Acoustical Model of Mach Cut-Off Flight

Project 42

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Atlanta, GA

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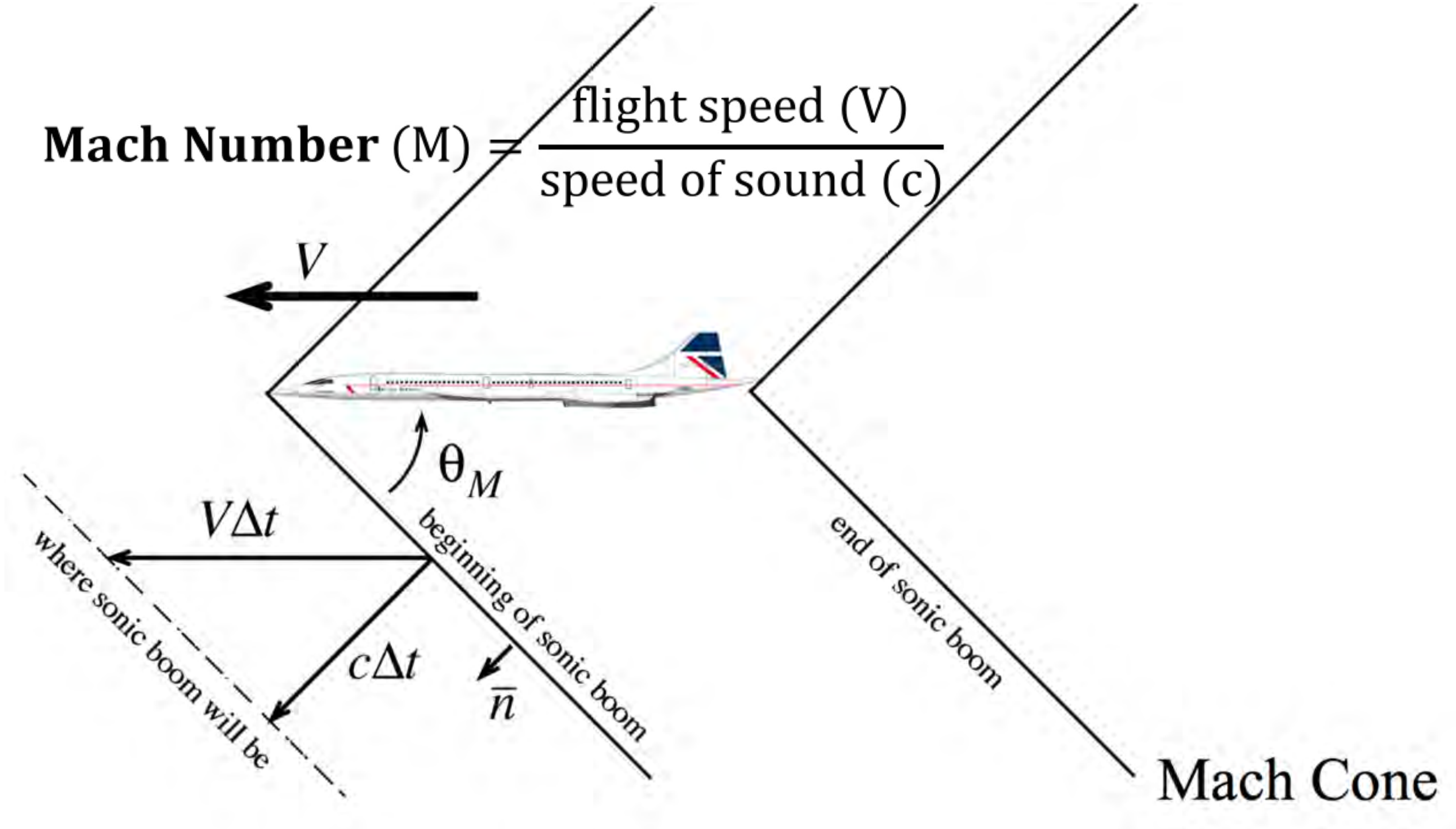
Motivations

- Some aircraft manufacturers would like to build supersonic aircraft and fly them over land without low-boom shaping:
  - Fly over land, slightly supersonic, where the conventional N-wave sonic boom never reaches the ground.
  - Call this **Mach cut-off flight**.
- Research needs to be conducted to provide a technical basis for the FAA and their international partners regarding Mach cut-off operations
  - Assess human response to the Mach cut-off noise with high quality recordings
  - Estimate the altitude and Mach number restrictions for focus boom avoidance including real-world atmospheric effects
  - Provide guidance to industry on how to enable Mach cut-off

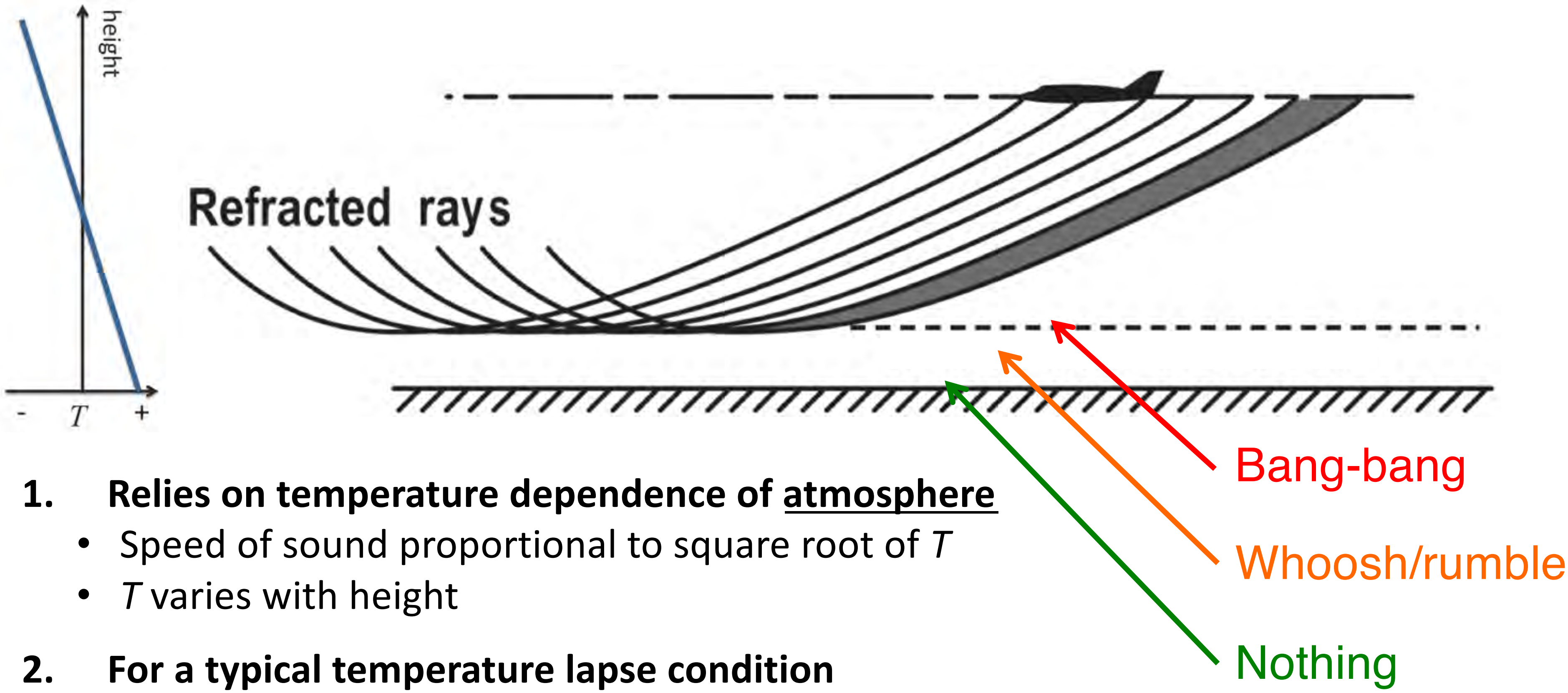
A larger Mach number increases chance for sound rays to reach the ground

$$\textbf{Mach Number } (M) = \frac{\text{flight speed (V)}}{\text{speed of sound (c)}}$$



$$\textbf{Mach Angle } (\theta_M) = \sin^{-1}\left(\frac{1}{M}\right)$$

Mach cut-off occurs when the aircraft flies supersonically without producing a sonic boom on the ground



1. **Relies on temperature dependence of <u>atmosphere</u>**
   - Speed of sound proportional to square root of *T*
   - *T* varies with height
2. **For a typical temperature lapse condition**
   - Aircraft is supersonic at flight altitude, but not at ground
   - Rays refract upwards, so no boom on the ground
3. **What you hear depends on how close you are**

[4] HAGLUND, G., & KANE, E. (1973). Flight test measurements and analysis of sonic boom phenomena near the shock wave extremity. NASA Report CR-2167.

Project 42 research in 2018-19

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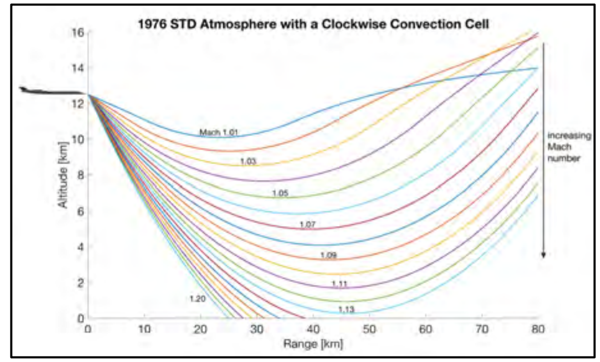
- Prediction of how often Mach cut-off sounds would be heard
  - Advanced ray tracing
  - High-resolution weather data across U.S.



