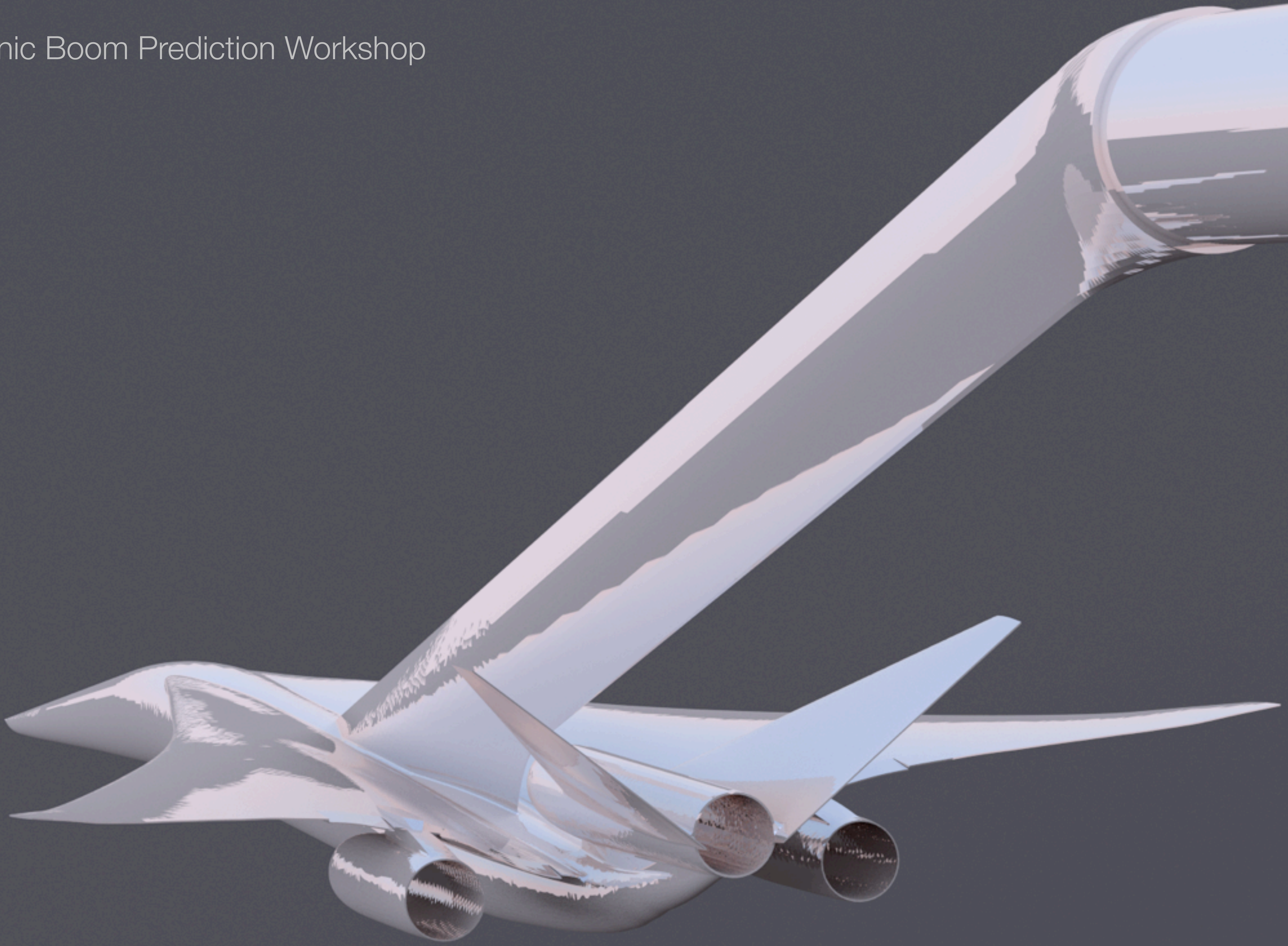
2nd AIAA Sonic Boom Prediction Workshop



2nd AIAA Sonic Boom Prediction Workshop

sBOOM Propagation for the Second AIAA Sonic Boom Prediction Workshop

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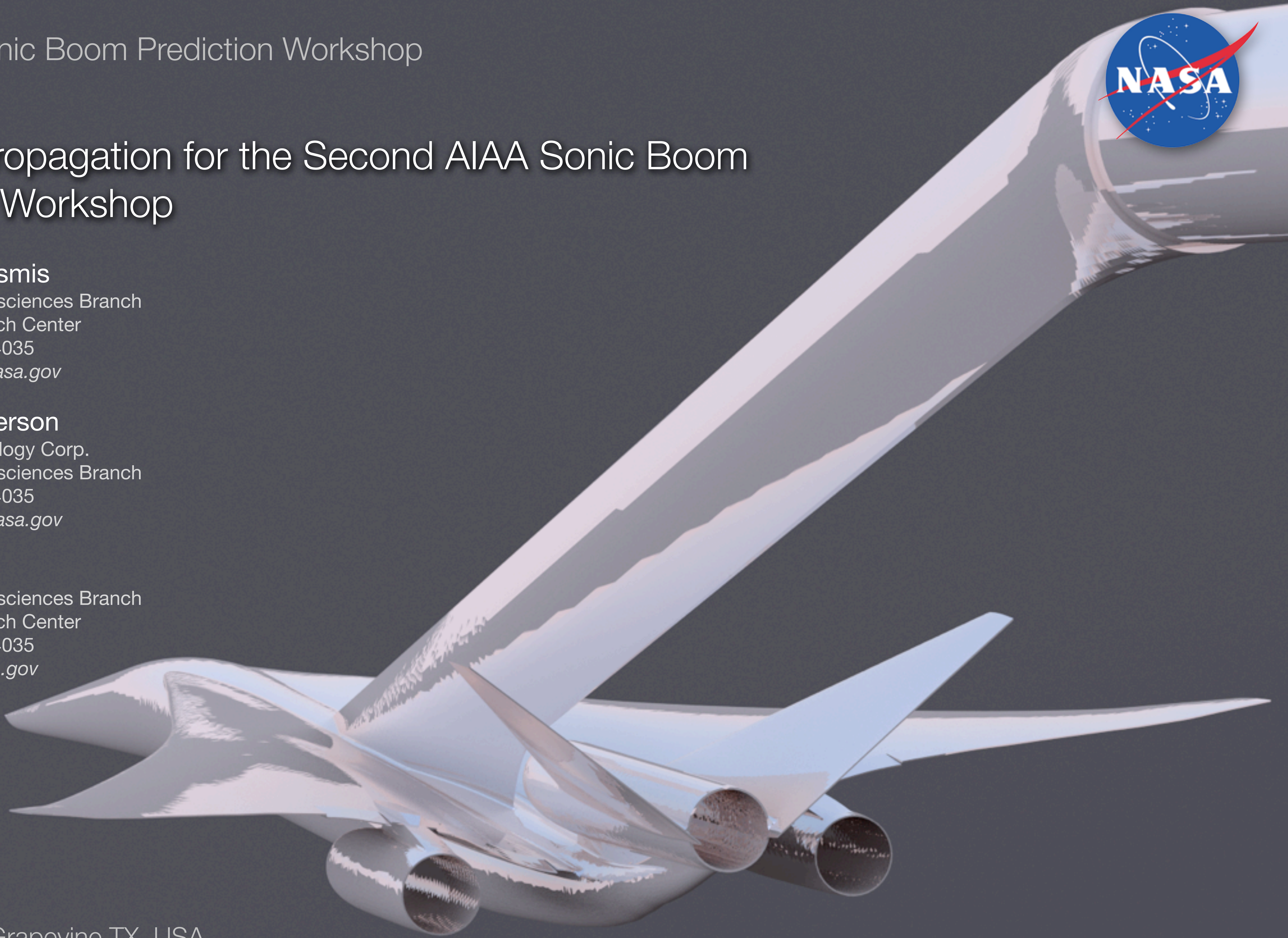
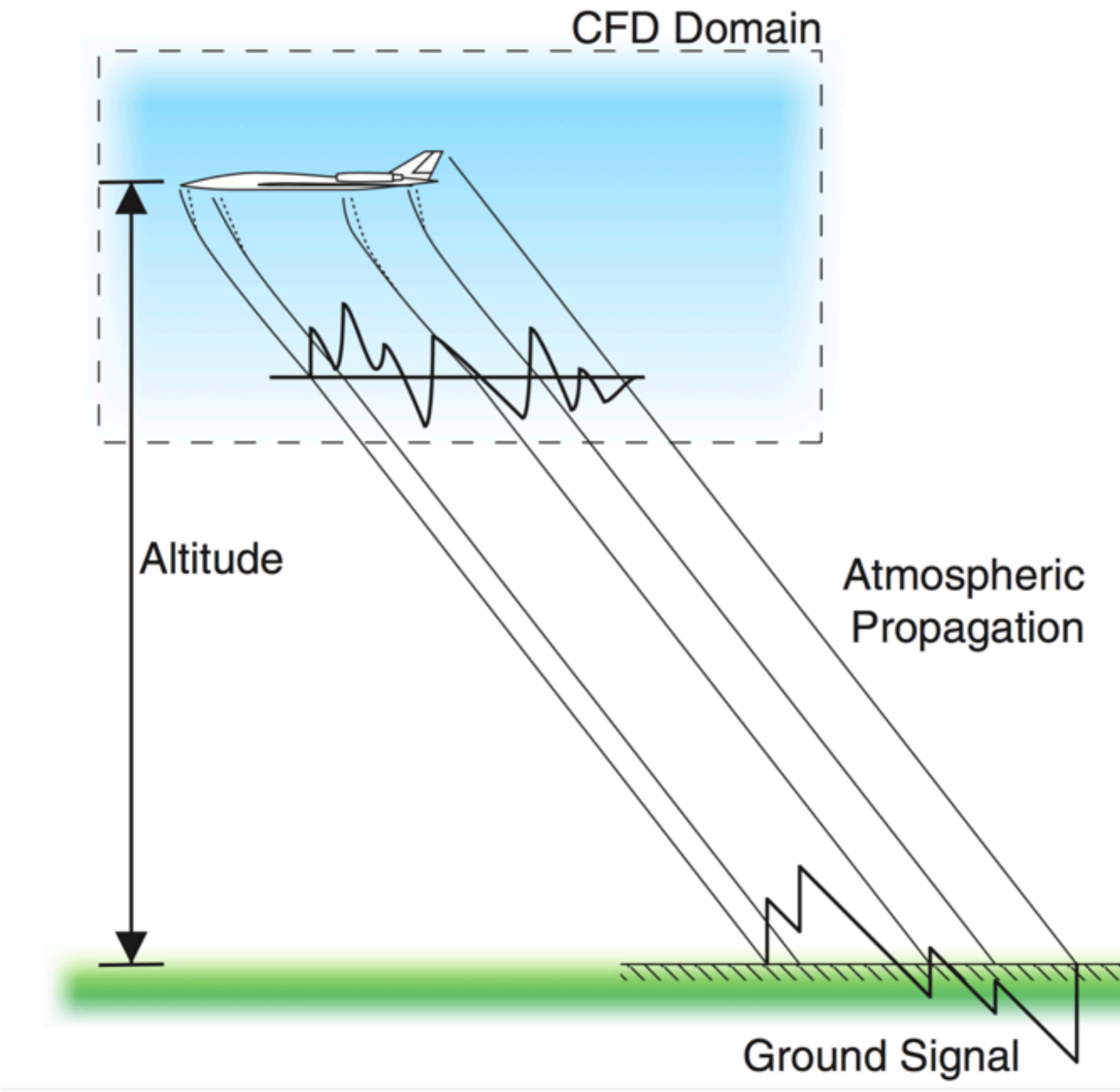


7-8 Jan 2017, Grapevine TX, USA

Introduction

- Propagation using sBOOM (v2.5)* for all cases
  - Solves augmented Burgers' equation
