagation path of sonic booms and therefore their loudness. It may either increase or decrease the boom level depending on its direction relative to the nominal propagation direction of the sonic boom. In this study, a set of basic linear wind profiles was added to the otherwise unchanged reference atmosphere. Although these profiles are not realistic, they are helpful in understanding the effect that wind has on loudness in general. Ground wind speeds were taken to be zero to satisfy the no-slip condition, whereas peak wind speeds at the simulated flight altitude of 55,000 ft ranged from an 80 ft/s headwind to an 80 ft/s tailwind in increments of 10 ft/s. Changes in both PL and ISBAP relative to the windless reference atmosphere were determined. The result from PCBoom 6.7b is shown below, with the updated 6.7.1.1 result following shortly after.

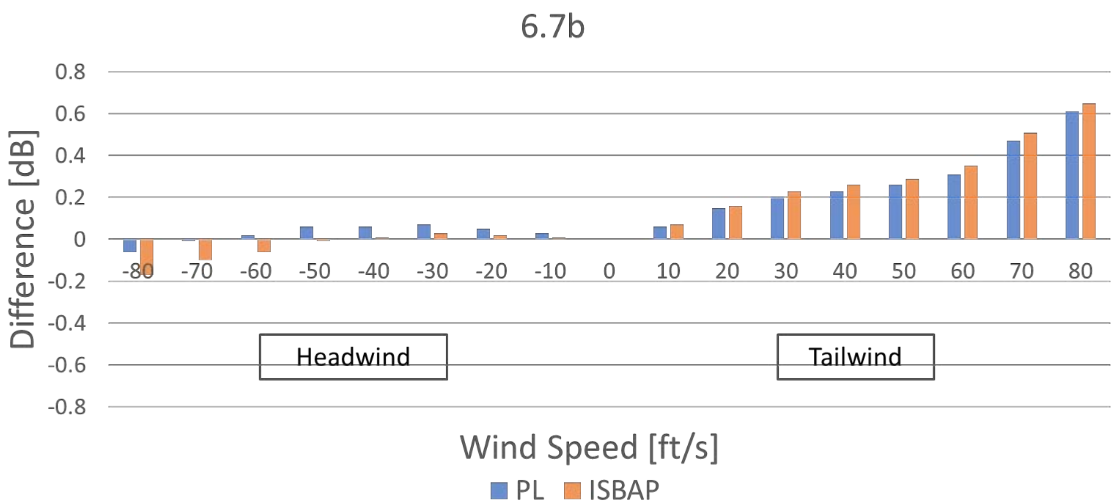

Figure 4. Difference in boom level due to linear wind gradient, as computed in PCBoom 6.7b.

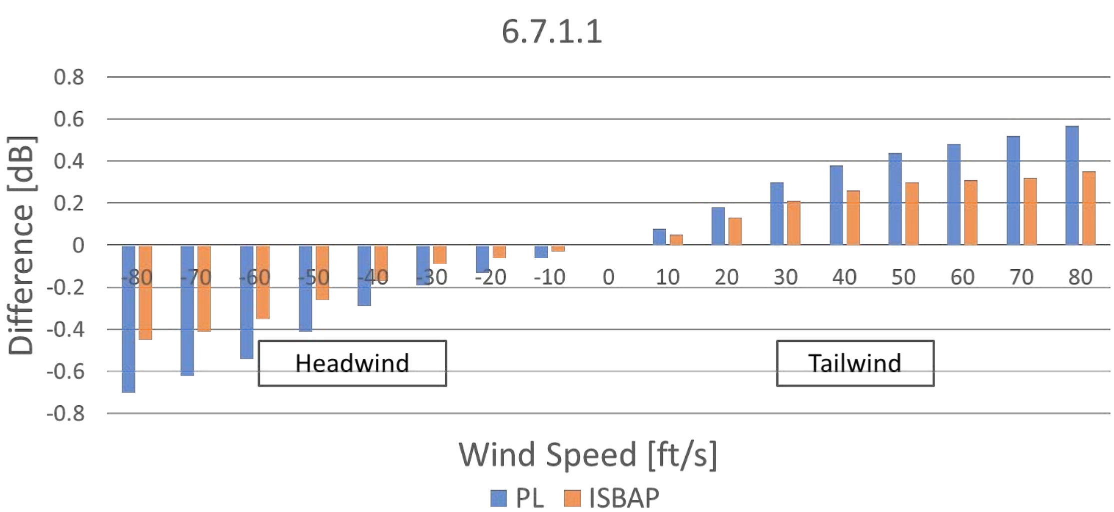

Figure 5. Difference in boom level due to linear wind gradient, as computed in PCBoom 6.7.1.1.

