Recent progress on sonic boom research at NASA

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Sonic boom research conducted at NASA through the Supersonics Project of the Fundamental Aeronautics Program is oriented toward understanding the potential impact of sonic boom noise on communities from new low-boom supersonic aircraft designs. Encompassing research in atmospheric propagation, structural response, and human response, NASA research contributes to knowledge in key areas needed to support development of a new noise-based standard for supersonic aircraft certification. Partnerships with several industry, government, and academic institutions have enabled the recent execution of several acoustic field studies on sonic booms. An overview of recent activities funded by NASA includes: focus boom model development and experimental validation, field experiments of structural transmission of sonic booms into large buildings, and low boom community response testing.

1 INTRODUCTION

The sonic boom that occurs when aircraft travel at supersonic speeds is perhaps the most significant environmental barrier to unrestricted civilian supersonic flight. NASA research emphasizes understanding and overcoming this barrier, both through the development of approaches to reduce sonic boom noise and to improve understanding of the impact of these reduced noise booms. Existing knowledge of the effect of sonic booms on communities is based primarily on field experiments conducted during the 1960s. It was concluded that high-amplitude sonic booms, such as those from the Concorde, were unacceptable to a large segment of the population, and overland supersonic flight was prohibited. Although much progress was made in modeling the sonic boom and its effects in the 1990s, boom minimization resulted in aircraft designs with compromised aerodynamic performance.

Recent work has led to technologies that potentially will lower the boom to acceptable levels without serious effects on performance and could lead to a replacement of the current prohibition on civil supersonic overland flight with a noise-based certification criterion. To help inform the regulatory process on the effects of such booms on overflown communities, NASA is

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concentrating its sonic boom research on atmospheric effects, transmission into structures, and human reaction to low-amplitude booms. Accurate predictions of sonic boom propagation through the atmosphere under a variety of realistic atmospheric and flight conditions are desired. In addition, in order to fully understand human reaction to low-intensity shaped sonic booms, prediction of the transmission of booms into buildings is required, since that is where the majority of people spend most of their time. Predictions of structural vibrations of buildings and corresponding noise levels inside these buildings are of interest since both are important characteristics of the indoor environment. Finally, subjective laboratory and field studies are critical to understanding and developing prediction models for human annoyance to these low booms.

This paper presents an overview of recent activities, conducted by NASA and its partners, related to understanding the potential impact of low-amplitude shaped booms on communities. Three sonic boom field tests are described here and involve studies of sonic boom focusing, noise transmission into large buildings, and community response. Preliminary data is presented, as well as some of the progress in developing prediction models for sonic boom focusing.

2 FOCUS BOOM MODEL DEVELOPMENT AND EXPERIMENTAL VALIDATION

Focus booms are caused by focusing of sound rays due to supersonic accelerations and some other aircraft maneuvers. The maximum shock amplitude of a focus boom is much higher than that for a cruise boom during steady level supersonic flight[1]. Although most focus booms can be avoided or minimized, the transition focus during acceleration from subsonic to supersonic speeds is unavoidable. Hence, focus booms from future low-boom aircraft must be evaluated in order to assess acceptability of overland supersonic flight. In support of this goal, NASA is funding the development and assessment of models to predict sonic boom focusing. As part of this research, NASA has recently performed field measurements of focused sonic booms in order to assess the performance of prediction models. The field measurements and model predictions are being utilized to investigate several aspects of focus booms, including the spatial extent of the pre-focus, focus, and post-focus regions both under and off track; the details of waveforms in these three regions; and how acceleration rate influences focusing.

The focus boom experiment led by NASA Dryden Flight Research Center (DFRC) and Wyle Laboratories took place during May 2011. Using NASA F-18B aircraft performing supersonic acceleration and dive maneuvers, focus booms were created over an isolated desert location at the Cuddeback Air-to-Ground Gunnery Range northeast of Edwards Air Force Base (EAFB). A large linear array of 81 microphones, extending 3,048 m with an inter-microphone spacing of 38 m, was used to record the sonic booms on the ground. In addition, microphones were mounted on a tethered blimp at elevations up to 457 m above ground to capture evolution of the focus boom. A microphone was also mounted on a TG-14 motorized sailplane flying approximately 1,981 m above the ground to capture the focus boom above the turbulent planetary boundary layer.