  - Finite-difference with space-operator splitting
- Loudness metrics computed with LCASB†
- Applied current "best practices" for sampling frequency and signal close-out
- Ran all required & optional cases



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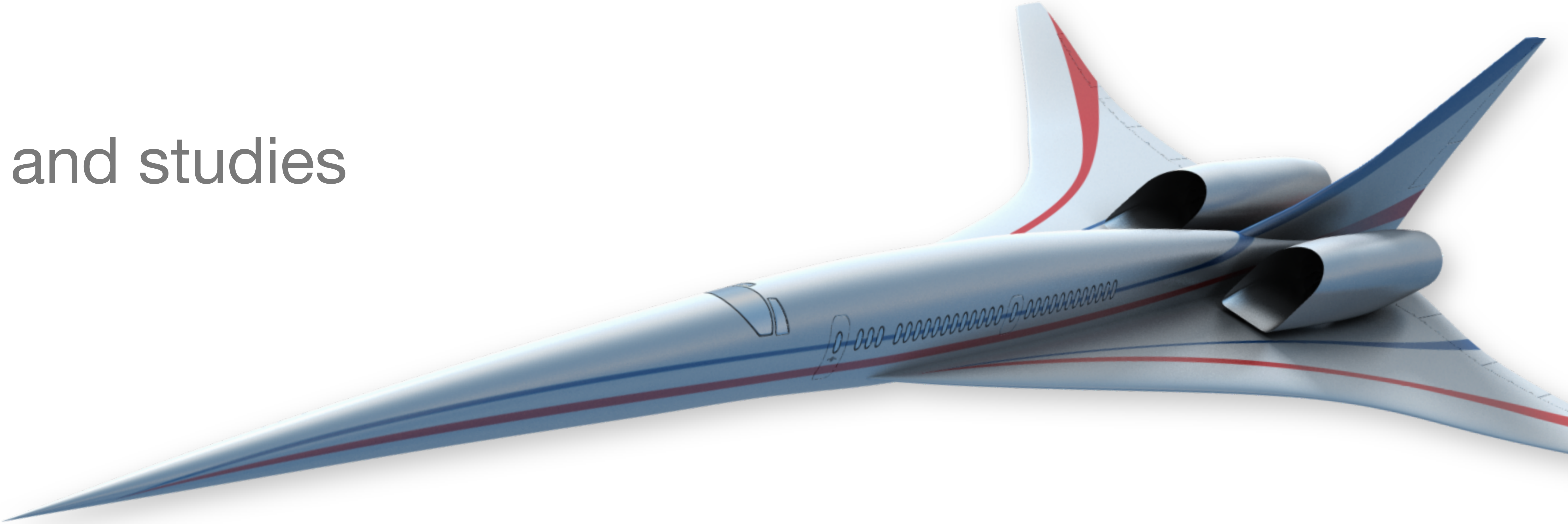
* Rallabhandi, S. "Advanced Sonic Boom Prediction Using the Augmented Burgers Equation" *J. of Aircraft,* **48**:1245–1253, 2011.

