Project 042 Acoustical Model of Mach Cut-off Flight

Pennsylvania State University
University of Washington
Georgia Institute of Technology
Volpe National Transportation Systems Center (non-University IAA)

Project Lead Investigator

Victor W. Sparrow
Director and Professor of Acoustics
Graduate Program in Acoustics
Penn State
201 Applied Science Bldg.
University Park, PA 16802
+1 (814) 865-6364
vws1@psu.edu

University Participants

Pennsylvania State University

- P.I.(s): Dr. Victor W. Sparrow (PI), Dr. Michelle C. Vigeant (Co-PI)
- 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. Develop a test plan for laboratory experiments for Mach cut-off that might be possible in the future

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 of Mach Cut-off flight
    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

FAA funds were distributed at the following levels:
$170K, The Pennsylvania State University
$15K, University of Washington
$70K, Georgia Institute of Technology
$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 R. Bailey PhD, University of Washington
Wayne Kreider, PhD, source characterization, University of Washington
Oleg A. Sapozhnikov, DSc, atmospheric stratification, University of Washington
Vera a. Khokhlova, DSc, numerical simulation, University of Washington
Barbrina Dunmire MS, gel layer fabrication, University of Washington
Julianna Simon PhD, postdoc, University of Washington

Georgia Institute of Technology
Principal Investigator: Dimitri Mavris
Co-Investigator: Jimmy Tai
Research Faculty: Greg Busch
Graduate Research Assistant: Ruxandra Duca
Graduate Research Assistant: 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.

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 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.

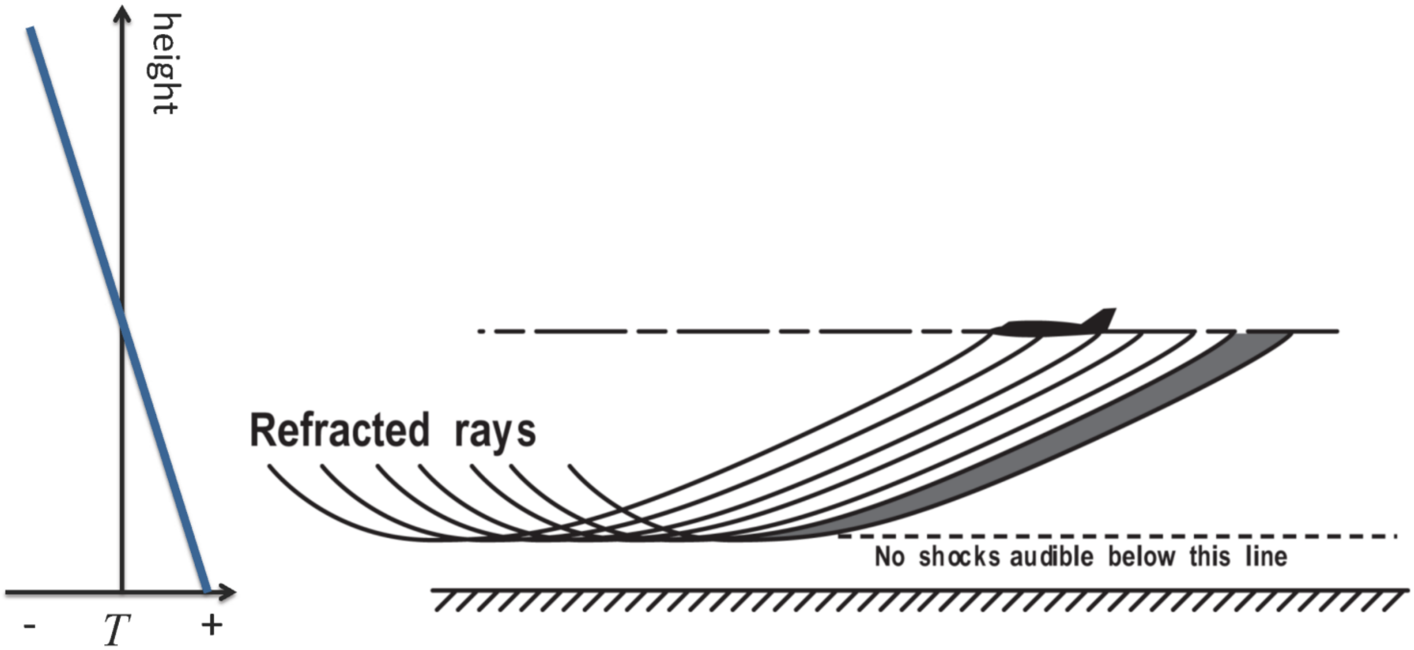

Figure 1 - Simplified view of Mach cut-off where sonic boom noise does not reach the ground surface. Left: ambient temperature versus height. [Sparrow] Right: aircraft and ray diagram showing refraction of sonic boom [NASA].

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.

ASCENT Project 42 is a joint effort between the participants. Georgia Tech is responsible for Tasks 4 & 5 and the final report-out for these tasks are detailed in this report.

<u>**NOTE:**</u> As Georgia Tech, the University of Washington, and Volpe are concluding their efforts in ASCENT Project 42, those task reports are given first. The tasks at Penn State, which are continuing, are provided last.

Task #4: Sensitivity Study of Mach Cut-off Flight

Georgia Institute of Technology

Objective(s)

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 is 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 is assessed using computational data provided by Aerion under ASCENT 42. Through studying the sensitivity of Mach cut-off flight to atmospheric conditions, the ASCENT 42 team aims to provide insight on the degree of robustness for Mach cut-off flight as it pertains to a supersonic business jet. The goal of this task is to help provide Aerion (and other supersonic aircraft developers), 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

Introduction

The research approach for task 4 was heavily dependent on data, advice, and research provided by the other members of the ASCENT 42 team. Throughout the first year of the ASCENT Project 42, the various members had a lot of interaction and shared opinions and insights into each other's work – which has worked very well for this effort. Project 42, as a whole, has been very collaborative and GT acknowledges and thanks the other team members for their continued assistance and enthusiasm. The Acoustical Model for Mach Cut-off Flight project has thrived in this collaborative environment.

The preliminary step of the research performed by Georgia Tech for the sensitivity study was to select a tool for the analysis. Since NASA's PCBoom (v6.7) was made available to the Project 42 and Juliet Page of Volpe was brought in as a participant in the project, PCBoom was decided to be the primary method in which Georgia Tech assessed the sensitivity of Mach cut-off flight. This required Georgia Tech to understand the mechanics and operating procedures of NASA's PCBoom. This involved running test cases, analyzing results, and understanding the data required to input into PCBoom as well as breaking down the output and understanding what the program was calculating and how it was preforming the analyses. This preliminary step in the research approach took approximately one month, which was expedited primarily due to the help and guidance from Juliet Page in instructing the Georgia Tech researchers and students on intricacies of PCBoom and how to properly run a sonic boom analysis using the software.

The preliminary sensitivity study using PCBoom and the provided F-18 geometry was performed to understand the code and determine if the results made physical sense. This was 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 had a good handle on the PCBoom settings required to accurately generate results. This model was run through various atmospheric conditions. The results of this preliminary study was shared with the ASCENT 42 participants to gather their opinions, advice, and suggestions regarding the execution of PCBoom. After a few iterations, the GT team developed a comfortable level of knowledge of PCBoom and was able to produce results for both Mach cut-on and cut-off flight.

After the analysis tool was selected and learned, the Georgia Tech team laid out a plan for the research approach for Task 4. This plan included four step for the sensitivity study of Mach Cut-off Flight:

- PCBoom Wrapper – Develop a capability to run large amounts of analyses automatically and rapidly
- Atmospheric Profiles – Create / Gather a large library of both "standard" and "realistic" temperature profiles (include temperature, relative humidity, and horizontal winds)
- Sensitivity Study: Standard Profiles – Perform study for both F-18 signature and Aerion AS2 signature for various flight conditions in standard atmospheric profiles
- Sensitivity Study: Realistic Profiles - Perform study for both F-18 signature and Aerion AS2 signature for various flight conditions in realistic atmospheric profiles

The research plan allows Georgia Tech to show how sensitive Mach cut-off flight is to both flight conditions and a wide range of atmospheric profiles, and assess the robustness supersonic Mach cut-off flight. Georgia Tech's goal was also to determine the key factors that drive the sensitivity. Through the results, Georgia Tech seeks to assist other participants in Project 42, the FAA, and the supersonic industry in understanding Mach cut-off and assessing its feasibility as a method of over-land supersonic flight. The details of each phase of the research plan are described in the following sections as well as the results of Task 4: Sensitivity Study of Mach Cut-off Flight.

PCBoom Wrapper

To facilitate the execution of Task 4, Georgia Tech decided to develop a capability to easily and rapidly execute PCBoom to generate large amounts of data for analysis. The effects of atmospheric variables and flight conditions on sonic boom metrics and cut-off conditions were investigated through sensitivity studies. The variables – temperature, humidity, and wind – were systematically modified to produce various atmospheric profile combinations, or "cases". The near-field noise signature was then propagated through these profiles and the results were recorded for further analysis. The computational tool used to obtain the results – PCBoomv6.7 – had several executable programs that required numerous inputs and produced various output files. To efficiently run all the cases, the process was automated by creating a wrapper in a different tool – Matlab. The wrapper's purpose was to read a table of cases (created a priori in Excel), go through each of them, create all the required input files, run the relevant executable programs, parse the output files, and record the metrics of interest in an Excel sheet.

To propagate a noise signature, PCBoom required a main input file, a trajectory file and an atmospheric file. These were produced by copying templates created as part of the pre-processing stage and replacing specific portions with data from the table of cases. After the program was run, the cut-off conditions, noise metrics, and the noise signature at the ground were read from various output files and recorded in a table of results. All files generated for each case were saved for archiving purposes. The process is illustrated in the following figure:

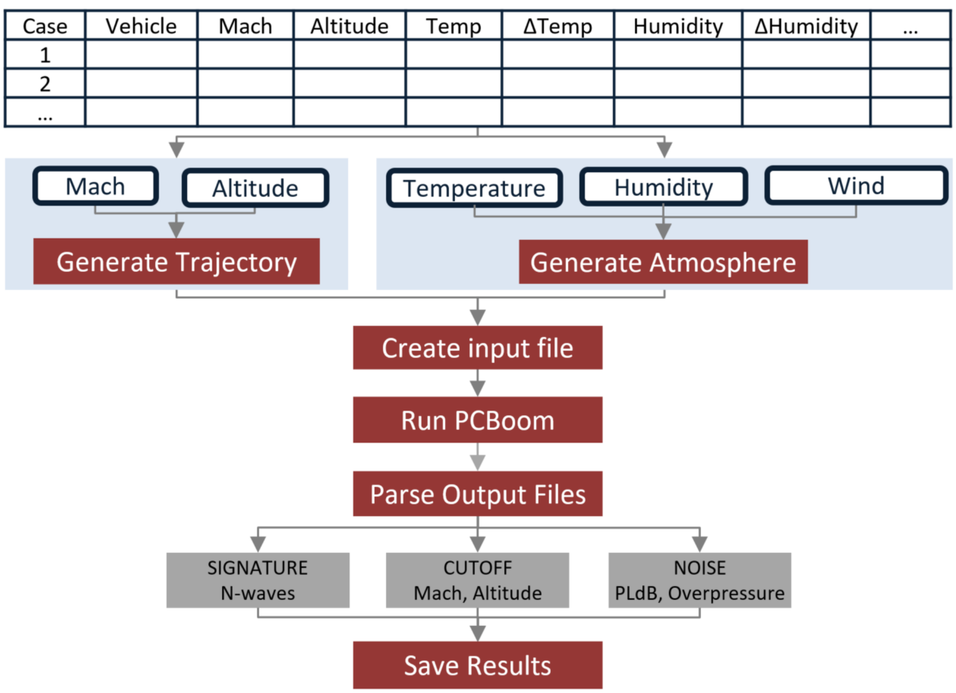

Figure 2 - PCBoom Wrapper Flowchart

Inputs – Trajectory File
For the purpose of this project, only steady, level, un-accelerated flight was considered. This was decided upon through consensus with the entire Project 42 team in an effort to scope the project to accomplishable tasks for the first year. Thus, a point trajectory was sufficient, where only the flight altitude and Mach number were specified. Based on the flight conditions read from the table of cases, the wrapper created a trajectory file by replacing placeholders in a template file with the desired Mach and altitude of the aircraft.

Inputs – Atmospheric File
Two main types of atmospheric profiles were analyzed for this project: standard and realistic. The standard profiles were mathematical descriptions of the variable profiles as functions of altitude. The realistic ones involved real weather data from various locations in the United States. To generate the atmospheric file required by PCBoom, several operations were needed as described further. Note: this section will detail the generation of the standard atmospheric profiles in the PCBoom Wrapper and how the wrapper uses the profiles. A more detailed description of the realistic atmospheric profiles and reasoning behind various standard atmospheric profiles are enumerated in the Atmospheric Profiles phase following the complete description of the PCBoom Wrapper.

Standard profiles
The standard profile used in PCBoomv6.7 is the U.S. Standard Atmosphere, No Winds, ANSI S1.26 Annex C. The first step in creating varying standard profiles was to specify the type of profile desired. The options are shown in the following table.

Table 1: Reference profile types for standard atmospheres

Temperature	Humidity	Wind
Linear	Standard	Constant
Constant	Constant	No wind
Concave	No humidity	
Convex		

For each of the temperature options, the tropopause temperature was set to -56.5°C and the variation was created with mathematical formulae based on the ground temperature, as specified in the table. The following figure illustrates how a ground temperature of -7°C and one of 49°C result in different profiles.

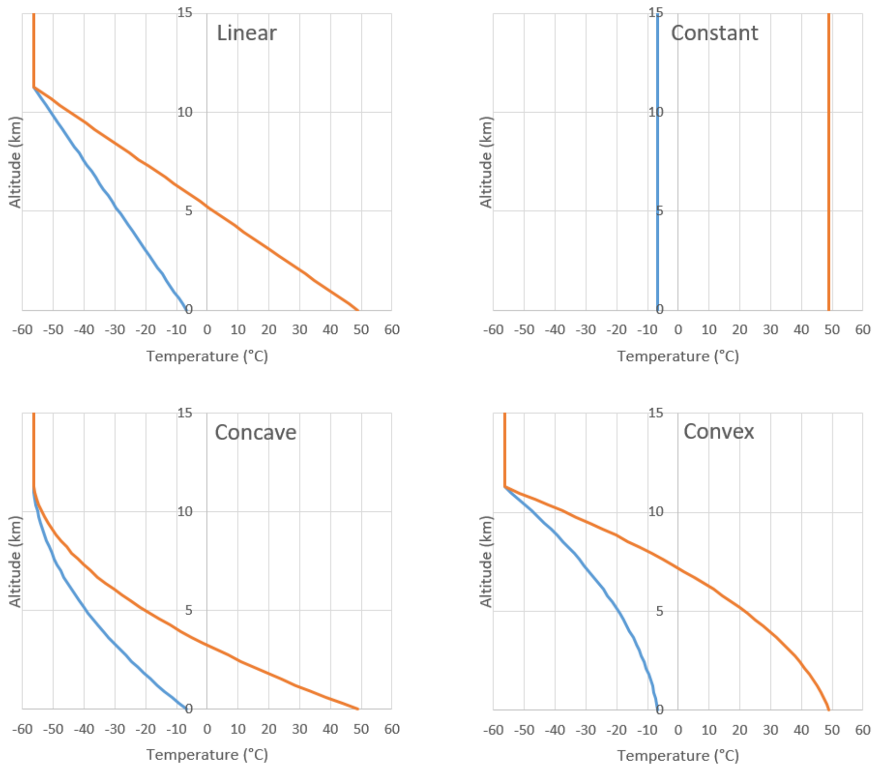

Figure 3 - Variation of Temperature Profiles: Linear, Constant, Concave, Convex

For humidity, the standard profile (which was the US standard ANSI 1976 atmosphere) was varied by shifting the entire curve by a value specified in the table, without going outside of the range 0-100%. The constant humidity profile was simply set to the value specified at all altitudes, while no humidity meant 0% for all altitudes. The only available wind profiles were no wind or constant wind in various directions. For the latter, the magnitude and direction read from the table were used to calculate the x and y components of the wind at each altitude. The resulting curves for temperature, humidity, and wind in both x and y directions were written in the atmospheric file following the format required by PCBoom. This process was repeated for each case.

Realistic profiles
The second type of atmospheric files was based one real weather data gathered a priori (The details of the gathering and creation of these profiles is detailed in the next phase of Task 4). Five locations were chosen to be representative of the following combinations of temperature and humidity: humid and hot, humid and cold, arid and hot, arid and average temperature, and finally arid and cold. Five templates with this data were created. Then, the wrapper picked the corresponding profiles from the templates and shifted them based on the specifications of each case. A new atmospheric file was generated for each case. An example of this would be: humid/cold reference profile where the temperature is shifted by +10˚C, the humidity by -10%, and the wind by +40 m/s in magnitude and -10˚ in direction.

Inputs - Main File
Once the auxiliary files – the trajectory and the atmosphere – were generated, the main input file was created. To do this, the wrapper made a copy of a template file and replaced placeholders with the following data:

- Vehicle, as specified in table (Aerion AS2 or generic supersonic aircraft available in the PCBoom library)
- Format of near-field signature and propagation mode (done automatically based on the vehicle type)
- Angle where noise metrics are to be recorded (such as 0˚ for directly undertrack)

Running PCBoom

Two executable programs were of interest in this project: FOBoom and PCBurg. FOBoom was the main boom calculation program and its outputs included ray paths and ray tube areas to be used by PCBurg, as well as cut-off conditions: maximum Mach to maintain cut-off flight at current altitude and minimum altitude to maintain cut-off flight at current Mach. This executable, however, did not account for the effects of humidity and temperature. Thus, PCBurg was subsequently used to consider the added effects of molecular relaxation on sonic boom signature evolution. This tool propagated the near field signature in increments of 304.8 m, all the way down to the ground (if cut-off did not occur) through the atmospheric profiles specified in the input files. To propagate the signature, the wrapper read the following options for PCBurg from the table

- Sampling rate (available options were 10000, 25600, 512000, and 102400 Hz)
- Activation of the anti-Gibbs filter
- Angle for the desired ray (which matched the one in the input file)

The wrapper ran each case in batch mode and placed all the generated files in various folders for storage. The following table shows an example of the required “table of cases”. It contains all the data necessary to create the required input files described previously and to run the program.

Table 2 - Inputs in the table of cases to be used by the PCBoom wrapper

	Flight Conditions			Atmospheric Conditions							Run Conditions		
Case	Vehicle	Mach Number	Altitude (m)	Temperature Profile	Temperature Delta from 15 (°C)	Humidity Profile	Humidity Delta (%RH)	Wind Profile	Wind Magnitude Delta (ft/s)	Wind Direction Delta (deg)	PHI	SR	Gibbs
1	F-18	1.4	13716	Linear	-61.7	Standard	0	No Wind	0	0	0	1	1
2	F-18	1.4	13716	Linear	-58.9	Standard	0	No Wind	0	0	0	1	1
3	F-18	1.4	13716	Linear	-56.1	Standard	0	No Wind	0	0	0	1	1
4	F-18	1.4	13716	Linear	-53.3	Standard	0	No Wind	0	0	0	1	1
5	F-18	1.4	13716	Linear	-50.6	Standard	0	No Wind	0	0	0	1	1
6	F-18	1.4	13716	Linear	-47.8	Standard	0	No Wind	0	0	0	1	1
7	F-18	1.4	13716	Linear	-45	Standard	0	No Wind	0	0	0	1	1
8	F-18	1.4	13716	Linear	-42.2	Standard	0	No Wind	0	0	0	1	1
9	F-18	1.4	13716	Linear	-39.4	Standard	0	No Wind	0	0	0	1	1
10	F-18	1.4	13716	Linear	-36.7	Standard	0	No Wind	0	0	0	1	1

Parsing the outputs

The cut-off conditions, namely the maximum Mach to maintain cut-off flight at current altitude and minimum altitude to maintain cut-off flight at current Mach, were obtained from a text file outputted by FOBoom. Then, if the given case was not cut-off, PCBurg produced several noise metrics including the loudness (in PLdB), the maximum overpressure (in psf) and A- and C- weighted sound exposure levels (in PLdB). The noise signature at the ground was also an output of PCBurg. All these values as well as the corresponding input values were recorded in a Matlab file for easy manipulation and post-processing. The wrapper also generated an Excel spreadsheet with all the resulting data (with the exception of noise signatures which are saved in a separate Matlab file). The following table shows the columns of outputs that are appended to the table of inputs cases described in Table 2:

Table 3: Outputs of the PCBoom Wrapper

Max Overpressure (Pa)	Loudness (PLdB)	ESEL	CSEL	ASEL	Max Mach for Cut-off	Min Altitude for Cut-off
44.529	95.34	114.18	102.11	80.38	1.0618	0
45.007	95.34	114.19	102.28	80.15	1.0678	0
45.486	95.69	114.23	102.5	80.65	1.0738	0
45.965	96.28	114.24	102.7	81.54	1.0798	0
46.444	96.98	114.25	102.87	82.58	1.0857	0
46.444	97.71	114.25	103.01	83.63	1.0916	0
46.444	98.39	114.25	103.1	84.57	1.0974	0
46.444	98.88	114.26	103.18	85.29	1.1033	0
46.444	99.26	114.25	103.19	85.67	1.1091	0
45.965	99.39	114.24	103.19	85.91	1.1148	0

Data Visualization Graphical User Interface

Developing the wrapper capability ultimately allowed for fast evaluation of thousands of cases by automatically creating all the required files and recording all desired outputs, without any intervention from the user. Because the computational time was significantly reduced, more focus was put on post processing the data and understanding the results. To visualize the vast amount of data generated, a data visualization capability in the form of a graphical user interface (GUI) was developed, as seen in the figure below. In the top left corner, the user must select among the various options which types of cases to investigate. The bottom half shows two plots of maximum overpressure and loudness. In the top right corner, a plot shows a superposition of all the pressure signatures from all the cases satisfying the options in the top left.

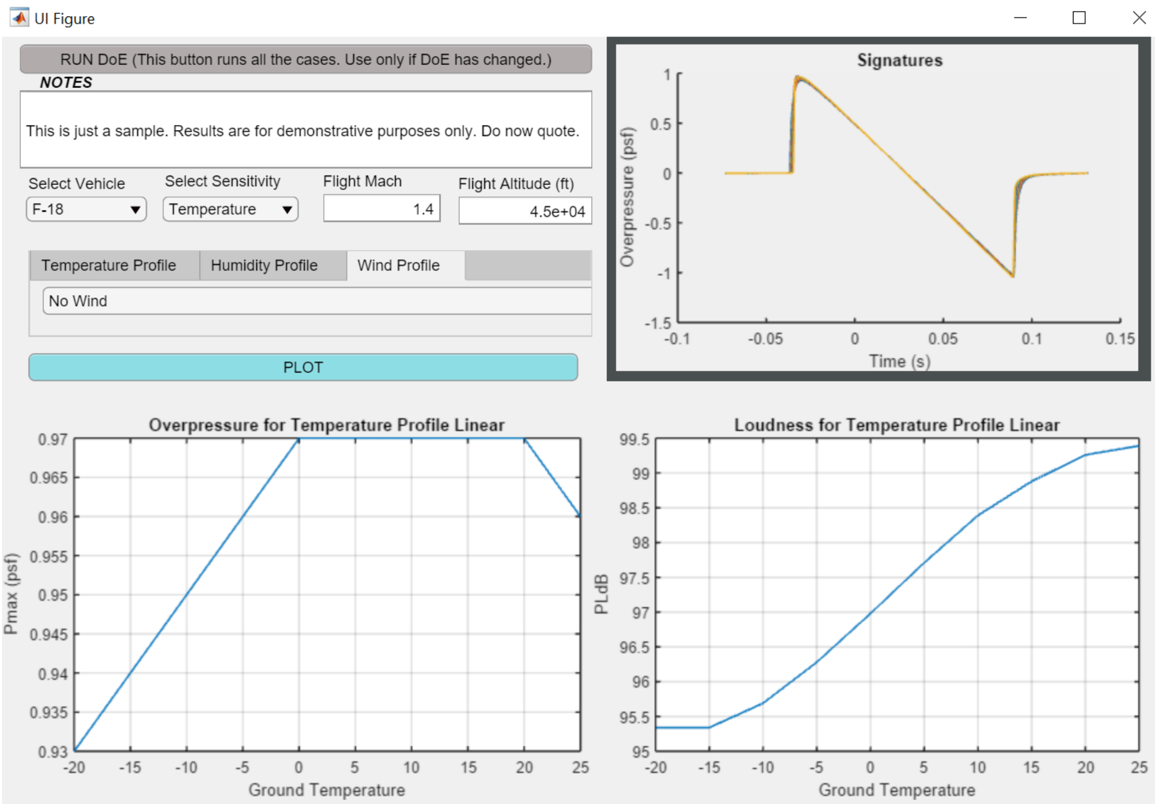

Figure 4 - General View of the Data Visualization GUI

Once the wrapper finished running all the cases, it also saved the results in a MATLAB specific "Table" format which allows for easy manipulation. The GUI uses this table to generate various plots: maximum overpressure and loudness versus changes in either temperature, humidity, or wind magnitude or direction. To successfully generate them, the user must input a number of options. Because two airplanes were investigated in this study, a dropdown menu allows the user to select the vehicle (either F-18 from the PCBoom library or Aerion AS-2). Then, the user must select the type of sensitivity desired for the plots, which will modify the x-axes of the plots accordingly. The options are the four atmospheric parameters analyzed in this study: temperature, humidity, and wind magnitude and direction. The user must also specify the desired flight conditions. The following figure illustrates some of these options:

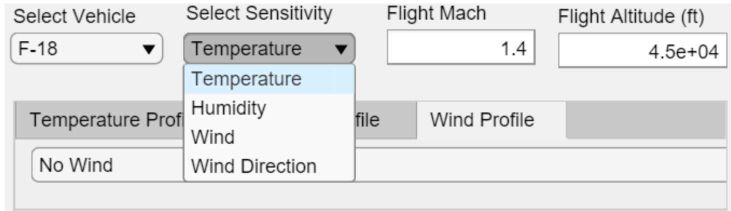

Figure 5 - Various Options Available for User Selection in GUI

For each of the atmospheric parameters, various profiles were investigated. Thus, the user must go through the three tabs ("Temperature Profile", "Humidity Profile", and "Wind Profile") and select the desired case for each of them. The following figures illustrates the concept:

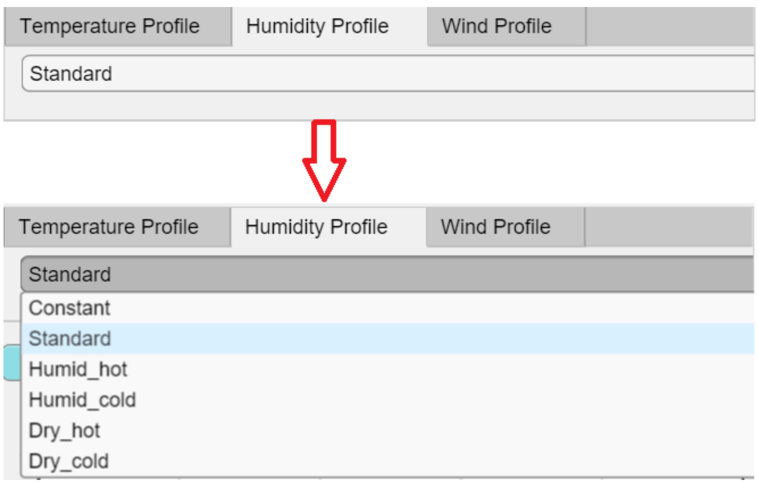

Figure 6 - Dropdown Options for Atmospheric Parameter Profiles

These options are predicated on the fact that the combinations selected by the user were present in the table of input cases and have been run by the wrapper. If the combination required does not exist, the plots will simply not show any curves. The GUI allows the user to make new selections and click on the button "Plot" to repopulate the graphs. Every time this button is pressed, the corresponding cases are selected and sorted from all the outputs. There is also a button called "Run DOE" that allows the user to run an entirely new batch of cases directly from the GUI. This graphical user interface capability allows for fast sorting through large amounts of data and automated plotting. By being able to quickly change the options, the user can rapidly visualize very different types of cases and assess general trends, without spending time on processing the data and generating graphs. Thus, more focus can be placed on understanding the results.

Atmospheric Conditions

In an effort to perform the sensitivity study of Mach cut-off flight as extensively as possible, the Georgia Tech team strived to create a large library of atmospheric profiles to capture large amount of variation in the atmospheric parameters used by PCBoom. The atmospheric parameters the user has the ability to alter include temperature, relative humidity, and horizontal winds (both in the lateral and longitudinal directions). Mach cut-off conditions are sensitive to all three of these parameters and also vertical winds, as shown in Penn State's tasks for Project 42. However, vertical winds are currently not within the capabilities of PCBoomv6.7 so Georgia Tech decided to only develop profiles to include temperature, relative humidity, and horizontal winds – but adding in vertical winds to the profiles and atmosphere file generator in the PCBoom Wrapper can be easily done.

