FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

Acoustical Model of Mach Cut-Off Flight

Project 42

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Motivations

- Industry is interested in developing supersonic aircraft and flying them over land.
- Some want to develop aircraft that produce low-boom signatures, so quiet that the sounds are no longer annoying.
- Others want to develop supersonic aircraft that are not low-boom, yet are efficient enough to build and fly NOW:
  - 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

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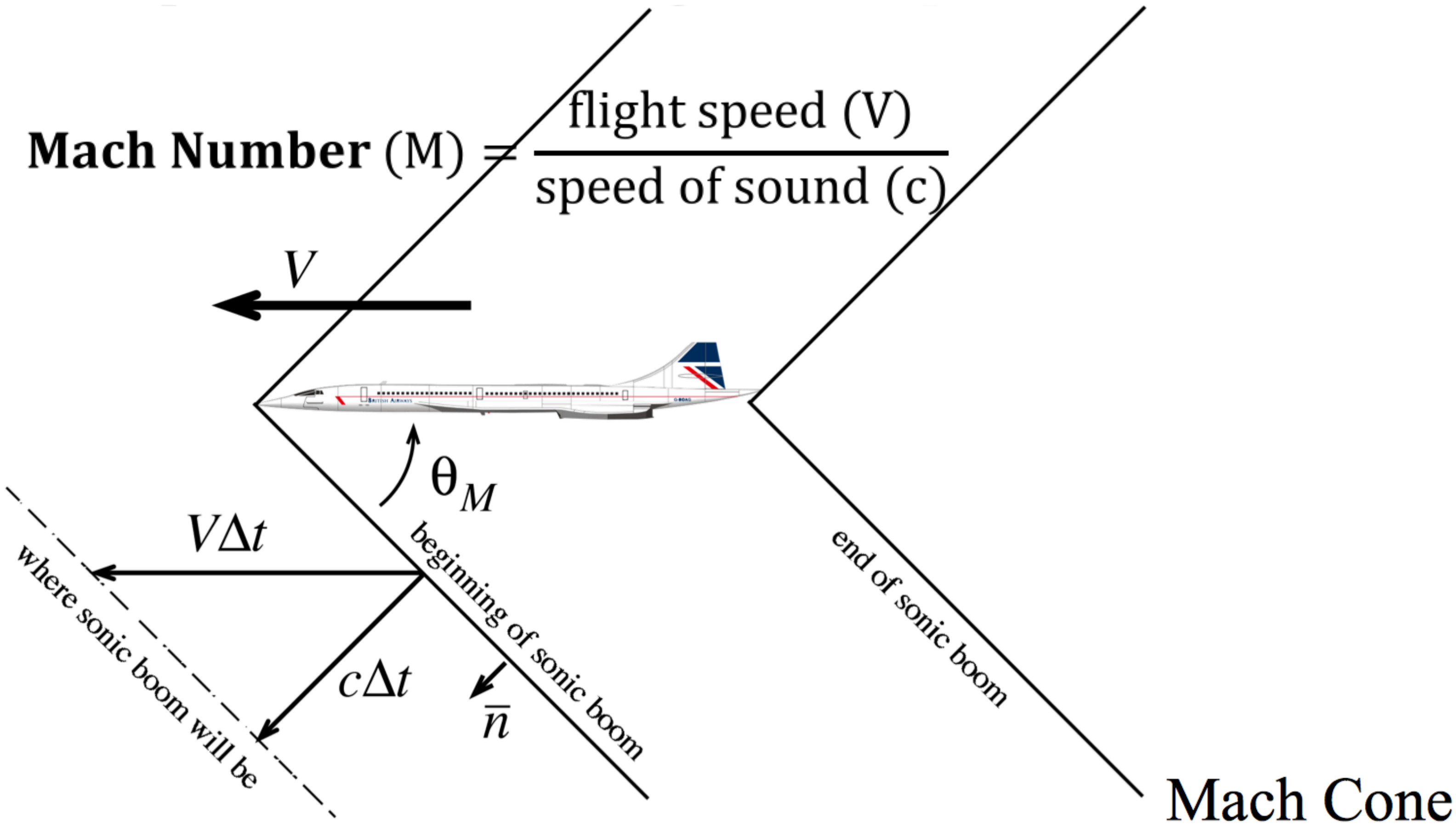
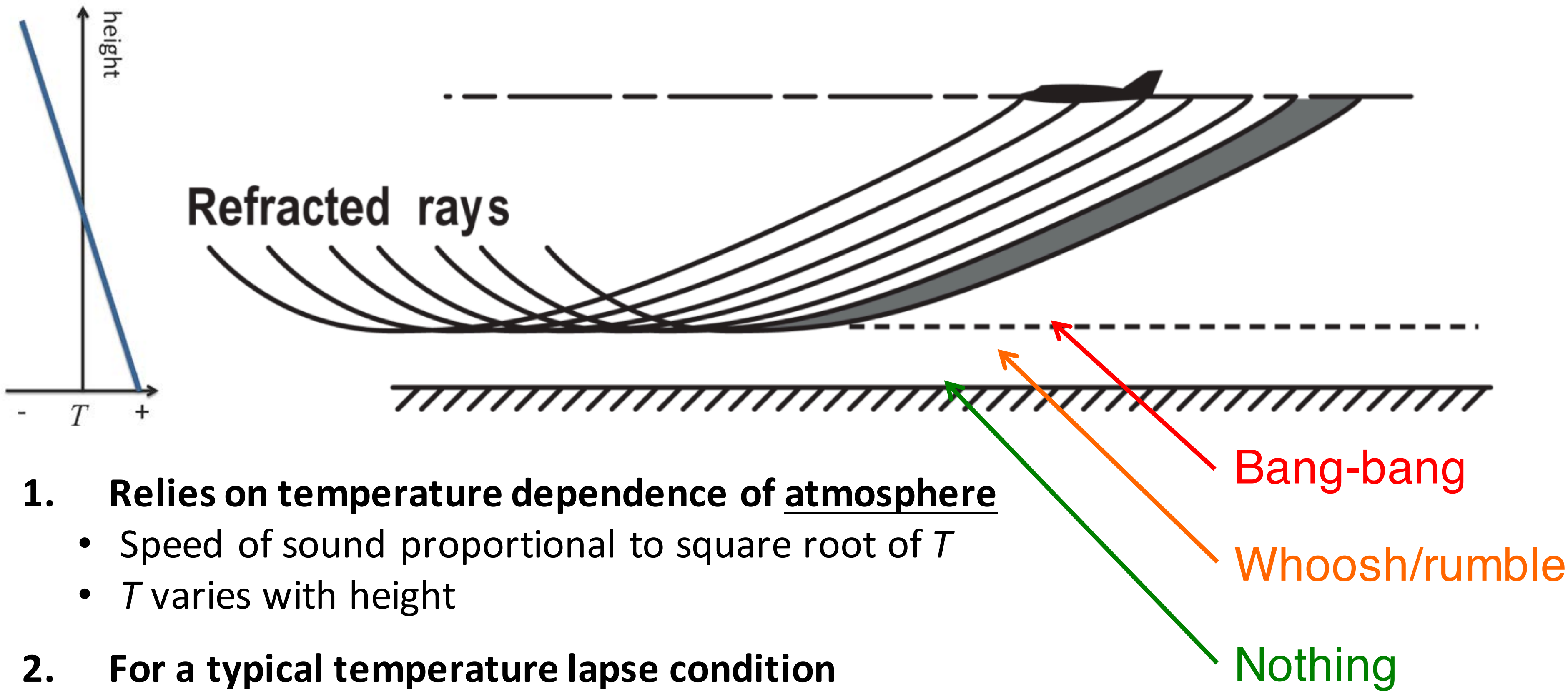
$$\textbf{Mach Number } (\mathrm{M}) = \frac{\text{flight speed (V)}}{\text{speed of sound (c)}}$$