- Perceptual analysis of the new Mach cut-off sounds
  1. Descriptor study
  2. Factors of annoyance study
  3. Degree of annoyance study

Advanced ray tracing of boom energy

- Want to predict the statistical occurrence of focus booms on the ground due to atmosphere
- A 3-D ray-tracing algorithm was developed to predict the Mach cut-off operation
  - Includes effects of vertical winds
- Atmospheric data from the Climate Forecast System Version 2 (CFSv2) was used previously [Saha, 2014]
  - But not enough resolution
- Want to use High-Resolution Rapid Refresh (HRRR) numerical weather model for atmosphere [Benjamin, 2016]
- Plan to run many ray-tracing simulations combining different flight paths, flight altitudes and realistic atmosphere

Using HRRR for the atmosphere

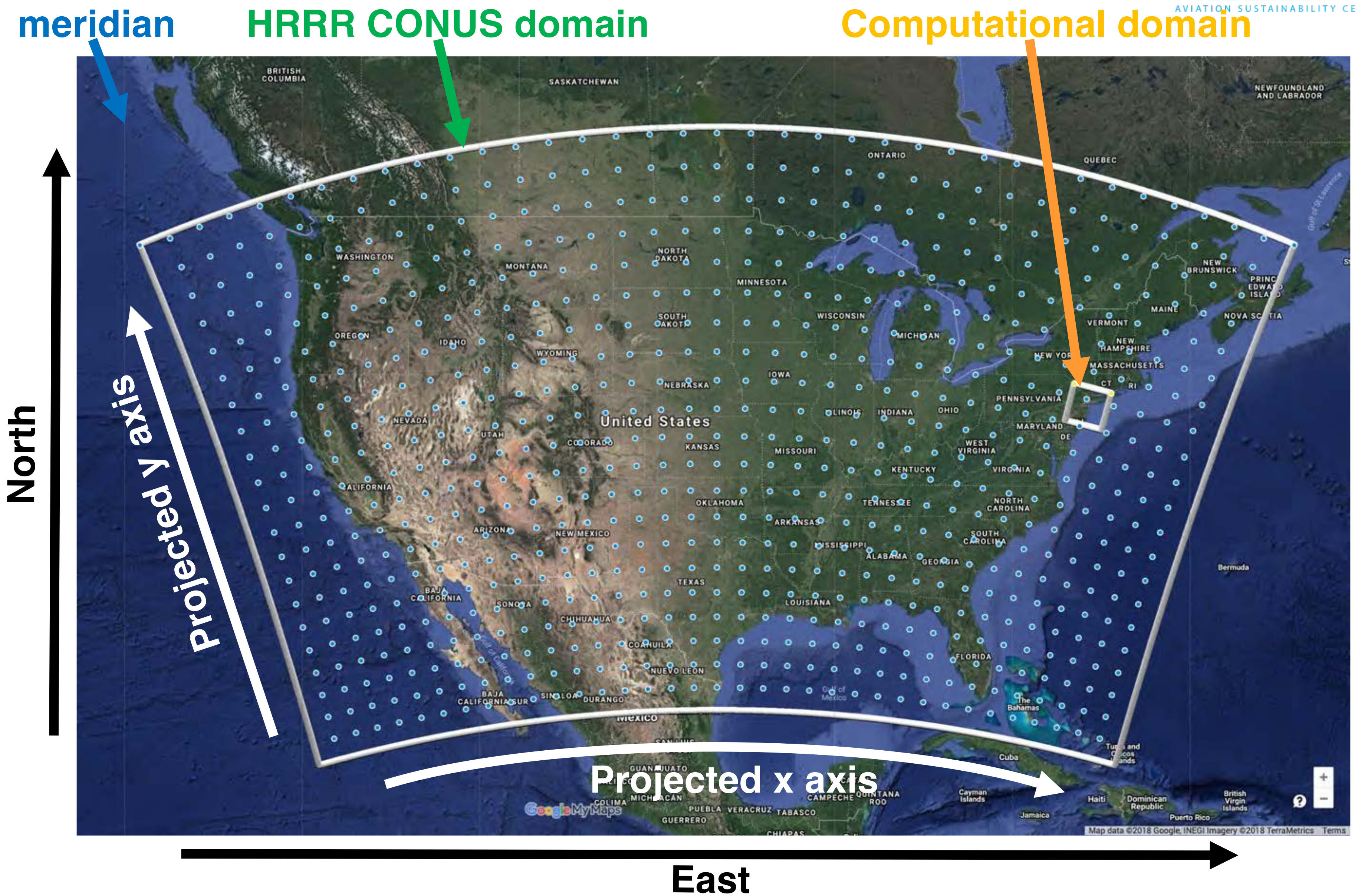
- High-Resolution Rapid Refresh model [Benjamin, 2016]
  - A numerical weather model developed by NOAA ESRL and is run operationally every hour at NCEP's Environmental Modeling Center
  - The operational HRRR generates hourly forecasts gridded at 3 km for 18 to 36 hours over the contiguous United States.
  - The highest spatial and temporal resolution forecast system run by NCEP
  - Contains surface and upper-level pressure fields for analyses and forecasts
  - The Lambert Conformal Conic Projection is used by NOAA for the HRRR data grid.

Why choose HRRR?

- HRRR has much better spatial and temporal resolution.

Model	Domain	Grid Points or # of Stations	Grid Spacing	Vertical Levels	Pressure Top	Initialized
IGRA	Global	Nearly 1000 stations	--	50 ~ 82	--	12 hours
CFSv2	Global	720 x 361	0.5 degree/55 km	37	1 mbar	6 hours
HRRR	CONUS	1799 x 1059	3 km	50	20 mbar	Hourly

