# Third Sonic Boom Prediction Workshop: PCBoom Analysis

## *At the AIAA SciTech Conference*

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# Outline

- Modeling Tools & Procedures
- Test Cases & Selected Results
  - C25P – Case 1
  - C25P (with focus) – Optional
  - C609 – Case 2
- Observations & Suggestions

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# PCBoom Suite of Programs

FOBoom – "Focused Boom" propagation module

- Considers vehicle operational state
- Environmental Factors – Atmosphere & Terrain
- Vehicle Source Characteristics
  - *Linear acoustic propagation* to large distances, accounts for atmospheric gradients via the method of geometrical acoustics. Amplitude of acoustic disturbance is governed by change in area of ray tubes (bundles of differentially separated rays) and local acoustic impedance (environmental parameters).
  - *Non-linear steepening* of boom signature based on Middleton-Carlson-Hayes "advance" or "age" parameter (part of the geometrical acoustics solution); non-linear distortion of boom signature consists of an advance proportional to its original strength times the age parameter.

# PCBoom Suite of Tools applied to SBPW3

- FOBoom – Main Ray Tracing program- computes ray paths and signature evolution parameters
- PCBurg – Interactive graphical Burgers' solver: uses ray path info from FOBoom and computes the effect of molecular relaxation on shock structures on sonic boom signature evolution; computes loudness metrics
- HeadlessBurgers – Command line version of PCBurg without interactive signature graphical viewing piece
- PCBFoot – Organizes FoBoom output, applies "simple" Taylor shock structures to shocks and computes loudness metrics
- WCon6 – Interactive footprint and signature display module
- LNTE- Lossy NonLinear Tricomi Equation solver (2D) for computation of focus signatures near a caustic
- Raycau - interface between PCBoom and LNTE: interprets focus location and establishes PCBurg input conditions for preparation of lossy delta-tangent ray at diffraction zone edge

# Modeling Tools & Procedures

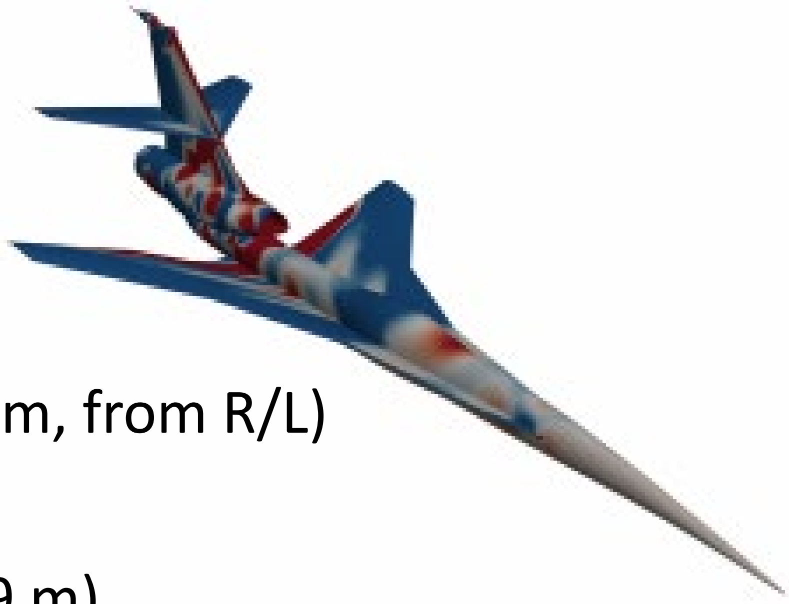
- Analysis utilized PCBoom Version 6.8/7
  - FOBoom V6.8b (Volpe QSF18 version)
  - Updated allocatable array handling for cylinder inputs
  - Dimension increases for OTT
  - Support of geomode lat/long output in the runstream
  - Minor i/o formatting differences and bug fixes (Meteo)
  - HeadlessBurgers 7 (V2, Volpe modification to PL algorithm)
- Starting Signature Preparation
  - FOBoom run in single-ray mode due to inconsistent axial spacing between azimuths
  - PCBoom6 (X,Y,Z) data formats & sequencing
  - Independent variable in units of feet
  - Pressure signatures downsampled due to array limits in FOBoom 6.8b

# Azimuth and Wind Conventions

- Azimuth Angles:
  - SBPW convention: “from the point of view of the pilot, positive azimuths are defined as being to the right and negative azimuths are to the left”
  - PCBoom convention: “positive phi out the left wing”
- Wind Directions:
  - SBPW convention: X (East) and Y (North) components of wind represent direction the wind is blowing toward
  - PCBoom wind convention: “given in the engineering vector sense, rather than the meteorological sense, and should contain data concerning the direction the wind is blowing toward"

# Case 1

- C25P: powered equivalent of NASA C25D configuration from SBPW2
  - Mach number = 1.6
  - Cruise alt = 51706.037 ft
  - R/L = 3.0
  - Vehicle Length = 110 ft. (33.528 m, from R/L)
  - Ground reflection factor = 1.9
  - Ground alt = 866.368 ft (264.069 m)
  - Measured atmospheric profile

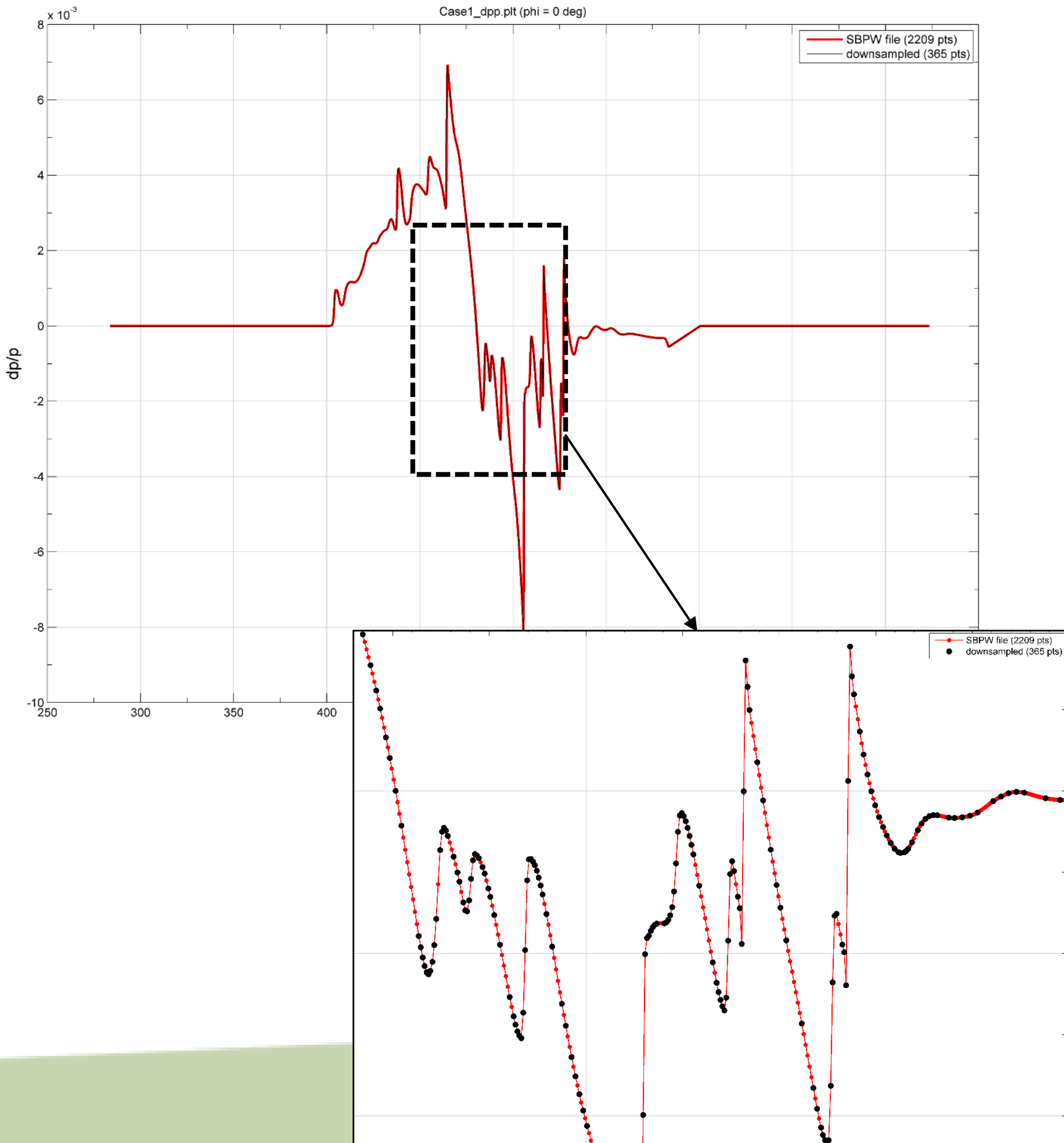


# Starting Pressure Data

Near-field pressure data were downsampled due to point limits in FOBoom 6.8b

Red markers: original data (2209 points); Black markers: downsampled data (365 points)

Ramer-Douglas-Peucker algorithm used- selectively removes points based on minimizing deviation between original data and segments connecting downsampled data

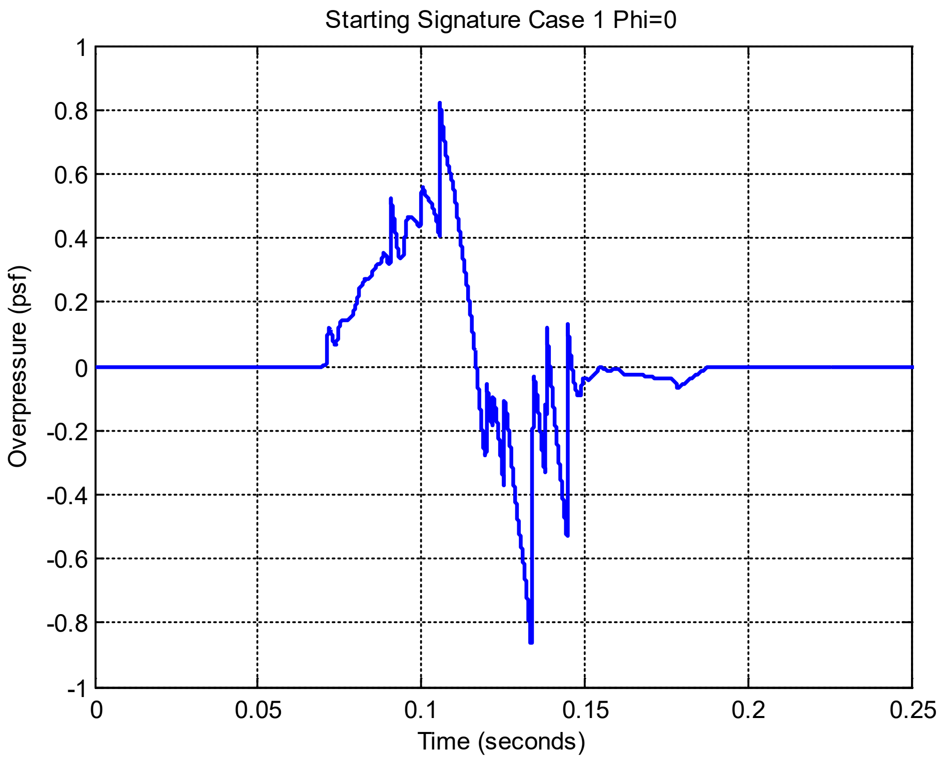


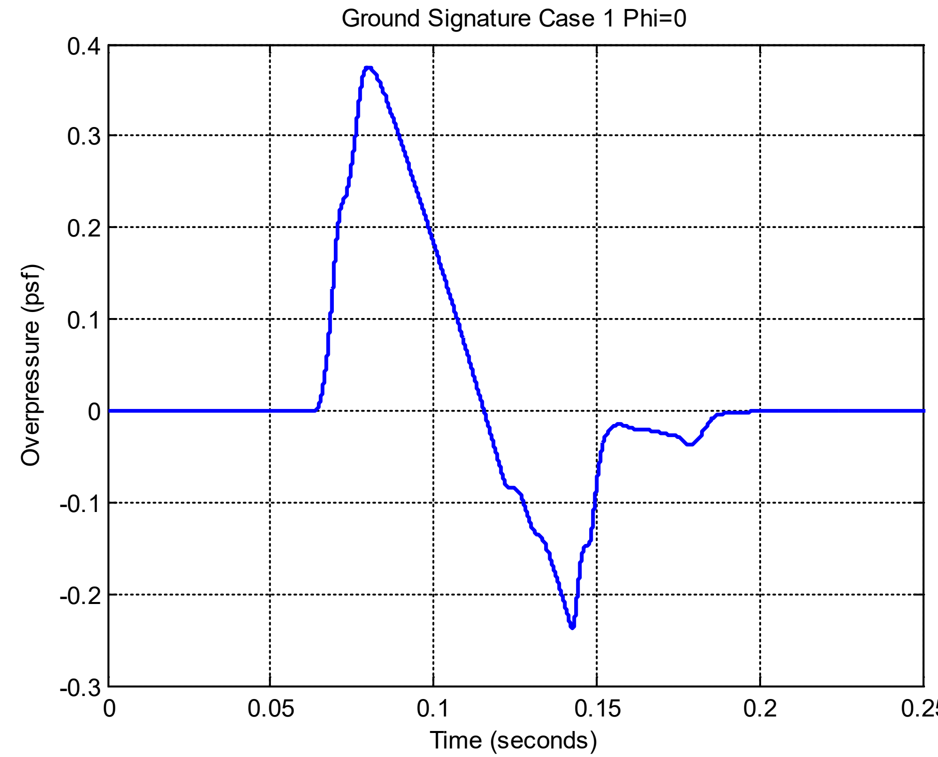
# Selected Results – Case 1 Measured Atmosphere