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

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**

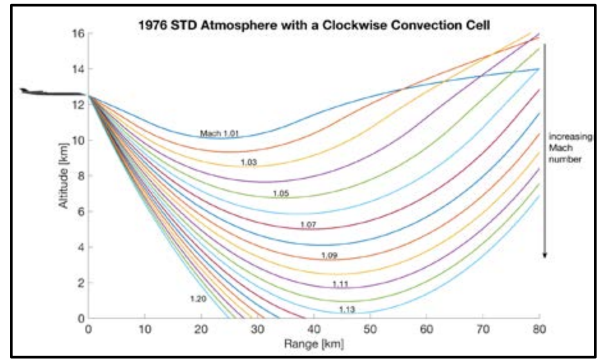
[4] HAGLUND, G., & KANE, E. (1973). Flight test measurements and analysis of sonic boom phenomena near the shock wave extremity. NASA Report CR-2167.

Potential Problems with Mach Cut-off

- **Never** have a perfect temperature gradient.
- The world is 3-D. Is a 2-D model enough?
- Turbulence can send sound energy down to the ground.
  - 1970's claim in Shurcliff (p. 63): "Typically, there *is* turbulence; thus the scheme would fail frequently."
- A focus is formed aloft. This is LOUD sound energy over people's heads.
- Mountains or other high elevations could extend up into the focus region directly.

