Project 42
Acoustical Model of Mach Cut-off Flight

Background and Motivation

- It may be possible to fly at speeds between Mach 1 and 1.15 wherein the sonic booms do not reach the ground.
  - ➢ Under these conditions, an evanescent wave does reach the ground and may be audible.
  - ➢ Mach cut-off depends on atmospheric refraction to bend the sound upwards.

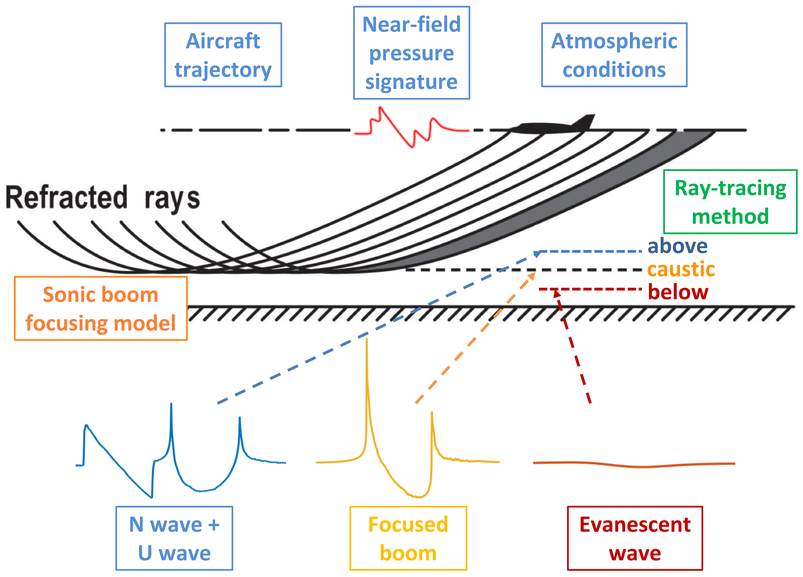


Diagram courtesy NASA[1]; adapted.

- This research aims to assess the possibilities for Mach cut-off flight over land using both sound propagation simulation (task 1) and subjective studies (task 2).

Methodology

Enhanced Ray-tracing Capabilities

- Mach cut-off operation predicted using ray-tracing method
- Weather model and data used for the atmosphere
- Modeling includes temperature and 3-D wind effects
- Synthesized Mach Cut-off Sounds using linear theory

Perceptual Studies

- Perceptual study divided into descriptor and annoyance tasks
- Free-choice profiling used to analyze descriptors
- Paired comparison used to rate annoyance and other factors
- Metrics analyzed for correlation with perceptual factors

Ray Tracing Using Atmospheric Data

Realistic Atmospheric Data

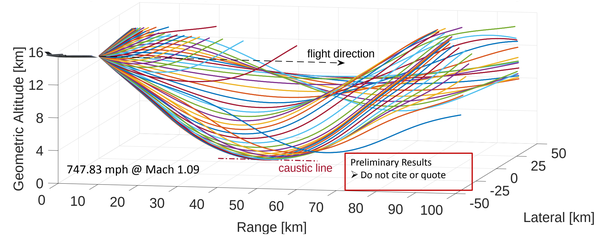
- Good "snapshots" of the atmosphere are desired for the studies.
- IGRA and CFSv2 datasets have been used in this study.
- Future work will be focused on High-Resolution Rapid Refresh (HRRR) model.

Atmospheric Datasets

Model	Domain	Grid Points/ # of Stations	Grid Spacing	Vertical Levels	Pressure Top	Initialized
IGRA	Global	Nearly 1000	--	Depends (50 ~ 82)	--	12 hours
CFSv2	Global	720 x 361	0.5°/55 km	37	1mbar	6 hours
HRRRv2	CONUS	1799 x 1059	3 km	50	20 mbar	Hourly

Advanced Ray Tracing

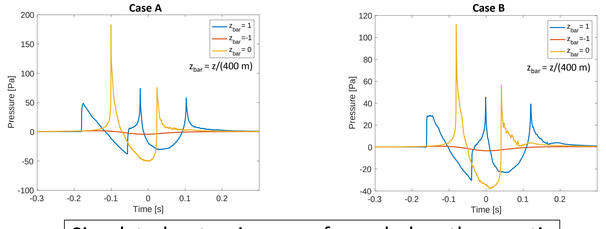
- A 3-D ray-tracing scheme has been developed[2].
- Temperature, pressure, eastward and northward winds, and vertical wind effects have been included.
- A 3-D ray-tracing diagram using CFSv2 data[3]:
  - ➢ 7 AM EST on Jan 1, 2017 over Los Angeles
  - ➢ Mach 1.09 (747.83 mph) at altitude of 12.5 km (41,000 ft)