The Georgia Tech research team decided to split the atmosphere profiles studied into two groups. The first being "standard" atmospheric profiles and the second being "realistic" atmospheric profiles. The term "standard" profiles indicates that the atmospheric profiles are deviations from the standard US atmosphere profile, but maintain continuity and have no inversions. The reason for investigation of both types of atmospheric profiles was to identify sensitivities in both ideal and non-ideal conditions. By assessing the Mach cut-off conditions in realistic profiles and comparing those results to the Mach cut-off conditions in standard profiles, Georgia Tech was able to determine the impact of varying temperature gradients and temperature inversions on the Mach cut-off altitude and Mach number.

Standard Profiles
The standard temperature profiles generated and used in this study are based on the standard profile used in PCBoomv6.7, the U.S. Standard Atmosphere, No Winds, ANSI S1.26 Annex C, with the ability to add in horizontal winds. Georgia Tech created four "types" of standard profiles for temperature, two for relative humidity, and three for wind. The temperature profiles created fall into four different categories: Linear, Constant, Concave, and Convex. In the linear set of temperature profiles, the US standard atmosphere is used as the baseline and then the ground temperature is shifted while maintaining the tropopause temperature (-56.5ºC). This provides different slopes to the temperature profile are the sound propagated from altitude down to the ground. A sample of the linear temperature profiles is given in Figure 7 below.

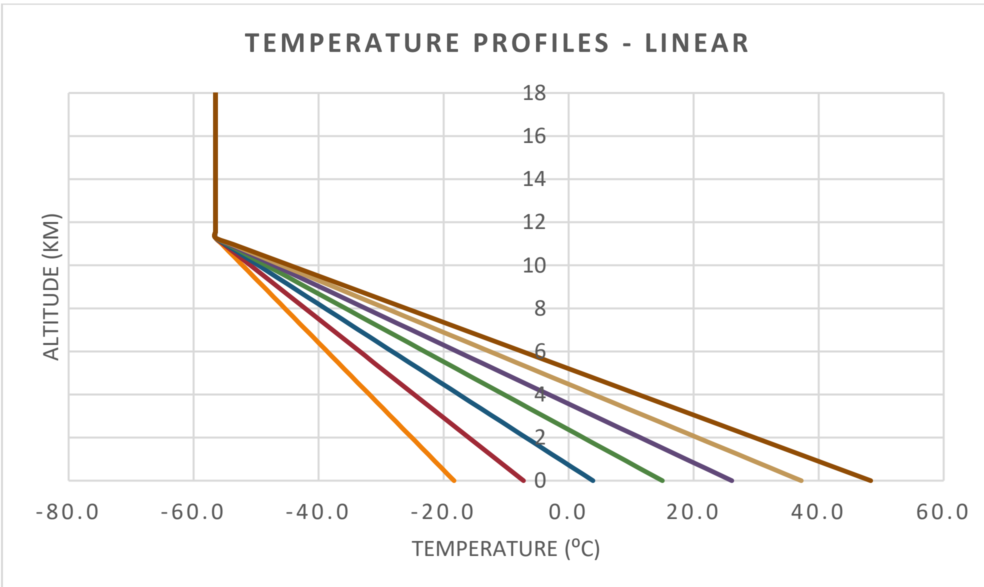

Figure 7: Standard Profiles: Linear Temperature

The next type of temperature profiles created were constant temperature profiles. These temperature profiles are constant temperature from the ground up to altitude. These profiles were not used extensively, but rather as a way to determine what PCBoom would predict as the Mach cut-off conditions if the speed of sound at altitude and at ground level were equal. The third and fourth types of temperature profiles are concave and convex profiles. These follow the same basic function as the linear profiles in changing the ground temperature, but in these profiles the temperature gradient is non-constant. An example of these profiles can be seen in Figure 8.

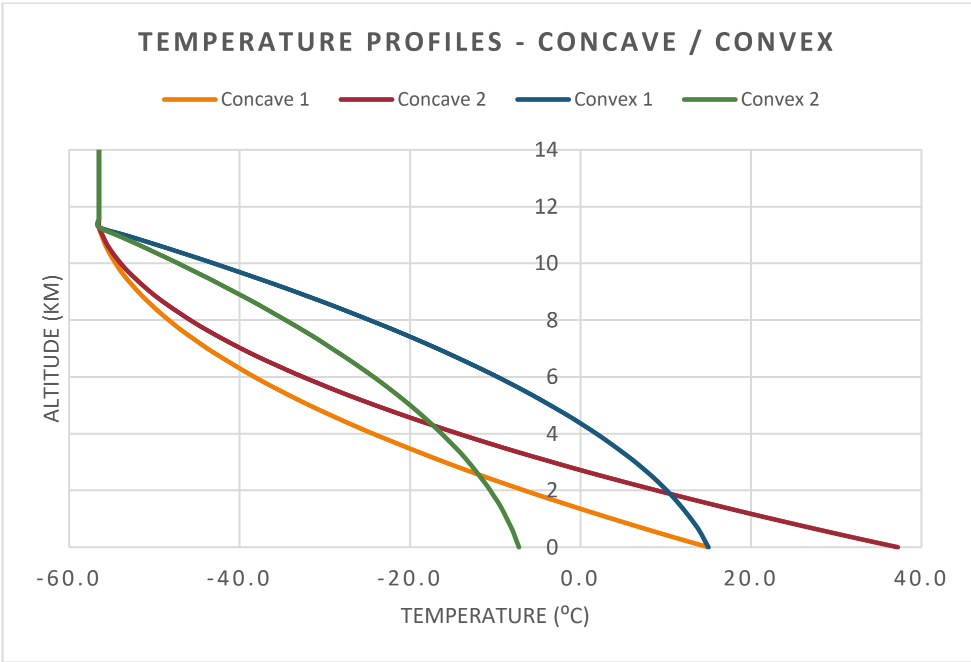

Figure 8: Standard Profiles: Concave and Convex Temperature

The humidity and wind are also included in the standard atmosphere profiles. For relative humidity, there are two options. The first is a constant relative humidity throughout the entire profile, which can be set from anywhere from 0 to 100% relative humidity. The second humidity profile is the U.S. standard atmosphere humidity profile, which can be shifted by a constant percentage throughout the profile. An example of these profiles can be seen in Figure 9.

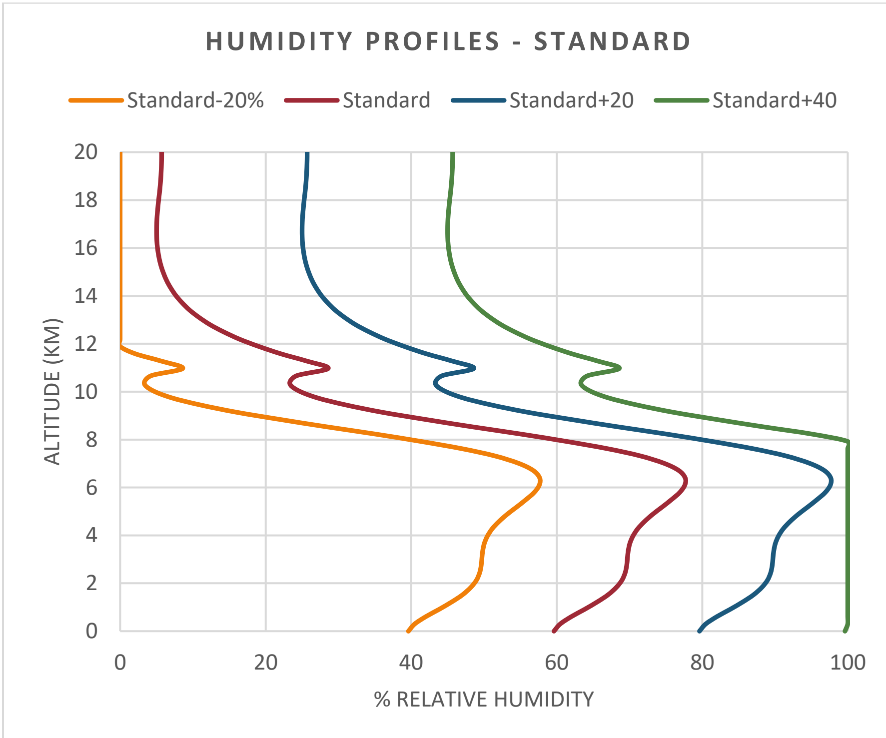

Figure 9: Standard Profiles: Relative Humidity

The remaining attribute in the standard profiles is the horizontal wind. Horizontal winds are set to zero in the standard atmosphere file for PCBoom 6.7, but can be altered easily. Using GT's PCBoom Wrapper, the user can create any wind profile desired by giving discrete wind information at every altitude station in the profile. The other option is to choose a constant wind profile with a given magnitude and direction. The PCBoom Wrapper then takes this information and splits the horizontal wind into x and y components for the atmospheric input file. The wind direction is defined for the remainder of this task as shown in Figure 10 – where 0º is a tailwind and 180º is a headwind.

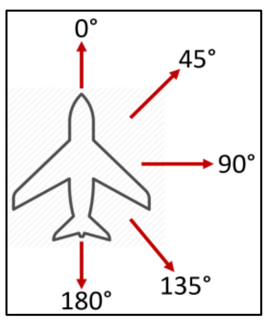

Figure 10: Wind Directions Definitions

The combination of temperature, relative humidity, and horizontal winds completely defines the atmospheric profile in PCBoom. Through the use of the atmospheric file generator developed for the PCBoom Wrapper, the Georgia Tech Research team has created over 10,000 unique atmospheric profiles for case analyses in PCBoom. However, many of these atmospheric profiles are idealistic and don't actually represent what an aircraft would experience in real-world flight. This led the Georgia Tech team to develop "realistic" atmospheric profiles from publically available data.

Realistic Profiles

The Georgia Tech team developed a set of realistic atmospheric profiles to study the sensitivity of Mach cut-off flight in real-world conditions. The purpose of studying these profiles and shifting the temperatures within these profiles, was to capture the impact of temperature fluctuations and inversions as well as variable horizontal winds on the Mach cut-off conditions. The Georgia Tech team decided to investigate these impacts in four distinct climates (Temperature/Rel. Humidity):

- Hot/Humid: Miami, FL, USA
- Hot/Arid: Tucson, AZ, USA
- Cold/Humid: Minneapolis, MN, USA
- Cold/Arid: Denver, CO, USA
- Average/Average: Oakland, CA, USA

These realistic atmospheric profiles were generated from radiosonde data from the Department of Atmospheric Sciences at the University of Wyoming [http://weather.uwyo.edu/upperair/sounding.html]. The data tracked included altitude relative humidity, temperature, and wind magnitude and direction. The Georgia Tech team used this data and translated it to a format for input to PCBoom using the PCBoom Wrapper. The profiles gathered were from cities that represented extremes on both the temperature and humidity ranges and an average city: Miami, FL, Tucson, AZ, Minneapolis, MN, Denver, CO, and Oakland, CA. The realistic temperature profiles are shown in Figure 11, the humidity profiles are shown in Figure 12, and the wind profiles are shown in Figure 13.

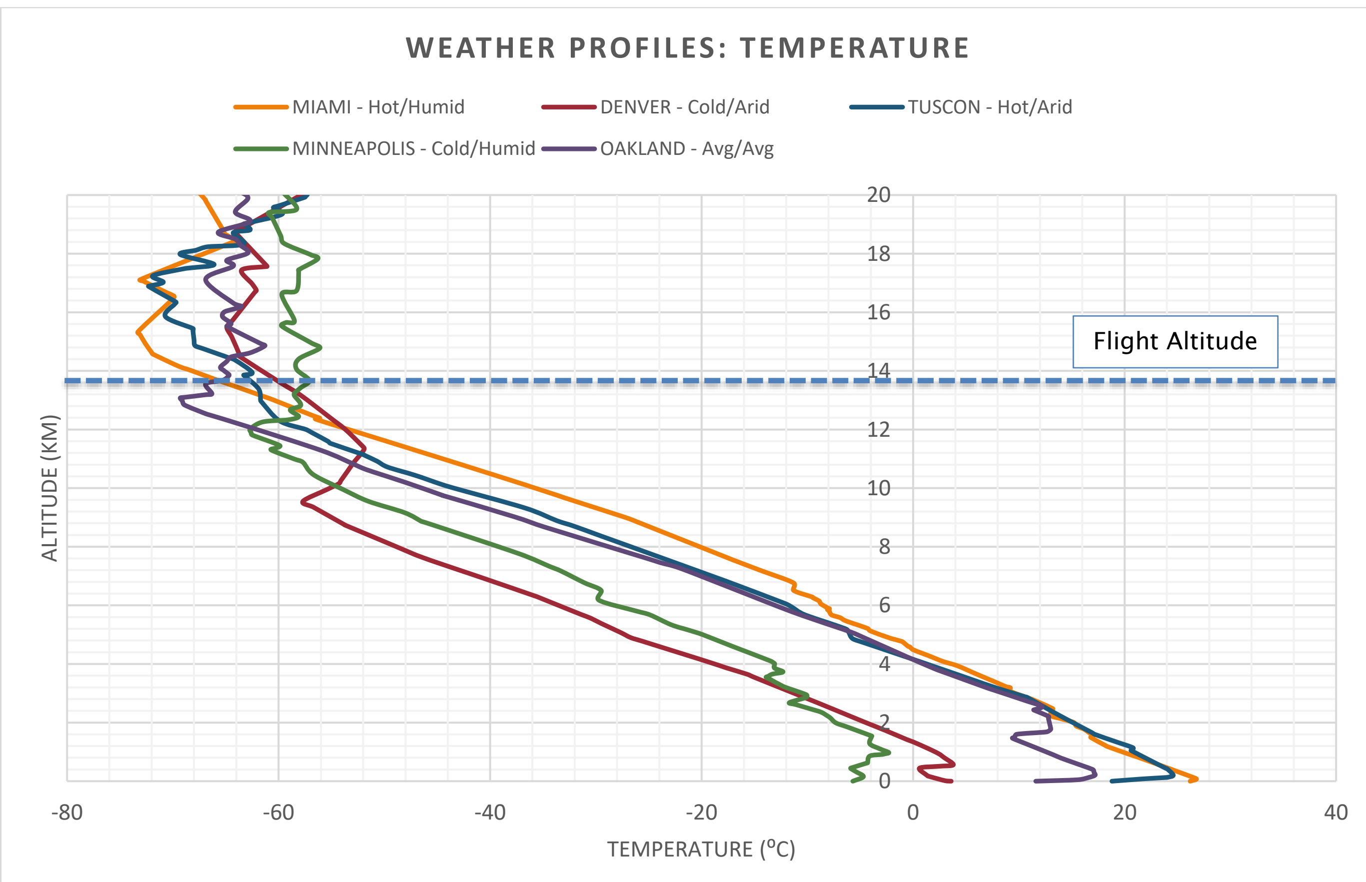

Figure 11: Realistic Profiles: Temperature

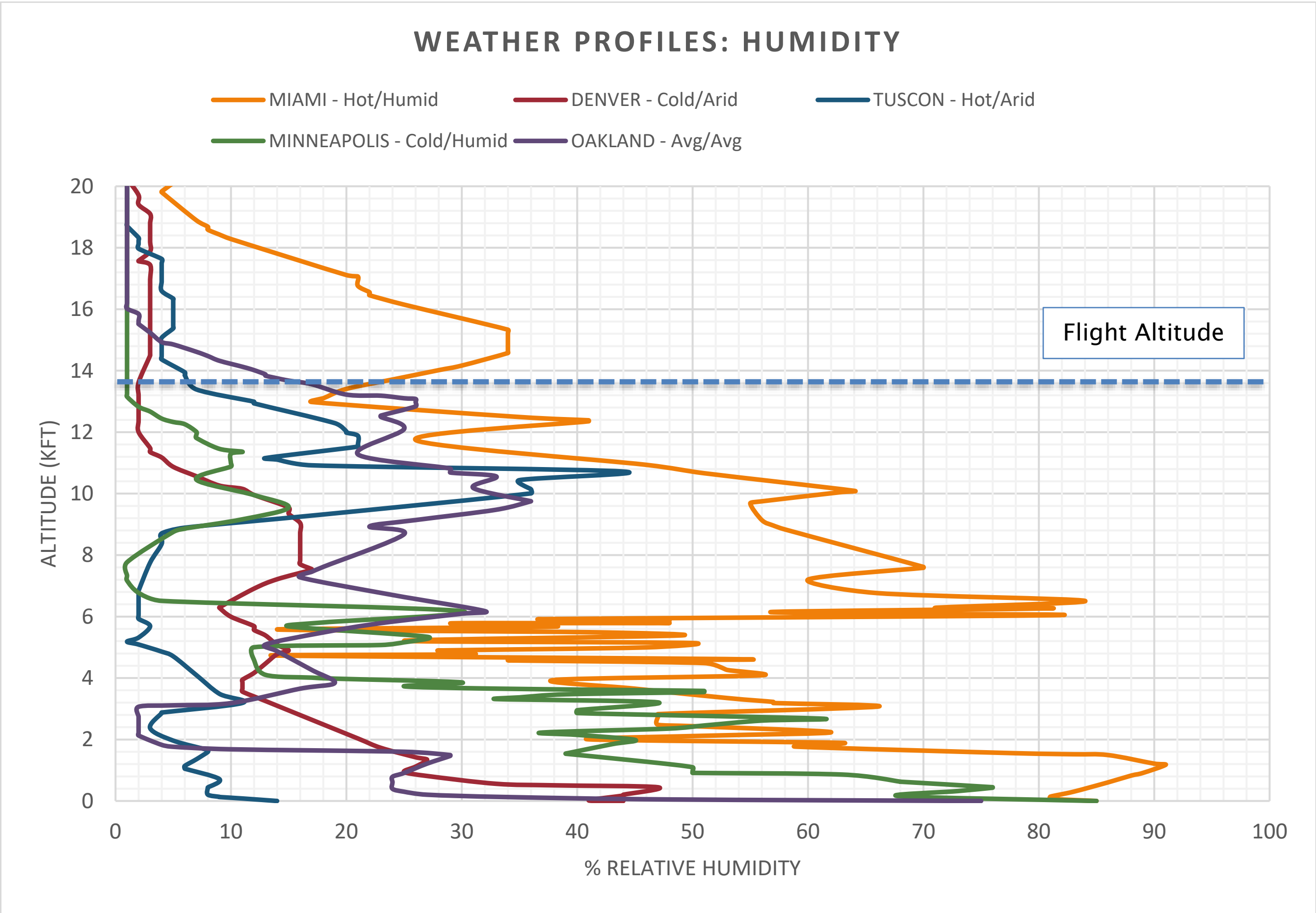

Figure 12: Realistic Profiles: Relative Humidity

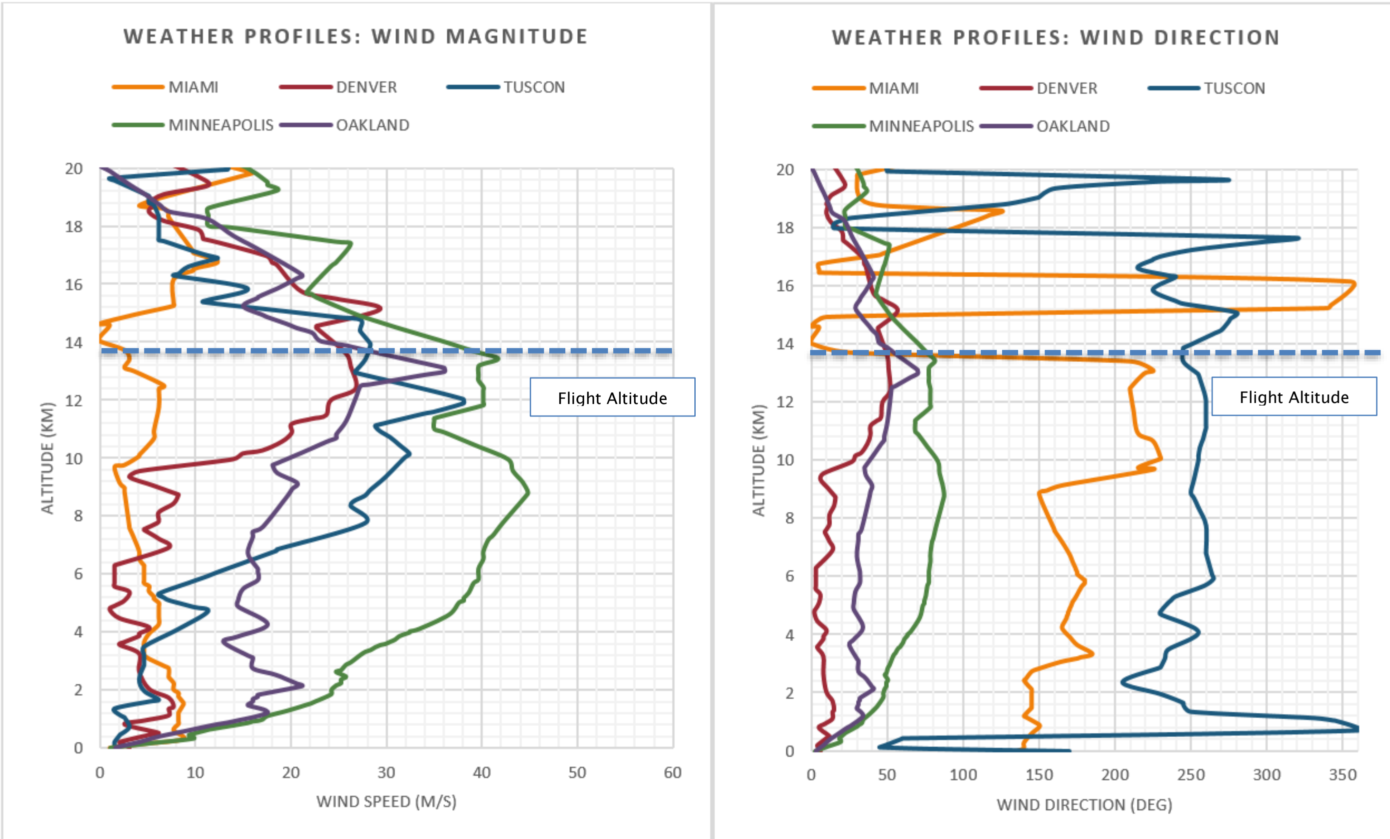

Figure 13: Realistic Profiles: Wind Magnitude and Direction

The five realistic atmospheric profiles were integrated into the PCBoom Wrapper to allow for use in large designs of experiments. This allowed for the altering of the profiles from the baseline profiles generated from data. This enabled the Georgia Tech team to study the sensitivity of certain aspects of each atmospheric profile to Mach cut-off conditions. The sensitivity study performed during the first year of Project 42 was accomplished through shifting and altering the temperatures of both the realistic and standard atmospheric profiles. The results of the sensitivity study are presented in the following section.

Sensitivity Study & Results

Introduction

The main sensitivity study performed for Task 4 was performed in three stages. The first stage consisted of benchmarking the results and generating baseline results using PCBoom to study the sensitivity of Mach *cut-on* results to atmospheric conditions. Through studying what happens to the cut-on sonic boom metrics (such as overpressure and Loudness at the ground), Georgia tech hoped to gain insight on the physics of the sonic boom propagation through different atmospheres. The second stage of the study was performed for Mach cut-off conditions through standard atmospheric profiles. This provided Georgia Tech a controlled response to set temperature gradients that could be studied and easily obtain a sensitivity of Mach cut-off conditions to variations in the standard atmospheric profiles. The third stage of the sensitivity study was performed for Mach cut-off conditions under realistic atmospheric profiles. The goal of this stage was to observe how non-standard profiles impact Mach cut-off conditions and how abnormalities (such as temperature inversions) impact an aircraft's ability to maintain Mach cut-off flight. The results of these three stages of the sensitivity study are presented in this section. It is important to note that all three stages were performed with Aerion's AS2 nearfield sonic boom signature and Georgia Tech would like to extend it's gratitude to Aerion Corporation for making the data available to the participants of Project 42. The results presented in this report do not detail Aerion's near field pressure signal, only the propagated PCBoom results and cut-off conditions.

Benchmarking & Mach Cut-On
The benchmarking stage of the results was done with Mach cut-on conditions. For this study, Georgia Tech used a flight altitude of 13.7km (45,000ft) at a flight Mach number of 1.4. This consistently produces signatures on the ground. In order to observe the impact of the atmosphere on the resulting noise levels, the GT team chose to run the Mach cut-on conditions through both standard and realistic atmosphere profiles. The first sensitivity investigated was ground boom strength to atmospheric temperature. This was done by observing the changes in both loudness (PLdB) and maximum overpressure (Pa) to changes in humidity and wind for various temperature profiles.

Humidity/Temperature Sensitivity - Loudness
The sensitivity of loudness to changes in relative humidity are shown in Figures 14-17, Figure 14 displays the sensitivity under linear temperature profiles, Figure 15 displays the sensitivity under constant temperature profiles, Figure 16 displays the sensitivity under concave temperature profiles, and Figure 17 displays the sensitivity under convex temperature profiles.