# HeadlessBurgers Molecular Relaxation

- Utilized FOBoom to determine Ray Paths
- Propagates Signatures along Prescribed Ray
- Utilizes Atmospheric Parameters as output by FOBoom
- Flight Altitude = 51,706 ft
- Burgers Propagation started at 51,000 ft Altitude
- Sampling rate = 102.4 kHz, time-step factor = 0.002
- Anti-Gibbs phenomenon filter used
- Ground reflection factor = 1.9

# Case 1 – Ground – Measured Atmo

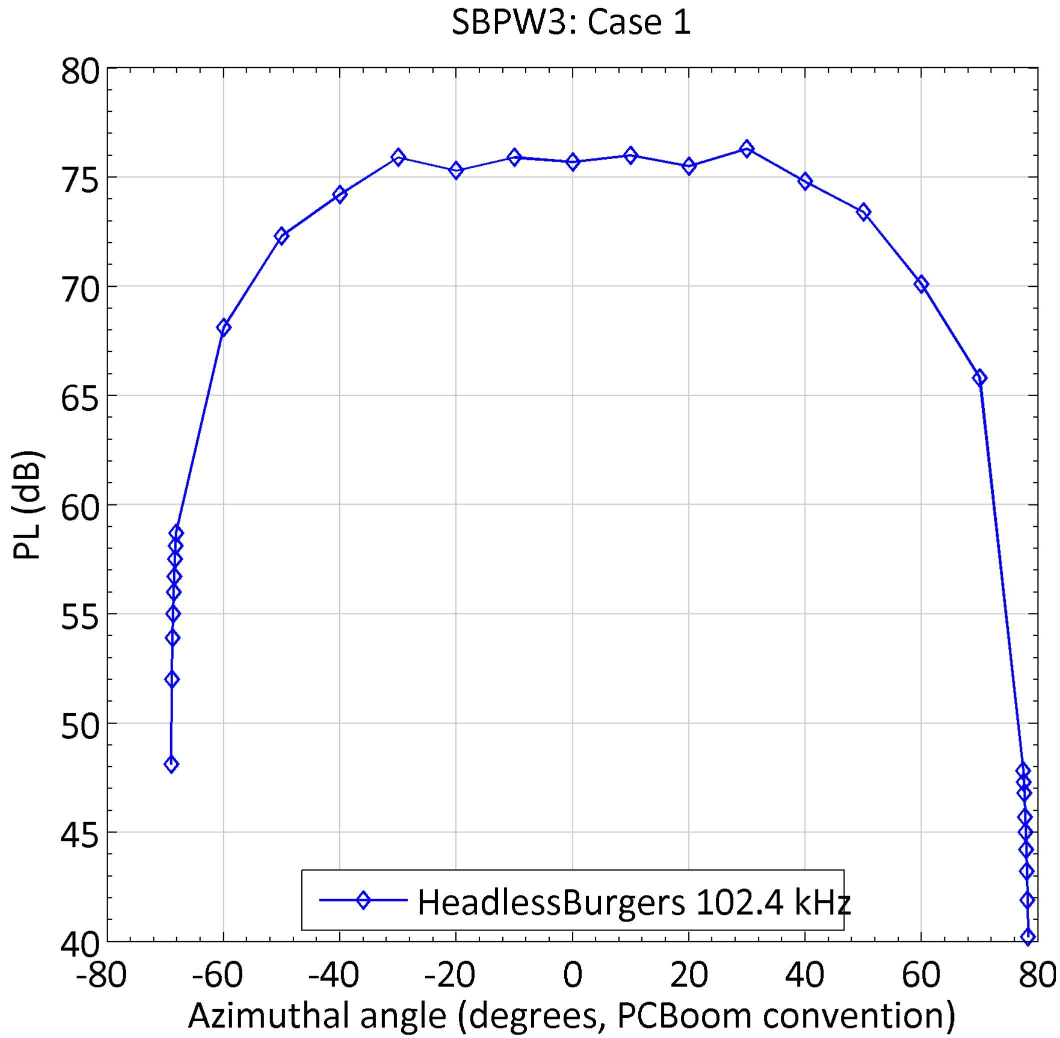


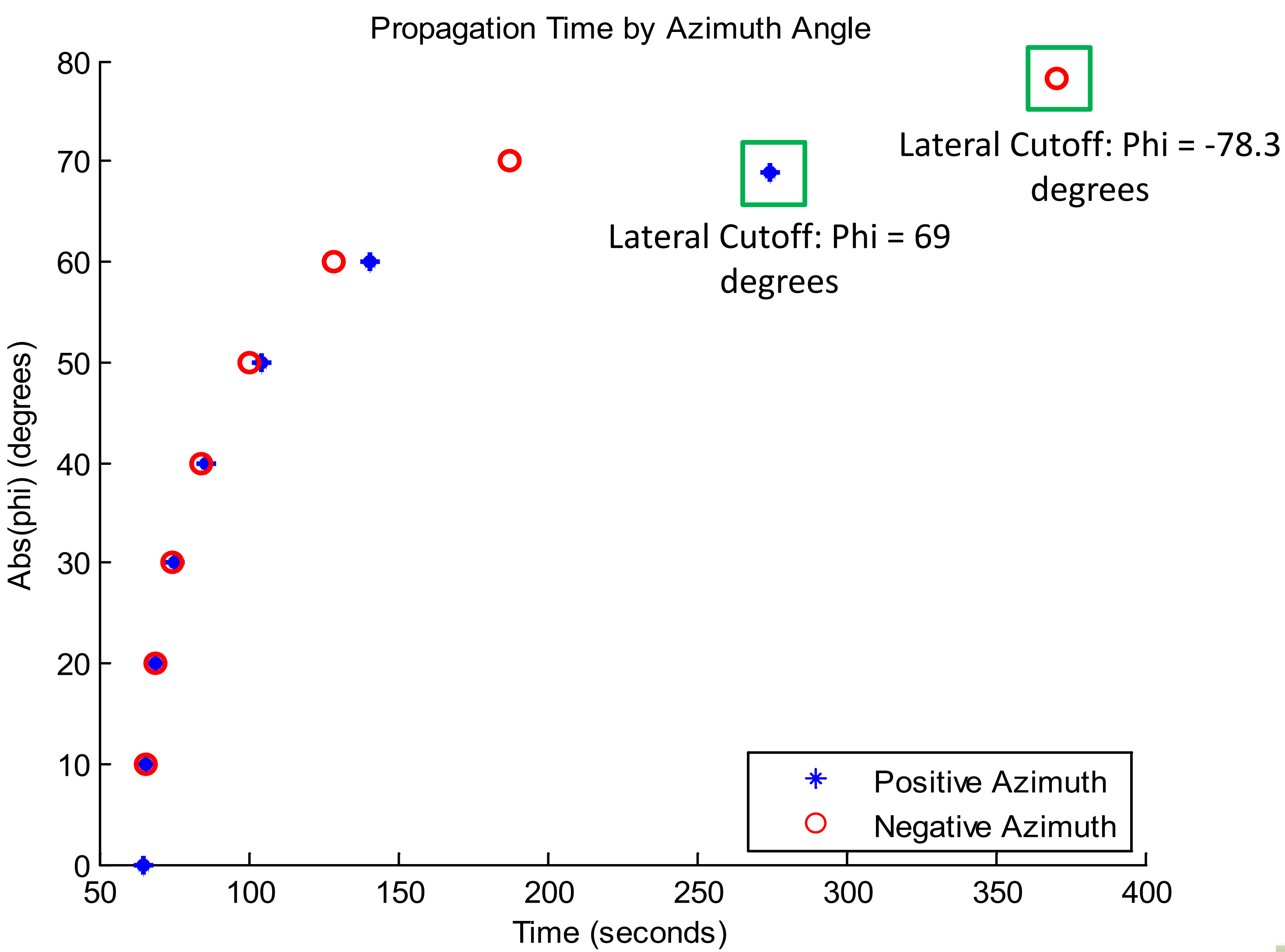

| Ground Signature Metrics at Phi = 0 | |
|---|---|
| PLdB | 75.70 |
| ASEL | 61.68 |
| BSEL | 76.80 |
| CSEL | 91.08 |
| FSEL | 103.12 |
| Pmax | 0.38 |

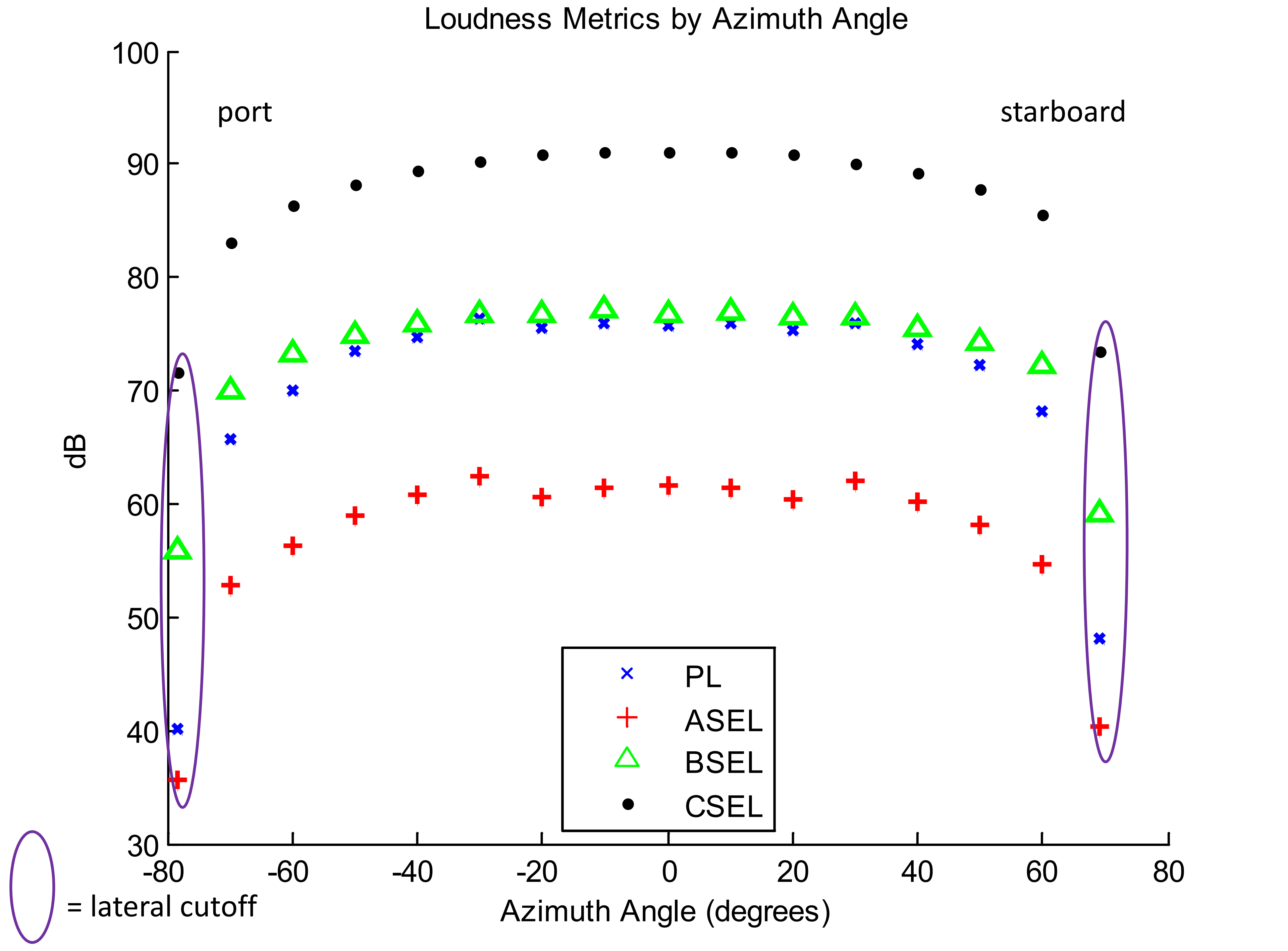
# Lateral Cutoff Determination

- Lateral cutoff angles determined using built-in FOBoom algorithm
- FOBoom ray tracing:
  - LEGACY mode
  - 0.25° ray tube angular width
  - 0.1 time step integration along a ray
- Lateral cutoff angles refined by incrementing azimuth angles 0.1°; resulting cutoff angles were around 0.5° farther offtrack
- Burgers propagation results and ray paths examined near cutoff to ensure reasonable results



