U.S. Department of Transportation
Federal Aviation Administration

FINAL PROJECT REPORT

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PART I - PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. FAA Program	3. FAA Award Number
Georgia Tech Research Corporation	Environment and Energy	13-C-AJFE-GIT-023
505 Tenth Street NW Atlanta, GA 30332-0420	4. Award Period From 6/28/2016 To 8/14/2017	5. Cumulative Award Amount $70,000.00

6. Project Title

Sensitivity Analysis of Acoustical Model for Mach Cut-off Flight

PART II - SUMMARY OF COMPLETED PROJECT (For Public Use)

Georgia Tech has completed the research plan for this task. Georgia Tech has also acquired both the source code and executable for PCBoom 6.7. PCBoom 6.7 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. 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.

PART III - TECHNICAL INFORMATION (For Program Management Uses)

1. **ITEM** (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (X)	Approx. Date
a. Abstracts of Theses	✘				
b. Publication Citations	✘				
c. Data on Scientific Collaborators	X				
d. Information on Inventions	✘				
e. Technical Description of Project and Results		✘			
f. Other (specify)					

2. Principal Investigator/Project Director Name (Typed)	3. Principal Investigator / Project Director Signature	4. Date
Dimitri Mavris		11/19/2017

FAA Form 9550-5 (03-03) Supersedes Previous Edition

Georgia Institute of Technology | Final Report:

Project 42
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)

*Note: This final report describes only Georgia Tech's contributions to ASCENT Project 42, for a complete description of the project's accomplishments please refer to the Project 42 team's Annual Report.

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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. Determine feasibility for obtaining Mach Cut-off data via scale experiments

Georgia Institute of Technology
- P.I.(s): Dr. Dimitri Mavris (PI), Dr. Jimmy Tai (Co-PI)
- FAA Award Number: 13-C-AJFE-GIT-023
- Period of Performance: June 28, 2016 – August 14, 2017
- Task(s):
  4. Sensitivity study 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

$170K, The Pennsylvania State University
$70K, Georgia Institute of Technology
$15K, University of Washington
$15K, Volpe National Transportation Systems Center

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

Investigation Team

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

University of Washington
Principal Investigator: Michael Bailey

Georgia Institute of Technology
Principal Investigator: Dimitri Mavris
Co-Investigator: Jimmy Tai
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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 42.1, it is possible to fly in a range of Mach numbers (perhaps between Mach 1.0 and Mach 1.15) while having the sonic boom noise refract (bend) upwards such that the rays never reach the ground. However, the reader should be aware that this picture is over-simplified since the temperature profile in the atmosphere is never a smooth, linear function as depicted here. For higher Mach numbers, the sonic boom will impact the ground before refracting upward.

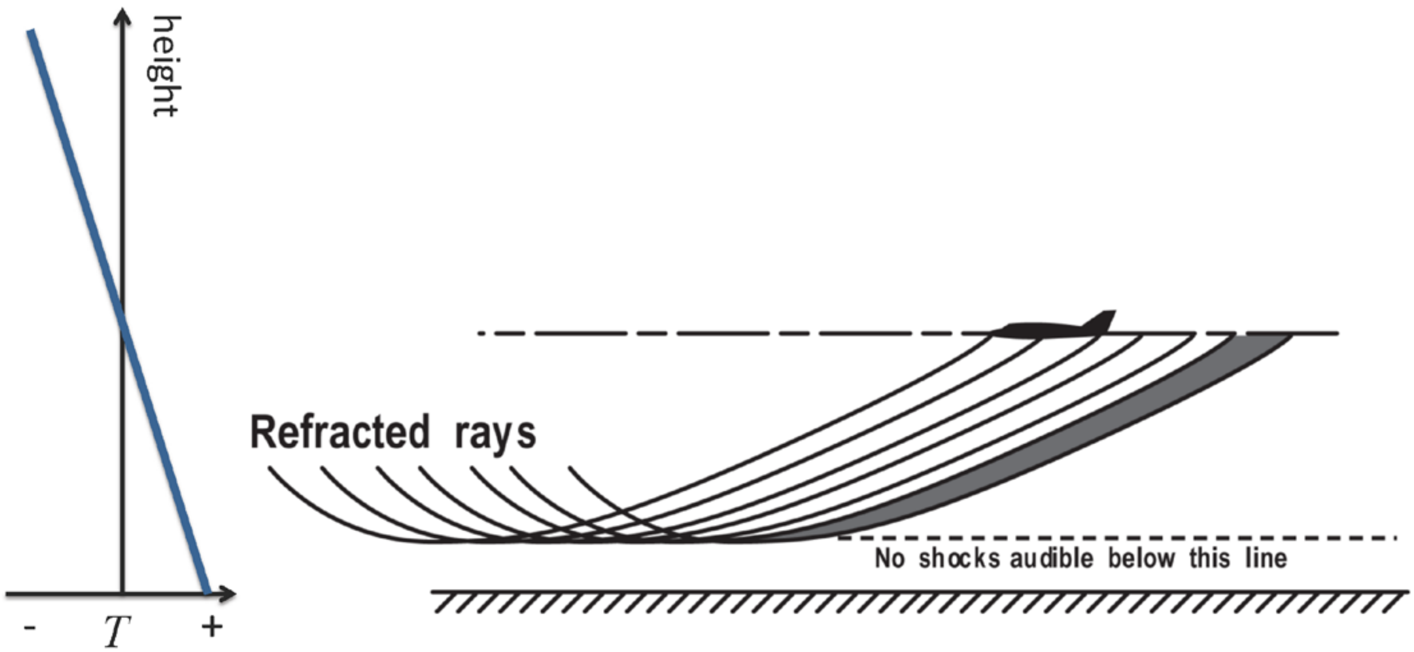

Figure 42.1: Simplified view of Mach cut-off where sonic boom noise does not reach the ground surface. Left: ambient temperature versus height. [Sparrow] Right: aircraft and ray diagram showing refraction of sonic boom [NASA].

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

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

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.

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 is 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 porfiles, 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

In order 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 as well as 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:

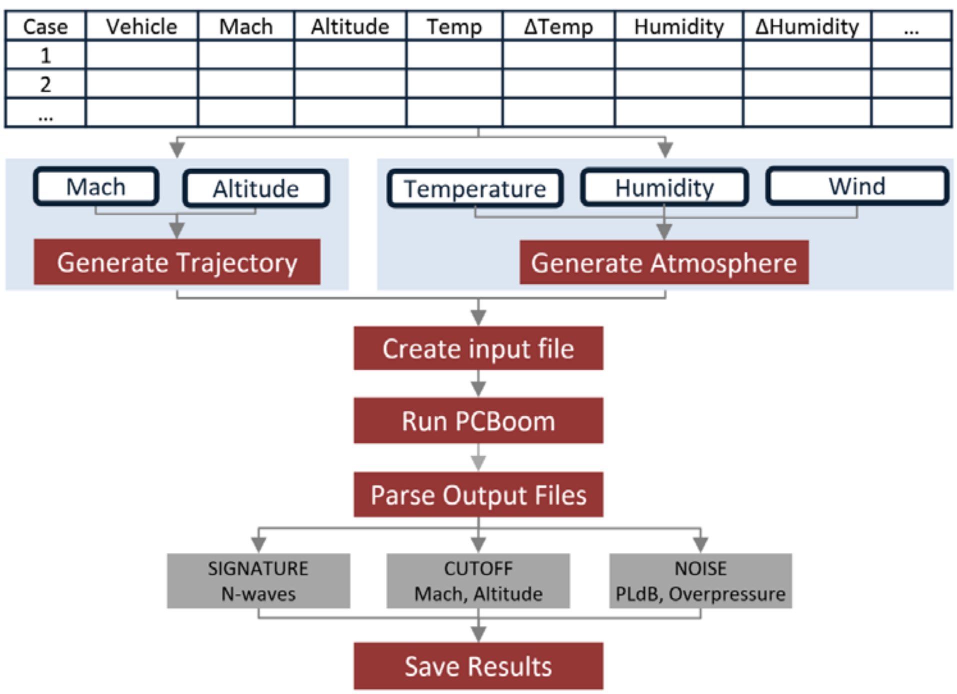

Figure 1 - PCBoom Wrapper Flowchart

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 ones 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 PCBoom6.7 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.

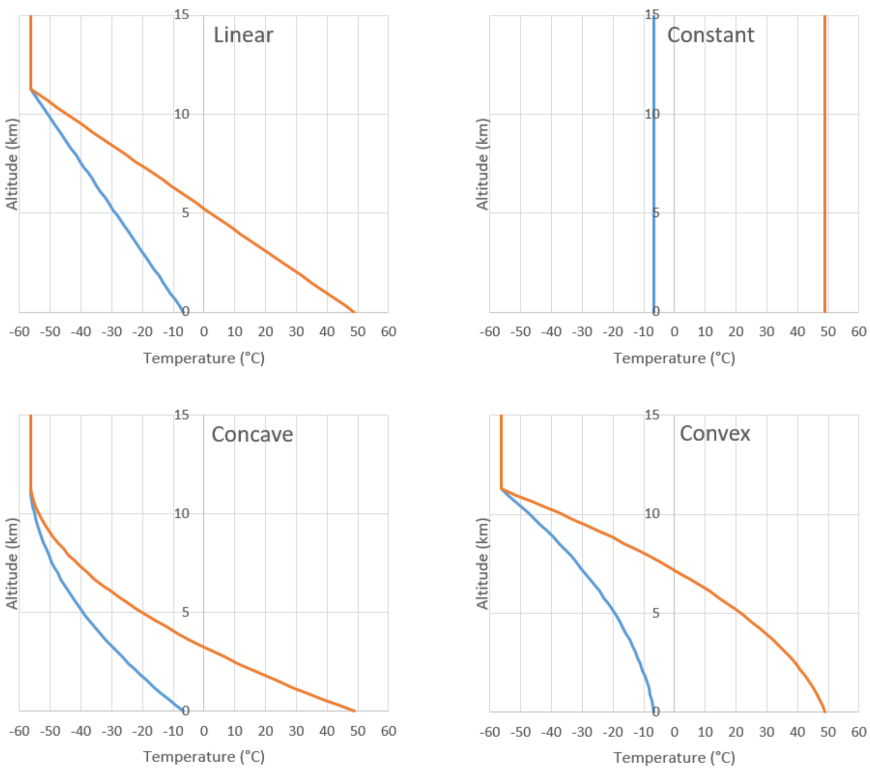

Figure 2 - Variation of Temperature Profiles: Linear, Constant, Concave, Convex

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.

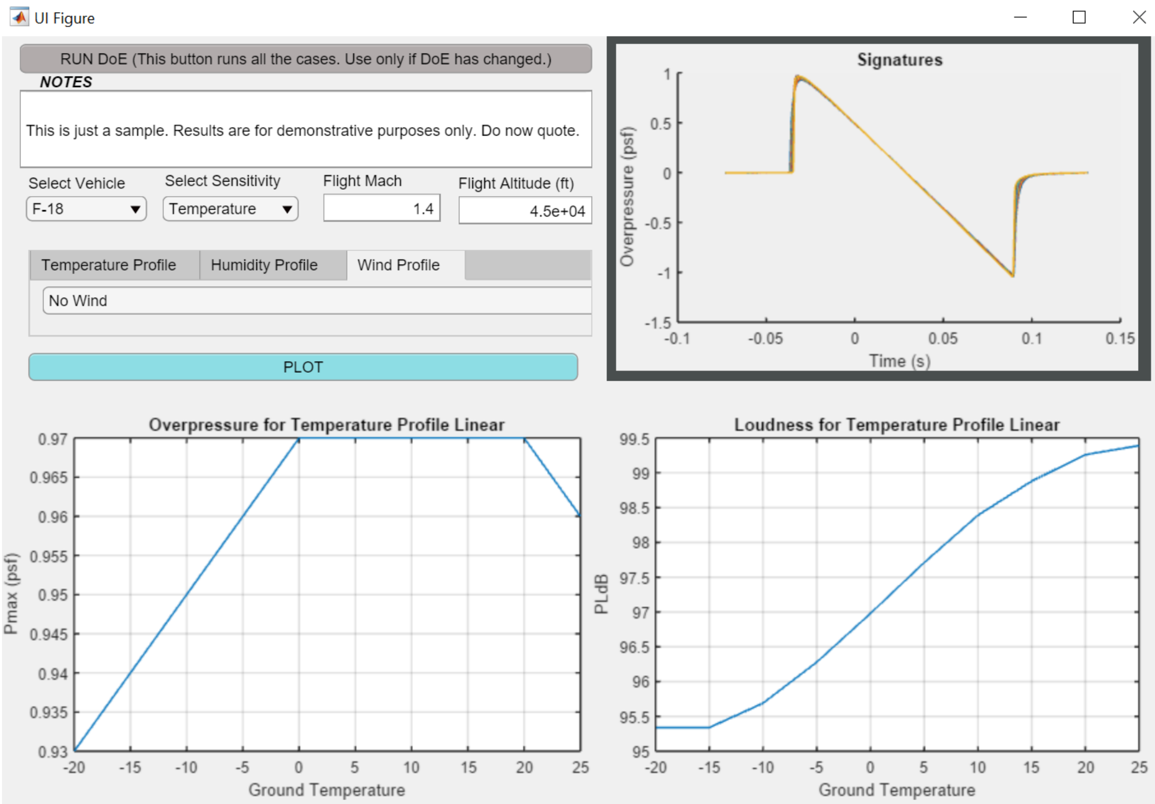

Figure 3 - General View of the Data Visualization GUI

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:

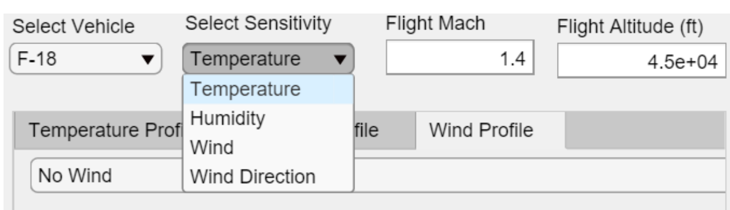

Figure 4 - Various Options Available for User Selection in GUI

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:

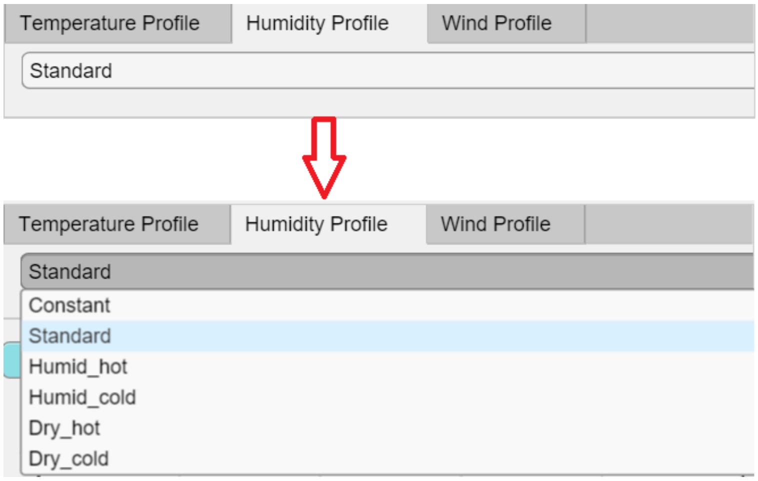

Figure 5 - Dropdown Options for Atmospheric Parameter Profiles

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 PCBoom6.7 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 the standard profile used in PCBoom6.7, 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 stmosphere 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 the FIGURE below.