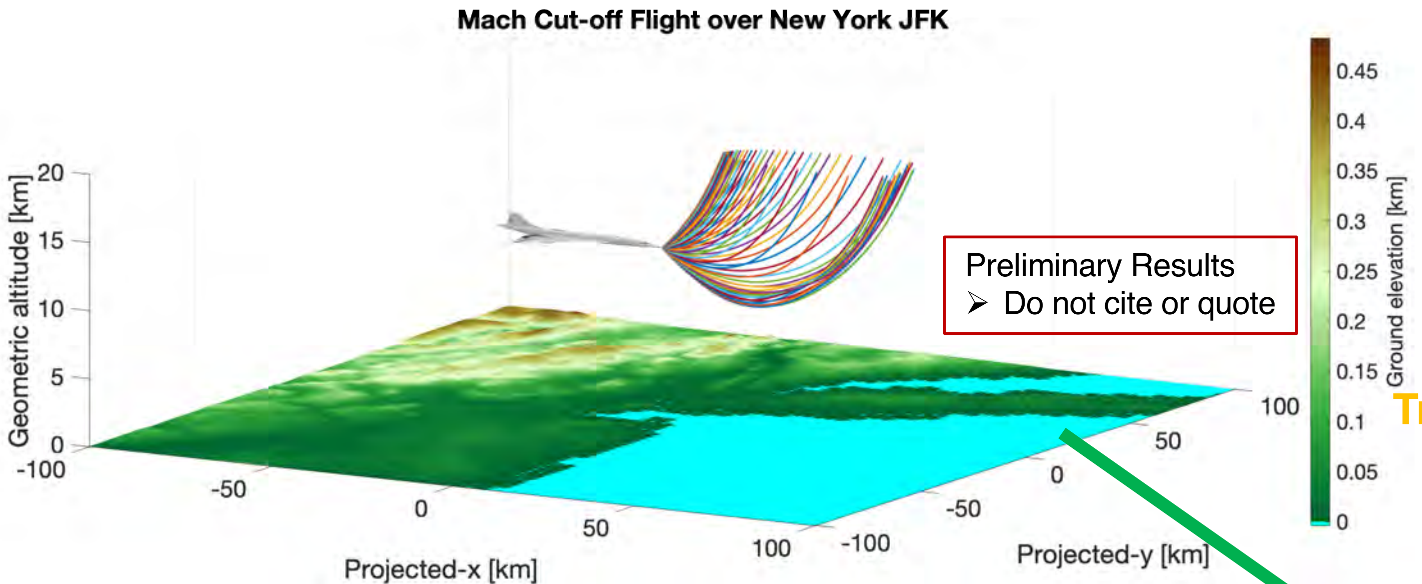
HRRR CONUS domain

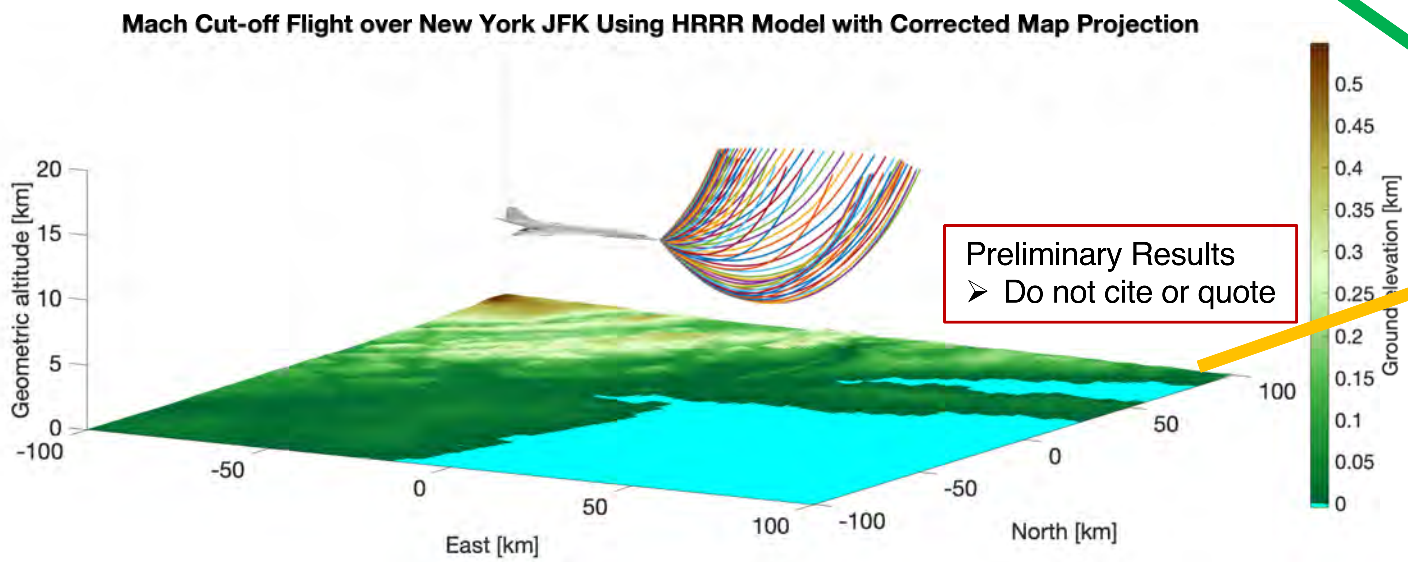


- Only 1 out of every 50 HRRR grid points is plotted along each axis.

Ray-tracing calculations using HRRR

- 12 PM UTC – Jan 1, 2017 – New York – Eastward Flight @ 12.5 km





Projected-y

True North

Not a constant, approximately 14º

Ray tracing results – CFSv2 vs. HRRR

Atmospheric & flight variables	CFSv2	HRRR	HRRR + angle correction
Cut-off Mach number	1.05	1.05	1.06
Temperature @ aircraft	218.14 K	219.38 K	219.38 K
True air speed	695.47 mph	697.44 mph	704.08 mph
Longitudinal wind @ aircraft	119.62 mph	122.44 mph	120.76 mph
Crosswind @ aircraft	-22.26 mph	-9.08 mph	-22.14 mph
Aircraft ground speed	815.39 mph	819.92 mph	825.14 mph
Maximum sound speed (below aircraft)	749.87 mph (@ 0.14 km)	752.49 mph (@ 0.03 km)	754.58 mph (@ 0.04 km)
Maximum effective sound speed (below aircraft)	828.78 mph (@ 7.15 km)	843.20 mph (@ 8.03 km)	845.72 mph (@ 8.50 km)
Altitude of caustic	9.81 km	8.92 km	8.57 km
Ground elevation (below caustic)	0.00 km	0.00 km	0.00 km
Caustic to ground distance	9.81 km	8.92 km	8.57 km

*A negative crosswind means wind comes from the left side of the aircraft.

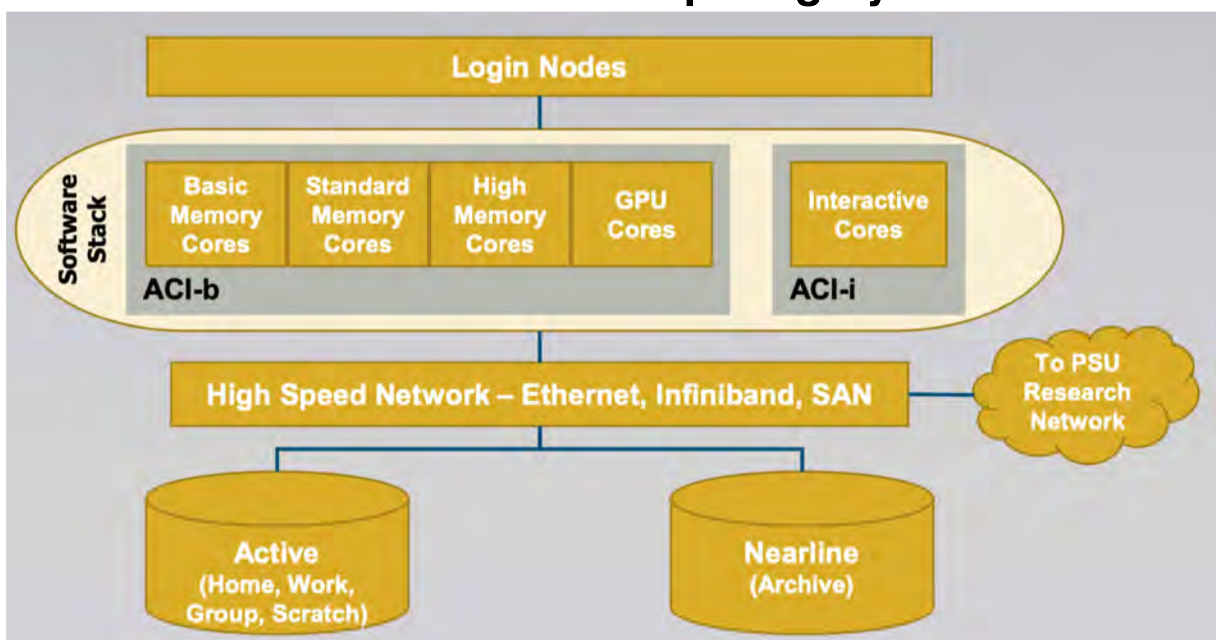
Ray tracing results

- HRRR vs. CFSv2 (for this example)
  - Calculated cut-off Mach numbers and aircraft ground speeds are close
  - 1.24 km difference in caustic to ground distances
- Using HRRR, calculated aircraft ground speed (825.14 mph) is faster than maximum sound speed below the aircraft (754.58 mph), but is slower than the maximum effective sound speed below the aircraft (845.72 mph).
- "The criterion for shock wave cutoff above the ground from a supersonic airplane is that the airplane ground speed must be less than the maximum speed of propagation of the shock wave beneath the airplane." [Haglund and Kane, 1973].
  - This "maximum speed of propagation of the shock wave" may correspond to the maximum **effective** sound speed.

Moving toward parallel computing for Mach cut-off study

- If the ray-tracing simulations run one by one:
  - 6-10 mins is needed for one simulation
  - May need 50 simulations for a single flight
  - So will need many thousands of simulations to get good sampling of typical U.S. atmospheres at different times of day and year
- Exploiting embarrassing parallel capabilities since each atmosphere is independent, at Penn State Institute for Cyberscience:

The ICS-ACI Computing System



Switch gears: Perceptual study

- Overall perceptual study objective: To provide guidance in creation of metric-based regulations of Mach-cutoff flight based on human perception

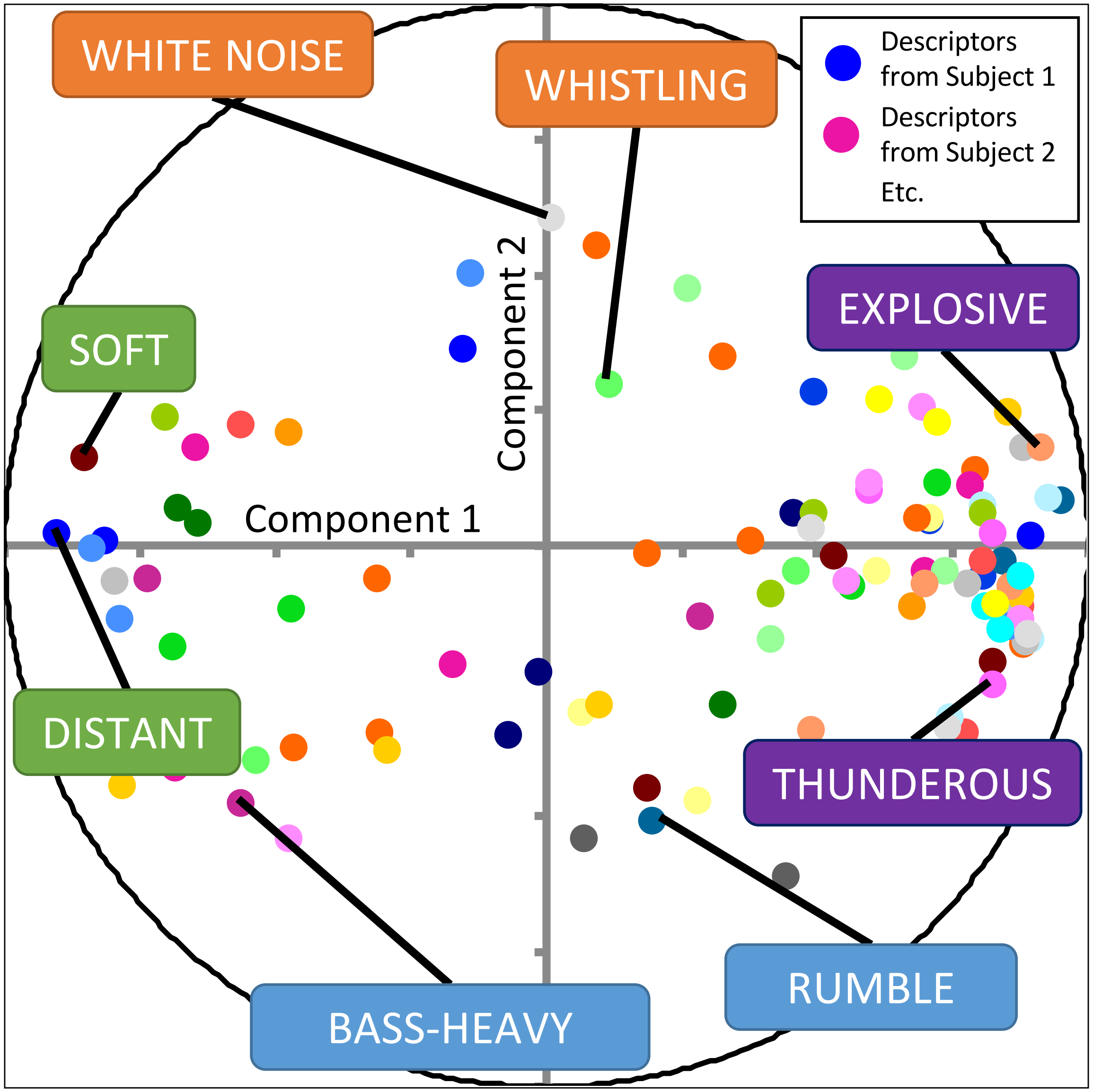
- Individual study objectives:
  1. Mach Cut-off **Descriptor** study
     - Identify terms appropriate for describing ground recordings of Mach-cutoff flight
  2. **Factors** of ***Annoyance*** study
     - Identify perceptual attributes contributing to annoyance and appropriate metrics to predict these characteristics
  3. **Degree** of ***Annoyance*** study
     - Identify metric levels at which annoyance due to Mach cut-off becomes unacceptable