† Shepard & Sullivan, "Loudness Code for Asymmetric Sonic Booms(LCASB)", NASA TP 3134, 1991

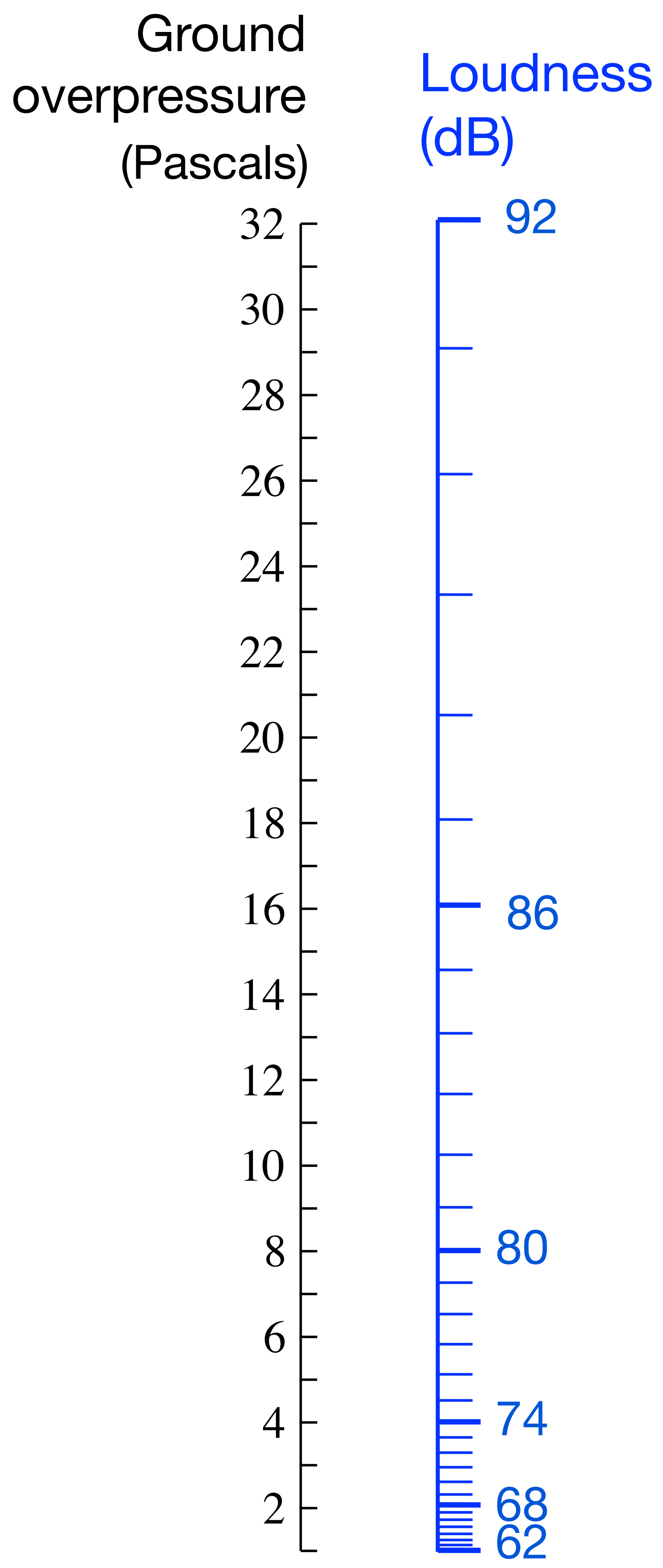
Outline



- Intro - codes, conventions and studies
  - Codes & conventions
  - Accuracy requirements
  - Mesh refinement study
- Results Highlights
  - “Axibody” - Body of revolution
  - “LM 1021” - Wind tunnel model of full configuration from 2014 boom workshop
- Summary

Caveats on Accuracy Requirements

Decibels are logarithmic units!



Double the loudness ⟶ ~10 dB more sensed loudness level (psycho acoustic)
Double the sound pressure level ⟶ 6 dB more measured sound pressure level)

Caveats on Accuracy Requirements

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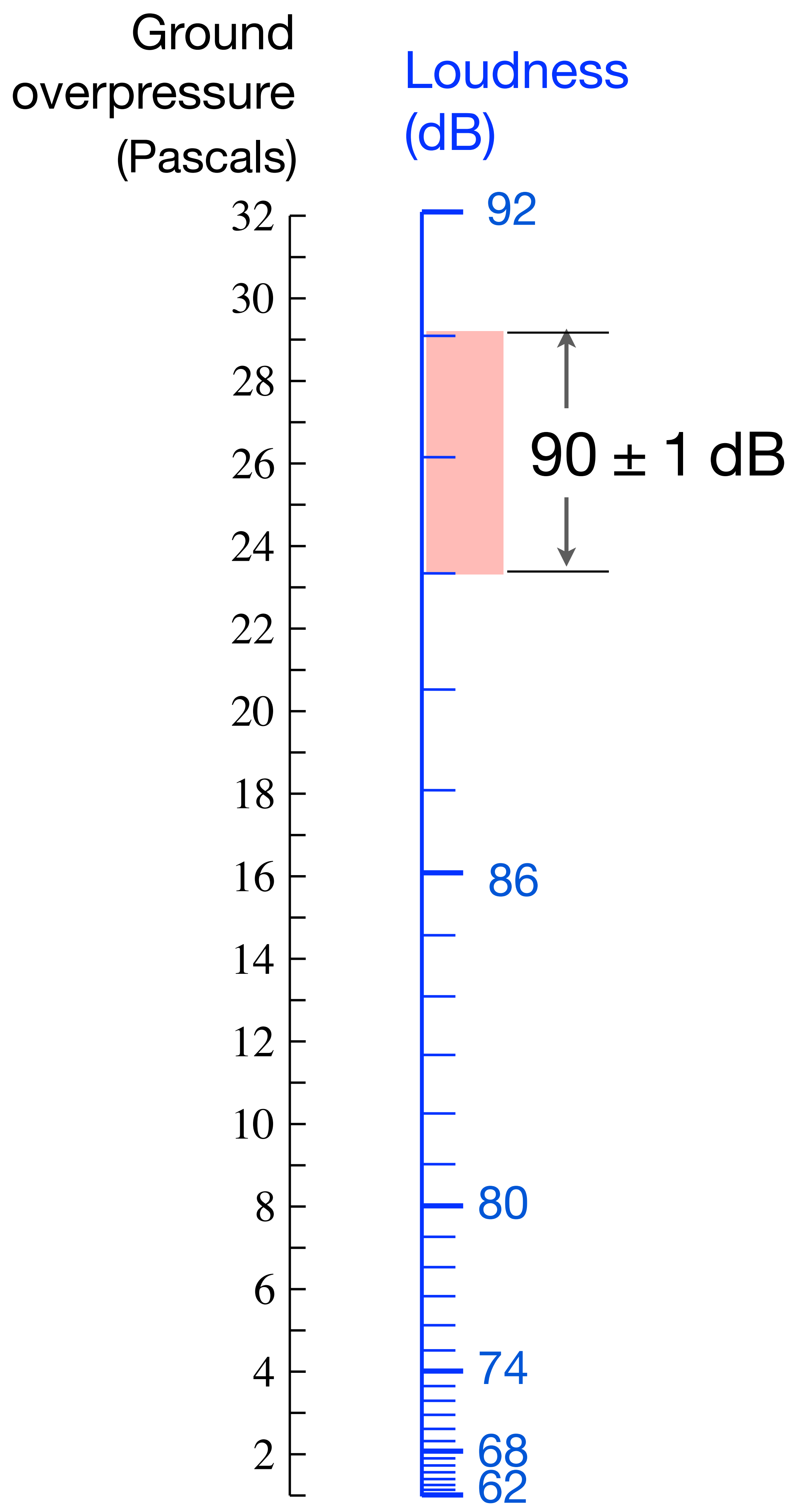
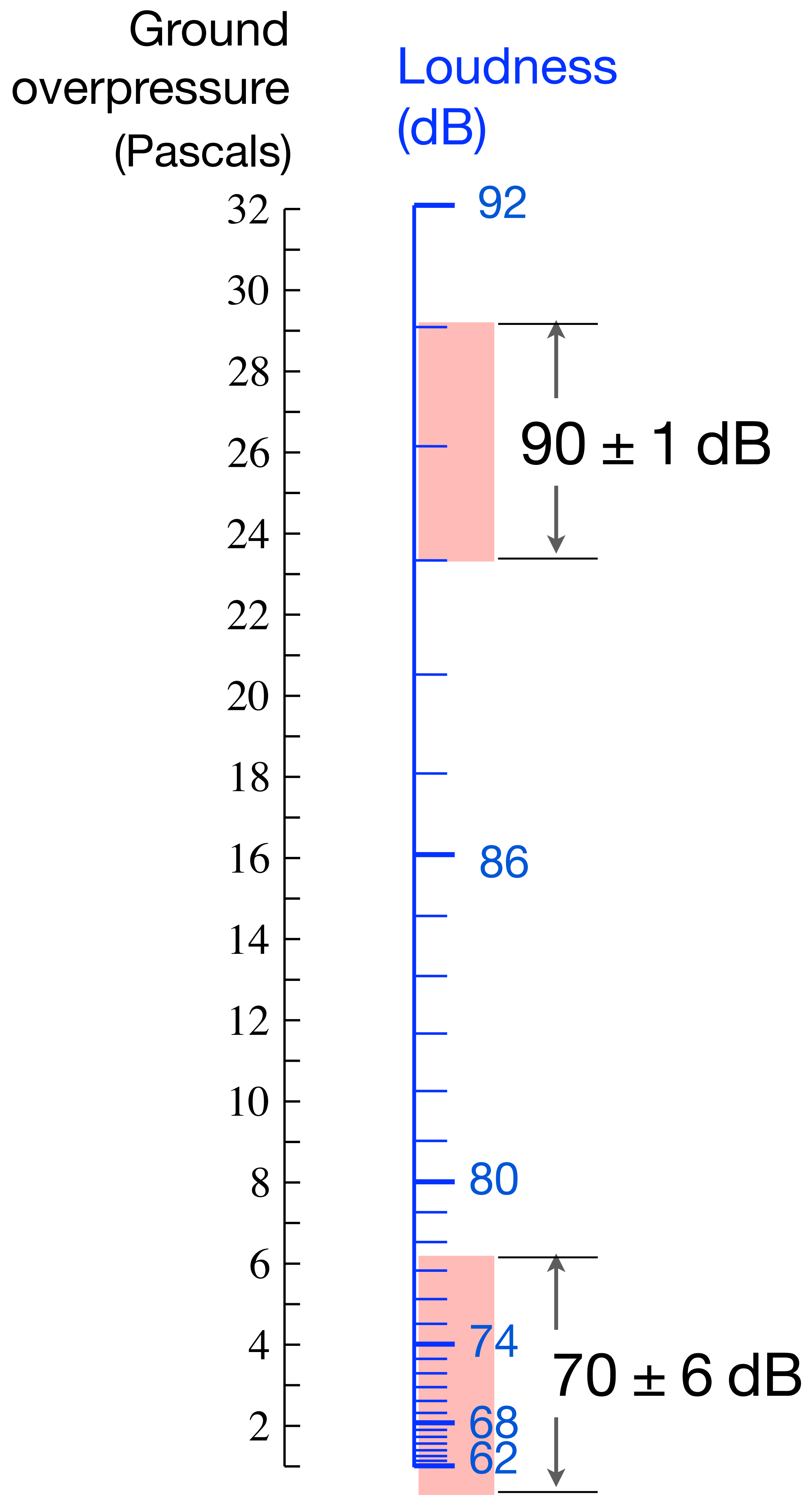


