Project 042 Acoustical Model of Mach Cut-off Flight

Pennsylvania State University
University of Washington
Georgia Institute of Technology
Volpe National Transportation Systems Center

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University Participants

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- FAA Award Number: 13-C-AJFE-PSU-020
- Period of Performance: June 28, 2016 - December 31, 2017
- Task(s):
    1. Assess and extend modeling capability for Mach Cut-off events (a.k.a. Task 1A)
    2. Study human perception of Mach Cut-off sounds

University of Washington

- P.I.(s): Dr. Michael Bailey (PI)
- FAA Award Number: 13-C-AJFE-UW-005
- Period of Performance: June 27, 2016 – December 31, 2017
- Task(s):
    3. Determine feasibility for obtaining Mach Cut-off data via scale experiments

Georgia Institute of Technology

- P.I.(s): Dr. Dimitri Mavris (PI), Dr. Jimmy Tai (Co-PI)
- FAA Award Number: 13-C-AJFE-GIT-023
- Period of Performance: June 28, 2016 – August 14, 2017
- Task(s):
    4. Sensitivity Study (a.k.a. Task 1B)
    5. Evaluate technologies to enable Mach cut-off flight

Volpe National Transportation Systems Center (non-University, Interagency Agreement)

- P.I.(s): Juliet Page
- Volpe Project Number: FA5JCT
- Period of Performance: execution date – December 31, 2017
- Task(s):
    6. ASCENT Project 42 support

Project Funding Level

$170K, The Pennsylvania State University

$70K, Georgia Institute of Technology
$15K, University of Washington
$15K, Volpe National Transportation Systems Center

Aerion Corporation is providing cost-share matching funds to Penn State and U. Washington. Our point of contact at Aerion is Jason Matishek, jrmatisheck@aerioncorp.com. Aerion is providing the necessary near-field CFD data and other relevant information to help guide the project team make accurate predictions of the Mach cut-off sonic boom signatures that may be produced by Aerion's future supersonic aircraft.

Investigation Team

Pennsylvania State University
Principal Investigator: Victor W. Sparrow
Co-Investigator: Michelle C. Vigeant
Graduate Research Assistant Zhendong Huang (assessment and extension of Mach cut-off models)
Graduate Research Assistant Nick Ortega (human perception of Mach cut-off sounds)

University of Washington
Principal Investigator: Michael Bailey

Georgia Institute of Technology
Principal Investigator: Dimitri Mavris
Co-Investigator: Jimmy Tai
Research Faculty: Greg Busch
Graduate Research Assistants Ruxandra Duca & Ratheesvar Mohan

Volpe National Transportation Systems Center
Principal Investigator: Juliet Page

Project Overview

ASCENT Project 42 brings together resources to provide preliminary information to the FAA regarding the noise exposure of supersonic aircraft flying under Mach cut-off conditions. Studies in the 1970s showed that Mach cut-off supersonic flight was possible, but there is currently no data establishing the frequency and extent of noise exposures and no guidelines for managing such exposures. Penn State will lead a team of investigators from Penn State, University of Washington, Georgia Tech, and Volpe—each bringing unique contributions to shed light on the Mach cut-off phenomena.

Background for Project 42

Aerion Corporation and many others believe that Mach cut-off supersonic flight is both viable [Plotkin, et al., 2008] and very likely to be acceptable to the public. But there is a lack of data to back up this assertion. Thus, research needs to be conducted to provide a technical basis for rulemaking regarding Mach cut-off operations.

The basic concept of Mach cut-off relies on the fact that the ambient temperature is substantially colder at flight altitudes than on the ground. Hence, the speed of sound is substantially slower at flight altitudes than at the ground. As illustrated in Figure 42.1, it is possible to fly in a range of Mach numbers (perhaps between Mach 1.0 and Mach 1.15) while having the sonic boom noise refract (bend) upwards such that the rays never reach the ground. However, the reader should be aware that this picture is over-simplified since the temperature profile in the atmosphere is never a smooth, linear function as depicted here. For higher Mach numbers, the sonic boom will impact the ground before refracting upward.

