2^{nd} Boom Prediction Workshop: sBOOM Propagation Results

Sriram K. Rallabhandi

NASA Langley Research Center

Outline

- Overview of cases analyzed
- Propagation prediction code
- Propagation parameters
- Loudness convergence
- Comparison of the following at different roll angles for both LM1021 and Axi-symmetric body
    - Ground signatures
    - Loudness metrics and statistics
    - Lateral cut-offs and ranges
    - Spectra
- Summary

Overview of Cases Analyzed

CASE 1: NASA N+2 LM 1021-01 Configuration

- Runs carried out:
  - Roll angles of 10^0 intervals using all prescribed atmospheric profiles
- Submitted Data:
  - Ground signatures across the carpet including those corresponding to the lateral cut-off
  - Lateral cut-off angles on both sides of the carpet
  - Loudness metrics (PL, ASEL) corresponding to all the ground signatures being reported
  - Loudness convergence history with increasing sampling frequencies
  - Carpet ranges

Sriram.Rallabhandi@nasa.gov

Overview of Cases Analyzed

CASE 2: Axi-symmetric body of revolution

- Runs carried out:
    - Roll angles of 5^0 intervals using all prescribed atmospheric profiles
- Submitted Data:
    - Ground signatures across the carpet including those corresponding to the lateral cut-off
    - Lateral cut-off angles on both sides of the carpet
    - Loudness metrics (PL, ASEL) corresponding to all the ground signatures being reported
    - Loudness convergence history with increasing sampling frequencies
    - Carpet ranges

Sriram.Rallabhandi@nasa.gov

Propagation Prediction Code: sBOOM

sBOOM[1]
- Propagation based on lossy Burgers equation
- Features
  - Under-track, off-track signatures
  - Horizontally stratified winds
  - Acceleration, trajectory, maneuvers

Uses
- High-fidelity analysis and design optimization capability
- Used at NASA, and some industry and academic partners
- Demonstrated over multiple shape optimization exercises
- Adjoint sensitivities with respect to atmospheric conditions for robust design optimization

Unique Features
- Discrete-adjoint[2] based design capability
  - Ground loudness optimization
  - Ground target signature matching
  - Equivalent area matching
  - Target equivalent area generation
  - Atmospheric sensitivities

New Features
- *Boom focusing*
- *Lateral cut-off angle prediction of primary boom carpet*

[1]*Rallabhandi, S. K., "Advanced Sonic-Boom Prediction Using the Augmented Burgers Equation", Journal of Aircraft, Vol. 48, pp: 1245-1253, 2011*

[2]*Rallabhandi, S. K., Nielsen, E. J., Diskin, B., "Sonic-Boom Mitigation Through Aircraft Design and Adjoint Methodology", Journal of Aircraft, Vol. 51, pp: 502-510, 2014*

sBOOM is under active development. Contact Sriram.Rallabhandi@nasa.gov or Lori.Ozoroski@nasa.gov to get a copy of sBOOM

Propagation Prediction Code: sBOOM

- Current implementation of sBOOM based on numerical solution of the augmented Burgers Equation
- Non-dimensional version of augmented Burgers equation

$$\frac{\partial P}{\partial \sigma} = P\frac{\partial P}{\partial \tau} + \frac{1}{\Gamma}\frac{\partial^2 P}{\partial \tau^2} + \sum_{\nu} C_{\nu} \frac{\frac{\partial^2}{\partial \tau^2}}{1+\theta_{\nu}\frac{\partial}{\partial \tau}} P - \frac{\frac{\partial A}{\partial \sigma}}{2A} P + \frac{\frac{\partial(\rho_0 c_0)}{\partial \sigma}}{2\rho_0 c_0} P$$

- Solution process involves operator splitting scheme

$$\begin{aligned}
\frac{\partial P}{\partial \sigma} &= p\frac{\partial P}{\partial \tau}\text{[Non-Linearity]}\\
\frac{\partial P}{\partial \sigma} &= \frac{1}{\Gamma}\frac{\partial^2 P}{\partial \tau^2}\text{[Absorption]}\\
\frac{\partial P}{\partial \sigma} &= \Sigma_{\nu}\frac{C_{\nu}\frac{\partial^2}{\partial \tau^2}}{1+\theta_{\nu}\frac{\partial}{\partial \tau}}P\text{[Molecular Relaxation]}\\
\frac{\partial P}{\partial \sigma} &= -\frac{1}{2G}\frac{\partial G}{\partial \sigma}P\text{[Ray Tube Spreading]}\\
\frac{\partial P}{\partial \sigma} &= \frac{1}{2\rho_0 c_0}\frac{\partial(\rho_0 c_0)}{\partial \sigma}P\text{[Atmospheric Stratification]}
\end{aligned}$$

- Crank-Nicolson finite difference scheme used for absorption and relaxation

Propagation Prediction Code: Loudness

Loudness calculation
•NASA Langley's LCASB[3] code
•Used at NASA, and some industry and academic partners

Computing platform
• All propagation runs carried out on Linux
• One processor for each roll angle
• Extrapolations at multiple roll angles carried out simultaneously
• Computational wall run times: few seconds to ~30 minutes depending on the sampling frequency etc.

[3] *"A loudness calculation procedure applied to shaped sonic booms" K.P. Shepherd and B.M. Sullivan, NASA-TP-3134, 1991*

Prediction Code Parameters

Propagation parameters LM1021

- Cruise Mach = 1.6, Cruise Altitude = 55000 ft, Off-body distance = 730.3 ft
- Sampling frequencies: 10 – ~200 kHz

Propagation parameters Axibody

- Cruise Mach = 1.6, Cruise Altitude = 52000 ft, Off-body distance = 423.0 ft
- Sampling frequencies: 10 – ~500 kHz

Common propagation parameters and schemes

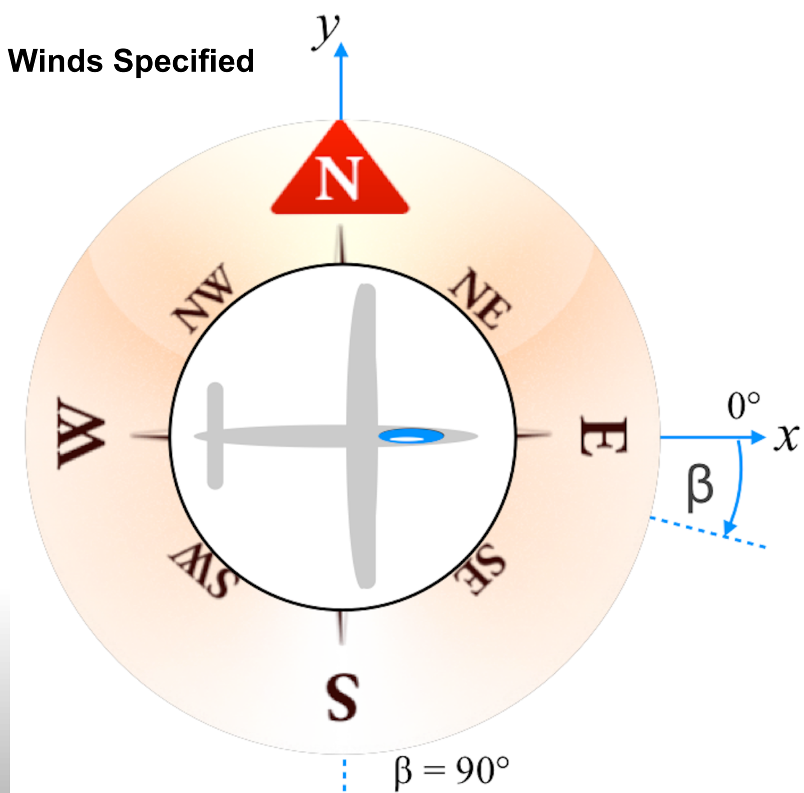
- Linearly interpolated the given near-field pressures to desired sampling
- Non-dimensional initial step size = 0.001. Dynamically controlled within the algorithm as the waveform evolves
- Ground reflection factor 1.9
- Zero climb angle
- No acceleration
- Zero turn-rate, and climb-rate
- Heading angle: East
- Winds specified

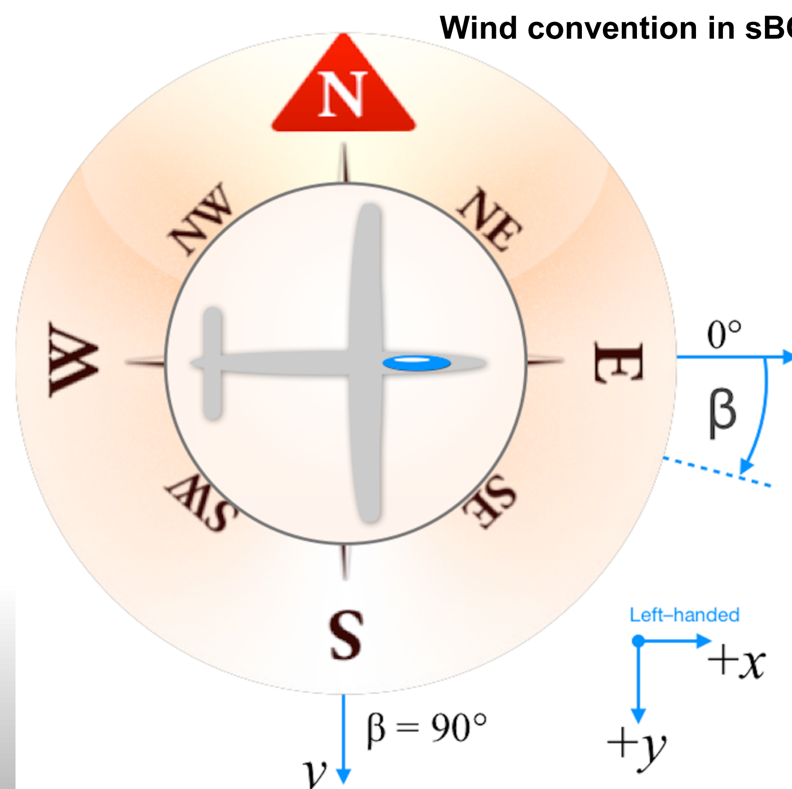
Propagation mechanisms used

- Non-linearity
- Thermo-viscous absorption
- Molecular relaxation (N_2, O_2)
- Ray-tube spreading
- Stratified atmosphere with winds

Prediction Code Parameters: Wind Convention

- Winds convention within sBOOM is different from standard
- Standard definition
  - Meridional wind: positive when blowing from south toward north
  - Zonal wind: positive when blowing from west to east
- sBOOM: Zonal wind is same as standard, Meridional wind is reversed





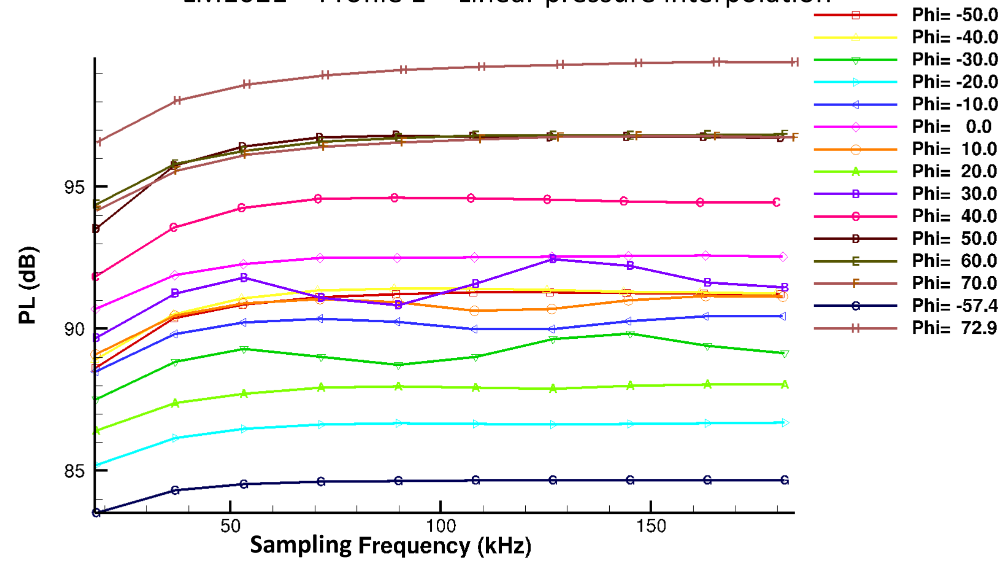
Figures Source: Michael Aftosmis

Sriram.Rallabhandi@nasa.gov

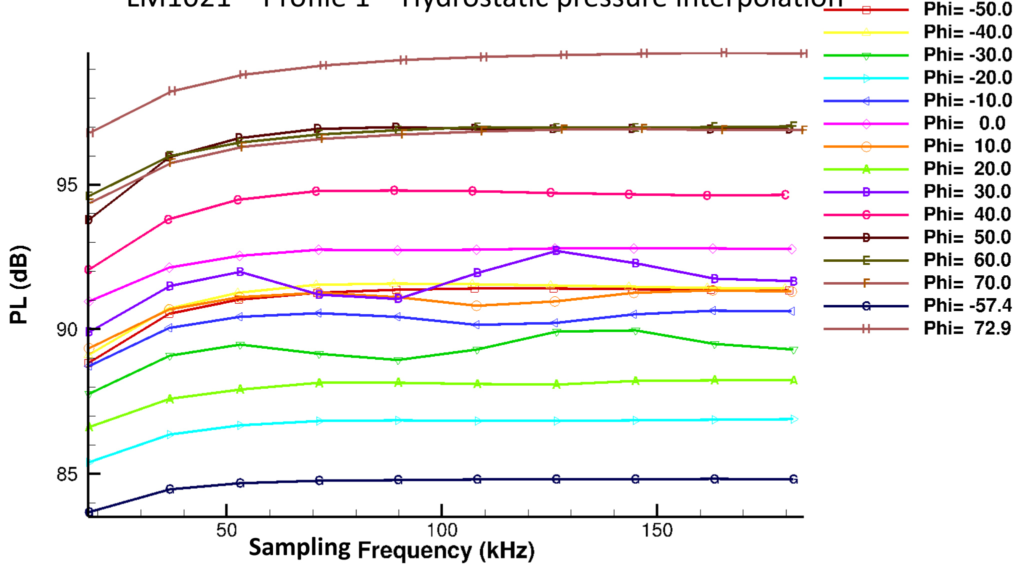
Loudness Convergence: LM1021

- Convergence criteria
  - No criteria used, just plotting values with increasing sampling frequency
- Linear and hydrostatic pressure interpolation yield almost same loudness values in this case
- Higher loudness for positive roll angles compared to negative roll angles