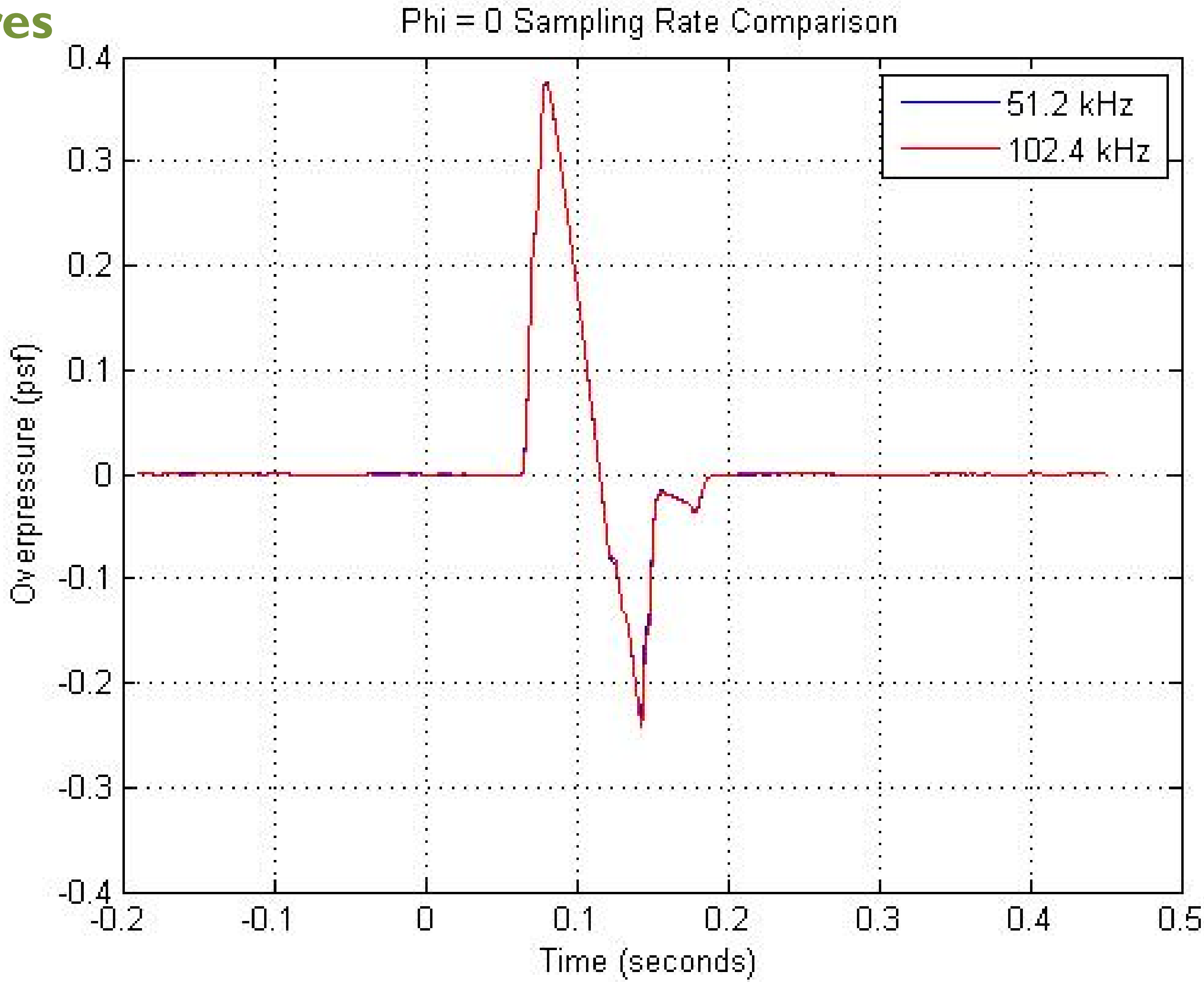
# Case 1: Measured Atmosphere





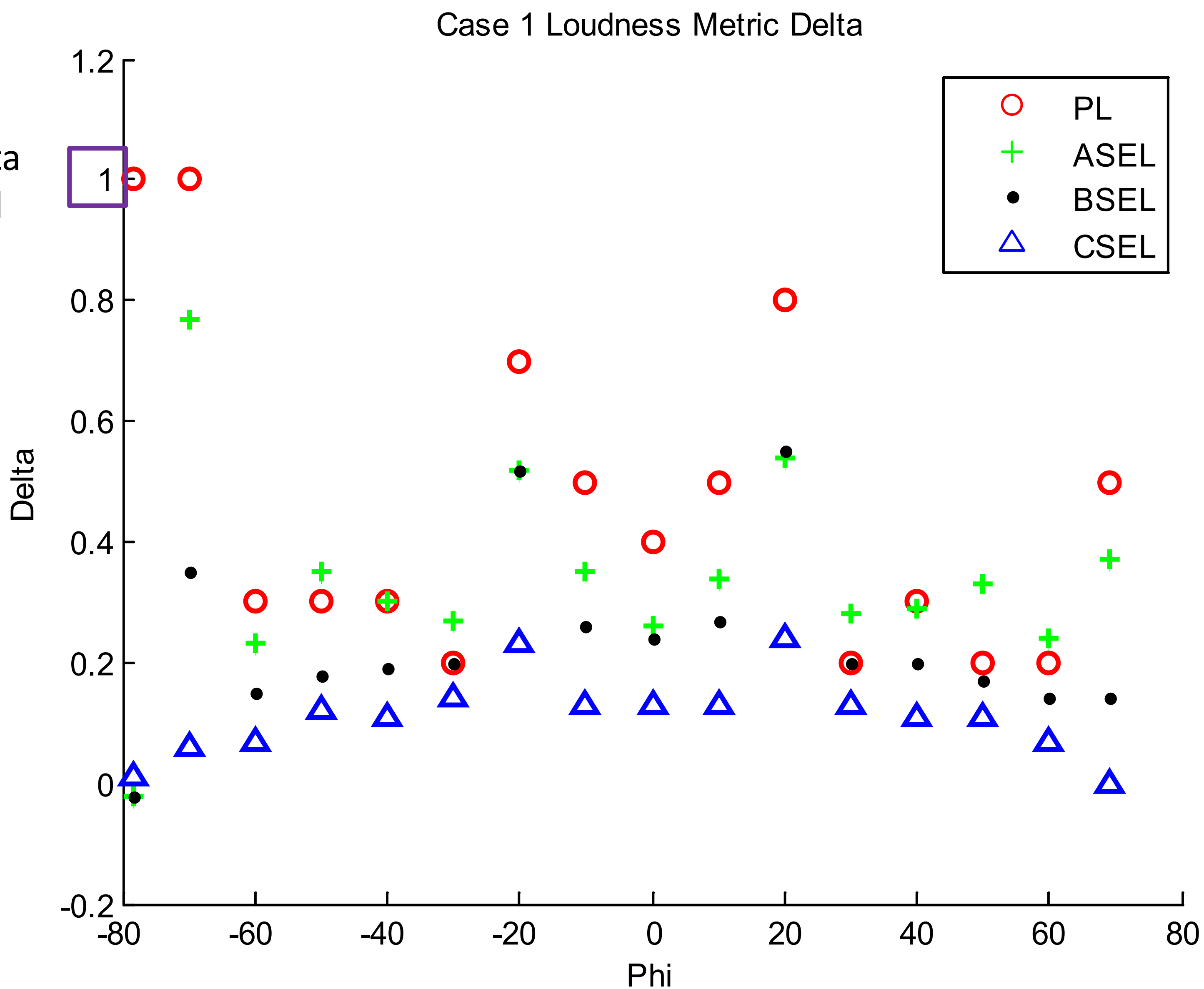
Loudness Metrics by Azimuth Angle
100
90
80
70
60
50
40
30
dB
port
starboard
PL
ASEL
BSEL
CSEL
-80
-60
-40
-20
0
20
40
60
80
Azimuth Angle (degrees)
= lateral cutoff

# HeadlessBurgers Sampling Rate Comparison – Ground Signatures



# Case 1: HeadlessBurgers Loudness Metrics Sampling Rate Comparison (102.4 kHz - 51.2 kHz)

<1 dB delta across all metrics



# Optional Case 1: Focus

# Case I Focus

- Mach = 1.4121
- dM/dt = 0.015681
- d2M/dt2 = 0.000359
- Flight Path Angle = 0.0
- Flight Altitude = 45000 ft
- AoA = 3.668
- R/L = 3.0
- Ground altitude = 190.289 ft
- Standard Atmospheric Profile
- Starting Pressures Provided – *did not need point reduction*

# Lossy Nonlinear Tricomi Code (LNTE)

- Part of the PCBoom Suite of tools
  - Developed by Joe Salamone (PSU / Gulfstream)*
  - SCAMP project (NASA CR-2015-218871)
- Runstream:
  - Ray trace (FOBoom)
  - Ray Identification (Raycau)
  - Input Lossy Signature (PCBurg)
  - Propagation through Focal Zone (LNTE)

```
FOBoom.exe c1opt-HiRes.dat 17
Raycau.exe c1opt-HiRes
pcburg.exe -c1opt-HiRes TW0.0 PW0.0 SR3 GR1.0 FT Un
tricomi_delta.exe Tricomi.inp Try5-fs24k-tm18.out -tt0.5
-ii999999 -tm18.0 -fs24000.
```