Project 42 research in 2017-18

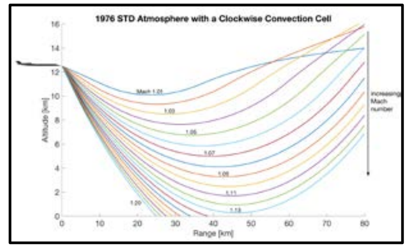
- Predicting the Mach cut-off sounds and what aircraft and atmospheric states produce them
  - Advanced ray tracing (Penn State)



- Determining what people think of Mach cut-off sounds
  - Subjective analysis (Penn State)

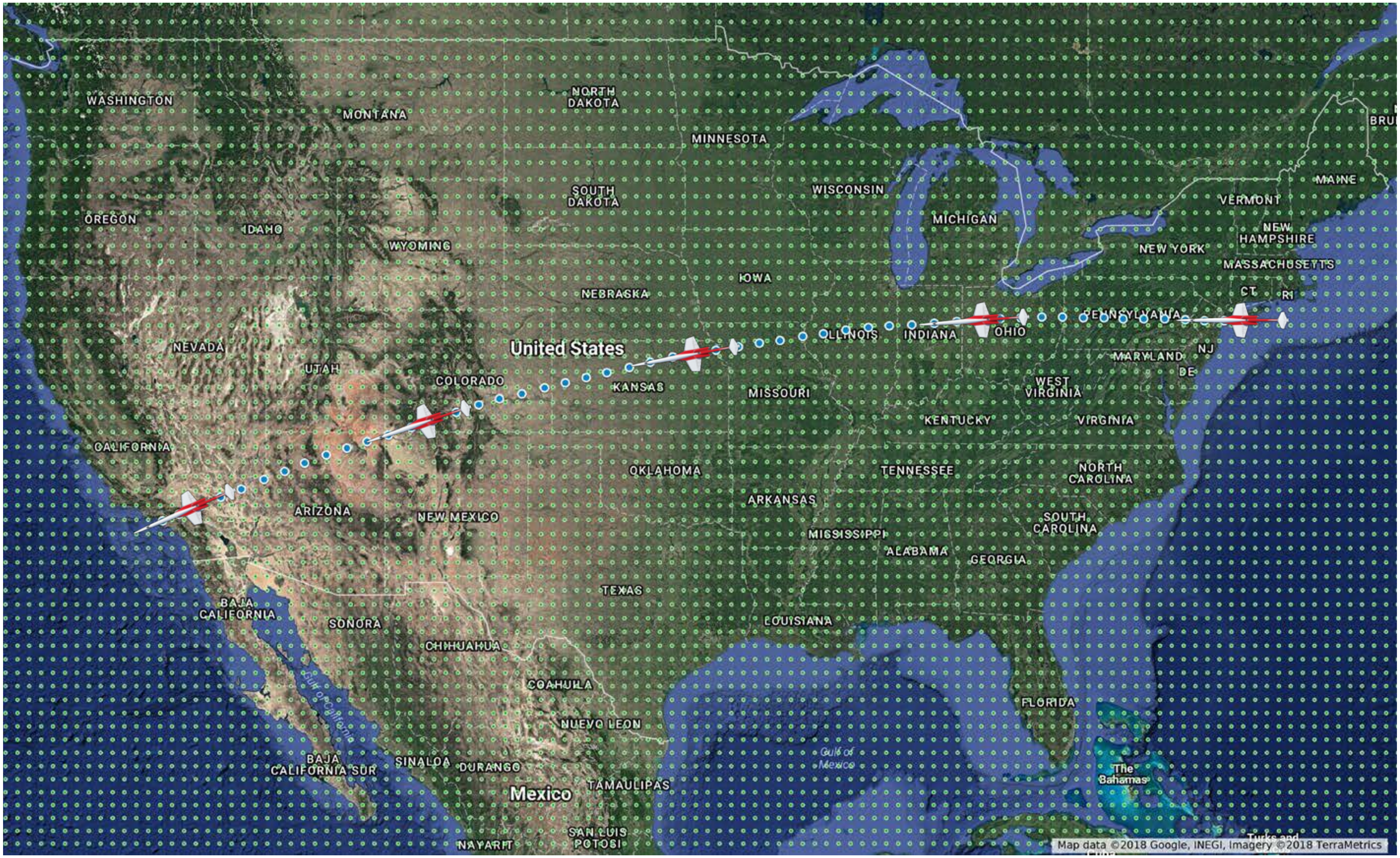
With guidance from
- AERION (industry partner)
- FAA
- NASA Armstrong and NASA Langley
- Other institutions funded in 16-17:
  - Georgia Tech
  - University of Washington
  - Volpe