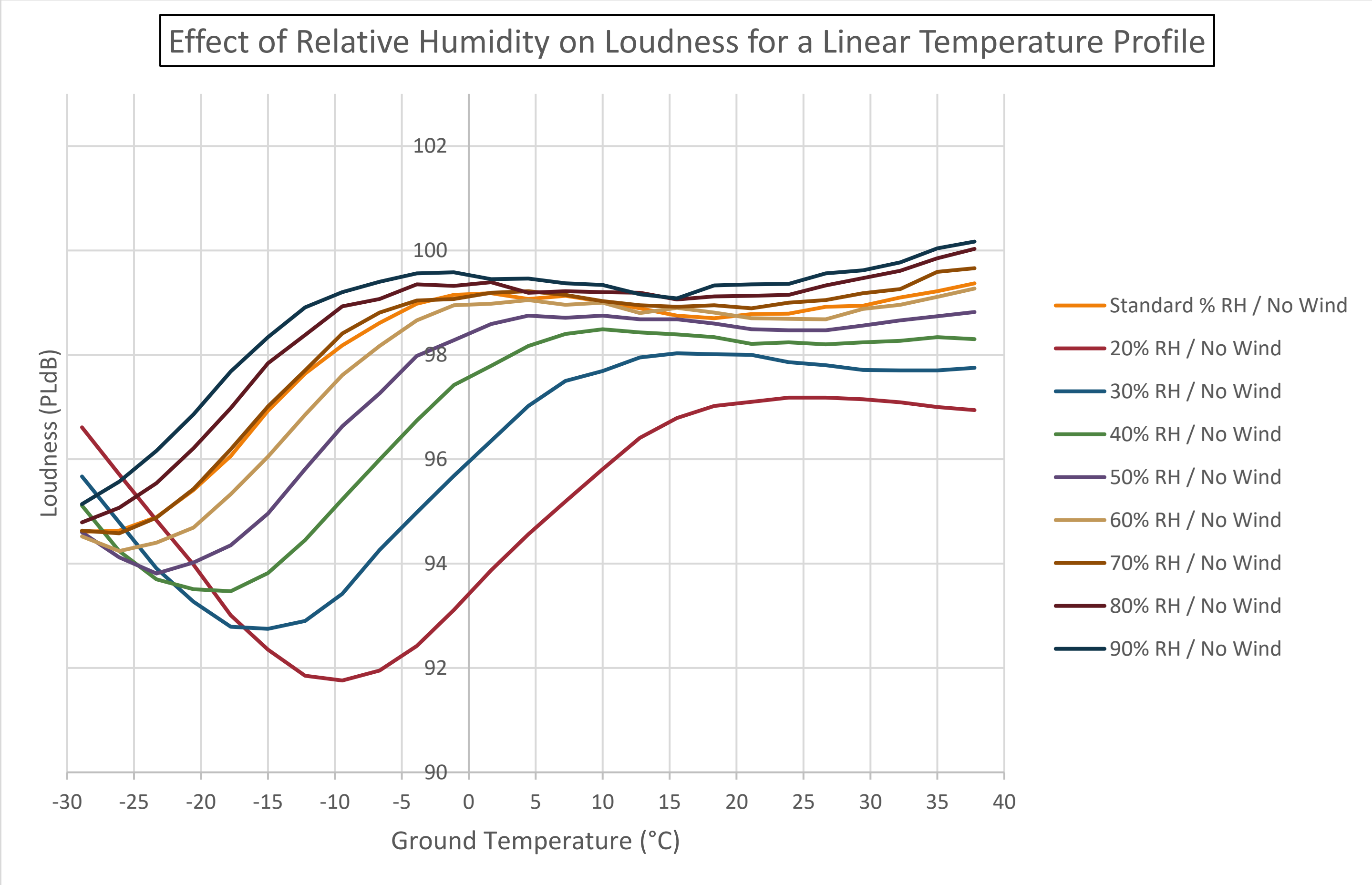

Figure 14: Loudness Sensitivity to Humidity - Linear Temperature Profiles

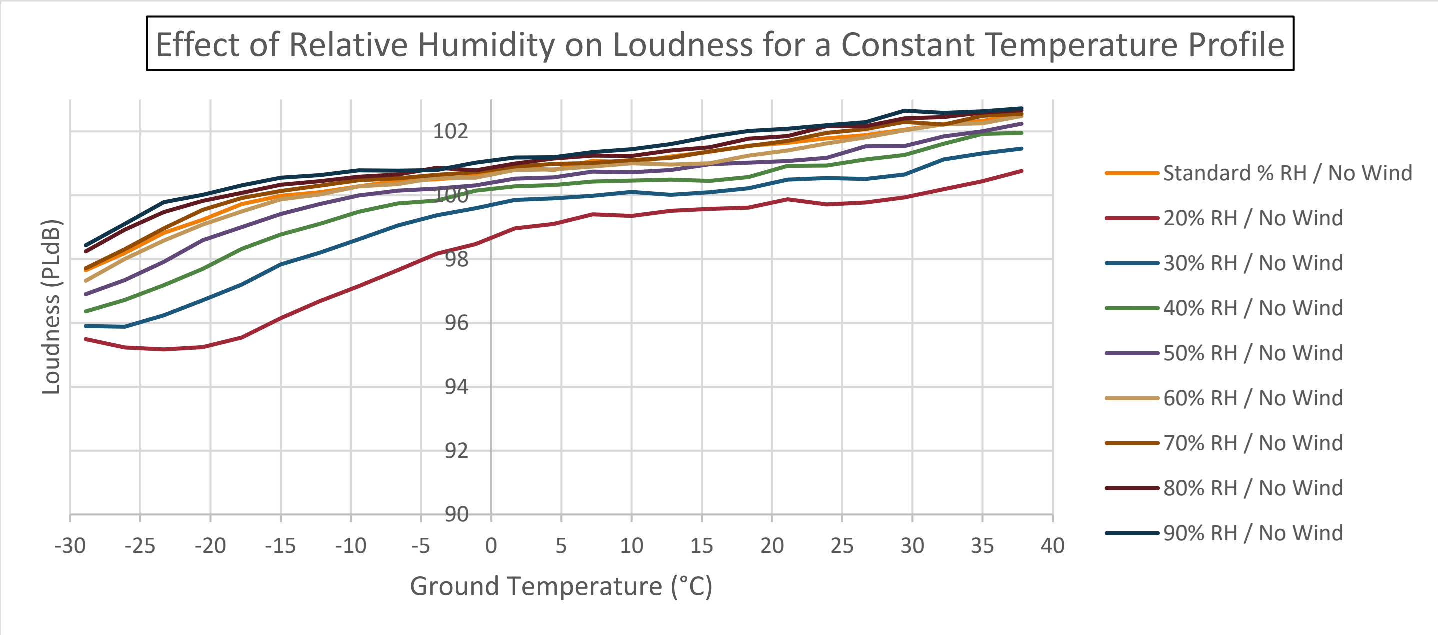

Figure 15: Loudness Sensitivity to Humidity - Constant Temperature Profiles

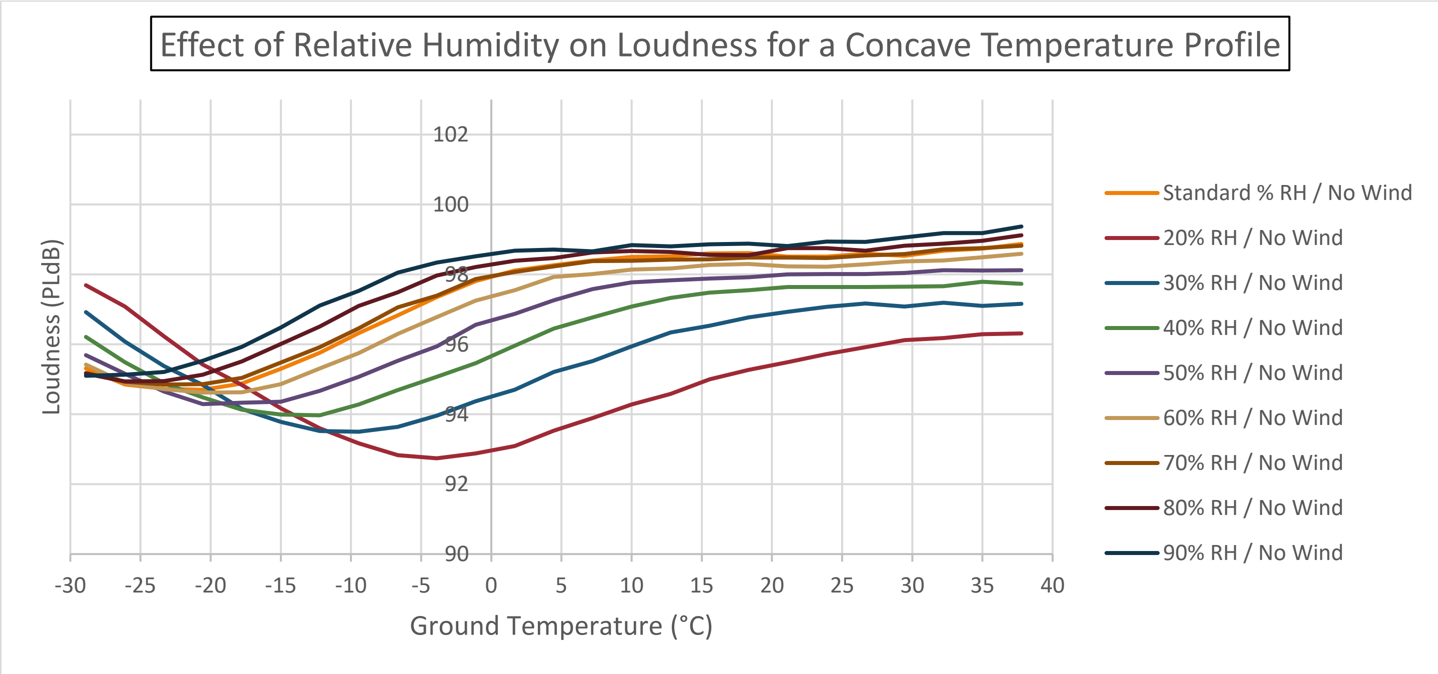

Figure 16: Loudness Sensitivity to Humidity - Concave Temperature Profiles

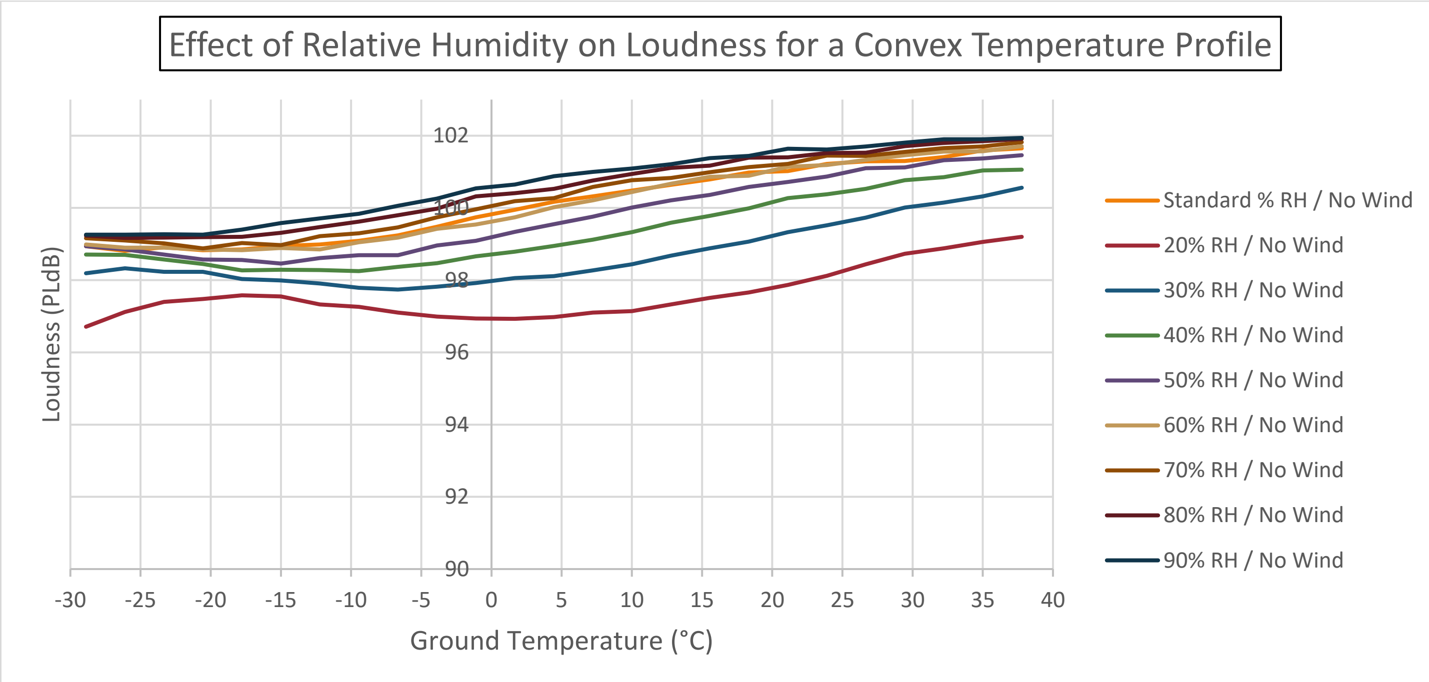

Figure 17: Loudness Sensitivity to Humidity - Convex Temperature Profiles

The above results show that the relative humidity impact on loudness is sensitive to absolute ground temperature, temperature gradient, and relative humidity. As shown in Figure 15, the impact of absolute ground temperature on loudness is almost linear. In general, as constant atmospheric temperature increases, the loudness of the ground boom increases roughly 4-5 PLdB going from -30 C to +40 C. The only exception happens in the extreme cold region for low humidity; when the air is arid and cold, the loudness seems to asymptote to a low value of 95PLdB. For varying temperature gradient, the sensitivity becomes non-linear as you alter the gradients within the propagation path. In general, it seems that the convex temperature profiles produce a higher loudness on the ground than linear profiles and concave profiles produce the quietest ground booms. This appears to be the case regardless of relative humidity or wind. The impact of humidity on ground boom follows the general trend that if the atmosphere has more humidity, the loudness on the ground will increase. The exception to this trend appears in Figures 14 and 16, when the ground temperature gets extremely cold and a low humidity causes a much louder ground boom. The Georgia Tech team is investigating this behavior to determine if this is a physical phenomenon or if it is a result of reaching the limitation of PCBoom and is a computational error.

Humidity/Temperature Sensitivity – Max Overpressure

The sensitivity of maximum overpressure (Pa) to changes in relative humidity are shown in Figures 18-21, Figure 18 displays the sensitivity under linear temperature profiles, Figure 19 displays the sensitivity under constant temperature profiles, Figure 20 displays the sensitivity under concave temperature profiles, and Figure 21 displays the sensitivity under convex temperature profiles.

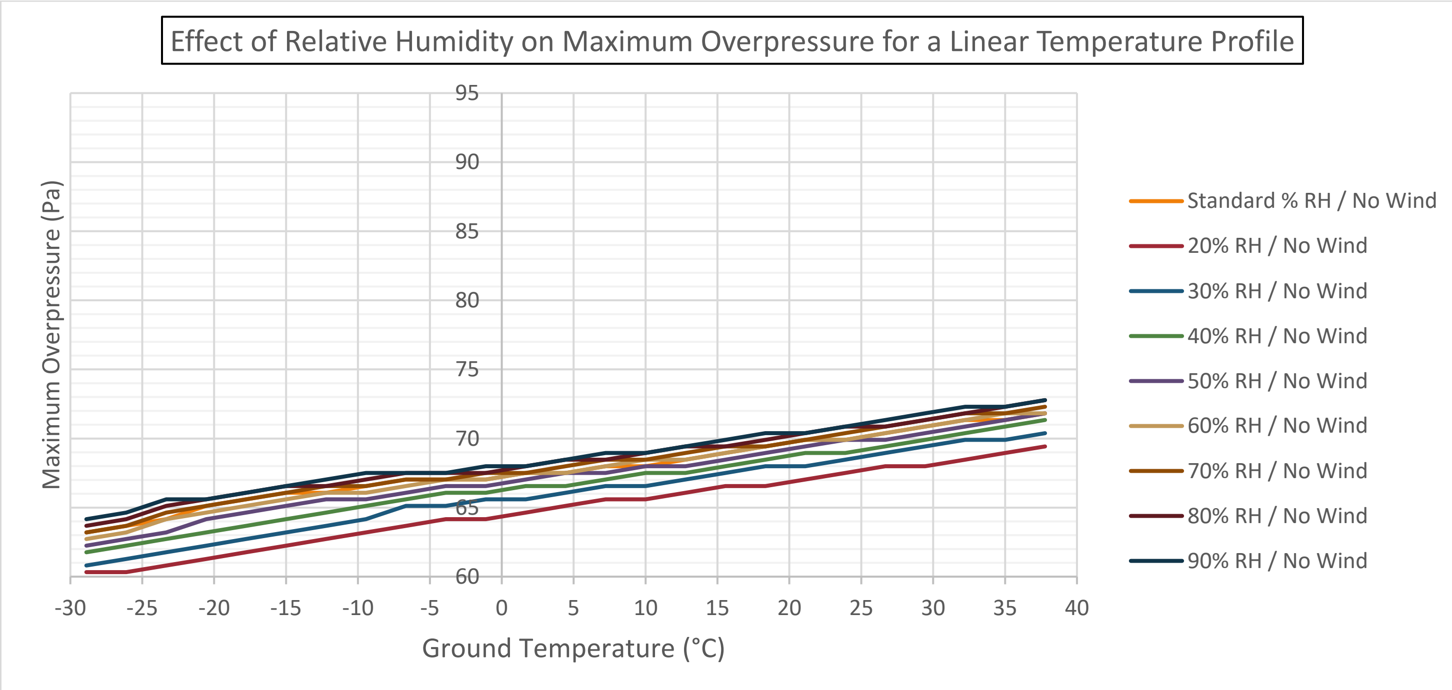

Figure 18: Max Overpressure Sensitivity to Humidity - Linear Temperature Profiles

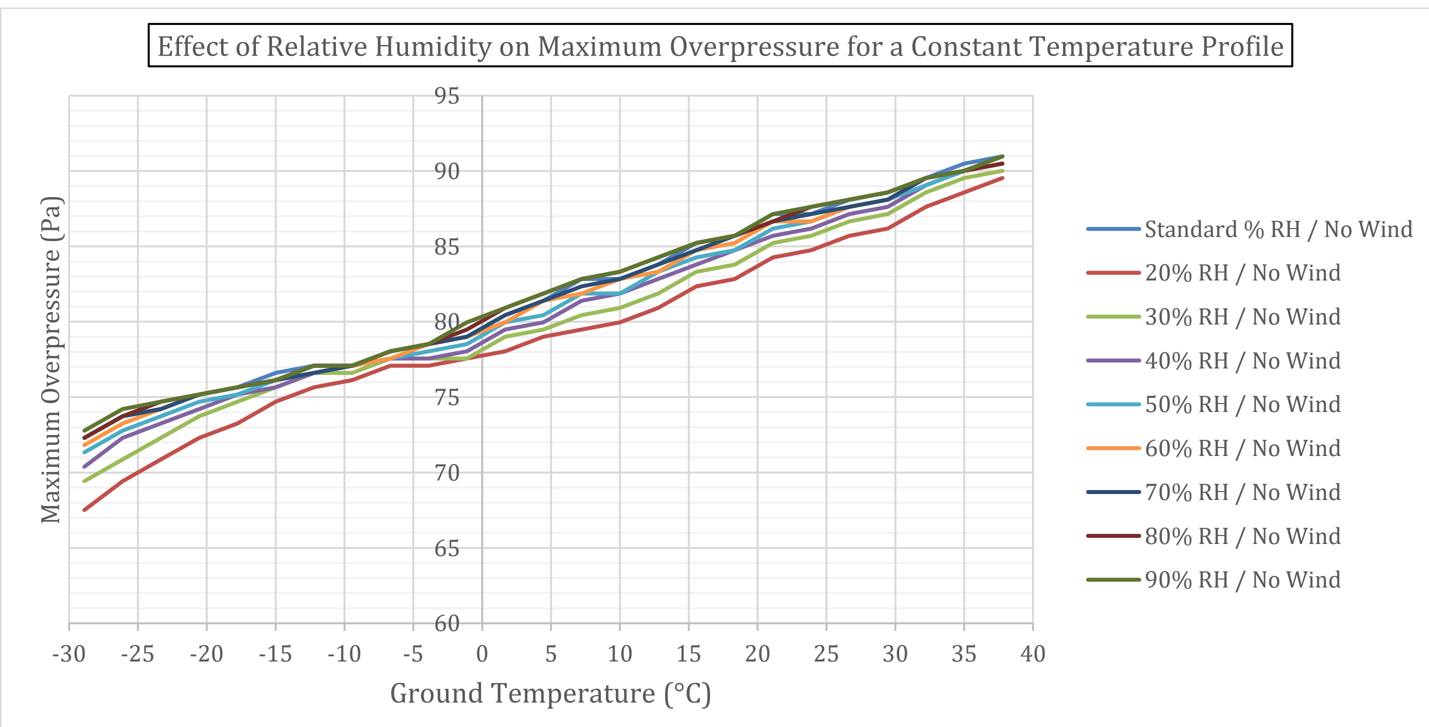

Figure 19: Max Overpressure Sensitivity to Humidity - Constant Temperature Profiles

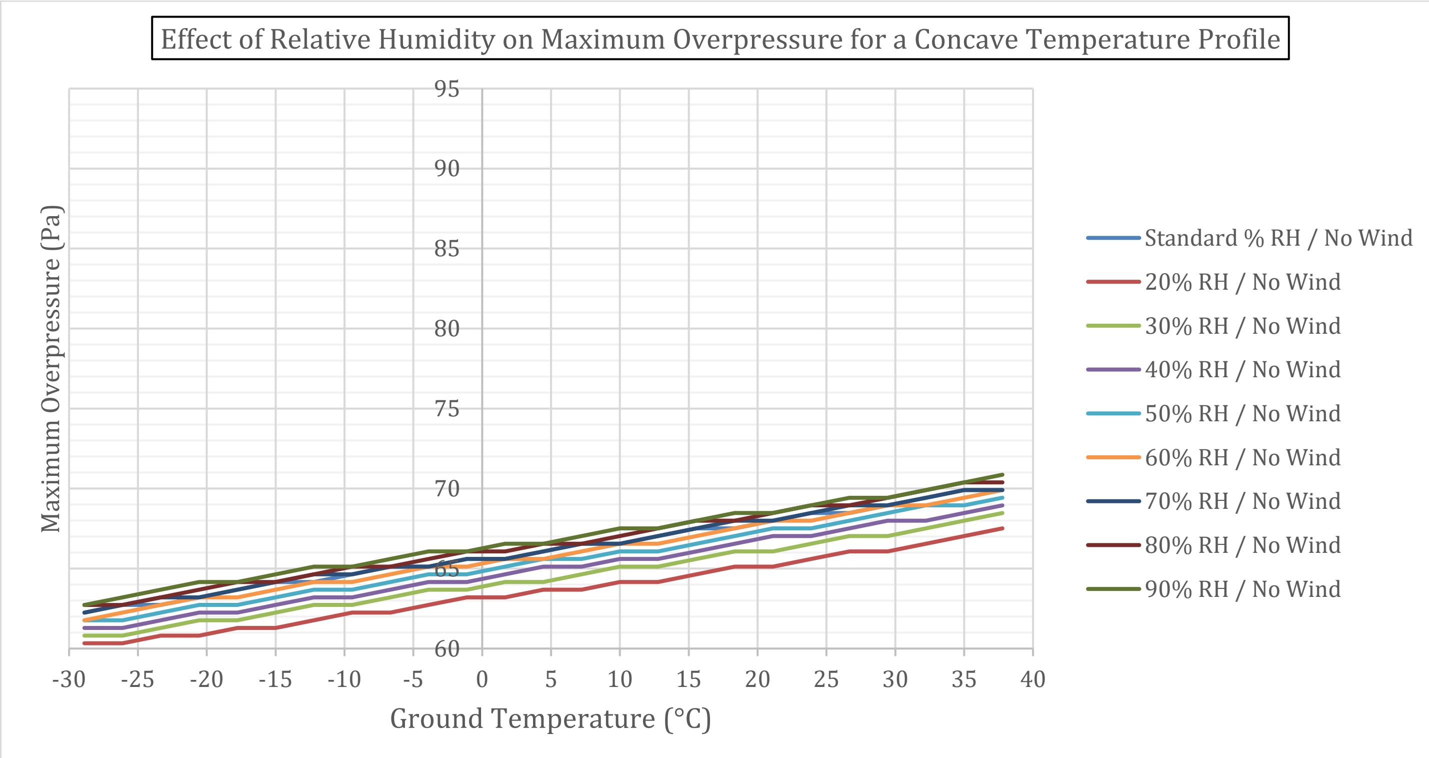

Figure 20: Max Overpressure Sensitivity to Humidity - Concave Temperature Profiles

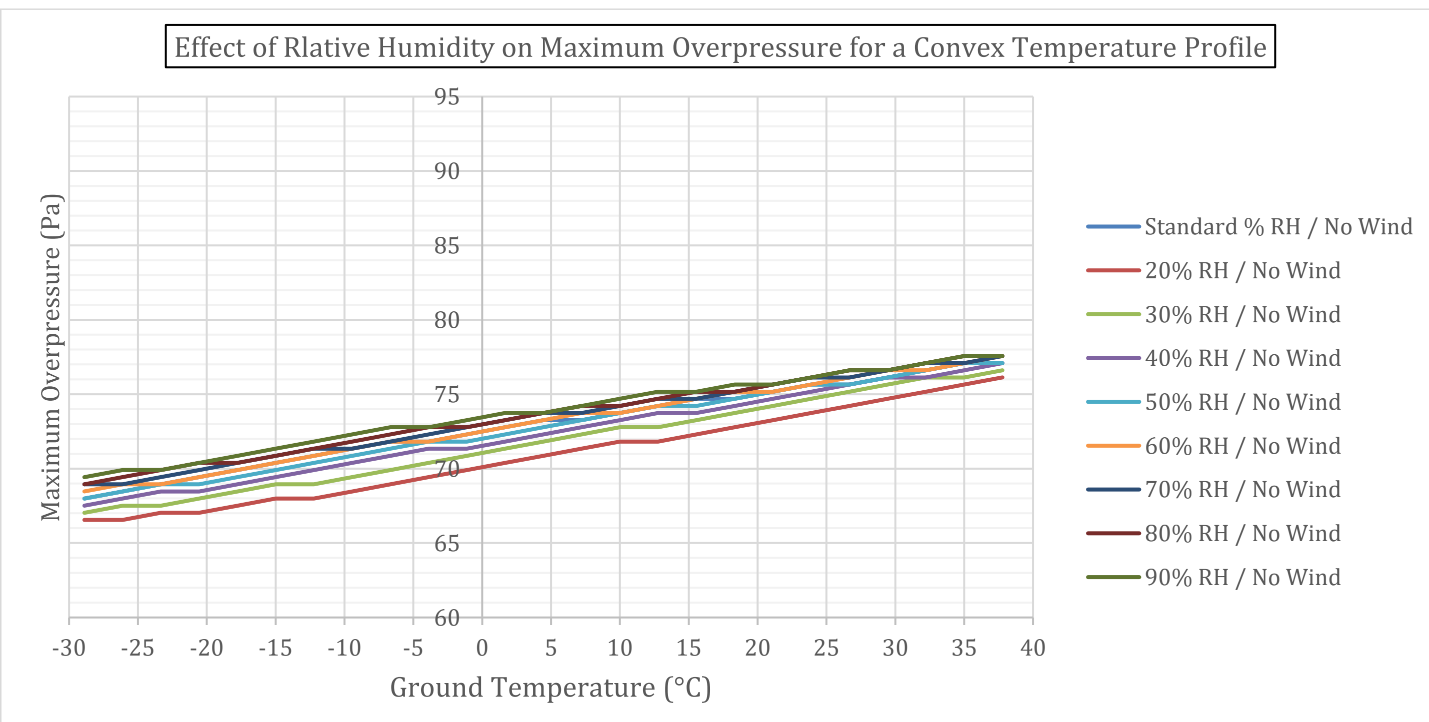

Figure 21: Max Overpressure Sensitivity to Humidity - Convex Temperature Profiles

The impact of humidity and temperature on max overpressure is more linear than the impact on loudness, most likely because loudness has a frequency dependency to it while max overpressure does not. For all standard temperature profiles, constant, linear, concave, and convex, the higher the relative humidity, the higher the max overpressure of the ground boom. It also appears that linear and concave temperature profiles are more sensitive to changes in relative humidity than constant temperature profiles – most likely because in a constant temperature profile atmosphere the propagation path does little to no bending as it travels down through the atmosphere.

Wind/Temperature Sensitivity – Loudness

The sensitivity of loudness (PLdB) to changes in wind direction and magnitude are shown in Figures 22-25. The wind direction was varied from a pure tailwind (0º) to a pure crosswind, to a pure headwind (180º). The magnitude of the wind was taken at both 12.2 m/s and 24.4 m/s. For the wind sensitivity studies, the relative humidity was set to 0% (even though this is un-realistic) in an attempt to isolate the impact of horizontal winds. Figure 22 displays the sensitivity under linear temperature profiles, Figure 23 displays the sensitivity under constant temperature profiles, Figure 24 displays the sensitivity under concave temperature profiles, and Figure 25 displays the sensitivity under convex temperature profiles.