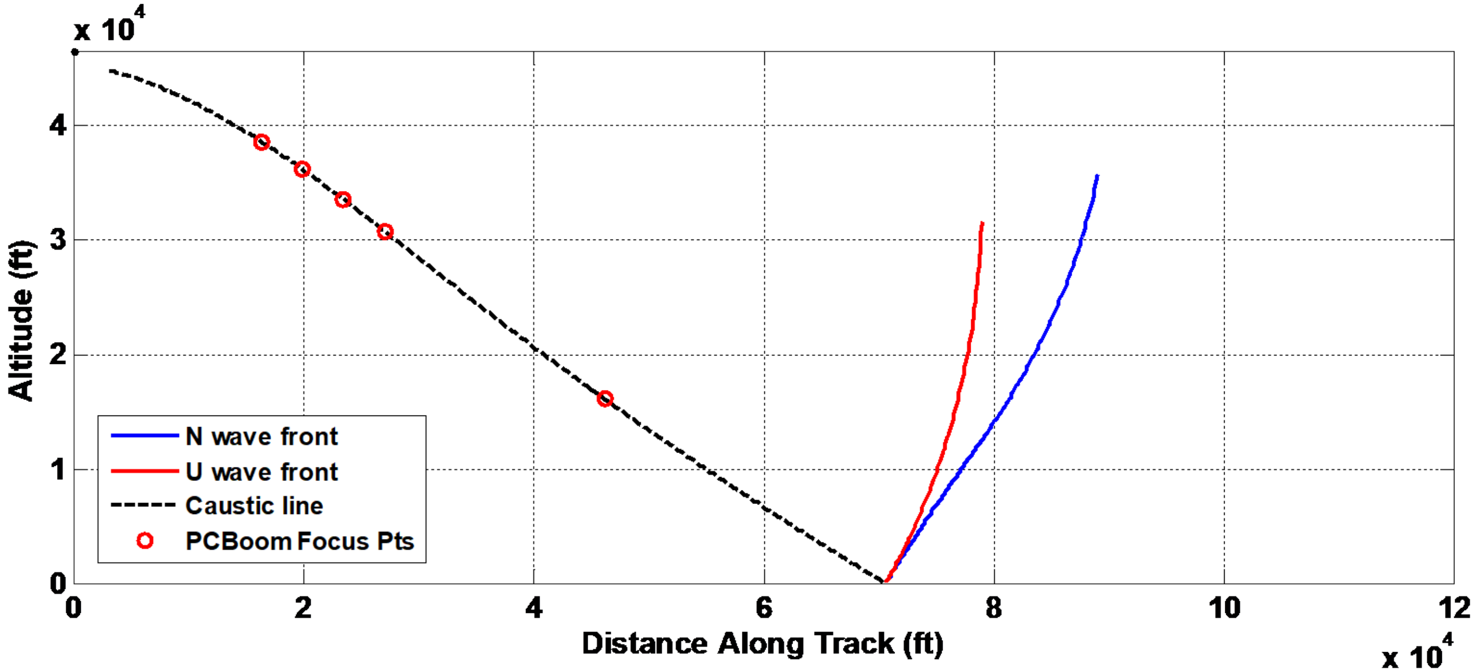
* Salamone, "Solution of the Lossy Nonlinear Tricomi Equation with Application to Sonic Boom Focusing", PSU PhD Thesis, 2013

# Lossy Nonlinear Tricomi Equation (LNTE)

SCAMP - Superboom Caustic Analysis and Measurement Program

$$\frac{\partial^2 p}{\partial \bar{z}^2} - \bar{z}\frac{\partial^2 p}{\partial \bar{t}^2} + \frac{\beta}{\varepsilon^2 \rho_0 c_0^2}\frac{\partial^2 p^2}{\partial \bar{t}^2} + \left(\frac{\bar{\alpha}}{\varepsilon^2} + \sum_{v=1}^{2} \frac{\bar{\theta}_v / \varepsilon^2}{1 + \bar{\tau}_v \frac{\partial}{\partial \bar{t}}}\right)\frac{\partial^3 p}{\partial \bar{t}^3} = 0$$

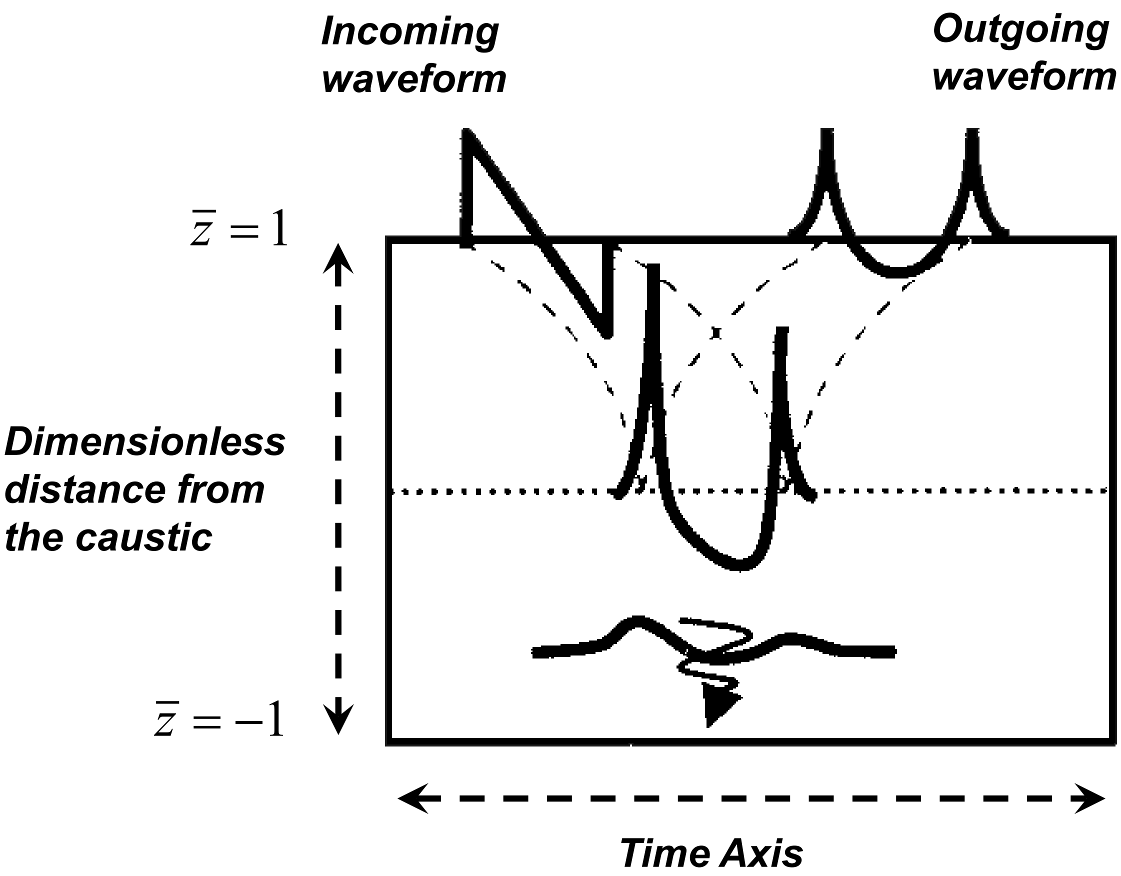
**diffraction** **nonlin**




Source: SCAMP Final Oral Review. Gulfstream: Salamone

# Tricomi Domain Description



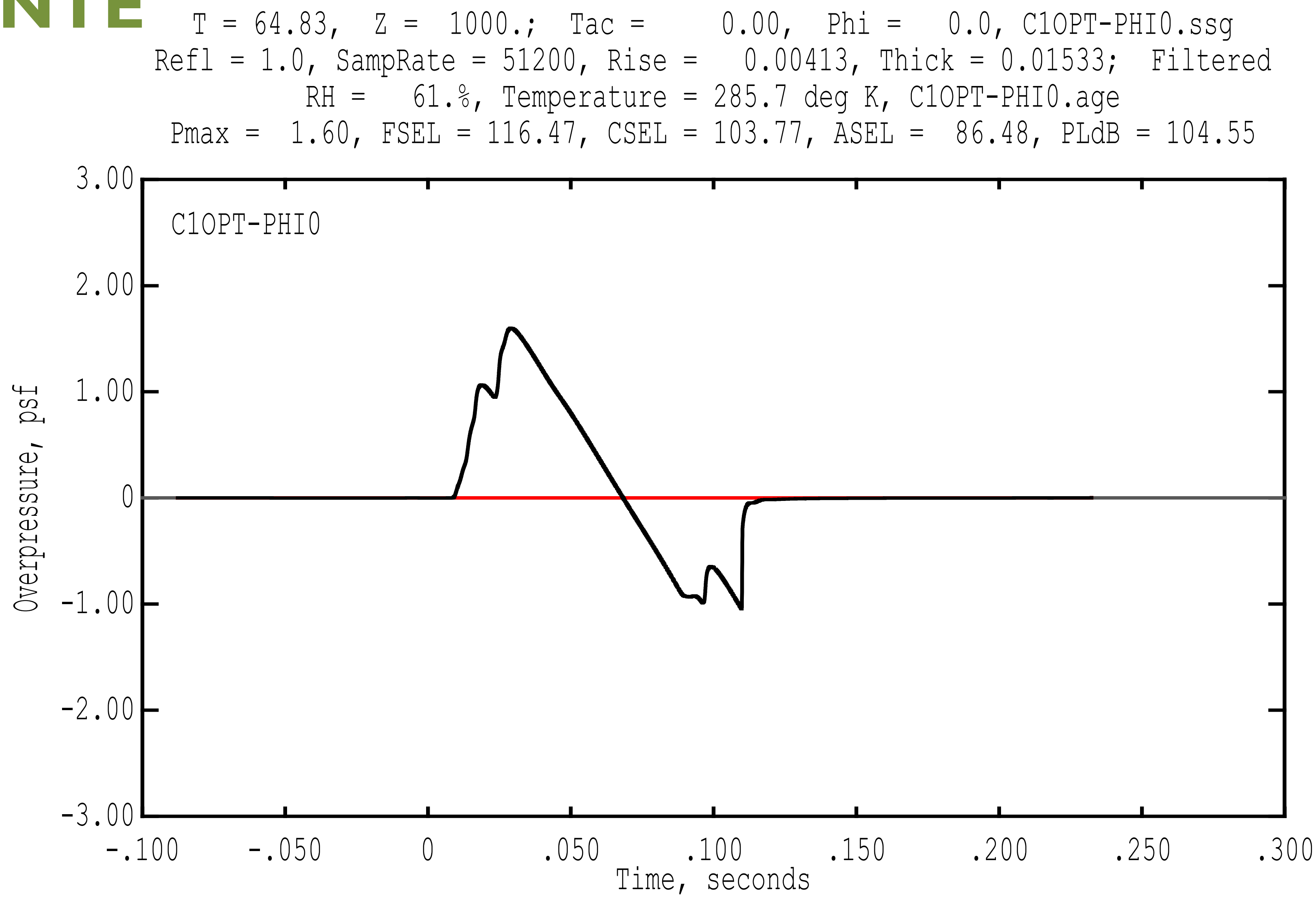



***Illuminated zone – two rays at each location, one ray has not passed through the caustic and the other ray that has passed through the caustic***

***Shadow zone – no rays exist in this location, evanescent decay of the pressure field***

Source: SCAMP Final Oral Review. Gulfstream: Salamone

# PCBurg (7.0.0) Solution – Starting input for LNTE



# Selected Results – Case 1 Focus

# Test Cases – Parameter sweeps

- Baseline (tm 10.1 fs 13k dz 4000)
- Highres (tm 17.0 fs 13k dz 4000)

} Included here

- tm comparison (tm 12, 14, 16  fs 13k  dz 4000)
- dz comparison (tm 10.1 fs 13k dz 4000 6000 8000)
- fs comparison (tm 18.0 fs 13k 16k 20k 24k 28k dz 4000)*