Advanced ray tracing



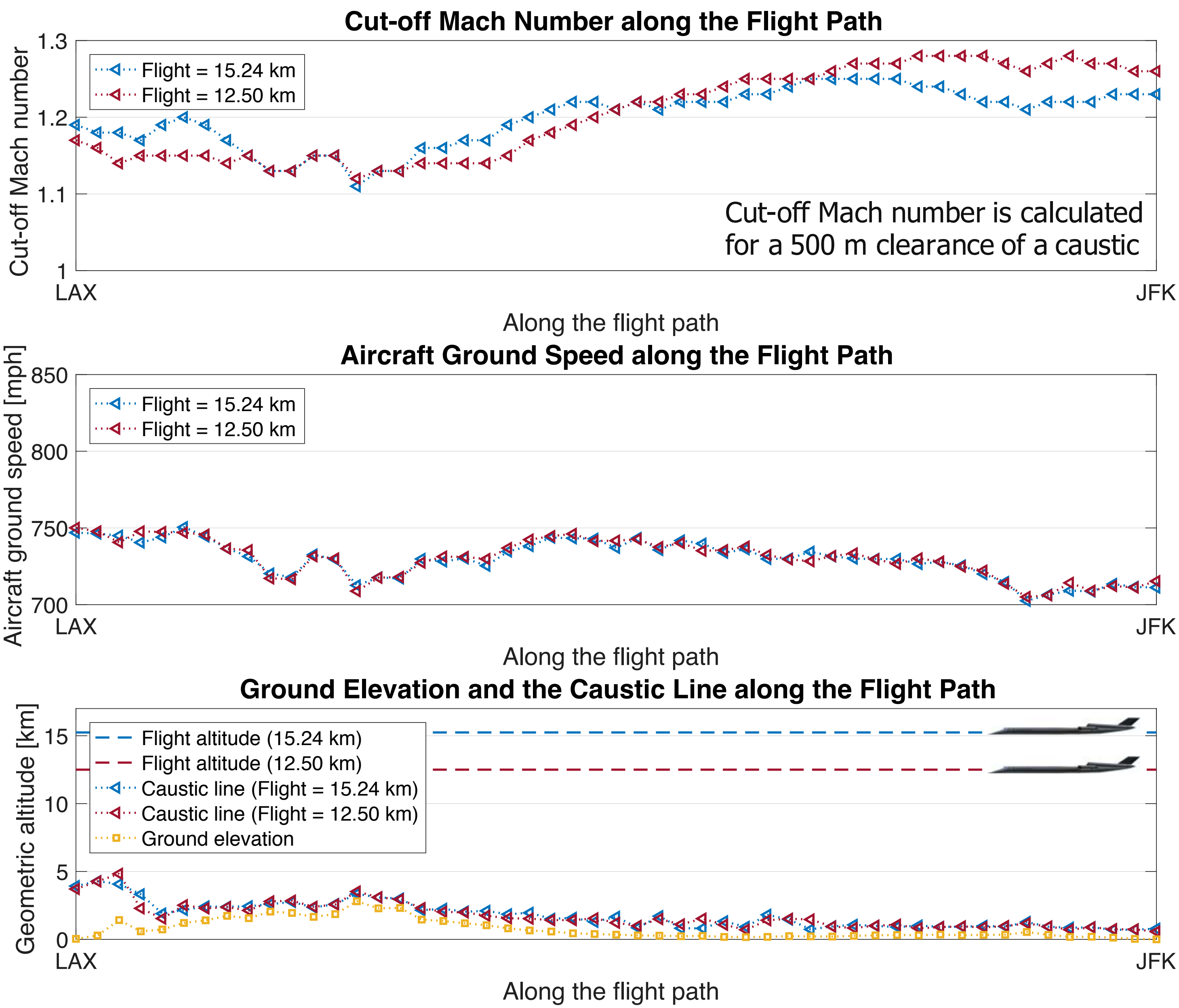
- **<u>Sometimes</u>** Mach cut-off will work for overland flight, and this depends on the atmosphere
- A 3-D ray-tracing algorithm was developed to predict the Mach cut-off operation
  – includes effects of vertical winds
- Atmospheric data from the Climate Forecast System Version 2 (CFSv2) is used [Saha, 2014], which **includes:**
  – Temperature, pressure, eastward and northward winds, and vertical wind
  – Would like to have "snapshots" of these variables at the same instant, but will use the CFSv2 for now as it's the best we have.