Schedule and Status

Milestone	Completion Date	Status
Report on results of first "Mach Cut-off Descriptor" study	February 1, 2018	Complete
Experimental design for second "Factors of Annoyance" study will be complete	September 1, 2018	Complete
The second study will be completed and a single metric will be proposed	February 1, 2019	Complete
The simulation of indoor Mach cut-off signatures for the third "Degree of Annoyance" study will be completed	May 1, 2019	In progress
The third study will be completed, and results will yield a predicted percentage highly annoyed curve due to indoor Mach cut-off signatures	July 31, 2019	In progress

Study 2: Factors of Annoyance

Approach – First study suggested appropriate terms for Mach cut-off



Approach - Descriptors were selected for the "Factors of Annoyance" study

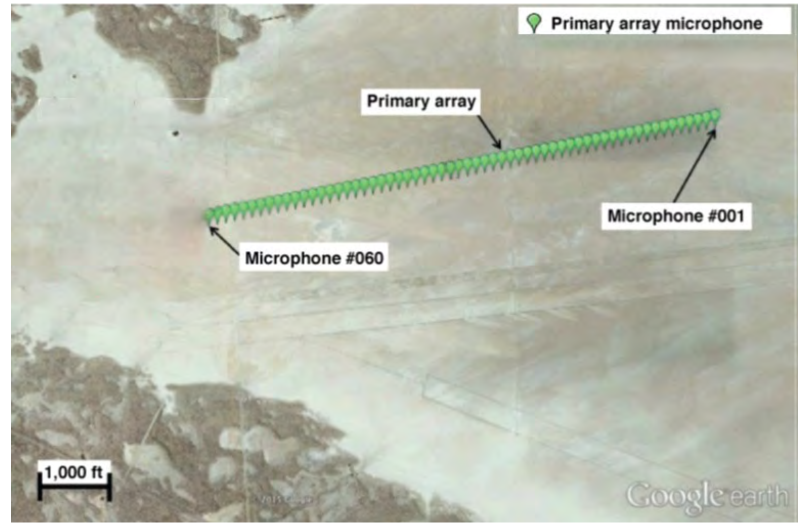
- Factor 1 ~ **Thunderous**
  - Most common descriptor used
  - Definitions associated with crack of thunder

- Factor 2 ~ **Rumbly**
  - Commonly used in HVAC noise control
  - Tied to low-frequency dominance

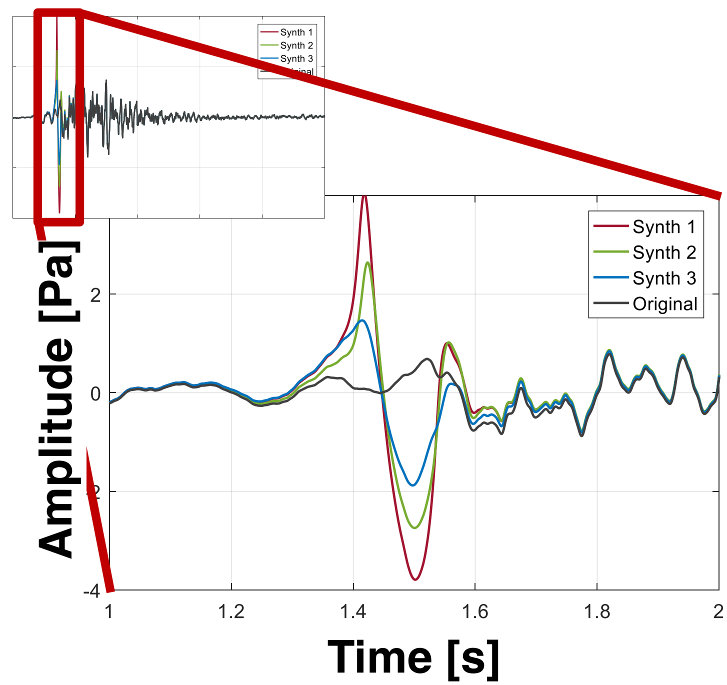
- Factor 3 ~ **Swooshing**
  - Next most significant factor
  - Swoosh used by non-musicians

Approach - Stimuli came from NASA's FaINT study and simulation

- 6 stimuli from "Descriptor" study
  - All six originally from NASA's "Farfield Investigation of No-boom Thresholds"
  - Stimuli represented the range of subjective ratings in the first study

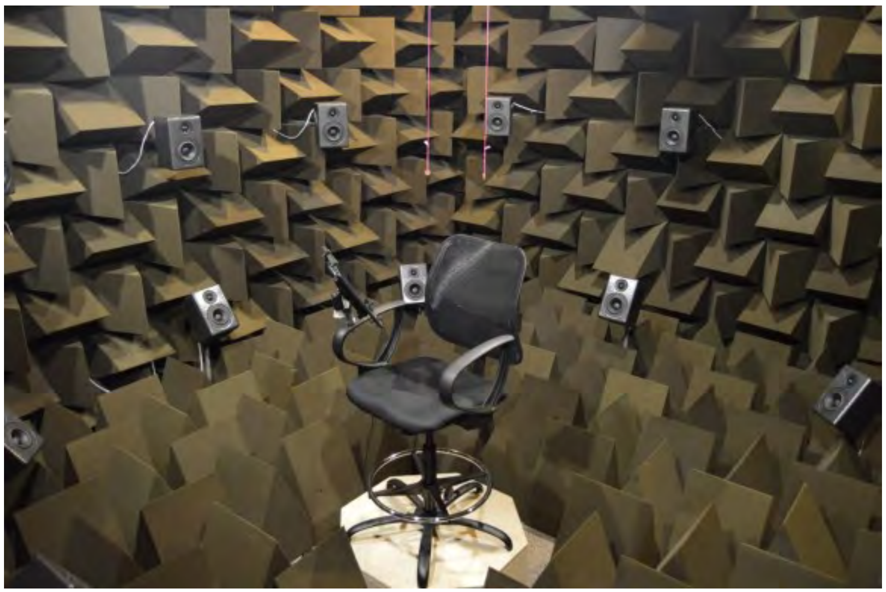


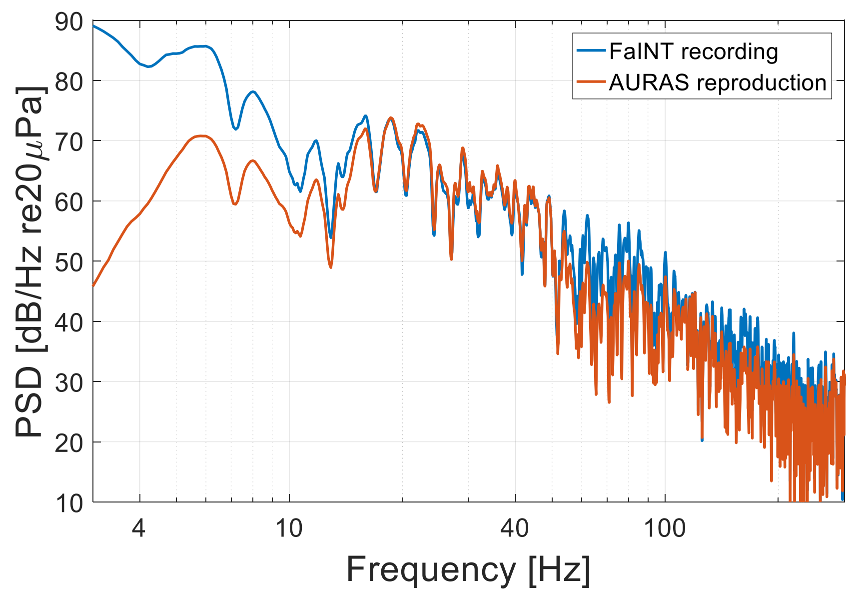
- 3 additional stimuli from simulation
  - Zhendong Huang used a Hilbert transform method to propagate N-wave shocks below the caustic line
  - Simulated shocks were layered on top of a recording of post-boom noise (FaINT) for realism and comparison