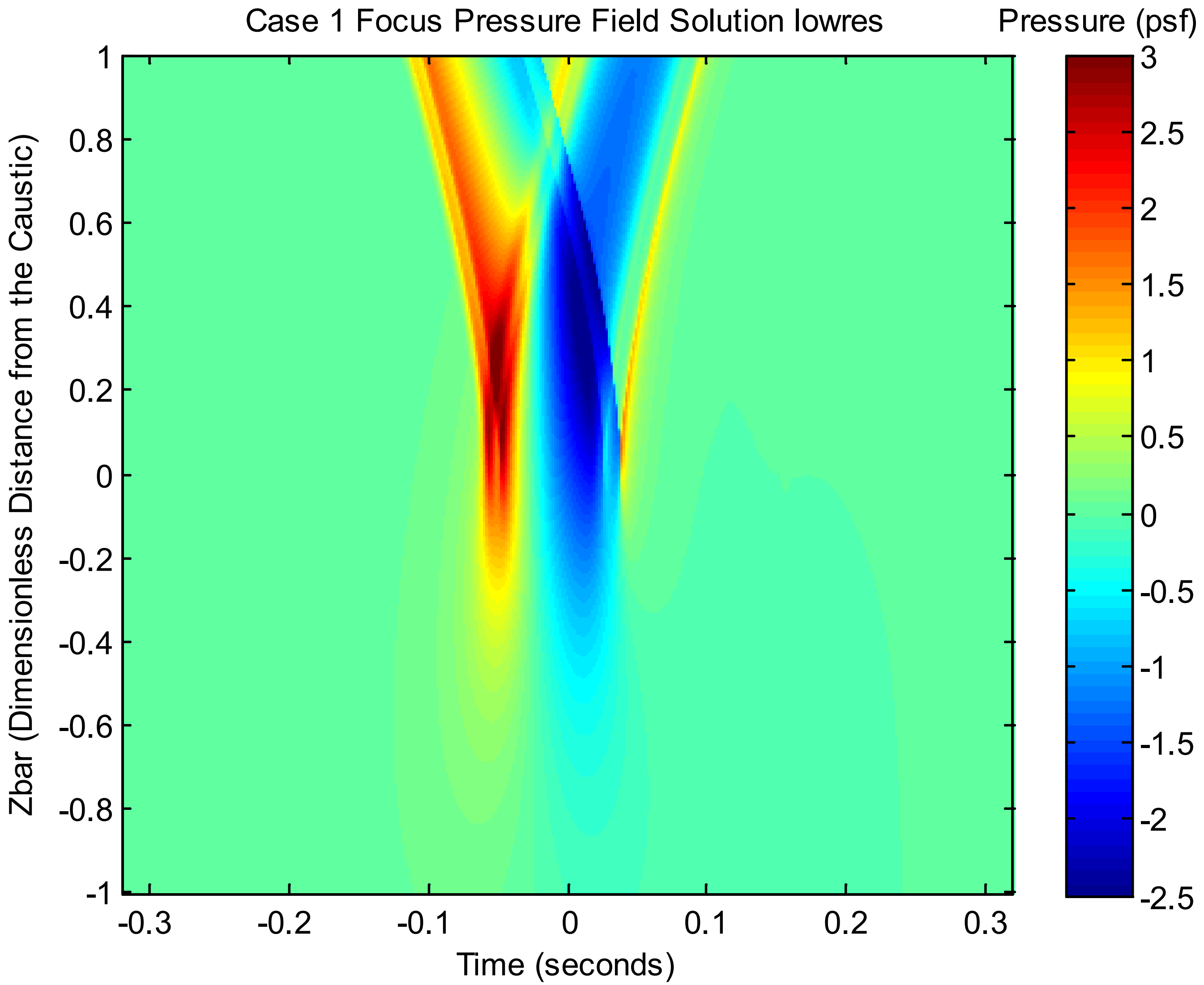
Final Submitted Analysis:

```
tricomi_delta.exe Tricomi.inp Try5-fs24k-tm18.out -tt0.5 -ii999999 -tm18.0 -fs24000.
```