LM1021 – Profile 1 – Linear pressure interpolation



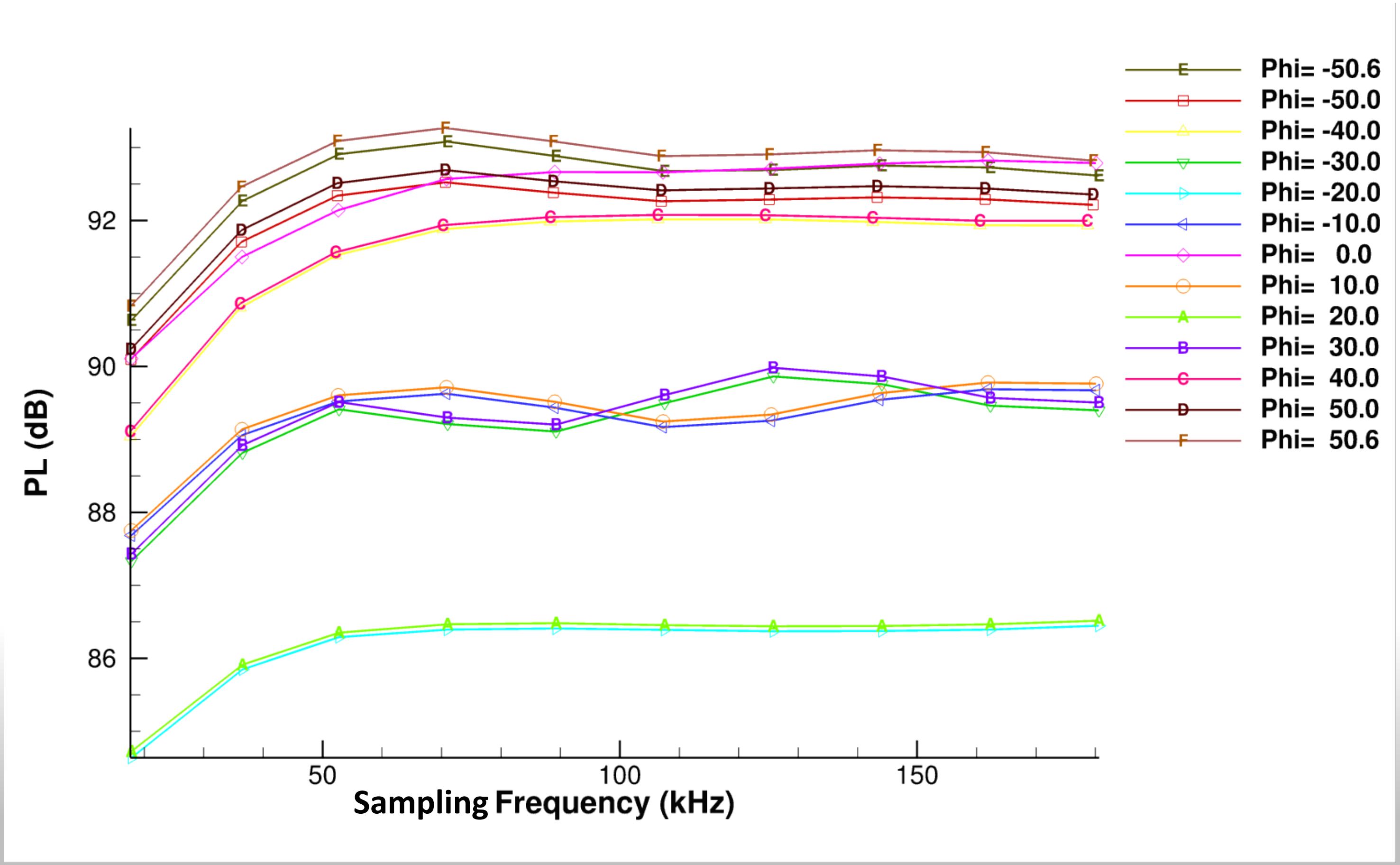
LM1021 – Profile 1 – Hydrostatic pressure interpolation



- Asymmetrical cut-off angles
- Lateral cut-off angles have the highest and lowest loudness values
- Most cases converged within 0.1 dB tolerance for < 100 kHz
- Roll angles -30 and 30 needed much higher sampling for convegence

Loudness Convergence: LM1021

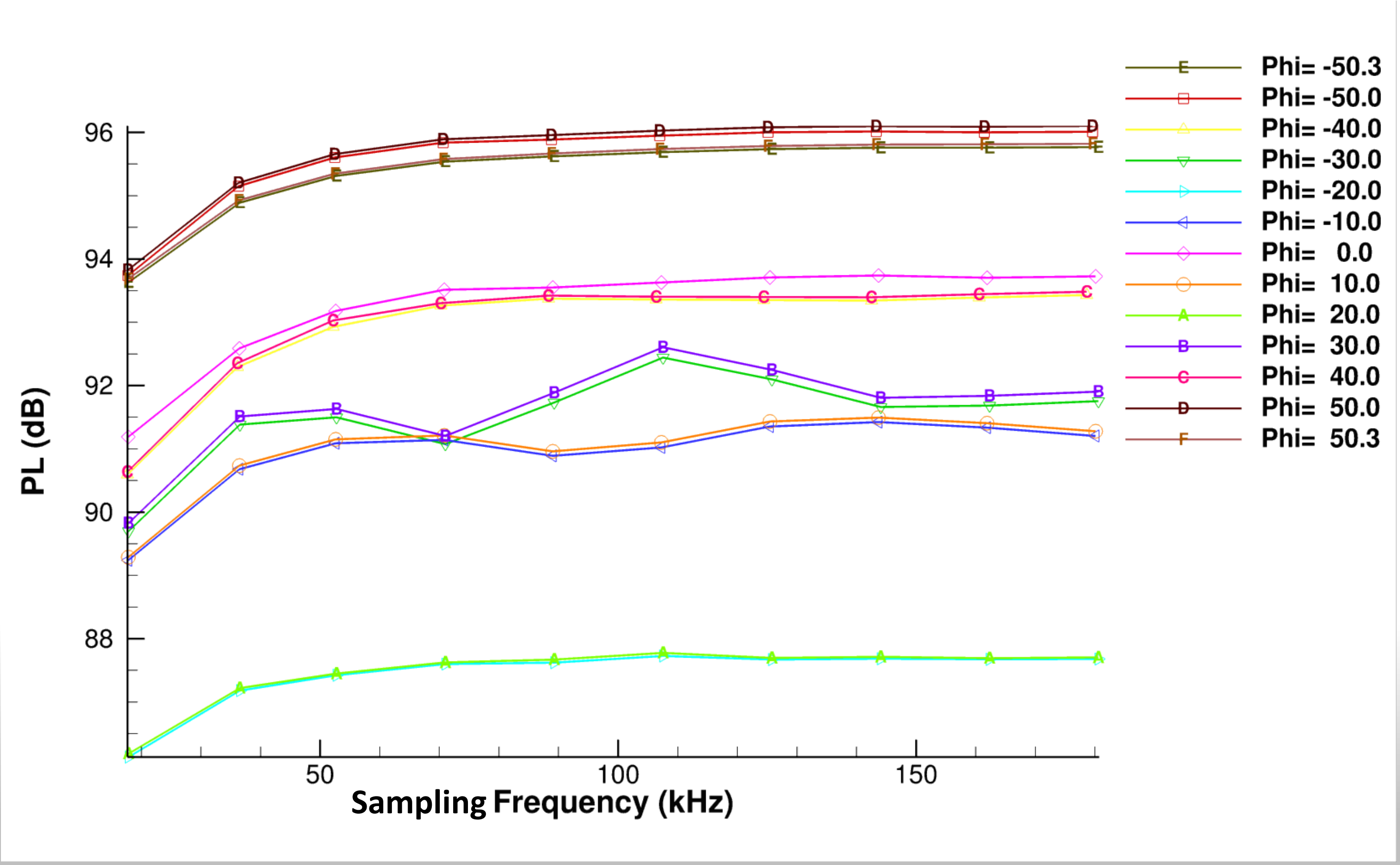
- Symmetric carpet – no winds!
- Hydrostatic interpolation has under-track and lateral cut-offs all with almost the same loudness, close to the maximum
- Most roll angles converged below 100 kHZ, except -30^0 and 30^0 roll angles



Sriram.Rallabhandi@nasa.gov

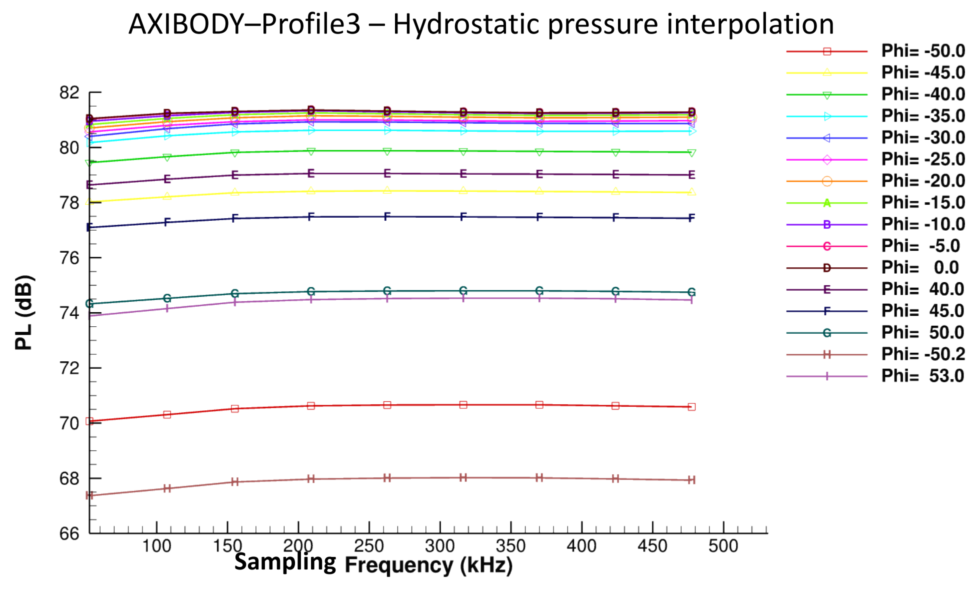
Loudness Convergence: LM1021

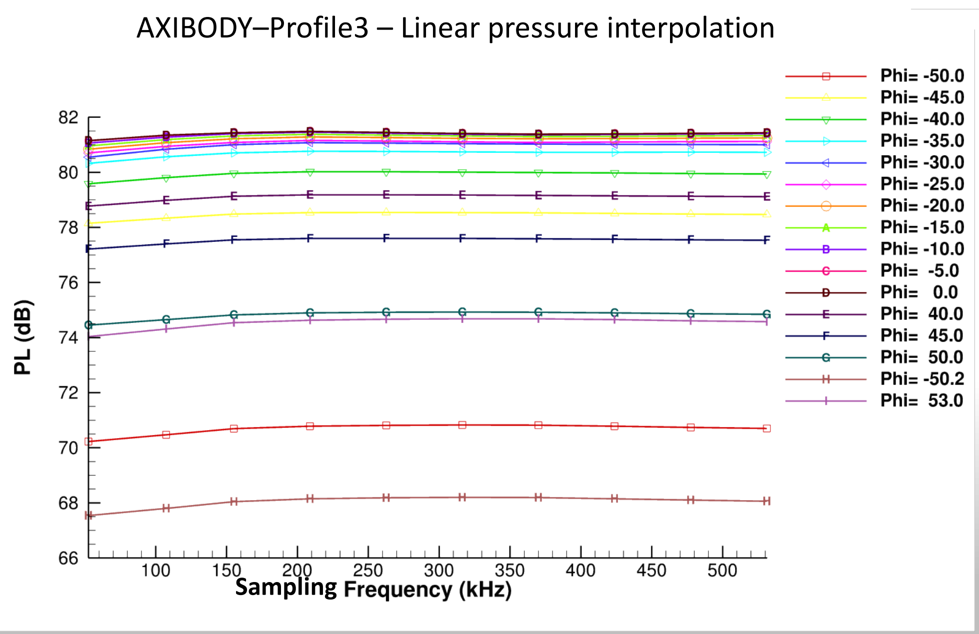
- For standard atmosphere, linear and hydrostatic pressure interpolation yield different loudness values, ~ 4dB in some cases
- With linear interpolation, under-track signature does not have the maximum loudness



Loudness Convergence: AXIBODY

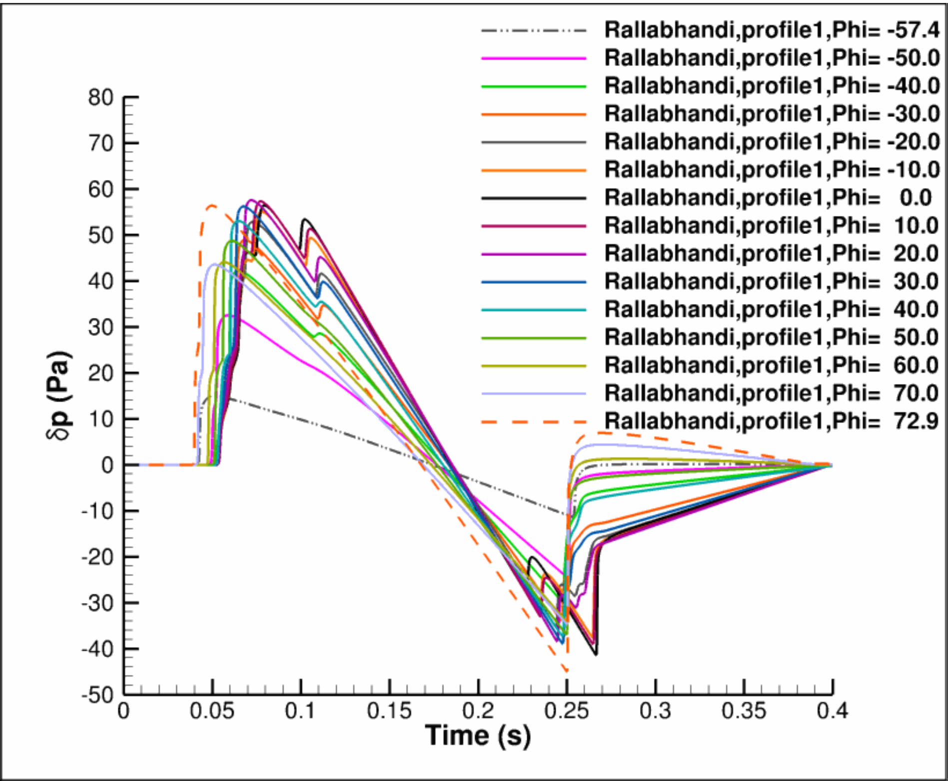
- Linear pressure interpolation produces slightly higher loudness values than hydrostatic interpolation
- Converged at ~ 150 kHz
- Higher loudness for positive roll angles compared to negative roll angles

