Overview

- Preliminaries
  - Conventions & propagation primer
  - Mesh Convergence & oversampling
- Results for Cases 1 & 2
  - Ground signals for Standard Atm. & Required Atm.
  - Cutoff angles
  - Carpet noise metrics
  - Ground Intercepts, boom carpets & raytubes
- Summary & observations
Wind Convention in sBOOM

- sBOOM wind uses left handed coord. sys.
- $\beta = \text{heading}$
- $\beta = 0^\circ$ A/C pointed East, cw+
- sBOOM wind tables are in meters vs m/s
- $x$ and $y$ are wind components ("blows toward")
  - $(x, y) = (1, 0)$ is tail wind if heading is East
  - $(x, y) = (0, 1)$ is tail wind if heading is South
  - $(x, y) = (1, 1)$ is tail wind if heading is SE

- Workshop has aircraft flying E,
  - This is $0^\circ$ heading in sBOOM

Propagation Primer

- Quasi-1D integration of Burger’s equations occurs in tube along the ray path
- Determines the ground intercept of sound emanating from given trajectory point & azimuth
- Ray path determines time required for signal propagation
Wind Effects

- Only consider crossrange and downrange winds (no up/down drafts)
- Wind can alter path of raytube (ray at $\phi = 0^\circ$ shown)
- Paths are scaled by $k$

Mesh Convergence

Sensitivity of noise output to discretization of near field signal

- Propagation code is solving augmented Burgers’ via finite difference
- Need to make sure loudness metrics are sufficiently mesh converged
  - Mesh convergence of propagation is case dependent (on signal, azimuth & atm.)
  - Mesh refinement study done for each near field signal (using Std. and Reqd. Atm.’s)
- Truncation error directly impacts accuracy, resolution requirements are driven by need to minimize error in propagation
  - Initial signal typically has < 2000 points
  - Propagation typically requires 40000-100000 points (oversampled by 20-50x)
  - Discrete ASEL filter can be poorly behaved at high sampling frequencies (> ~250kHz)
    - this limits maximum allowable oversampling
- How much accuracy is needed?
  - Atmospheric variability generally 2-5 dB, but may be ~10 dB in some cases
  - Generally tried to keep propagation error under ±0.2 dB
Mesh Convergence

Sensitivity of noise outputs to refinement of the propagation mesh

- C25P signals at $\phi = 0^\circ$, using from 20k 300k points (80-1230 kHz) for propagation
- Despite similarities in ground signal, mesh convergence of ASEL is quite slow
**Mesh Convergence**

Convergence of ASEL noise metric with sampling frequency

- ASEL converges slowly
  - Need ~600kHz (~150k pts) to converge ASEL to ±0.01dB
- However, discrete ASEL filter starts to have issues at ~250kHz, and blows up ~500kHz
- On this case (C25P) hard to guarantee ASEL error < ±0.1dB
- Discrete BSEL and CSEL remain well behaved till ~1 & 10 MHz (respectively), so generally easier to mesh converge

![Graph of ASEL convergence](image)

Convergence of BSEL, CSEL & PLdB noise metrics with sampling frequency

- BSEL, CSEL and PLdB all show good mesh convergence (all on 1 dB scale)
- FFT used for all metrics except for BSEL, but appears to be well behaved
- C-weighting converges fastest (±0.02 dB @ 200kHz)
- PLdB converges slowest (approx. ±0.1 dB @ 200kHz)
Mesh Convergence

Convergence of BSEL, CSEL & PLdB noise metrics with sampling frequency

- To avoid excessive discretization error in propagation used 500-800kHz sampling frequencies for all workshop cases
- Computed noise metrics with FFT in LCASB (adloud) for ASEL, CSEL and PLdB noise metrics
- Used digital BSEL filter in sBOOM (well behaved at 500-800kHz)

Case 1: C25P
Powered version of the NASA Concept 25D

Conditions:
\[ M_{\infty} = 1.6 \]
Altitude = 15.760 km (52k ft)
Ground height = 264.069m (866ft)
\[ L_{\text{prop}} = 33.53m \text{ (110 ft)} \]
\[ r/L = 3.0 \text{ at signal extraction} \]
Ground reflection factor = 1.9
Heading East (\( \beta = 0^\circ \))

Atmospheric Profiles:
1. Required Atm: with profiles for wind, temp, pressure & humidity
2. Standard Atmosphere
Case 1: C25P Standard Atmosphere

Near field and ground pressure signals

- Near field data provided for half-cylinder \([-90^\circ, 90^\circ]\), \([-50^\circ, 50^\circ]\) shown

Case 1: C25P Standard Atmosphere

Propagation altitude = 15760m, ground height = 264m

- Near field data provided for half-cylinder \([-90^\circ, 90^\circ]\), \([-50^\circ, 50^\circ]\) shown
- Propagation shown used 500kHz sampling frequency (142k pts)
Case 1: C25P Ground Signatures

Propagation altitude = 15760m, ground height = 264m

- Required Atm. has profiles of crosswind, temperature, humidity and pressure
  - Shows lots of asymmetry, and cutoffs are farther out on both sides