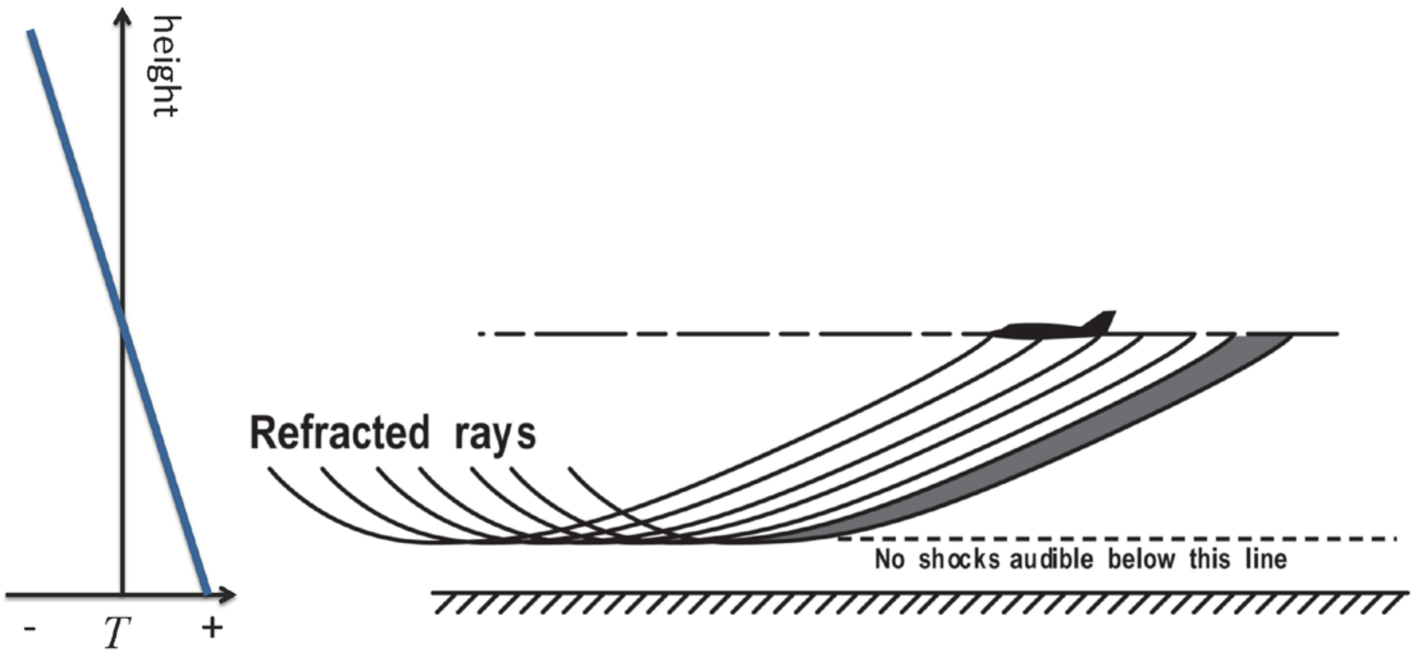

Figure 42.1: Simplified view of Mach cut-off where sonic boom noise does not reach the ground surface. Left: ambient temperature versus height. [Sparrow] Right: aircraft and ray diagram showing refraction of sonic boom [NASA].

Little is known about the noise impact of Mach cut-off operations for future supersonic aircraft. The concept of Mach cut-off was introduced by Lockheed engineers in the mid-1960s [Shurcliff, 1970]. NASA conducted some field experiments in the early 1970s, focusing on other speed regimes of flight, validating some of the Mach cut-off theory for some of the sound field. This research was conducted in Nevada with a 466 m (1,529 ft) tower [Haglund and Kane, 1973]. Then to more directly address the Mach cut-off issue, a theoretical and experimental study was conducted in the mid-1970s with FAA support. The studies estimated altitudes and Mach number regimes to ensure the focus boom does not reach the ground. That field campaign used fighter jets flying out of Langley AFB to a test area in the Atlantic Ocean off Wallops Island, Virginia [Perley, 1977]. Using the available instrumentation, the study concluded that Mach cut-off flight was feasible.

In none of those studies were any recordings made of sufficient quality to assess human response to the Mach cut-off noise. The theoretical studies estimating the altitude and Mach number restrictions for focus boom avoidance assumed a simple atmospheric model (linear sound speed profile), and did not include real-world atmospheric effects. Hence the 1960s-1970s work was very good, but is only a start to determining appropriate flight conditions for routine Mach cut-off supersonic flights over the continental United States.