** tm17 fs 32k and 50k crash*

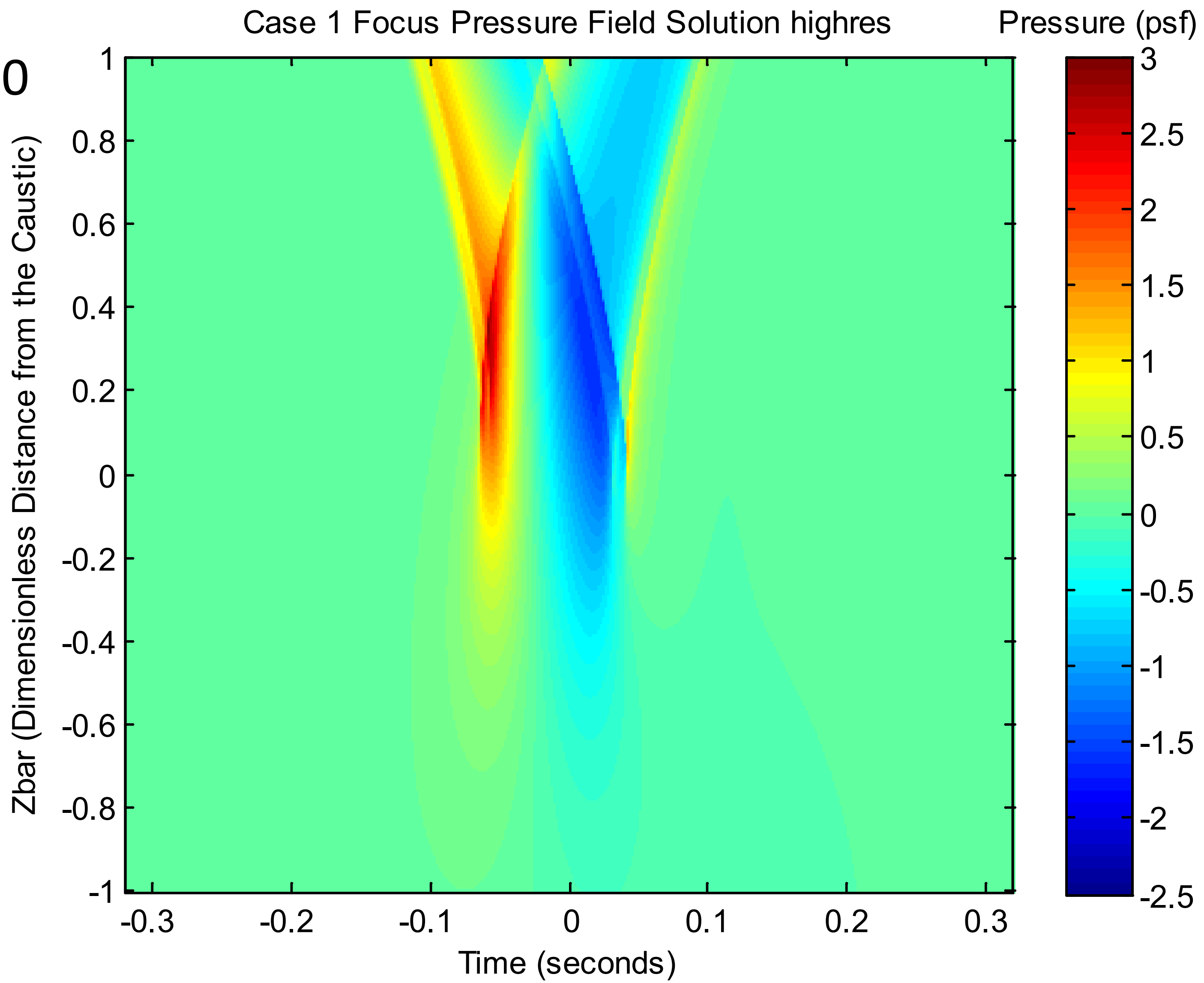
# Baseline "lowres" – tm10.1

- fs 13000, dz 4000
- *10.1 was too short as parameters haven't converged*

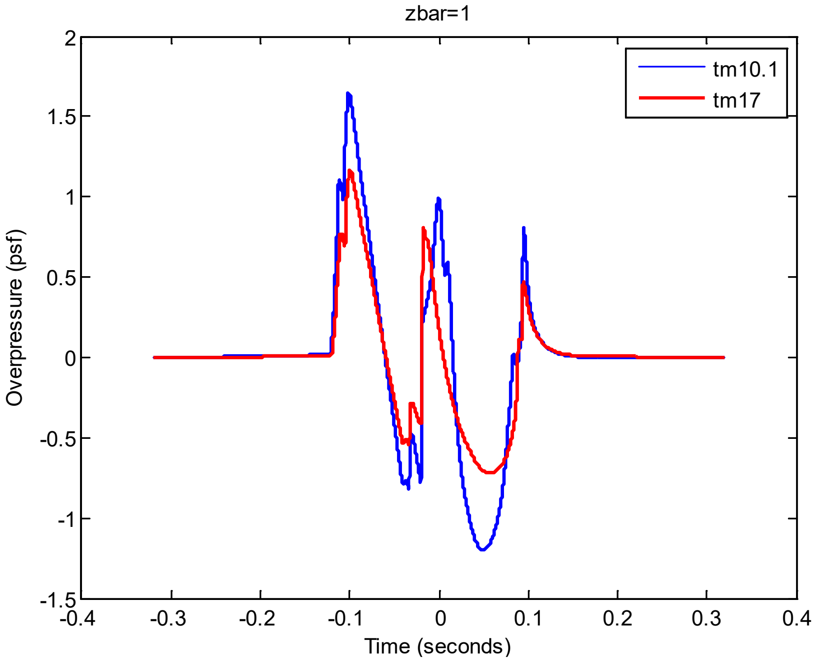


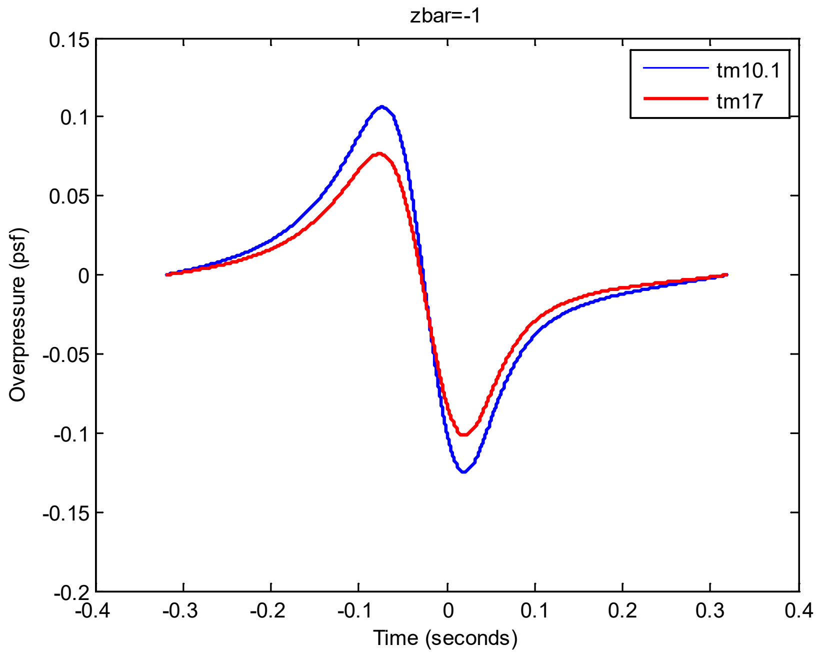
# "Highres"– tm17

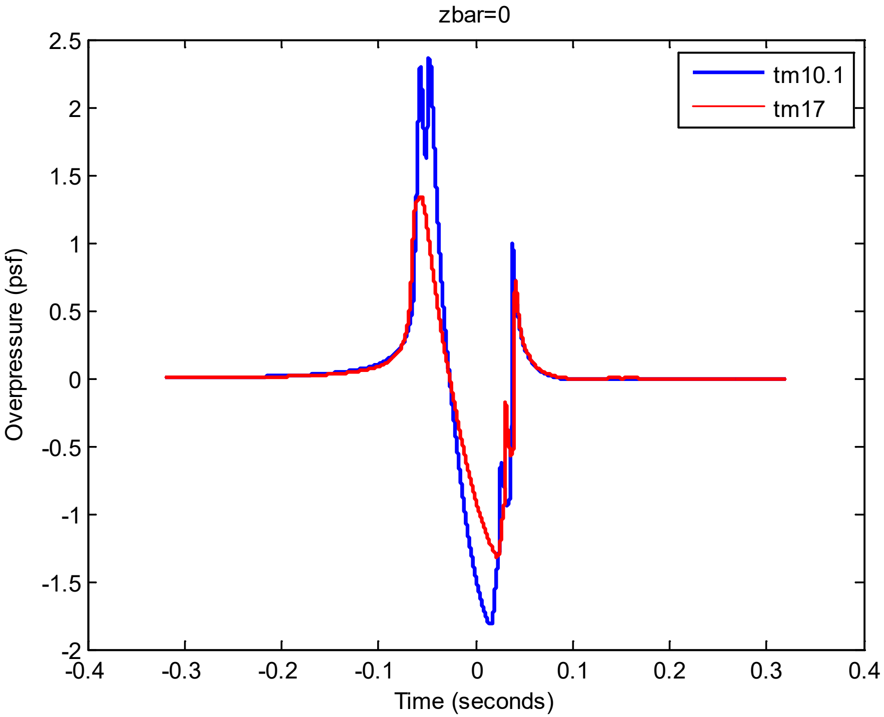
- fs 13000, dz 4000



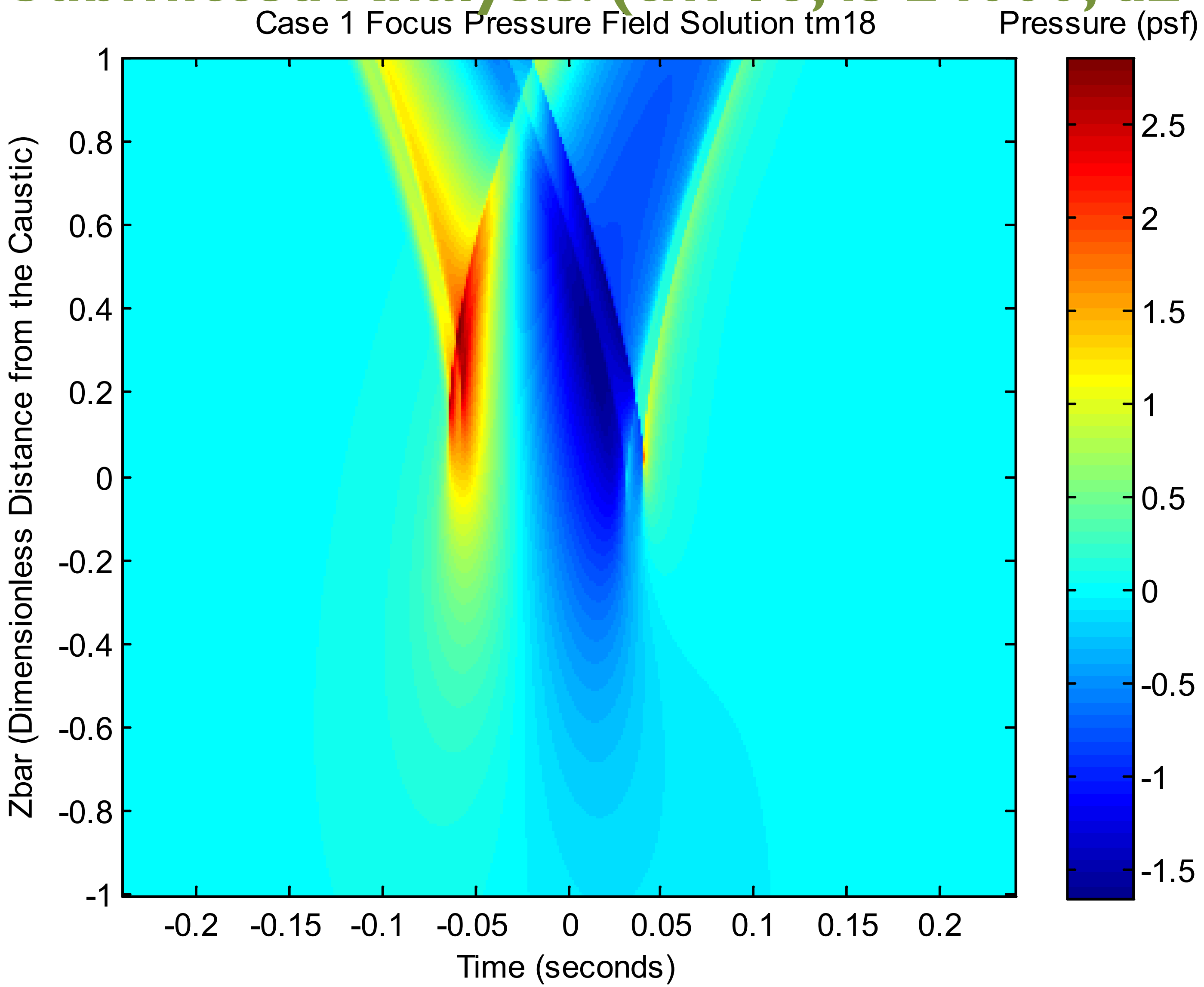
# tm 10.1 vs tm 17 – Signature Comparison

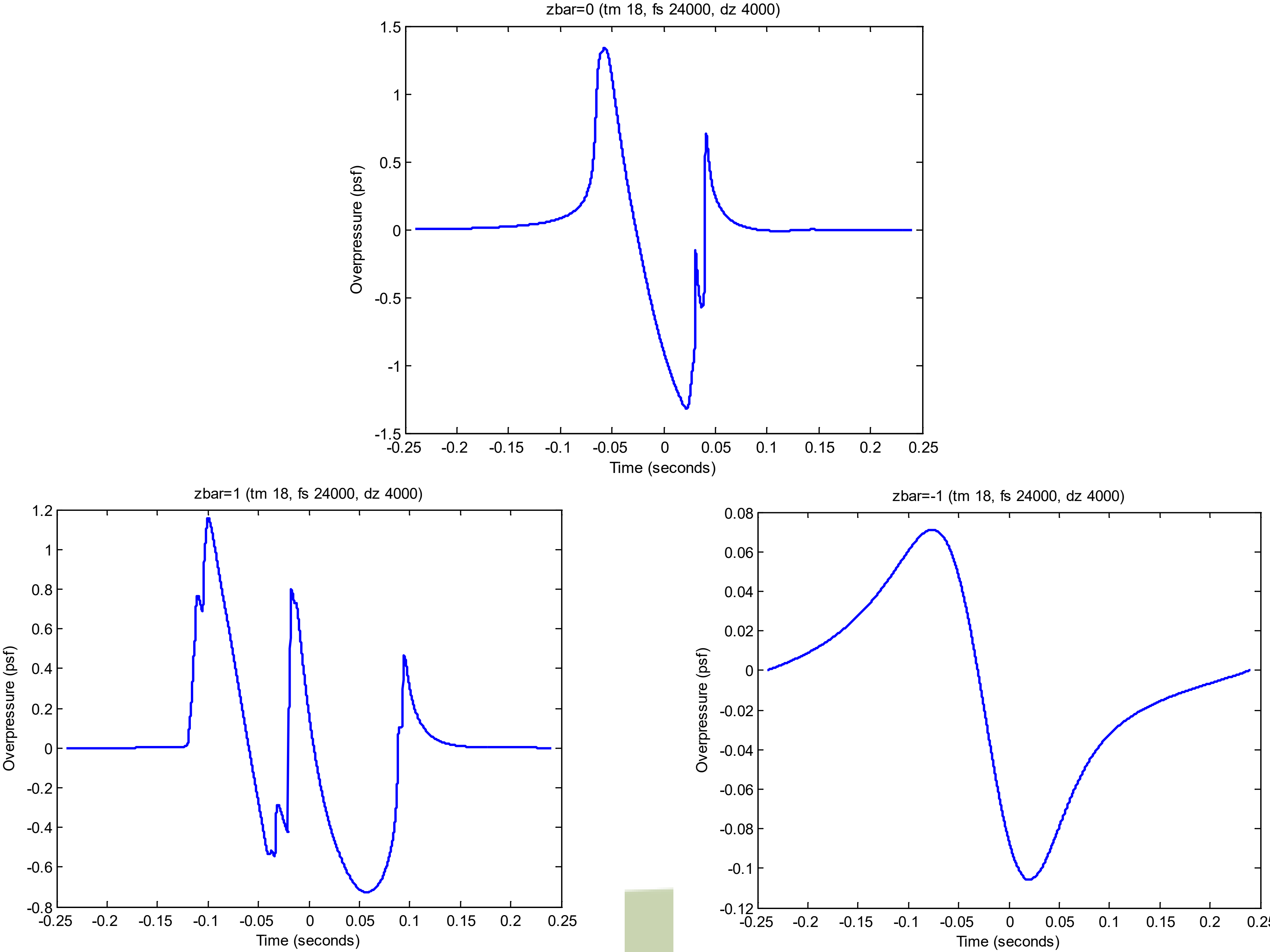


# Results of Convergence Parameter Study Final Submitted Analysis: (tm 18, fs 24000, dz 4000)




zbar=0 (tm 18, fs 24000, dz 4000)
Overpressure (psf)
Time (seconds)
zbar=1 (tm 18, fs 24000, dz 4000)
Overpressure (psf)
Time (seconds)
zbar=-1 (tm 18, fs 24000, dz 4000)
Overpressure (psf)
Time (seconds)

# Focus Metrics

| Ground Intersection Point (zbar=0) | | | |
|---|---|---|---|
| X (ft) | Y (ft) | Z (ft) | T (seconds) |
| 51,715. 7 | 0 | 190 | 66.086 |

| Loudness Metrics | | | |
|---|---|---|---|
| | PL | ASEL | CSEL |
| Zbar=1 | 99.98 | 84.56 | 104.67 |
| Zbar=0 | 101.19 | 86.62 | 105.08 |
| Zbar=-1 | 3.17 | 13.05 | 70.08 |

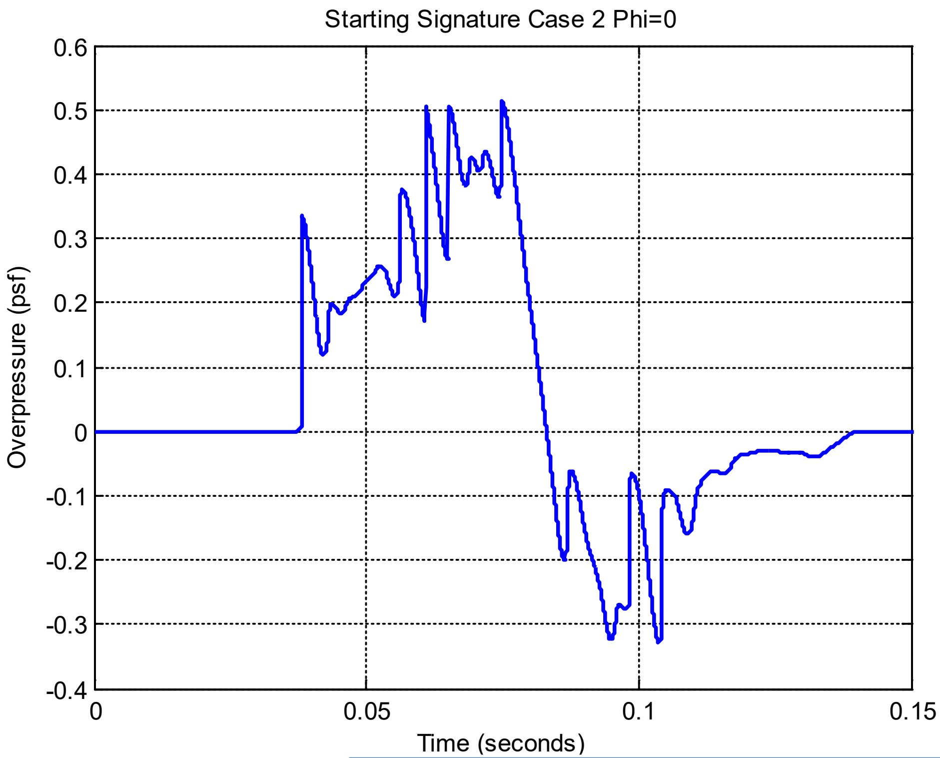
# Case 2: C609 early version of X-59 QueSST