Case 1: C25P Ground Noise

Compare ground noise metrics across the carpet as a function of azimuth

- Azimuthal range of carpet with real atm. is much wider than Standard Atm.
- Real atm. (with wind) reduces peak loudness by ~1dBA, ~0.5dB, ~0.4dBC & ~0.7PLdB
- Noise at carpet edge drops, but can still be significant
Case 1: C25P Ground Carpet

Project raytube ground intercepts on aircraft ground track

- Boom carpet computed from the intercepts of raytubes on the ground-plane projection of the trajectory. Showing both standard and required atmospheres
- Crossrange wind profile makes the required atm. asymmetric
- Cutoff angles: Std. Atm. = [±50.8°], Req. Atm. = [-78.4°, +69.1°]
- Long propagation distances near signal cutoff imply that these raytubes take a long time to reach the ground
  - Raytube for $\phi = -78.4^\circ$ takes over 6 mins in Required atm.
  - Mesh convergence near signal cutoff is not nearly as good as at low azimuth angles
  - Higher discretization error due to much longer propagation
  - Propagation for signal cutoff used higher sampling frequency (800 kHz)
- Ground track for required atm is ~160 km, more than 2x as wide as standard atm. (~70 km)

Case 1: C25P Raytubes for Required Atmosphere

Plot 3D raytubes colored by raytube area

- 3D plot of raytubes for real atmosphere
- Shows extremely long propagation times & large raytube areas near edges of the carpet
Case 2: C609 Near Field Signals

**Sign Convention for Azimuth, \( \phi \)**

\( Alt = 16459.2 \text{ m} \)

- Near field signals provided for 23 azimuths from -70° to +70°
  \( \phi = [0, \pm 10, \pm 20, \pm 30, \pm 40, \pm 50, \pm 60, \pm 62, \pm 64, \pm 66, \pm 68, \pm 70] \)
- Signals symmetric \( \pm \phi \)
Case 2: C609 Sampling Frequency

Metric convergence with sampling frequency (Std. Atm.)

- Using FFT for metric computation get reasonable mesh convergence of ASEL, CSEL and PLdB by 500kHz.
- Discrete BSEL filter appears well behaved as well
- Similar mesh convergence behavior for other azimuths. Used 500kHz sampling frequency away from cutoff.

Case 2: C609 Ground Signals

Propagation altitude = 16460m, ground elevation = 110m

- Required Atm. includes profiles of crosswind, temperature, humidity and pressure
  - Very asymmetric, with much wider cutoffs on both sides
- Amplitude of ground signal in real atmosphere significantly reduced from Std. Atm.
Case 2: C609 Ground Noise

Compare ground noise metrics across the carpet as a function of azimuth.

- Azimuthal range of carpet with Required Atm. is much wider than Standard Atm.
- Despite wind & reduced ground amplitude, Real Atm. and Std. Atm. have similar loudness.
- Noise at carpet edge drops significantly in Required Atm.

Case 2: C609 Ground Carpet

Project raytube ground intercepts on aircraft ground track.

- Boom carpet computed from the intercepts of raytubes on the ground-plane projection of the trajectory. Showing both standard and required atmospheres.
- Crossrange wind profile makes the required atm. asymmetric.
- Cutoff angles Req. Atm = [-64.1°, 70.6°], Std. Atm = [±44.9°].
- Long propagation distances near signal cutoff imply that these raytubes take a long time to reach the ground.
  - Raytube for ϕ = -64.1° cutoff takes over 8.5 mins in Req. atm.
  - Mesh convergence near signal cutoff is not nearly as good as at low azimuth angles.
  - Higher discretization error due to much longer propagation.
- Ground track for required atm is ~160 km, more than 2.7x as wide as standard atm. (~60 km).
Case 2: C609 Raytubes for Required Atmosphere

Plot 3D raytubes colored by raytube area

- 3D plot of raytubes for real atmosphere
- Shows extremely long propagation times & large raytube areas near cutoff

Summary

- Applied sBOOM v2.82 & LCASB to all required and optional steady propagation cases
- Mesh convergence studies across the carpet to ensure accuracy of the ground signal and loudness metrics. Error in noise metrics can be 2-4x higher near signal cutoff.
- Mesh convergence is relatively slow on intricate non-smooth input signals
- Real atmosphere is usually quieter than Standard Atmosphere, (but not always - e.g. case 2)
- Ground track of real atmosphere can be nearly 3x wider than Standard day. Crosswinds generally increase track width and can result in large cutoff azimuths
- On windy days, boom may not arrive off-track for over 5 mins after a/c passes (case 2 took 8 mins!)
- Raytube visualization shows potential for loud off-track azimuths to be blown back under-track
Acknowledgments

• Thanks to Sriram Rallabhandi for developing and supporting sBOOM, and to Marian Nemec and David Rodriguez for technical discussions on the various cases.

• SBPW3 organizers for their effort in organizing and coordinating the workshop, particularly Melissa Carter, Sriram Rallabhandi & Mike Park

• ARMD Commercial Supersonic Technology Project for support of this work and advancing the state of the art in boom prediction over the last decade

• NASA Advanced Supercomputing Division for providing computing resources

• NASA Ames Research Center contract NNA16BD60 and Science & Technology Corp. for supporting Wade Spurlock’s involvement.

Questions?