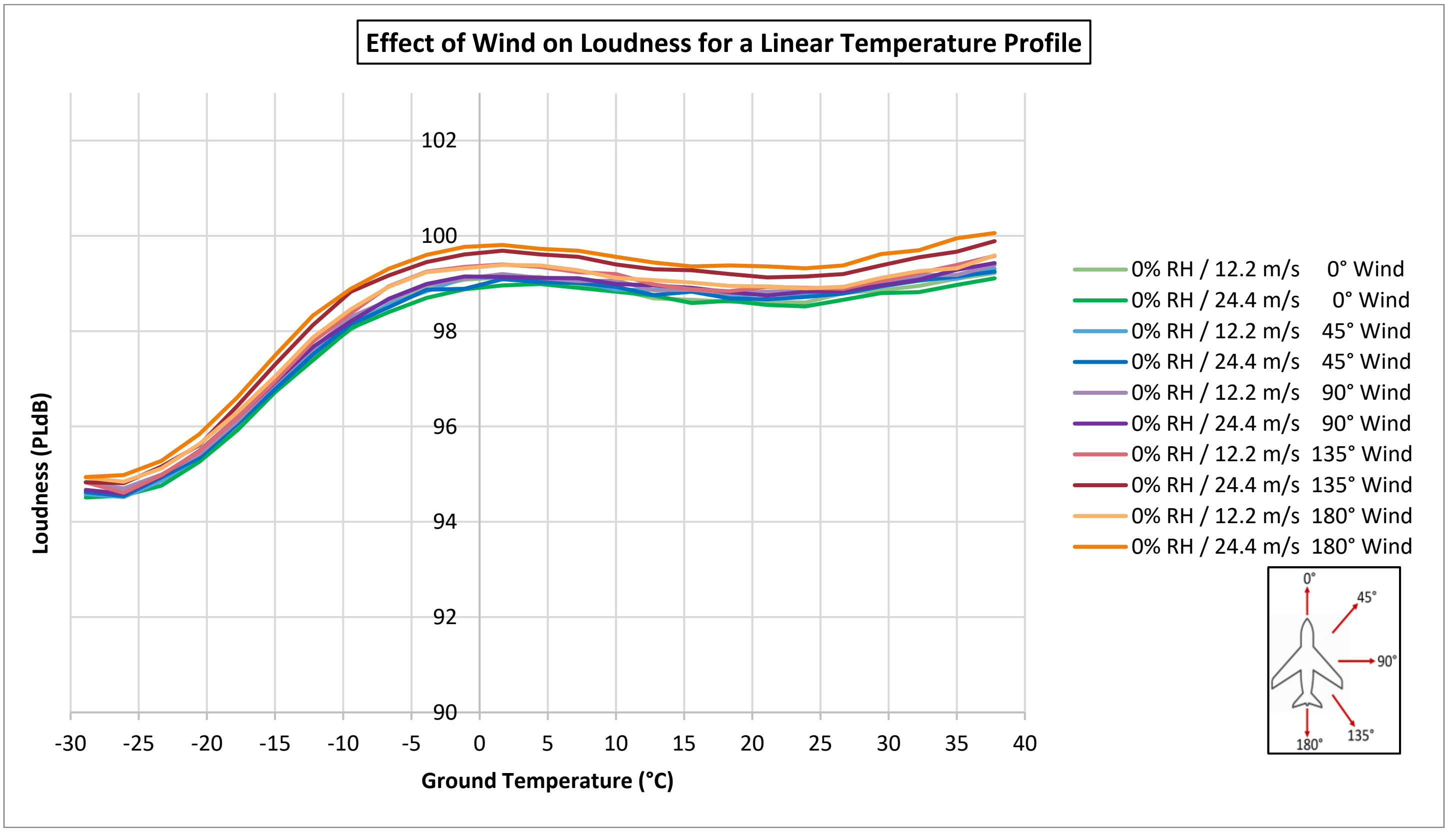

Figure 22: Loudness Sensitivity to Wind - Linear Temperature Profiles

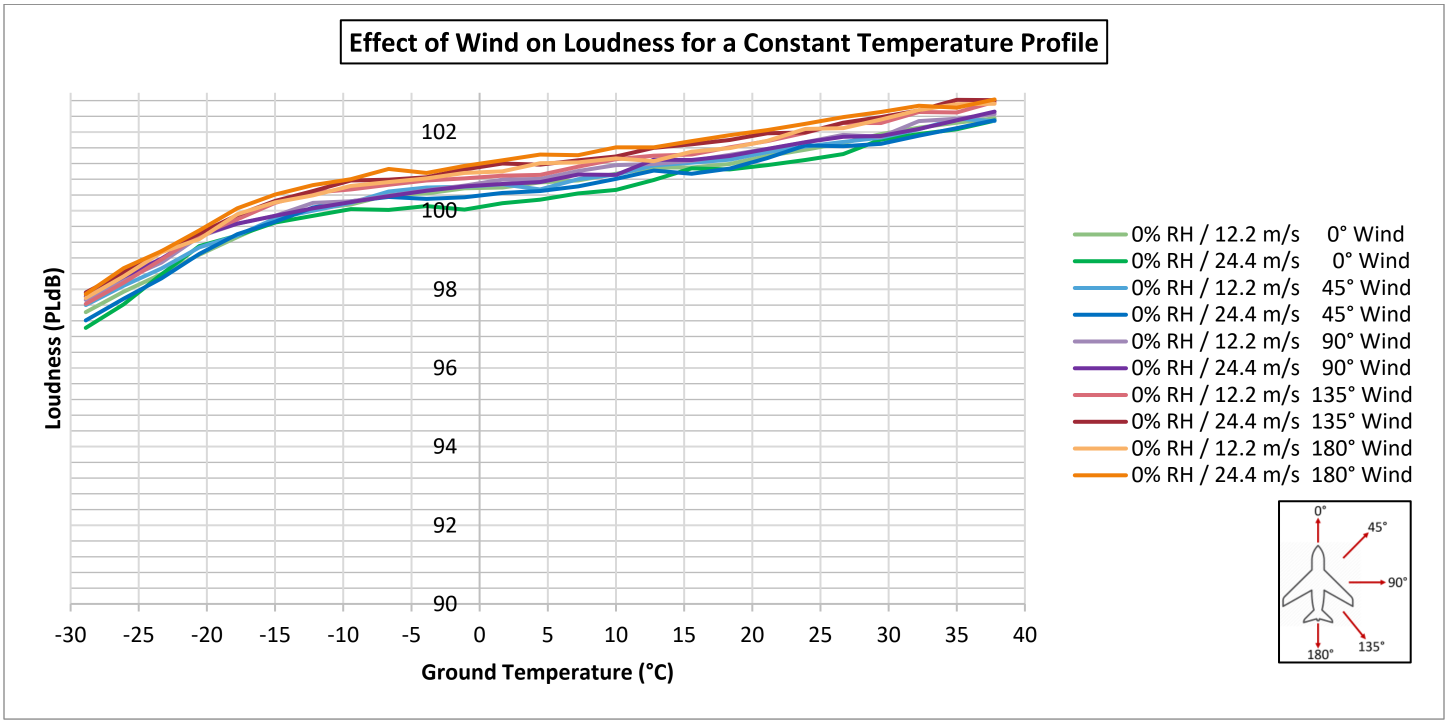

Figure 23: Loudness Sensitivity to Wind - Constant Temperature Profiles

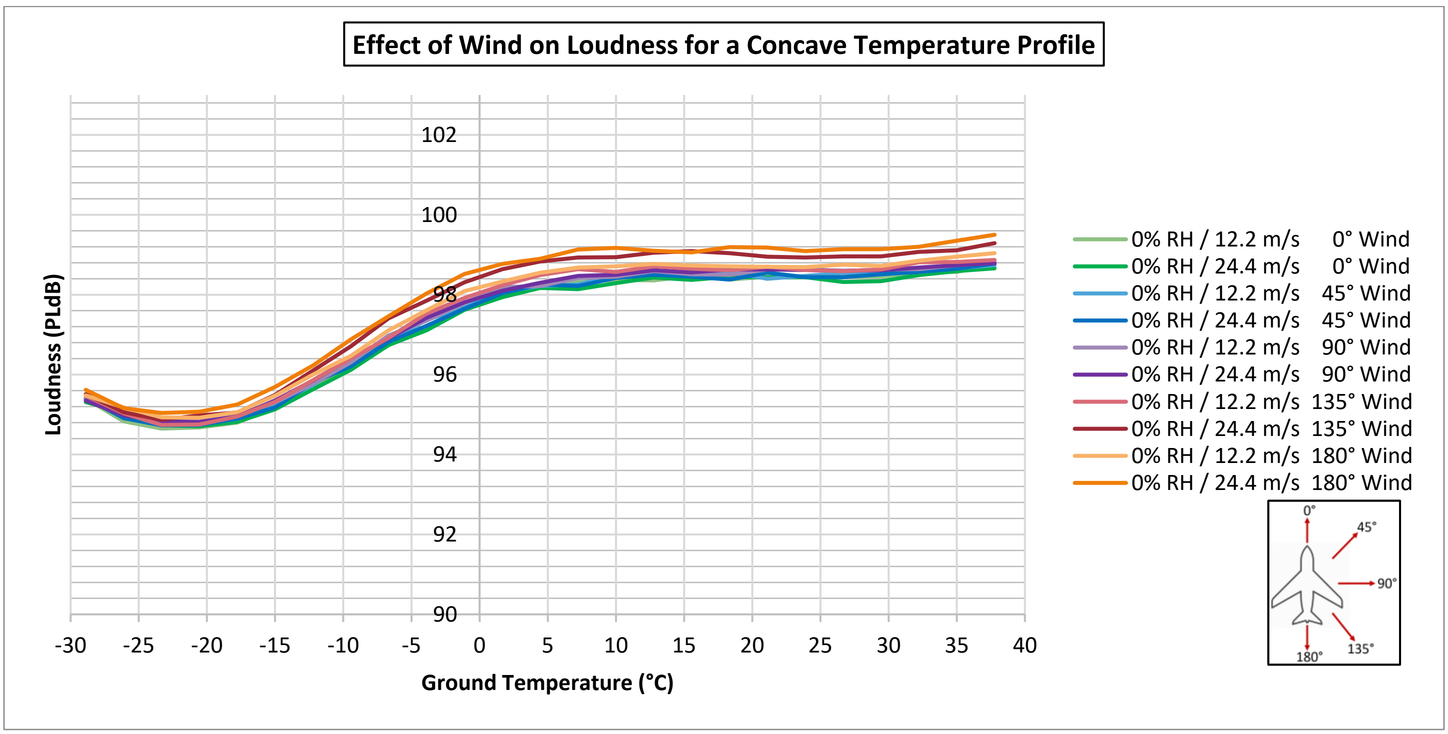

Figure 24: Loudness Sensitivity to Wind - Concave Temperature Profiles

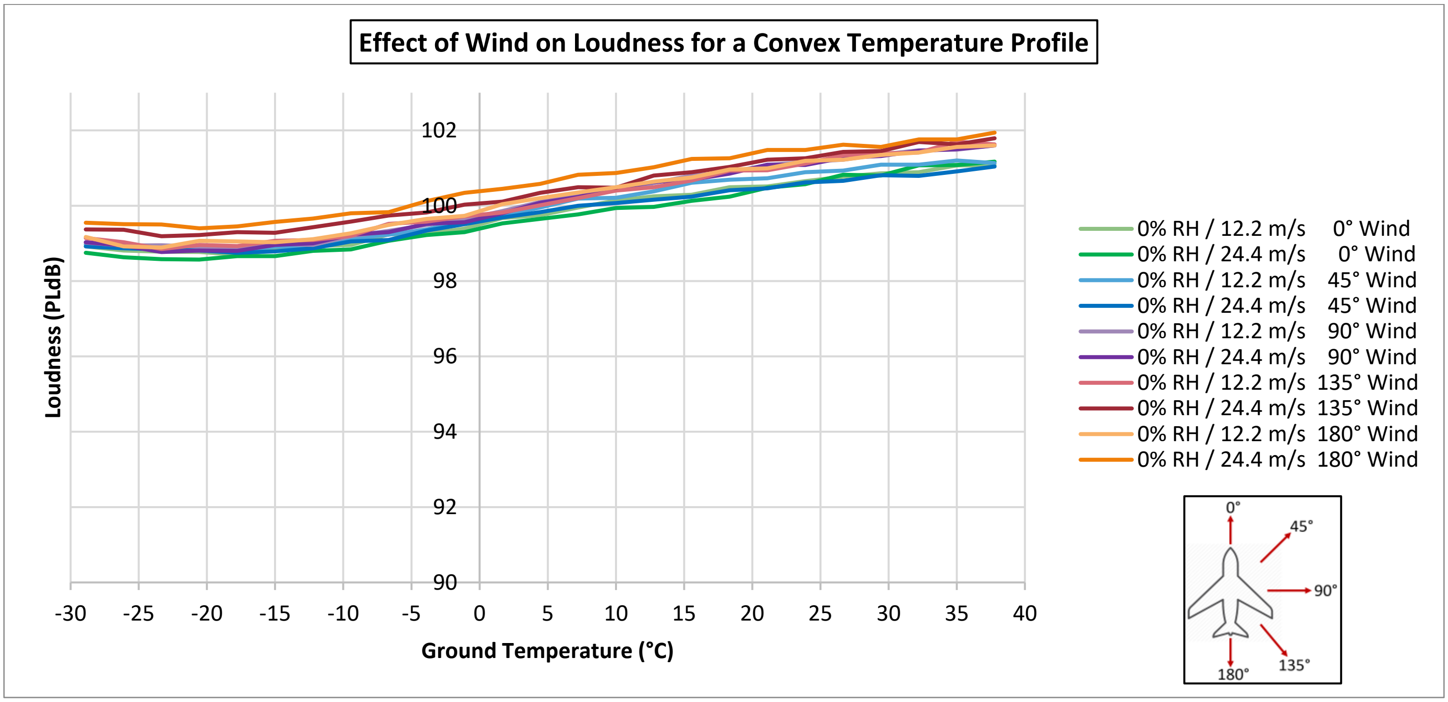

Figure 25: Loudness Sensitivity to Wind - Convex Temperature Profiles

The sensitivity of the loudness of ground booms in Mach cut-on conditions to wind direction and magnitude is consistent for constant, linear, and concave, and convex temperature profiles. Pure tailwinds result in the quietest ground booms while pure headwinds result in the loudest ground booms. This is consistent with what the Penn State team has shown in their horizontal wind studies. The variation in PLdB due to wind is smaller than that dues to changes in relative humidity. The difference between a strong headwind and a strong tailwind is only about 1-1.5 PLdB. The differences seen in the loudness due to changing ground temperatures are consistent with the humidity/temperature studies implying that impact of temperature profiles are primarily independent of wind and humidity (the one exception might be at colder temperatures with low humidity).

Wind/Temperature Sensitivity – Max Overpressure

The sensitivity max overpressure (Pa) to changes in wind direction and magnitude are shown in Figures 26-29 The wind direction was varied from a pure tailwind (0º) to a pure crosswind, to a pure headwind (180º). The magnitude of the wind was taken at both 12.2 m/s and 24.4 m/s. For the wind sensitivity studies, the relative humidity was set to 0% (even though this is un-realistic) in an attempt to isolate the impact of horizontal winds. Figure 26 displays the sensitivity under linear temperature profiles, Figure 27 displays the sensitivity under constant temperature profiles, Figure 28 displays the sensitivity under concave temperature profiles, and Figure 29 displays the sensitivity under convex temperature profiles.

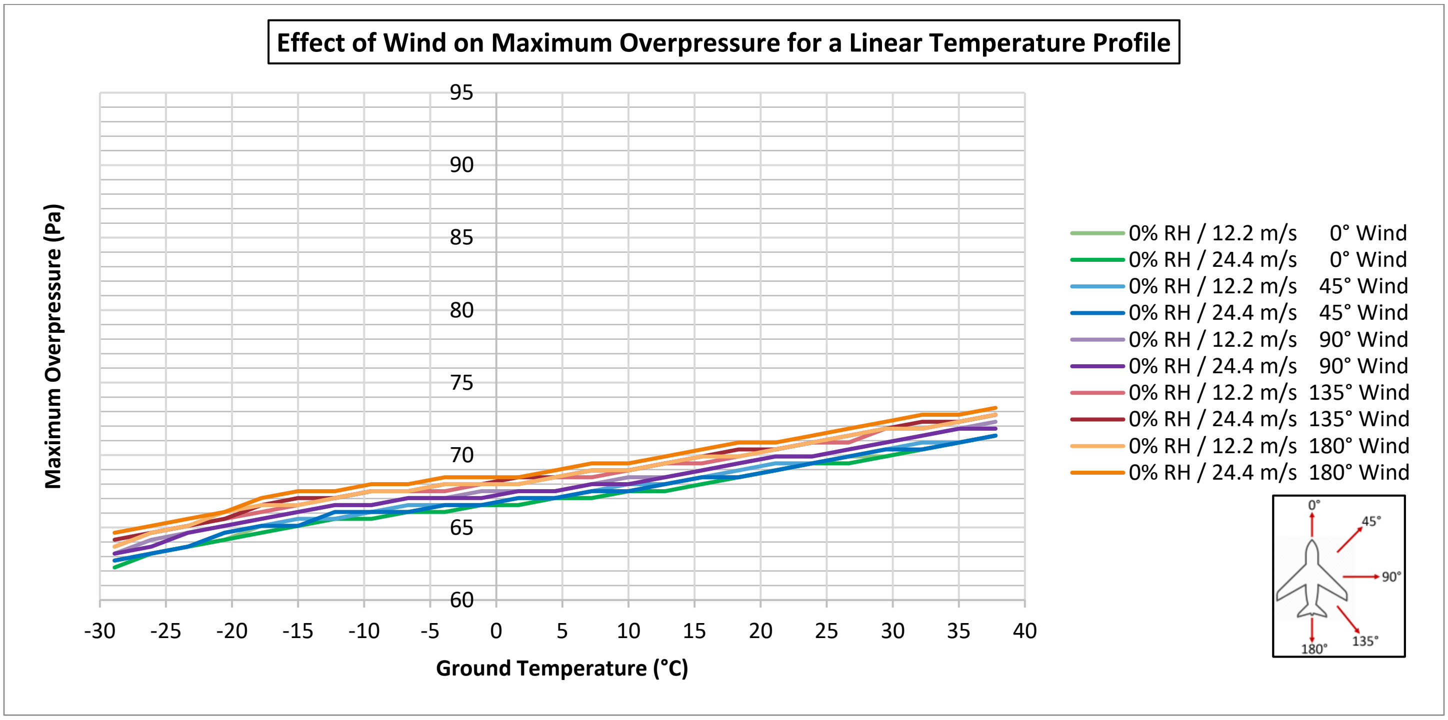

Figure 26: Max Overpressure Sensitivity to Wind - Linear Temperature Profiles

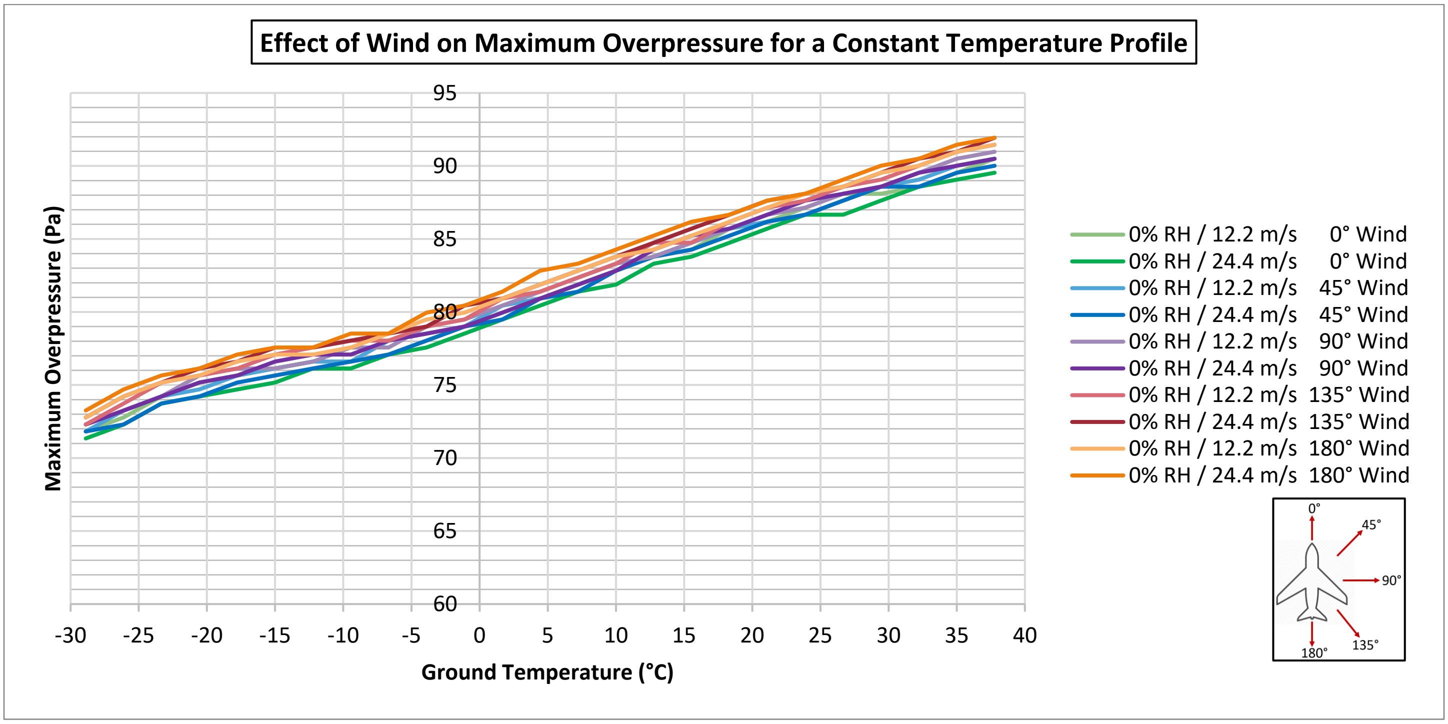

Figure 27: Max Overpressure Sensitivity to Wind - Constant Temperature Profiles

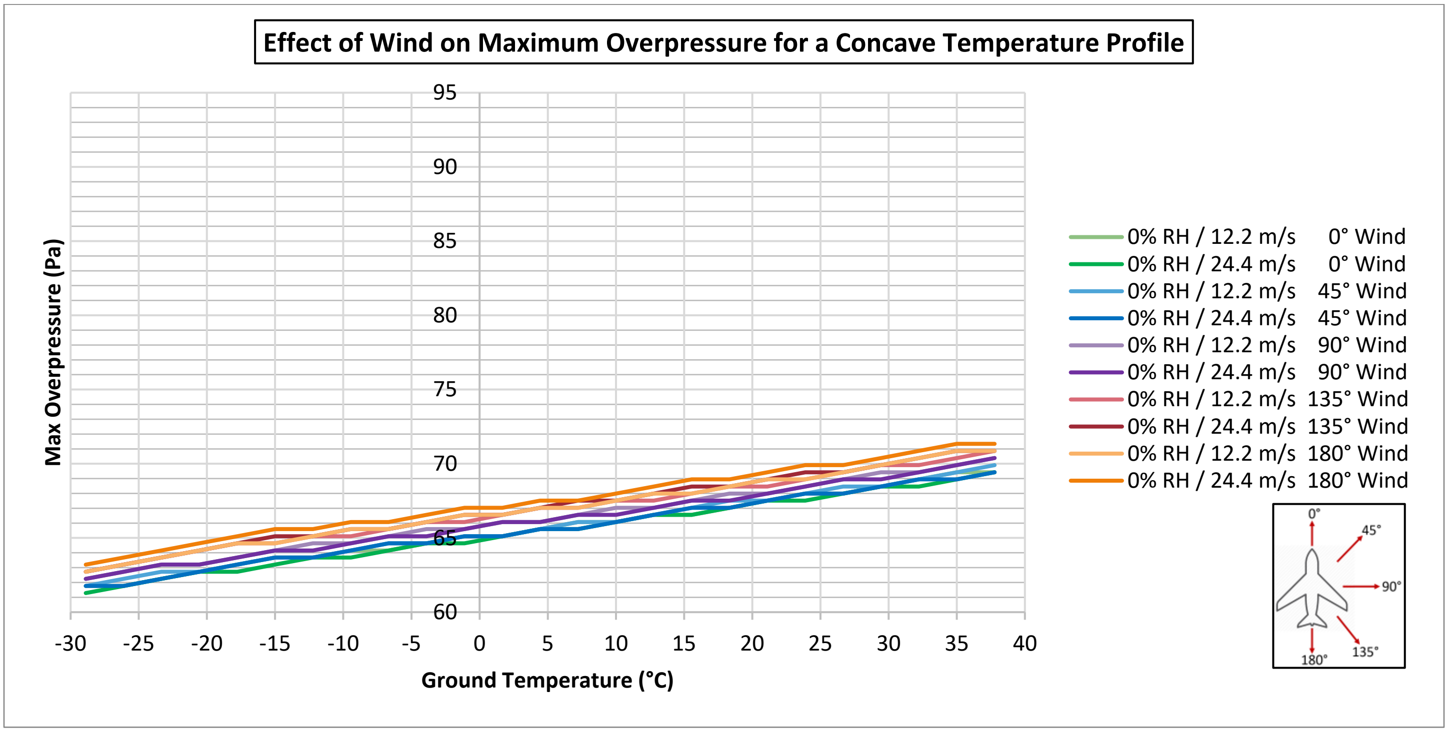

Figure 28: Max Overpressure Sensitivity to Wind - Concave Temperature Profiles

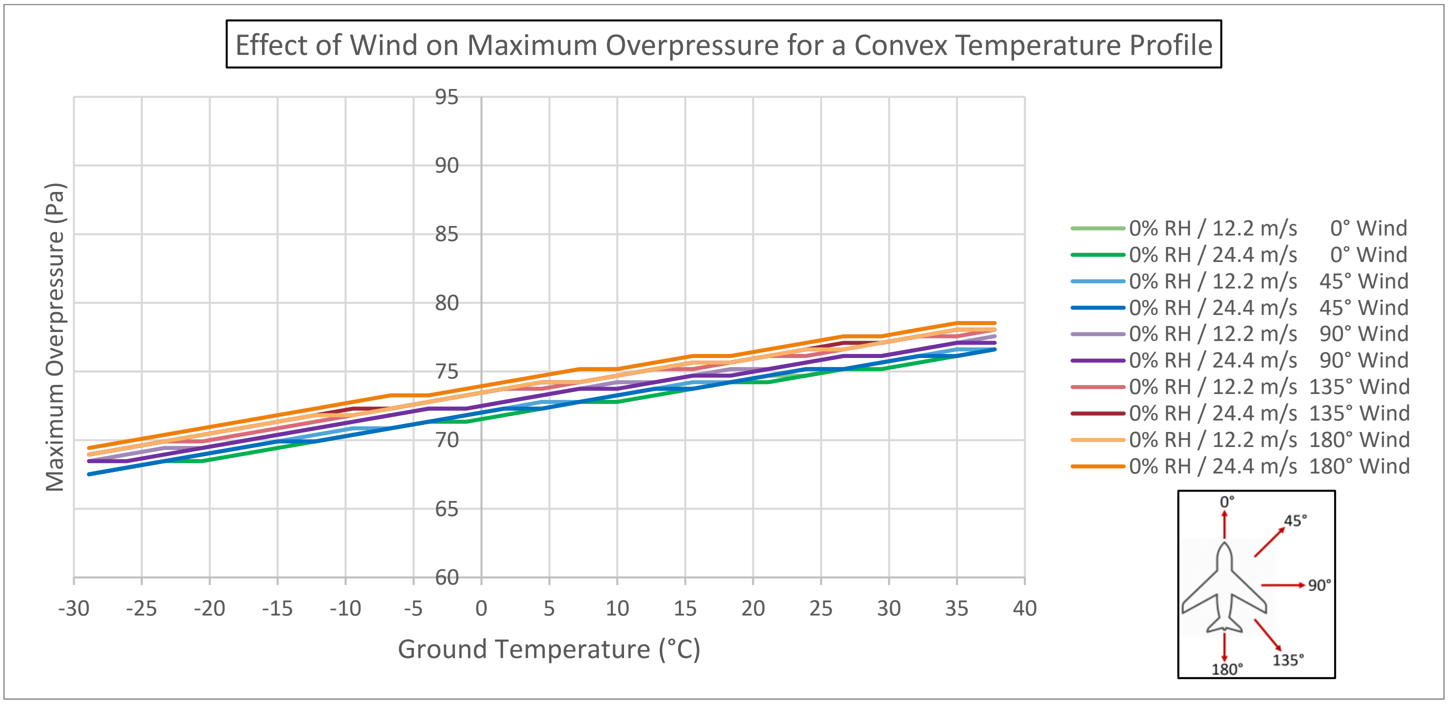

Figure 29: Max Overpressure Sensitivity to Wind - Convex Temperature Profiles

The sensitivity of the max overpressure of ground booms in Mach cut-on conditions to wind direction and magnitude is consistent for constant, linear, and concave, and convex temperature profiles, and follows the same general trends as loudness. Pure tailwinds result in lower max overpressure ground booms while pure headwinds result in higher max overpressure ground booms. The difference between a strong headwind and a strong tailwind is about 2-3 Pa, and is the roughly the same regardless of the temperature profile.

Realistic Profiles
Mach cut-on conditions were also studied for the realistic temperature profiles in order to ascertain the impact of changing the temperature profile on these atmospheres. The realistic temperature profiles contain real data for temperature, wind, and humidity. The sensitivity study was run by shifting the temperature profiles by a constant temperature to see the impact of flying over these locations in during different seasons. This study was also done to benchmark the realistic profiles before performing the Mach cut-off studies. The sensitivity of loudness to temperature changes in the realistic profiles is shown in Figure 30. The sensitivity of max overpressure to temperature changes in realistic profiles is shown in Figure 31.