Task 1A: Assess and Extend Modeling Capabilities for Mach Cut-off Events

Pennsylvania State University

Objectives and Research Approach

For Task 1A, the original propagation theory [Nicholls, 1971] will be retraced for extensibility and to incorporate the operational parameters proposed by Aerion. Ray calculations will be made to assess the back-of-the-envelope predictions for Mach cut-off operations that were known to the FAA in the 1970s. A number of existing tools such as NASA's PCBoom and/or sBOOM prediction codes will be employed to assess the robustness of the theory to realistic atmospheric conditions. Aerion will provide key Computational Fluid Dynamics (CFD) input data to initialize the propagation predictions for the Mach cut-off noise. Volpe will provide guidance on using near-field CFD solutions as inputs to the boom prediction codes [Plotkin and Page, 2002].

Milestones and Accomplishments

The project just began in August 2016. The Nicholl's theory is being investigated thoroughly and results will be available in Spring 2017.

References

G. Haglund and E. Kane, "Flight test measurements and analysis of sonic boom phenomena near the shock wave extremity," NASA Report CR-2167 (1973).
J. Nicholls, “A note on the calculation of `cut-off’ Mach number,” Meteorological Mag. **100** 33-46 (1971).
R. Perley, “Design and demonstration of a system for routine, boomless, supersonic flights,” FAA Report No. FAA-RD-77-72 (1977).
K. Plotkin and J. Page, "Extrapolation of sonic boom signatures from CFD solutions," AIAA paper 2002-0922, 40th Aerospace Sci. (Reno, NV, January 2002).
K. Plotkin, J. Matisheck, and R. Tracey, "Sonic boom cutoff across the United States," AIAA paper 2008-3033, 14th AIAA/CEAS Aeroacoustics Conf. (Vancouver, BC, Canada, May 2008).
W. Shurcliff, "S/S/T and sonic boom handbook," (Ballentine, 1970), p. 63.

Task 2: Study Human Perception of Mach Cut-off Sounds

Pennsylvania State University

The experimental design of a perceptual study to investigate the subjective response to Mach cut-off sounds is nearly complete. The stimuli for this study will be recordings selected from NASA’s “Farfield Investigation of No-boom Thresholds” (FaINT) field measurements. To select sounds for this subjective listening test, over 400 recording were listened to and categorized based on the perceived quality of the sounds. The listening test has been designed to have two parts: (1) a vocabulary development study, and (2) an annoyance rating study. To this point the vocabulary study has been designed as an exploratory study, where subjects will be asked to provide descriptors of recorded Mach cut-off sounds. Some of these descriptors will be selected for use in the follow up annoyance rating study.

L. Cliatt, *et al.*, "Lateral cutoff analysis and results from NASA's farfield investigation of no-boom thresholds," NASA TM-2016-218850 (2016).

Task 3: Determine Feasibility for Obtaining Mach Cut-off Data Via Scaled Experiments

University of Washington

Task 3 is a limited study at the University of Washington to determine the feasibility of laboratory-scale measurements of Mach cut-off. Previous work in Europe [H. Hobaek, *et al.,* 2006] has shown that a refracting medium can be created in a water/ethanol mixture, and ultrasonic waves can be bent in the refracting medium, just like Mach cut-off waves are refracted in the atmosphere. The results of this pilot study will show if such small-scale experiments are possible, as full-scale flight tests are prohibitively expensive. Lab tests with ultrasound can run continuously for hours, and one can easily probe anywhere in the test tank. If viable, it would be very attractive to introduce turbulence into the refractive medium (similar to turbulence in the atmosphere) and evaluate if the turbulence-scattered energy increases the Mach cut-off sound heard on the ground. It was thought by some in the 1970s that turbulent scattering of the focus boom noise down to the ground would render Mach cut-off operations unacceptable [Shurcliff, 1970]. Future laboratory work could investigate this effect.

The UW team has attended the teleconferences to better understand the Program's efforts and challenges and had monthly internal meetings to begin the planning process. The modification to the proposed design that is under consideration is to not replicate the mixture of fluids as done by Hobaek, but to build a more permanent, fixed, controllable and durable atmospheric analogue from layers of gels. These gels behave very much like fluids with negligible shear wave generation but hold their form. We are also practiced at manipulating what may be more levers to adjust the local speed of sound, attenuation, inhomogeneities, and nonlinearity than with layered fluids alone. NASA is currently funding us to develop similar acoustic phantoms for medical ultrasound training and investigation.