The trend of version 6.7b seen in Figure 4 was a source of confusion when the chart was produced, because increasing the tailwind with all other parameters held fixed would be expected to invariably increase boom level. However, with wind effects properly accounted for (Lonzaga, 2019), as in PCBoom 6.7.1.1 (Fig. 5), this trend is indeed recovered. As shown in Figure 5, the difference in the PL metric in dB can vary as much as 0.7 dB because of the wind effects, and a similar effect is observed for ISBAP, the indoor sonic boom annoyance predictor metric.

Milestone
The impacts of various perturbations of a reference atmosphere on sonic boom levels were assessed in two different versions of the PCBoom propagation software.

Major Accomplishments
ASCENT Project 41 Task 1 has determined potential variability in sonic boom PL/ISBAP due to various atmospheric perturbations, which may prove useful in sonic boom noise certification of supersonic aircraft.

Publications
Published Conference Abstract

Wade, L. & Sparrow, V. (2019). Effects of perturbing a reference atmosphere on sonic boom propagation metrics. Journal of the Acoustical Society of America. **145**(3, Pt. 2) 1903.

Outreach Efforts
N/A

Awards
None.

Student Involvement
Luke Wade was the Penn State graduate research assistant who worked on ASCENT Project 41 during the 2018–2019 academic year. In addition to the work outlined above, he provided support within CAEP Working Group 1 and submitted cases for the 3rd AIAA Sonic Boom Prediction Workshop to be held in January 2020. He has since received a Fellowship from NASA for conducting further research in the area of sonic booms. Graduate research assistant Joshua Kapcsos is currently learning the PCBoom software and will be taking over from Luke in future Project 41 tasks.

Plans for Next Period
Further work on the study of atmospheric perturbations may be carried out, including the study of more realistic wind profiles, crosswinds, and statistical analysis of boom level variability due to changes in the atmosphere.

References
Lonzaga, J.B. (2019). Recent enhancements to NASA's PCBoom sonic boom propagation code. AIAA Aviation Forum, Dallas, Texas, USA.

Maglieri, D., Bobbitt, P., Plotkin, K. Shepherd, K., Coen, P., & Richwine, D. (2014). Sonic boom: Six decades of research. NASA SP-2014-622.

Task 2 - Assessing Secondary Sonic Boom Propagation
The Pennsylvania State University
Queensborough Community College, City University of New York

Objective

Because both normal boom and low-boom supersonic aircraft are getting closer to implementation, assessing all aspects of the sonic boom noise that reaches the ground is important. This includes the need to more comprehensively understand secondary sonic booms, when and why they occur, and the resulting signatures.

Research Approach

Background

Most of the research in the United States to understand the regular occurrence of secondary sonic booms observed on the northeast coast as a result of the Concorde was completed in 1980. There are two main types of secondary sonic booms. Type I is the ground boom resulting from shock waves emanating off the top of the aircraft that refract downward for certain atmospheric conditions. Type II is the boom that bounces off the ground or water surface and is bent in the atmosphere, then returns to the ground. To better predict the conditions that result from these secondary sonic booms, the variance in the atmospheric conditions, type of aircraft and trajectory should be examined.

The primary focus of the initial work in Task 2 of ASCENT Project 41 in 2019 was the re-creation of the original 1980 work by Rickley and Pierce by using the PCBoom modeling software (Plotkin et al., 2007). The 2019 research was primarily undertaken by postdoctoral scholar Trevor Stout. After his departure from Penn State, the work was continued by Dr. Kimberly Riegel of Queensborough Community College and the project PI Dr. Victor Sparrow.

Original FAA results

The original FAA report number ADA088160, authored by Ed Rickley and Allan Pierce, measured and simulated the sonic booms that were being heard in New England because of the Concorde. At the time, supersonic flight over land was already banned by the FAA, so the sonic booms that were impinging on land near the coast were not from the undertrack boom. The authors measured the signatures in several places where secondary sonic booms were perceived, including Malden, MA, and Applebachsville, PA. Using measured atmospheric data at the locations where sonic booms were being heard, the authors also predicted where the type I and type II secondary sonic booms would be heard for a Concorde aircraft flying into New York City and Washington, DC. Figure 44 from the report shows their predicted focus lines for both type I and type II and the primary boom carpet edge that would be created on a flight into New York. The original figure has been reproduced here as Figure 6 for reference.