Double the loudness ⟶ ~10 dB more sensed loudness level (psycho acoustic)
Double the sound pressure level ⟶ 6 dB more measured sound pressure level)

- We numerically propagate pressure signals to the ground
  → *Propagation error* has units of pressure
- *Example*
  - Error of ±2 Pa on a 90 dB signal may be less than ± 1 dB
  - The same error on a 70 dB signal would be ± 8 dB
- For dB metrics, propagation accuracy requirements increase logarithmically as signals get quieter!
- Sampling frequency for a 90 dB signal is likely to be insufficient for a 70 dB signal

Caveats on Accuracy Requirements

Decibels are logarithmic units!



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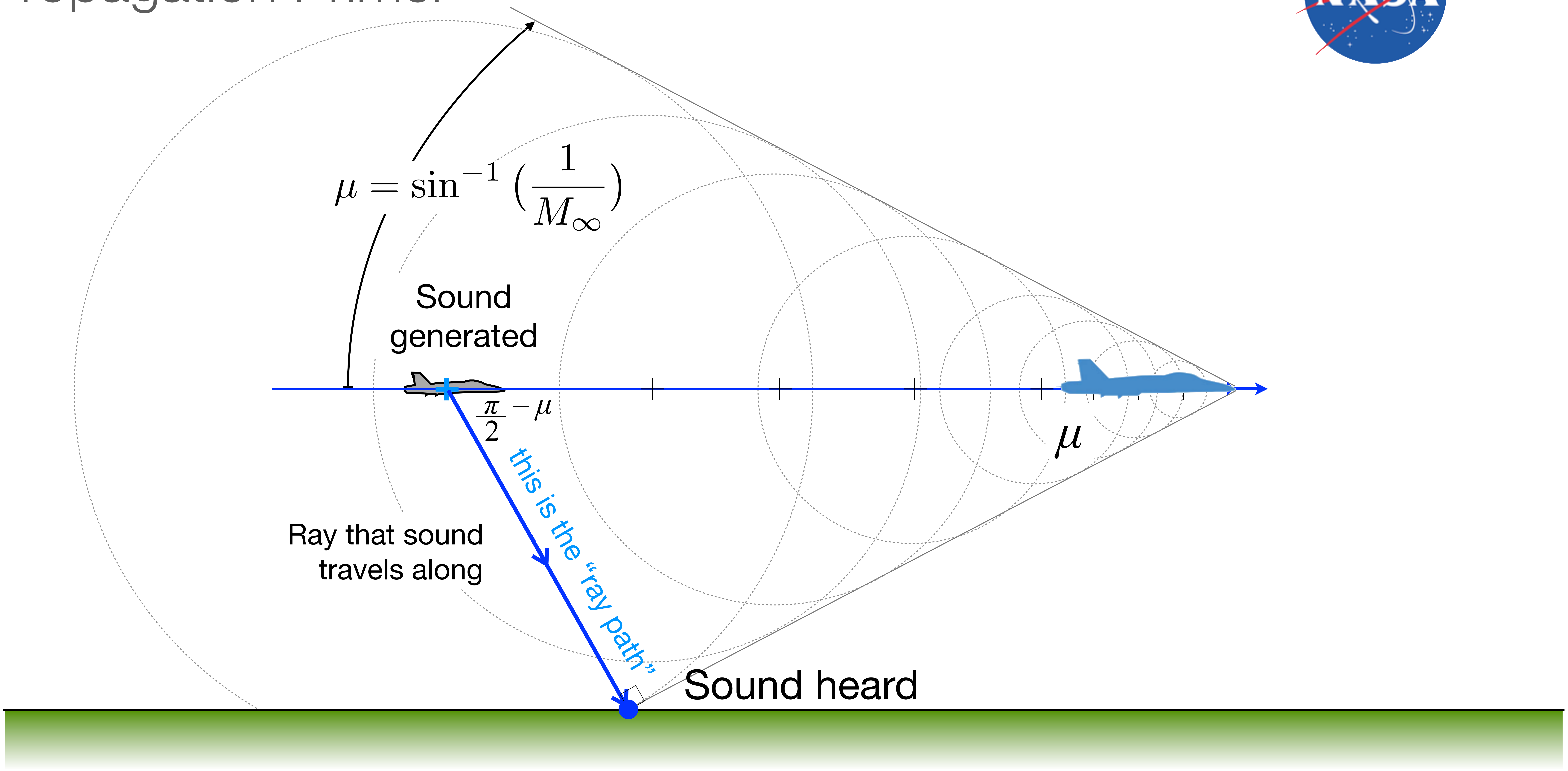
Propagation Primer