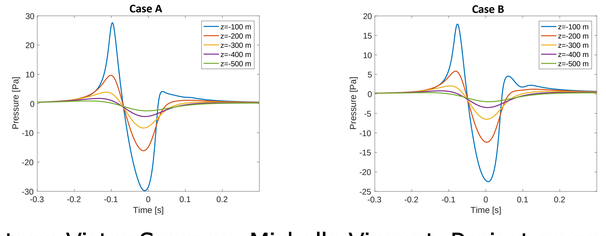
Synthesized Mach Cut-off Sounds

- Input sonic boom signatures from NASA
- Diffraction effect modeled as a diffraction boundary layer around the caustic
- Output sound signatures at different altitudes below the caustic predicted using linear lossless Tricomi equation

Waveforms in the neighborhood of the caustic



Simulated out-going waveforms below the caustic

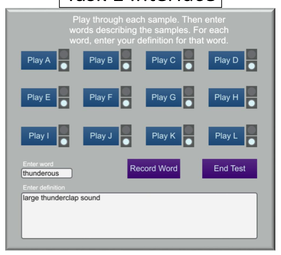


Subjective Evaluation of Mach Cut-off

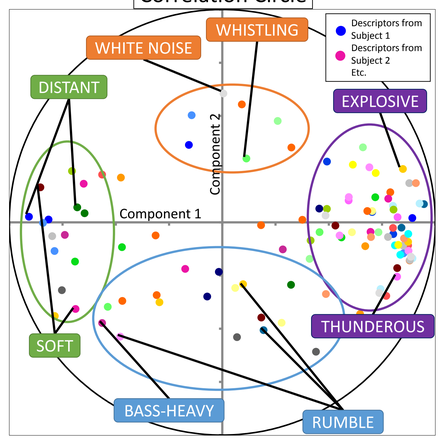
Descriptor Study

- Subjects listened to recordings of Mach cut-off and developed their own descriptors
  - 28 total participants
- Ratings were collected on these descriptors
- Generalized Procrustes Analysis[4] used to establish Principal Components (PC) across all subjects
- 24 stimuli used from NASA's FaINT[5] dataset

Task 1 Interface



Correlation Circle

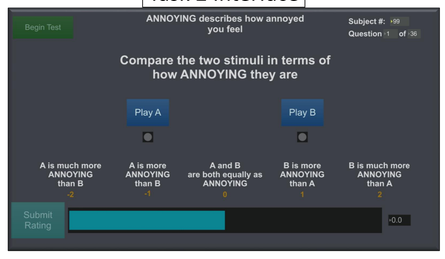


- Descriptors plotted (left) using correlation values with PCs; major clusters circled and example terms highlighted
- Terms clustered around extreme component axis endpoints
- **PC 1** related to **loudness** (soft/distant vs thunderous)
- **PC 2** related to **frequency** (bass-heavy vs white noise)
- **Most common terms:** "**thunderous**" and "**rumbly**"
- 3rd set (not shown) related to "pulsing" / "swooshing"
- Some metrics correlated with component 1 (not shown)

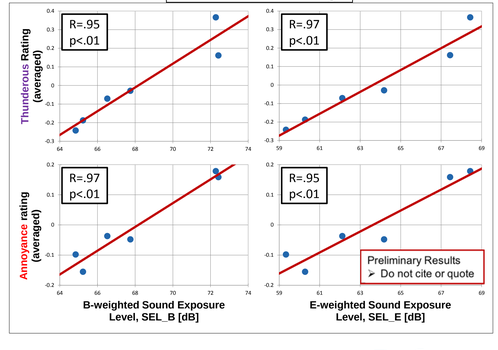
Annoyance Study

- 3 descriptors chosen for more careful analysis: "**thunderous**", "**rumbly**", and "**swooshing**"
  - "**Annoying**" also included
- Ratings collected through paired comparison to increase validity
- Interface (shown right) repeated for each descriptor and each pair
- 6 stimuli + 3 synthesized

Task 2 Interface



Metrics vs Ratings



- "**Thunderous**" ratings most consistent
- "**Rumble**" increased consistency (compared to study 1 PC2)
- "**Swooshing**" ratings dominated by loudness
- Various metrics calculated
- Ratings and metrics correlated, potential for prediction
- Data for **38 / 40** subjects collected so far

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