Approach - Reproduction was possible through the AURAS facility

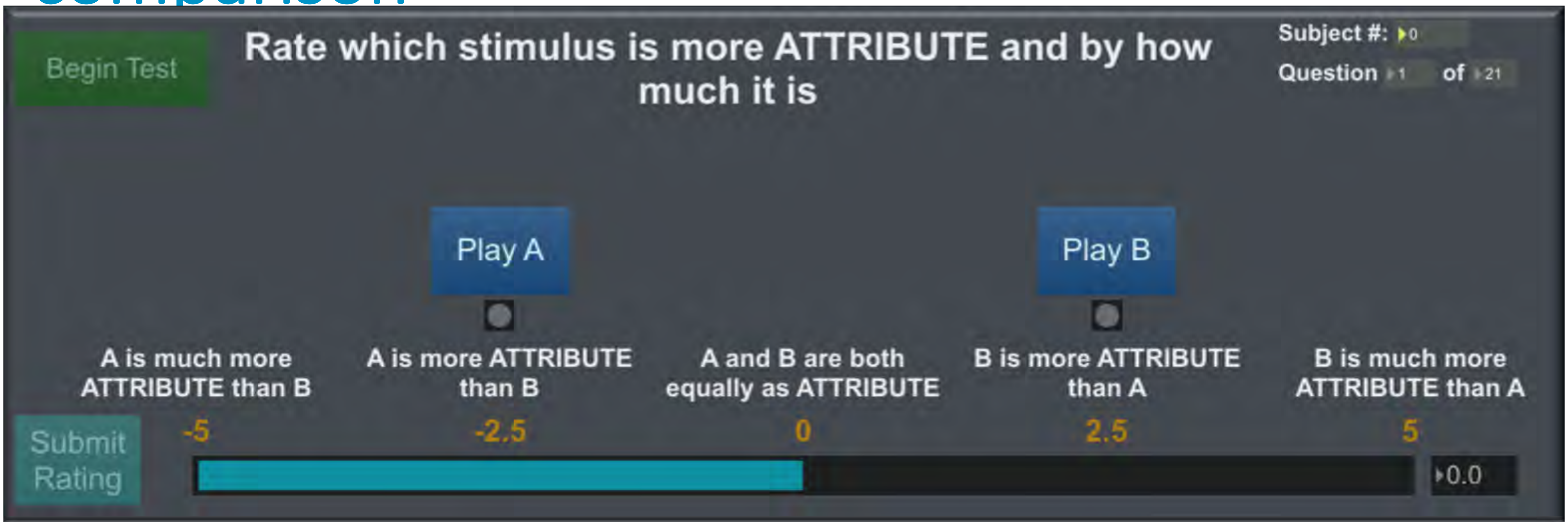
- Penn State's "Auralization and Reproduction of Acoustic Sound-fields" (AURAS) facility includes 30 2-way speakers and 2 subwoofers for accurate reproduction of spatial sound





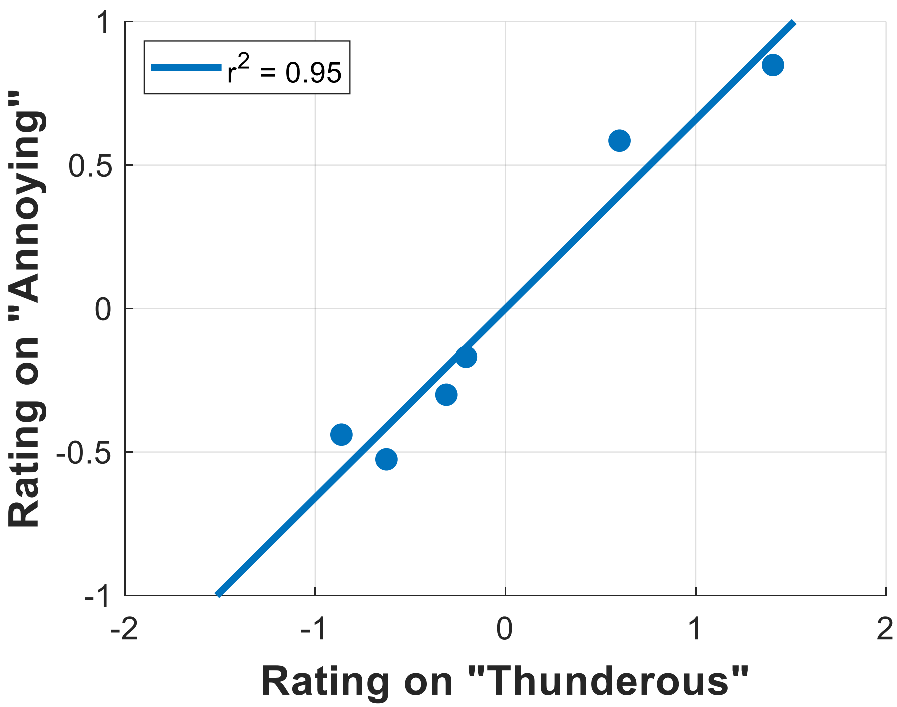
- 42 subjects participated in the study, with ages ranging from 18 – 60 years old and about

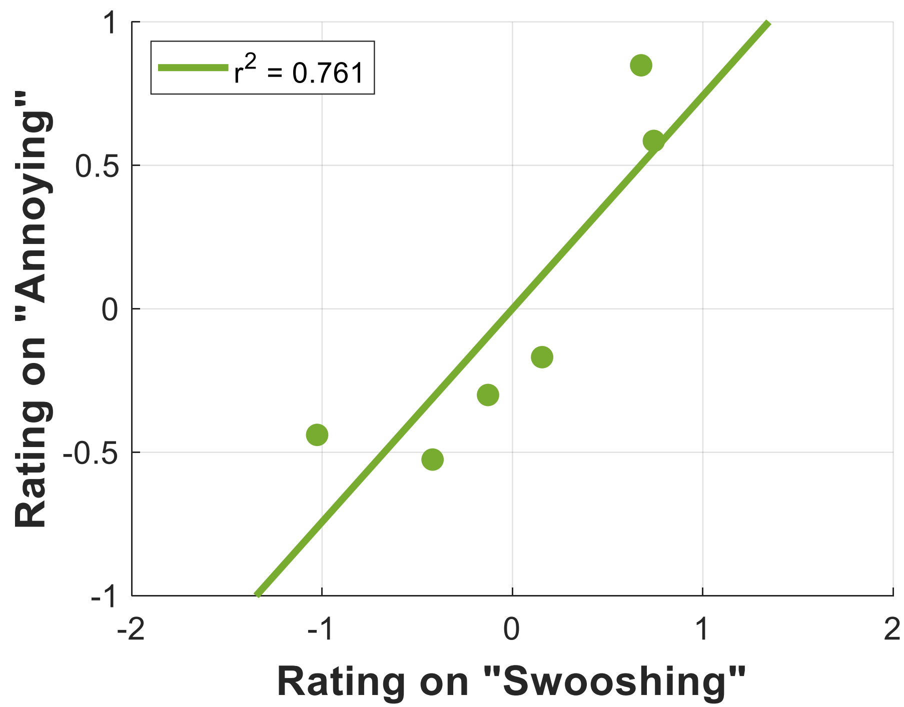
Approach - Subjects rated differences using pairwise comparison