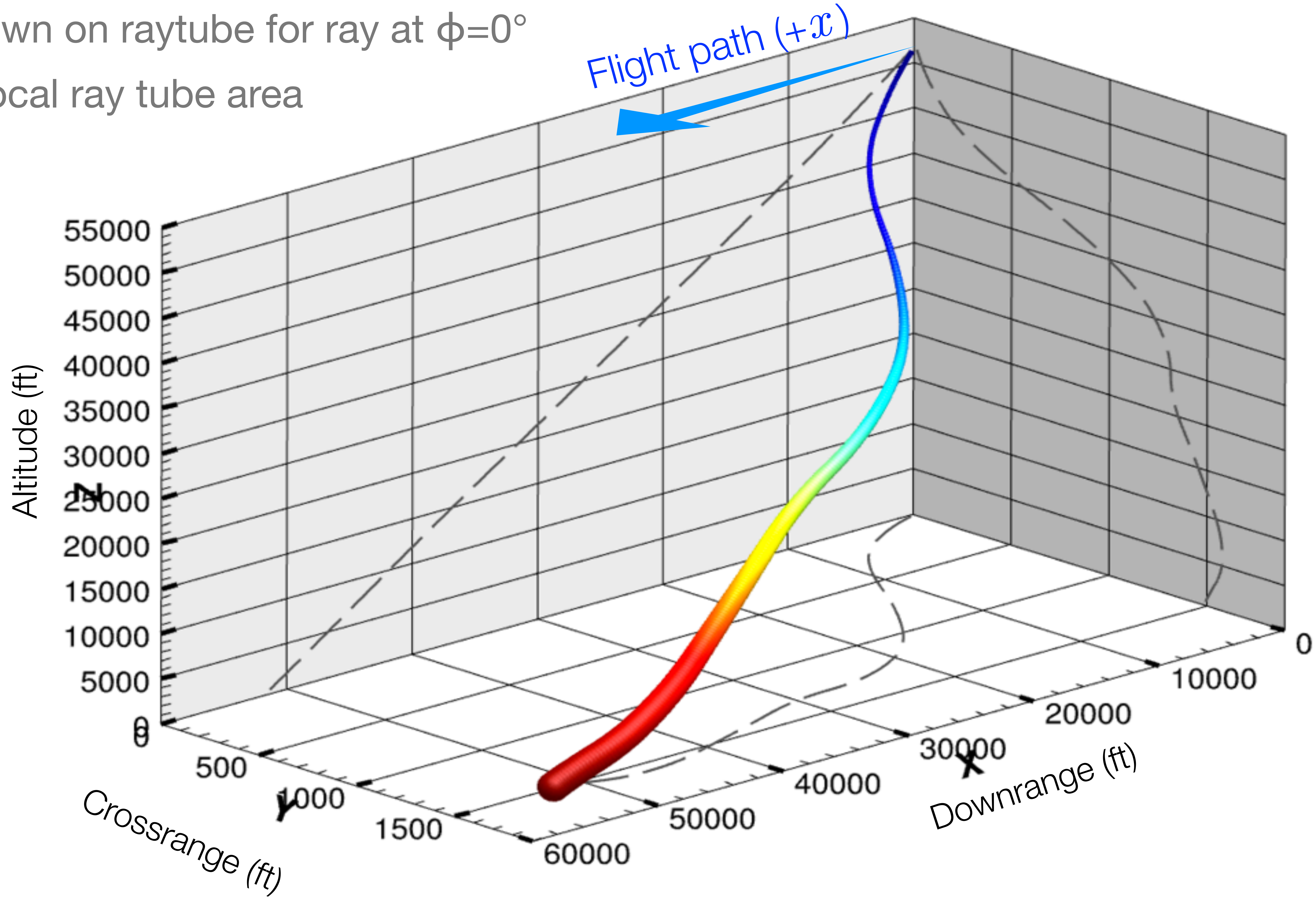


- Quasi-1D integration of Burger's equations occurs in tube along the ray path
- Determines the ground intercept of sound emanating from given trajectory point & azimuth
- Ray path determines time required for signal propagation

Wind Effects

- Only consider crossrange and downrange winds (no up/down drafts)
- Effects of wind shown on raytube for ray at ϕ=0°
- Path is scaled by local ray tube area

Case: Axibody
Atmosphere #3



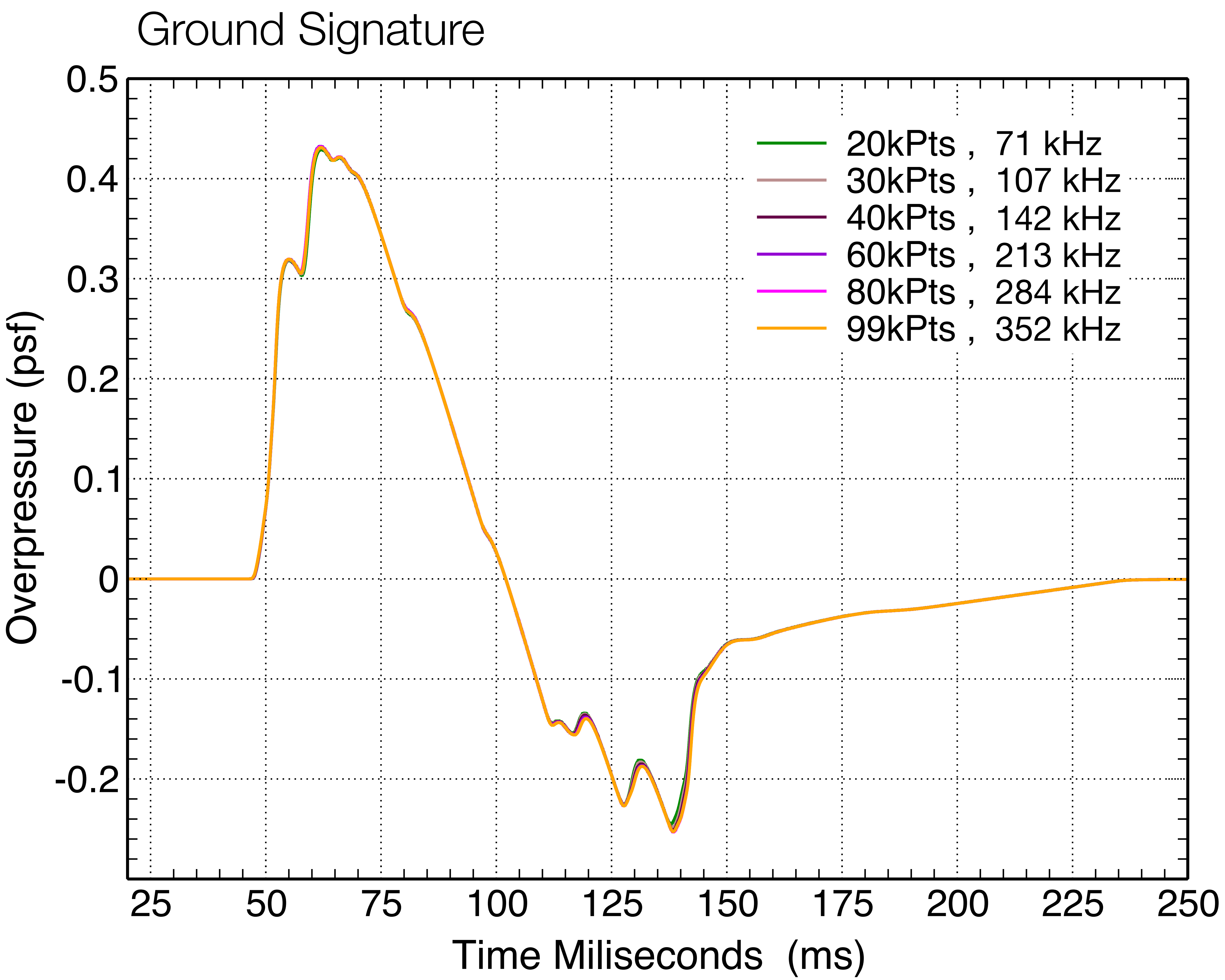
Mesh Convergence

Sensitivity of noise output to discretization of near field signal

- Propagation code is solving augmented Burgers' via finite difference
- Need to make sure outputs are sufficiently mesh converged
  - Mesh convergence is case dependent
  - Mesh refinement study done for each input signal (std. atmosphere)
- 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 20000-50000 points (oversampled by 20-50x)
- 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 ±0.1 dB