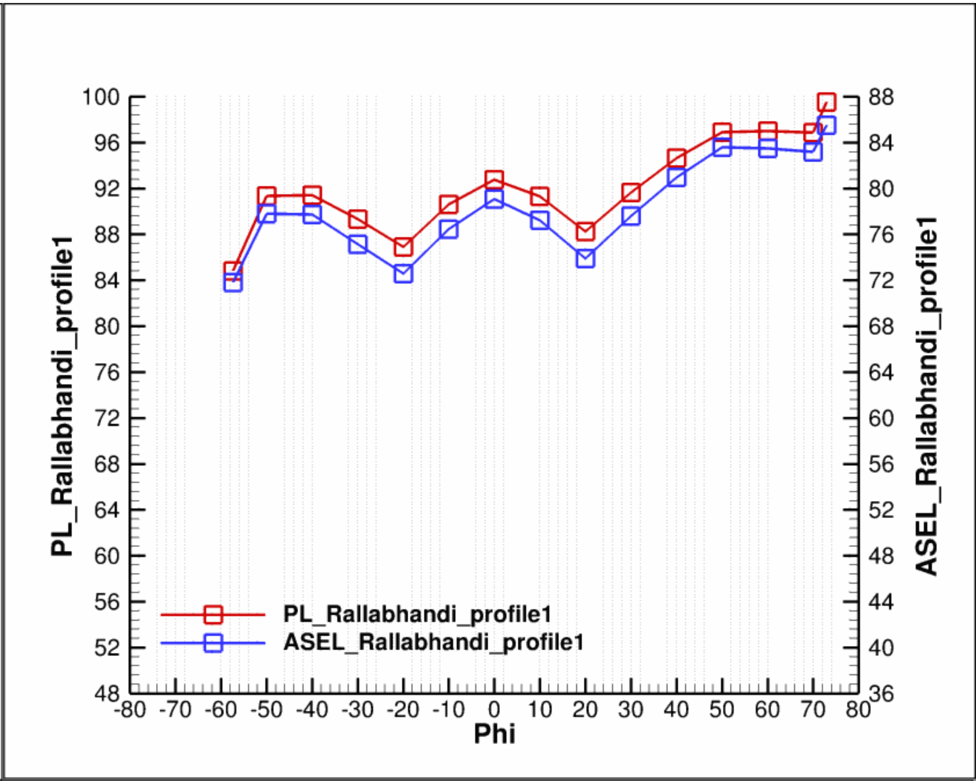


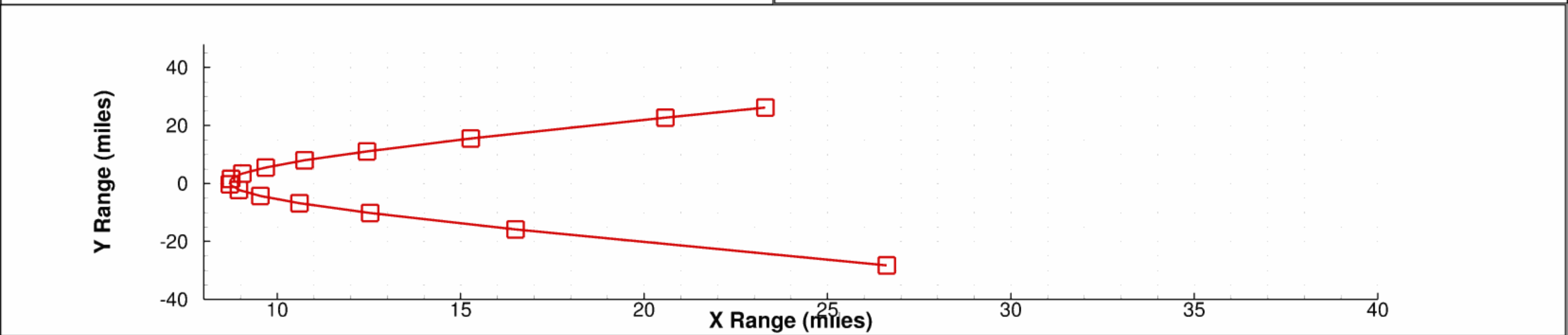


- Slightly different lateral cut-off angles

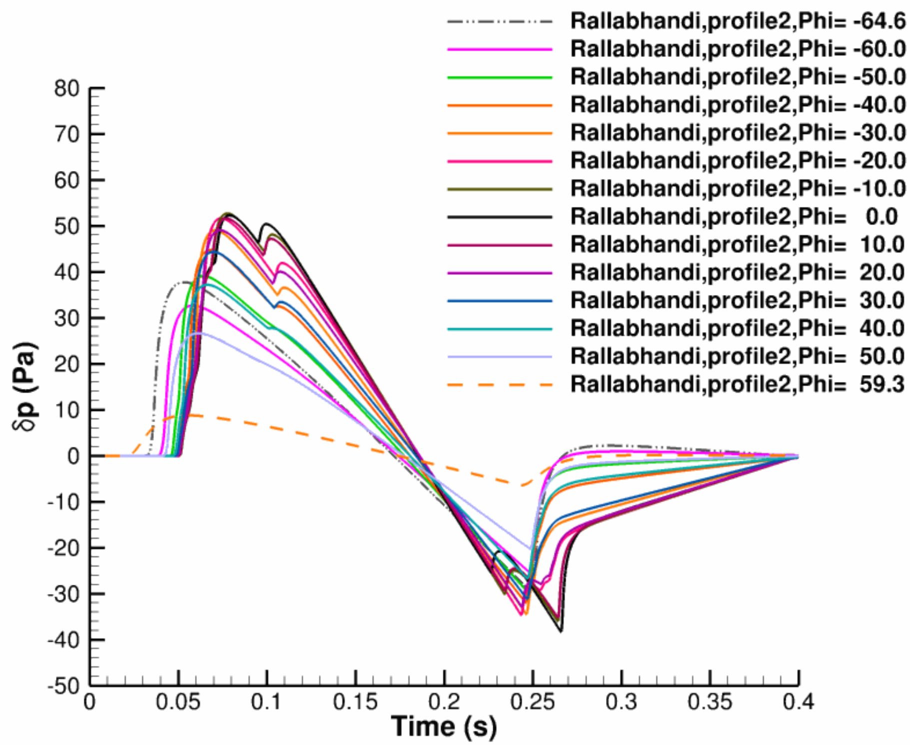
LM1021: Profile 1

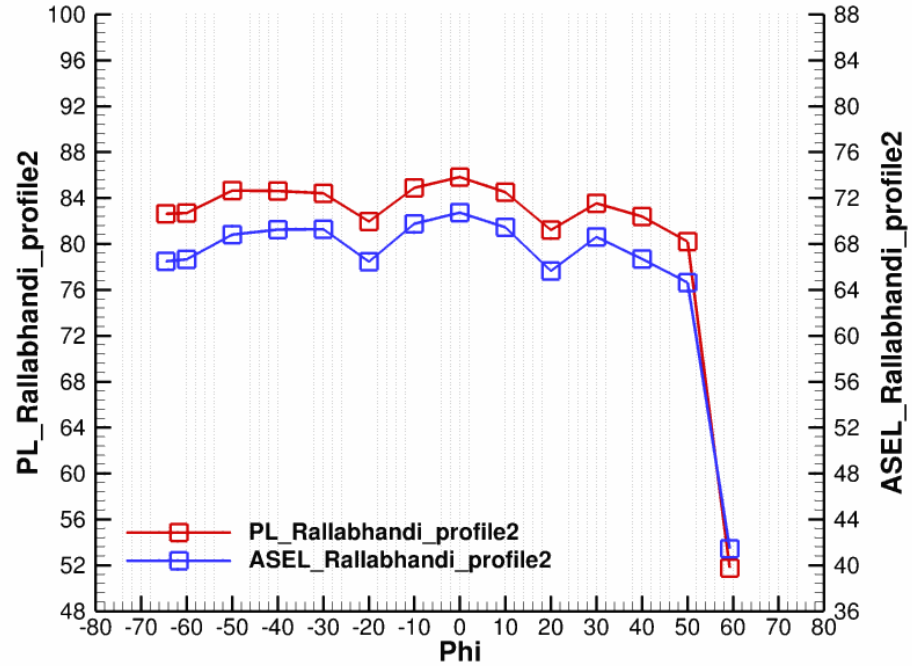


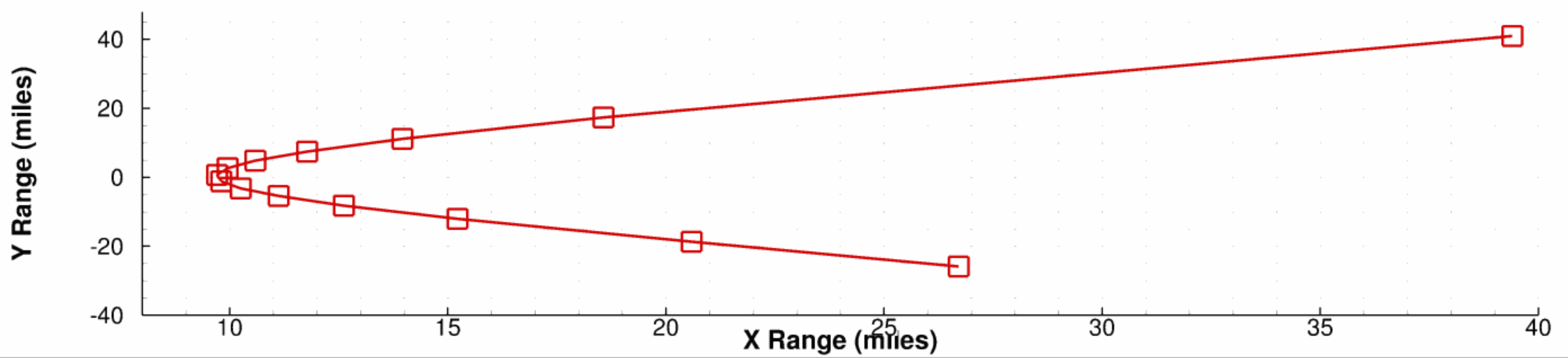




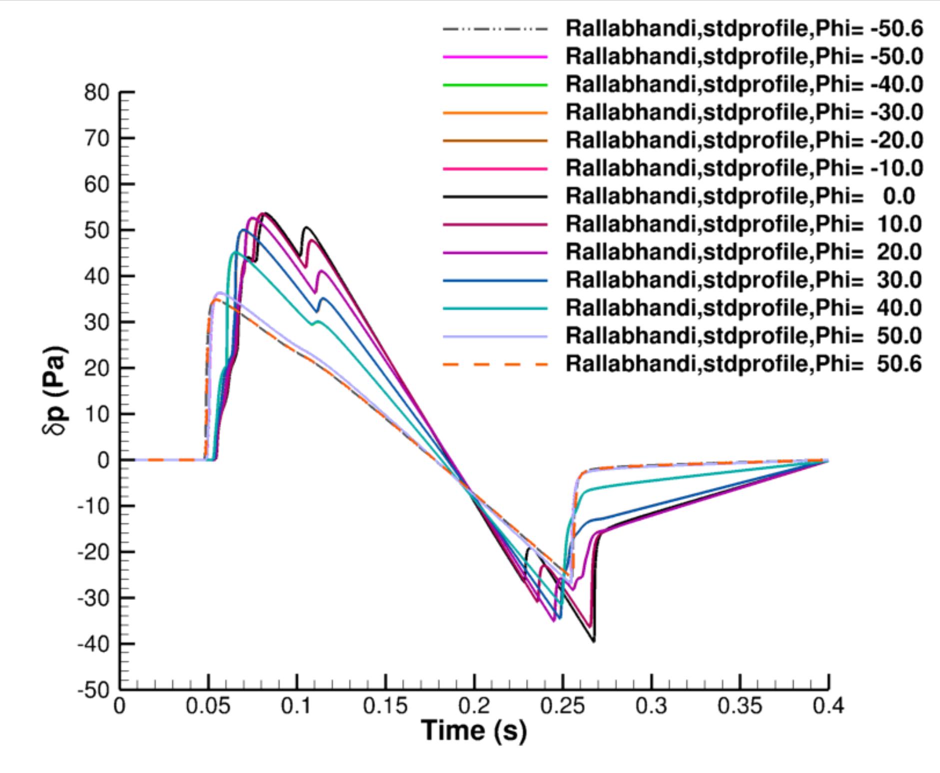
LM1021: Profile 2

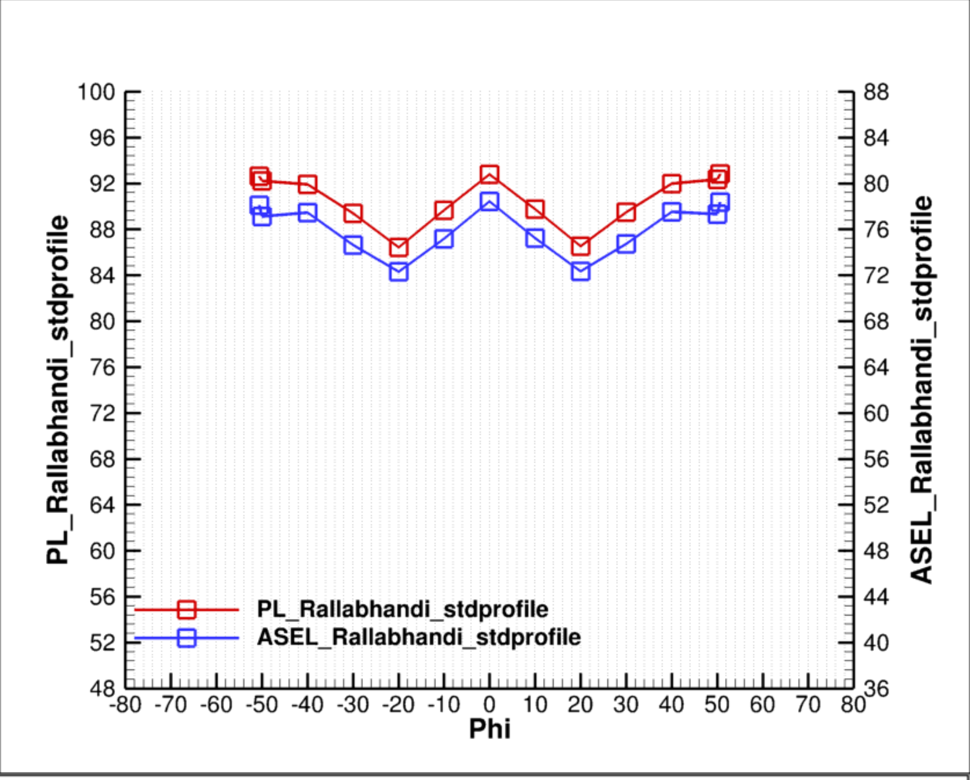


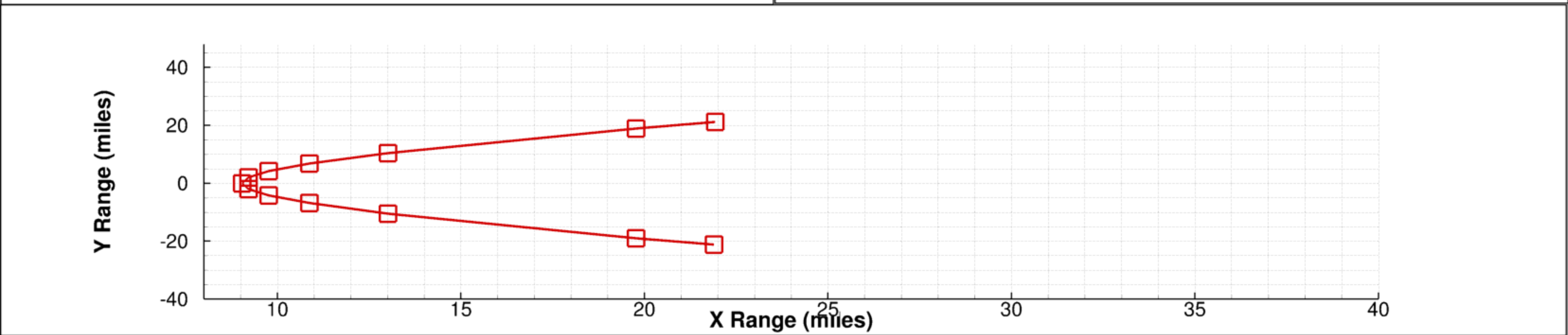




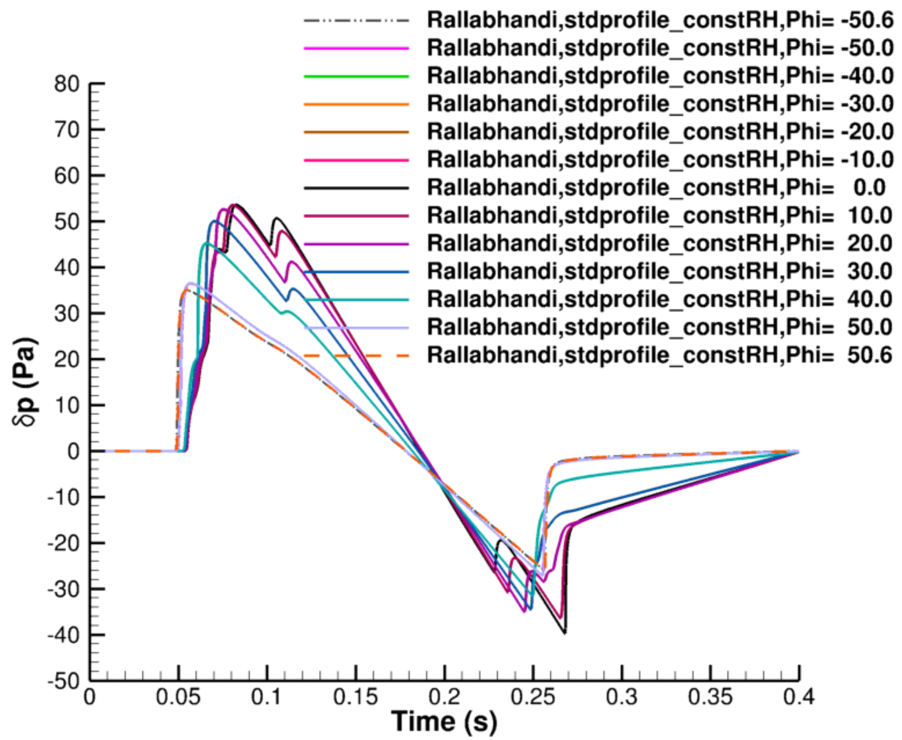
LM1021: Std Profile