H. Hobaek, *et al.*, "Experiment on finite amplitude sound propagation in a fluid with a strong sound speed gradient," in *Innovations in Nonlinear Acoustics: 17th Intl. Symposium on Nonlinear Acoustics*, Conf. Proc. 838 (American Institute of Physics, 2006).
W. Shurcliff, "S/S/T and sonic boom handbook," (Ballentime, 1970), p. 63.

Task 4 (a.k.a. 1B): Sensitivity Study

Georgia Institute of Technology

Objectives

Georgia Tech's primary task for the ASCENT 42 project is to perform a sensitivity study on the acoustical model for Mach cut-off flight. This task aims to identify the major variables that can impact a supersonic aircraft's ability to fly (and maintain) Mach cut-off and determine the sensitivity of Mach cut-off flight to these variables. This will be determined by assessing both atmospheric variability and flight condition variability. This task will be performed for both a standard vehicle model (the F-18 input model in PCBoom), as well as a model representative of Aerion Corporation's AS2 vehicle. Aerion's vehicle will be assessed using data provided by Aerion under ASCENT 42. The final objective of this task is to determine the sensitivity of Mach cut-off flight to various parameters for Aerion's proposed concept in order to provide insight on the degree of robustness for Mach cut-off flight as it pertains to a supersonic business jet. The hope of this task is to help provide Aerion, the FAA, and the aerospace community at large, a better understanding of how feasible Mach cut-off flight could be and to assist in guiding policy regarding supersonic flight using Mach cut-off.

Research Approach

The research approach for this task is heavily dependent on data, advice, and research to be provided by the other member of the ASCENT 42 team. The final results of this task will be reliant on data from Aerion, advice and guidance from Volpe and NASA, and research performed at Penn State University. The first goal of the research to be performed by Georgia Tech is to understand the mechanics and operating procedures of NASA's PCBoom. This involves running test cases, analyzing results, and understanding the data both given and received from the program. PCBoom will be the primary method in which Georgia Tech will assess the sensitivity of Mach cut-off flight.

The first step in the process is to execute a "preliminary" sensitivity study using PCBoom and the provided F-18 geometry to understand the code and determine if the results make physical sense. This will be done by running the F-18 model through PCBoom at various flight conditions (steady-level flight, acceleration, and a handful of maneuvers) to determine if Georgia Tech has a good handle on the PCBoom settings required to accurately generate results. This model will also be run through various atmospheric conditions as well. The results of this preliminary study will be presented to the ASCENT 42 team to gather their opinions, advice, and suggestions regarding the execution of PCBoom.

After the first step is completed, the AS2 (from Aerion) will be incorporated into PCBoom and a proposed design space of runs will be presented to the ASCENT 42 team. Next, the modeling space that captures the desired combinations of atmospheric and flight conditions will be agreed upon. Since PCBoom, as it currently stands, may encounter numerical error close to Mach cut-off flight, it will be important to incorporate the research being conducted at Penn State University in order to remedy this issue. Georgia Tech will execute a large set of runs through PCBoom to gather the results. An agreed upon metric for assessing the impact of sonic booms, evanescent waves, and Mach cut-off conditions will need to be agreed upon by the ASCENT 42 team and the FAA. Georgia Tech will then present the results of this study to show how sensitive Mach cut-off flight is to both atmospheric and flight conditions.

Milestones

- Research plan for task was completed
- First quarterly report was submitted
- PCBoom 6.7 was received from NASA
- Volpe (Juliet Page) provided instruction on how to use PCBoom
- Initial data from Aerion was received for AS2 at Mach 1.4 undertrack.

Major Accomplishments

Georgia Tech has completed the research plan for this task. Georgia Tech has also acquired both the source code and executable for PCBoom 6.7. This program will be used to perform the sensitivity analysis on the acoustical model provided by Aerion, Volpe, and Penn State University. Georgia Tech has begun learning syntax and operation of PCBoom and has spent a significant amount of time delving into the user's manual to fully understand each component of an input file and the resulting output files generated by the program. Georgia Tech has started an initial study for the sensitivity of Mach cut-off flight on a standard sonic boom signature (F-18 geometry provided with the executable). Georgia Tech has assessed the sensitivity of the resultant boom strength and shape of the F-18 model with variations in atmospheric temperature and humidity as well as various flight Mach numbers. An example of the preliminary results to temperature gradient can be seen in Figure 42.2. It should be noted that these are preliminary results and will change as Georgia Tech becomes more familiar with PCBoom. Georgia Tech has already received valuable guidance from Volpe on how to improve the results generated by PCBoom to account for molecular relaxation and numerical error. These results will mostly likely change at a later date as well, once the model for Mach cut-off flight is received from Penn State University and incorporated into PCBoom. Currently, the immediate goals of this task for the upcoming weeks is to incorporate the suggestions made by Volpe, execute the sensitivity for various wind patterns, assess the sensitivity of the F-18 model to different flight conditions, and incorporate the pressure field data by Aerion into PCBoom.