The large data set acquired in this field test has been used to assess the prediction models and to identify potential improvements to them. Four prediction models have been implemented and assessed: Gill-Seebass single-shock method[2], lossless nonlinear Tricomi method[3-4], Nonlinear Tricomi Equation (NTE)[3] with added absorption, and Nonlinear Progressive Wave Equation (NPE) method[5-6]. Each of these methods calculates the focus boom in the vicinity of a caustic line tangent to sound ray crossings and requires input from a conventional sonic boom propagation model, such as PCBoom[7], for the overall footprint and ray geometry analysis. Preliminary predictions from the NTE method, which accounts for atmospheric absorption including molecular relaxation effects, are able to predict the focus boom waveform shape accurately, as shown in the example comparisons in Fig. 1. The comparisons to field measurements are shown for focus booms from an F-18B flying at Mach 1.23 and executing a -0.25 degree/second pushover maneuver at a Mach rate of 0.0035/second at an altitude of 13,122 m. Amplitudes of the predicted waveforms show reasonable agreement, and there is also generally good agreement on spacing between the N and u waves in the post-focus region. Several of the focus boom models are being revised based on the comparisons between predictions and field data gathered during this flight experiment.

The revised focus boom prediction methods are also being used to calculate transition focus booms from low-boom aircraft designs. Four vehicle designs, which have only been optimized for cruise flight, have been examined for transition focusing. It is desired to know whether vehicles shaped for low-boom cruise also produce low booms during off-design transition flight. In addition, the strength of focusing from shaped boom aircraft is being compared to that from current aircraft. Lastly, the characteristics of the shaped sonic booms during transition flight are being investigated. Examples of two preliminary focus boom predictions for two vehicle designs, a Boeing medium-sized N+2 SuperSonic Transport (SST)[8] and a configuration based on a target Gulfstream Quiet Supersonic Jet (QSJ)[9], are included in Fig. 2. Preliminary results show that the Gill-Seebass method tends to overpredict local peaks, and thus it is not applicable to complex signatures. In contrast, the NTE method with absorption appears to be better suited to prediction of complex signatures.

3 STRUCTURAL TRANSMISSION OF SONIC BOOMS INTO LARGE BUILDINGS

Prediction tools are also being developed with NASA funding to simulate sonic boom transmission into buildings[10-11]. These tools will be used to develop a model of people's exposure to noise heard in buildings from future low-boom vehicles. Supporting the development of these prediction tools, NASA has performed measurements in two residential dwellings exposed to sonic booms of varying amplitude generated by F-18 aircraft[12-13]. However, additional data is needed to ensure applicability of the modeling approaches to larger structures.

Two additional field tests were conducted at EAFB in 2009 and 2010 to study the transmission of sonic booms into large buildings, typical of office environments and other large buildings such as "big-box" stores. This effort was a collaboration between NASA Langley Research Center (LaRC) and DFRC. The structural response to 53 sonic booms and resulting indoor noise were measured for both level flyovers and low-boom dives[14] of an F-18 aircraft. Acoustical measurements were made inside and outside of three large buildings, and the vibration of windows was also measured. Outdoor measurements were also aimed at quantifying diffraction and reflection of the sonic boom around buildings to validate numerical models describing the sound field exciting the building exterior[15-16]. Pictures of the three buildings are included in Fig. 3 and include an older office building consisting of modular trailers, a hangar building similar to a "big-box" store in construction, and a modern office building. The measurements have been collected in a database that quantifies the indoor transmitted noise and the exterior field exciting the buildings for sonic booms of varying amplitude.