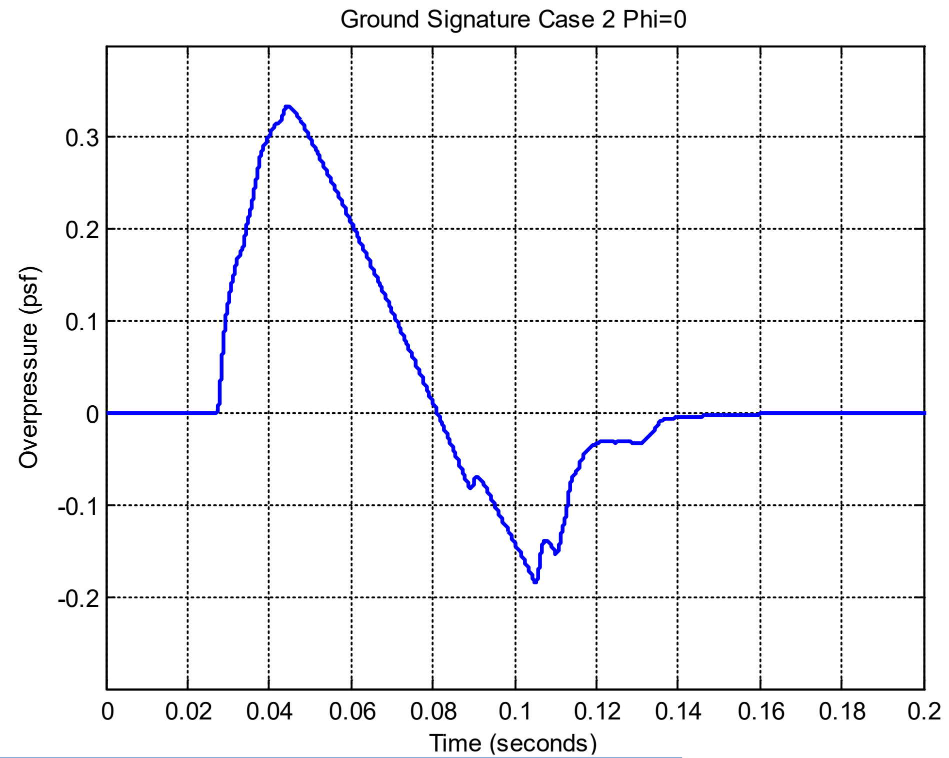
- Mach number = 1.4
- Flight alt = 54,000 ft (16,459.2 m)
- Propagation starting distance from the body = 270 ft (82.296 m)
- R/L = 3.0
- Vehicle length = 90 ft (27.432 m, from R/L)
- Ground refl. factor = 1.9
- Ground alt = 361 ft (110.011 m)
- CFD source characteristics

# Selected Results – Case 2 Measured Atmosphere

# HeadlessBurgers: Propagation with Molecular Relaxation

- Utilized FOBoom to determine ray paths
- Propagates signatures along prescribed ray
- Utilizes atmospheric parameters as output by FOBoom
- Flight altitude = 54,000 ft
- Burgers equation propagation started at 53,000 ft altitude
- Sampling rate = 102.4 kHz, time-step factor = 0.002
- Anti-Gibbs phenomenon filter used
- Ground reflection factor = 1.9

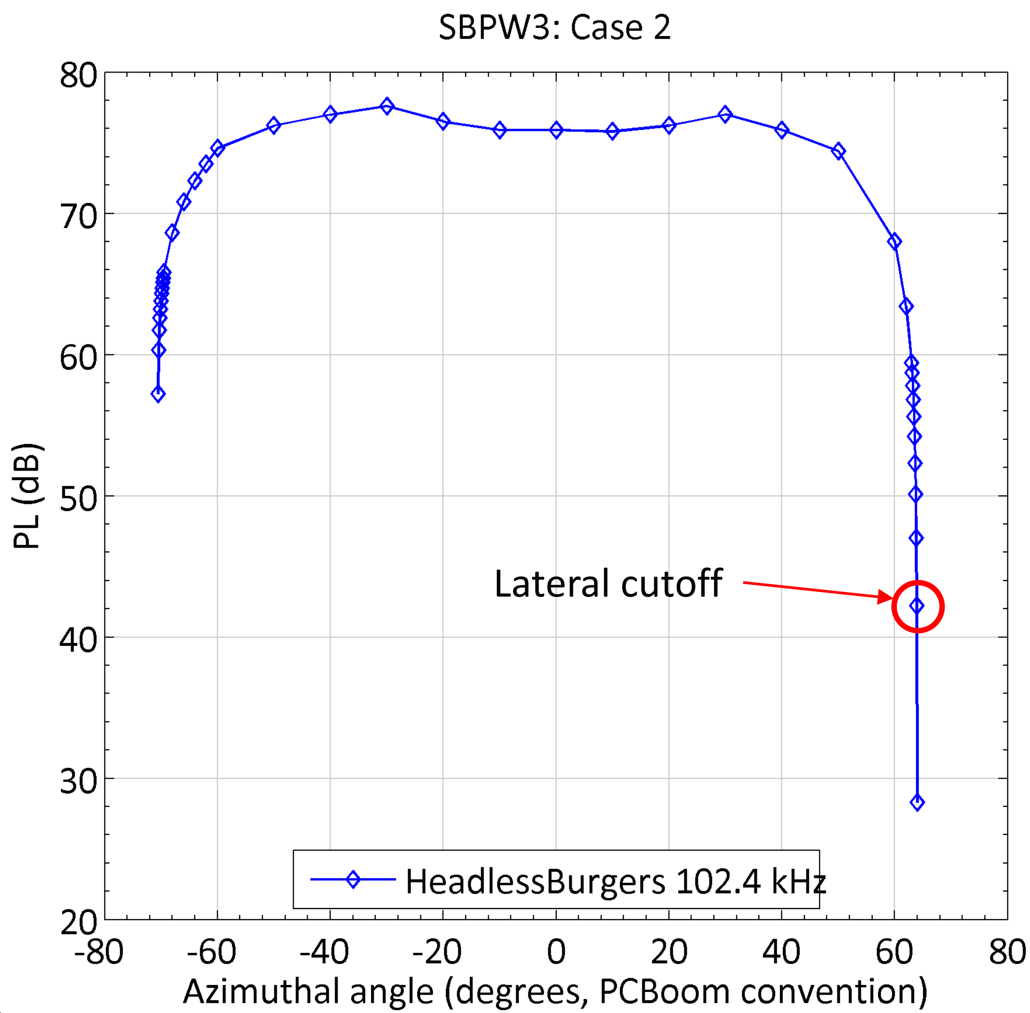


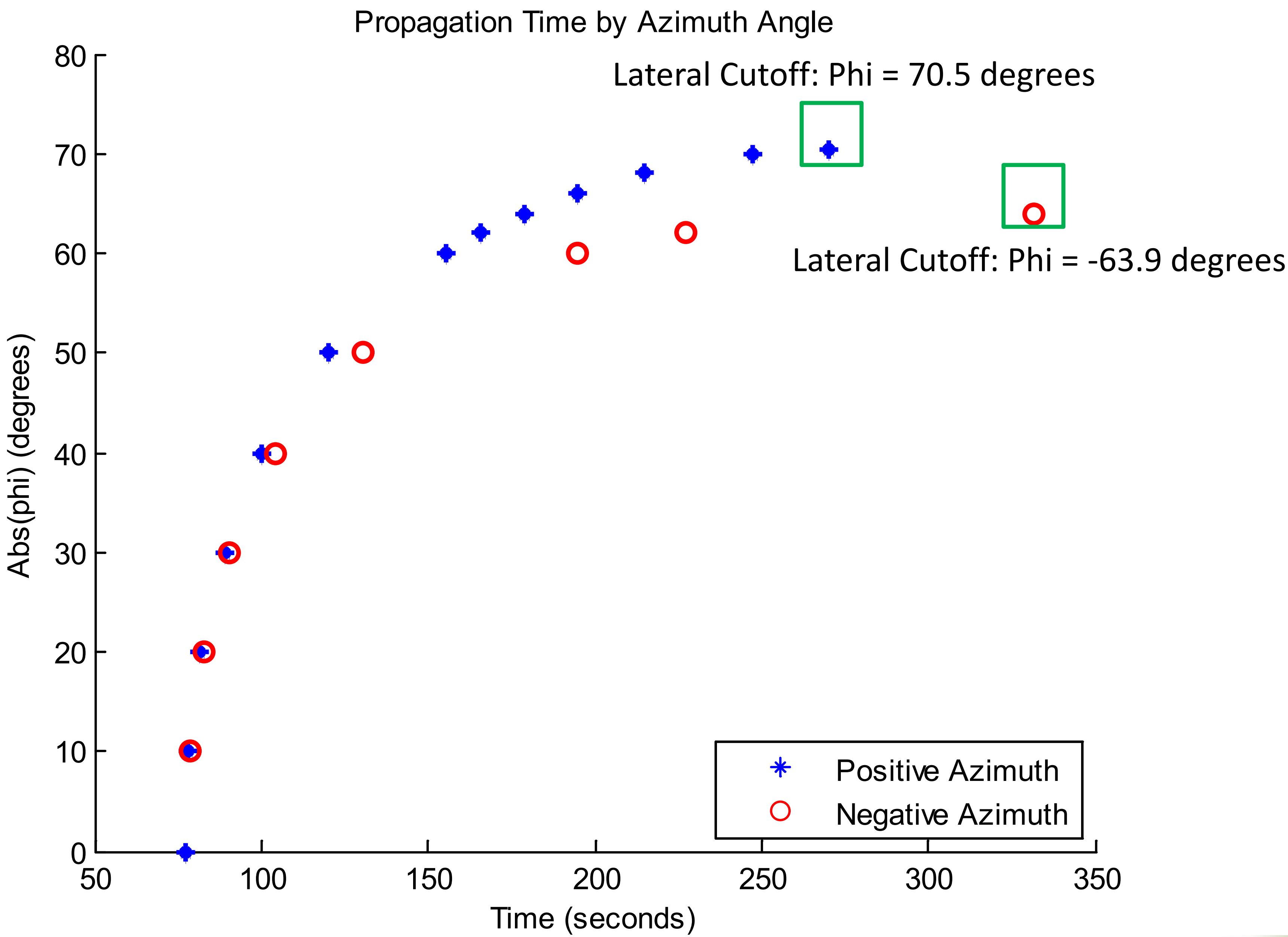



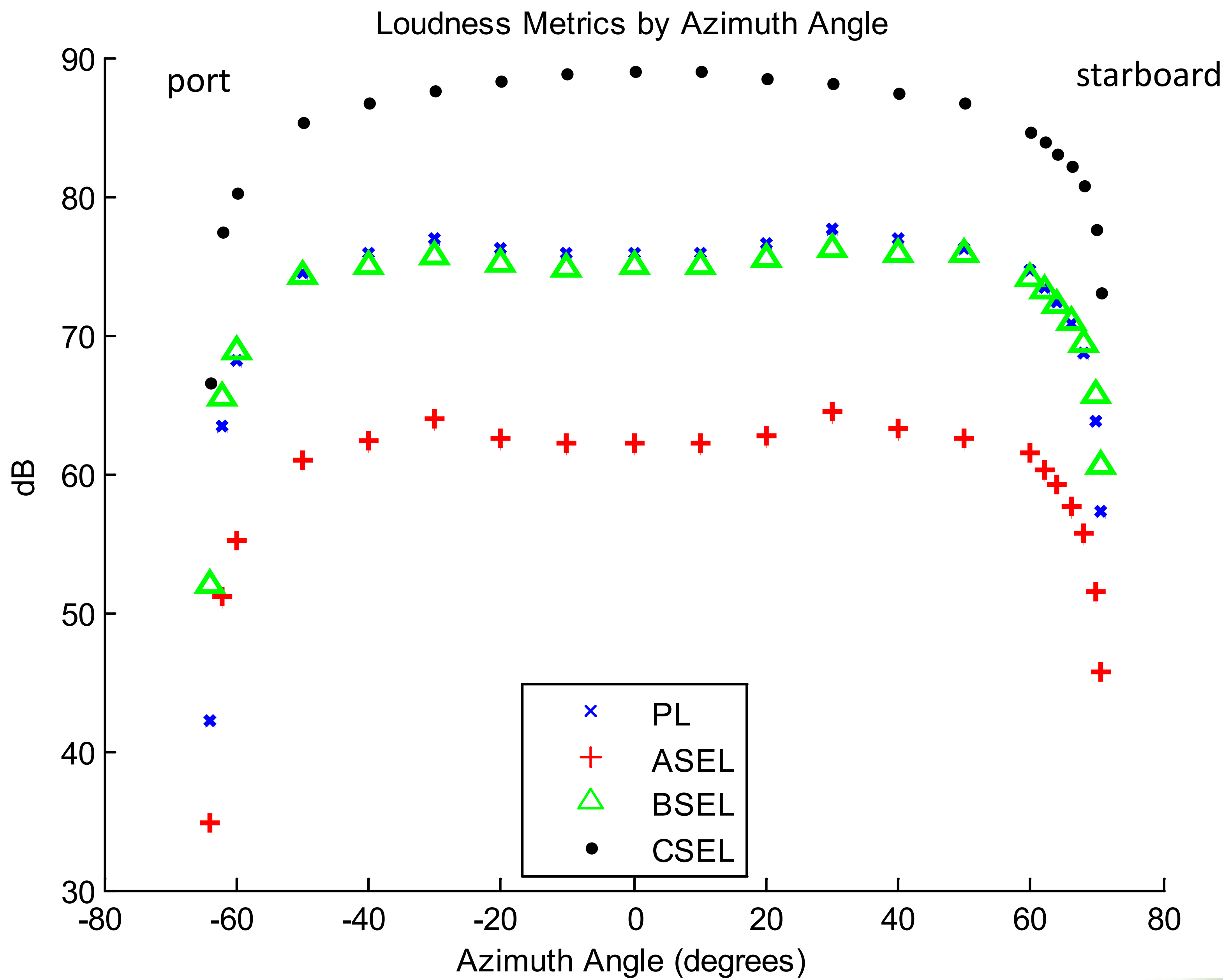

| Ground Signature Metrics at Phi = 0 | |
|---|---|
| PLdB | 75.90 |
| ASEL | 62.25 |
| BSEL | 74.97 |
| CSEL | 89.12 |
| FSEL | 102.34 |
| Pmax | 0.34 |