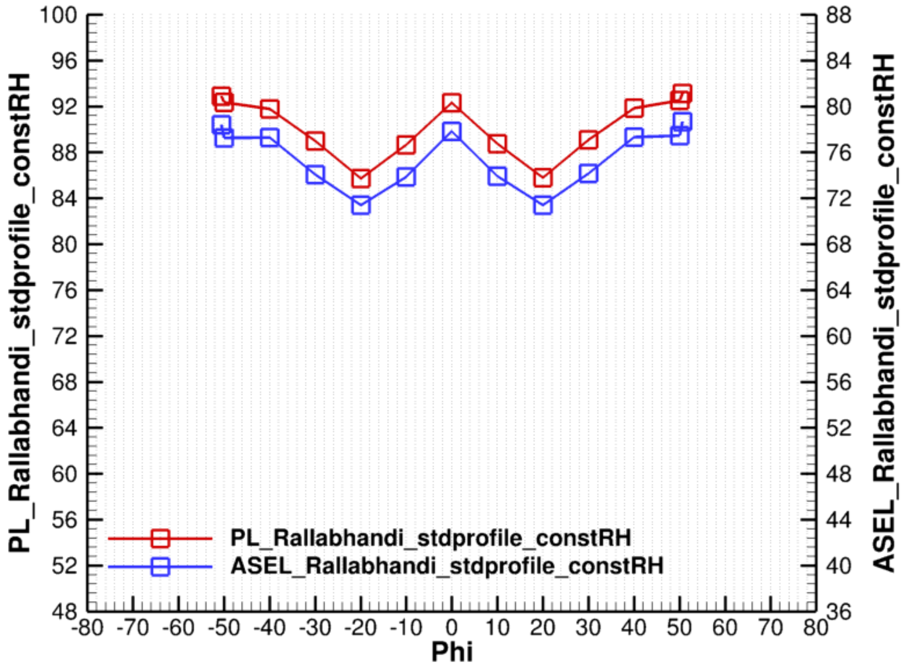


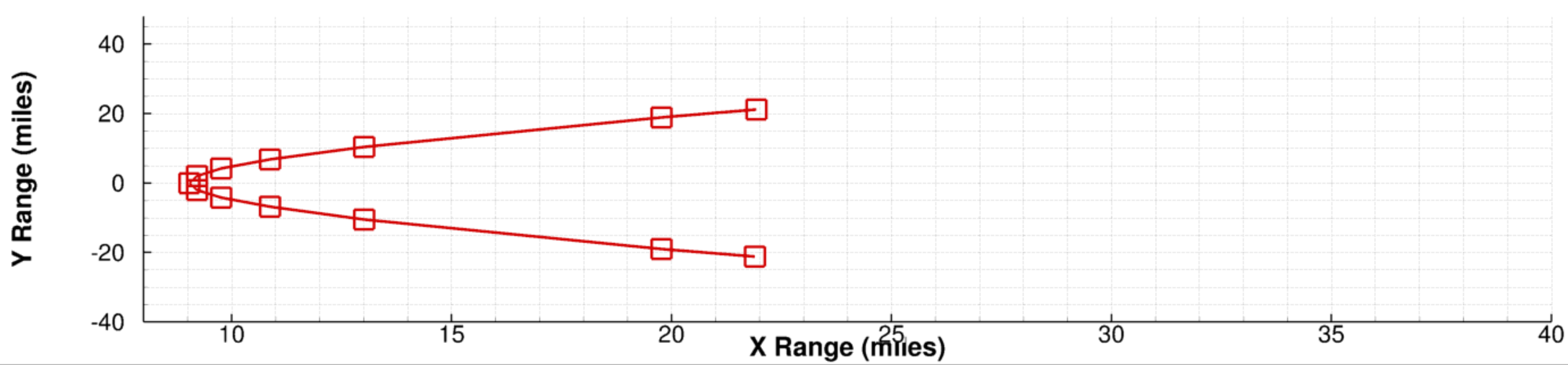




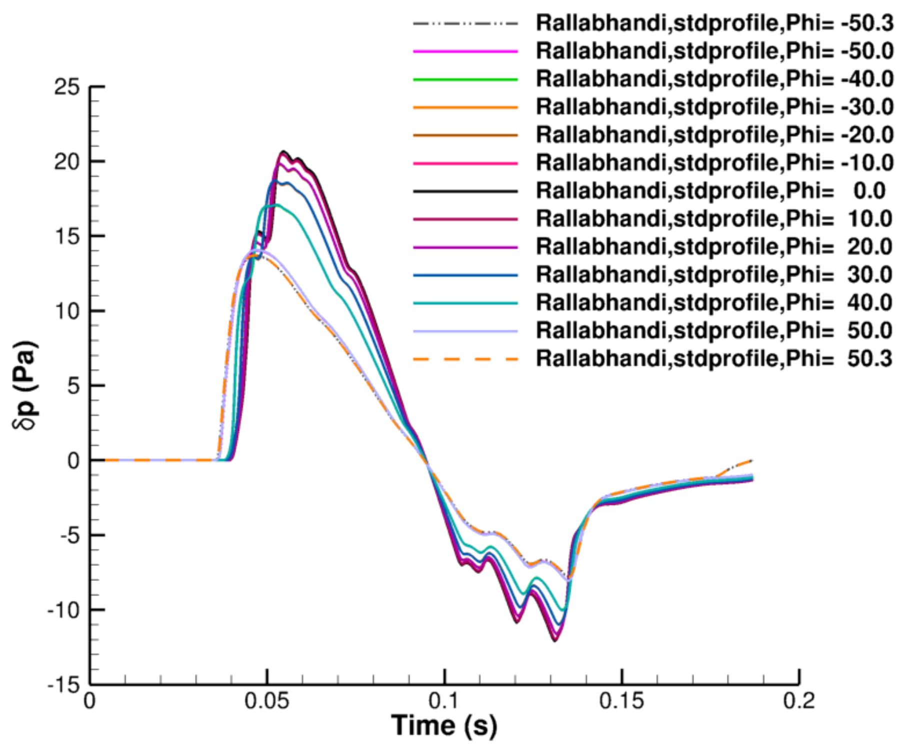
LM1021: Std Profile, Const RH

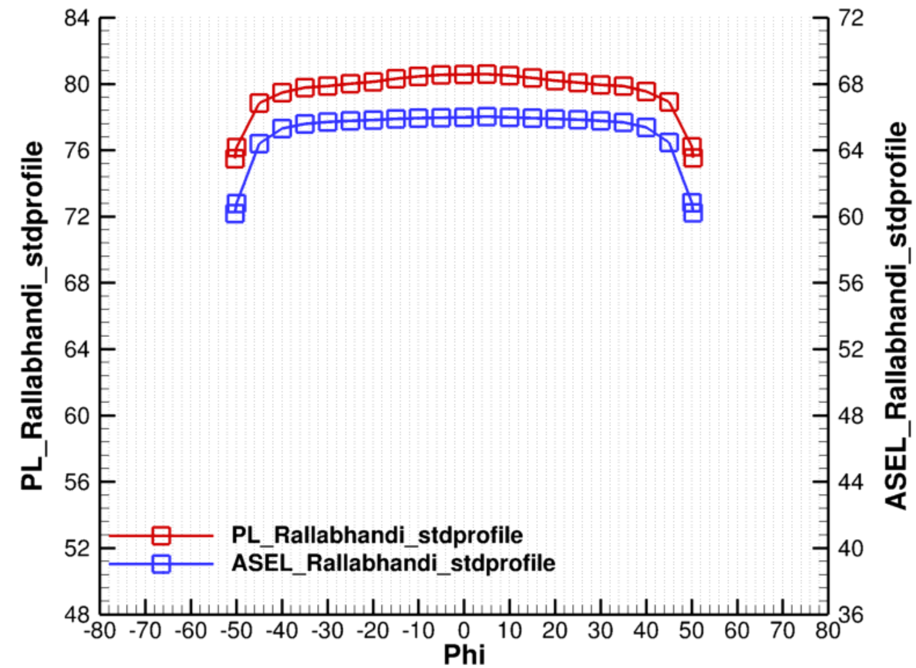


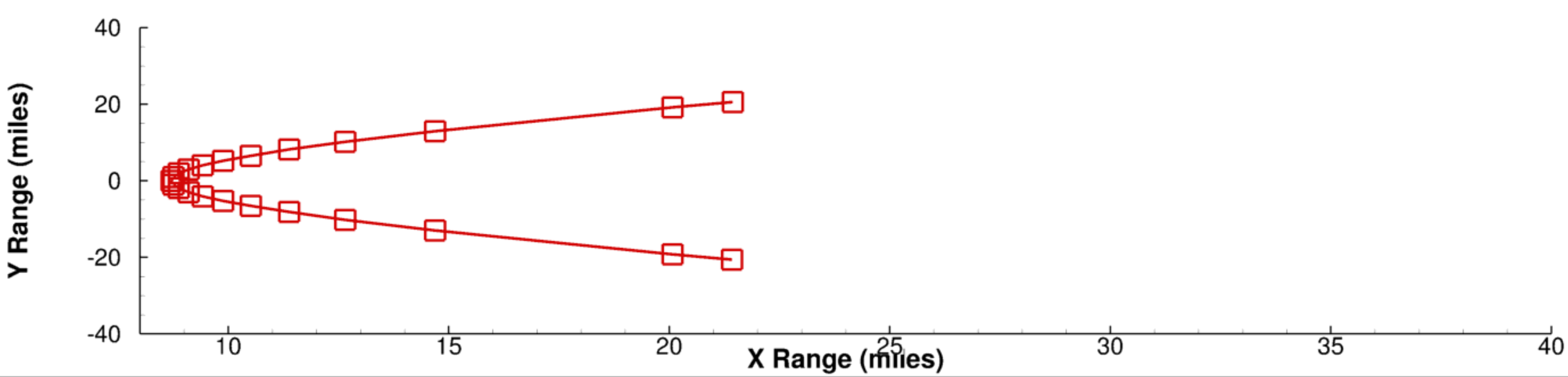




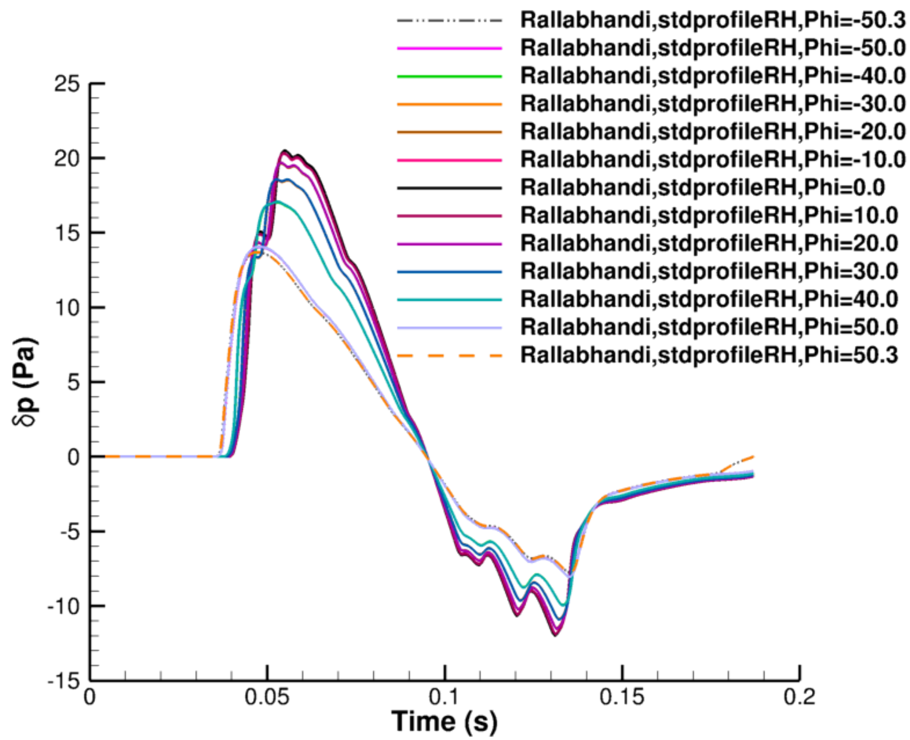
AxiBody: Std. Profile

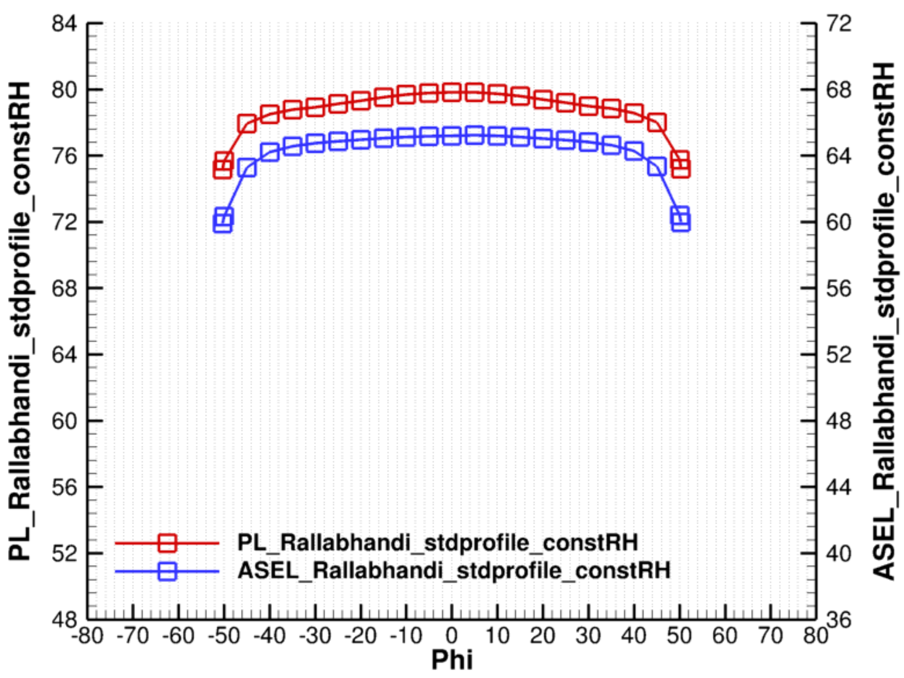


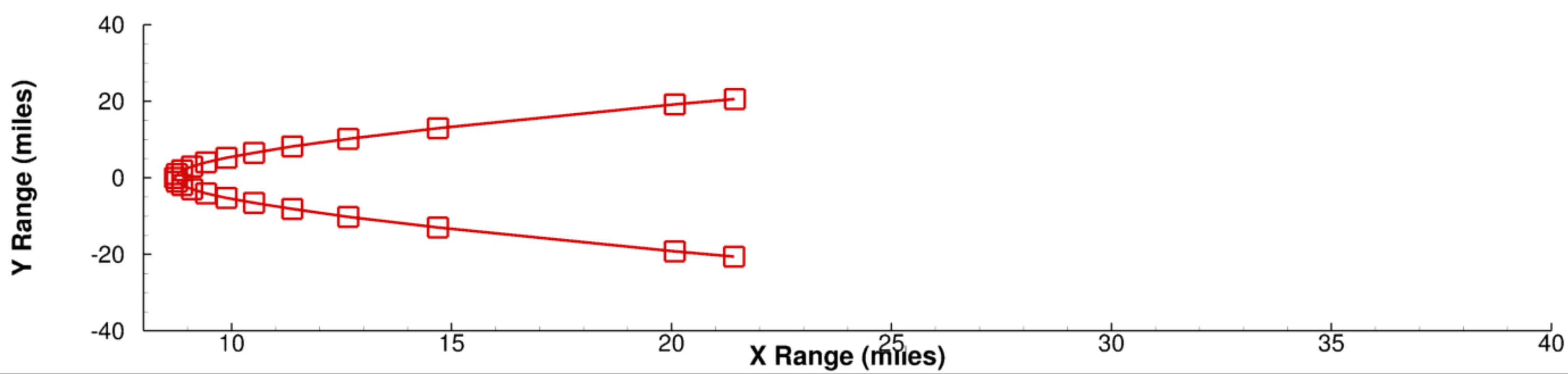




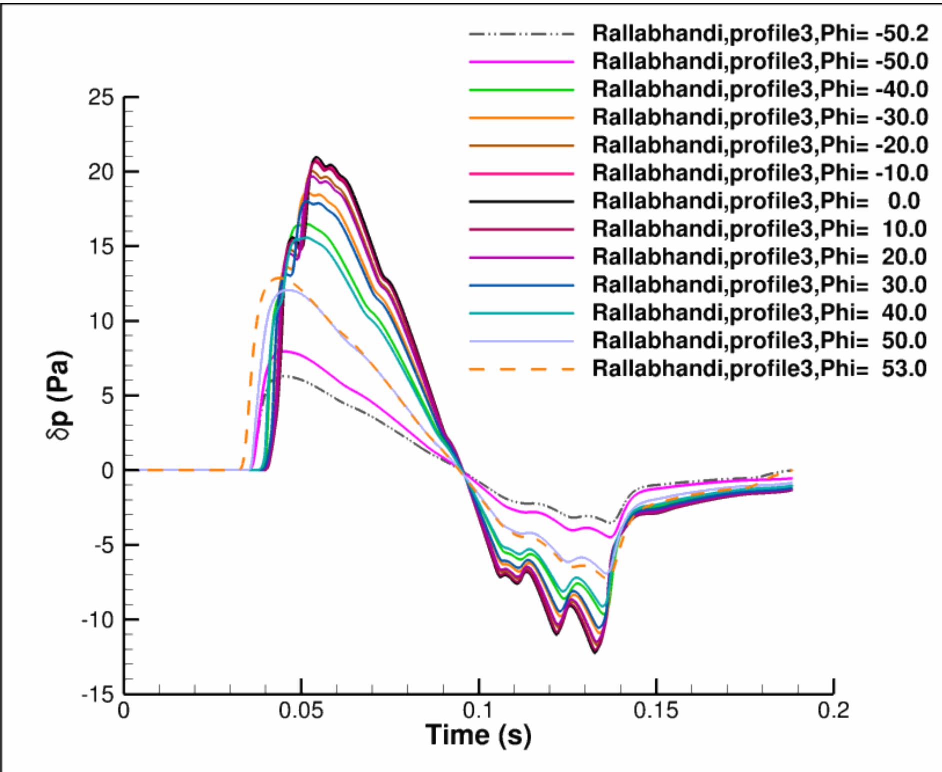
AxiBody: Std Profile, constRH

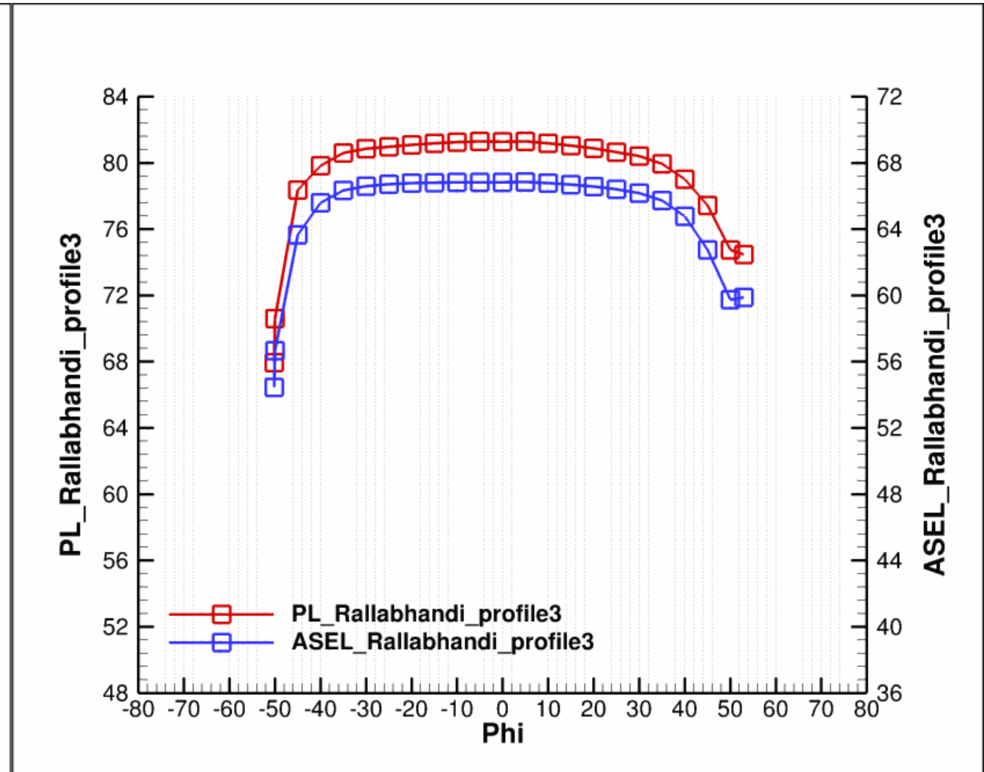