A plot of the relationships between indoor vs. outdoor Perceived Level (PL)[17] for the modern office building and for a townhouse[13] is included in Fig. 4. Best-fit lines for the relationship between outdoor and indoor loudness level at several receiver locations within different rooms of each structure are presented. As expected, attenuation through the structure results in reduced loudness levels indoors, with all data falling below the y = x dashed black line.

In spite of very different physical characteristics, the loudness levels inside the large office building (green and red lines) are only about 5 dB higher than inside the residence (blue lines). Measurements in environments with prominent rattle are depicted with colored dashed lines, while locations without prominent rattle are indicated by solid lines. Position within a particular room does not make much of a difference, but indoor environments with prominent rattle can result in an increase of up to 10 dB of PL indoors. Thus it appears that rattle can substantially increase the variance in indoor PL for a given boom incident on a particular structure.

The relationships of indoor and outdoor PL in Fig. 4 constitute a preliminary model for boom transmission into a small subset of structures. The data sets that have been acquired are being used to develop and validate an indoor exposure model that is valid for a wider variety of structures.

4 LOW-BOOM COMMUNITY RESPONSE TESTING

Sonic boom community response studies are envisioned as a key component toward understanding the potential impact of overland supersonic flight of low-boom aircraft. In order to prepare for these eventual studies, a pilot test was conducted to develop and assess experimental methodologies, including sonic boom data acquisition, subjective data collection, and data analysis. This effort was conducted by two contractor teams led by Wyle Laboratories and Fidell Associates[18], in conjunction with LaRC and DFRC. Over a two-week period in 2011, the EAFB housing area was exposed to low-amplitude sonic booms created by F-18 low-boom dives[14]. The boom amplitudes ranged from 0.1 to 2 psf over the test period, and the number of planned booms per day was varied from 4 to 13 during daytime hours.

The EAFB community was ideally suited for this pilot test because of its geographical location and low risk potential. Firstly, NASA Dryden is located at EAFB, and Dryden has the aircraft and personnel expertise required for the supersonic flights. Furthermore, a supersonic corridor exists over the area, which allows unrestricted supersonic flight over the community. Because of this corridor, the EAFB community is already accustomed to hearing sonic booms from Air Force supersonic flight operations. This familiarity avoids issues associated with the introduction of a new noise source to a community, but also means that the EAFB community is not likely to be representative of the general population that is not familiar with sonic booms. Nonetheless, EAFB was an accommodating environment for developing experimental methods that could eventually be applied to the general population. In addition, the community is small and isolated, which simplifies boom placement and flight planning. In particular, the high-amplitude focus booms generated during the F-18 low-boom dive maneuver must be placed away from neighboring communities. Figure 5 shows example boom contour predictions in relation to the EAFB community and nearby communities. In this case, a boom with an overpressure amplitude of 0.15 psf is predicted over the EAFB community, while the unavoidable high-amplitude focus booms are placed far from other communities adjacent to EAFB.

To quantify boom variation over the test area, thirteen networked sonic boom monitors were placed throughout the community to record the individual sonic boom events. Various noise metrics to quantify the community exposure were calculated from the boom recordings made at these locations. With a total of 110 booms over the test period, the desired range of sonic boom amplitudes was achieved, including the low-boom targets of 0.1, 0.3, and 0.5 psf. The C-weighted Day-Night Level (CDNL) ranged from 41 to 67.3 dB, a wide enough range that will allow for comparison with other sonic boom and impulsive noise community studies[19].

In all, 101 residents participated in the test while at home and going about their daily activities. Residents were asked to respond to a series of questions for each boom event that they experienced while at their home and also to respond at the end of the day to the multiple booms heard that day. Residents were assigned to respond using one of three data collection modes: paper, website, or smartphone, in order to test newer data collection technologies in relation to the traditional paper method. Evaluation of data quality and completeness, efficiency, cost-effectiveness, and respondent experience for each mode will inform what data collection methods are used in future tests. After an initial analysis, the different data collection modes appear to have been equally successful, and no single mode proved clearly superior in terms of completion rate or participant experience.