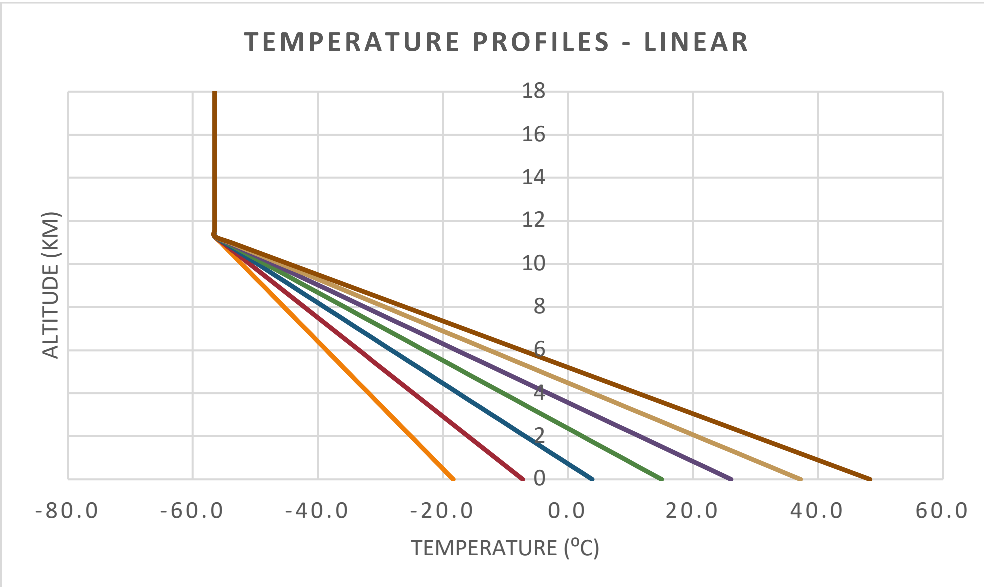

Figure 6: Standard Profiles: Linear Temperature

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 7.

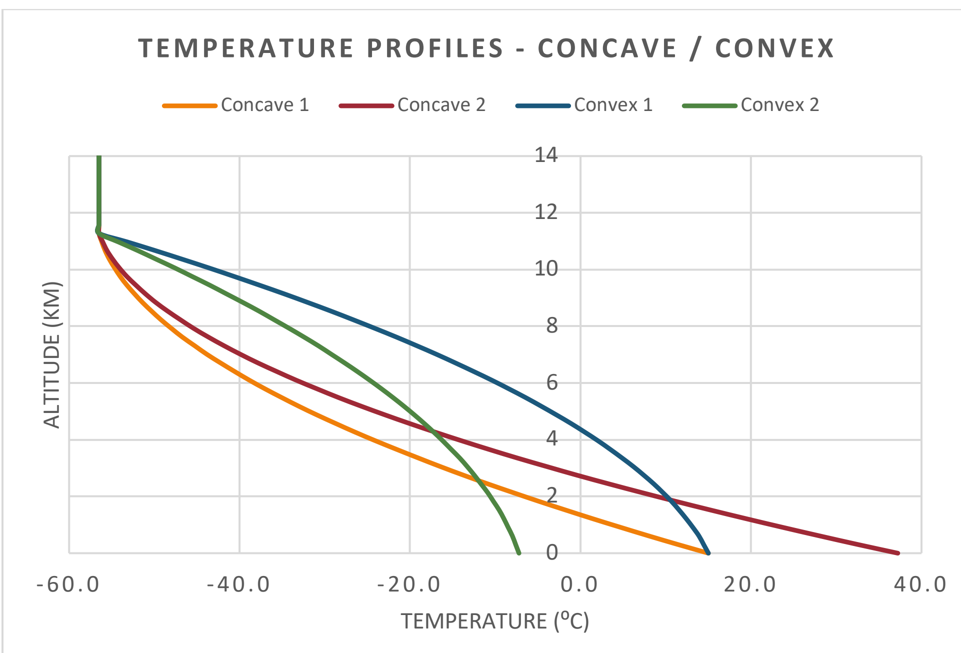

Figure 7: Standard Profiles: Concave and Convex Temperature

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 8.

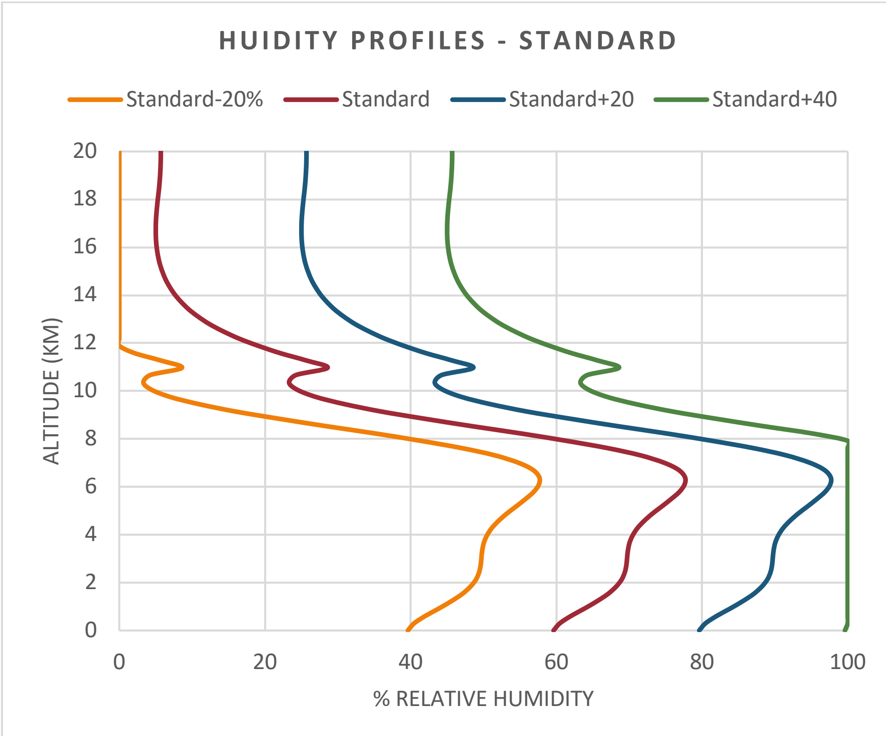

Figure 8: Standard Profiles: Relative Humidity

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. Through the use of 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 9 – where 0º is a tailwind and 180º is a headwind.

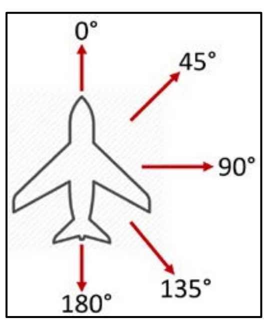

Figure 9: Wind Directions Definitions

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 publicly 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 10, the humidity profiles are shown in Figure 11, and the wind profiles are shown in Figure 12.