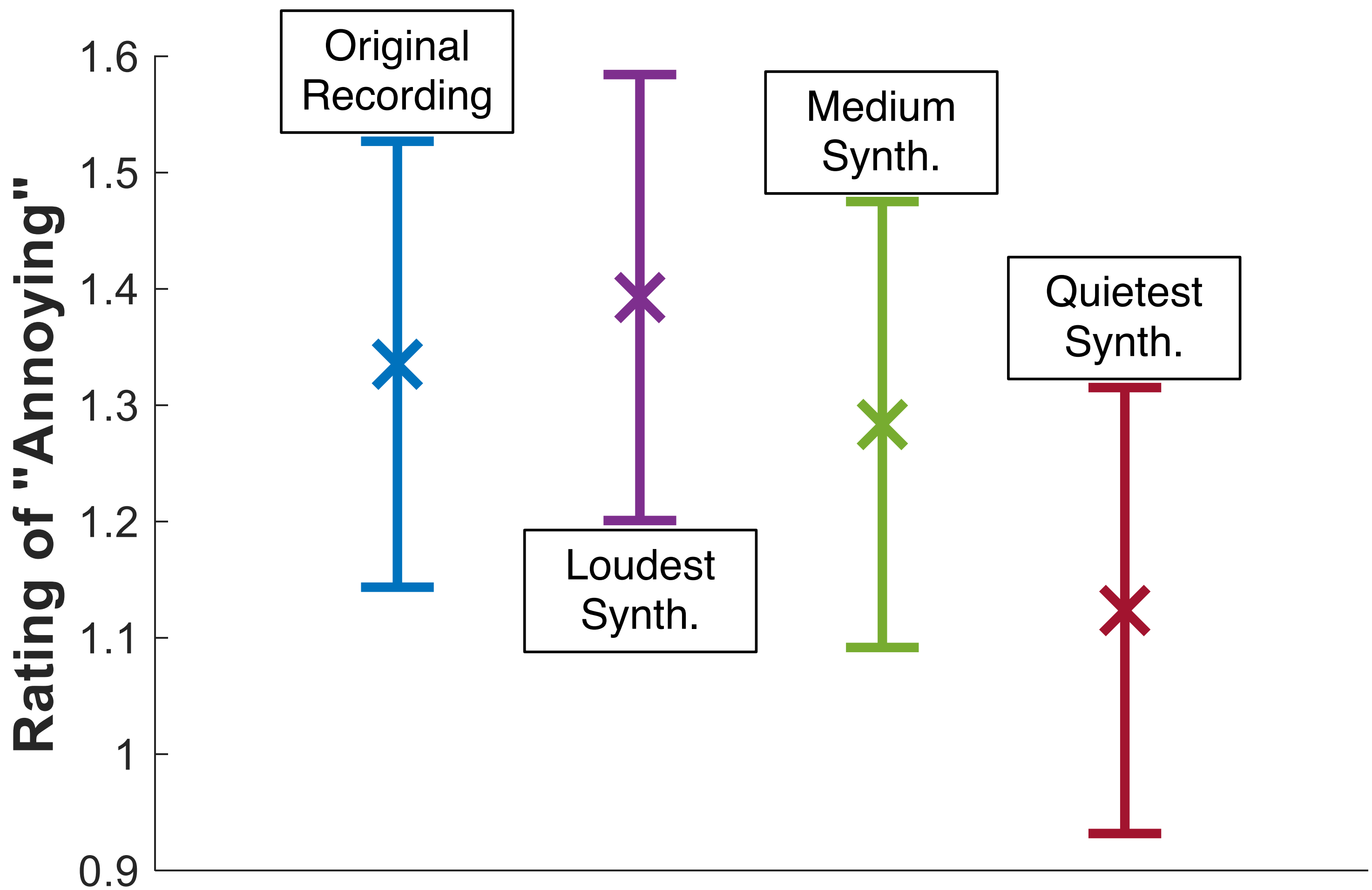
- Pairwise comparison is more robust than absolute rating methods
- Each pair of stimuli compared on each attribute (“Thunderous”, “Rumbly”, “Swooshing”, “Annoying”)
- In addition, simulated decayed shocks rated on “Annoying” scale
- Comparisons combined, giving a single rating for each stimulus

Results - Ratings of "Annoying" increased with other perceptual scales, especially "Thunderous"

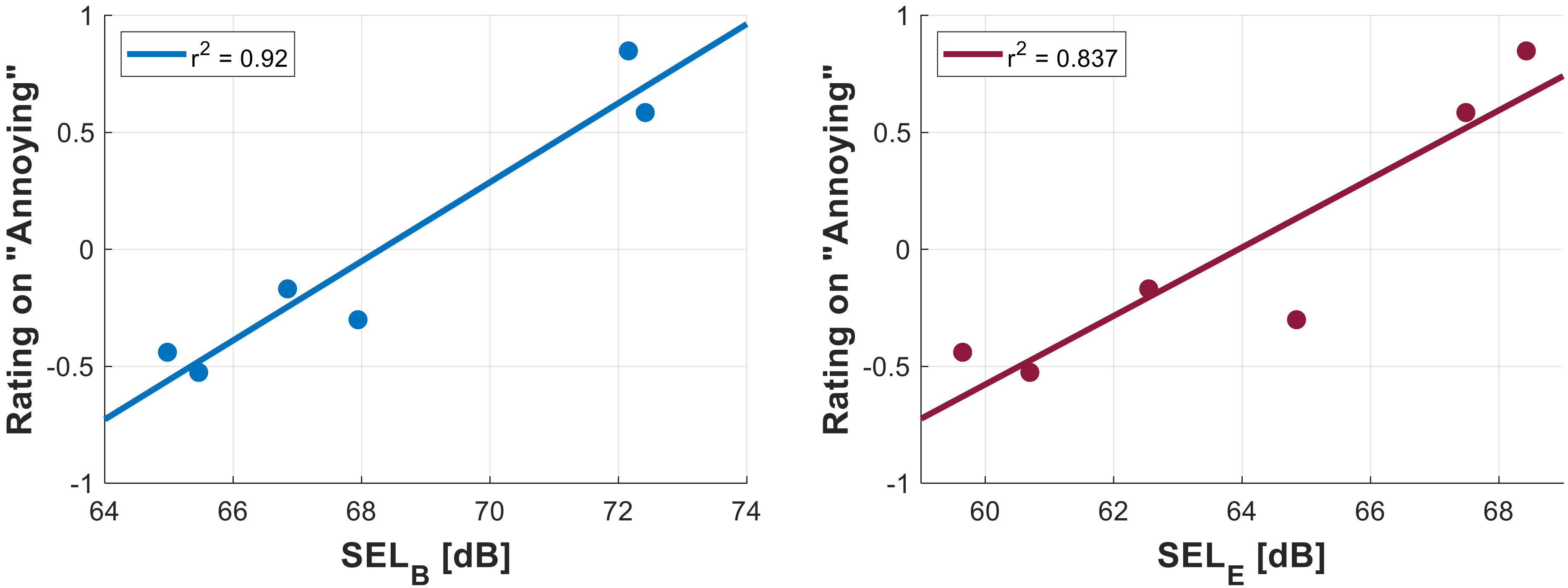




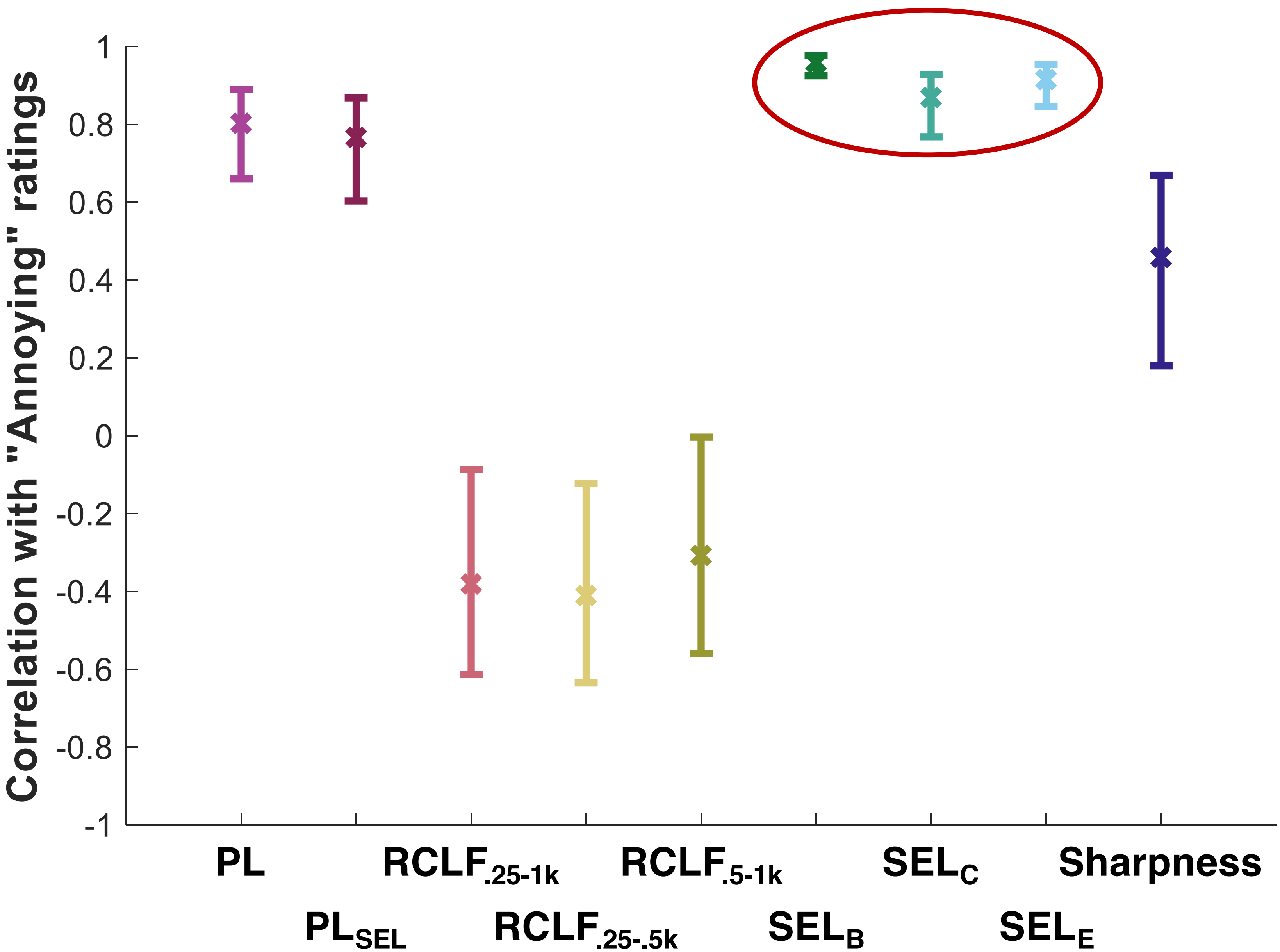
Results - Addition of synthesized boom did not significantly affect "Annoying" ratings