As would be expected based on previous annoyance studies[20], annoyance increased with increasing level and number of booms. Minimal annoyance was reported for the lowest amplitude individual boom events. Preliminary dose-response data, shown in Fig. 6, shows the percent of smartphone participants[a)] noticing booms as a function of boom overpressure measured at a central location in the community. The percent of participants responding affirmatively to the question, “Were you bothered or annoyed by the sonic boom you just heard?” are also included. For example, a boom overpressure of 0.3 psf corresponds to an average of only 6% of respondents being bothered.

5 SUMMARY

Collaboration between NASA, other government agencies, industry, and academia have enabled the execution of acoustic field studies on sonic booms. Results from the recent field studies summarized in this paper will advance the state-of-the-art related to predicting the potential impact of low-amplitude shaped booms on communities. Investigations of focus booms and of sonic boom transmission into large buildings are being used to develop new models that will enable predictions for a variety of aircraft designs and building structures, respectively. Lessons learned from the community response test will facilitate future community testing with actual low-boom aircraft in communities not familiar with sonic booms. The atmospheric propagation, structural response, and human response research elements addressed are each critical to supporting the goal of enabling overland supersonic flight.

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[a)] Forty-nine of the smartphone participants are included in this preliminary analysis.

boom transmission into buildings was performed by Jacob Klos. Predictions of sonic boom contours were performed by Christopher M. Hobbs. Analysis of smartphone participant responses was performed by Richard Horonjeff and Sanford Fidell.

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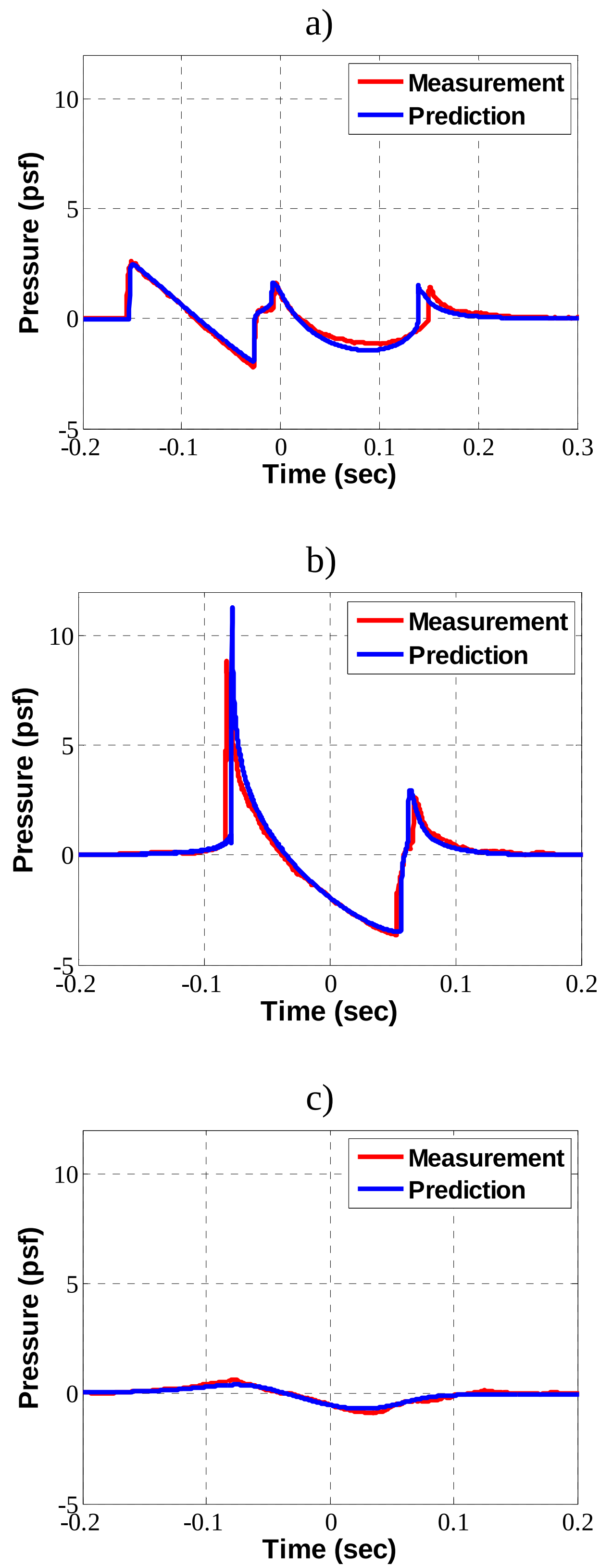