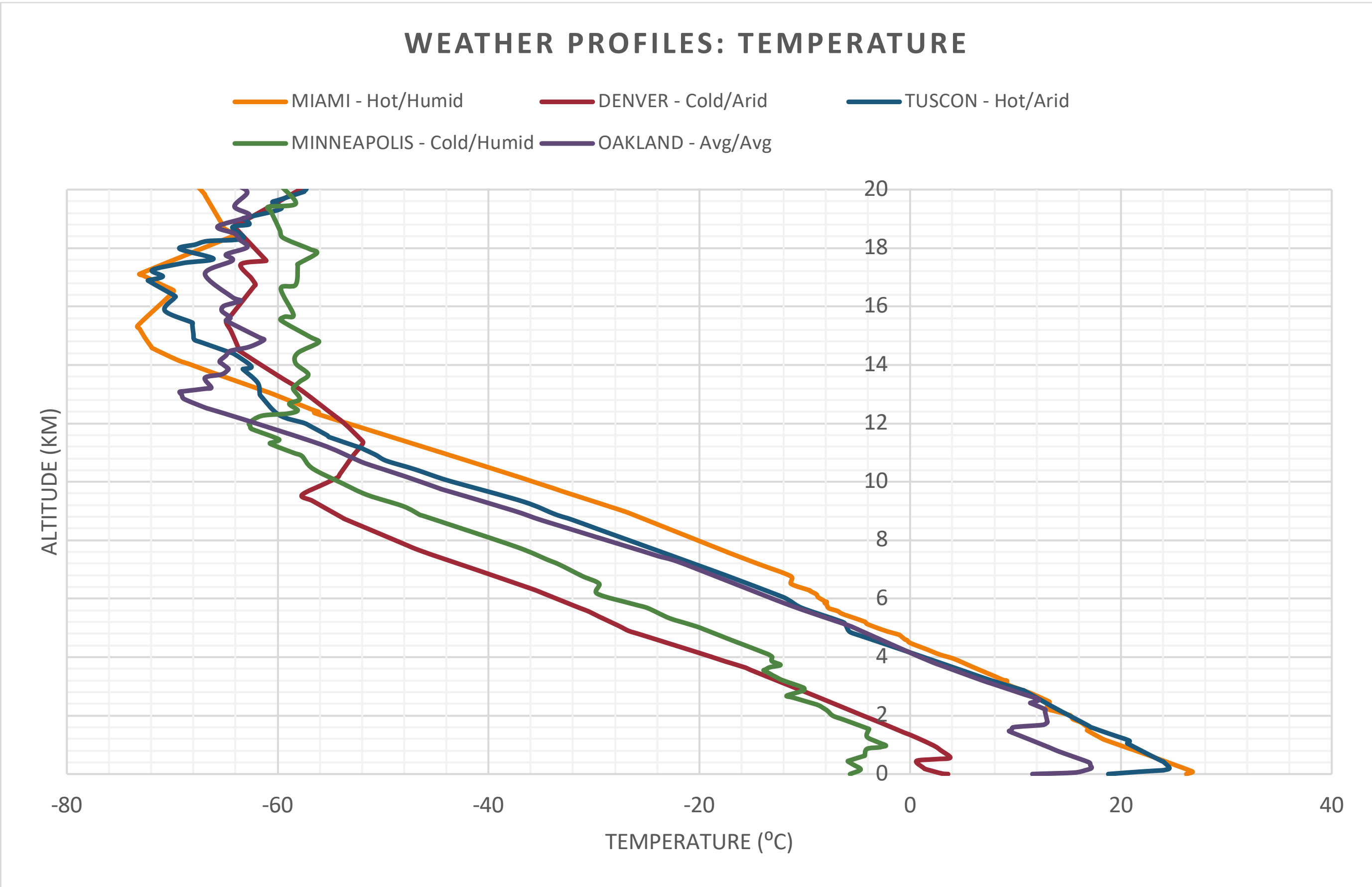

Figure 10: Realistic Profiles: Temperature

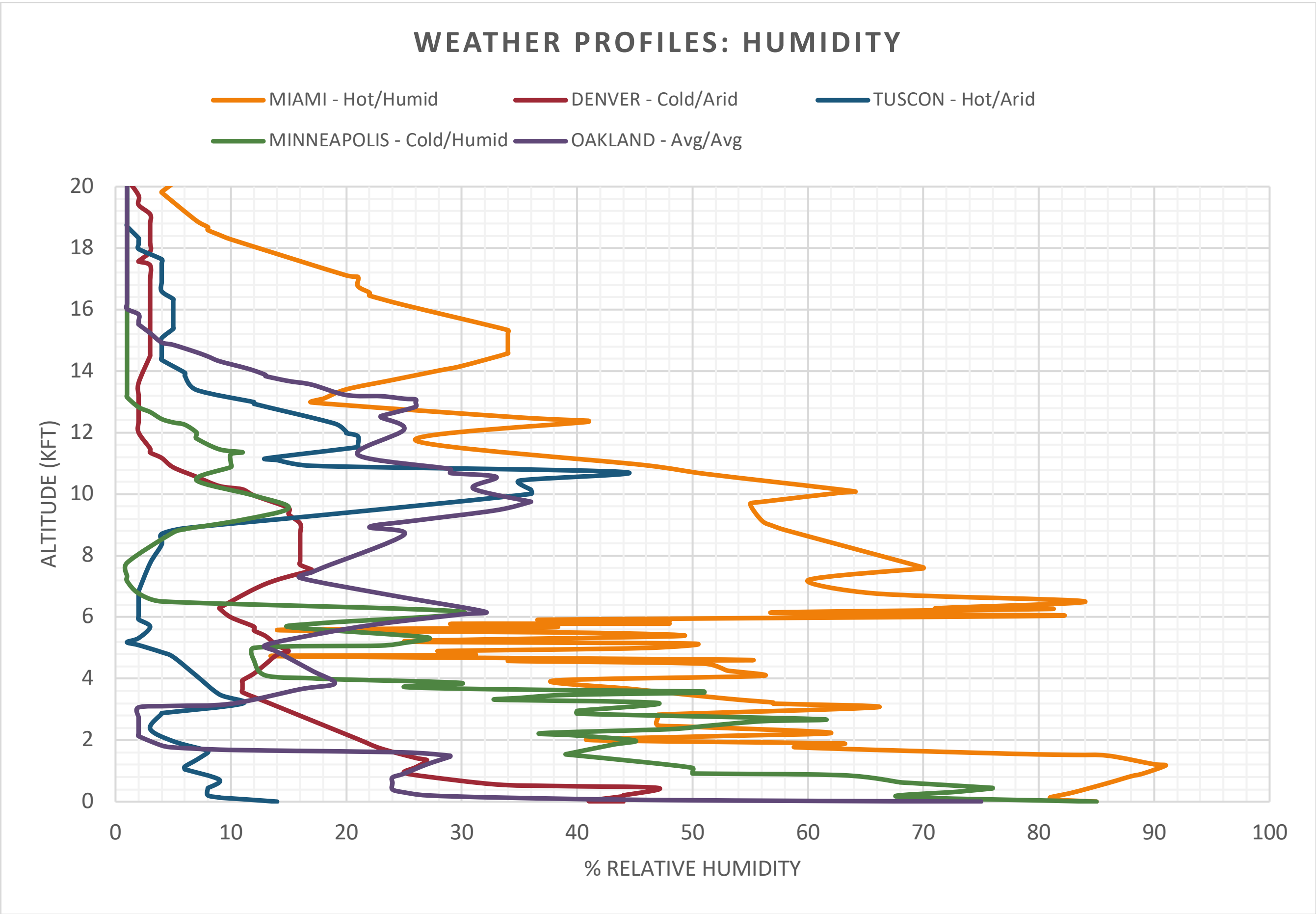

Figure 11: Realistic Profiles: Relative Humidity

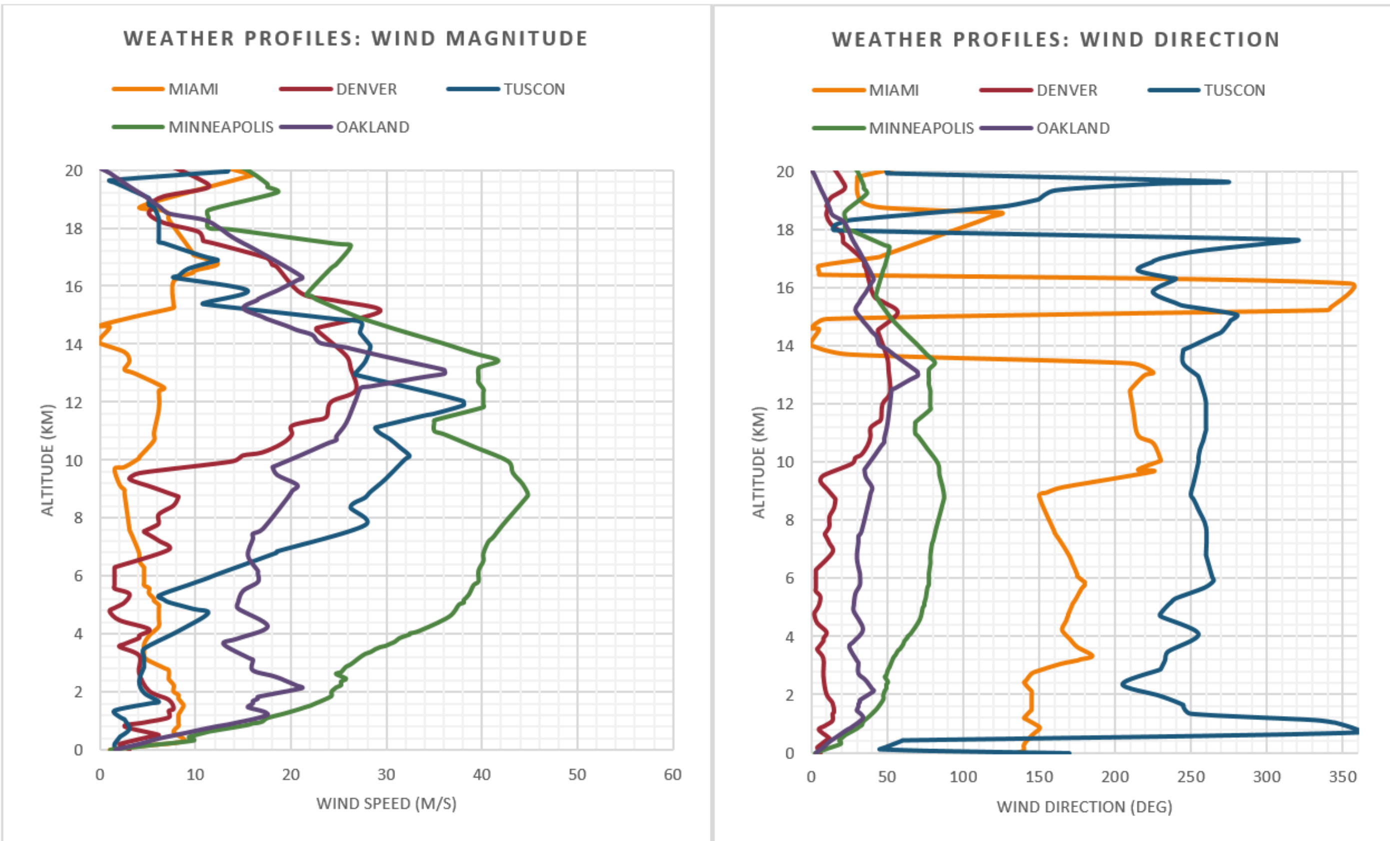

Figure 12: Realistic Profiles: Wind Magnitude and Direction

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. The sensitivity of loudness to changes in relative humidity are shown in Figures 13-16, Figure 13 displays the sensitivity under linear temperature profiles, Figure 14 displays the sensitivity under constant temperature profiles, Figure 15 displays the sensitivity under concave temperature profiles, and Figure 16 displays the sensitivity under convex temperature profiles.

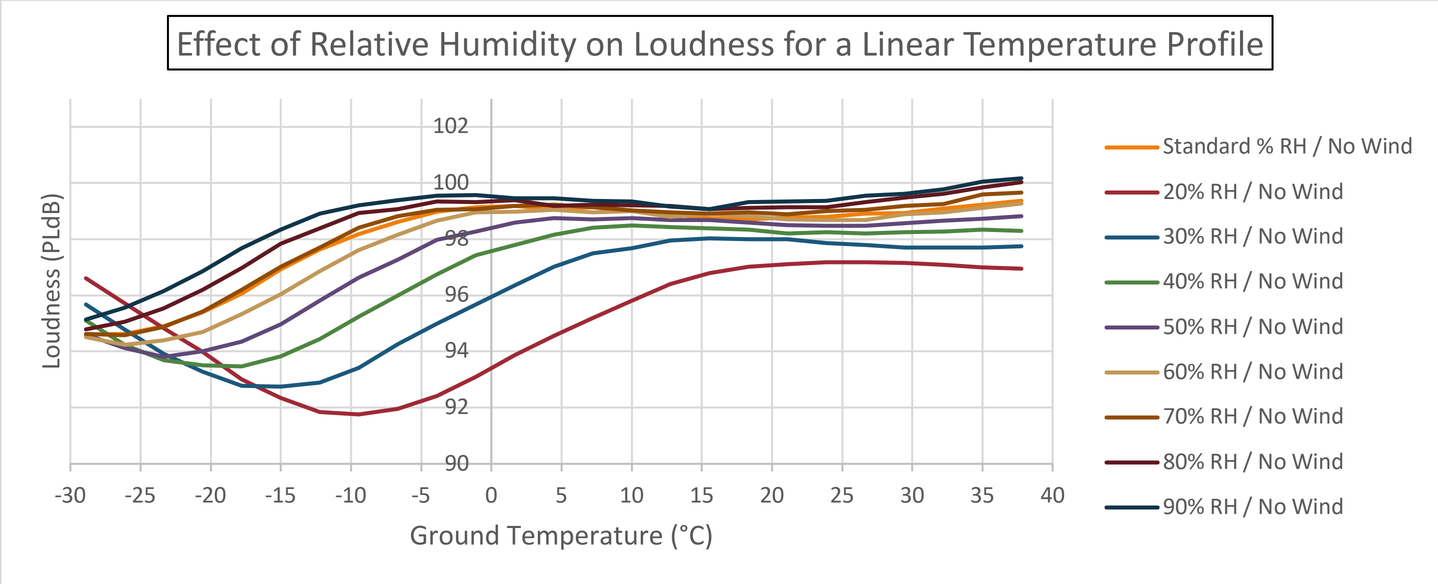

Figure 13: Loudness Sensitivity to Humidity - Linear Temperature Profiles

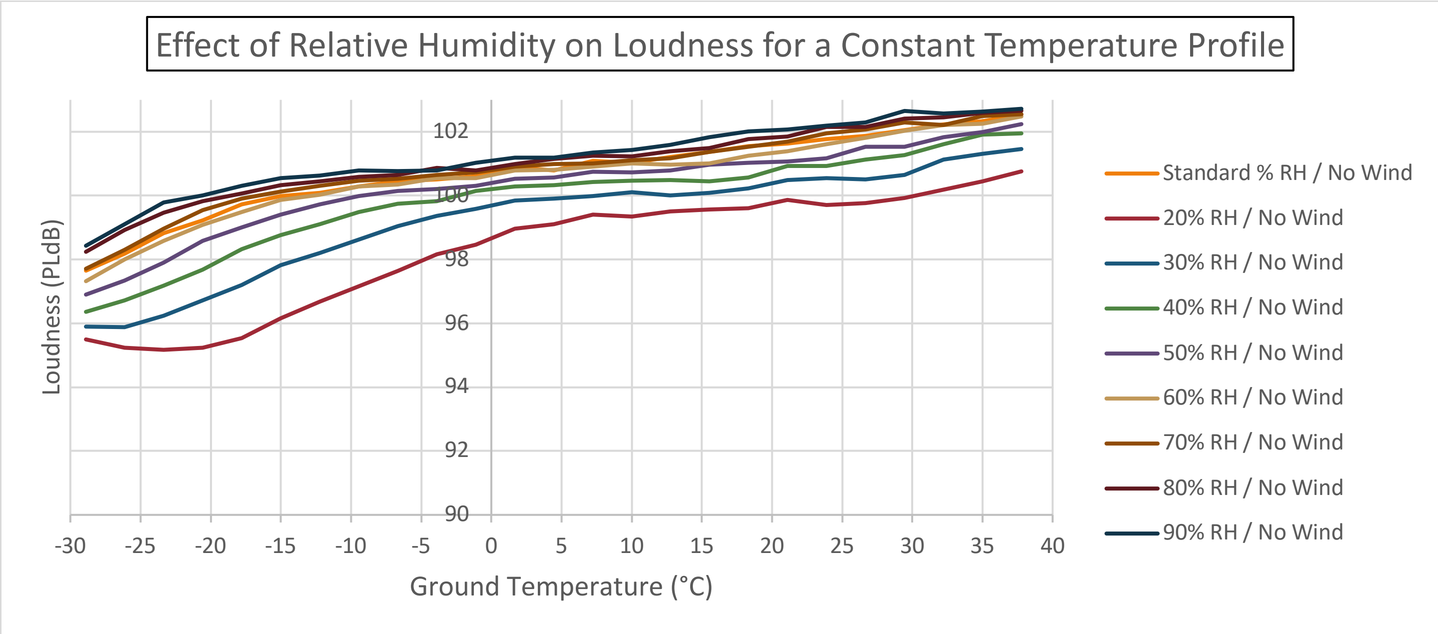

Figure 14: Loudness Sensitivity to Humidity - Constant Temperature Profiles

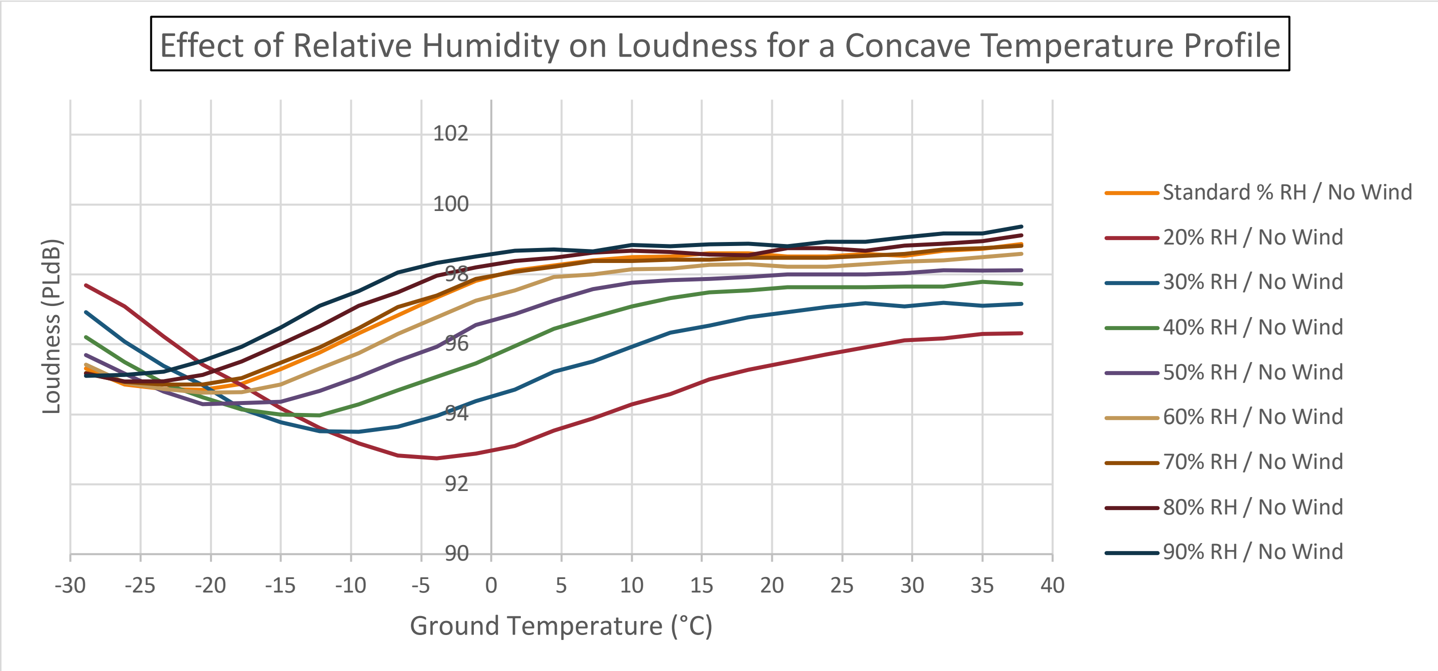

Figure 15: Loudness Sensitivity to Humidity - Concave Temperature Profiles

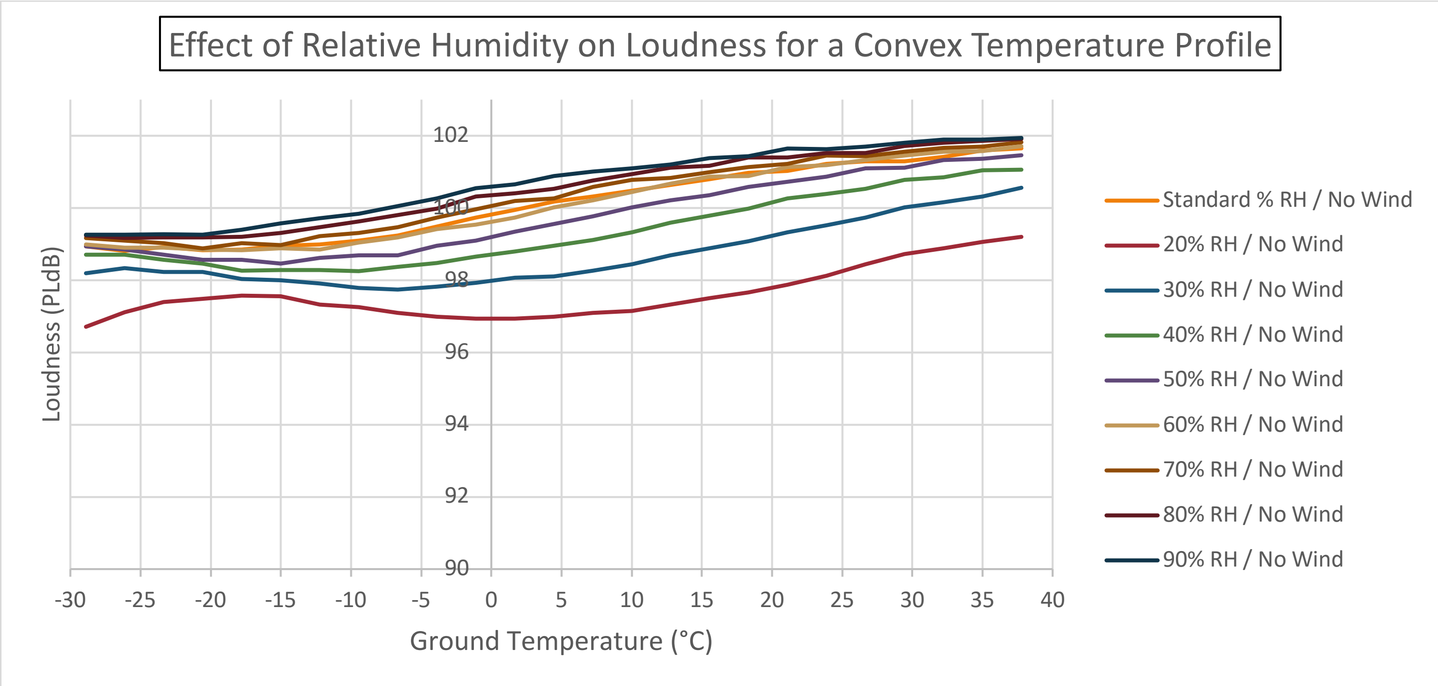

Figure 16: Loudness Sensitivity to Humidity - Convex Temperature Profiles

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 14, 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 13 and 15, 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.