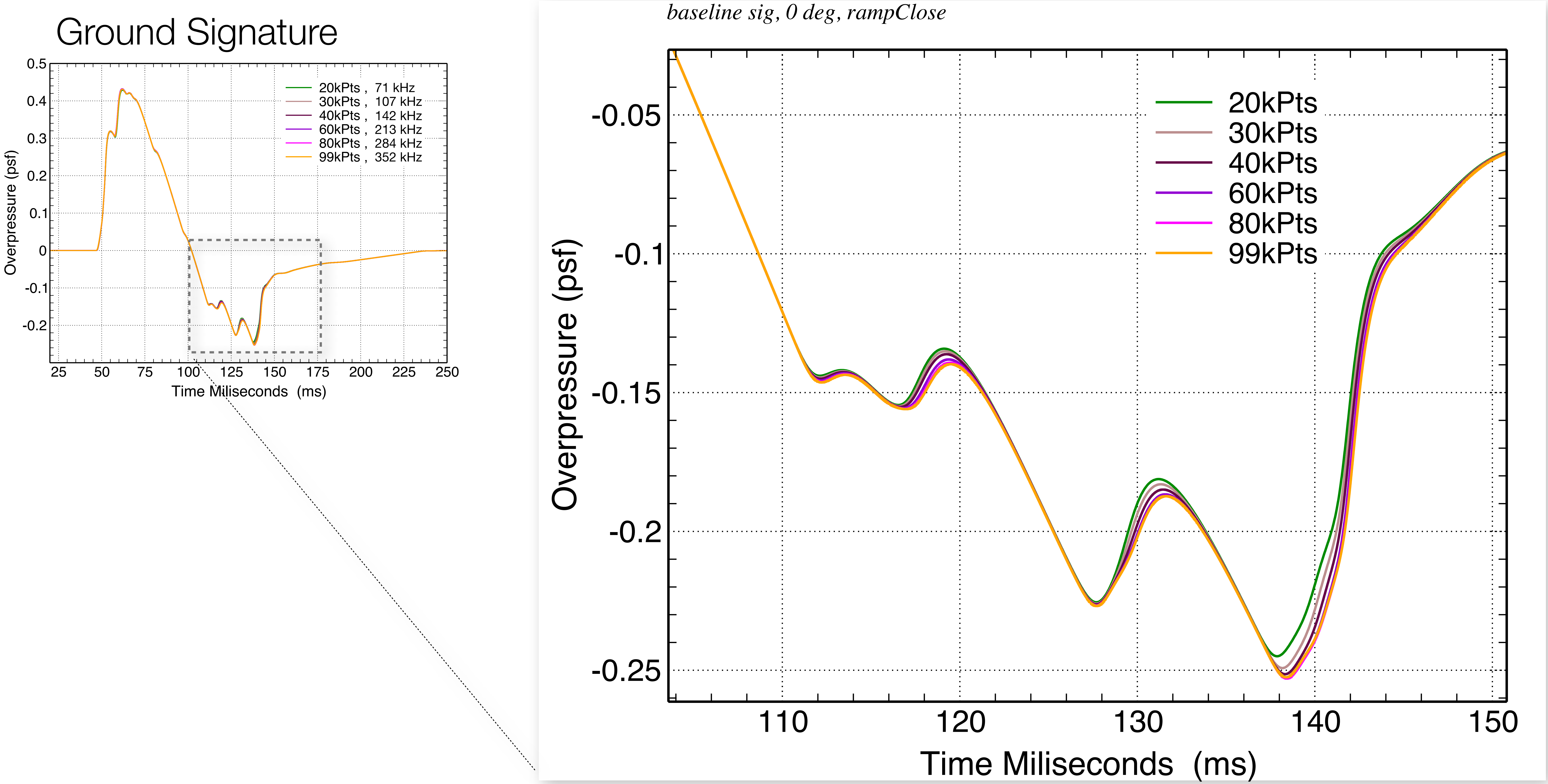
Mesh Convergence

Sensitivity of noise output to refinement of the propagation mesh



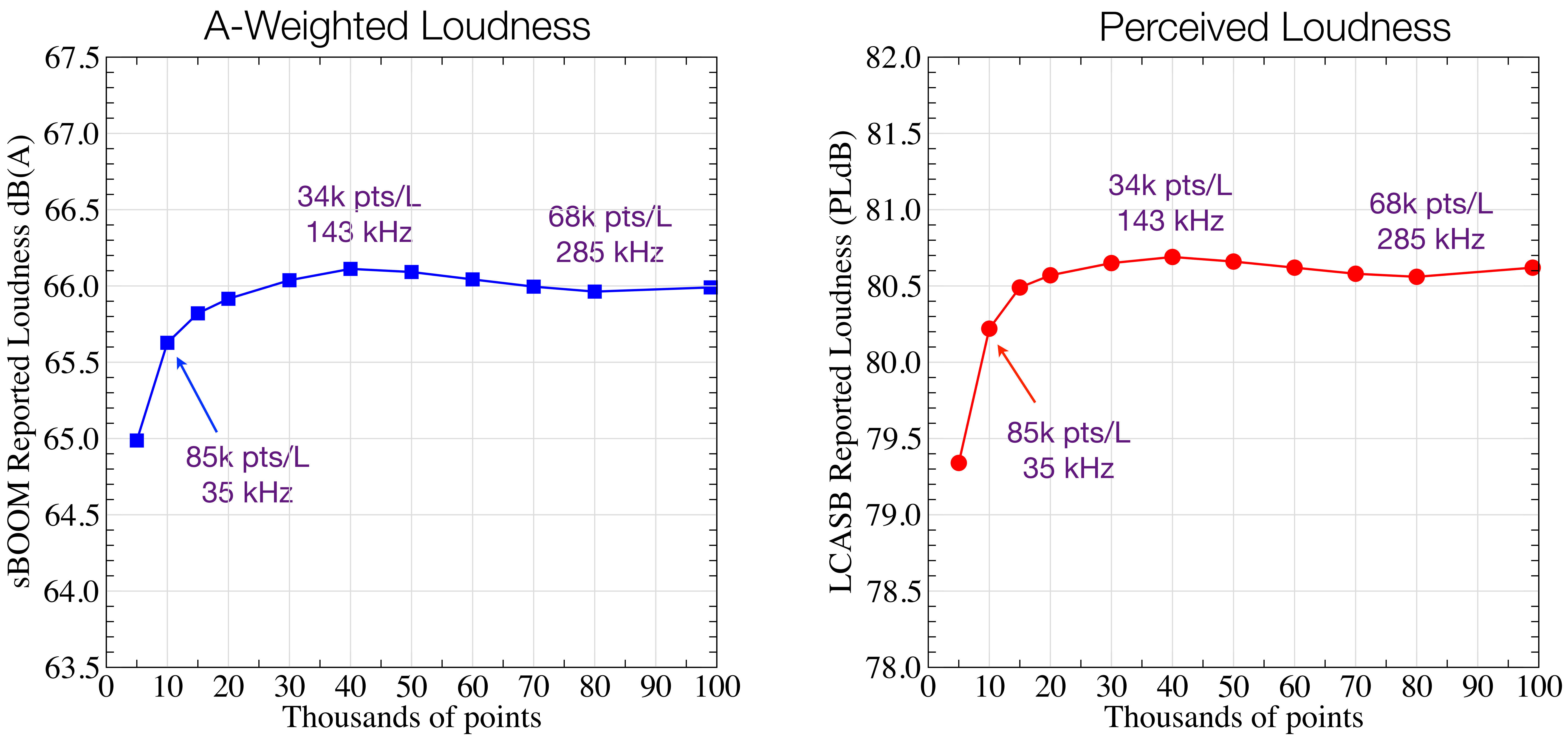
Mesh Convergence

Sensitivity of noise output to refinement of the propagation mesh



Mesh Convergence