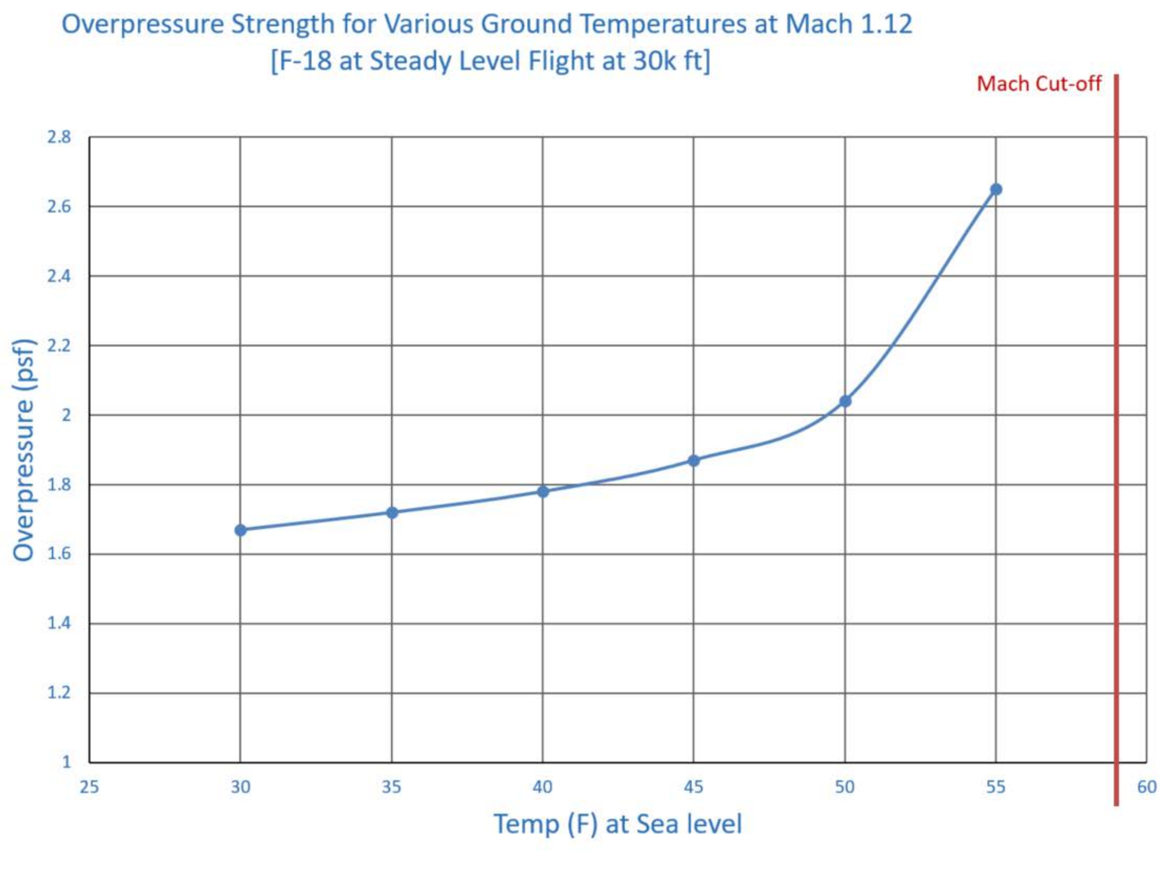

Figure 42.2: Example of Preliminary PCBoom Sensitivity Runs for F-18 Model

Task 5: Evaluation of Technologies to Facilitate Mach Cut-off Flight

Georgia Institute of Technology

Objectives

The objective of this task is to identify and evaluate technologies that could be utilized to facilitate Mach cut-off flight. This task will primarily focus on nearer-term technologies that could be utilized by supersonic business jets. Most of these potential technologies will be external to the aircraft or technologies that can be placed on an aircraft with minimal to no change in the design. However, Georgia Tech will also investigate more long-term technologies that could be integrated into future aircraft designs and could potentially be applicable to larger supersonic aircraft.