The sensitivity of maximum overpressure (Pa) to changes in relative humidity are shown in Figures 17-20, Figure 17 displays the sensitivity under linear temperature profiles, Figure 18 displays the sensitivity under constant temperature profiles, Figure 19 displays the sensitivity under concave temperature profiles, and Figure 20 displays the sensitivity under convex temperature profiles.

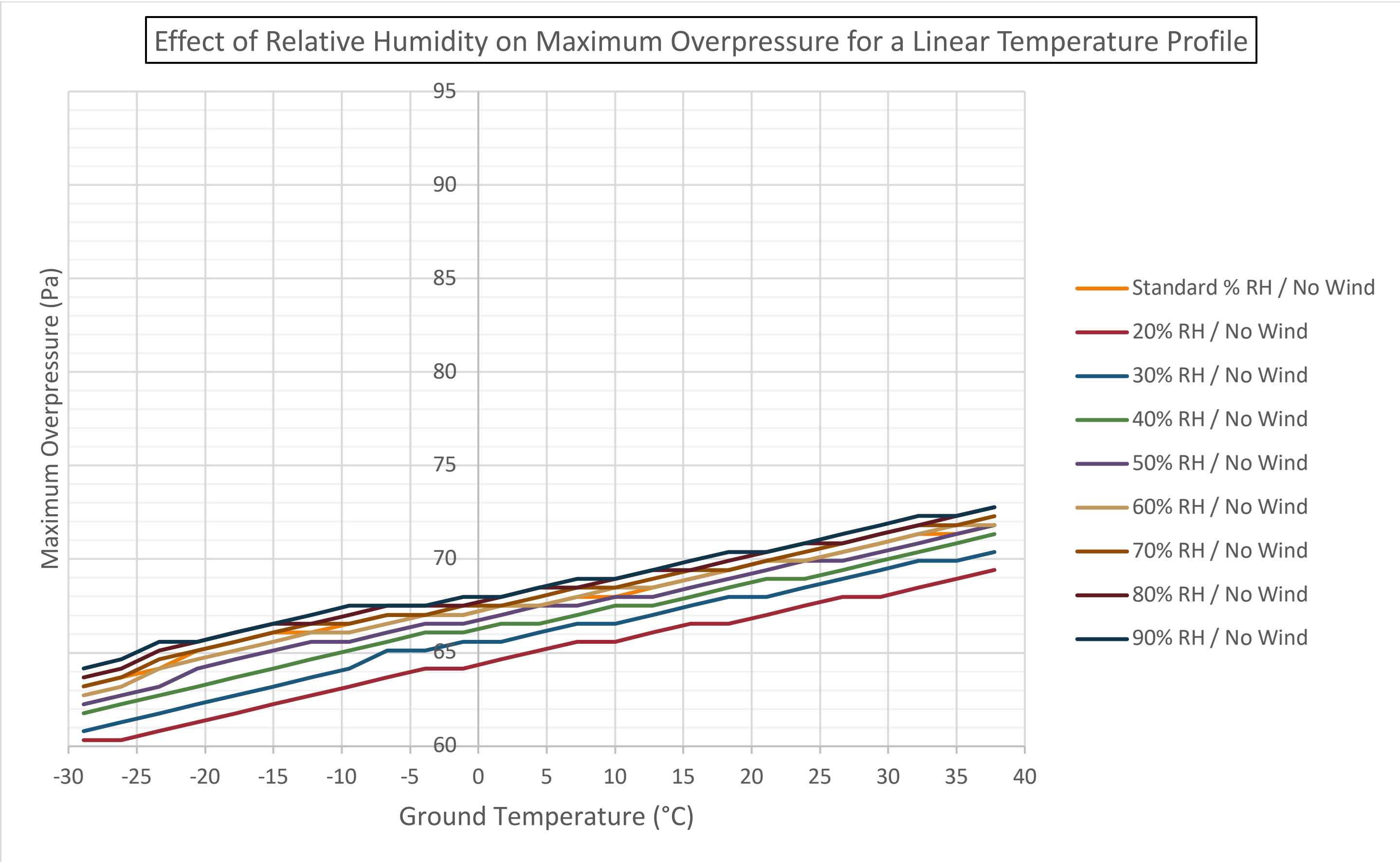

Figure 17: Max Overpressure Sensitivity to Humidity - Linear Temperature Profiles

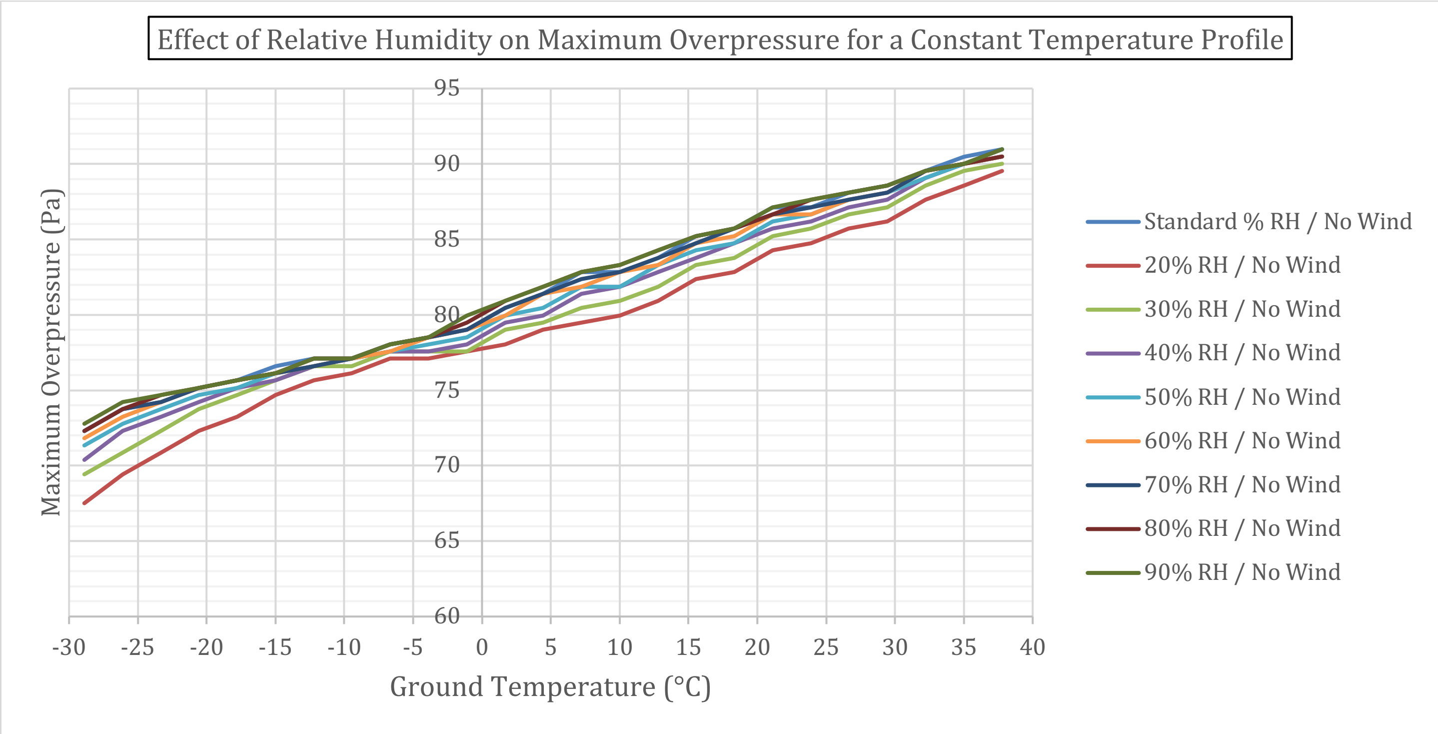

Figure 18: Max Overpressure Sensitivity to Humidity - Constant Temperature Profiles

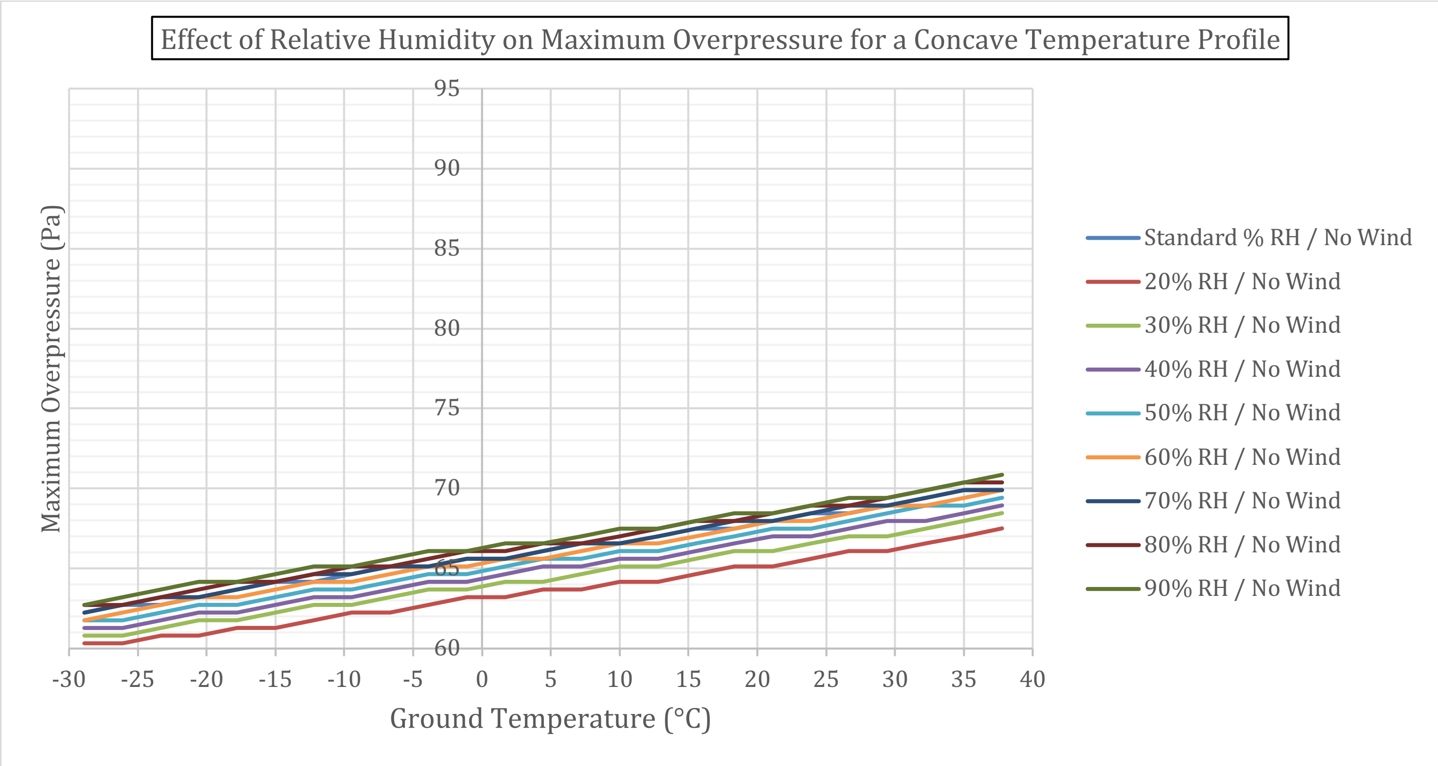

Figure 19: Max Overpressure Sensitivity to Humidity - Concave Temperature Profiles