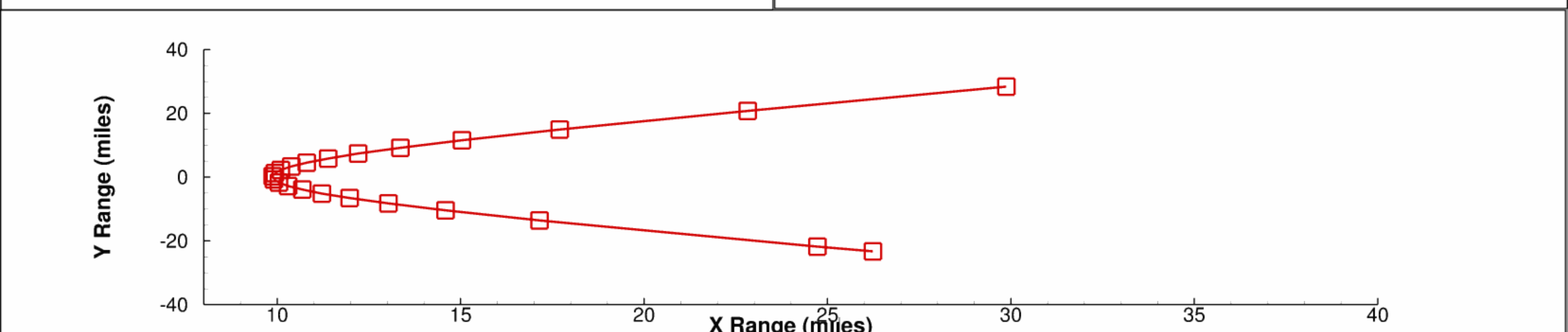




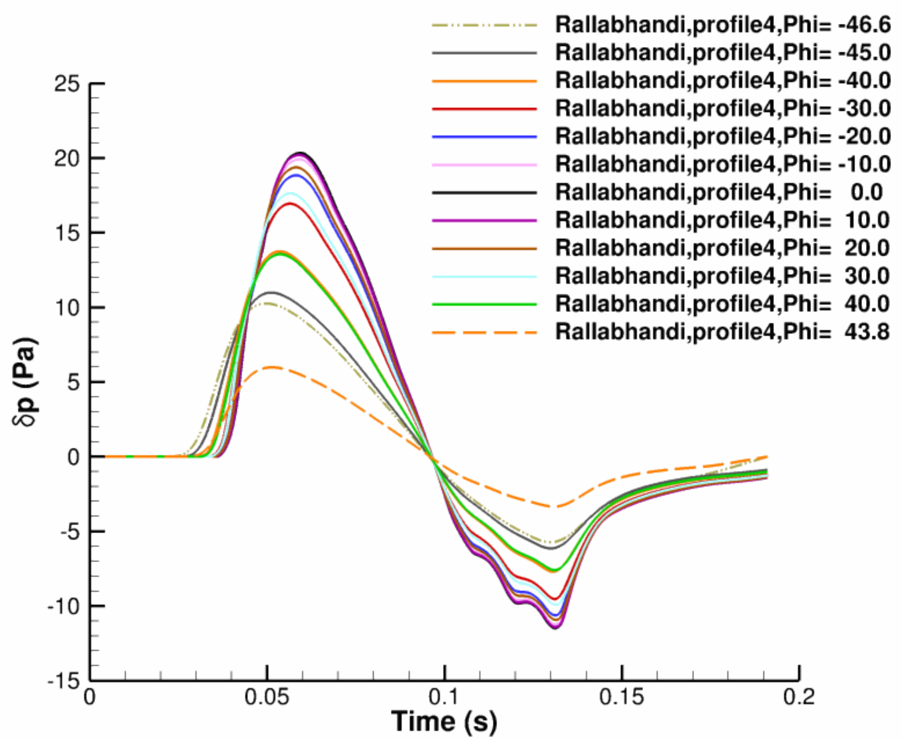
AxiBody: Profile 3

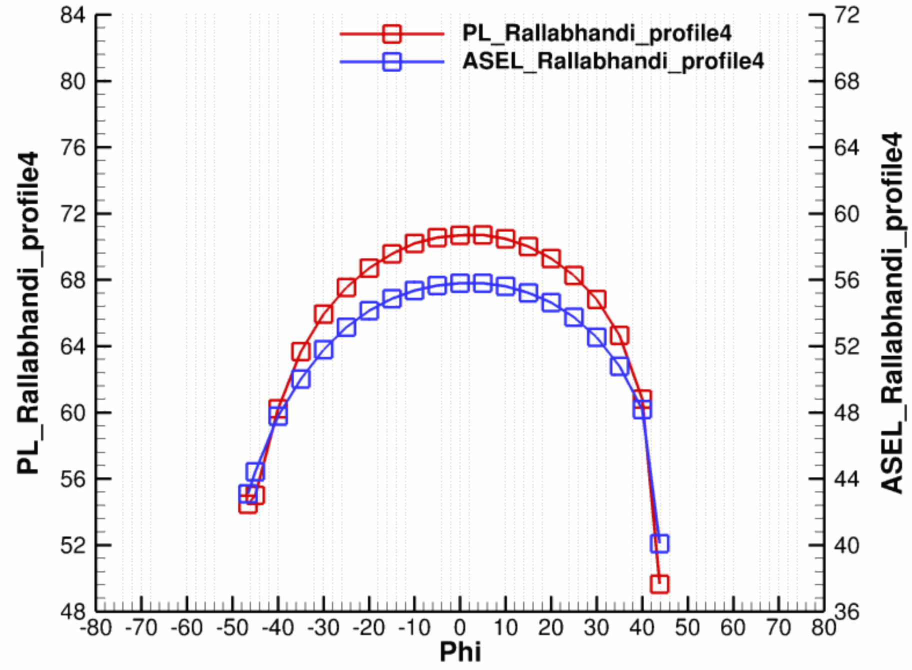


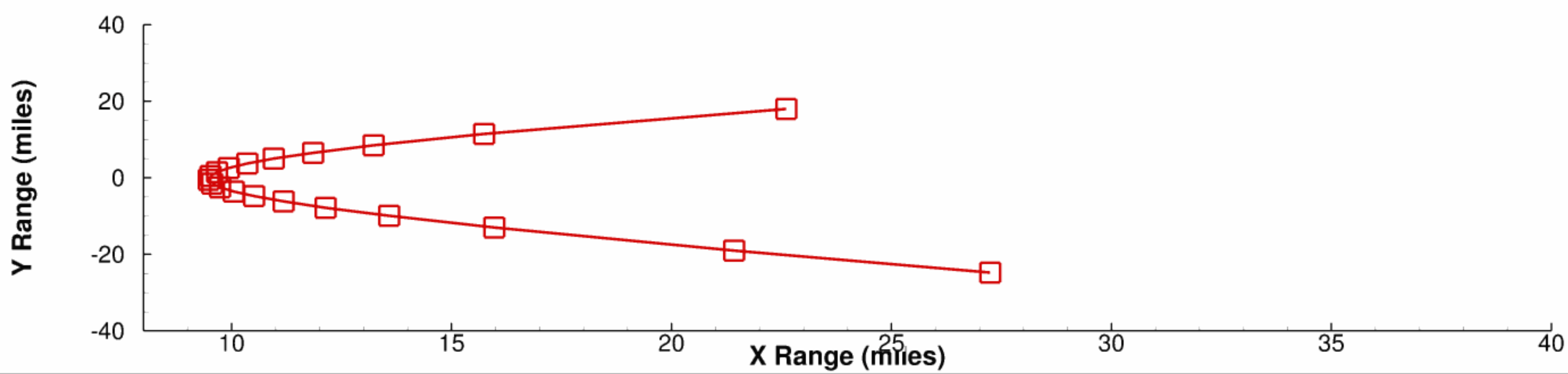




AxiBody: Profile 4

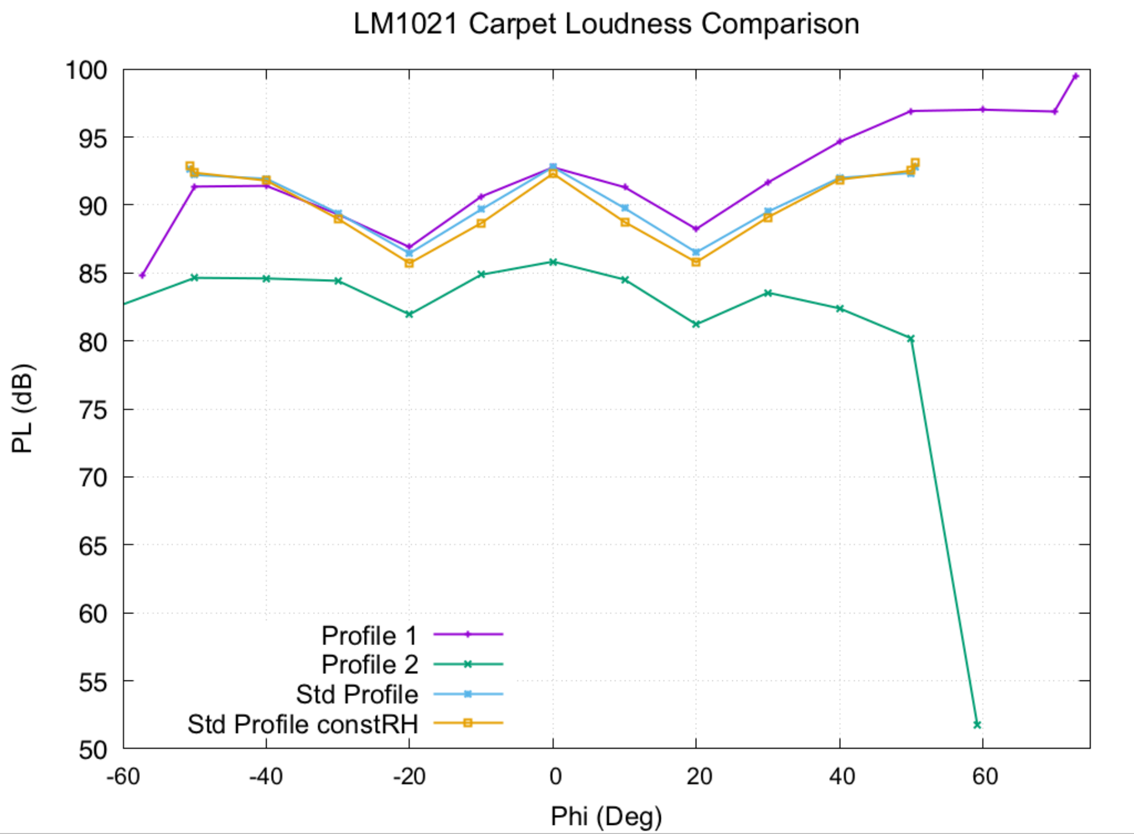






Loudness carpet comparison: LM1021

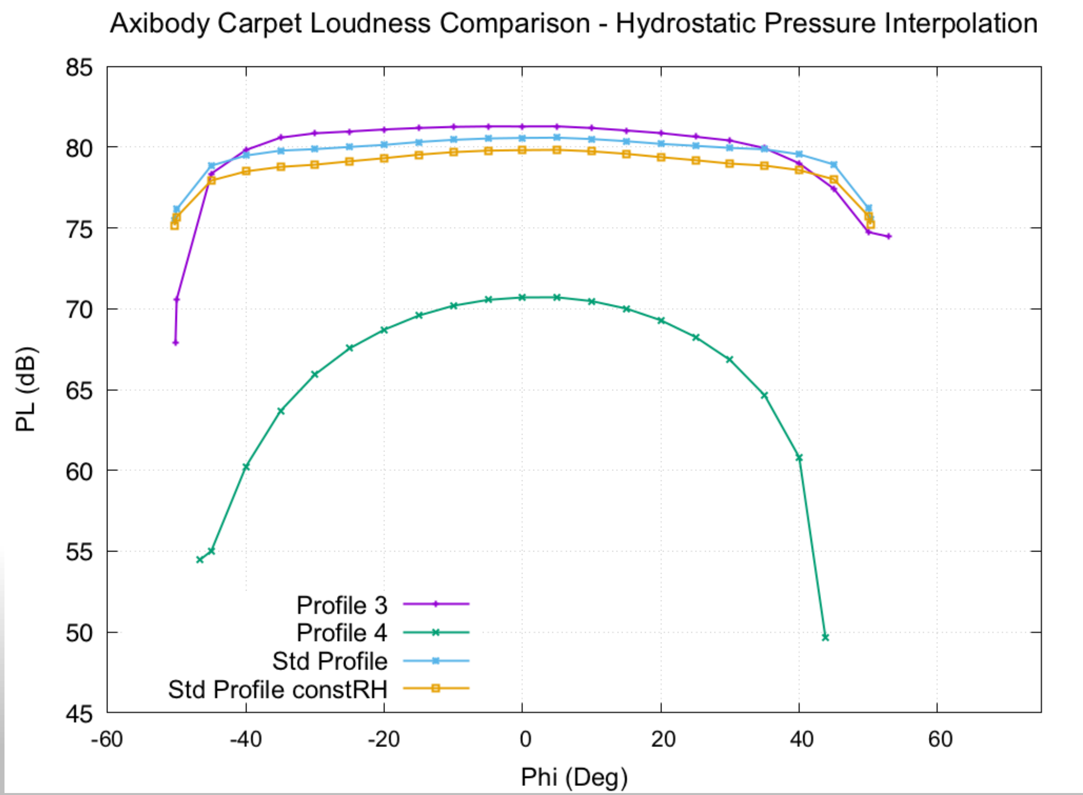
- Lateral cut-off perceived level of loudness could be much higher than under-track
- Pressure interpolation seems to affect the standard profile more than the measured profiles