Research Approach

Georgia Tech's research approach in this task is primarily through literature review and solicitation of opinions from experts in the fields of aerospace, policy making, meteorology, and manufacturing. Georgia Tech will perform this task in a phased approach. The first phase is performing an initial literature survey to identify potential technologies that would benefit Mach cut-off flight. Based on the team's initial knowledge and understanding of Mach cut-off flight, the first phase of literature review will target technologies that could make it easier for operators of supersonic business jets to identify or predict atmospheric conditions. These technologies will undergo a cost-benefit type of evaluation to identify both the strengths and potential weakness of each technology. At the time of writing, this first phase has been completed by the Georgia Tech team.

The second phase of this task will be done in concurrence with task 4. This phase will focus on researching more long-term technologies that could be of benefit to Mach cut-off flight. These technologies might impact the design of a supersonic aircraft, or may require additional aircraft capabilities (not available on current aircraft) in order to utilize them to their fullest potential. Some technologies that have been suggested include: active flow control, morphing structures, boom-spikes, etc.

The final phase of this task will be done after the sensitivity study from task 4 has been completed. With the knowledge and insight gained through performing task 4, the ASCENT 42 research team will have a better understanding on how flight conditions and atmospheric conditions impact the capability of a supersonic aircraft to fly at Mach cut-off. This will allow the Georgia Tech team to identify any additional technologies that were overlooked during the initial phases of this task. This phase of research will also identify which technologies have the best potential impact (and least amount of cost), and Georgia Tech will do more research and evaluation of these "big-hitter" technologies, as well as reaching out to subject matter experts to provide opinions on these technologies. The result of this phase will be a portfolio of technologies that will be able to guide investment in technologies to facilitate Mach cut-off flight.

Milestones

- Research plan for task was completed
- First quarterly report was submitted
- Phase 1 of task was performed

Major Accomplishments

After ASCENT 42 project was initiated, Georgia Tech created a research plan for this task. Since Georgia Tech had a period of time before PCBoom was acquired, it was determined that this task would be done in separate phases. The first phase of this task was started soon after the start of the project and has continued until the present (although work on this task has taken a back-seat to task 4 after Georgia Tech received PCBoom). During the first phase of this task, Georgia Tech has identified a number of technologies that could potentially be used or adapted for facilitation of Mach cut-off flight. An example of some of these technologies can be seen in Figure 42.3. Research for phase two of this task will begin in the coming months of the overall ASCENT 42 research effort.