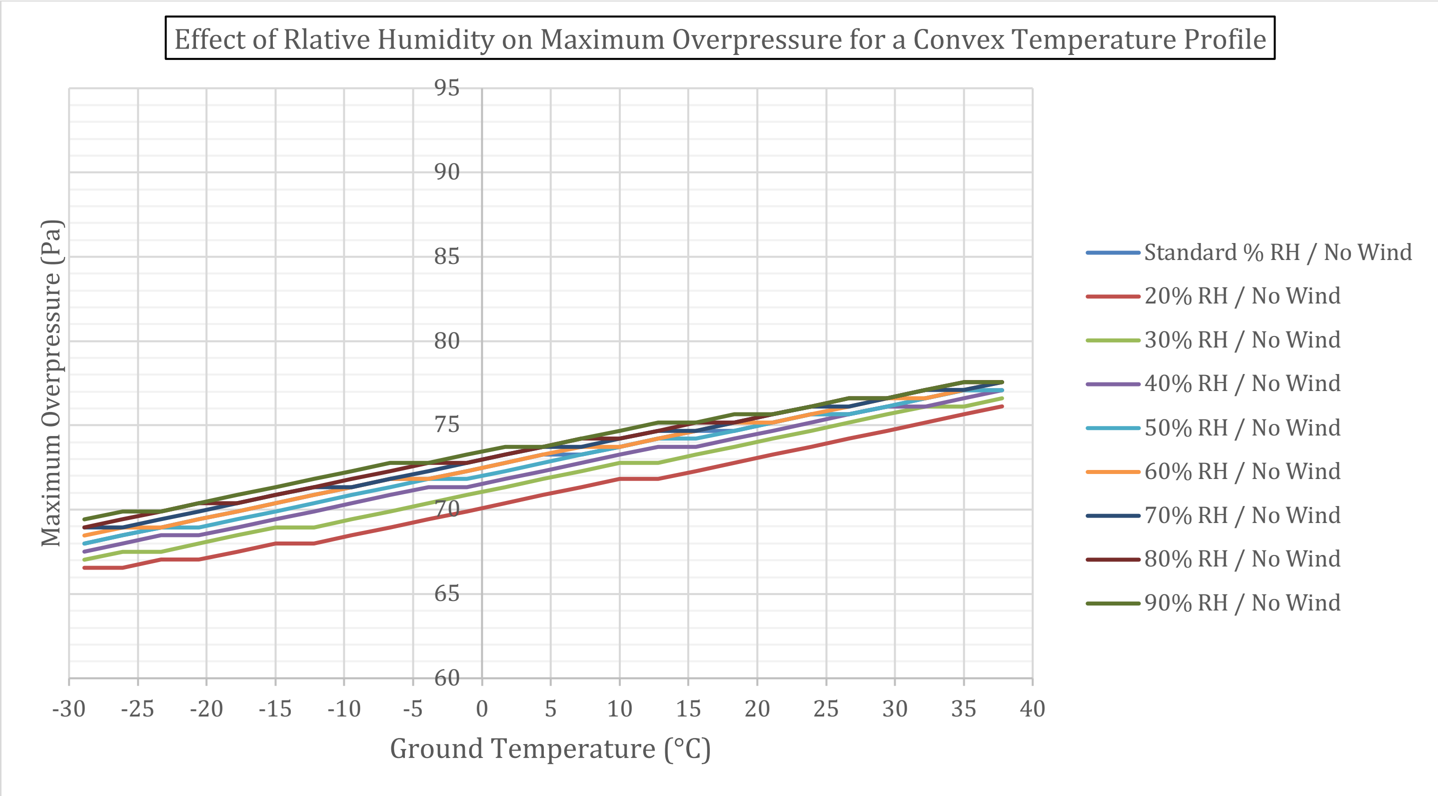

Figure 20: Max Overpressure Sensitivity to Humidity - Convex Temperature Profiles