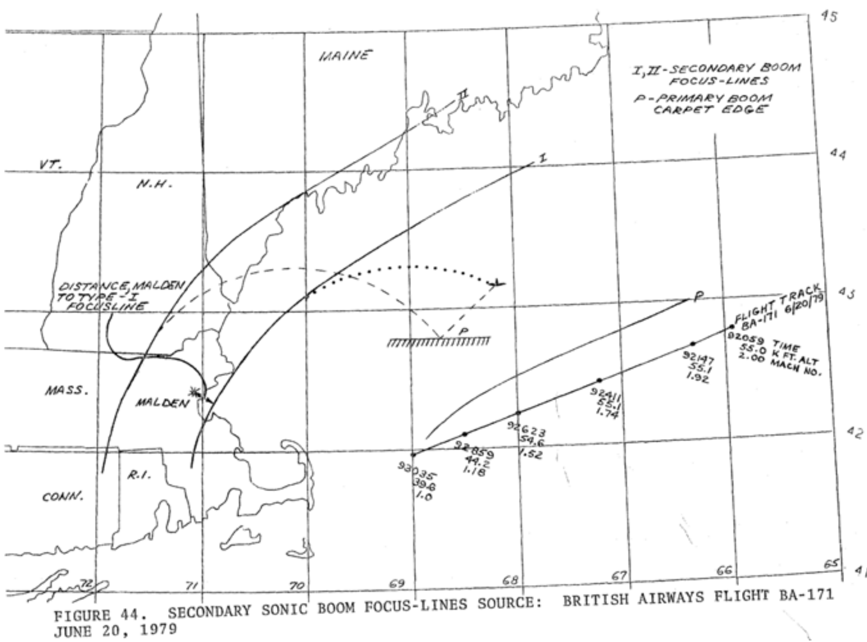

Figure 6. The predicted sonic boom type I and type II focus lines for a Concorde Aircraft approaching New York City, as produced in the original 1980 FAA report by Rickley and Pierce.

Re-creation of results with PCBoom

To determine the agreement between the results from the PCBoom software version 6.7b and the original predictions, we used the same atmospheric conditions outlined in the report and the same flight trajectory and signature from the Concorde as inputs into the PCBoom software. Originally, a flat earth was assumed. Figure 7 shows the ray trajectories for the first run of PCBoom. The black ray trajectories do not hit the ground, whereas the blue ray trajectories bounce off the ground. After the rays that intersected with the ground were identified, the propagated rays were then refined so that only the rays that intersected with the ground would be calculated. PCBoom was run again with the refined set of rays. This process resulted in a set of rays where the ray/ground intersection could be identified, and a plot of the locations where secondary sonic booms would have reached the ground was created. Figure 8 shows the resulting secondary carpet and compares the results to the original predictions from the 1980 Rickley and Pierce report. The flat earth model shows good agreement with the original data and increases the confidence that PCBoom is accurately modeling the secondary sonic booms.

However, Figure 7 shows that these secondary sonic booms can travel distances of 600 km. At these distances, the flat earth approximation may not be the most accurate representation. PCBoom has the option to include a spherical earth or an ellipsoidal earth approximation. Therefore, both simulations were performed, and the results were compared to the original predicted 1980 report simulations. The agreement for the spherical earth is still reasonable. However, there are some differences, primarily in the type II ground intersection locations as well as some differences in all the ray trajectories directly in front of the aircraft. Figure 9 shows the spherical earth results, and Figure 10 shows the ellipsoidal earth results. Although there are substantial differences between the flat earth approximation and the other simulations, the differences between the spherical and the ellipsoidal earth are very small.