Fig. 1 – Comparison of measured focus booms with preliminary NTE model predictions for flight of an F-18B flying at Mach 1.23 and executing a -0.25 degree/second pushover maneuver at an altitude of 13,122 m. a) Post focus N-u region. b) Maximum focus. c) Evanescent wave.

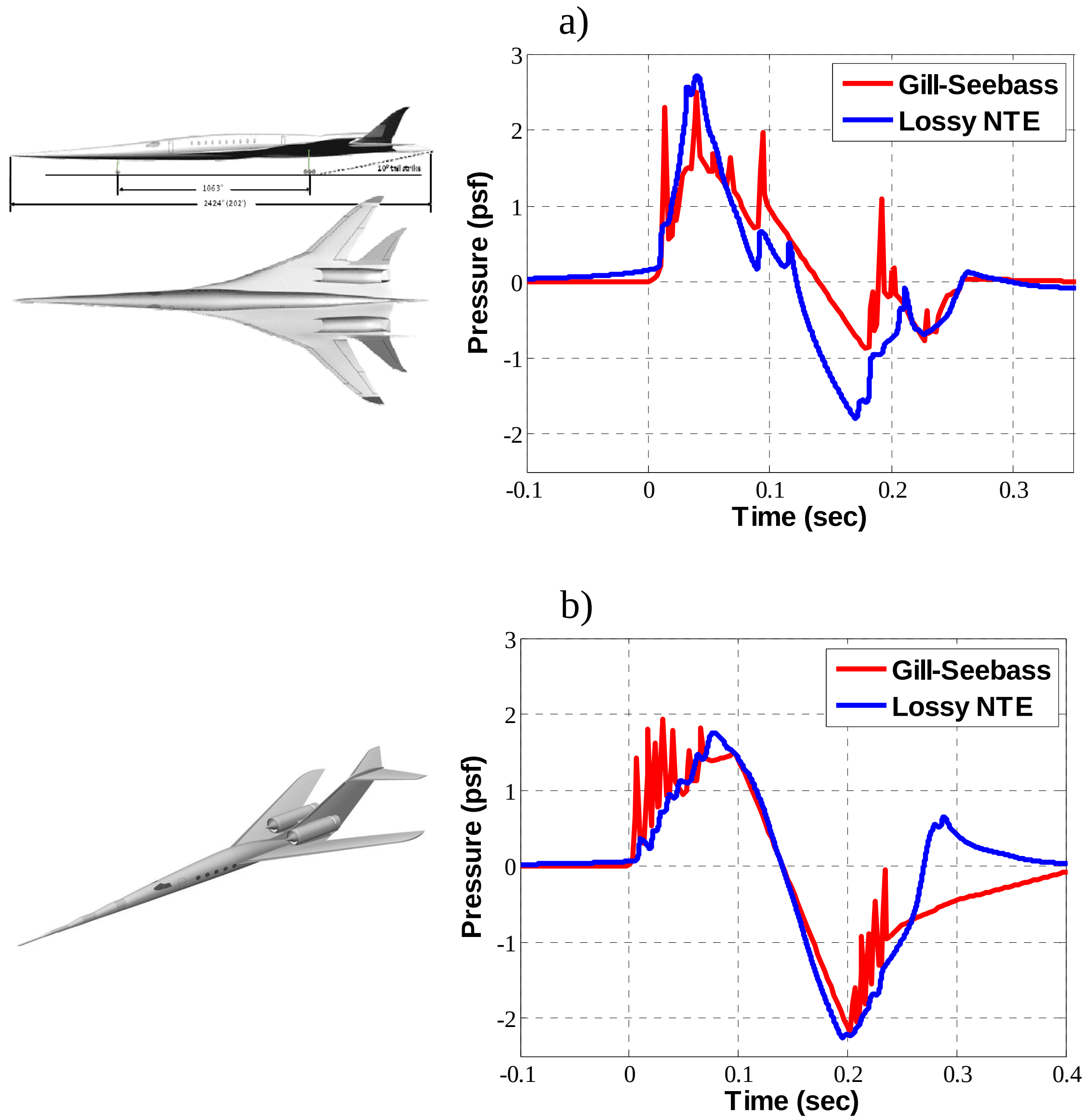

Fig. 2 – Preliminary comparison of predicted focus booms from the Gill-Seebass and NTE methods for low-boom shaped vehicle designs. a) Boeing N+2 SuperSonic Transport (SST)[8]. b) Gulfstream Quiet Supersonic Jet (QSJ)[9].