Wind – Loudness

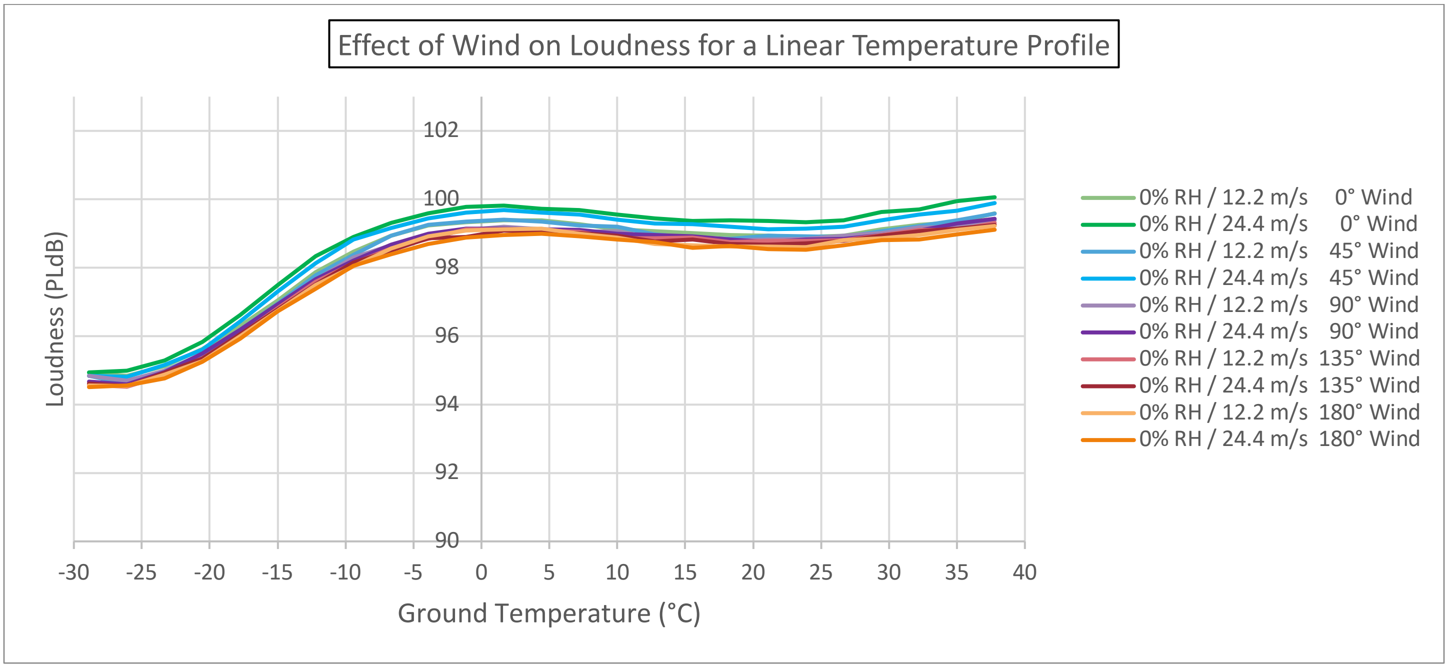

Figure 21: Loudness Sensitivity to Wind - Linear Temperature Profiles

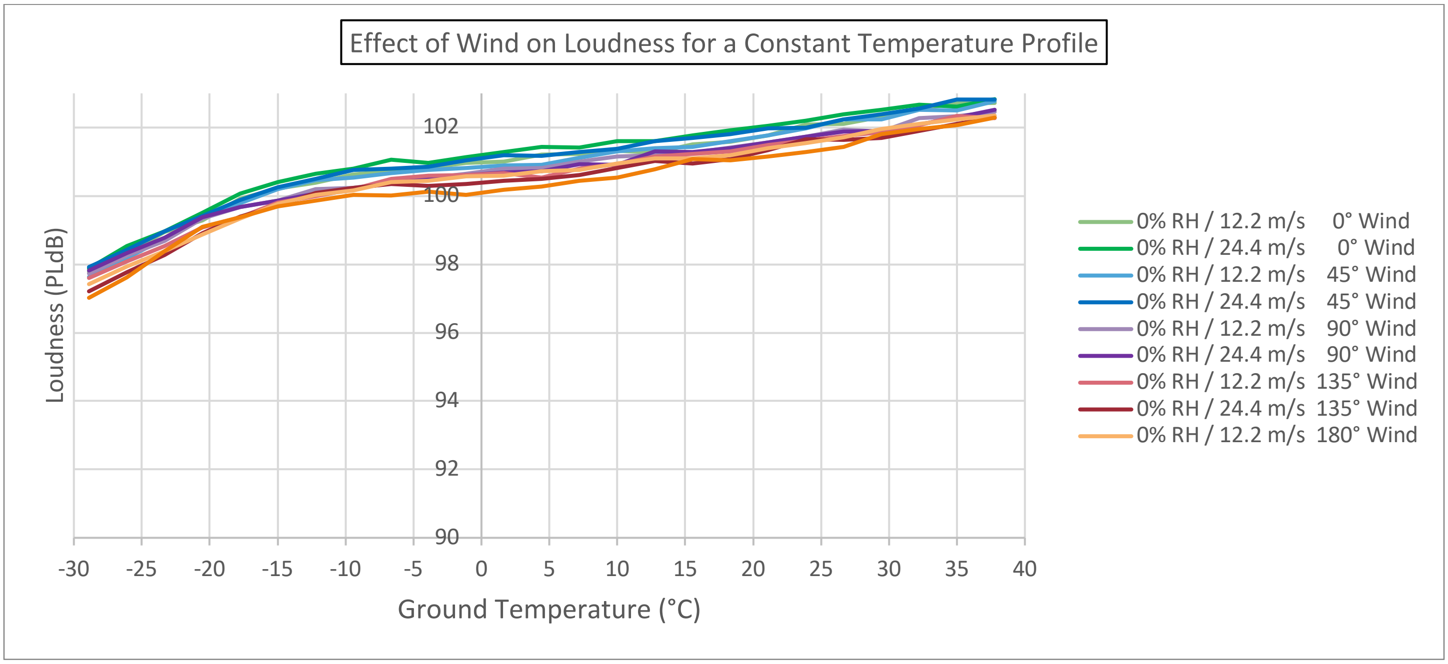

Figure 22: Loudness Sensitivity to Wind - Constant Temperature Profiles

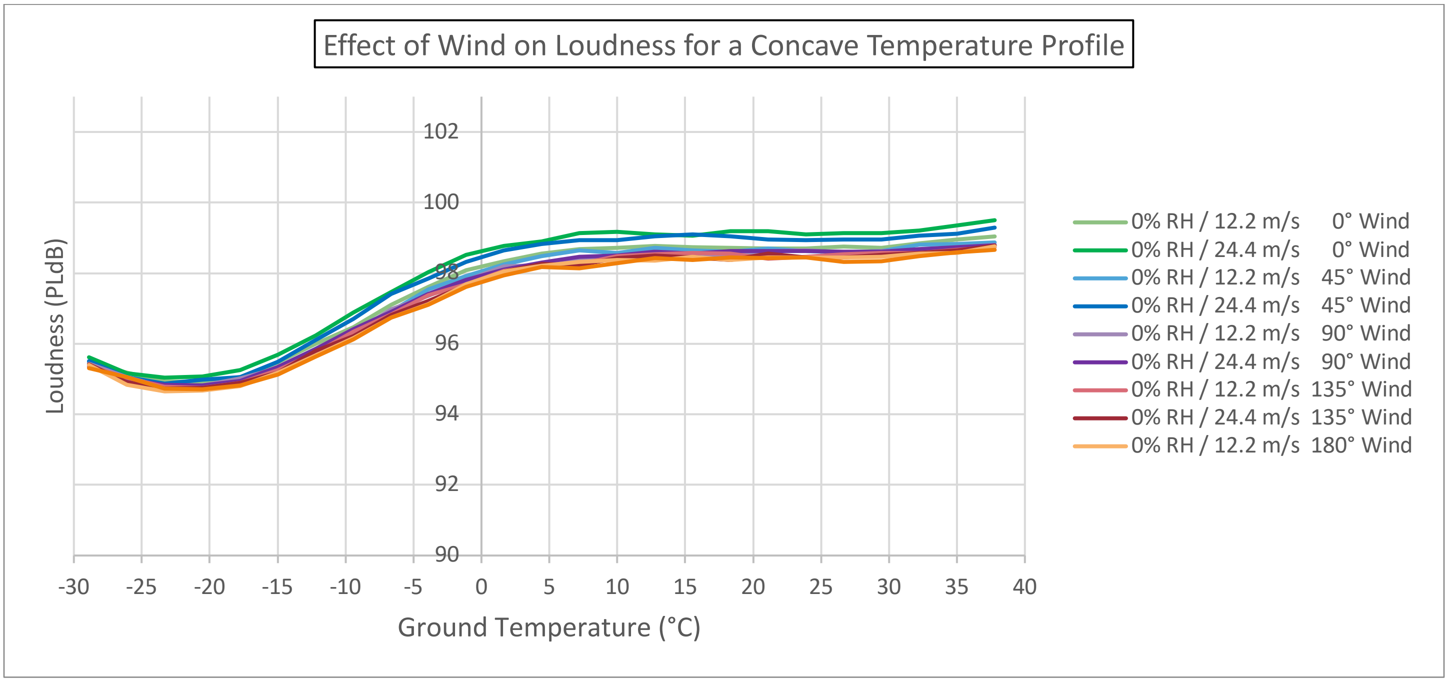

Figure 23: Loudness Sensitivity to Wind - Concave Temperature Profiles

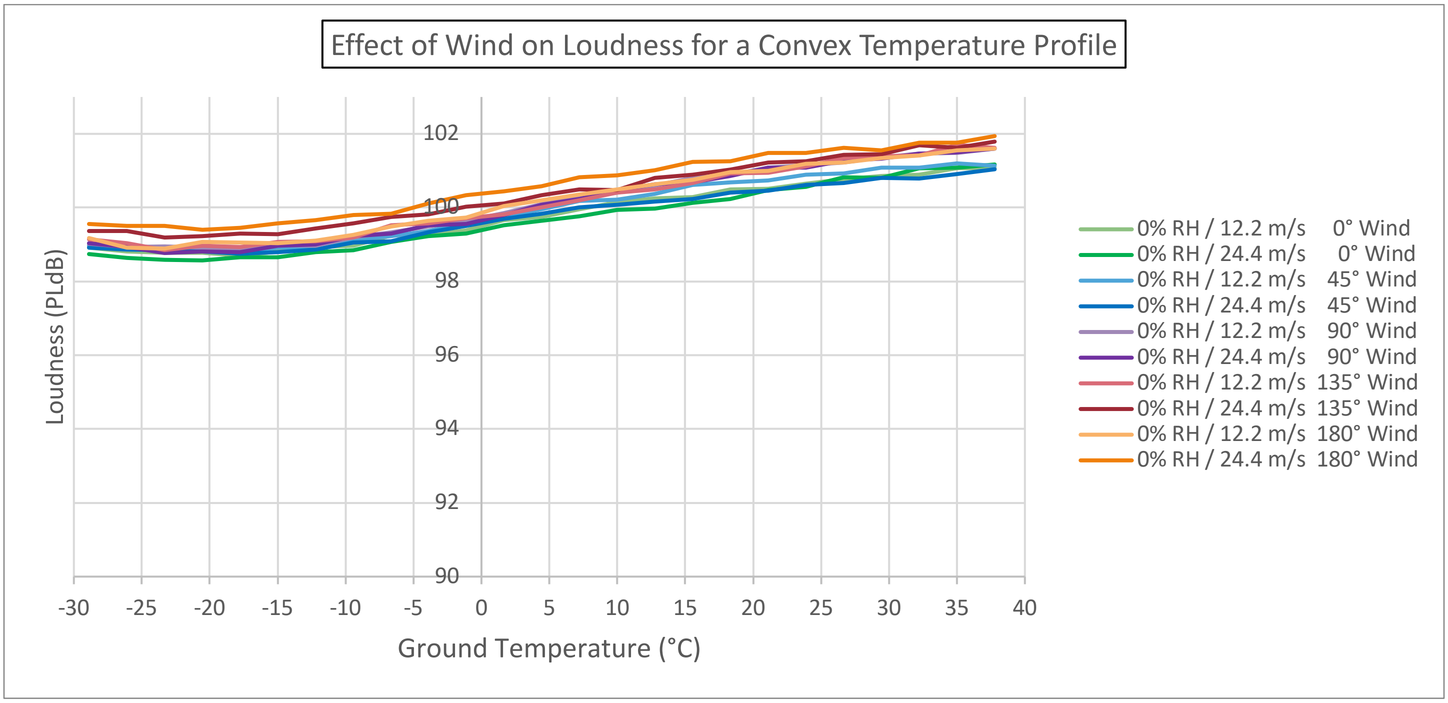

Figure 24: Loudness Sensitivity to Wind - Convex Temperature Profiles

Wind – Max Overpressure

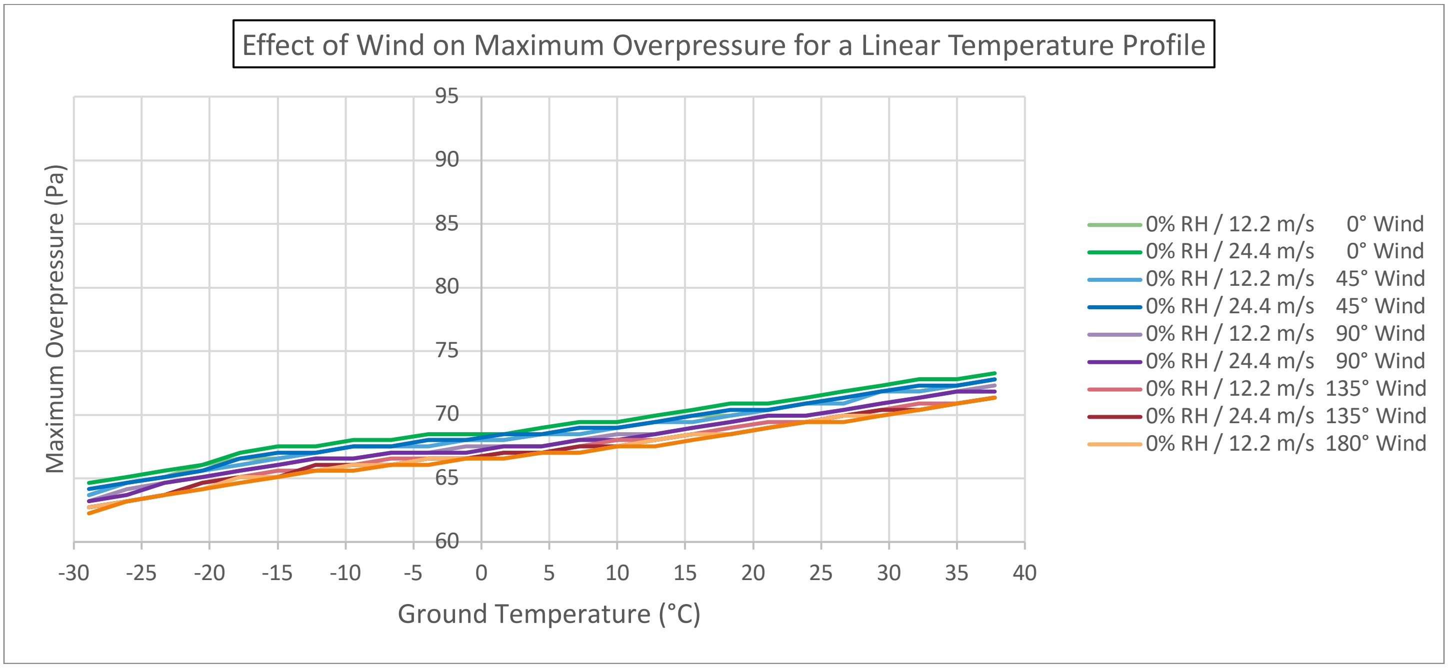

Figure 25: Max Overpressure Sensitivity to Wind - Linear Temperature Profiles

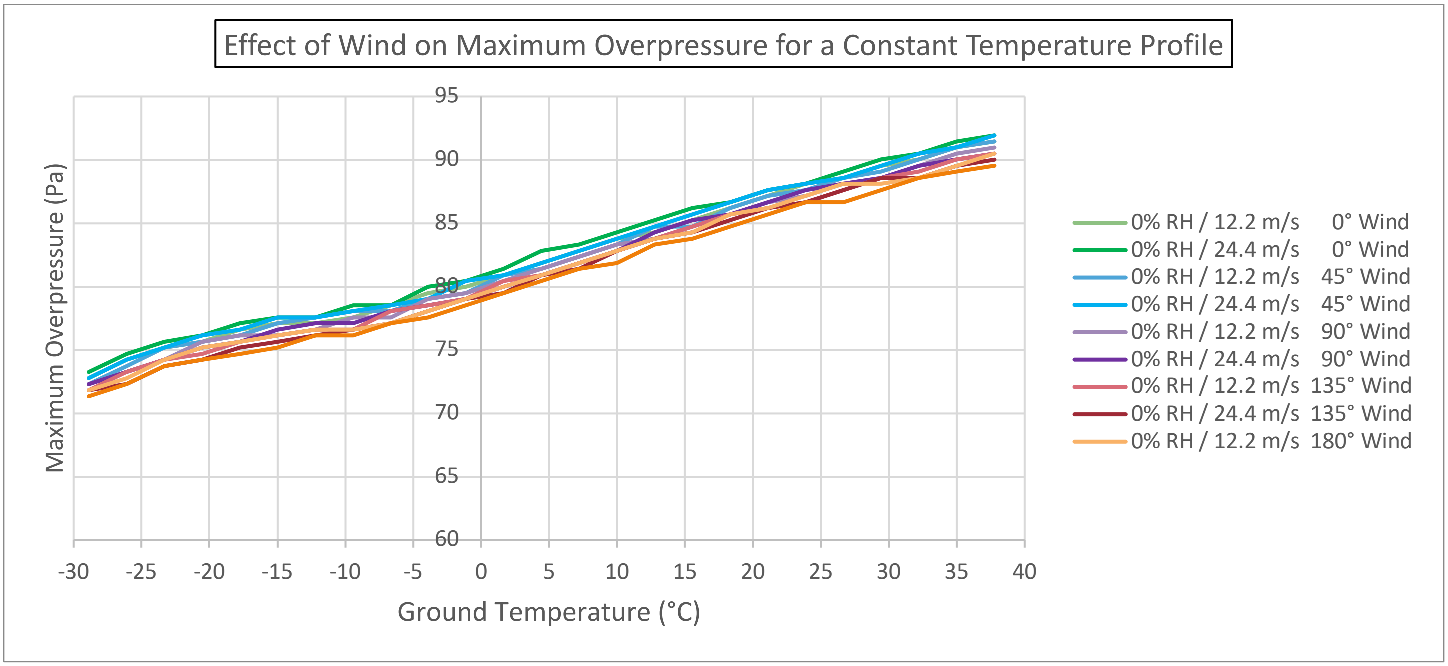

Figure 26: Max Overpressure Sensitivity to Wind - Constant Temperature Profiles

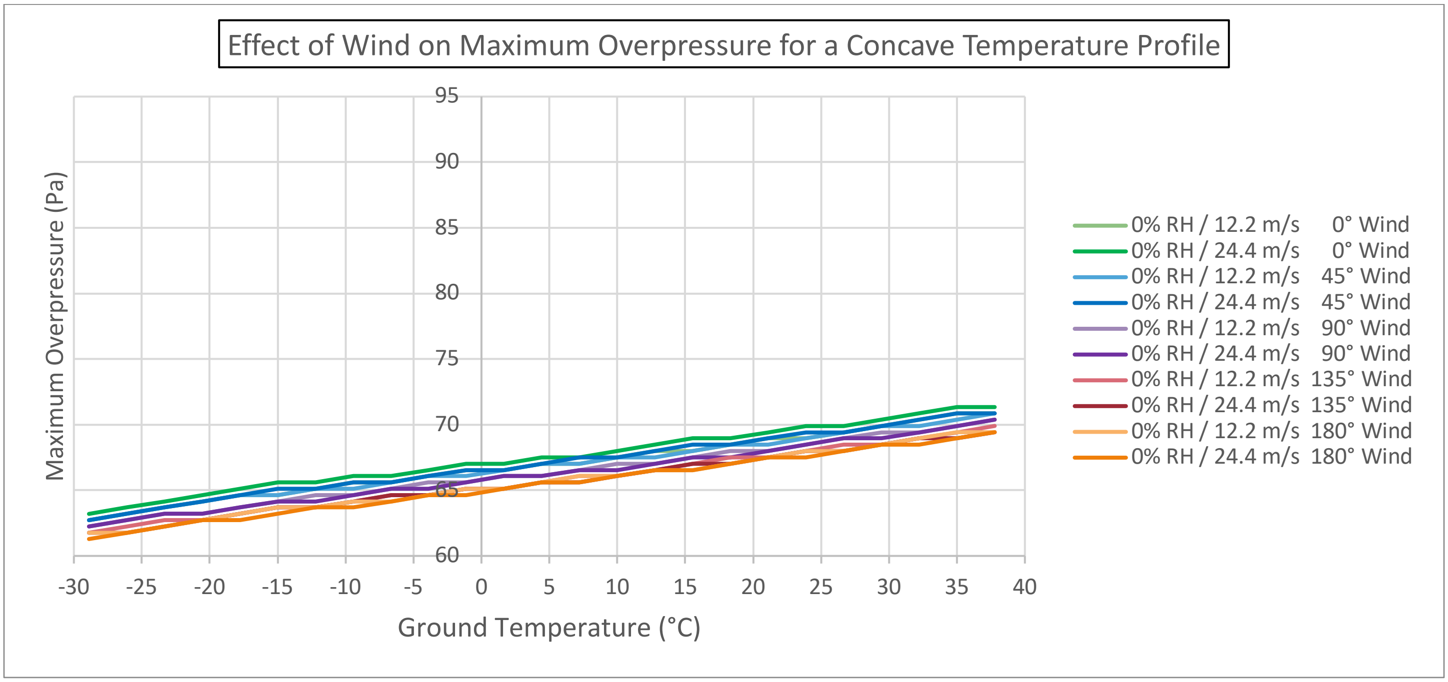

Figure 27: Max Overpressure Sensitivity to Wind - Concave Temperature Profiles

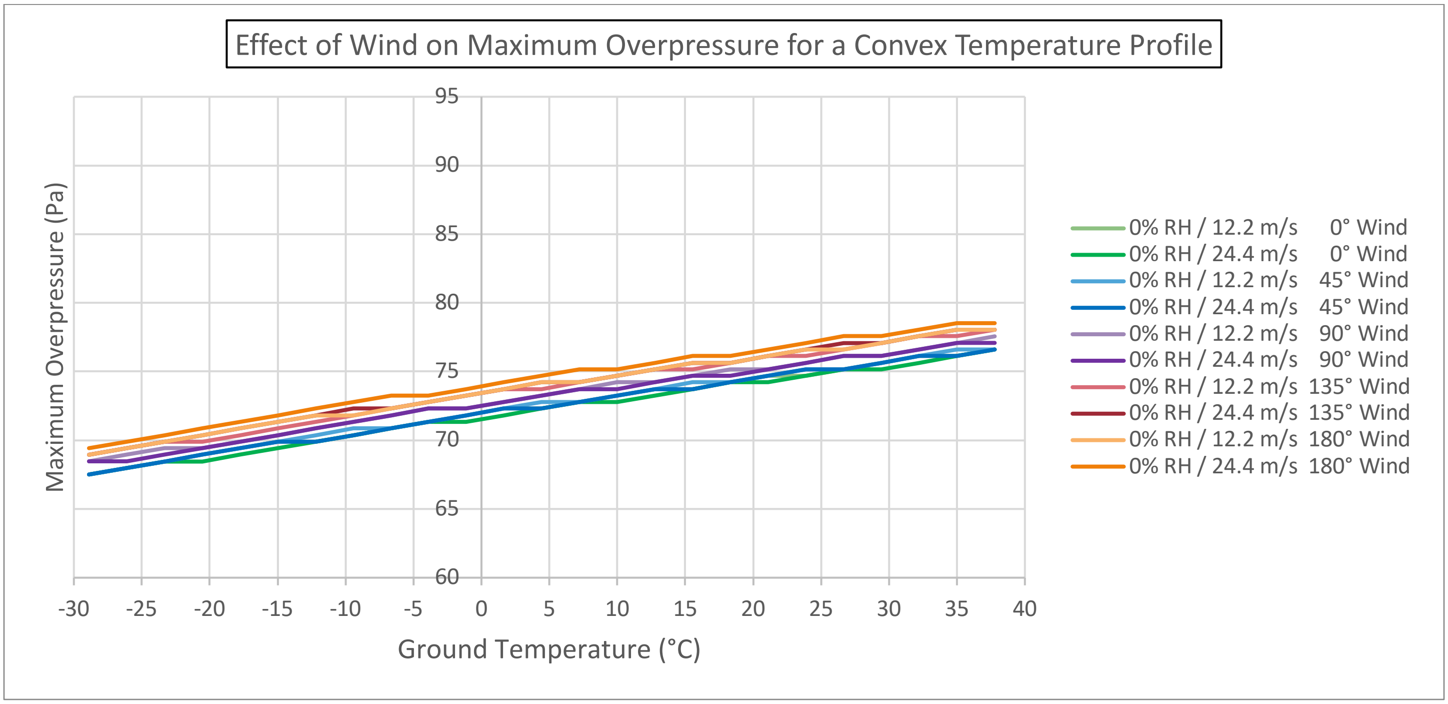

Figure 28: Max Overpressure Sensitivity to Wind - Convex Temperature Profiles

Realistic Profiles

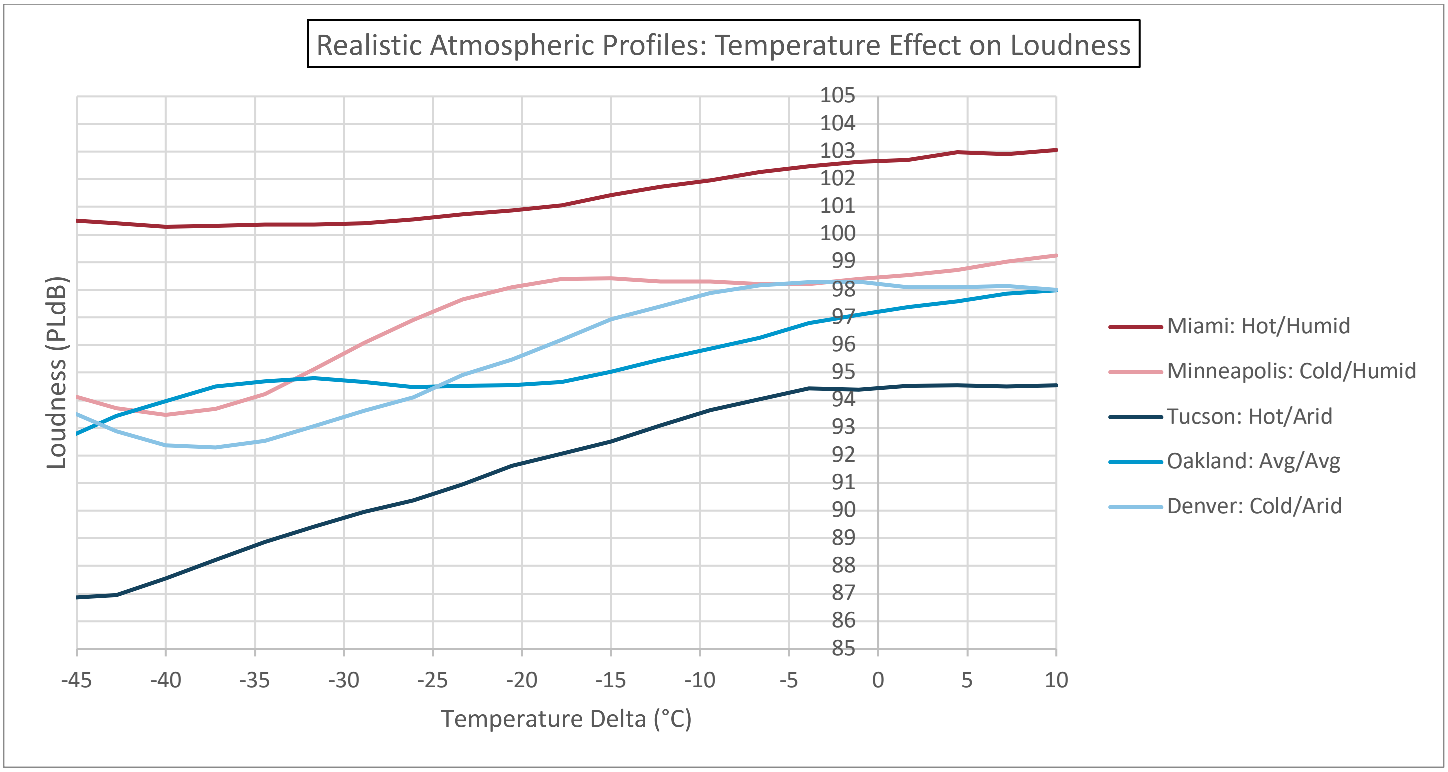

Figure 29: Loudness Sensitivity to Temperature - Realistic Profiles

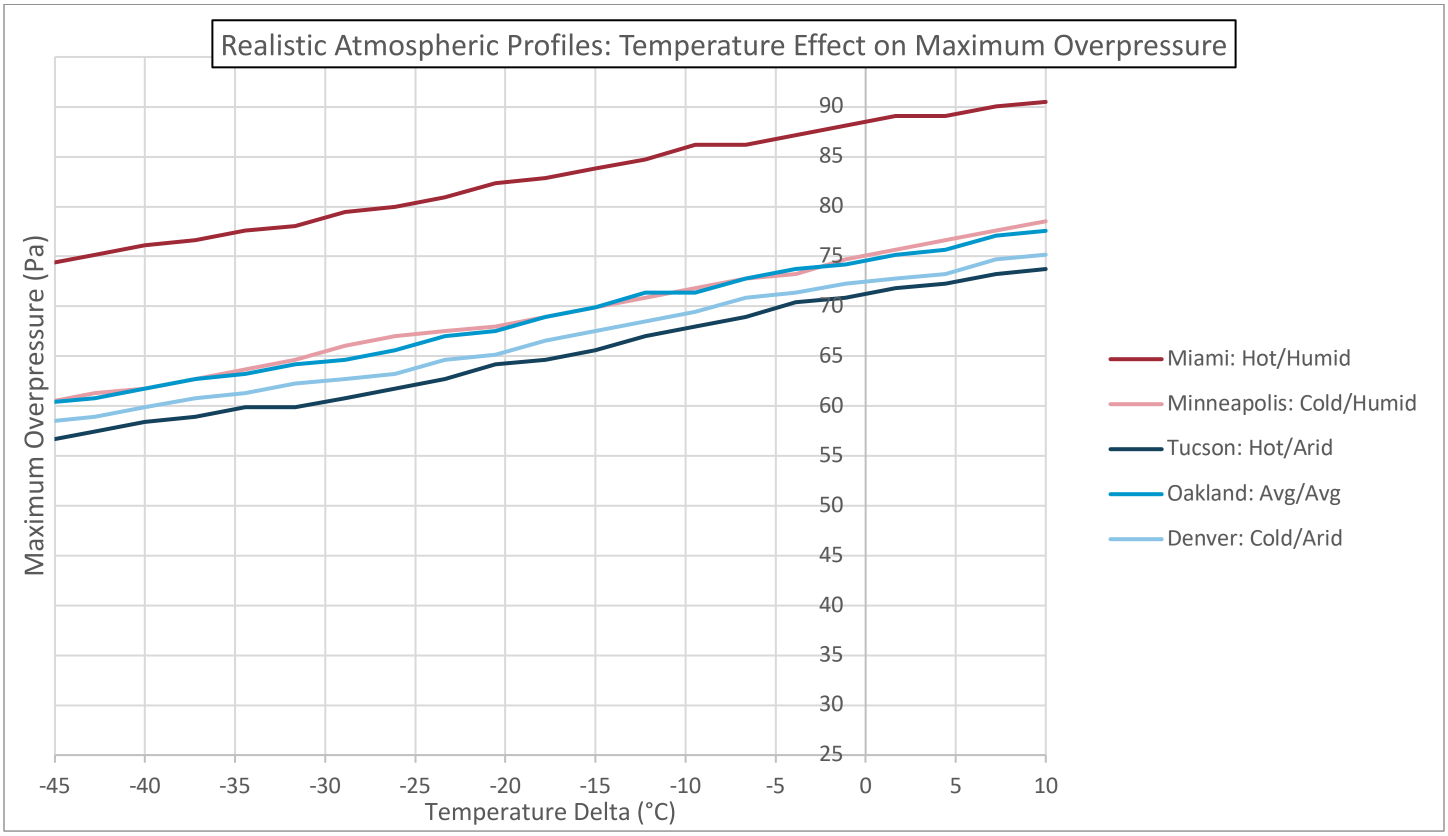