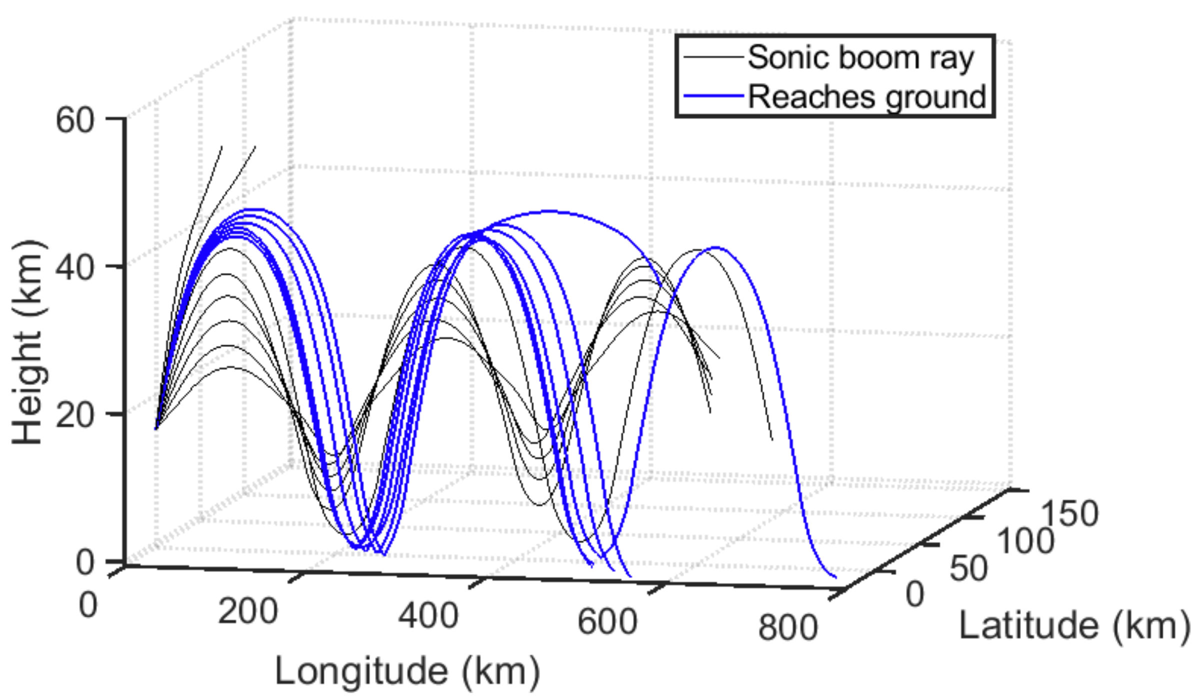

Figure 7. The ray trajectories of the propagated sonic boom rays, with the rays that reach the ground highlighted in blue.

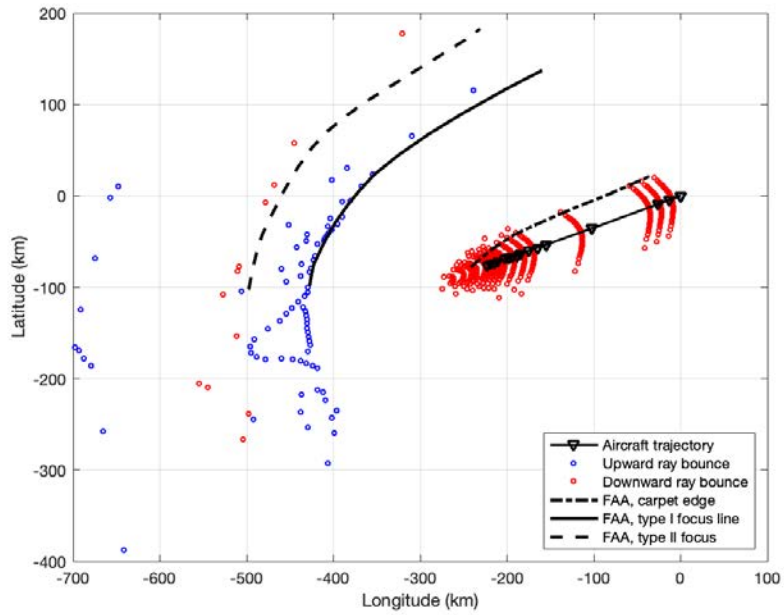

Figure 8. The secondary boom carpet for a flat earth approximation is shown with type I secondary sonic booms shown in blue and type II shown in red. The original focus lines from the 1980 Rickley and Pierce report area are shown in the figure as solid and dashed black lines.