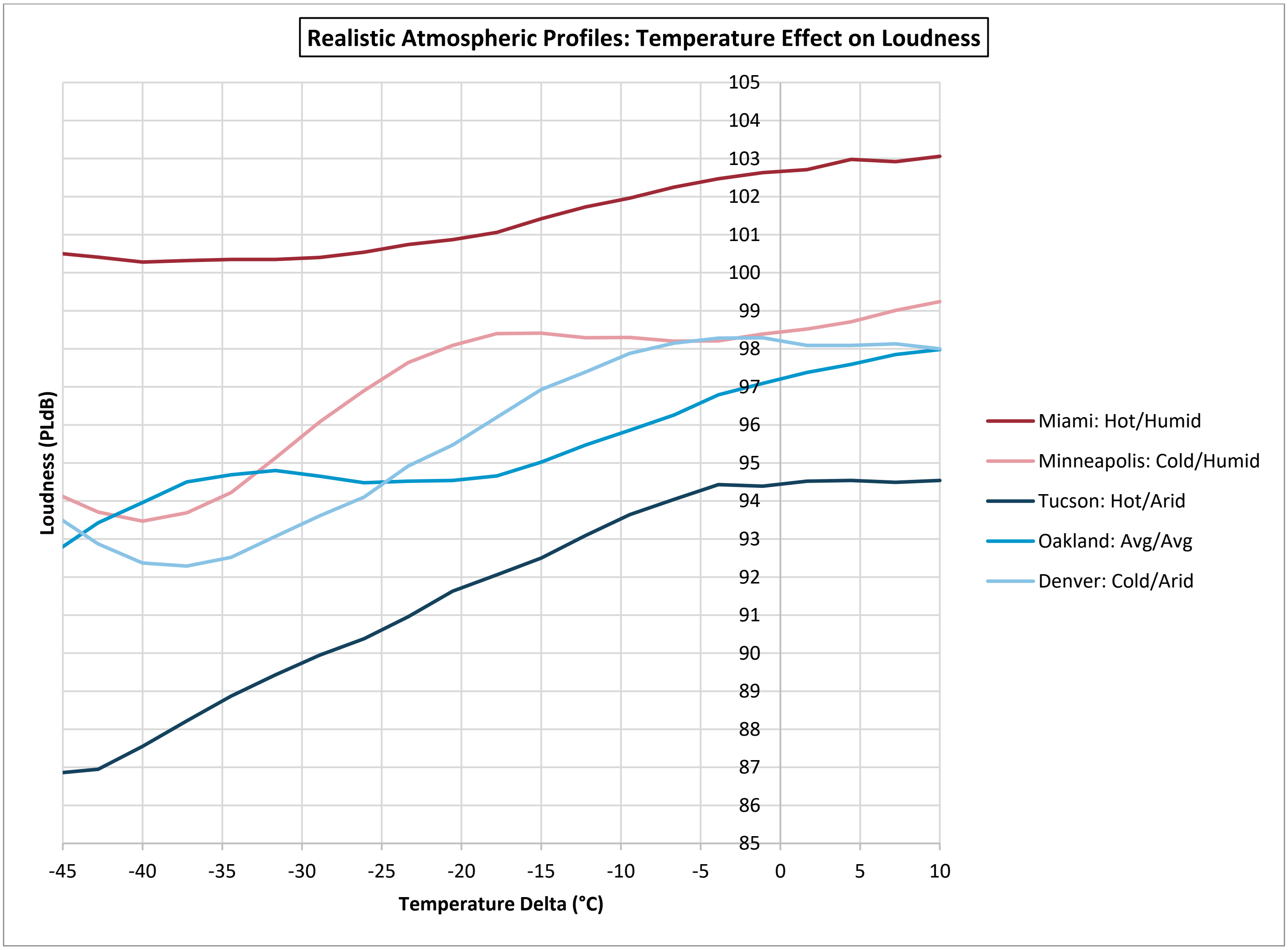

Figure 30: Loudness Sensitivity to Temperature - Realistic Profiles

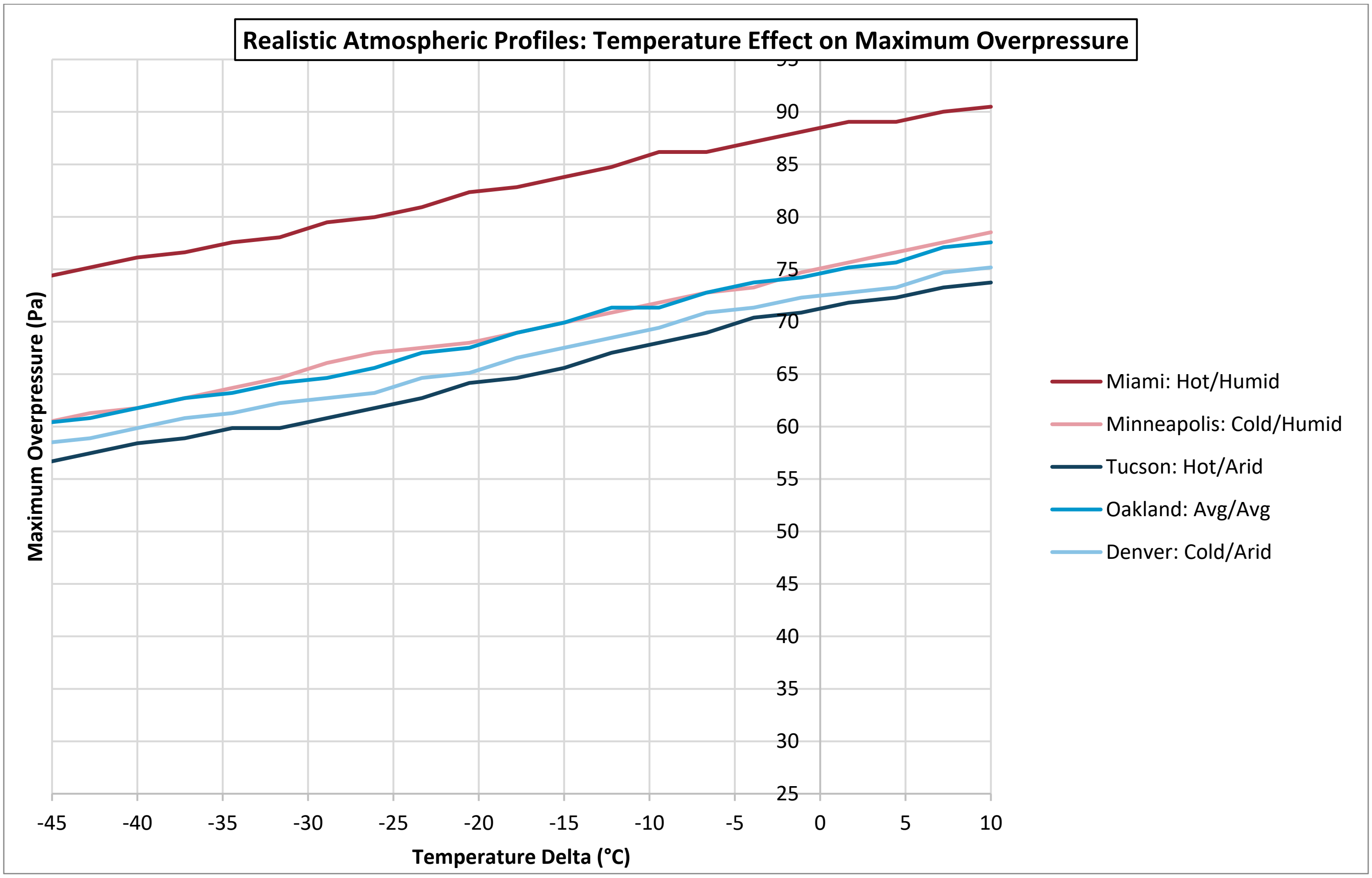

Figure 31: Max Overpressure Sensitivity to Temperature - Realistic Profiles

As can be seen in the above results, the impact of shifting the temperatures in the realistic profiles mimics that show in the standard profiles. As the overall temperature in the atmosphere increases, both the loudness and the max overpressure of the ground boom increases. This trend is much more linear in the max overpressure results than the loudness results. For loudness, there is a more non-linear relationship for colder atmospheres. Most likely due to the frequency dependency of the loudness metric. Another interesting observation from this study is that humidity has a large influence on the loudness and max overpressure, almost more than temperature. Both the humid climates (regardless of hot or cold) have higher max overpressures and loudness results for ground boom. For example, even Miami on a very cold day would have a louder ground boom than Tucson on a very hot day due to the difference in relative humidity. These results were important to gather to help benchmark the realistic profiles going into the Mach cut-off study.

Mach Cut-Off Results: Standard Profiles

The primary goal of Task 4 was to study the impact of atmospheric changes on Mach cut-off conditions. This was done through using PCBoom and using the near-field pressure signature for Aerion's AS2 vehicle. The conditions run for Mach cut-off flight were a flight speed of Mach 1.1 at an altitude of 13.7km (45,000ft). The metrics tracked in this study were Mach cut-off Mach number and Mach cut-off altitude. Mach cut-off Mach number indicates the *fastest* speed at which the aircraft could fly at 13.7km (45,000ft) and still maintain cut-off. Flying at any speed faster than the Mach cut-off Mach number will result in a ground boom. Mach cut-off altitude indicates the *lowest* altitude at which the aircraft could fly a Mach 1.1 and still maintain Mach cut-off. Flying at any altitude lower than the Mach cut-off altitude at Mach 1.1 will results in a ground boom. The first Mach cut-off study performed was for the standard profiles. Initially, this was done for humidity, wind, and temperature variations. However, it was discovered that the PCBoom calculations for Mach cut-off conditions do not consider humidity. The calculations do consider horizontal winds (not vertical winds), but the Georgia

Tech team initially only created constant wind speed changes which did not impact the Mach cut-off results. Studying Mach cut-off sensitivity to varying horizontal winds could potentially be a task for future research, although Penn State has done much of this in Task 1A: Assess and Extend Modeling Capabilities for Mach Cut-off Events. Georgia Tech decided to focus primarily on the impact of varying temperature gradients on Mach cut-off flight conditions. Both realistic and standard temperature profiles were examined, and the results are presented below.

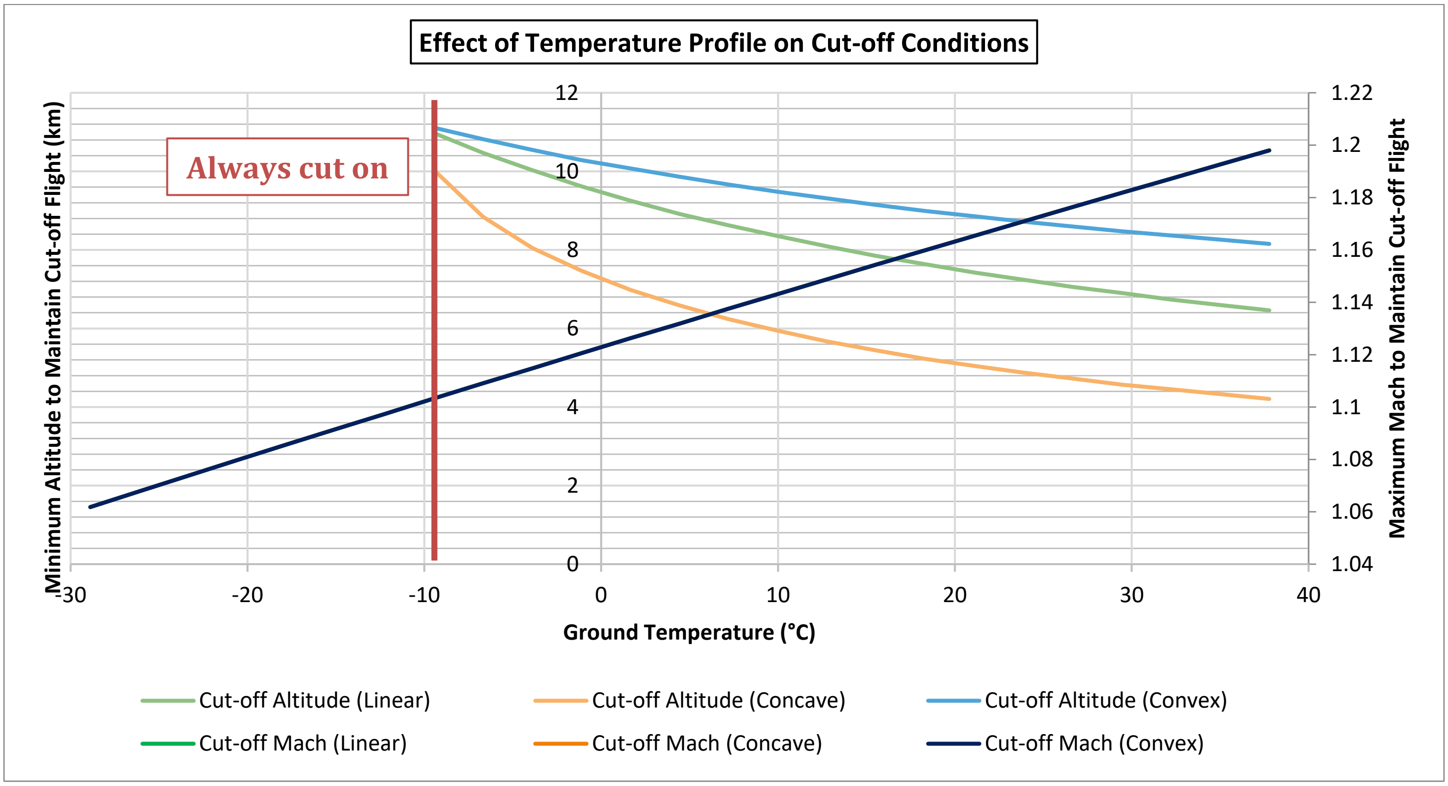

Figure 32: Mach Cut-off Conditions for Variations in Standard Profiles

Figure 32 displays the sensitivity of Mach cut-off conditions to changes in temperature gradients of standard atmospheric profiles. The first observation made pertains to the Mach cut-off Mach number. It was discovered that the Mach cut-off Mach number is independent of changes in the temperature profiles gradients, if flying at a fixed altitude. The only temperatures that impact the Mach cut-off Mach number are the temperature at altitude and the ground temperature; the temperature profile in-between these points do not impact the results. This is because the speed of sound at altitude and the ground are the only parameters that vary Mach cut-off conditions. Therefore, this implies that phenomena such as temperature inversions do not impact the Mach cut-off Mach number. The insensitivity to temperature gradients is logical since PCBoom utilizes Snell's law to map the propagation path through the atmosphere and the refraction is directly proportional to the change in speed of sound (temperature). It was observed, for all temperature profiles, as the ground temperature increases the maximum Mach cut-off flight Mach number increases monotonically. This implies that if a supersonic aircraft is flying at a constant altitude and Mach number it will be more likely for the aircraft to produce a ground boom as it flies over colder locations.

The sensitivity of Mach cut-off flight to temperature gradients is also observed in the Mach cut-off altitude. The Mach cut-off altitude differs from the trends seen for Mach cut-off Mach number as the shape of the temperature profile does impact the Mach cut-off altitude. Using a linear temperature profile as a reference point, a convex temperature profile will result in a higher Mach cut-off altitude and a concave temperature profile will result in a lower Mach cut-off altitude. This is a result of the temperature enabling Mach cut-off flight being located at different altitude for the different profile shapes. This is shown in Figure 33. For flight at 13.7km and Mach 1.1, the cut-off altitude is a function of where the "cut-off temperature" is located in the atmosphere. This temperature is located at a higher altitude in the convex temperature profile than the linear and concave temperature profiles.

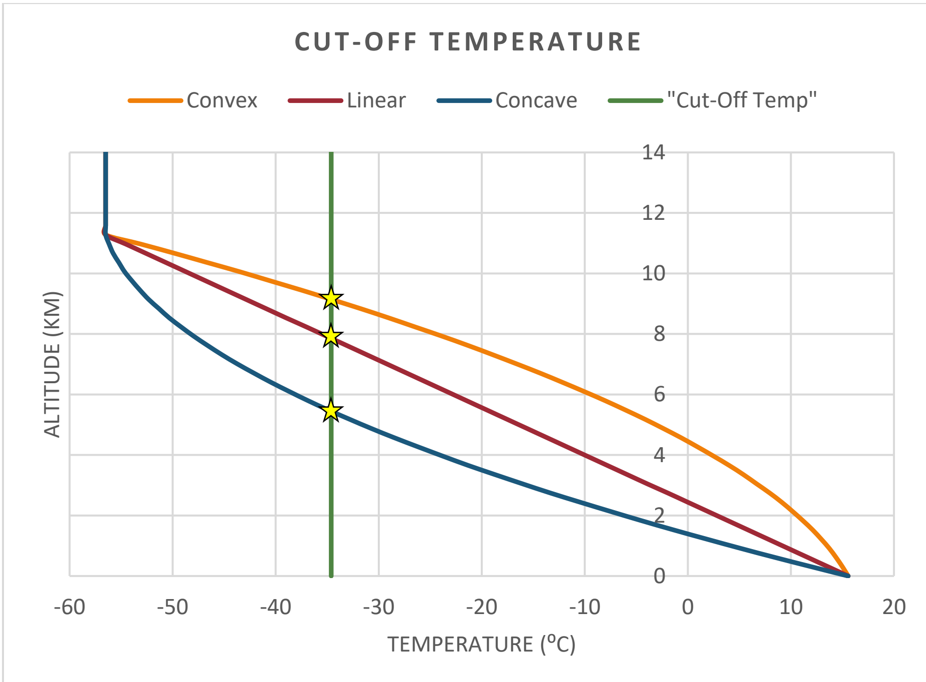

Figure 33: Mach Cut-off Altitudes Resulting from Different Temperature Profiles

The other observation made during this study was, for the same temperature profile shape, as the ground temperature increases the Mach cut-off altitude decreases. This implies that as the ground temperature increases, a supersonic aircraft flying at constant Mach number would need to lower its flight altitude in order to maintain Mach cut-off flight. It was also observed that as the ground temperature decreases past a certain point, the boom will always be cut-on for a fixed flight velocity. This is because the tropopause temperature (which does not change) and the ground temperature do not provide a large enough difference in temperature to allow for Mach cut-off conditions. All the results from the standard temperature profile sensitivity study provided insight to the Georgia Tech team and the other Project 42 participants.

Mach Cut-off Results: Realistic Profiles

The final part of Task 4 was to study the sensitivity of Mach cut-off flight conditions under realistic atmospheric conditions. This was done using the same five atmospheric profiles utilized in the Mach cut-on benchmarking exercise: Hot/humid, hot/arid, cold/humid, cold/arid, and average/average. It should be noted that for this study the Georgia Tech team maintained the wind and relative-humidity profiles and shifted the temperature profiles by constant deltas. The goal of this study was observed that changes in both Mach cut-off altitude and Mach cut-off Mach number as the temperatures in the realistic profile changed. The sensitivity of Mach cut-off altitude is shown in Figure 34 and the sensitivity of Mach cut-off Mach number is shown in Figure 35. The data represented in red corresponds to humid climates and the data represented in blue corresponds to climates with lower humidity. The results were divided in this way because the largest difference in observed behavior seemed to correlate to relative humidity.

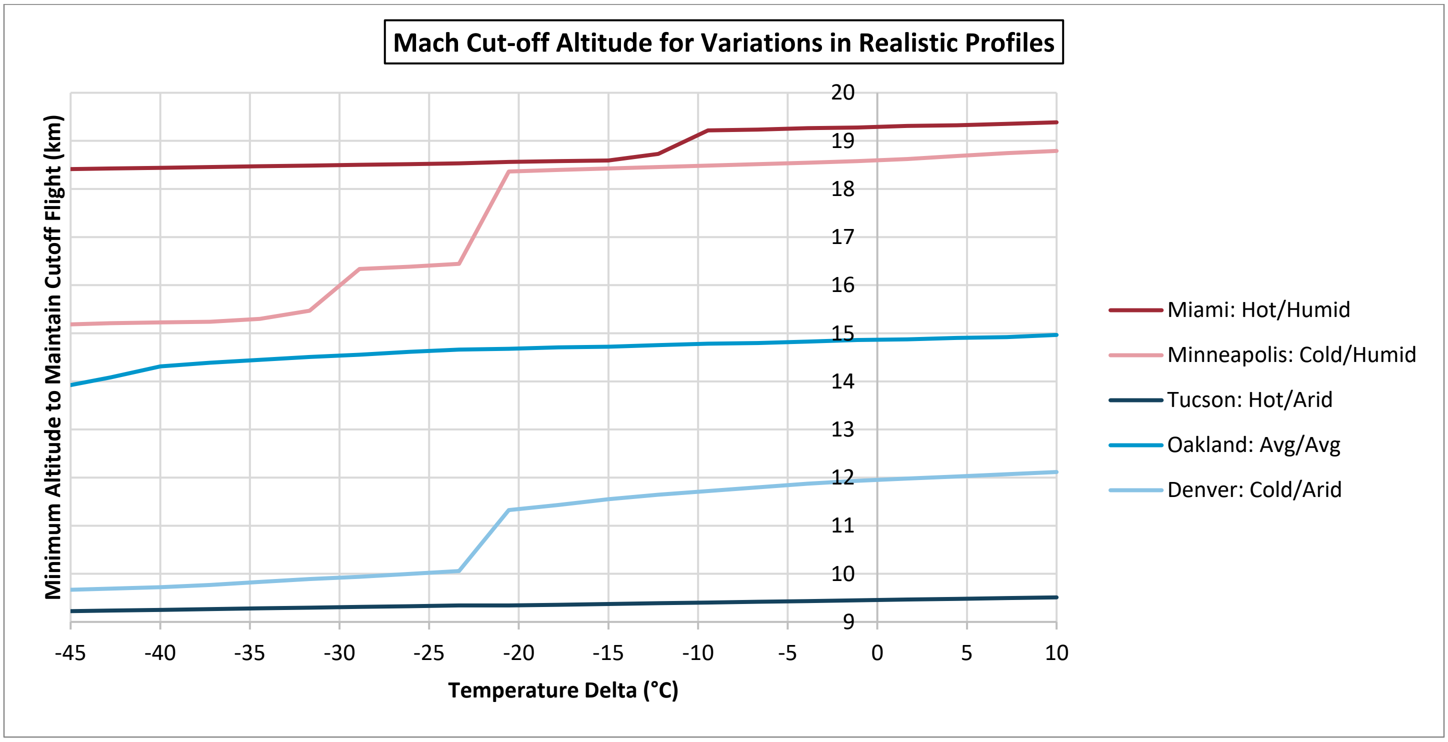

Figure 34: Mach Cut-off Altitude for Variations in Realistic Profiles

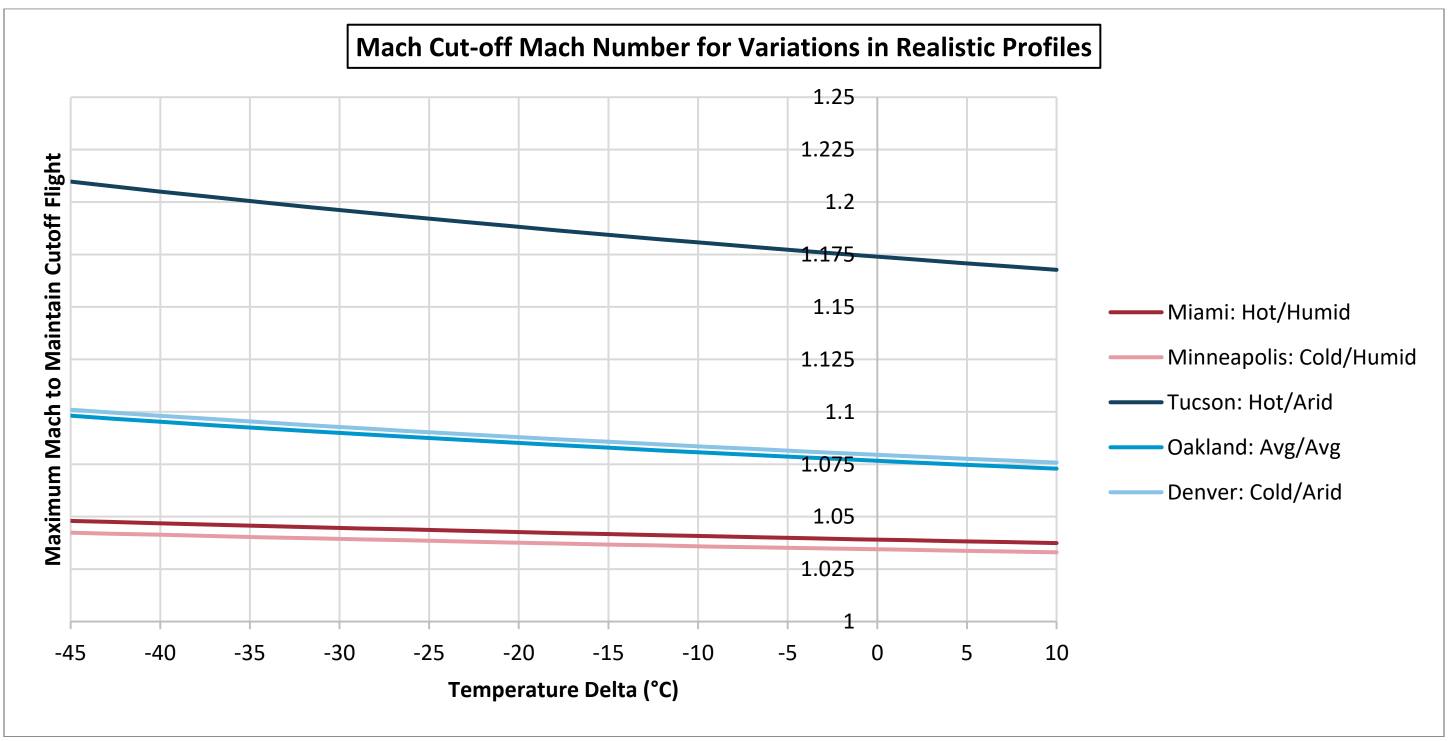

Figure 35: Mach Cut-off Mach Number for Variations in Realistic Profiles

The sensitivity observed for Mach cut-off altitude to constant shifts in the entire temperature profile for the realistic atmospheres is that as the temperature increases the Mach cut-off altitude increases (for a constant flight Mach number). This highlights the difference between changing the temperature gradient (as was done for the standard profiles) and shifting the temperature profile. As the entire atmosphere gets warmer the Mach cut-off altitude increases, whereas if only the ground temperature increases, the Mach cut-off altitude decreases. As can be seen in Figure 34, the Georgia Tech team also observed large jumps in the Mach cut-off altitude for both the Denver and Minneapolis atmospheres. This was traced back to a combination impact of both the location/altitude of the temperature required to maintain Mach cut-off flight and large changes in wind direction and magnitude. If the Mach cut-off temperature is located at an altitude around which there is large variations in horizontal winds, small changes in the temperature can significantly impact the Mach cut-off altitude.

The sensitivity for Mach cut-off Mach number to constant shifts in the entire temperature profile for realistic atmosphere is as the temperature in the entire atmosphere increases, the Mach cut-off Mach number decreases (for a constant flight altitude). This is also a different behavior than the observed sensitivity for changing the temperature gradient (ground temperature). It was also observed that in climates with more humidity, the sensitivity to temperature was less than climates with lower atmospheric relative humidity. The results of the Mach cut-off sensitivity study show that in terms of atmospheric conditions, the gradients tend to produce greater alterations to Mach cut-off conditions than absolute shifts. This confirms that the propagation path of sonic booms is heavily dependent on the refraction through the atmosphere and less dependent on the absolute conditions.

Conclusions

The research performed for Task 4: Sensitivity Study of Mach Cut-off Flight provided interesting results that shine light on the behavior of Mach cut-off flight and the conditions which enable it. Important observations were made in the sensitivity of Mach cut-off flight to temperature, and minor observations were made relative to wind and humidity. With further expansion of sonic boom propagation tools, the sensitivity to wind and humidity could be studied more completely. An important aspect of this is capturing the impact of vertical winds on Mach cut-off flight, as being actively pursued by the Penn State research team. A large benefit of the research done through this task was Georgia Tech's development of the PCBoom Wrapper. This tool will help facilitate any future studies using PCBoom to quickly assess a large amount of cases, whether it be for different atmospheric parameters, flight conditions, or aircraft.

Georgia Tech also concluded that the initial boom signature at flight altitude does not impact the propagation path for Mach cut-off flight. The only factors that Mach cut-off flight is sensitive to are the speed and altitude at which the aircraft is flying at as well as the atmospheric profile. The implications of this are that a large supersonic cruiser, such as the Concorde, will have the same Mach cut-off restriction as a small supersonic business jet. This results from the fact that the propagation path of sound is not a function of amplitude or frequency of the sound; only the initial angle of propagation and the changes in the atmospheric speed of sound. A lot was learned about Mach cut-off flight through this task; however, this is just the beginning of the effort to fully understand Mach cut-off flight.

Milestone(s)

- Finished development of PCBoom Wrapper
- Gathered atmospheric data for realistic profiles
- Completed initial benchmarking Mach cut-on study for standard profiles
- Completed initial benchmarking Mach cut-on study for realistic profiles
- Completed Mach cut-off study for standard profiles
- Completed Mach cut-off study for realistic profiles
- Completed Task 4

Major Accomplishments

Georgia Tech has completed the research plan for this task. Georgia Tech has also acquired both the source code and executable for PCBoomv6.7. PCBoomv6.7 was used to perform the sensitivity analysis on the acoustical model provided by Aerion, Volpe, and Penn State University. Georgia Tech completed the initial benchmarking study for the sensitivity of Mach cut-off flight on a standard sonic boom signature (F-18 geometry provided with the executable). Georgia Tech assessed the sensitivity of the resultant ground boom strength and shape of the F-18 model with variations in atmospheric temperature and humidity as well as various flight Mach numbers. A tool to help facilitate the execution of task 4, the PCBoom wrapper, was developed and utilized. The Aerion AS2 model was successfully incorporated into the study and the sensitivity of the model was assessed for both Mach cut-on and Mach cut-off conditions. The sensitivity study was performed and completed for various temperatures, winds, and relative humidity in both standard atmospheric profiles and realistic atmospheric profiles. The results of the study were compiled and presented in this report.

Publications

Gregory Busch, Jimmy Tai, Dimitri Mavris, Ruxandra Duca, and Ratheesvar Mohan, "Sensitivity analysis of supersonic Mach cut-off flight," J. Acoust. Soc. Am.,Vol. 141, No. 5, Pt. 2, 3565 (2017).