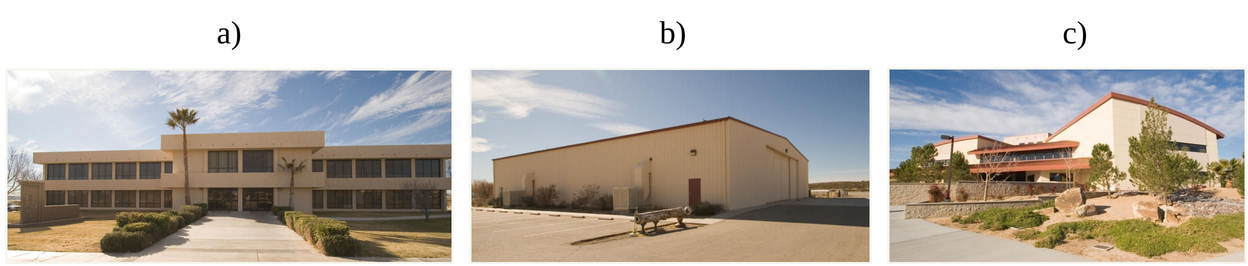

Fig. 3 – Three large buildings tested for transmission of sonic booms. a) Office building consisting of modular trailers. b) Museum hangar building. c) Modern office building.

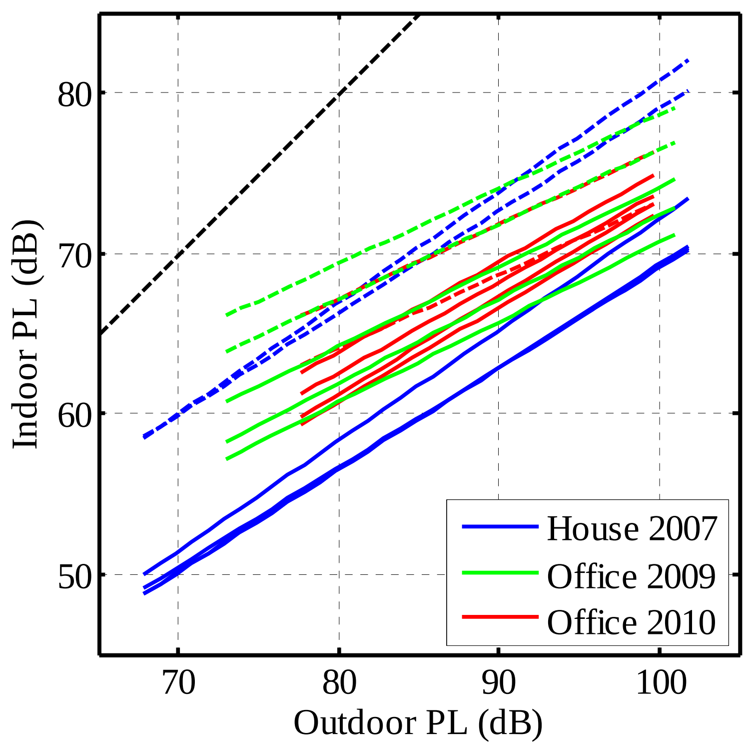

Fig. 4 – Indoor vs. outdoor Perceived Level (PL) for three low-amplitude sonic boom transmission field tests: house in 2007 (blue), modern office building in 2009 (green), and the same modern office building in 2010 (red). Measurements in environments with prominent rattle are depicted with dashed lines.