# Lateral Cutoff Determination

- Lateral cutoff angles determined using built-in FOBoom algorithm
- FOBoom raytracing:
  - LEGACY mode
  - 0.25° ray tube angular width
  - 0.1 time step integration along a ray
- Lateral cutoff angles refined by incrementing azimuth angles 0.1°; resulting cutoff angles were around 0.5° farther offtrack
- Burgers propagation results and ray paths examined near cutoff to ensure reasonable results
  - Results at 64° deemed unrealistic
  - 63.9° taken as lateral cutoff on that side



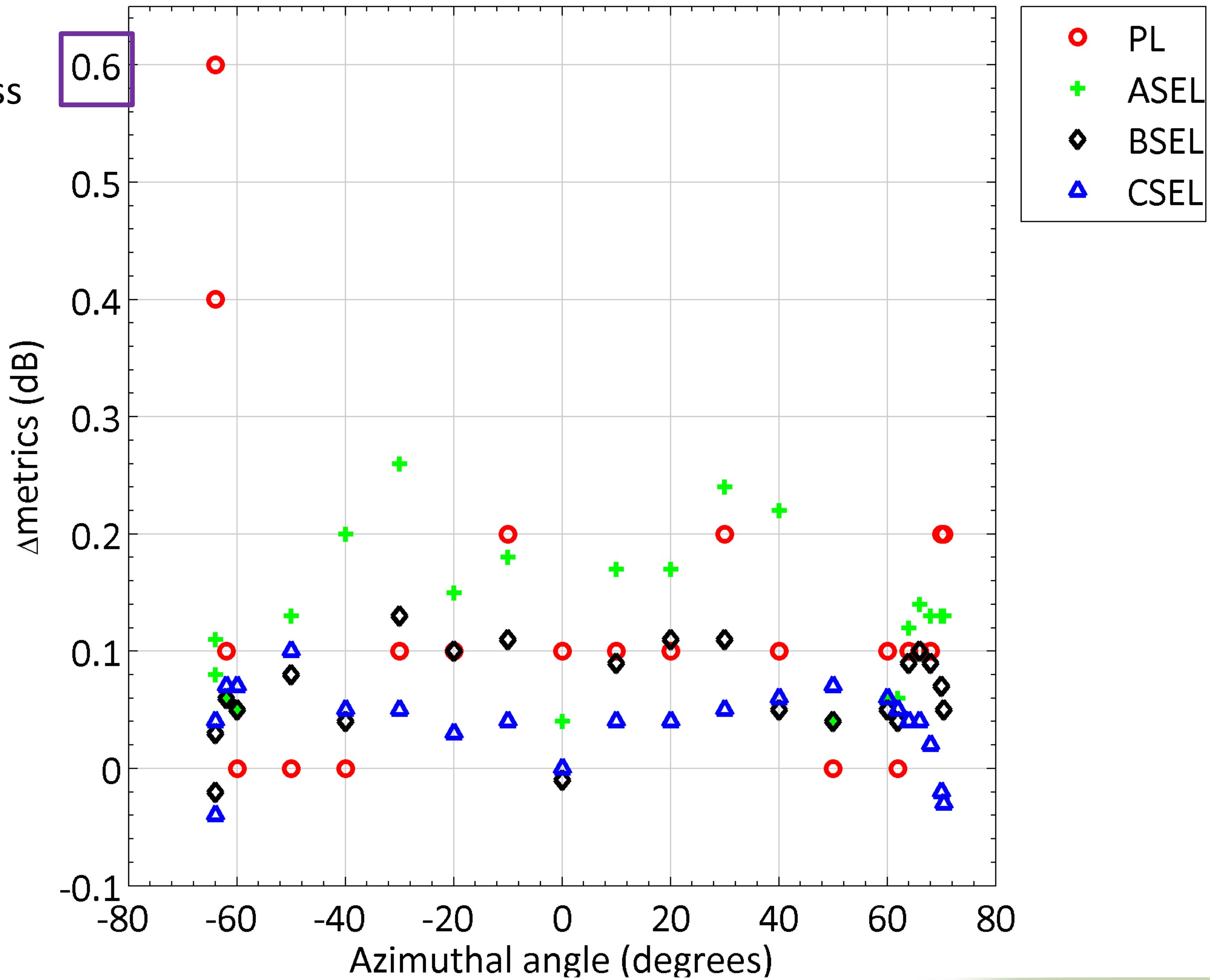

Propagation Time by Azimuth Angle
Lateral Cutoff: Phi = 70.5 degrees
Lateral Cutoff: Phi = -63.9 degrees
Abs(phi) (degrees)
0
10
20
30
40
50
60
70
80
Time (seconds)
50
100
150
200
250
300
350
Positive Azimuth
Negative Azimuth



Loudness Metrics by Azimuth Angle
port
starboard
dB
90
80
70
60
50
40
30
-80
-60
-40
-20
0
20
40
60
80
Azimuth Angle (degrees)
PL
ASEL
BSEL
CSEL

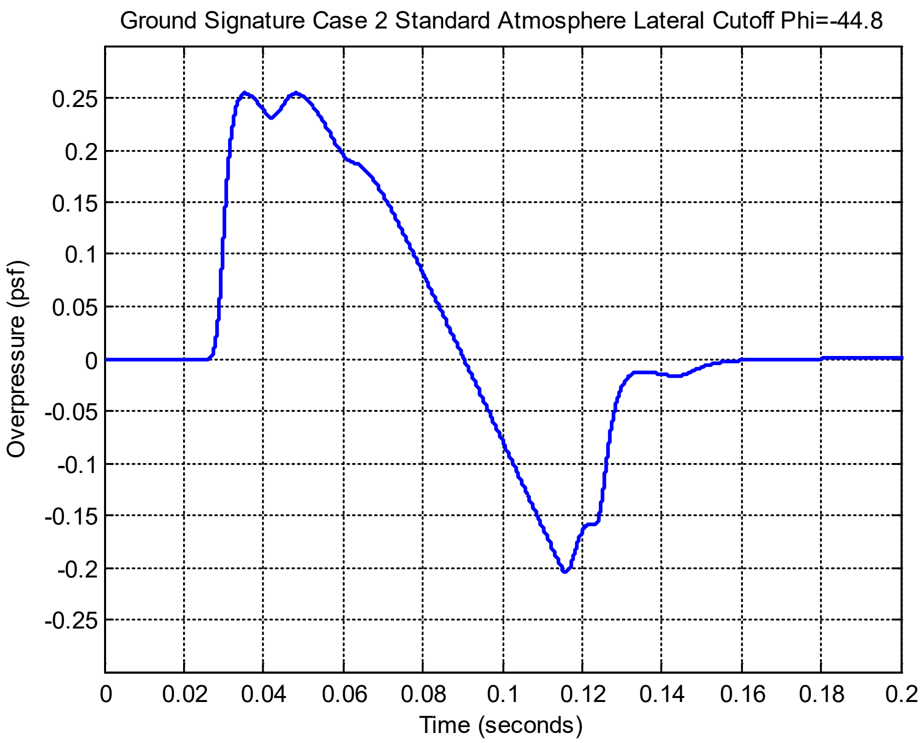
# Case 2: HeadlessBurgers Loudness Metrics Sampling Rate Comparison (102.4 kHz - 51.2 kHz)

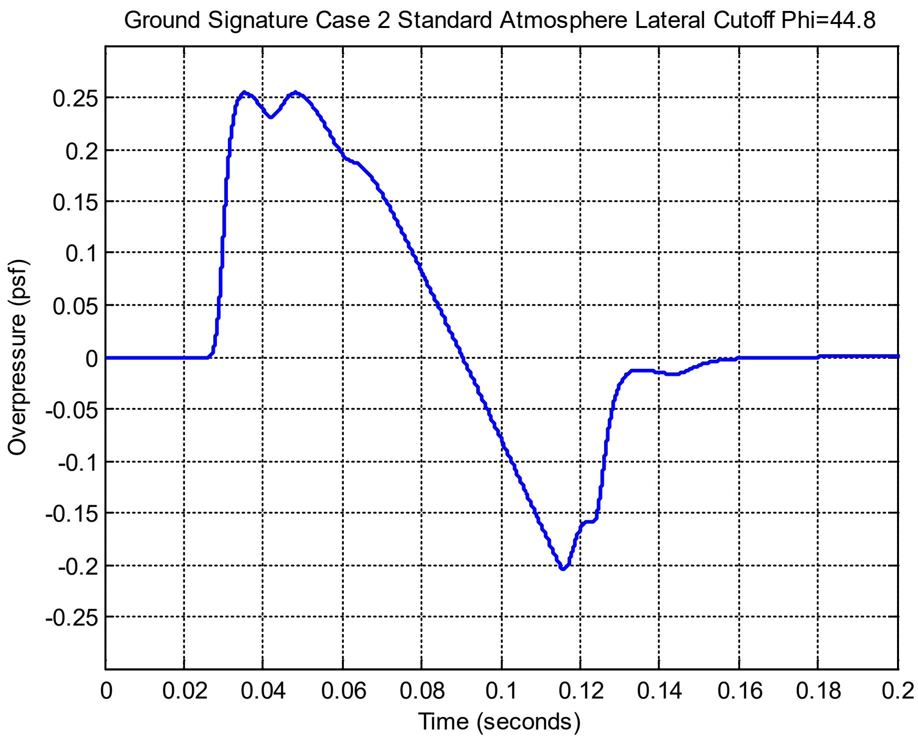
<0.6 dB delta across all metrics



# Case 2 Standard Atmosphere Lateral Cutoff

# Standard Atmosphere Lateral Cutoff Ground Signatures



# Standard Atmosphere Lateral Cutoff Metrics

| Ground Intersection Point | | | | |
|---|---|---|---|---|
| Phi | X (ft) | Y (ft) | Z (ft) | T (seconds) |
| -44.8 | 133167.2 | 91938.3 | 361 | 165.252 |
| 44.8 | 133167.2 | -91938.3 | 361 | 165.252 |

| Loudness Metrics | | | | |
|---|---|---|---|---|
| Phi | PL | ASEL | BSEL | CSEL |
| -44.8 | 75.10 | 60.94 | 76.59 | 89.23 |
| 44.8 | 75.10 | 60.94 | 76.59 | 89.23 |

# Final Thoughts

# PCBoom Analysis Observations

- Inconsistency in signature point limit in various tools
- PL calculation discrepancy between some tools
  - Original version of HeadlessBurgers reports approximately 3 dB higher than tools which include a “two-shocks factor” of 1/2 in the frequency spectrum calculation
  - That factor added when recompiling HeadlessBurgers to create a new version of the software with which the metrics were calculated
- FOBoom lateral cutoff algorithm stops short of what can be run by manually incrementing azimuth angles by 0.1 degrees

# Some Possible Ideas for SBPW4

- Turbulence Modeling
  - PCBoom Crows' Method (legacy); FIR Filters; TURBO
- Additional focus cases: centerline and lateral positions
  - Lateral/Cutoff cases might require a 3D Tricomi solver (or is it possible to do some sort of coordinate transformation/reference geometry?)
- Analysis of shaped booms & propagation for Mach Cutoff into the zone of silence
- Effect of vertical wind speeds on lateral booms
- Over the Top propagation – e.g. "New England Booms" FAA 80-22 and the need for prediction of OTT footprints for non low-boom aircraft operations
- Prediction of signatures and metrics on elevated microphones
- Prediction over varying terrain

Thank you for your attention.
Any questions?