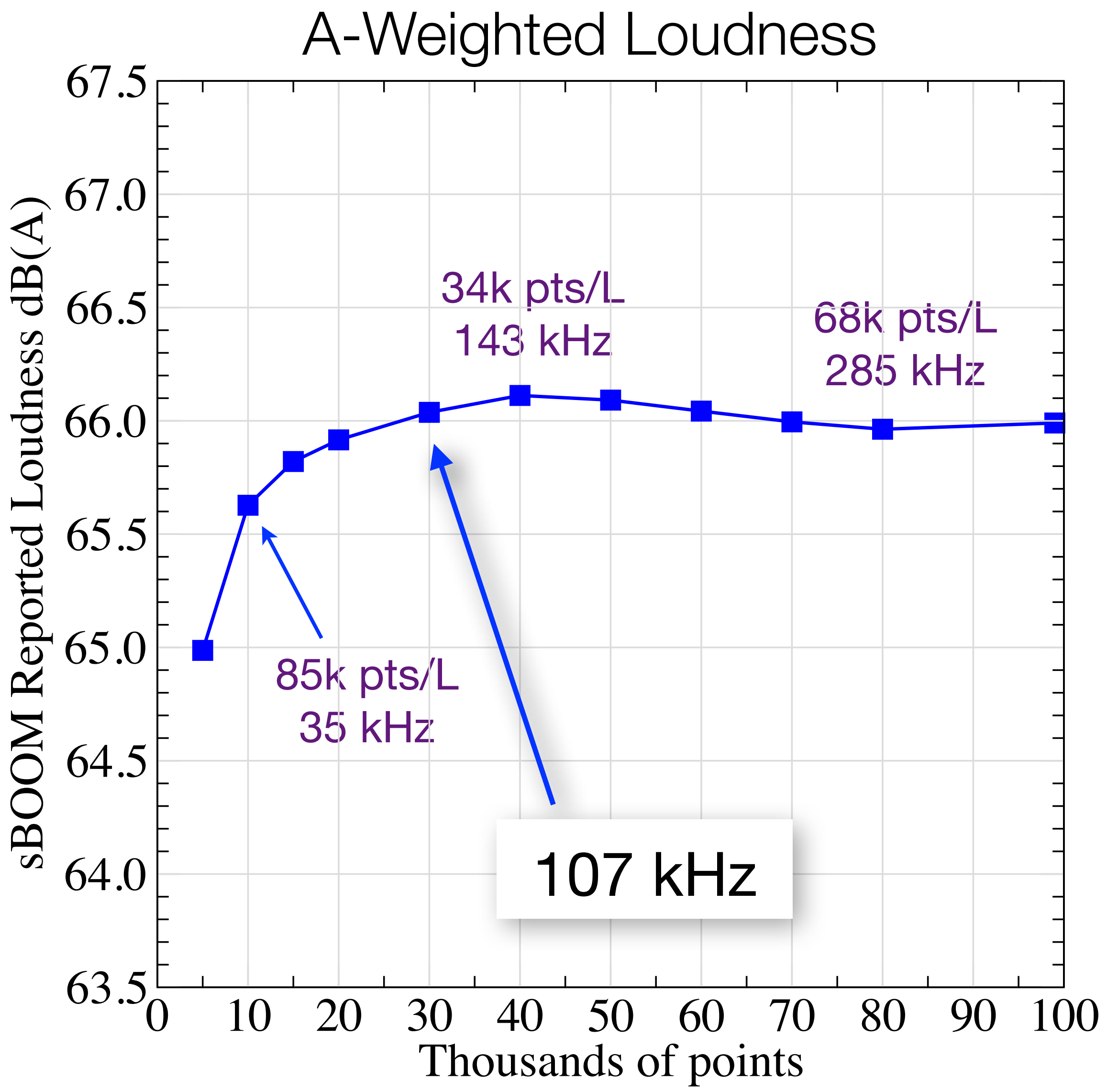
Sensitivity of noise output to refinement of the propagation mesh

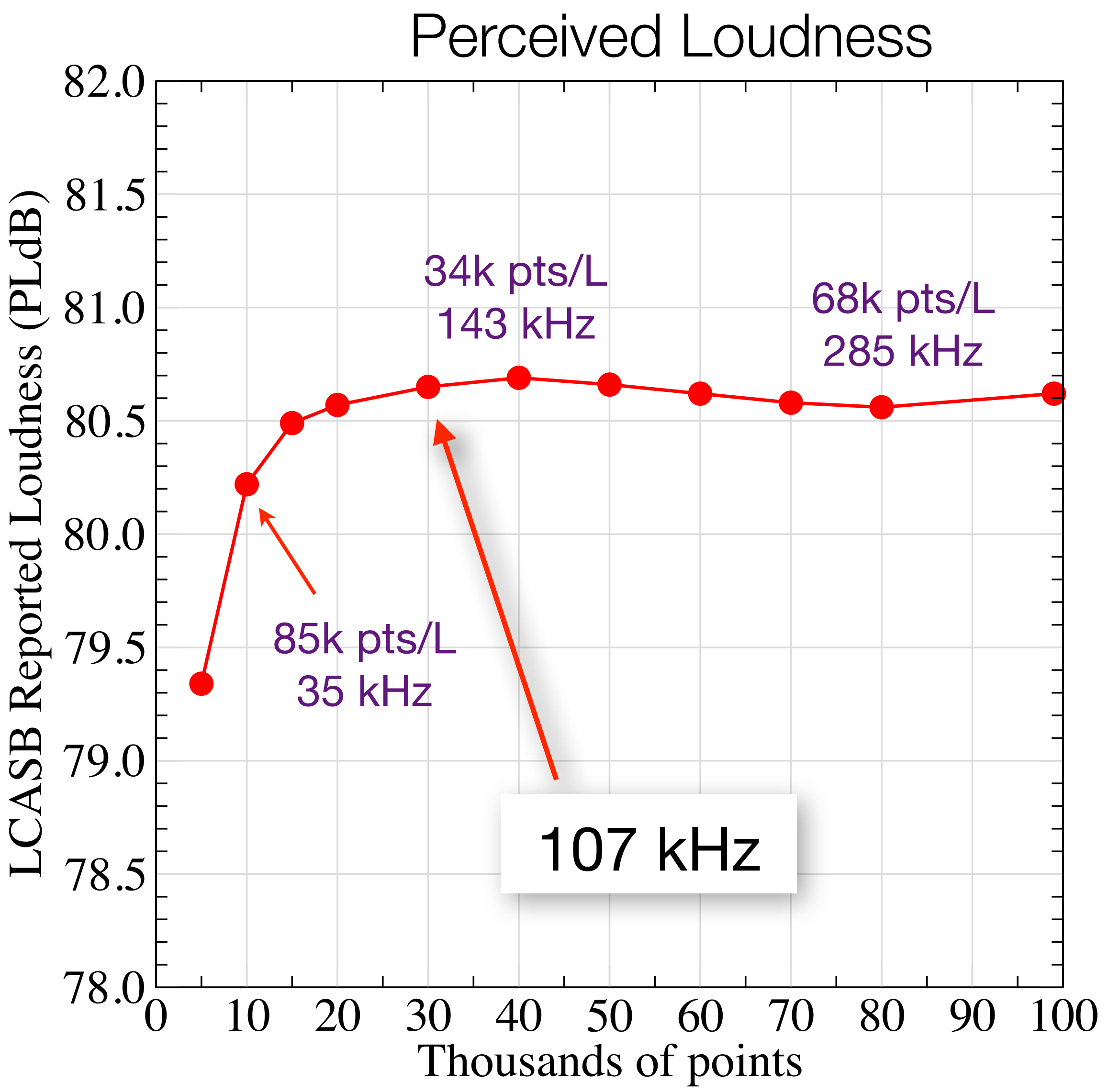


- Both dB(A) and PLdB show similar behavior
- Reasonable mesh convergence on ±2dB scale
- Absolute mesh convergence not great, even at higher frequencies