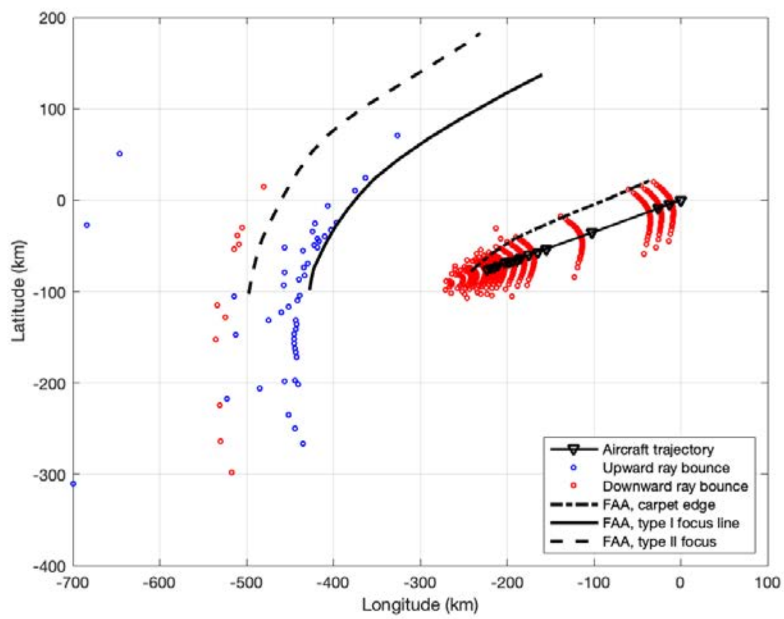

Figure 9. The secondary boom carpet with a spherical earth is shown with type I secondary sonic booms shown in blue and type II shown in red. The original focus lines from the 1980 Rickley and Pierce report area are shown in the figure as the solid and dashed black lines.

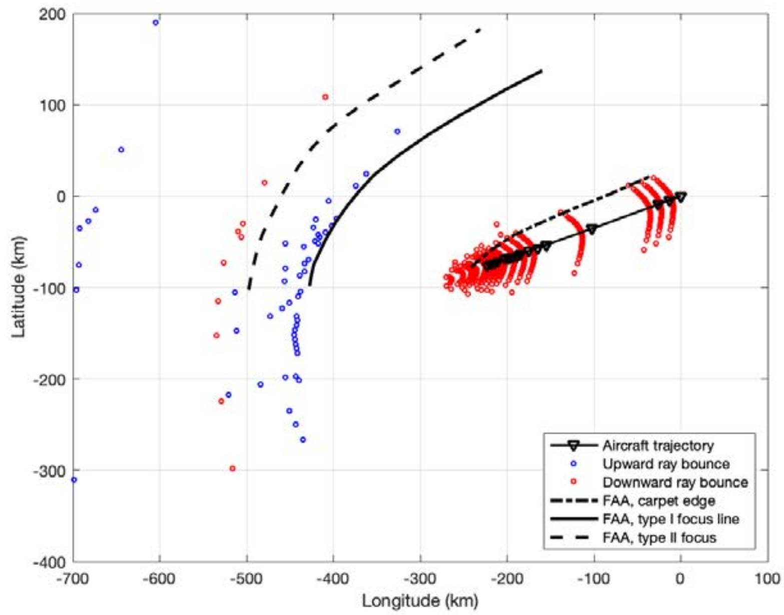

Figure 10. The secondary boom carpet with an ellipsoidal earth is shown with type I secondary sonic booms shown in blue and type II shown in red. The original focus lines from the 1980 Rickley and Pierce report area are shown in the figure as the solid and dashed black lines.

Milestone
The project is now underway.

Major Accomplishments
ASCENT Project 41 Task 2 has now successfully re-created the simulations performed by Rickley and Pierce in 1980 by using the PCBoom modeling software, and the new results show good agreement with the 1980 work.

Publications
Published Conference Abstract

Riegel, K., Sparrow, V., & Stout, T. (2019). Preliminary analysis of the PCboom software for calculating secondary sonic booms. Journal of the Acoustical Society of America. **146**(4) 2782.

Outreach Efforts
N/A

Awards
None.

Student Involvement
None.

Plans for Next Period
The project team will investigate the influence of upper atmospheric winds on the distribution of secondary sonic booms. The pressure signatures of the received secondary sonic booms will be predicted. If time allows, different aircraft will be used to determine differences in the received secondary sonic boom levels.

References

Plotkin, K., Page, J., & Haering, E. (2007). Extension of PCBoom to over-the-top booms, ellipsoidal earth, and full 3-D ray tracing. AIAA 2007-3677, 13th AIAA/CEAS Aeroacoustics Conference

Rickley, E. & Pierce, A. (1980). Detection and assessment of secondary sonic booms in New England. FAA-AEE-80-22, accessible as ADA088160