Air Route from JFK to LAX and CFSv2 Grid Points



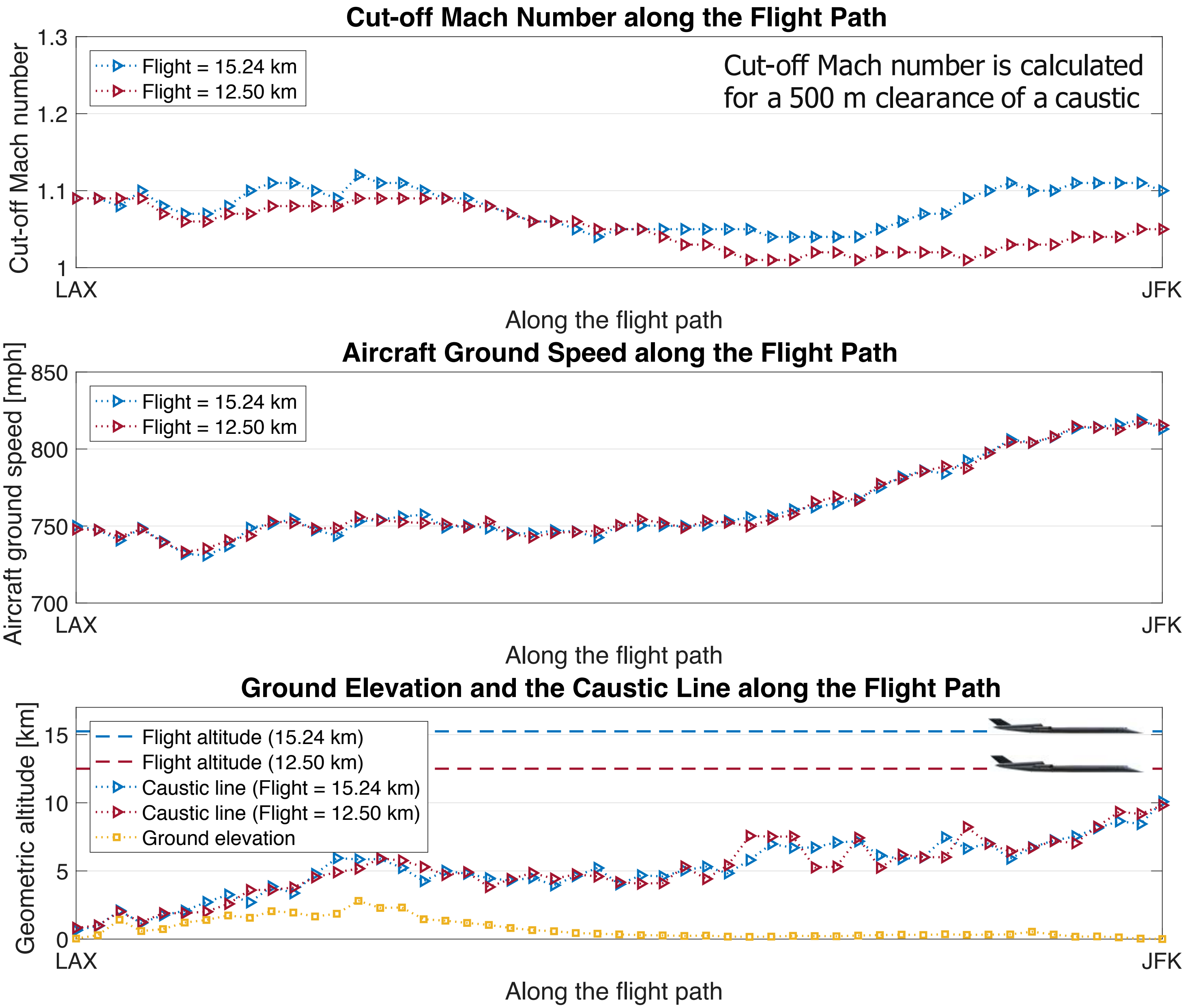
Air Route from JFK to LAX (Westbound)

- Jan 1 2017 at 12 PM UTC (7 AM EST)

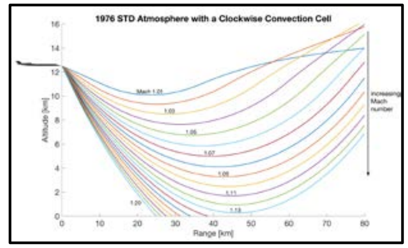


Air Route from LAX to JFK (Eastbound)

- Jan 1 2017 at 12 PM UTC (7 AM EST)