Outreach Efforts

Conference Presentations:

- Autumn ASCENT COE Meeting 2016: Alexandria, Virginia – Sept. 27-29, 2017
- Spring ASCENT COE Meeting 2017: Alexandria, Virginia – April 18-20, 2017
- ASA Acoustics 2017: Boston, Massachusetts – June 24-27, 2017
- Autumn ASCENT Meeting 2017 & ASCENT Noise Working Group: Alexandria, Virginia – Sept. 26-28, 2017

Awards

None

Student Involvement

Ruxandra Duca and Ratheesvar Mohan both preformed significant work under Task 4 and Task 5. Both students were integral parts of the Georgia Tech research team and worked diligently in researching technologies pertaining to Mach cut-off flight as well as learning how to operate PCBoom, generate results, and analyze the output/results. Ruxandra and Ratheesvar attended weekly research meetings and provided deliverables to the Georgia Tech ASCENT 42 research team. Ruxandra is currently still a Graduate Research Assistant and student at Goergia Tech and recently passed her PhD qualifying exams. Rathessvar graduated with his Master's degree in Aerospace Engineering in May 2017 and is currently working in industry.

Plans for Next Period

Task 4 is not continuing for the next research period.

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

Georgia Institute of Technology

Objective(s)

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 also investigated 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 was primarily through literature review and solicitation of opinions from experts in the fields of aerospace, policy making, meteorology, and manufacturing. Georgia Tech performed this task in a phased approach. The first phase was 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 targeted technologies that could make it easier for operators of supersonic business jets to identify or predict atmospheric conditions. These technologies were studied using a cost-benefit type of evaluation to identify both the strengths and potential weakness of each technology.

The second phase of this task was 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 had a better understanding on how flight conditions and atmospheric conditions impact the capability of a supersonic aircraft to fly at Mach cut-off. This allowed the

Georgia Tech team to identify any additional technologies that were overlooked during the initial phases of this task. The result of both of these phases was a portfolio of technologies that the Georgia Tech team hopes will be able to guide investment in technologies to facilitate Mach cut-off flight.

Mach cut-off flight is a phenomenon that occurs when the sonic boom rays of an airplane refract above the ground. This results in the absence of a sonic boom at the ground; only subsonic, evanescent waves reach the ground. This type of flight allows aircraft to fly at supersonic speeds while avoiding sonic booms that can be perceived by humans at the ground. This phenomenon is caused by changes in the local sound propagation speed, which is in turn a function of the local atmospheric properties. PCBOOM was used to investigate the sensitivity of Mach cut-off flight to various parameters, and it was discovered that the noise signature thereof is sensitive to the following factors:

- Temperature
- Wind speed
- Wind direction
- Relative Humidity
- Flight Mach number

Since it is evident that local weather conditions affect Mach cut-off flight, research was done into technologies that could be leveraged to accurately detect and/or predict weather ahead of an aircraft both in and out of its flight path. This would allow pilots to adjust the flight path and/or the flight speed such that the aircraft could operate in cutoff conditions as much as possible. The subsequent section summarizes the technologies identified.

Weather Sensing Technologies

List of Technologies Investigated

A. Dual Polarization Doppler Weather Radar
B. Wind Cube
C. WVSS-II
D. WSI Total Turbulence
E. Portable Scanning LIDAR for Profiling the Lower Troposphere
F. Honeywell Intuvue
G. Rockwell Collins MultiScan ThreatTrack

A. Name: Dual Polarization Doppler Weather Radar

Source: NOAA/NWS [http://www.nssl.noaa.gov/tools/radar/dualpol/]

Highlights:

- Determines composition and intensity of rain using electromagnetic pulses on water droplets.

Benefits:

- Clearly distinguishes between weather types (rain, snow, or hail) and even non-weather features (smoke, dust).
- Can detect aviation hazards such as birds.
- Can detect aircraft icing condition.

Drawbacks:

- On ground, cannot be installed on aircraft.
- Analyzes specific points of interest rather than entire areas.
- Cannot predict weather.

Features/Description:

- Location of the rain area can be determined from the time taken by the echoes returning back to the radar. For rainfall intensity, in general, stronger echoes (reflectivity) indicate heavier rainfall.
- Unlike traditional single polarization radar, the new radar can transmit and receive electromagnetic pulses from both of the horizontal and vertical polarizations.
- The two polarized waves give rise to echoes of varying characteristics when reflected by water droplets of different sizes or by different ice shapes.
- These characteristics can be analyzed to determine the composition of rain areas as well as the rainfall intensity.

Maturity Date: In service currently.

Adaptation: This system cannot be installed on an aircraft. It can only be used on the ground.

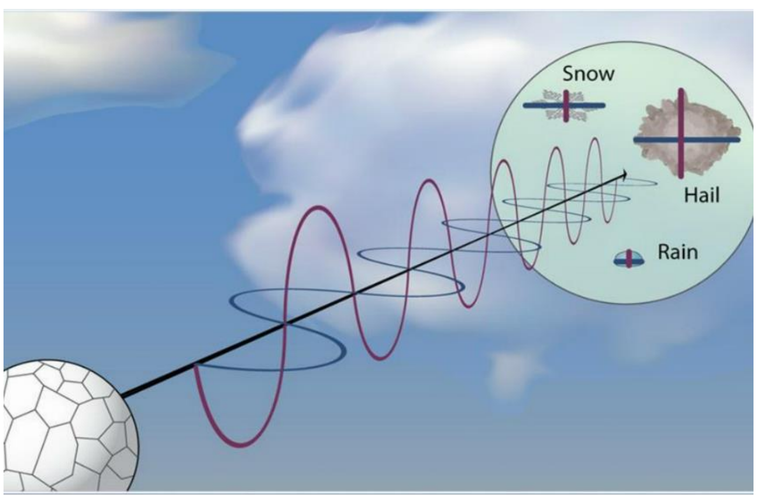

Figure 36: Dual Polarization Doppler Weather Radar

B. **Name:** Wind Cube
Source: NRG Systems [https://www.nrgsystems.com/products/lidar/detail/windcube-v2-lidar]
Highlights:
- Wind and Aerosol 3D Scanning (using Doppler LIDAR).

Benefits:
- Real-time wind, cloud layers, and aerosol (ice, ash, dust, smoke) layers measurements.
- Any scanning geometry up to 10km.
- Monitors height of the Planetary Boundary Layer (PBL).

Drawbacks:
- Dimensions: 1m x 1.3m. Therefore, it cannot be installed on an aircraft.

Features/Description:
- Based on optical fiber technology, WINDCUBE Scanning LIDARs are designed to run unattended and meet extreme operational requirements.
- Incorporates a fast endless rotation scanner head that enables capture of highly turbulent local phenomena or scans of a wide area at a high frequency.

Maturity Date: In service.
Adaptation: It is too large to be installed on an aircraft.

Figure 37: Wind Cube

C. **Name:** WVSS-II
Source: SpectraSensors/SWA [https://www.spectrasensors.com/wvss/]
Highlights:
- Water Vapor Sensing System: monitors moisture distribution and evolution in the atmosphere.

Benefits:
- Mounted on fuselage.
- Data collection in real-time.
- Good prediction capabilities.

Drawbacks:
- Data forwarded to US National Weather Service in near real-time.

Features/Description:
- Measures the amount of atmospheric water vapor in a sample of air continuously drawn from outside the aircraft.
- Sensor consists of:
  - Air Sampler
  - Connecting Hoses
  - Analyzer System Electronics Box (SEB)
- The SEB uses Tunable Diode Laser Absorption Spectroscopy to accurately measure the amount of water vapor in the atmosphere.
- Laser selected to be at wavelength corresponding to absorption wavelength of water.
- Absorption of laser light is proportional to the amount of water in the sampled air.

Maturity Date: In service currently.
Adaptation: Can be mounted on the fuselage of the aircraft.

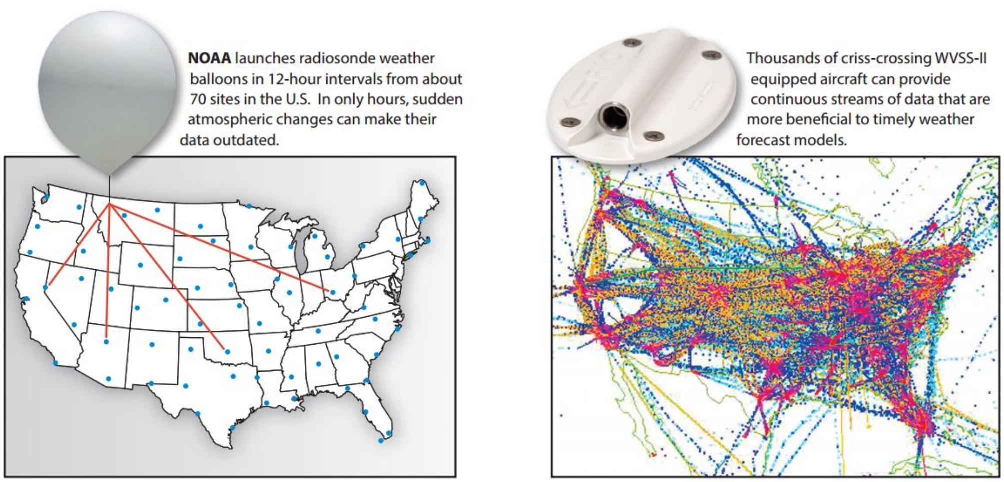

Figure 38: WWVS-II

D. Name: Total Turbulence

Source: WSI Corp [https://business.weather.com/products/total-turbulence]

Highlights:

- Real-time turbulence detection technology and reporting system.

Benefits:

- Delivers precise forecasts of turbulence for the next 24 hours.
- Delivers actionable turbulence alerts throughout all phases of flight.

Drawbacks:

- Crowdsourced data; only near real-time.
- Has to be incorporated in Aircraft Condition Monitoring System (ACSM).
- Coverage only in North America and East Asia.

Features/Description:

- State-of-the-art software monitors every bump and even measures the exact force of the turbulent air outside the plane.
- Automates the reporting of aircraft encounters with significant turbulence and severe loads based on certain g- load thresholds
- All of this data is instantly relayed to the ground where it is mapped and combined with the latest weather reports from aviation meteorologists.
- Combined, this vital information provides a detailed map of the world's turbulence which can then be beamed to pilots in the area, helping them to pick clean air.
- Some 700 aircraft worldwide are currently fitted with the system.

Maturity Date: In service currently.

Adaptation: This system can be installed directly on the aircraft.

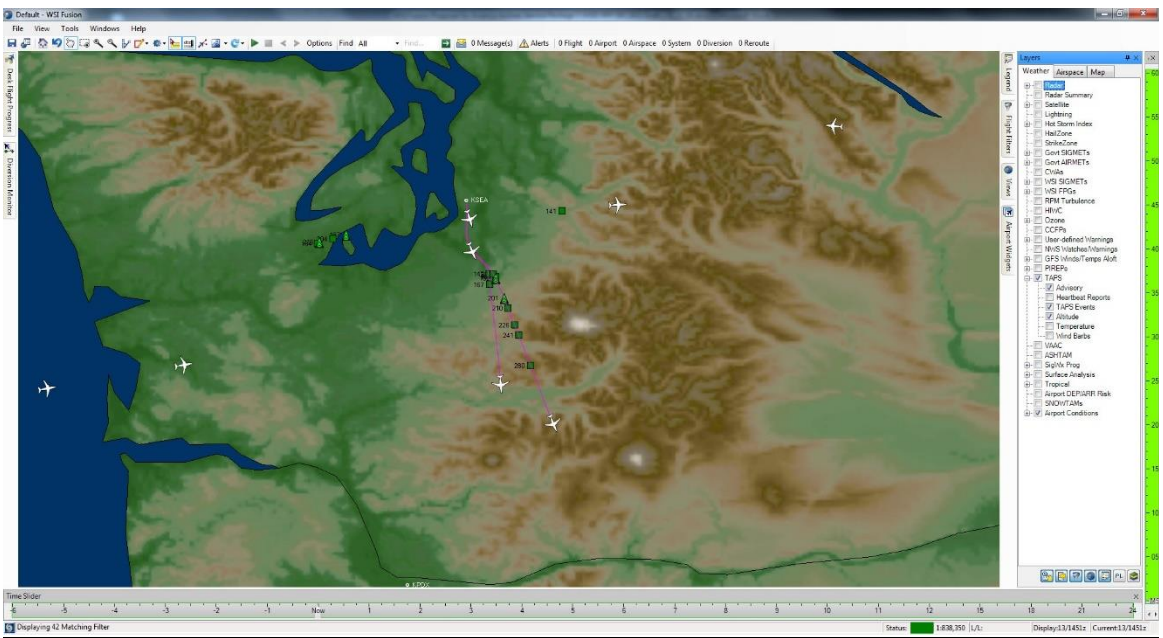

Figure 39: Total Turbulence

E. **Name:** Portable Scanning LIDAR for Profiling the Lower Troposphere
Source: [https://www.geosci-instrum-method-data-syst.net/4/35/2015/]
Highlights:
- Real-time measurement of atmospheric aerosols, clouds, and trace gases

Benefits:
- 3D
- Small size, light weight. This makes it suitable for installation in various vehicles.
- Real-time.
- Monitors atmospheric variables (aerosol, cloud, temperature, water vapor, optical depth of particulate matter, etc.) and meteorological processes (boundary-layer growth, aerosol and cloud layering, etc.).
- Horizontal coverage of 8-10km while scanning.
- In zenith mode good quality backscattered signals can be from 20 km away.

Drawbacks:
- Not fully developed yet.

Features/Description:
- Uses LIDAR (laser radar), which is based on the principle of light spectroscopy.
- The atmospheric species are sensitive to different wavelengths. Thus a multi-wavelength laser arrangement is used.
- The optical power measured with LIDAR is proportional to the signal backscattered by the atmospheric particles and molecules.
- The system includes:
  - The laser as a transmitter.
  - A Schmidt-Cassegrain telescope as a receiver.
  - Photomultiplier tube as a detector.
  - Real-time data acquisition and signal processing unit.
- Components are mounted on a vibration-isolated platform in an aluminum framework for good structural stability.
- All the hardware sections of the LIDAR system are controlled automatically via a computer with the Microsoft Windows platform with a user-friendly GUI.

Maturity Date: Unknown; system is not fully developed yet.
Adaptation: This system can be installed directly on a wide variety of aircraft, owing to its small size and light weight.

F. **Name:** Intuvue
Source: Honeywell [https://aerospace.honeywell.com/en/products/safety-and-connectivity/intuvue]
Highlights:
- Captures ‘all’ weather from -80 to +80 degrees in front of aircraft, up to 320 nm ahead of aircraft, and from 0 to 60,000 ft.
- Allows vertical scanning with high resolution.
- Can distinguish between types of convective weather.
- Features advanced turbulence detection capability (FAA certified) out to 40nm.

Benefits:
- 3D volumetric scanner is not limited to 2D scanning like most current systems.
- AUTO mode allows for scanning of both on-path and off-path weather.
- Capable of scanning vertical development of storms in 1000 ft increments.
- Internal terrain database removes ground clutter; corrects for Earth’s curvature.

Drawbacks:
- Definition of ‘all’ weather is unclear. Literature provided by the manufacturer fails to clarify this.
- Cost is unknown; appears to be very expensive. A quote would have to be requested from the manufacturer to determine the exact cost of purchasing and installing the system on an aircraft.

Features/Description:
- Key technological enhancements of the system are volumetric 3D scanning and pulse compression technologies, which vastly improve weather detection and predictive hazard warnings, compared to conventional 2D radar.
- Continuously and automatically scans all the weather in front of the aircraft and stores data in a 3D buffer, creating a three-dimensional image of the weather and terrain; eliminates the need for manual tilt control.
- Pulse compression increases long-range detection and resolution; utilizes fact that energy of pulse (P*T) is constant – results in pulses of shorter duration with much higher power (917W vs. 150W).
- Uses Maximum Reflectivity Indication (MRI) technology to display both weather in flight path and secondary weather below 25,000 ft.
- In MAP mode, plan-view map is generated continuously, and simultaneously with weather de-clutter based on the internal terrain database. Reflectivity data that is considered ground clutter is the basis for the Ground Map.
- Detects turbulence at lower signal-to-noise ratio, enhancing performance at lower reflectivity levels, and at greater distances. This enables better correlation to predicted aircraft turbulence response.

Maturity Date: In service on A320, A330, B737NG, B737Max, B777, E-170/175/190/195/E2, F5X, F7X, F8X and G650 aircraft.
Adaptation: This system is designed to be installed directly on the aircraft without requiring special adaptation.

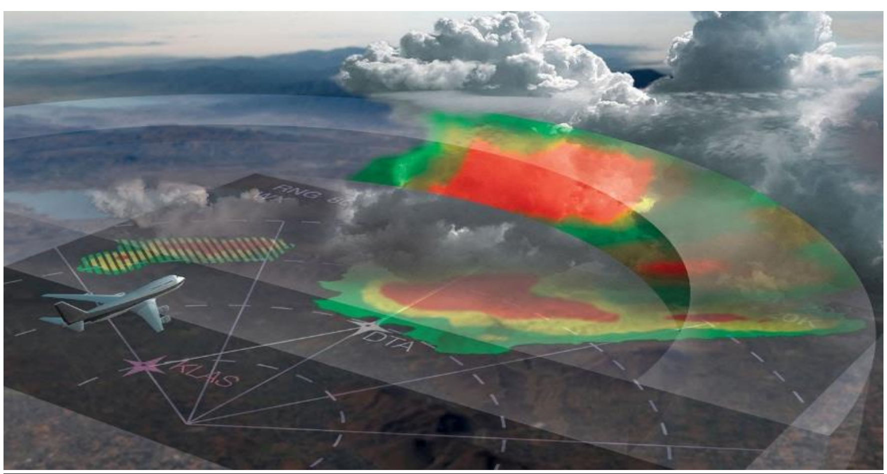

Figure 40: Honeywell Intuvue

G. Name: MultiScan ThreatTrack
Source: Rockwell Collins
[https://www.rockwellcollins.com/Products_and_Services/Commercial_Aviation/Flight_Deck/Surveillance/Weather-Radar/WXR-2100_MultiScan_Threat_Track_weather_radar.aspx]
Highlights:

- Optimized weather detection from 0 to 320 NM and all altitudes.
- Variable temperature based gain.
- Two-level enhanced turbulence detection - certified turbulence display plus "ride quality" turbulence display.
- Advanced ground clutter suppression at all ranges.
- Fully automatic operation.

Benefits:

- OverFlight™ Protection (prevents inadvertent thunderstorm top penetration).
- Geographic weather correlation using a database of historical data to augment algorithms.

Drawbacks:

- Seems to focus mostly on detection of thunderstorms; it is unclear what other types of weather phenomena it can detect.

Features/Description:

- Patented track-while-scan technology prioritizes weather threats out to 320 nm by performing dedicated horizontal and vertical scans on developed or fast-growing convective cells that pose an actual threat.
- Predictive OverFlight™ protection tracks thunderstorm cells ahead and below the aircraft, measures growth rate, predicts bow-wave turbulence and indicates potential threats in the aircraft's flight path.
- Two-level enhanced turbulence detection detects severe and ride-quality turbulence up to 40 nm ahead of the aircraft.

Maturity Date: In service on B737NG and B777 aircraft.
Adaptation: This system is designed to be installed directly on the aircraft without requiring special adaptation.

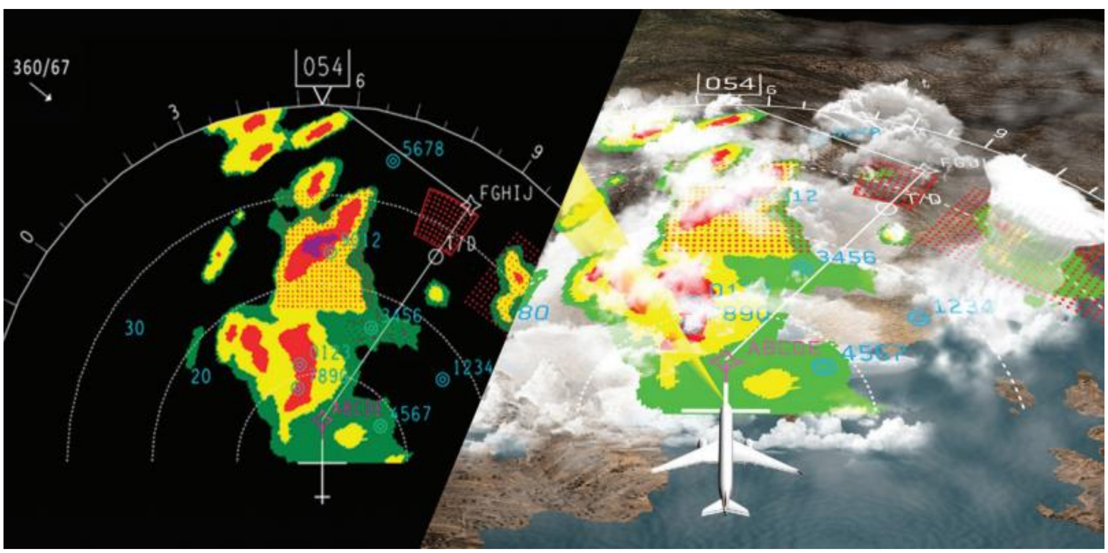

Figure 41: Rockwell Collins MultiScan ThreatTrack

H. **Name:** Cockpit Interactive Sonic Boom Display Avionics (CISBoomDA)
Source: NASA [https://www.nasa.gov/centers/armstrong/Features/CISBoomDA_software.html]
Highlights:

- Software that allows pilots the ability to physically see their sonic footprint on a map as the boom occurred.

Benefits:

- Pilots can identify where they need to fly to avoid sonic booms reaching the ground.
- Geographic weather correlation using a database of historical data to augment algorithms.

Drawbacks:

- This technology currently only provides descriptive data, not predictive data.
- The cost is unknown. Until development is finished, it is difficult to estimate the final price of installing this system on an aircraft.

Features/Description:

- Honeywell and Rockwell Collins are currently developing displays, using the same underlying algorithm, with predictive displays. These displays would allow identification of sonic booms on a proposed flight path. The flight path could then be modified to avoid sonic booms over populated areas.

Maturity Date: Currently in development. Estimated entry into service is unknown.
Adaptation: This system is being designed to be installed directly on aircraft, integrated with the aircraft's avionics.

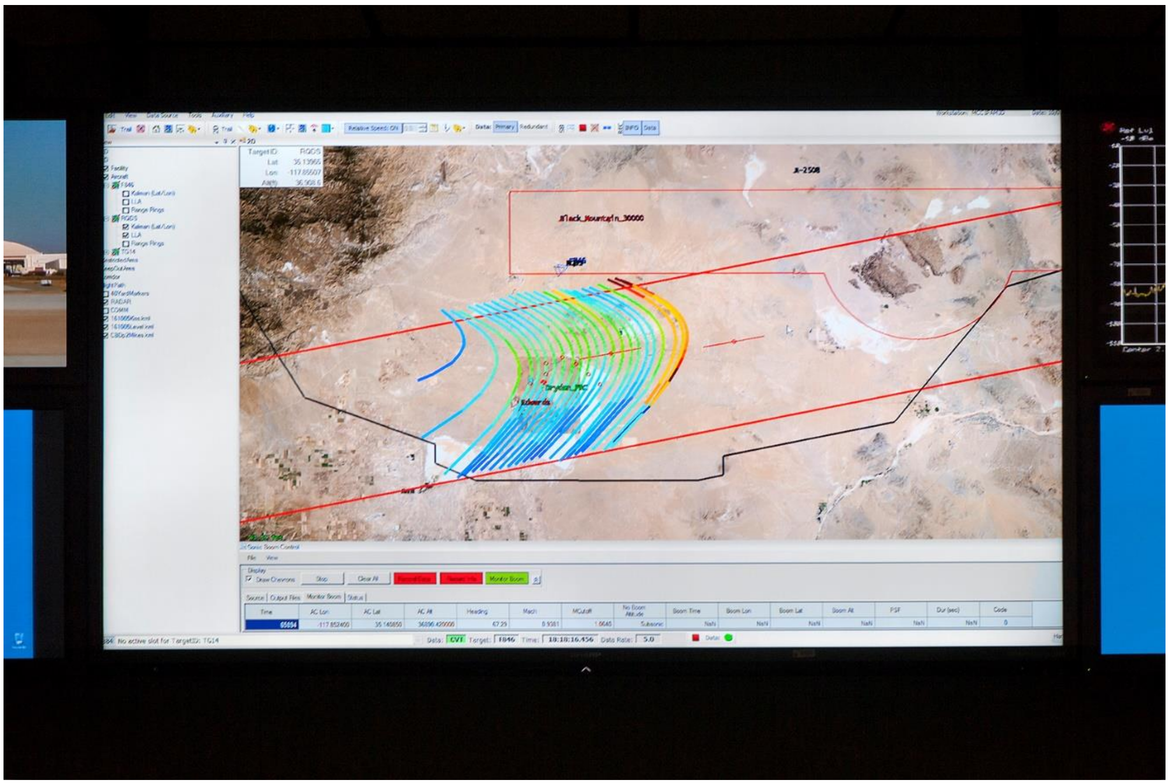

Figure 42: NASA CISBoomDA

Summary of Task 5

Various technologies were researched for Task 5. These technologies were discovered through extensive research in publicly available literature as well as recommendation from experts. Georgia Tech's presence at the Acoustics 2017 conference in Boston, MA was very helpful to gathering additional technologies as researchers and scientist there provided additional resources for this task. It was found through Task 4, that atmospheric conditions can greatly impact the ability to maintain Mach cut-off flight and being able to assess the atmosphere accurately and quickly will be crucial in avoiding any unwanted ground booms. Georgia Tech sees promise in accomplishing this task with the current state of technology, especially in NASA's CISBoomDA, but the technologies will need to mature further to make their way onto aircraft without causing a detriment to vehicle performance. A system for sensing the atmospheric profile will need to be compact and lightweight. The best answer for a technology that will help enable Mach cut-off flight is most likely not any singular technology presented here, but a combination of the best aspects of many different technologies.

Milestone(s)

- Initial technology information gathering completed
- Input from experts and researchers received
- Expansion of technology portfolio completed
- Identification of most promising technology completed and presented
- Task 5 completed

Major Accomplishments

Task 5 was completed through extensive research into various technologies that could help enable Mach cut-off flight. Insight on many of the technologies was solicited from scientists and researcher in the atmospheric sciences. The most promising technologies were investigated further, and a summary of those technologies is presented in this report.

Publications

None.

Outreach Efforts

Conference Presentations:

- Autumn ASCENT COE Meeting 2016: Alexandria, Virginia – Sept. 27-29, 2017
- Spring ASCENT COE Meeting 2017: Alexandria, Virginia – April 18-20, 2017
- Autumn ASCENT Meeting 2017 & ASCENT Noise Working Group: Alexandria, Virginia – Sept. 26-28, 2017

Awards

None.

Student Involvement

Ruxandra Duca and Ratheesvar Mohan both preformed significant work under Task 4 and Task 5. Both students were integral parts of the Georgia Tech research team and worked diligently in researching technologies pertaining to Mach cut-off flight as well as learning how to operate PCBoom, generate results, and analyze the output/results. Ruxandra and Ratheesvar attended weekly research meetings and provided deliverables to the Georgia Tech ASCENT 42 research team. Ruxandra is currently still a Graduate Research Assistant and student at Goergia Tech and recently passed her PhD qualifying exams. Rathessvar graduated with his Master's degree in Aerospace Engineering in May 2017 and is currently working in industry.

Plans for Next Period

Task 5 is not continuing for the next research period.

Task #3: Develop a Test Plan for Laboratory Experiments

University of Washington

Objective(s)

The University of Washington's Center for Industrial and Medical Ultrasound endeavored to develop a test plan for laboratory experiments for Mach cut-off that might be possible in the future.

Research Approach

A test plan for laboratory experiments for Mach cut-off that might be possible in the future was developed. A scaling argument was developed. The components of the design were characterized. And the design vetted in presentations.

In summary the design was to build a stratified atmosphere from layers of gel phantom of slightly varying sound speed. The sonic boom source was a collimated unfocused shock wave from a shock wave lithotripter. The speed of the aircraft was simulated by the angle of the shock wave axis. A 3D sound field was recorded by acoustic holography using a hydrophone. Modeling was to be accomplished with nonlinear acoustic wave propagation numerical models based on the KZK and Westervelt equations. All components were carefully characterized. Work was conducted in a tank < 1.5 m long in a laboratory setting. The simulated atmosphere was robust and did not change over time but could be reconfigured to simulate other atmospheres.

Milestone(s)

The design was completed by July 2017.

Major Accomplishments

A laboratory scale model for sonic boom tests was designed, characterized and developed. The original goal was to save cost and complexity of flight measurements and build a testbed for rapid more controlled but flexible measurements for comparison to rigorous numerical simulations. This was delivered.

Publications

MR Bailey, W Kreider, B Dunmire, VA Khokhlova, OA Sapozhnikov, JC Simon, VW Sparrow, "Laboratory test bed for sonic boom propagation," J. Acoust. Soc. Am. **141** (5, Pt. 2) 3565 (2017).

Outreach Efforts

The UW team has participated in monthly telecons with the ASCENT 42 team and presented at an ASCENT semi-annual meeting with the ASCENT 42 team.