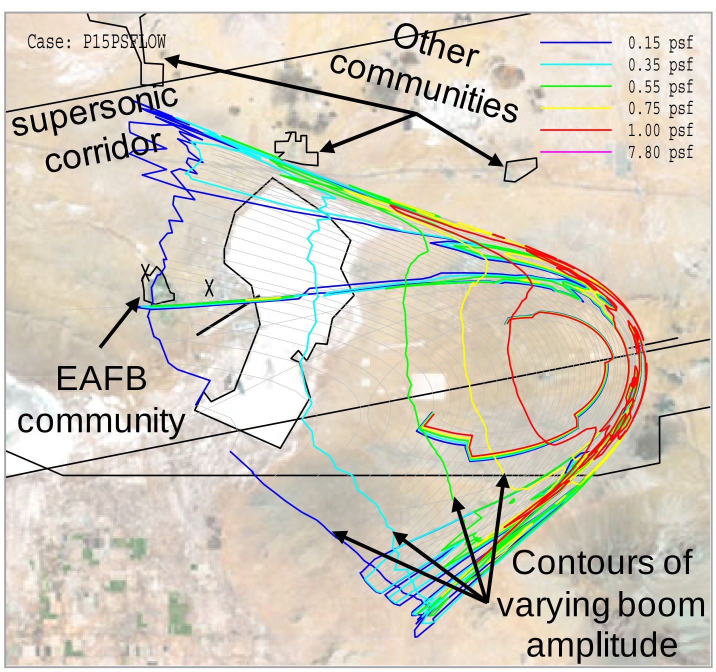

Fig. 5 – Example sonic boom contour predictions in relation to the EAFB community and nearby communities for the low-boom community response test.

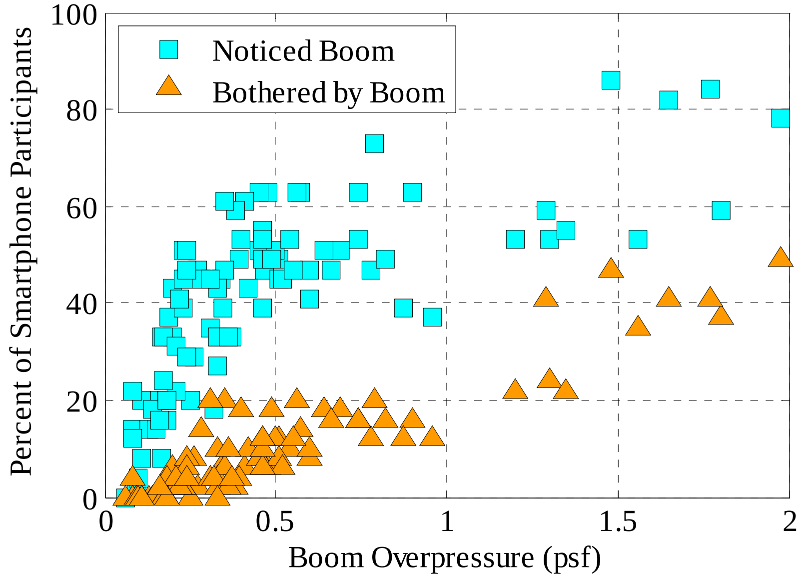

Fig. 6 – Preliminary dose-response data for the percent of smartphone participants noticing booms and being bothered by booms as a function of boom overpressure at a central location in the community during the low-boom community response test.