Ray tracing results



- The feasibility of Mach cut-off operation on Jan 1 2017 at 12 PM UTC (7 AM EST) is examined for the LAX - JFK air route
- For the JFK to LAX air route (westbound)
  - Possible to fly at speeds between Mach 1.12 and 1.28 at 12.50 km (41,010 ft) with a 500 m clearance of a caustic
- For the LAX to JFK air route (eastbound)
  - Possible to fly at speeds between Mach 1.04 and 1.12 at 15.24 km (50,000 ft) with a 500 m clearance of a caustic
- Flight altitudes affect the flight cut-off Mach numbers, but only have a small impact on the max aircraft ground speed
- Speeds here are only examples for the chosen **average atmosphere**.
  - For a real atmosphere, you could not go this fast and have a safety margin. ⇨ Focus of future work.

Perceptual Study

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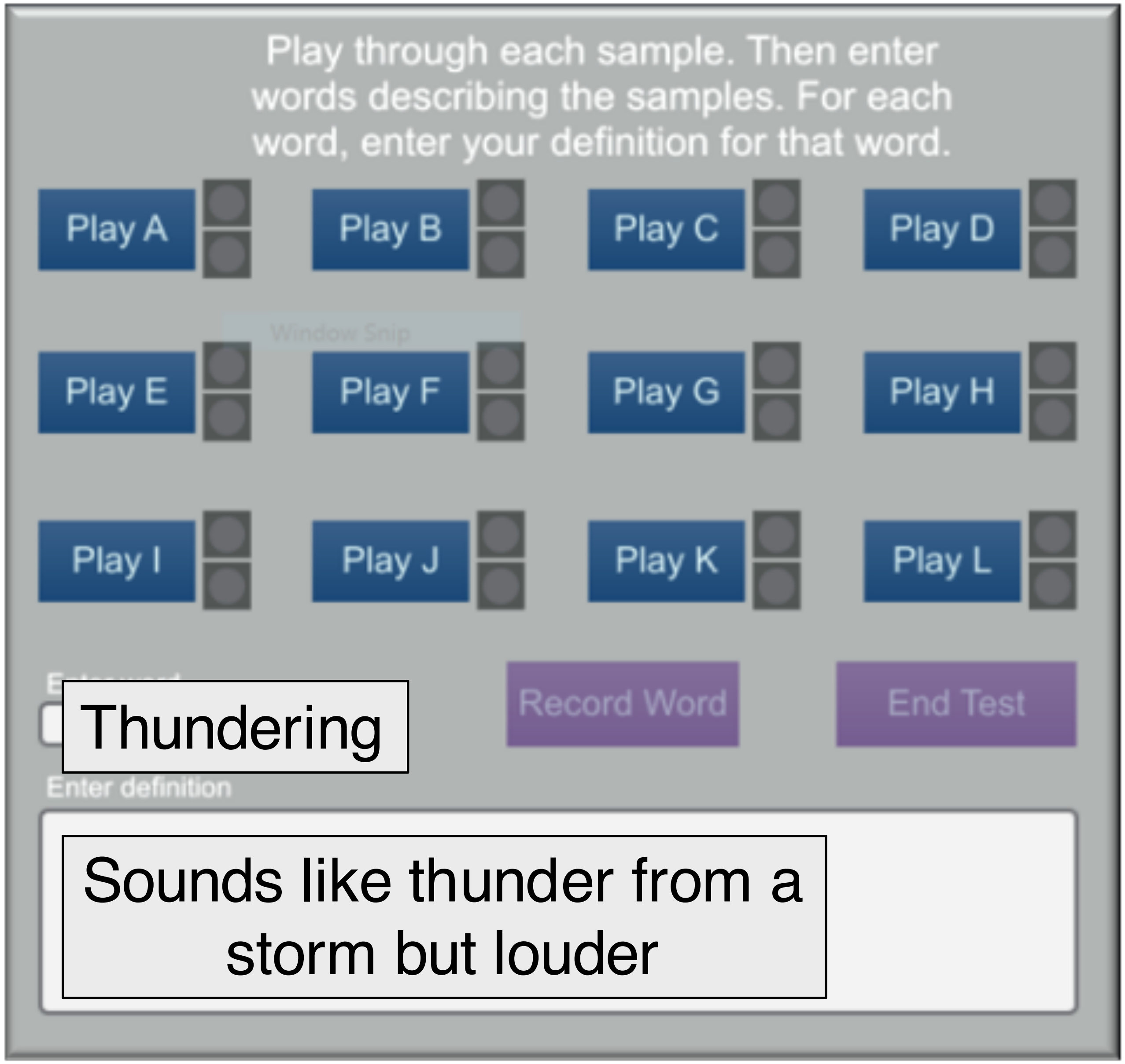
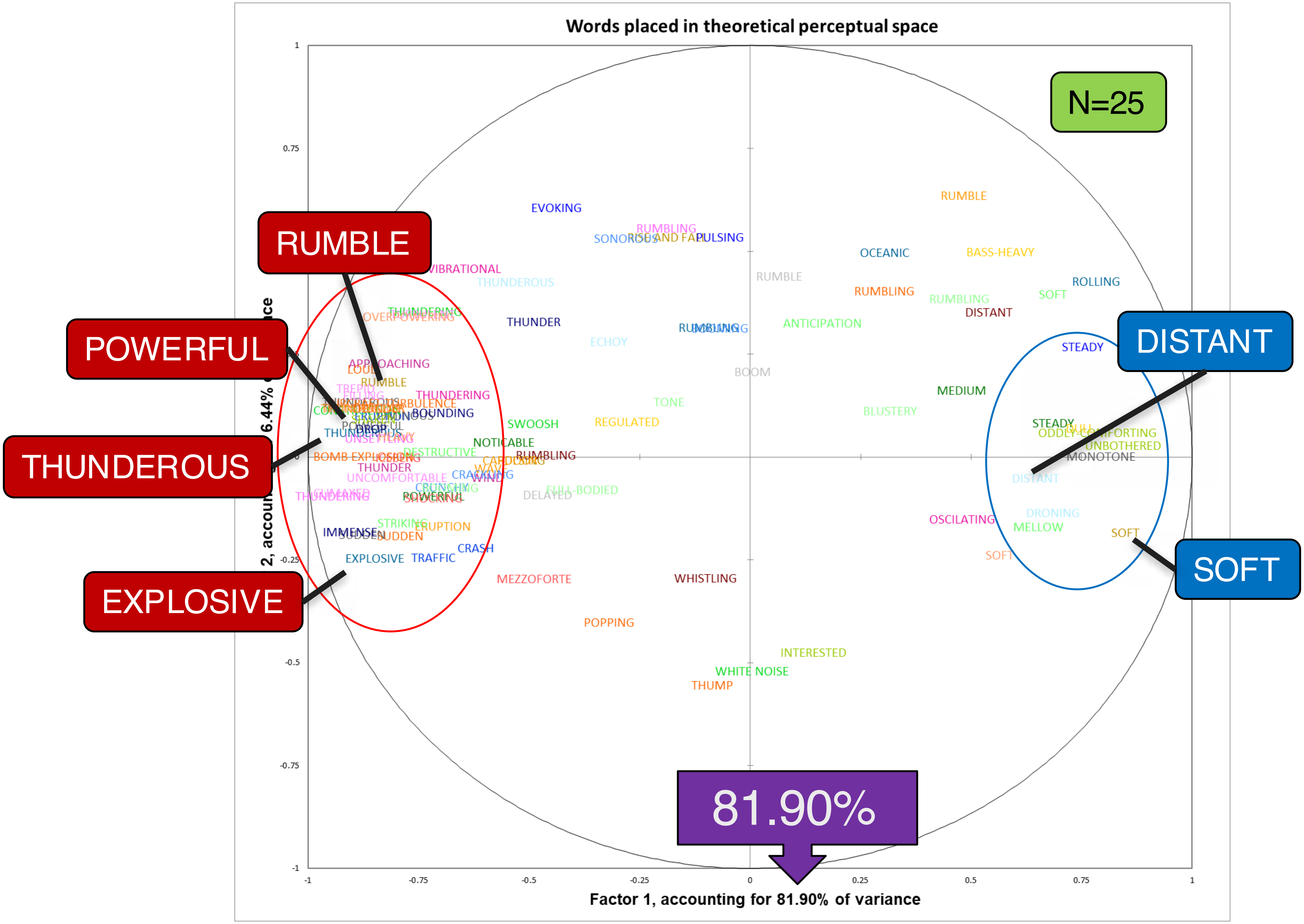
- The perceptual study aims to quantify human reaction to Mach cut-off sounds
  - Mach cut-off ground signatures do not sound like sonic booms
  - Vocabulary & metrics that are suitable for sonic booms may not apply
- The perceptual study has been divided into 3 parts:
  - A vocabulary study (today's report)
  - An annoyance study (late spring and summer 2018)
  - A metrics study (fall 2018)
- Stimuli for the perception study are from NASA's *Far-field Investigation of No-boom Thresholds* (FaINT) 2012
  - Stimuli are measured ground signatures of Mach cut-off booms
- In the upcoming annoyance/metrics studies, the stimuli could include a wider variety of sounds