- Lateral cut-off angles could be > 70^0 for certain atmospheric conditions



Sriram.Rallabhandi@nasa.gov

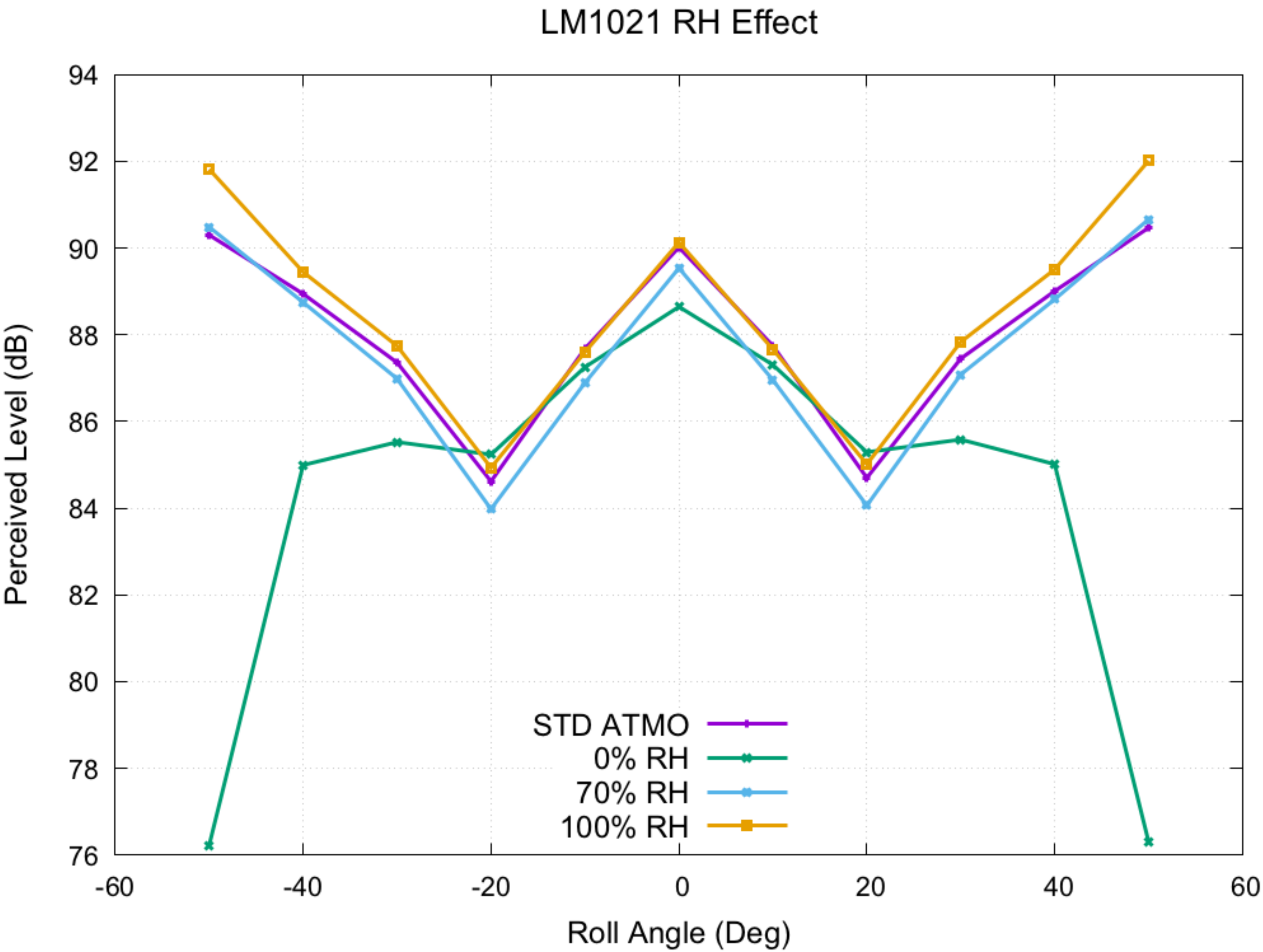
Loudness carpet comparison: AxiBody

- Prevailing atmospheric conditions have >10 dB impact, shaped signatures are more sensitive
- Pressure interpolation affects the standard profile more than the measured profiles because the standard profile defined/used is coarse; more points are needed closer to the ground due to exponential profile