Results - Loudness metrics correlate well with average "Annoying" ratings



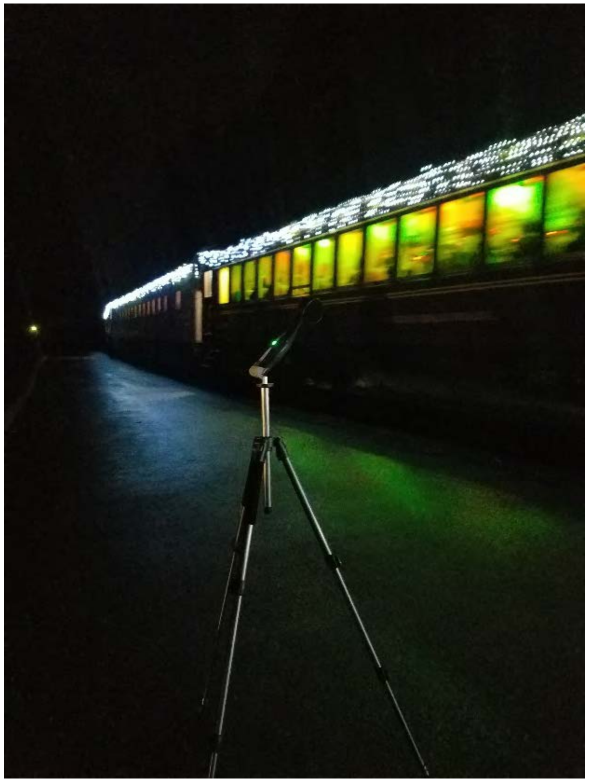
Results - B- and E- Weighted SEL have highest correlation with ratings



Factors of Annoyance Study
Major Accomplishments & Summary

- Factors selected from "Descriptor" study illustrated perception of Mach cut-off as "**Thunderous**", "**Rumbly**", and possibly "**Swooshing**".
- No correlation was found between age / gender demographics and perceptual ratings.
- Perception of "**Thunderous**" and "**Annoying**" were highly correlated.
- Loudness metrics, especially B- and E- weighted sound exposure level, were identified as best candidates for predicting annoyance due to Mach cut-off sounds.

Study 3: Degree of Annoyance



Approach – Relative degree of annoyance of Mach Cut-off vs. other transportation noises

- Study 3 is designed to answer the following questions:
  1. How do annoyance ratings compare for different noise sources?
  2. What is the relative preference of the four noise sources?

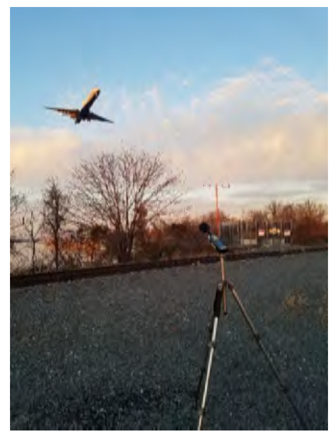
Road

I-80, I-99

Rail

Lewistown, Tyrone, Bellefonte Train Stations

Subsonic Aircraft



PHL and SCE Airports

Mach cut-off

NASA FAiNT Recordings

Approach – Recordings of road, rail and subsonic aircraft noise were obtained Nov ‘18 – Mar ‘19

Stimuli Type	Stimuli Details	Event Volume	Recording Permission	Obtained Recordings
Road	I-80, I-99	High Volume	Yes	Yes, Nov. 2018
Rail	Diesel Engines, Freight Cars	Low Volume	Yes	Yes, Dec. 2018
Subsonic Aircraft	Commercial Aircraft	Moderate Volume	Yes	Yes, Jan. 2019 (Landing), March 2019 (Take-off)

Approach – A set of stimuli with distinct characteristics were identified for use in the study

- Identified 10-s sound samples to use in study
- Are considering 4 different sound samples for each transportation mode (16 total)
  - Road, Rail, Subsonic Aircraft, and Mach Cut-off
- The sound samples differ on:
  - Vehicle transportation density (a vehicle pass vs. several vehicles pass)
  - Noise characteristics (train horn vs train brakes)
- Some of the stimuli will be reproduced as moving sources
  - Stimuli such as a plane pass and a truck pass sound like they are moving
  - Realistic sounding stimuli
- Stimuli will be reproduced for outdoor and indoor conditions

The outdoor transportation sound samples are attenuated to represent real listening scenarios

- Transportation sound samples are attenuated based on researched distances to generate the outdoor stimuli

Road

Houston, I-45

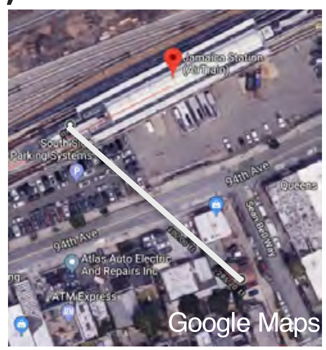
Distance:
185 ft, 57 m

Atlanta, I-85

Distance:
260 ft, 80 m

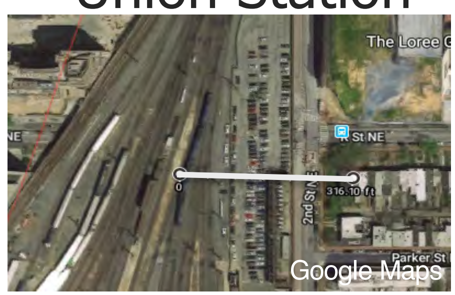
Rail

NYC, Jamaica Station



Distance: 285 ft, 87 m

Washington, D.C.
Union Station



Distance: 315 ft, 96 m

Subsonic

Chicago, ORD Airport

Distance:
3230 ft, 985 m

Atlanta, ATL Airport

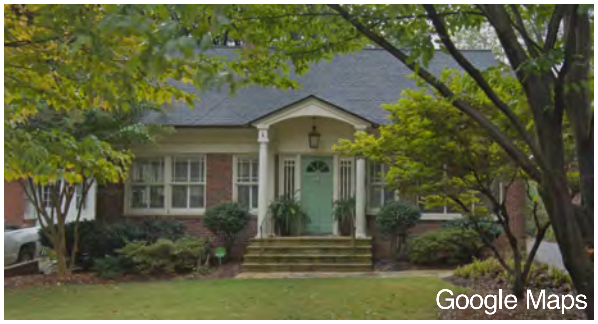
Distance:
1790 ft, 546 m

The indoor transportation sound samples are filtered to represent real listening scenarios

- Two different wall constructions with different transmission loss are used to generate the indoor sound samples

2x6 Wood Exterior Wall

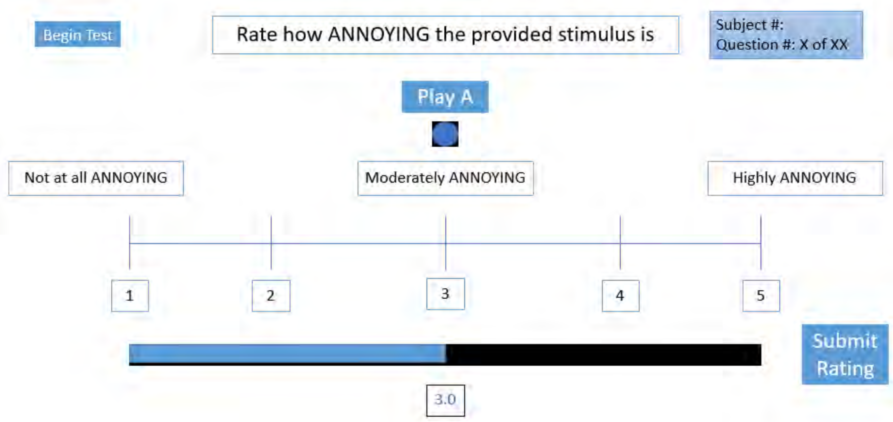
Brick Exterior Wall



- The walls will consist of 35% windows and 4% doors

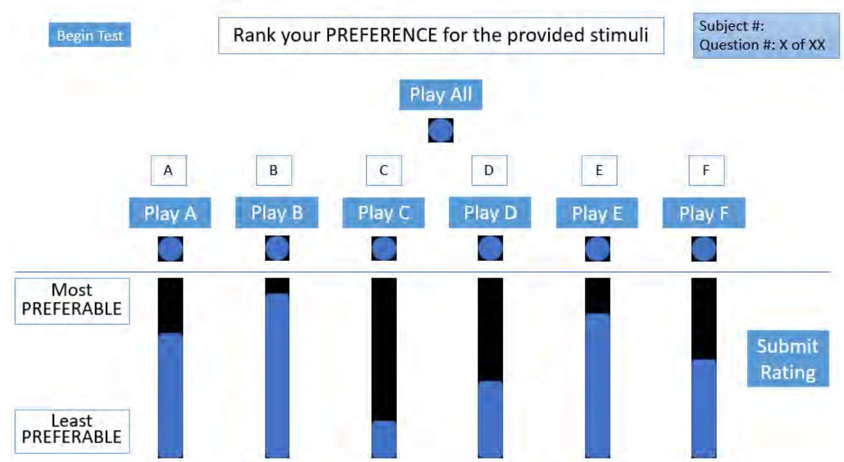
Approach – Two test methods will be used to compare the transportation stimuli

Method 1: Annoyance Ratings



- Each sound sample will be rated individually based on degree of annoyance

Method 2: Relative Preference Ratings



- Multiple sound samples will be ranked simultaneously according to preference

Degree of Annoyance Study
Major Accomplishments & Summary

- All transportation recordings have been obtained for the study
- The experimental design of the study has been finalized
- Two exterior wall filters have been developed to generate the indoor sound samples