Awards

None.

Student Involvement

Julianna Simon PhD graduated from UW and continued on as a post-doc funded by NASA. Julianna worked on the project at UW until she was hired at Penn State as an Assistant Professor where she continued in a consulting role.

Plans for Next Period

The project has been completed.

Task #6: Support Development of Acoustical Model of Mach Cut-off Flight

Volpe National Transportation Systems Center

Objectives

Volpe will provide guidance to the Project 42 team on using suitable CFD-solutions as source inputs to PCBoom. Configuration analysis and development of near field pressure characteristics from CFD will be provided to Volpe. Volpe support may also include a PCBoom web-based training session for team members. Volpe will provide insight to team members on the appropriate use of PCBoom so that team members can conduct sonic boom ray tracing and Mach cut-off analysis using PCBoom for a variety of environmental, flight operation and vehicle source conditions. Volpe will support team activities investigating the addition of supplemental operational parameters into the sonic boom analysis. Volpe will support the evaluation of the applicability of early Mach Cut-off theories under realistic atmospheric conditions by providing information relative to PCBoom capabilities and fundamental formulations.

Background

PCBoom is a full ray trace sonic boom program that calculates sonic boom footprints and signatures from flight vehicles performing arbitrary maneuvers. The PCBoom model has been developed [Plotkin & Cantril, 1975], refined [Plotkin, 1998; Page, Plotkin and Wilmer, 2010] and validated [Page *et al.*, 2010] over many decades with investments from NASA, the US Air Force and other entities. PCBoom computes detailed ground signature shapes starting from a variety of near-field signature definitions. It has its roots in the NASA sonic boom program written by Thomas [1972] in the early 1970s. Initial development consisted of adding focus boom prediction capability [Plotkin & Cantril, 1975]. Further development, through a series of versions extended the original code (which computed boom on a single ray for a single flight condition) to handle full maneuvers and a variety of aircraft source inputs. There have been improvements to the algorithms, such that boom aging is now handled by waveform steepening and shock fitting, rather than Thomas's waveform parameter method. Three dimensional ray tracing algorithms [Schulten, 1997] have replaced Thomas's original flat earth layered ray equations, although Thomas' original ray equations are present as an option.
PCBoom6 has the following capabilities:

- Specification of the vehicle as an F-function, a data line of $\Delta p/p$, via data from a CFD solution [Page & Plotkin, 1991; Plotkin & Page, 2002], as a simple form from a library of aircraft, or as a blunt hypersonic body. There is a launch vehicle mode, which includes the effect of the vehicle itself plus the effect of an underexpanded rocket plume.
- Ray tracing through a 3-D stratified atmosphere over either flat earth or over a WGS-84 ellipsoidal earth.
- Specification of arbitrary maneuvers in either local Cartesian coordinates or in geographic latitude and longitude.
- Calculation of superboom signatures at focal zones, and also the secondary post-boom signatures a distance away from the geometric focus.
- Calculation of booms along particular rays, or across the full width of the primary sonic boom carpet.
- Calculation of secondary booms including tracing of "Over the Top" complex 3D ray paths and computation of secondary sonic boom signatures [Plotkin *et al.*, 2007].
- Calculation of shock structures, either as a simple Taylor structure or via molecular relaxation and absorption processes [Burgers, 1939].
- Calculation of spectra and a variety of loudness metrics for ground booms.
- Calculation of the effect of finite ground impedance on boom signatures.
- Effect of turbulence on sonic boom ground signatures [Crow, 1969; Plotkin, Maglieri & Sullivan, 2002; Locey, 2008]
- Effects of wind and terrain [Rachami & Page, 2010] on boom propagation.
- Penetration of sonic booms and propagation underwater [Sparrow & Ferguson, 1997; Sawyers, 1968; Cook, 1970; Cheng *et al.,* 1996; Garrelick, 2002]

Major Accomplishments

Task 1: Volpe provided sonic boom modeling guidance on using suitable sonic boom configuration inputs including CFD-solutions for supersonic aircraft configurations as source characteristic inputs for PCBoom. Web-based training was provided to the team regarding configuration analysis and development of near field pressure characteristics suitable for sonic boom analysis.

Volpe interacted with the Aerion team to ensure the CFD analysis yielded suitable off body pressure results for sonic boom assessment. The resultant CFD pressure data for the Aerion vehicle was provided to Volpe and the other team members. Volpe supported the CFD analysis by processing the data and creating a complete set of input and output files and conducted a PCBoom web-based training session for Project 42 participants on the use of CFD data for sonic boom modeling. The analysis stream included capability to consider different atmospheres and environmental parameters, varying flight conditions and computation of footprints or single ray metrics using the Burgers' solver in the PCBurg module.

Task 2: Volpe provided insight on the appropriate use of PCBoom for conducting sonic boom ray tracing and Mach cut-off analysis for a variety of environmental, flight operation and vehicle source conditions. Volpe assisted with the investigation of supplemental operational parameters in the sonic boom analysis including fine tuning of ray tracing parameters within the main propagation module FOBoom. Guidance was provided to the team regarding shock structure as controlled by a combination of nonlinear steepening and molecular relaxation processes, and computed by solution of the Burgers equation solver (PCBurg). Web-based training included operation of FOBoom, PCBurg and the batch solver to support calculation of sonic boom metrics. Volpe also worked directly with Georgia Tech to fine tune PCBoom model parameters in support of their temperature sensitivity analysis examining Mach cut-off flight under both standard and real-world atmospheric conditions.

Task 3: Volpe supported evaluation of the applicability of early Mach cut-off theories under realistic atmospheric conditions by providing information relative to PCBoom capabilities, limitations and fundamental formulations. A set of benchmark condition results from PCBoom was provided to the team for curved ray calculations using PCBoom's horizontally stratified atmosphere with winds. An assessment of Concorde signatures was conducted using standard PCBoom source characteristics to support Aerion comparisons. Example files for the calculation of sonic boom over varying terrain was also provided to the ASCENT team (though it was not demonstrated in the online training). A ground terrain file for the Continental US was provided for use with PCBoom along with a set of example analysis files based on an earlier NASA NextGen study [Rachami & Page, 2010].

As part of all three tasks, Volpe provided PCBoom guidance and training to PSU, Georgia Tech and Aerion both as a group and individually as needed via email and phone. Two structured online training classes for PCBoom analysis were conducted. These classes used specific test cases by example and all PCBoom files were provided to the participants. The team independently acquired the PCBoom code directly from NASA using established protocols. The online training was recorded by Penn State and made available to the ASCENT team for supplemental review. Sample analysis covered during the two online PCBoom training classes with example input and output files distributed to ASCENT 42 participants included the following:

- Level flight from an F-18 using the simple Carlson source model
- Assessing Mach and lateral cutoff
- CFD pressure distribution inputs using the NASA LM1021 publicly available dataset[1]
- Burgers loudness propagation applying molecular relaxation
- Calculation of sonic boom signatures from the Concorde using built-in source data
- Complex maneuvering flight analysis involving an F18 executing a low-boom dive maneuver
- Analysis of the Aerion RL3 configuration starting with CFD data
- Ground metric calculations accounting for molecular relaxation using the LM1021 dataset and the Burgers solver module PCBurg
- Batch mode execution of FOBoom and PCBurg using the updated NASA batch executable.

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Task #1A: Propagation Modeling with Enhanced Ray-tracing Capabilities

The Pennsylvania State University

Objective(s)

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. This research will help to provide a technical basis for rulemaking regarding Mach cut-off operations, which includes estimating the altitude and Mach number restrictions for focus boom avoidance including real-world atmospheric effects.

Research Approach

Methodology

The original propagation theory [Nichols, 1971] has been retraced for extensibility. In that theory, the atmosphere is assumed to have only vertical variations of temperature and horizontal wind. In reality, however, for sonic boom propagation over a large distance, the horizontal variations of the atmospheric temperature and wind speed can be important for Mach cut-off, which are not included in Nicholls' theory.

Mach cut-off depends on the refraction of sound in the atmosphere. In Nicholls' theory, this has been described by one form of the sound refraction law which specifies the direction of the wavefront normal. By arguing the sonic boom would not reach the ground as long as the wavefront normal of the sound becomes parallel to the ground aloft, the "safe altitude" for Mach cut-off flight is determined. This is only true in the absence of vertical winds. When the vertical winds becomes non-negligible, ray-tracing is a more accurate tool to predict the cut-off Mach number and the "safe altitude" [Ostashev, 2001].

Besides that, in Nicholls' theory, by calculating the cut-off Mach number based on the atmospheric conditions only at the flight and ground levels, the impact of the detailed realistic atmospheric profile in between those two levels on the cut-off Mach number hasn't been taken into account.

In order to build an acoustical model that can lead to more accurate estimates of the safe cut-off altitude and Mach number for Mach cut-off flight, 2-D ray tracing equations have been examined [Pierce, 1989]. Based on which, a 4th order Runge-Kutta integration ray tracing scheme has been developed, which takes into account realistic atmospheric conditions including arbitrary speed of sound variations and arbitrary two-dimensional winds with a vertical wind component. In this version of the algorithm, the effect of the cross-wind is not included.

For ray calculations, the same atmospheric temperature profile has been used based on the 1976 U.S. Standard Atmosphere, and different wind speed profiles has been tested. To incorporate the Mach cut-off operational parameters proposed by Aerion Corporation, a flight altitude of 12.5 km, which corresponds to 41010 ft, has been consistently used, and results are given for flight Mach numbers from 1.01 up to 1.20.

Results

To assess the robustness of the theory, the results of which have been benchmarked with NASA's PCBoom code using the same 1976 U.S. standard atmosphere with no wind and with a linear tailwind of a gradient of 4 (m/s)/km, respectively, for both the Mach 1.15 and Mach 1.20 cases.

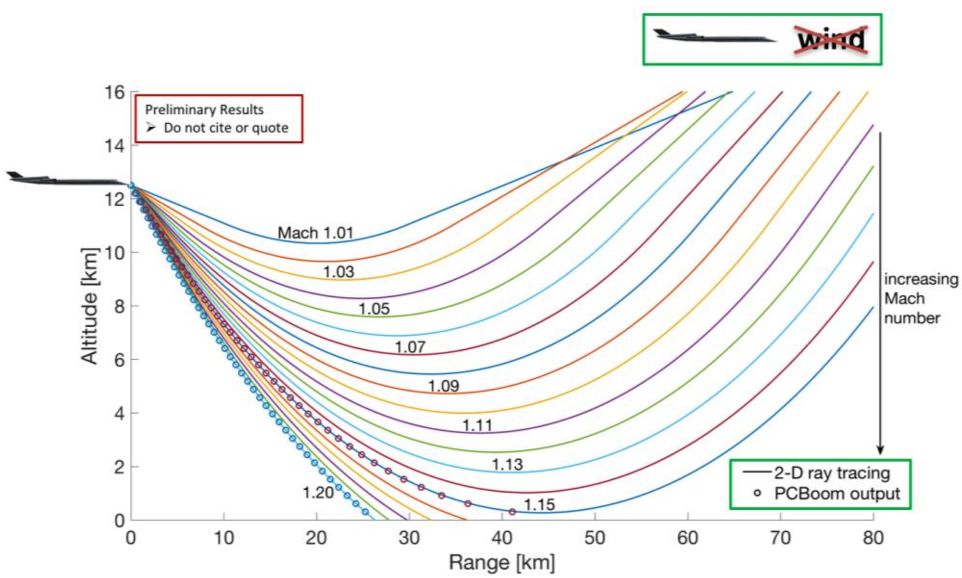

Fig. 43: 2-D Ray Tracing for Different Mach Numbers
Using the 1976 U.S. Standard Atmosphere with No Wind.

As shown in Figure 43, when the flight Mach number increases, the sound rays get closer to the ground. The ray calculation by the 2-D ray-tracing algorithm for a standard atmosphere and no wind case matches the results from NASA's PCBoom very well. The predicted cut-off Mach number of 1.15 for the no wind case also agrees with the results from an earlier technical report [Onyeonwu, 1971]. A linear headwind case and a linear tailwind case which both have the same wind speed gradient of 1 (m/s)/km are examined (see Figures 44 and 45). It shows that the wind direction matters. Linear horizontal winds can affect the Mach cut-off operations. A linear tailwind contributes to a downward refraction of the sonic boom so that a higher "safe altitude" is needed, while a linear headwind leads to a stronger upward sound refraction so that a higher cut-off Mach number can be achieved.

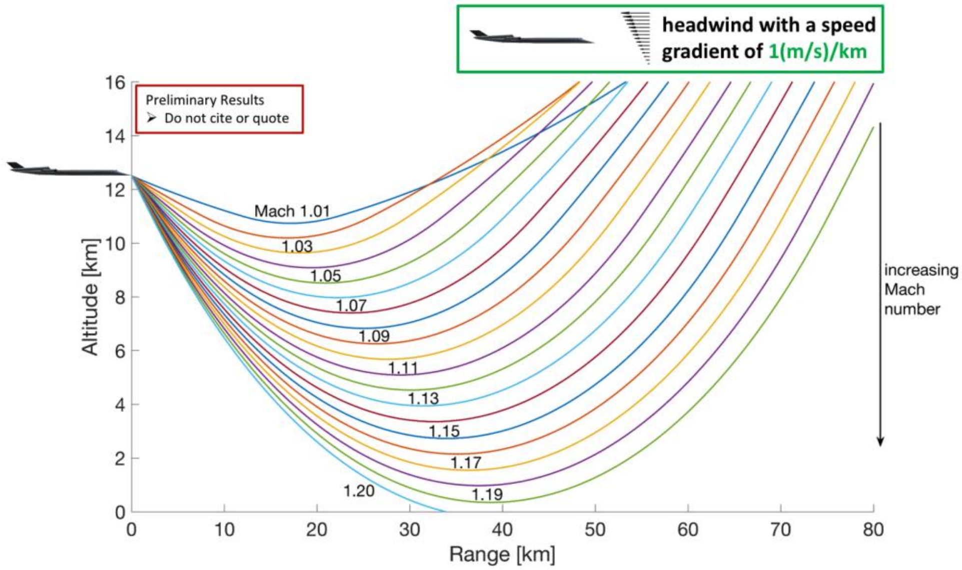

Fig. 44: 2-D Ray Tracing for Different Mach Numbers Using 1976 U.S. STD Atmosphere. and a Linear Headwind with a Wind Speed Gradient of 1 (m/s)/km

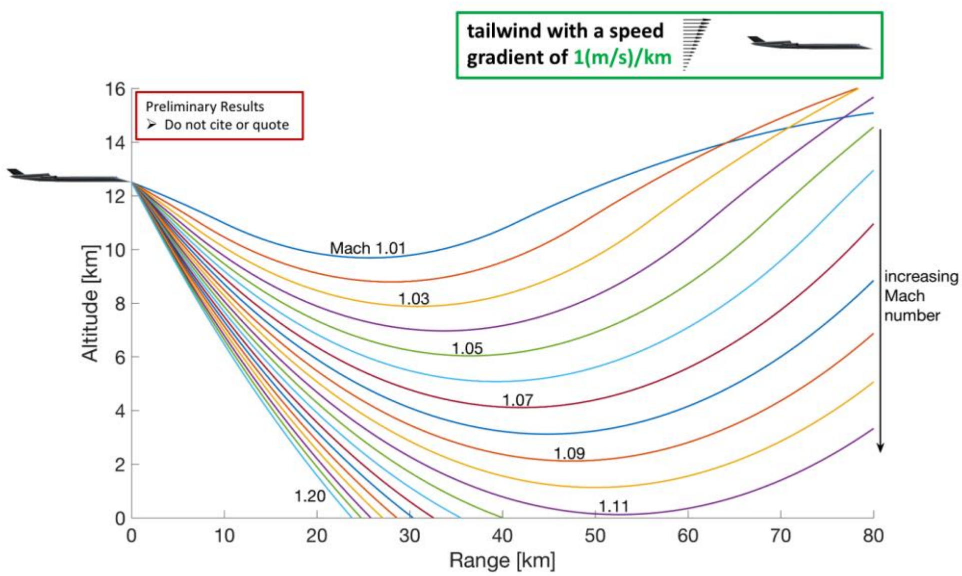

Fig. 45: 2-D Ray Tracing for Different Mach Numbers Using 1976 U.S. STD Atmosphere and a Linear Tailwind with a Wind Speed Gradient of 1 (m/s)/km

One limitation of earlier Mach cut-off theories (including Nicholls') and existing tools (e.g., PCBoom) is that vertical winds are not included. In a realistic atmosphere, however, a noticeable vertical wind can sometime exist. A sea breeze is a wind that blows from sea to land, which normally occurs along coasts during daytime (see Figure 46). This is driven by the pressure gradients in the air due to the differences in the heat capacities of sea water and dry land, that introduce temperature contrasts, which can often include a return flow from land back to sea aloft [Wallace, 2006].

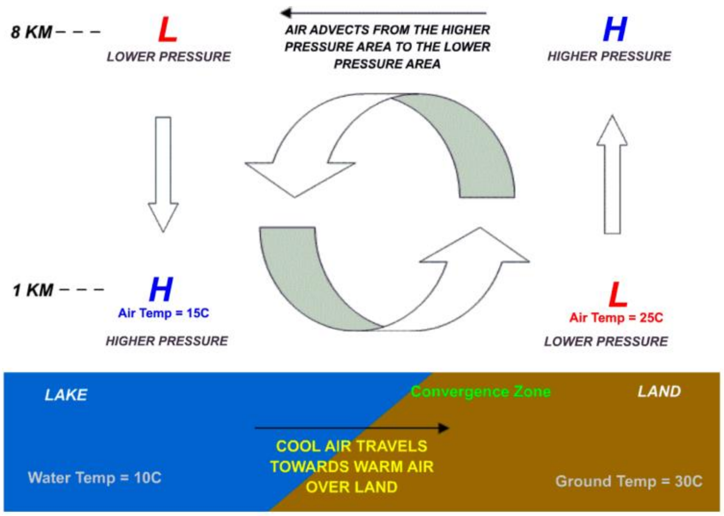

Fig. 46: A Sea Breeze Circulation. Adopted from https://en.wikipedia.org/wiki/Sea_breeze

In order to model a sea breeze circulation, a simple convective wind profile has been developed, in which a vertical wind component is included, and the size of the cell has been chosen so that it extends from the ground up to an altitude of 16 km for demonstration, as shown in Figure 47. Numerical results are given in Figures 48 and 49 for clockwise and counterclockwise convection cells respectively, in both of which, the maximum horizontal wind speeds are 8 m/s, and the vertical wind component can be seen which has a maximum value of 1.6 m/s.

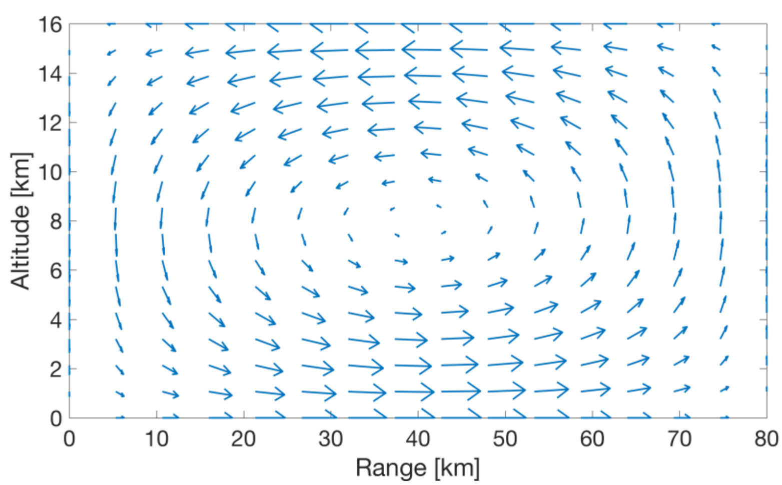

Fig. 47: Wind Speed Profile of a Counterclockwise Convection Cell

The direction of the wind circulation has been very important to the sonic boom refraction and thus the Mach cut-off operation. Depending on the flight direction, a clockwise wind circulation contributes to a downward refraction of the sonic boom similar to that of a linear tailwind, while a counterclockwise cell leads to a higher cut-off Mach number. Including vertical winds in sonic boom predictions seems very important to ascertain "safe altitudes" for Mach cut-off operations.

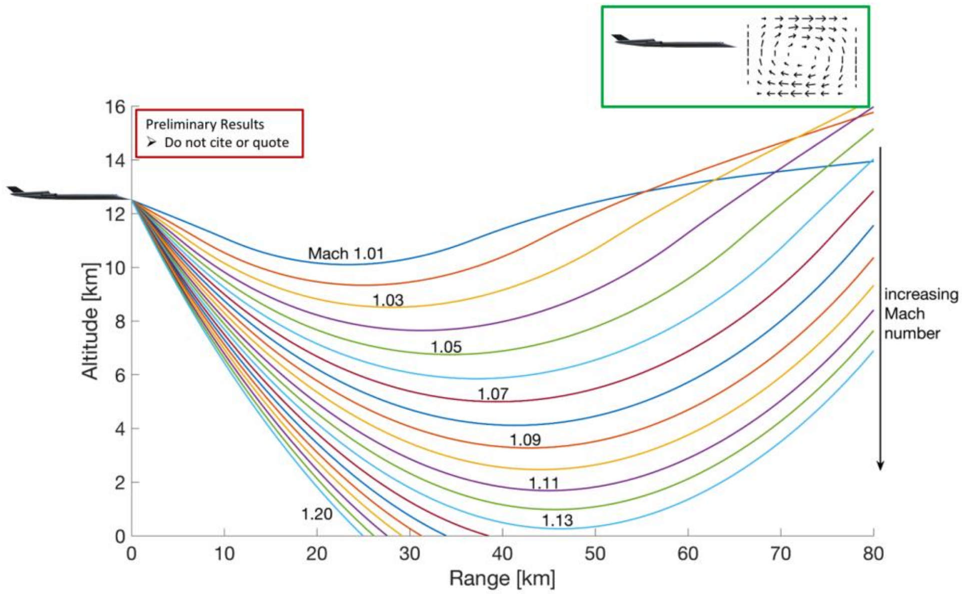

Fig. 48: 2-D Ray Tracing for Different Mach Numbers Using 1976 U.S. STD Atmosphere and a Clockwise Convection Cell

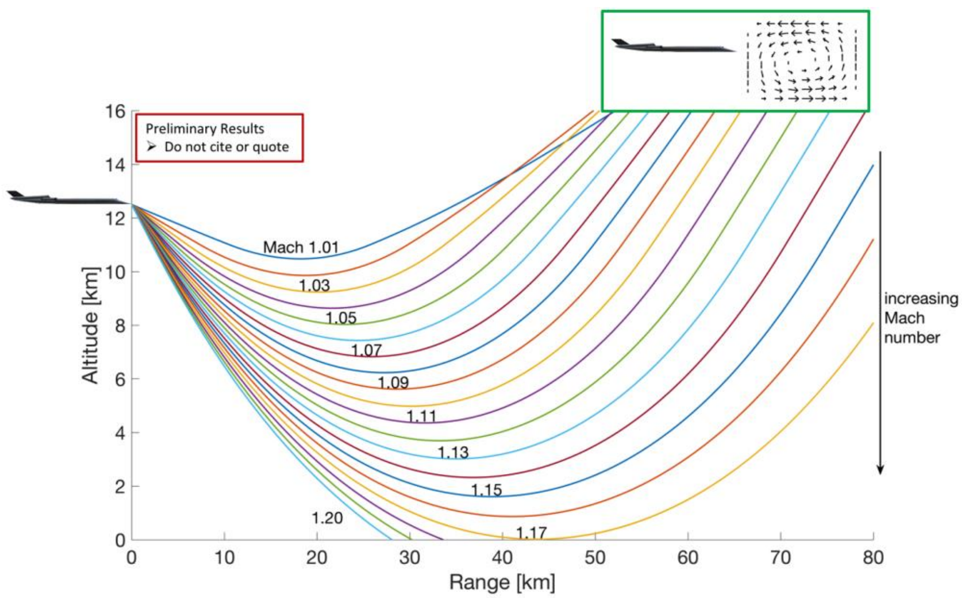

Fig. 49: 2-D Ray Tracing for Different Mach Numbers Using 1976 U.S. STD Atmosphere and a Counterclockwise Convection Cell

Results of each individual wind speed profile given above include the contribution from different Mach numbers. Since a caustic is formed aloft when the rays become parallel to the ground, which corresponds to a loud sound energy, to ascertain "safe altitudes" for Mach cut-off operations, ray calculations along a flight path at a fixed flight Mach number can also be useful. From Figure 50 to 52, it shows that the magnitude of the wind (or the gradient of the wind speed) affects Mach cut-off operations. When the wind speed gradient of the linear tailwind increases from 0 (m/s)/km (that corresponds to the no wind case) through 1 (m/s)/km up to 2 (m/s)/km, the caustic line gets closer to the ground surface, and eventually reaches the ground.

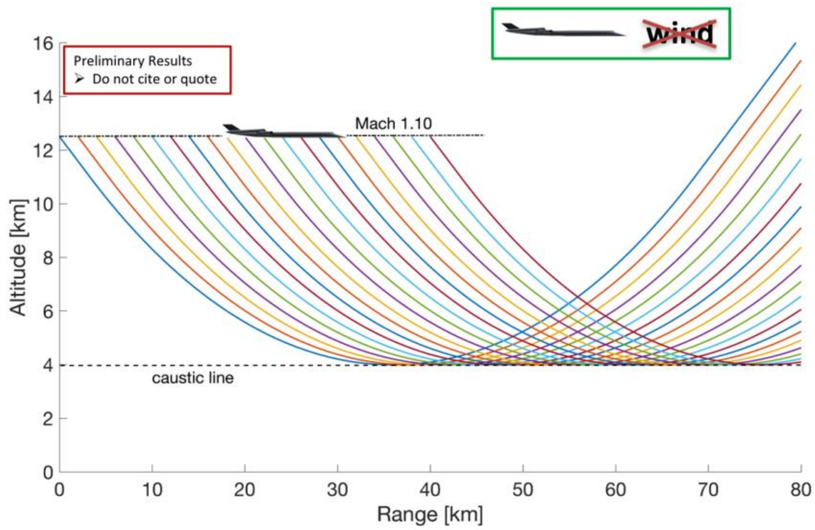

Fig. 50: 2-D Ray Tracing for Mach 1.10 Using 1976 U.S. STD Atmosphere and No Wind

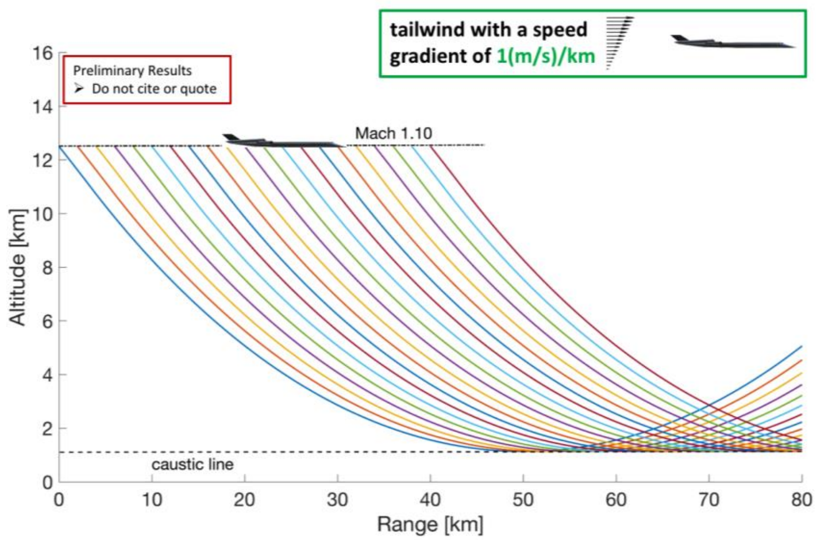

Fig. 51: 2-D Ray Tracing for Mach 1.10 Using 1976 U.S. STD Atmosphere and a Linear Tailwind with a Wind Speed Gradient of 1 (m/s)/km

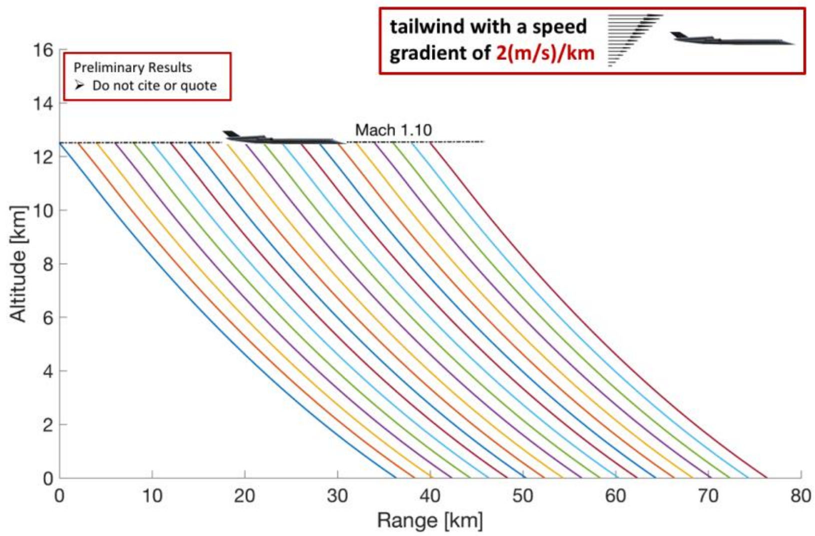

Fig. 52: 2-D Ray Tracing for Mach 1.10 Using 1976 U.S. STD Atmosphere and a Linear Tailwind with a Wind Speed Gradient of 2 (m/s)/km

Results of similar calculations for a clockwise convection cell shows a different caustic line pattern, in which the caustic line is not parallel to the ground (Figure 53), and people at some places on the ground that's closer to the caustic line over heads may hear a louder noise. This is because, for a circulative wind profile, the wind speed can also vary horizontally. Thus, accounting for realistic winds including the horizontal variations of the wind are important.