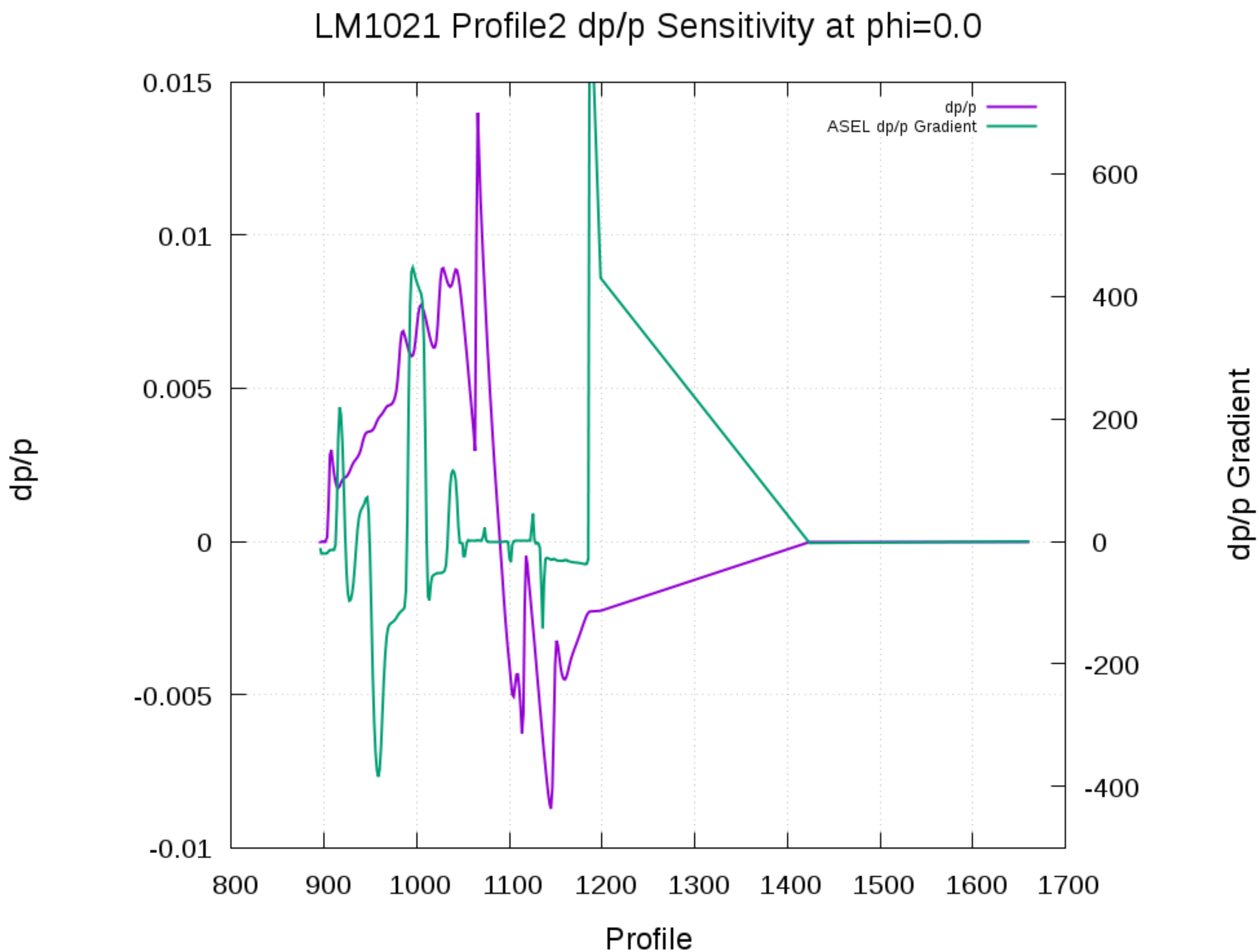


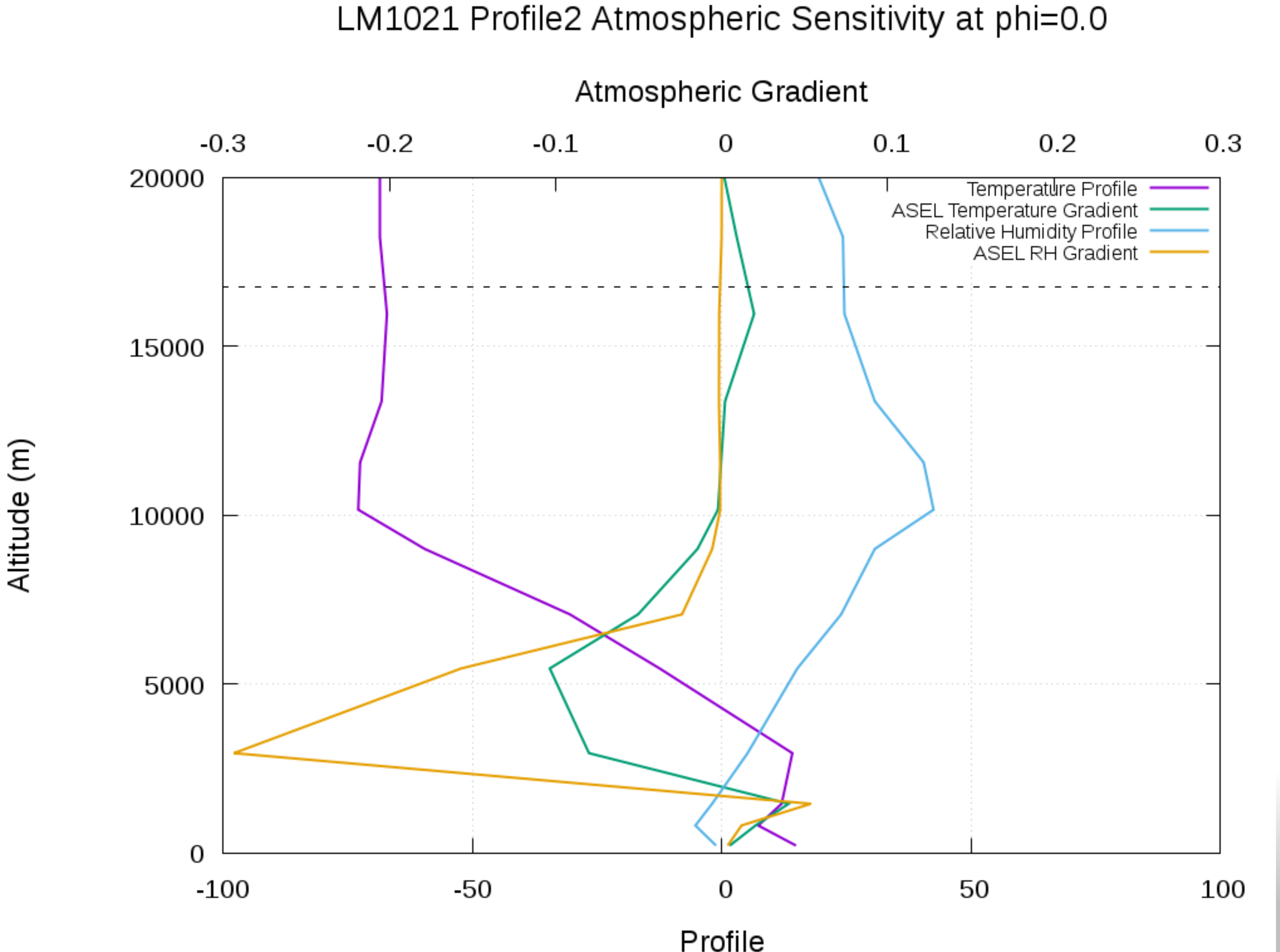
Sriram.Rallabhandi@nasa.gov

HIGHLIGHTS

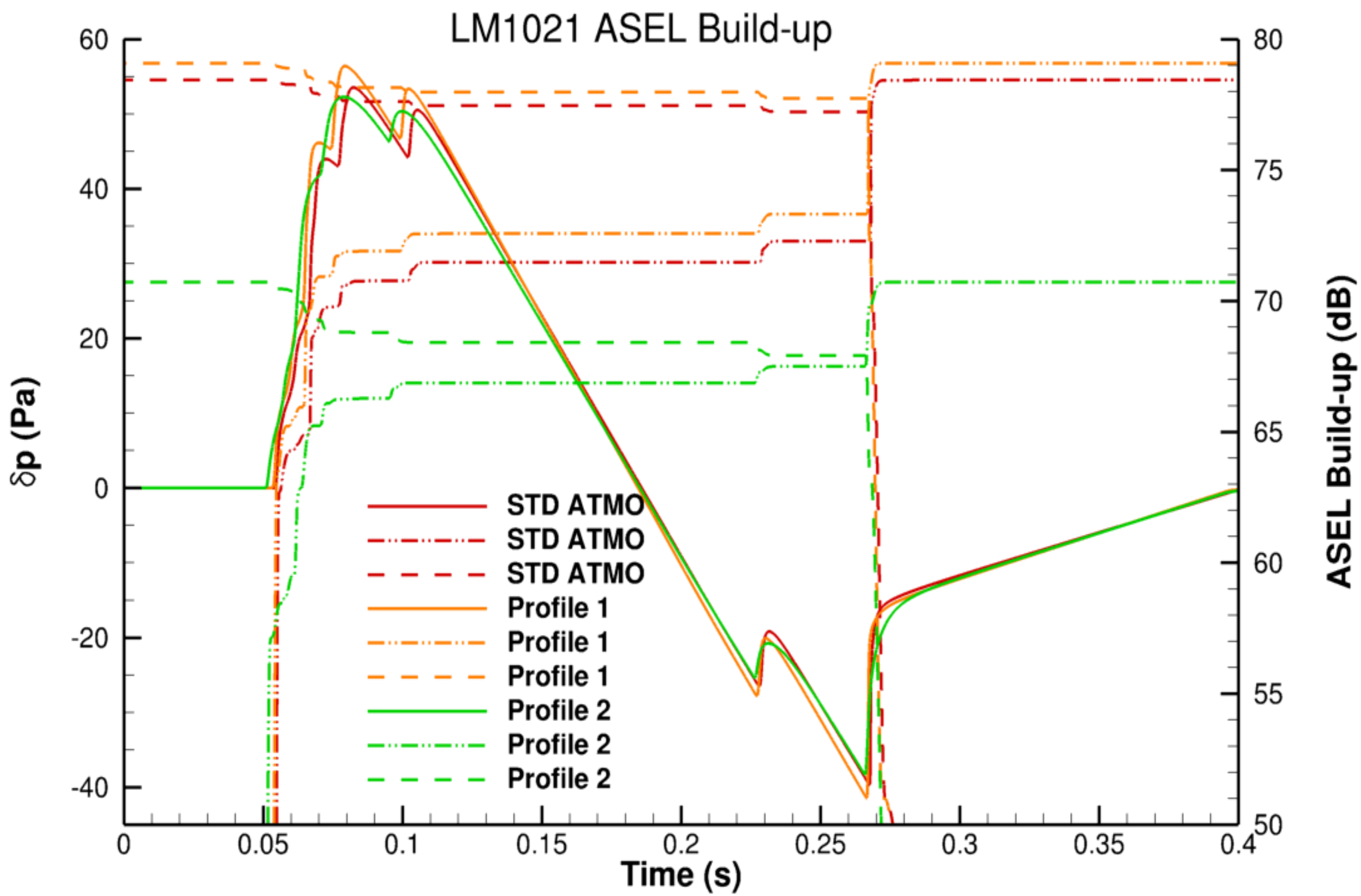


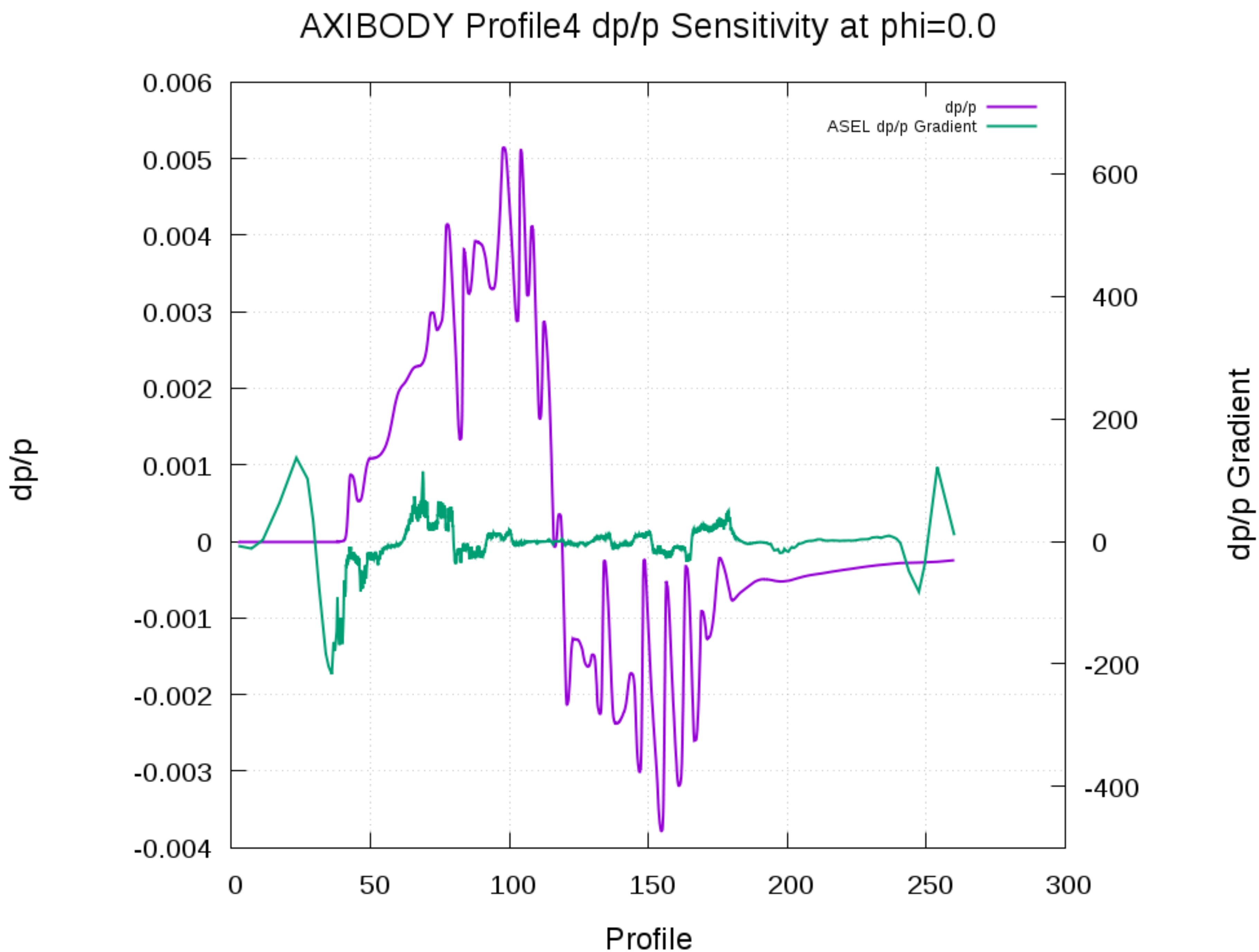
LM1021 RH Effect
94
92
90
88
86
84
82
80
78
76
Perceived Level (dB)
-60
-40
-20
0
20
40
60
Roll Angle (Deg)
STD ATMO
0% RH
70% RH
100% RH