In the first perceptual test, subjects **developed descriptors** to characterize Mach cut-off

- The custom user interface shown aided in descriptor generation
- After recording descriptors, subjects rated Mach-cutoff samples on their own set of descriptors
- These ratings allowed cross-subject comparison through generalized Procrustes analysis [Gower, 1975]



Initial perception of Mach cut-off seems to be controlled by **one factor**



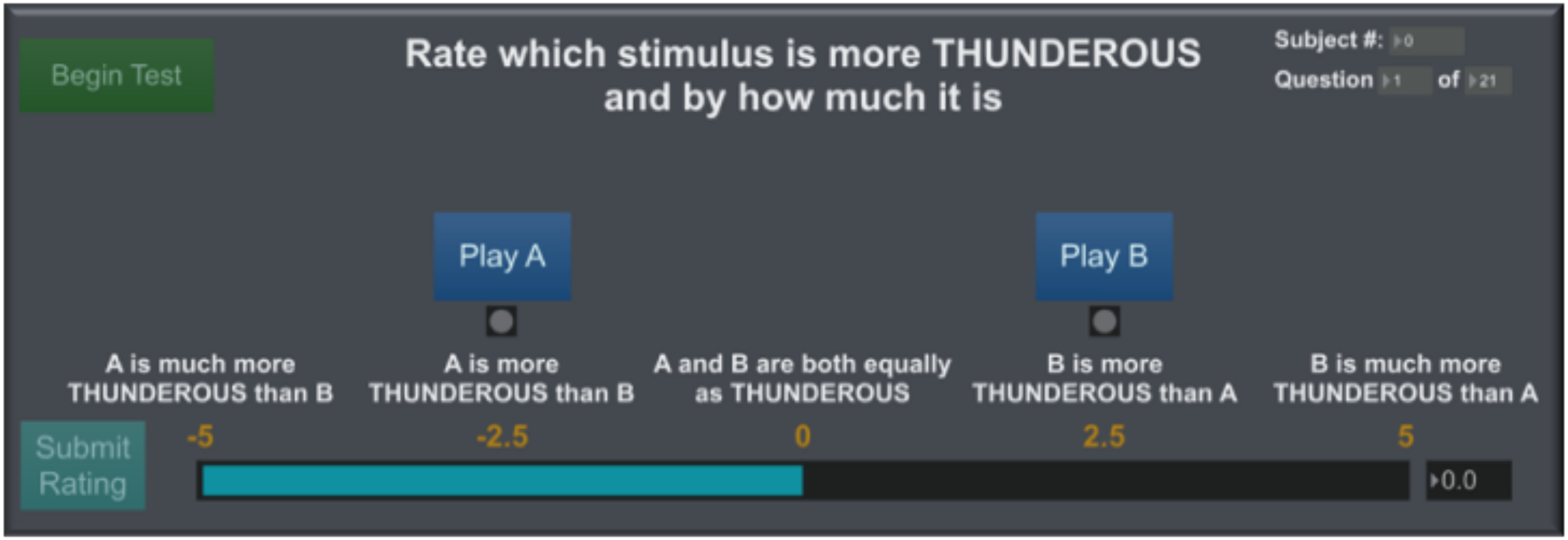
The main cluster is formed of words that relate the sounds to thunder

- These include *thunderous*, *rumble*, *powerful*, and *explosive*

- The second major cluster include words indicating a sense of quiet, such as *soft* and *distant*
  - These indicate the opposite impression of the *thunder* terms

- A third cluster does seem to be somewhat significant, consisting of words related to the crashing of waves, such as *wave* or *swoosh*
  - This cluster is more apparent when only musicians are considered

A follow-up annoyance study has been designed



- Experimental method will use paired comparison with a continuous rating scale, which yields more reliable data than other methods
- Aside from **annoyance**, 2-3 other **factors** (e.g. THUNDEROUS) will be analyzed for correlation with **annoyance**
- Results will inform metrics that may be used to predict annoyance

Overall Status for Project 42

- Good 2nd year of the project
  - Continued importance of vertical wind and accurate atmosphere representation to assess viable Mach cut-off operations
  - Vocabulary study almost completed and annoyance study about to commence
- **Sometimes**, Mach cut-off operations will work
  - Not there yet to predict statistical occurrence of public hearing
    - Mach cut-off sounds
    - Focus booms
- Key challenges/barriers
  - Currently, PCBoom or S-boom cannot include vertical winds

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Participants

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- The Pennsylvania State University
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