Summary

- Project 42 is wrapping up FAA-funded studies on Mach cut-off in summer 2019
- Good progress this year:
  - Almost ready to predict statistical occurrence of how often people would hear Mach cut-off sounds
  - Now have a good handle on appropriate metrics for Mach cut-off
  - Almost ready to state how annoying the sounds would be, compared to other transportation noise sources
- In the future the ray-tracing results could be useful to develop an in-flight prediction system for use by supersonic aircraft under development

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- The Pennsylvania State University
  Victor W. Sparrow, Project Director, and Penn State ASCENT PI
  Michelle C. Vigeant, Project Co-Investigator
  Zhendong Huang, Nicholas Ortega, Jonathan Broyles
- Volpe National Transportation Systems Center
  Juliet Page

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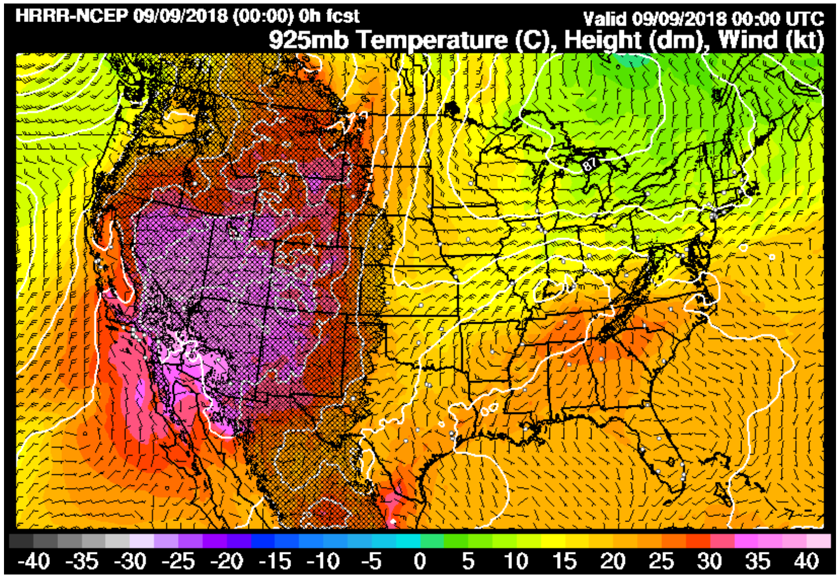
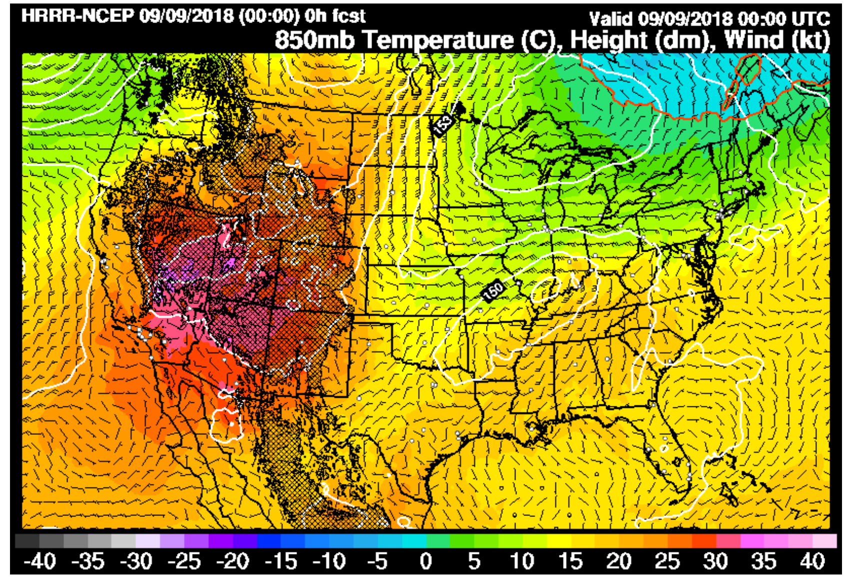
Appendix: Temperature profiles at different altitudes from HRRR

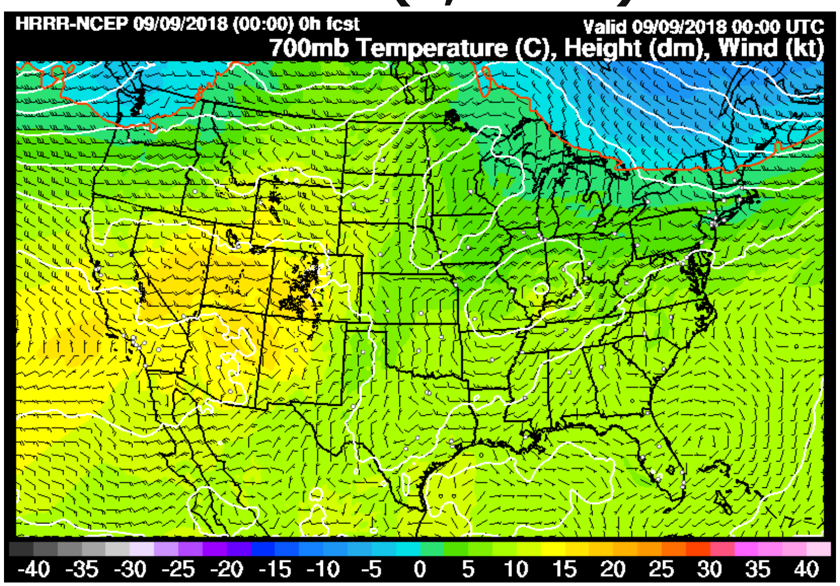
0.7 km (2,500 ft)



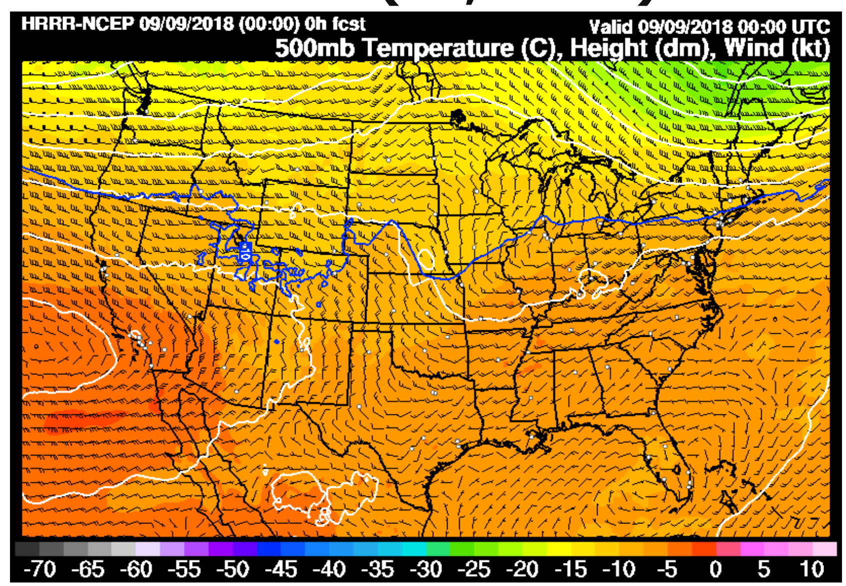
1.5 km (4,800 ft)



3.0 km (9,900 ft)

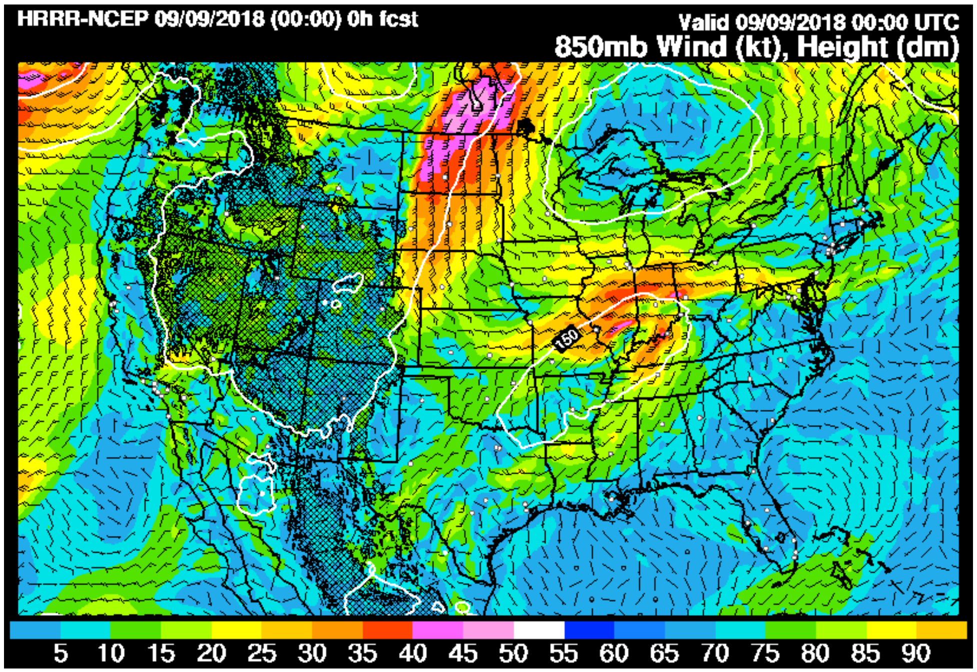


5.5 km (18,000 ft)



Appendix: Wind speed profiles at different altitudes from HRRR

1.5 km (4,800 ft)



10.4 km (34,000 ft)