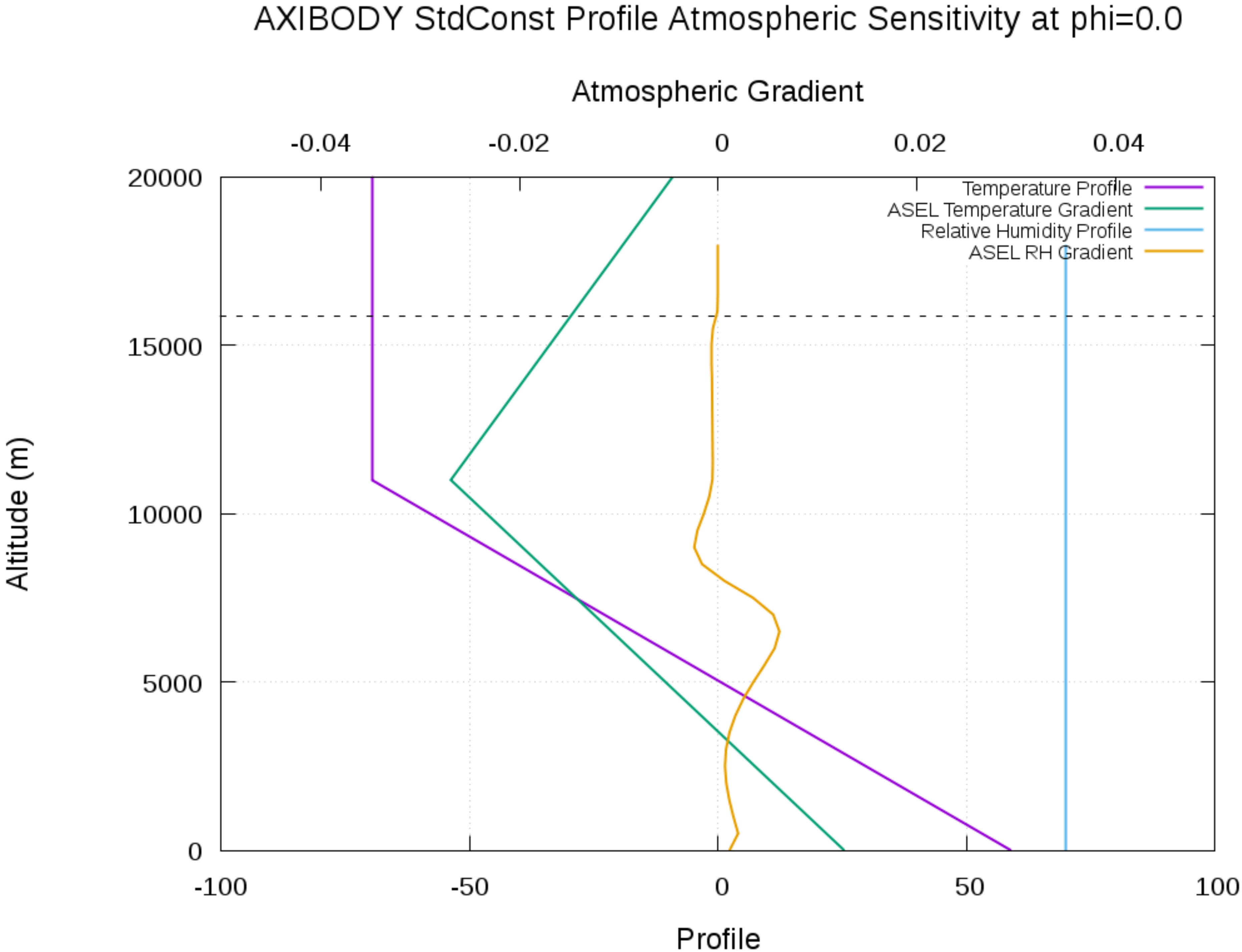

LM1021 Profile2 dp/p Sensitivity at phi=0.0
dp/p
ASEL dp/p Gradient
0.015
0.01
0.005
0
-0.005
-0.01
600
400
200
0
-200
-400
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Profile
dp/p
dp/p Gradient

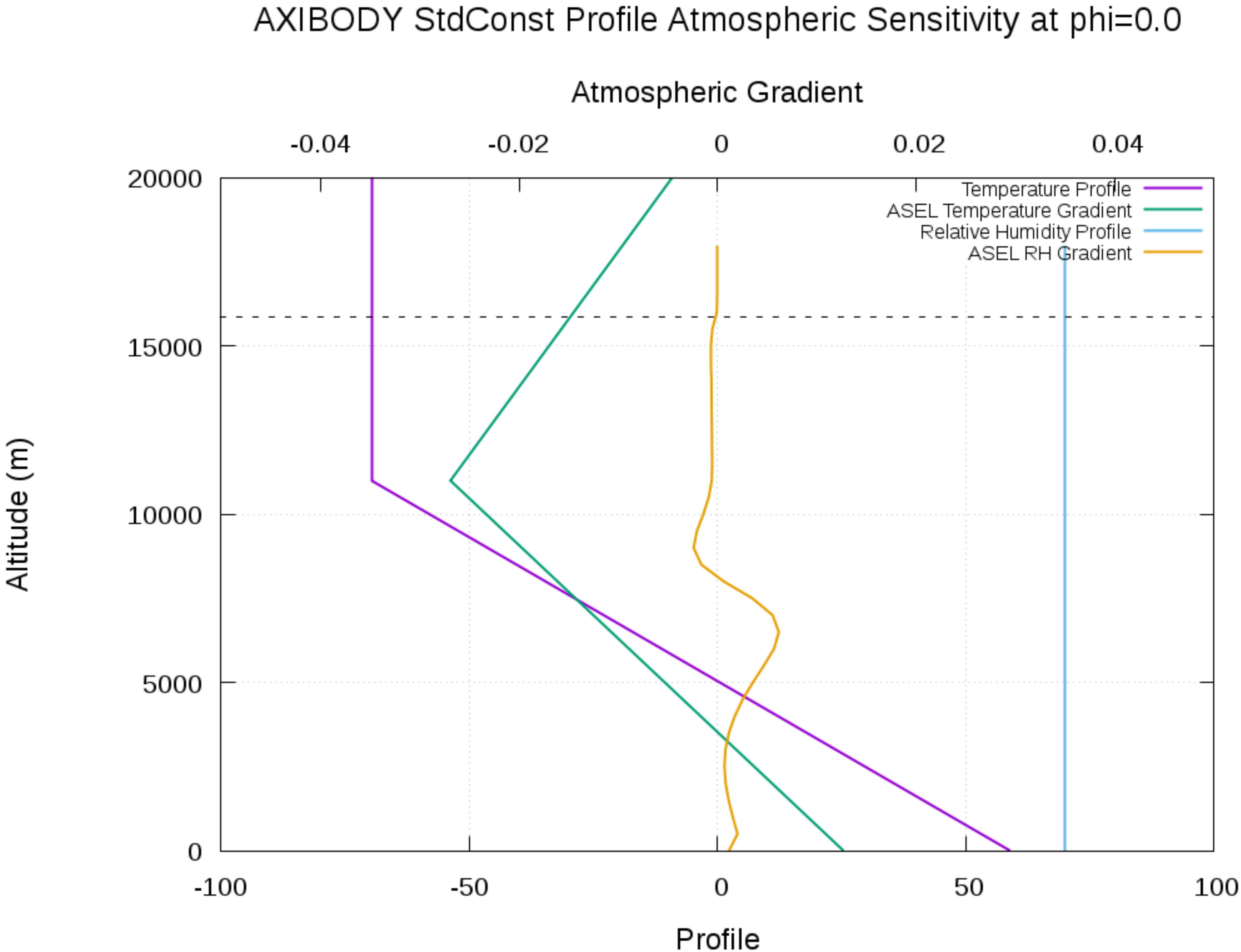

LM1021 Profile2 Atmospheric Sensitivity at phi=0.0
Atmospheric Gradient
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Temperature Profile
ASEL Temperature Gradient
Relative Humidity Profile
ASEL RH Gradient
Altitude (m)
20000
15000
10000
5000
0
-100
-50
0
50
100
Profile

LM1021: ASEL Build-up



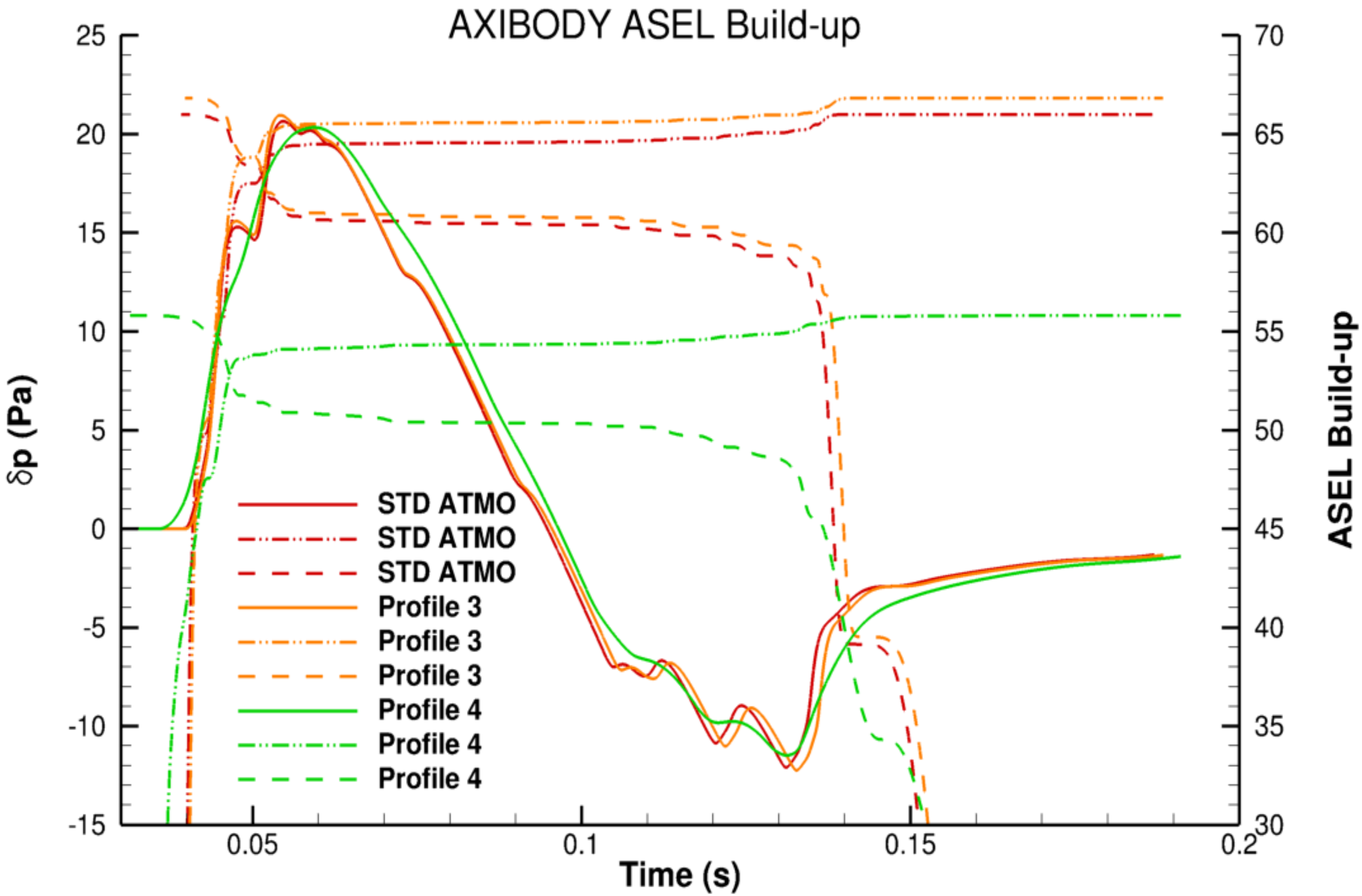

AXIBODY Profile4 dp/p Sensitivity at phi=0.0
dp/p
ASEL dp/p Gradient
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
600
400
200
0
-200
-400
0
50
100
150
200
250
300
dp/p
dp/p Gradient
Profile


AXIBODY StdConst Profile Atmospheric Sensitivity at phi=0.0
Atmospheric Gradient
-0.04
-0.02
0
0.02
0.04
Temperature Profile
ASEL Temperature Gradient
Relative Humidity Profile
ASEL RH Gradient
20000
15000
10000
5000
0
Altitude (m)
-100
-50
0
50
100
Profile



AXIBODY StdConst Profile Atmospheric Sensitivity at phi=0.0
Atmospheric Gradient
-0.04
-0.02
0
0.02
0.04
20000
15000
10000
5000
0
Temperature Profile
ASEL Temperature Gradient
Relative Humidity Profile
ASEL RH Gradient
Altitude (m)
-100
-50
0
50
100
Profile

AxiBody: ASEL Build-up



Summary/Conclusions

- Multiple runs were made under multiple atmospheric conditions to
  - LM1021 near-field dp/p
  - Axisymmetric body of revolution
- Prevailing atmospheric conditions have a large impact on
  - Ground signatures
  - Loudness values
  - Lateral cut-off angle
  - Extent of the asymmetric carpet
- Pressure interpolation has a large impact – mainly in dimensionalizing the input dp/p data
- Standard atmosphere and standard atmospheric profile with a fixed relative humidity seem to pretty close to each other, at least for the cases considered
- Lessons Learned
  - Atmospheric pressure interpolation can have a big impact
    - The standard pressure input should be fine-grained
  - Wind convention needs to be consistent

Acknowledgments

- NASA Commercial Supersonic Technology (CST) project
- Boom prediction workshop organizing committee and participants
- Mike Park for organizing and updating the GIT repo
- Michael Aftosmis/Marian Nemec for verifying and confirming the wind convention in sBOOM with standard wind definitions