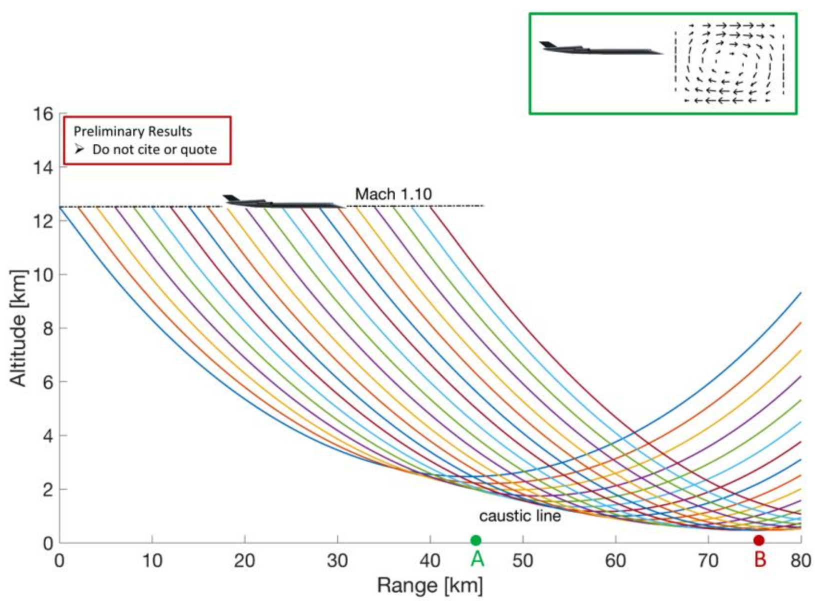

Fig. 53: 2-D Ray Tracing for Mach 1.10 Using 1976 U.S. STD Atmosphere and a Clockwise Convection Cell

Milestone(s)

Milestone	Date Finished
Nicholls' Mach cut-off theory has been examined, and it has been determined that there are some questionable assumptions in the Nicholls' formulation. The limitations of Nicholls' theory have also been identified.	6 mo. = February 1, 2017
A 2-D ray-tracing algorithm has been developed, and ray calculations of Mach cut-off parameter space are performed and benchmarked to the output from NASA's PCBoom code.	12 mo. = July 31, 2017

Major Accomplishments

In this research, a 2-D ray-tracing algorithm has been developed and validated for the acoustical model of Mach cut-off flight, which takes into account realistic atmospheric conditions including arbitrary speed of sound variations and arbitrary two-dimensional winds with a vertical wind component. Based on the 1976 U.S. standard atmosphere, the effects from the vertical wind speed and the horizontal variations of the wind on the "safe altitudes" for Mach cut-off operations have been examined.

Publications

Acoustics '17 abstract.

Outreach Efforts

Z. Huang and V. W. Sparrow, "Preliminary assessment and extension of an existing Mach cut-off model," Poster for the Penn State Center for Acoustics and Vibration (CAV) Spring Workshop, University Park, PA, April 25-26, 2017.

Awards

None.

Student Involvement

Zhendong Huang is the graduate research assistant supported by Project 42 at Penn State on this task. He is pursuing his Ph.D. in the Penn State Graduate Program in Acoustics.

Plans for Next Period

The project team is developing an improved Mach cut-off model using a 3-D ray tracing method so that both a 3-D atmosphere and arbitrary 3-D winds are accounted for correctly. Using measured atmospheric data provided by the Integrated Global Radiosonde Archive (IGRA), a radiosonde dataset from the National Centers for Environmental Information (NCEI) consisting of radiosonde and pilot balloon observations, as input, to perform ray calculations for certain busy air routes in the United States, and to examine the influence of realistic atmospheric profiles and flight conditions on the Mach cut-off operations.

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Task #2: Subjective Study on Annoyance, Metrics, and Descriptors

The Pennsylvania State University

Objective(s)

- Develop a set of descriptors suitable for describing Mach-cutoff ground signatures to identify the key perceptual attributes of Mach cutoff signals.
- Determine how these attributes are correlated with annoyance ratings of these signals.
- Identify a metric appropriate for predicting annoyance due to Mach-cutoff ground signatures.

Research Approach

Introduction

The research to be conducted in this task will be the seminal work in the perception of Mach cut-off. The overall objective is to identify a metric that corresponds to annoyance due to Mach-cutoff flights. Subjective data from listening tests will inform this identification. Mach-cutoff ground signatures are unique sounds, the likes of which are not part of day-to-day experience. They are perceived differently from traditional sonic booms. As such, a new set of vocabulary will also be developed as a prerequisite to running an annoyance study.

The task was subdivided into three stages: subjective (listening) test design, stimulus selection, and testing preparations. The first stage included designing a descriptor study that will feed into a multi-factor annoyance study. Stimuli were selected from NASA's FaINT dataset [1] through careful listening tests. Test preparations included improving the low-frequency output of an existing sound-field reproduction facility at Penn State and all subjective testing preparations. Each stage is explained in more detail in the sections below.

Design of the Subjective Listening Tests

General subjective impressions, such as annoyance and preference, are often studied using factor analysis. This type of test requires that attributes be selected as potential factors of the broader impression. Ratings on each attribute and on the broad impression are then analyzed to find which of the attributes most factor into the impression. However, these attributes must be named before this type of study can be done.

When developing a set of vocabulary, care must be taken to ensure that the descriptors chosen will represent words common to the general population. To this end, three test methods were considered: Free-Choice Profiling (FCP) [2], Flash profiling (Flash) [3], and Individual Vocabulary Profiling (IVP) [4]. Each method involves descriptor selection on an individual basis followed by rating stimuli on these developed descriptor scales. The main differences between the methods lie in the rating step. In FCP, subjects rate each stimulus individually on their own set of descriptors. In Flash, subjects rate each stimulus individually on a pooled set of descriptors. This method is disadvantageous, as it requires each participant to complete two testing sessions, where the second session cannot take place until all subjects have finished developing descriptors. In IVP, subjects rate stimuli simultaneously on comparative scales based on their own set of descriptors. This method is disadvantageous because the comparative scale limits the number of stimuli that can be included for rating. Given these disadvantages, FCP was deemed the most appropriate method for this study. Similar procedures have been used in the fields of virtual acoustics [4] and concert hall acoustics [5].

The procedure for each subject in the vocabulary development test is as follows:

1. Each subject listens to a set of 12 stimuli. Once a participant has listened to all 12 of the signals, they are required to provide their own words to describe the sounds they heard (descriptors) and a definition for each of these words. Subjects are allowed to listen to each stimulus as many times as they want in this part of the testing session, even after they have started providing descriptors. For example, a subject listens to the twelve stimuli. He or she might then choose to describe these stimuli using the word “rumble”. He or she would write down the word “rumble” with an appropriate definition, such as “like the sound rocks make tumbling down a hill”.
2. After this first part of the test, the test administrator meets with the participant to discuss the developed descriptors, refine provided definitions, and narrow down their list. The interview ensures each descriptor is appropriate for a rating scale and removes words that describe the same aspect of the sounds. Continuing the example, the subject might have provided the word “thunder-like” in addition to the word “rumble”. In the interview process, if these two words were determined to mean the same thing, then only one would be selected for use in rating.
3. For the last part of the testing session, each subject rates the stimuli based on their descriptor list. For each descriptor, the subject listens to each stimulus one at a time and are asked to rate the “presence” of that descriptor in the given stimulus. For example, a subject who used the word “rumble” to describe these stimuli would then rate how present the “rumble” is in each stimulus.

The statistical analysis technique used to analyze this type of data is the Generalized Procrustes Analysis, which is a type of factor analysis. This method rotates each subject’s rating space, finding alignment between attributes, which results in a list of descriptors that represent all major perceptual attributes of the stimuli. This final list will be used for the annoyance study, in which subjects will rate stimuli on the final descriptor list and annoyance.

Stimulus Selection

For the first part of this study, stimuli were taken from Mach-cutoff ground signatures recorded in NASA’s “Farfield Investigation of No-boom Thresholds” (FaINT) field measurements [1]. These measurements produced a large database with 36 total Mach-cutoff flyovers recorded on more than 120 microphones, which were divided into two arrays: (1) a 60-microphone linear array and (2) a 62-microphone spiral array, as shown in Figure 54. Only sounds recorded by microphones in the linear array were considered for producing stimuli because the spiral array used microphones that were not ideal for capturing the low-frequency energy of Mach-cutoff sonic booms.

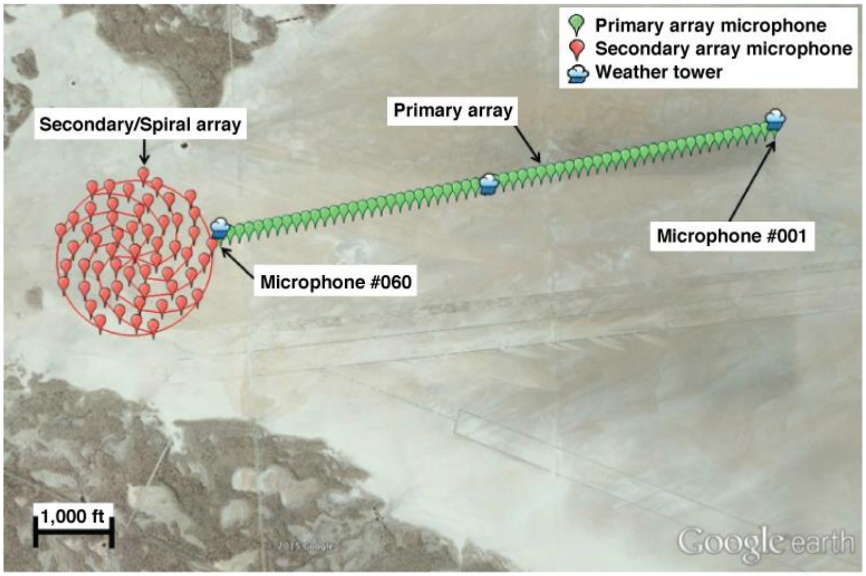

Fig. 54: FaINT microphone arrays. The descriptor study will use recordings made on the primary array (the linear array). Image reproduced from [1].

The 36 flyovers by 60 recordings were assumed to be a good sampling of all possible Mach-cutoff ground signatures. For this study, it was thus helpful to sample the database so that the final stimulus set represented the variety within the database. Stimulus categorization was first attempted through clustering then through methodical listening.

For the objective approach to categorize the signals, the method of K-means clustering was run on the time-domain signals in an attempt. Each time series was first normalized to its maximum amplitude and time shifted to maximize correlation. While the method did produce clusters that were related analytically, the raw time-series data did not produce clusters that were perceptually similar. Additionally, repeated runs of the clustering algorithm did not agree well with one another. These findings support the need for metrics that do correspond to perception.

Since the method of clustering the signals did not turn out to be a viable method to categorize the signals, a qualitative approach was used. Specifically, the set of signals were then categorized based on critically listening, which was broken into the following steps:

1. Before listening to any of the stimuli, any passes that did not result in successful Mach-cutoff ground signatures, as indicated by the FaINT researchers' notes and listening to the recordings, were discarded, which was a total of 7 passes.

2. With these passes eliminated, that still left a total of approximately 1700 (29 passes X 60 microphones) possible signals to use in the study. In order to listen to a representative sample of recordings, signals from several microphones along the array were evaluate to determine the amount of perceptual variation along the flight path each signature had. This qualitative analysis revealed that the most perceptually different signals for a given flight pass occurred between the two endpoints of the arrays, which thus reduced the possible number of stimuli to 58 recordings. Each of these signals were then perceptually evaluated to identify if there were any problems with the recordings, such as excessive wind noise, and if so they were eliminated from the set of possible stimuli for the study.

3. During the previous step, it was noted that the perceptual differences between recordings were much more apparent between passes as opposed to between microphones for a given pass. As a result, critical listening was carried out for one signal from each pass to develop a set of appropriate categories with which to organize the recordings. In the end, the stimuli were divided into four categories by Ortega. With the signals now organized into groups, 5 to 7 passes were chosen from each category and finally recordings from two microphones for a given flight pass were selected to form a reduced set of 48 stimuli.

4. With this reduced set of stimuli, both Vigeant and Ortega blindly listened to and categorized all 48 stimuli, which were given random identifiers (from 1 through 48) to disguise their related nature while evaluating the recordings. The process also resulted in only four categories, which were relatively similar across the two raters. In broad terms, the categories were “rumble”, “surge / surging rumble” (where the signal got louder over time), “thumps (not distinct booms)”, and “waving/hitting sheet metal”.

Finally, a set of 24 recordings were selected for use in the subjective study, where 5 to 7 representative signals were identified for each of the four categories as shown in Table 4. This set of 24 signals represents the variety of Mach-cutoff ground signatures recorded during the FaINT field test measurements. The 12 most distinctive signals were then selected for the development of descriptors for the first part of the formal subjective test, while all 24 will be used in the rating portion of the test.

Table 4: Selected stimuli from NASA's FaINT data sets with subjective descriptions, as described by Ortega and Vigeant. The last two columns indicate which recordings will be used in each part of the listening test.

	FaINT Recording Information				Inclusion in Subjective Study	
Category	**Flight**	**Pass**	**Mic**	**Description From Pilot Study**	**Part 1 - Descriptor Development**	**Part 2 - Ratings**
1 Rumble	1392	1	10	Rumble (like distant thunder)	X	X
	1392	3	46	Rumble	X	X
	1389	4	32	Rumble		X
	1391	4	58	Rumble (lower amplitude)		X
	1391	7	52	Rumble (lower amplitude)		X
	1392	2	36	Rumble		X
	1393	1	5	Rumble		X
2 Surge / surging rumble	1388	5	52	Surge (like water rushing upwards)	X	X
	1389	3	8	Surging rumble	X	X
	1393	4	17	Surging rumble	X	X
	1388	2	60	Surging rumble		X
	1390	1	3	Surge		X
	1390	4	43	Surge		X
	1390	6	3	Surging rumble		X
3 Thumps (not distinct booms)	1388	3	32	Thumps followed by surge	X	X
	1391	5	27	Thump followed by surge	X	X
	1388	4	5	Thumps followed by surge		X
	1389	6	5	Thump followed by surge		X
	1392	6	51	Sharper thump followed by surge		X
4 Waving / hitting sheet metal	1389	1	6	Hitting sheet metal	X	X
	1389	5	26	Waving sheet metal or surge	X	X
	1390	2	24	Hitting sheet metal or surge	X	X
	1392	4	50	Waving sheet metal or rumble	X	X
	1393	3	37	Waving sheet metal	X	X

Subjective Listening Test Preparations

The listening tests will be conducted in the AUralization Reproduction of Acoustic Sound-fields (AURAS) facility at Penn State, shown in Figure 55. The facility originally consisted of 30 custom loudspeakers installed in an anechoic chamber, but now also has two subwoofers that were designed and constructed for this study. Sound fields are reproduced using third-order Ambisonics.

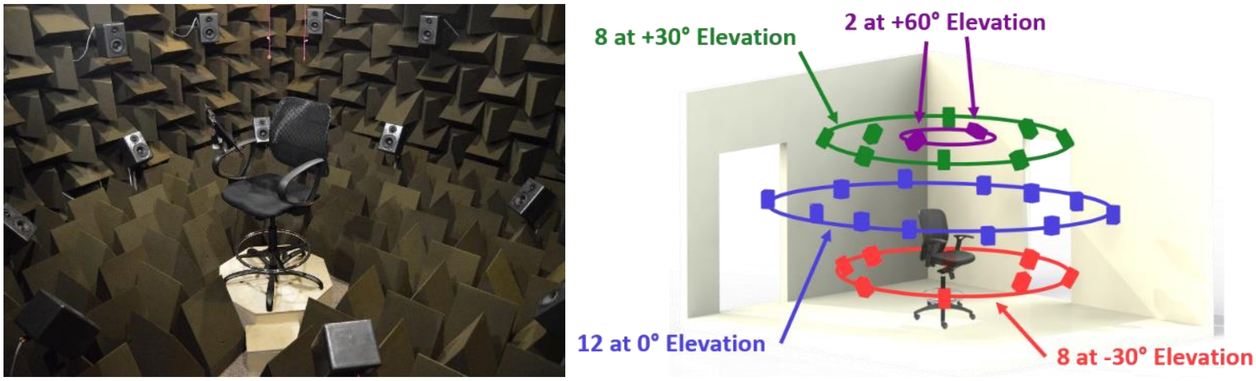

Fig. 55: The AURAS facility at Penn State, where the subjective listening tests will take place. This facility can be used to reproduce a range of sound fields, including interior aircraft noise and office environments.

To prepare for the listening tests, the low-frequency output of the existing AURAS facility needed to be increased. The existing 30 loudspeakers were designed to have a flat frequency response extending down to 60 Hz. While such a response is suitable for reproducing room-acoustics stimuli, Mach-cutoff signals have significant energy well below the audible cutoff of 20 Hz. In order to reproduce the signals, a pair of large subwoofers was designed and built, where each houses a Dayton Ultimax 18" driver in a 3'x2'x1.25' closed plywood box. A Crown K2 power amplifier supplies 800 W of power to each subwoofer. The boxes needed to be custom constructed to fit the existing chamber. The resulting frequency responses achieved for each of the subwoofers as installed in the anechoic chamber are shown in Figure 56. Note that the anechoic chamber in which the reproduction system is housed has a low-frequency room mode around 63 Hz. This results in the significant notch in the frequency response of Subwoofer 1. The subwoofer was positioned in the room to minimize this effect, but the effect could not be eliminated without affecting the distribution of sound. Also note the steep roll-off below 20 Hz. Both of these factors prompted the design of digital filters that would boost the low-frequency output and reduce the effect of the room mode.

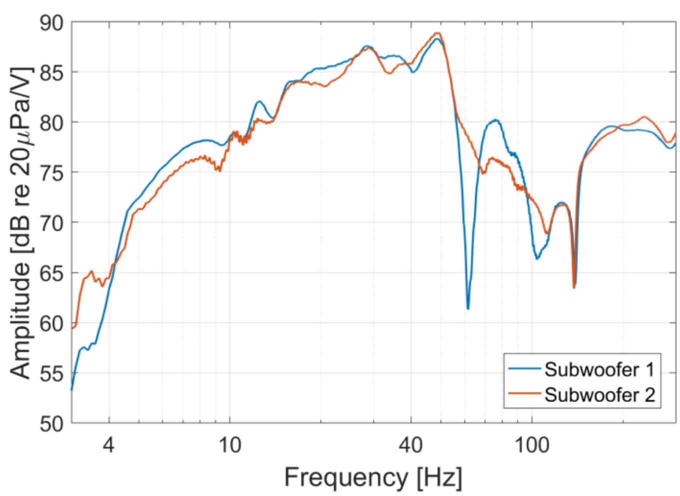

Fig. 56: Frequency response of constructed subwoofers. The two subwoofers are needed to produce the low frequency energy present in Mach-cutoff ground signatures.

Because of the significant low-frequency energy in the Mach-cutoff signals (see blue line in Figure 57), digital filters were designed to boost the low-frequency output of the subwoofers. In order to allow power output equal to the original signal levels across most frequencies, a 6 dB/octave roll-off was necessary below 20 Hz. Recordings of signals produced using these filters show faithful reproduction of the original signals, as seen in Figure 57.

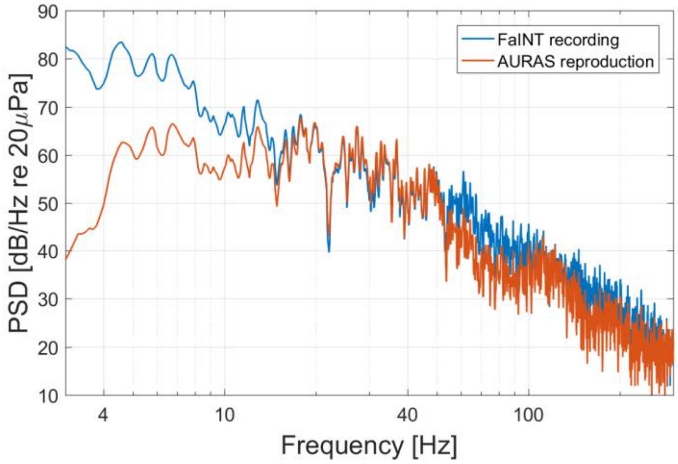

Fig. 57: Example Mach-cutoff ground signature, as recorded by FaINT and as reproduced in the AURAS facility

With a suitable sound system in place, the next step was to decide which direction the signals should appear to be coming from. Despite the fact that the majority of the energy is these signals is contained within the low frequencies, which radiate in a uniform (omnidirectional) manner, there is enough high-frequency content for listeners to identify a source location. Three possible locations were identified: from the front, overhead, and 60 degrees forward of vertical. Ortega, Vigeant, and Sparrow individually listened to each case and determined that the overhead sounds were the most natural and realistic.

In order to subjectively validate the quality of the reproductions of the Mach cutoff signals, Sparrow was asked to compare reproductions of post sonic boom noise, which have a similar character to Mach cutoff signals are sounds that he is very familiar with, to the Mach cutoff reproductions. An interface was developed which allowed for instantaneous switching between each of the signals to make it straightforward to easily do an A/B comparison of the presented pairs of signals. Switching between the post-boom signals and the Mach-cutoff signals, he determined they sounded similar. He also felt the post-boom noise sounded realistic and that the Mach-cutoff booms matched descriptions from other researchers.

User interfaces required for testing were developed in Cycling '74's Max programming environment. Max is a visual programming language that allows for easy audio interface and quick user interface setup. It was selected as the best environment based on the need to control 32 channels of audio. Two interfaces were created – one for entering descriptors and one for rating stimuli. The descriptor interface (Figure 58) allows the subject to play all 12 of the first set of stimuli, one-at-a-time in an order of their choosing. The circles adjacent to the 'play' buttons are used to indicate which signal is being played at any given moment and if they have already listened to that signal. Once subjects have listened to all stimuli, they can enter descriptors and accompanying definitions.

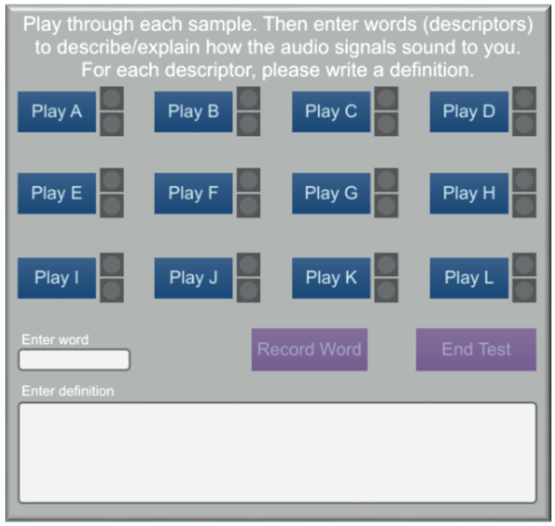

Fig. 58: User interface for descriptor entry. This interface allows test subjects to enter their own descriptors for Mach-cutoff stimuli along with accompanying definitions.

For the second part of the listening test, participants will use the rating interface shown in Figure 59. Participants will be asked to rate each of the 24 stimuli individually for three or four of the descriptors they developed. The stimuli will be played in random order and they will only rate one descriptor at a time to reduce the potential for rating bias that might occur if they were asked to rate multiple attributes at the same time. For example, if they had terms "loud" and "rumble" and were rating both of these terms at the same time, they might tend to give similar ratings for both attributes when rating both at the same time, which may or may not be an accurate representation of the relationship between the attributes.

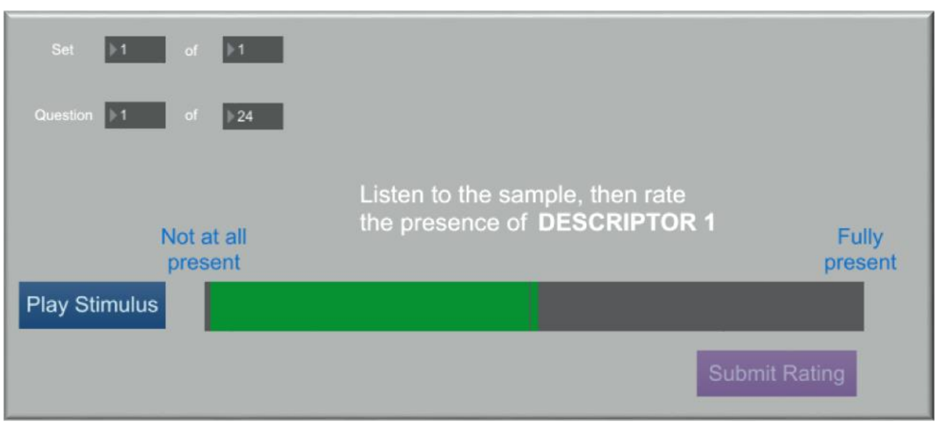

Fig. 59: User interface for stimulus rating. This interface allows subjects to rate stimuli on their own descriptors. During testing, a subject's descriptor will replace the label "DESCRIPTOR 1".

All procedures and testing material were reviewed and approved by Penn State's Human Subjects Institutional Review Board (IRB). Prior to receiving the award, a preliminary protocol and supporting documentation was submitted to the IRB for approval, but significant modifications were needed based on the work carried out in the past year to fully develop the upcoming listening study. The main document which describes the proposed study, known as the protocol, underwent significant revisions, wherein the details about the recruitment process, process of obtaining consent, testing procedure, data storage protocol, potential risks, and safeguards against those risks, were all updated. In addition, the supporting documentation and testing materials were also updated, which included: subject information forms, a tutorial slideshow, a noise sensitivity questionnaire, recruitment advertisement text and flyer, an informed consent form, and images and descriptions of the user interfaces.

Milestone(s)

Milestone	Planned Due Date	Status
Report on assessment of FaINT data for subjective tests	February, 2017	Complete
Report on pilot subjective test and initial metrics assessment	July 31, 2017	In progress
Report on initial metrics assessment	July 31, 2017	In progress

Major Accomplishments

- Descriptor study was designed: several different test methods were reviewed and the method of Free Choice Profiling was determined to be the most suitable for this research task. The results from the upcoming subjective study will provide a set of descriptors useful in describing Mach cut-off, which will then be used in a subsequent test to study annoyance due to this signals, which will then be used to propose metrics to predict public acceptance of these types of sounds.
- FaINT dataset characterized – Methodical listening was used to sort the FaINT recordings into four categories. This categorization made it possible to select a suitable subset of flight passes for use in the listening test and will helpful in later stages when comparing quantities of different metrics across signals
- Frequency range of existing testing facility extended Subwoofers constructed – A pair of subwoofers were designed and constructed to extend low-frequency output of Penn State's sound-field-reproduction facility, which was necessarily in order to accurately reproduce of the Mach-cutoff signals from the FaINT recordings.
- Descriptor study preparations completed – Administrative approvals were obtained and testing instruments (e.g. user interfaces, questionnaires) were developed. Subjective data collection will begin in November 2017.

Publications

Acoustics '17 abstract.

Outreach Efforts

CAV Workshop 2018 – Poster presentation: This consisted of one poster outlining the listening test design and preparation.

Awards

None.

Student Involvement

Nicholas Ortega was primarily responsible for test design, stimulus selection, test preparations, and presentation preparations. He also presented the poster at the CAV workshop and the talk at the ASA / EAA Conference. He will continue to work on this task during the following period.

Plans for Next Period

Over the next period, the work will be focused on obtaining subjective data and analyzing how this data relates to existing metrics. First the descriptor study will be administered and is projected to be completed by mid-January. Results from the descriptor study will then be analyzed and attributes will be selected for inclusion in the annoyance study, which will be run in early 2018. The results from this second study will be used to determine which attributes factor into annoyance. Calculated metrics will then be analyzed for correlation with the given ratings, and a metric or group of metrics will be proposed that may be useful in predicting response to Mach cut-off by April-May 2018.

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