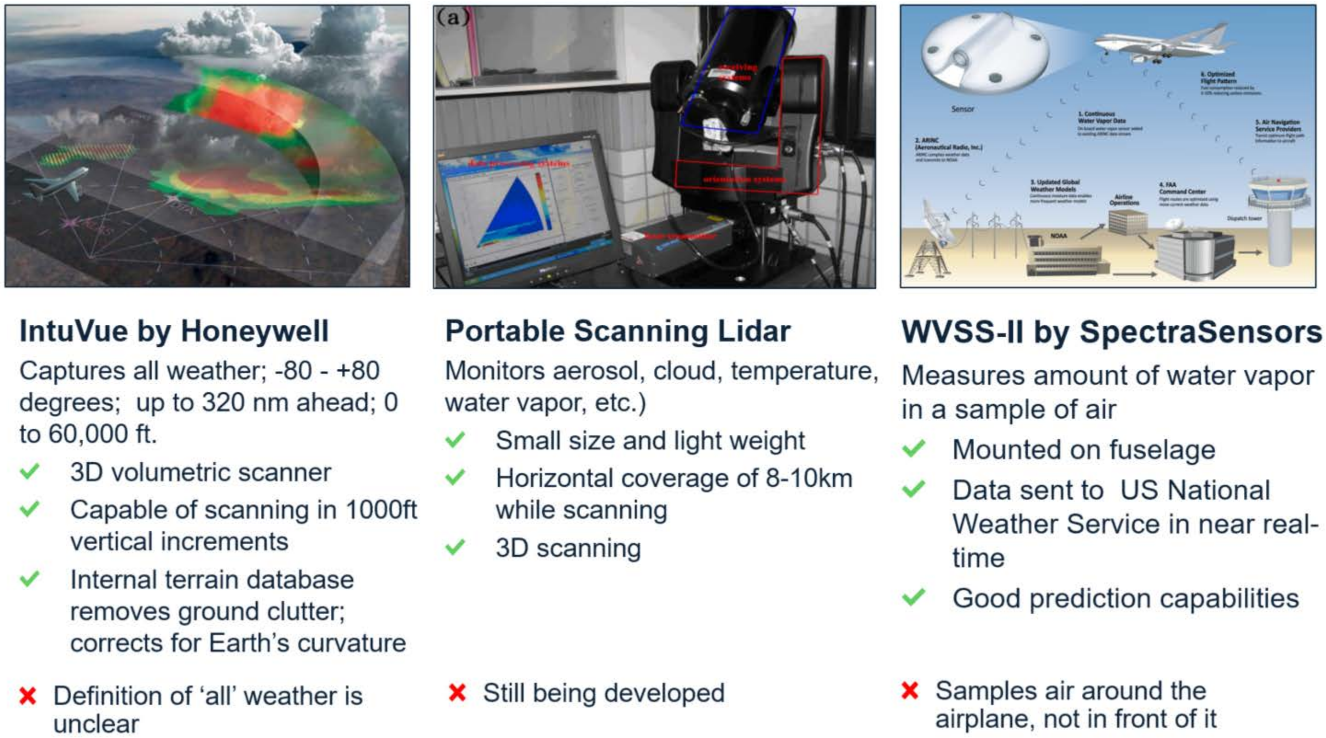

Figure 42.3: Example Technologies from First Phase of Research

Task 6: ASCENT Project 42 Support

Volpe National Transportation Systems Center

Volpe is supporting this project by providing PCBoom modeling expertise, including Mach cut-off and CFD source characteristic as well as specific sonic boom analysis guidance to the ASCENT 42 team.

Major Accomplishments

Volpe has provided initial sonic boom modeling guidance on using suitable CFD-solutions for supersonic aircraft configurations as source inputs to PCBoom. Documentation regarding coordinate system, orientation and CFD pressure extraction protocols has been provided to the ASCENT 42 team. Volpe support included a PCBoom Web based training session for Project 42 participants on November 9th, 2016. This training session was recorded by PSU and has been made available to team members. A set of training briefings, sample input files and test cases were provided to participants and reviewed during the training class.

Examples covered in the PCBoom training class included the following:

- Level flight from an F-18 using the simple Carlson source model
- Assessing Mach and lateral cut-off
- CFD pressure distribution inputs using the NASA LM1021 publicly available dataset
- Burgers loudness propagation applying molecular relaxation

In order to effectively build PCBoom analysis capability amongst team members, Volpe has recommended starting with cruise flight condition analysis and then reducing the Mach number to include acceleration to Mach cut-off conditions. This will lead towards eventual assessment of atmospheric and terrain variability on Mach cut-off using PCBoom.

Volpe has provided some initial guidance to Aerion regarding the development of PCBoom input cylinder formatted data and continues to work with them regarding specific file formatting protocols for PCBoom. Aerion has established an FTP file transfer site and has provided near-field pressure characteristics from CFD for the cruise flight condition. Volpe has assisted with development of cruise pressure input definition PCBoom files based on Aerion's cruise configuration CFD data.

Supporting Information

Publications

N/A. The project began in August 2016.

Outreach Efforts

N/A. The project began in August 2016.

Awards

V. Sparrow gave the 2016 Rayleigh Lecture to the American Society of Mechanical Engineers (ASME) Noise Control and Acoustics Division on November 15, 2016 at the 2016 International Mechanical Engineering Congress and Exposition in Phoenix, AZ. The title of the talk was "Two approaches to reduce the noise impact of overland civilian supersonic flight."

Student Involvement

Penn State: Graduate Research Assistant Zhendong Huang is a key participant in Task 1A. Graduate Research Assistant Nick Ortega is a key participant in Task 2.

Georgia Tech: Ruxandra Duca and Ratheesvar Mohan have both preformed significant work under task 4 and task 5. They are integral parts of the Georgia Tech research team and have worked diligently in researching technologies pertaining to Mach cut-off flight as well as learning how to operate PCBoom and analyze the output/results. Both students attend weekly research meetings and provide deliverables to the Georgia Tech ASCENT 42 research team.

Plans for Next Period

Continue the work described above.