Figure 30: Max Overpressure Sensitivity to Temperature - Realistic Profiles

Mach Cut-Off Results: Standard Profiles

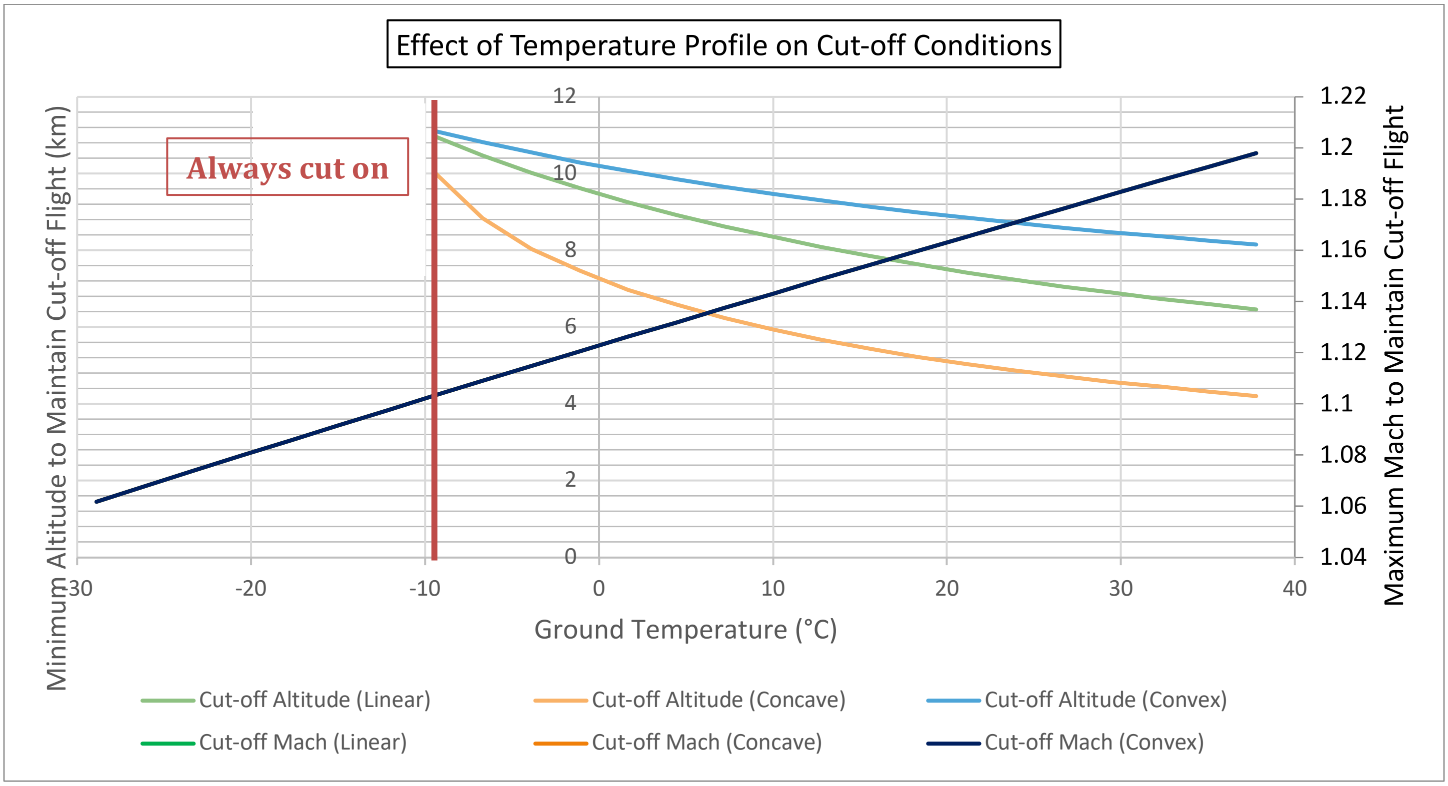

Figure 31: Mach Cut-off Conditions for Variations in Standard Profiles

Mach Cut-off Results: Realistic Profiles

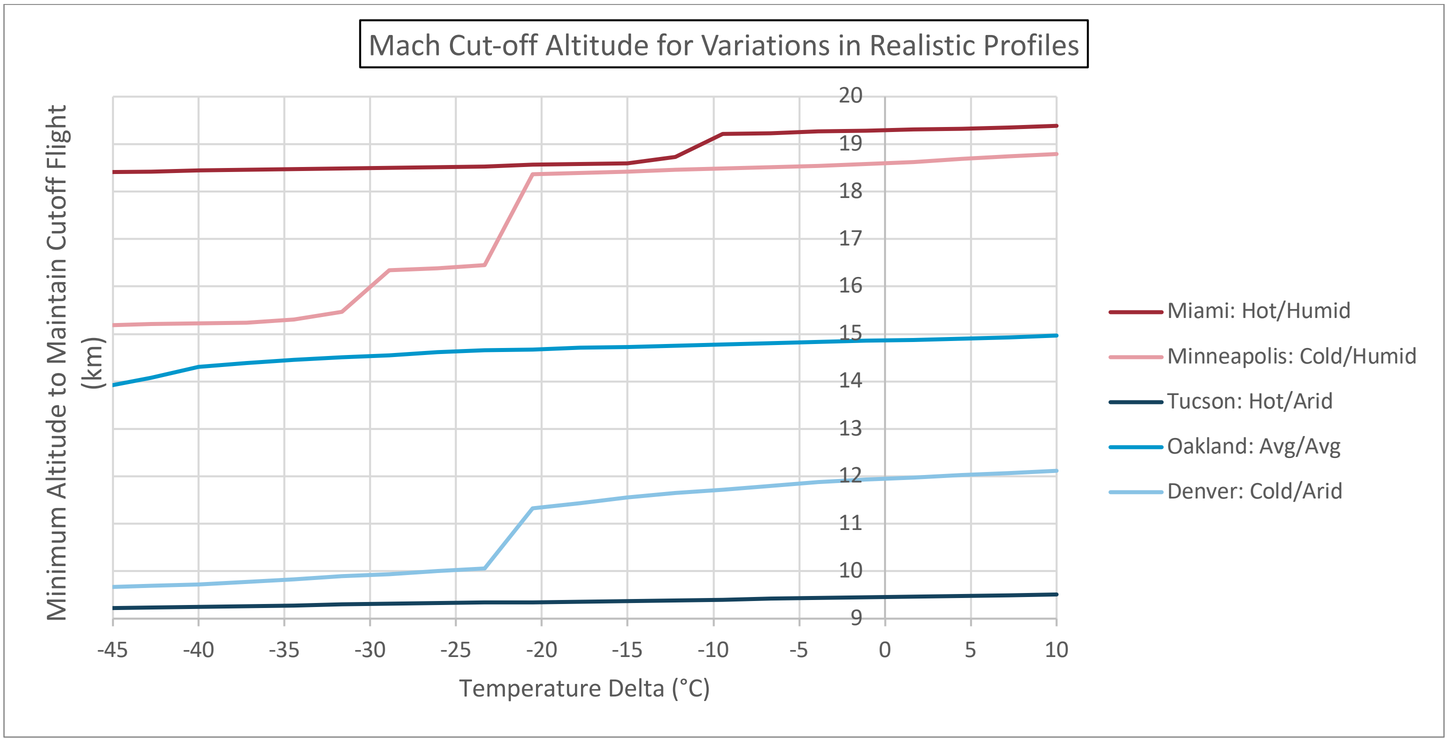

Figure 32: Mach Cut-off Altitude for Variations in Realistic Profiles

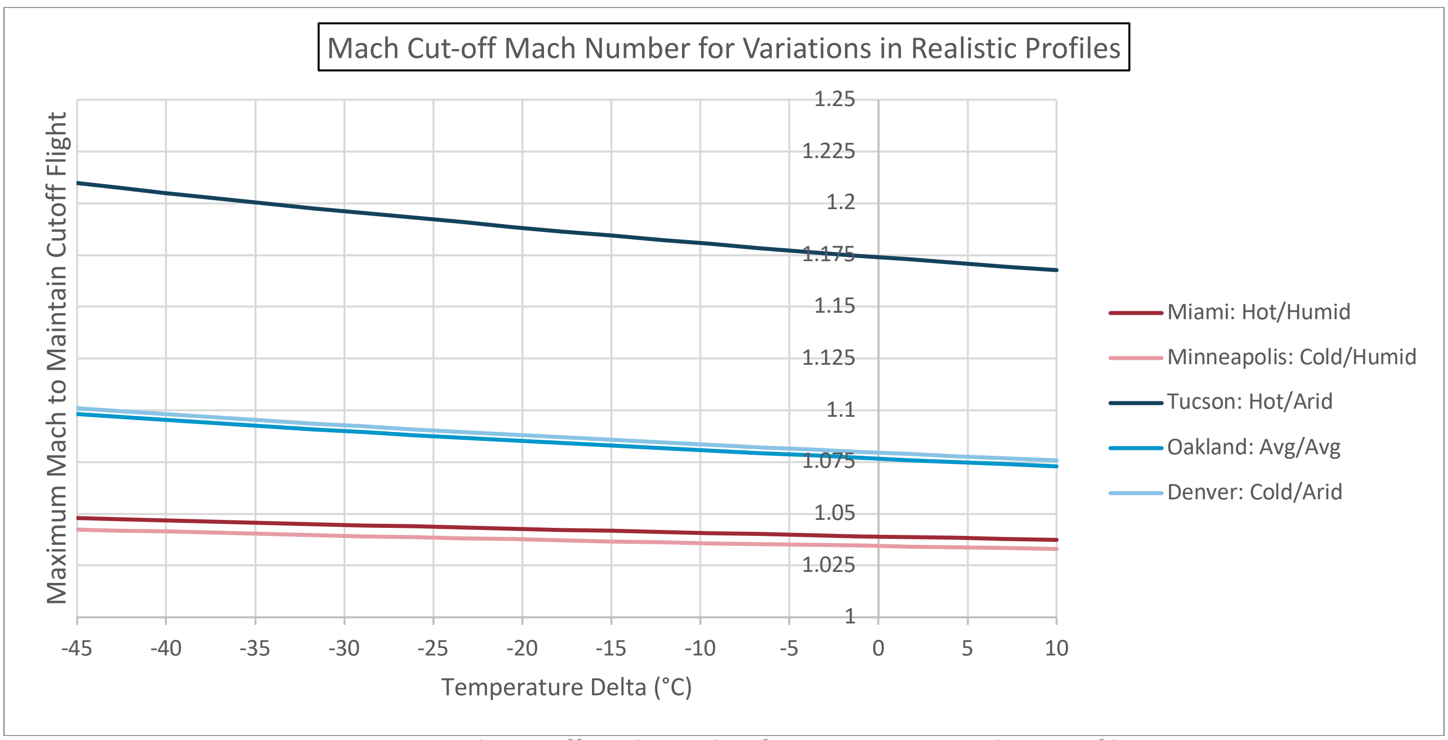

Figure 33: Mach Cut-off Mach Number for Variations in Realistic Profiles

Major Accomplishments

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

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 Georgia Tech and recently passes 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 will also investigate more long-term technologies that could be integrated into future aircraft designs and could potentially be applicable to larger supersonic aircraft.

Research Approach

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

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

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

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 Cutoff 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 Cutoff 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 conditions.

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.

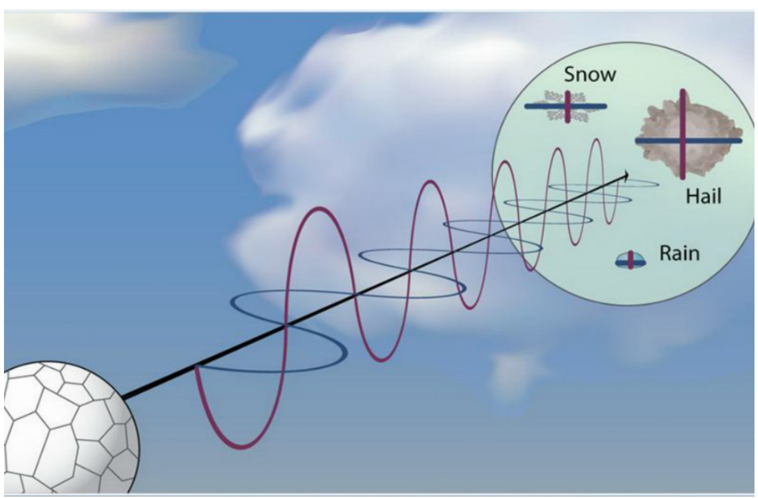

Figure 34. Dual Polarization Doppler Weather Radar

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 35. 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.

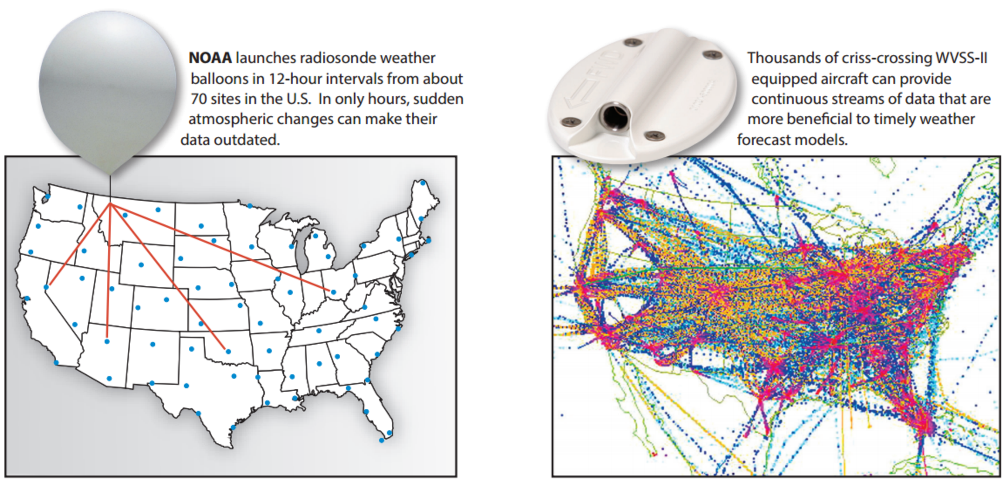

Figure 36. WWVS-II

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.

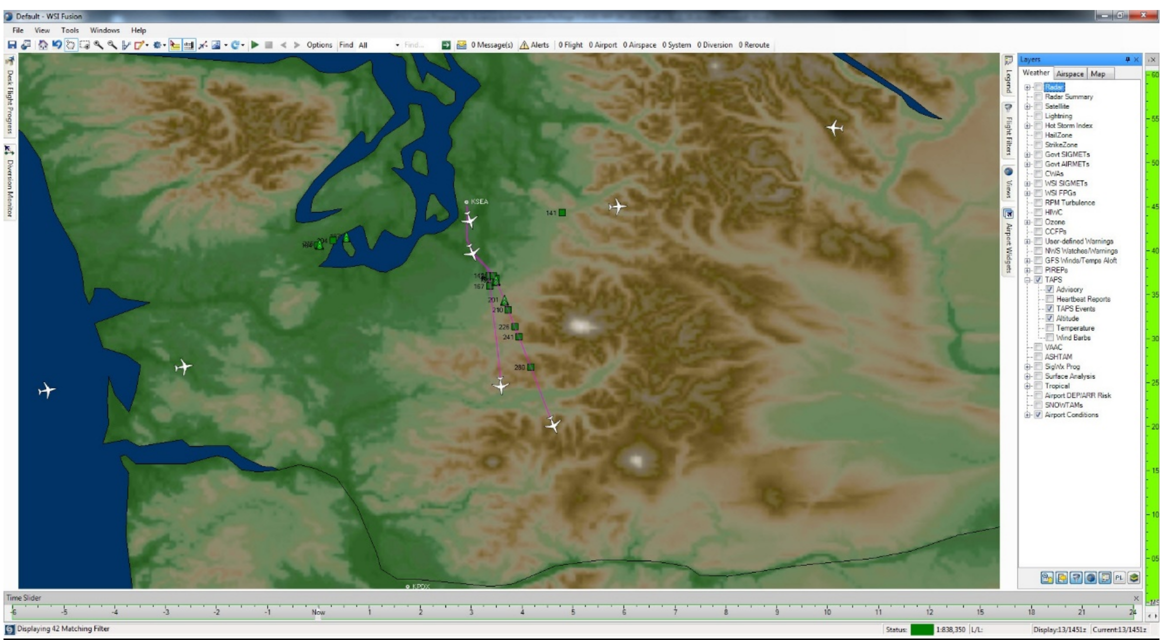

Figure 37. Total Turbulence

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 isn't 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.

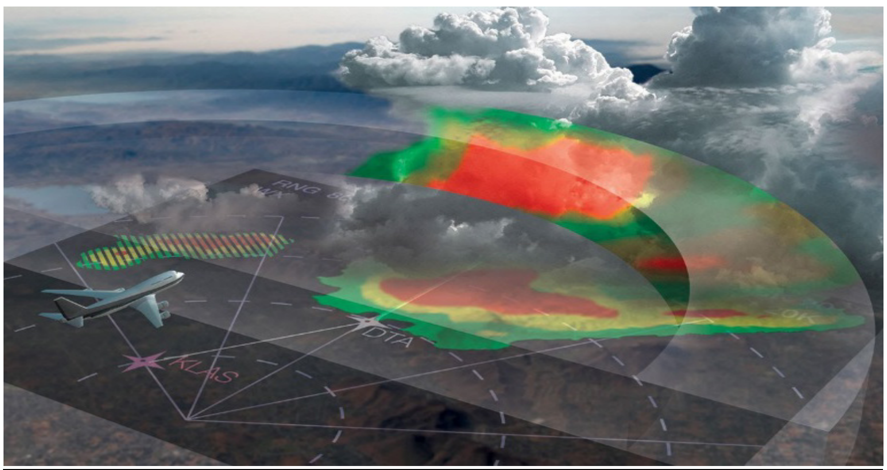

Figure 38. Honeywell Intuvue

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.

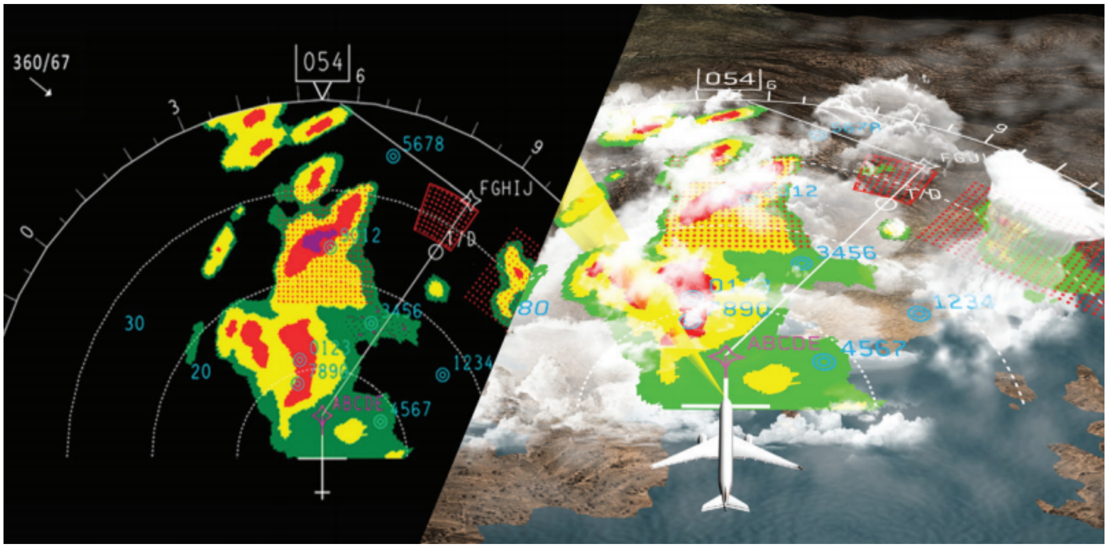

Figure 39. Rockwell Collins MultiScan ThreatTrack

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.

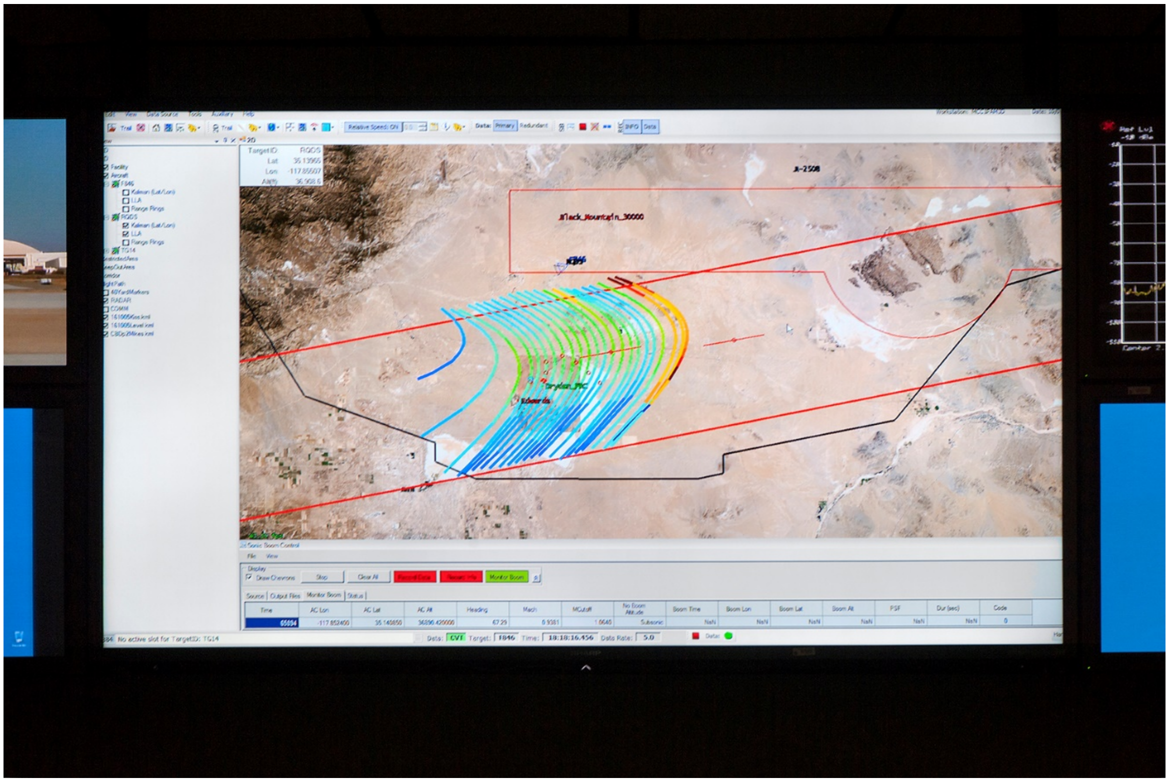

Figure 40. NASA CISBoomDA

Major Accomplishments

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

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 Georgia Tech and recently passes 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.