Mesh Convergence

Sensitivity of noise output to refinement of the propagation mesh





- Slow mesh convergence not surprising
  - Signal is non-smooth, and integrated loudness outputs are highly sensitive
- Oversampling of input introduces higher frequencies which effect loudness output
  - @ 285 kHz, we’re oversampling the non-smooth input by a factor of ~50x
- 107 kHz (30 kpts) gives better than ±0.1 dB accuracy – used for all axibody cases

Axibody

Shaped axisymmetric body of revolution

Conditions:

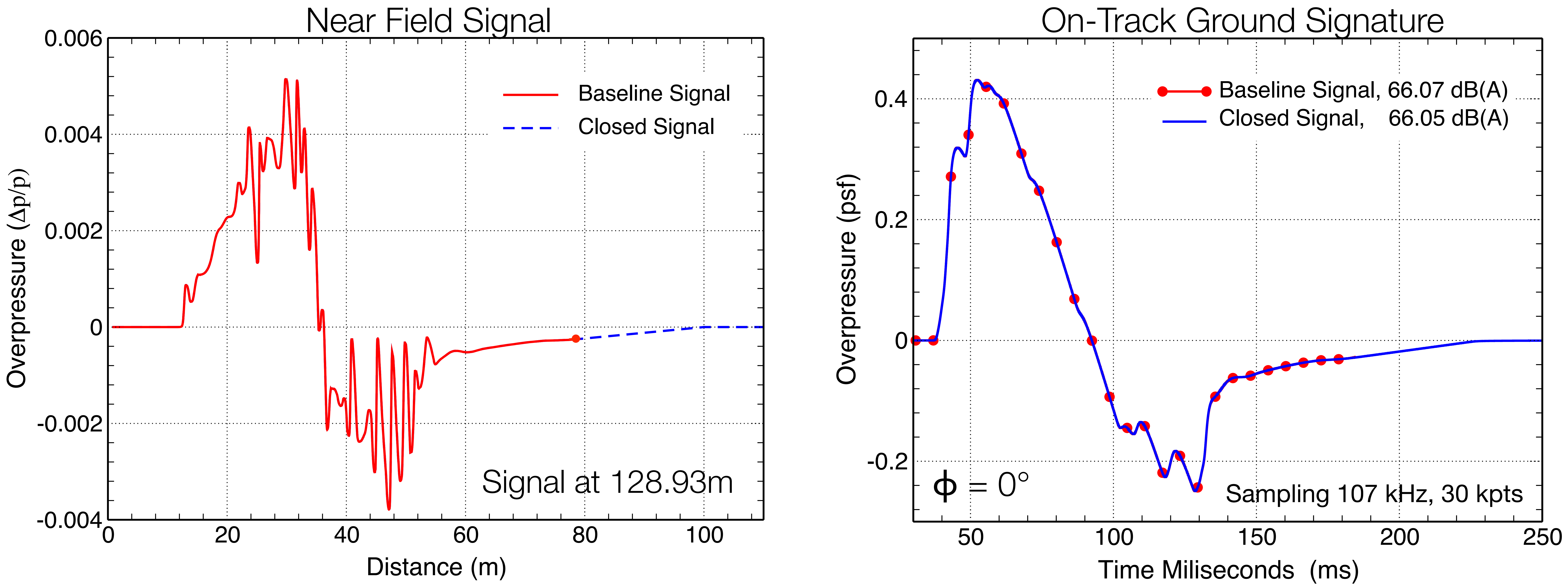
- $M_\infty = 1.6$
- Altitude = 15849.6 m (52 kft)
- $Lref$ = 42.98m (141 ft)
- r/L = 3.0 at signal extraction
- Ground reflection factor = 1.9
- Heading East ($\beta = 0°$)

Cases:

- Required: Atm #3
- Optional #1: Std. Atm.
- Optional #2: Atm #4
- Optional #4: Std. Atm. with 70% humidity

Axibody

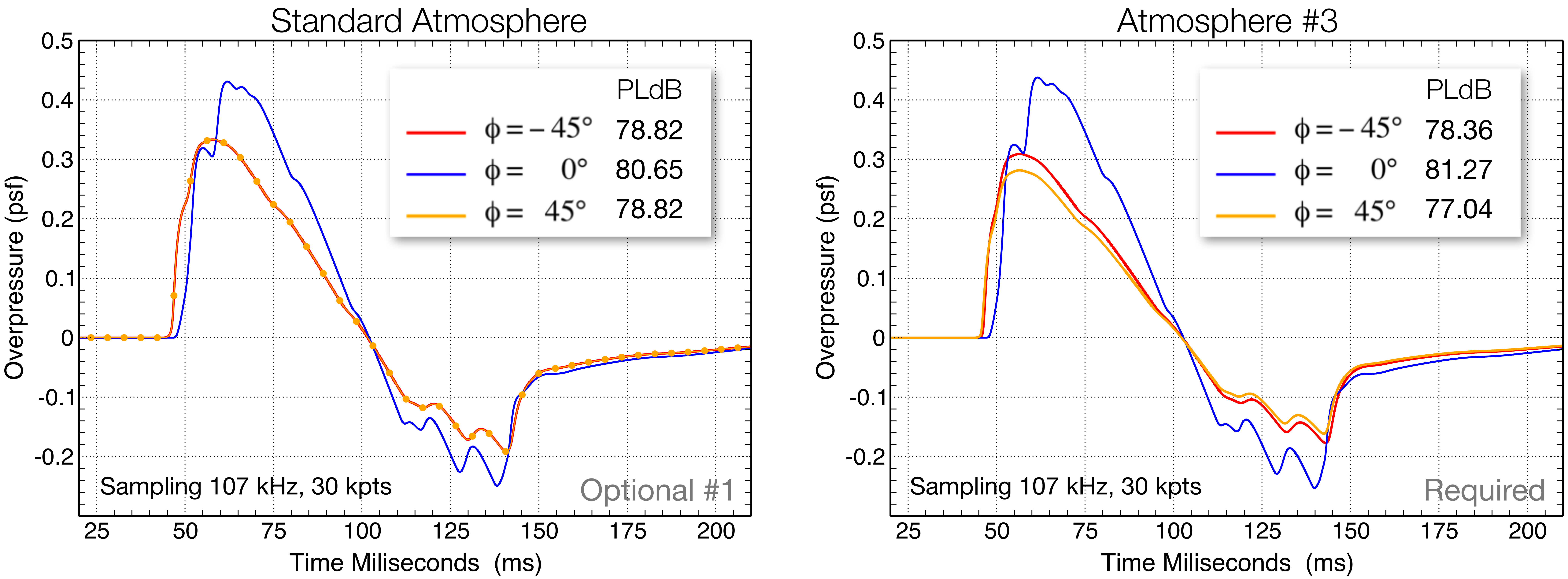
Close near field signal



- Compared 2 different closures (both linear ramps) gave consistent results
- Closed signal using linear ramp to 0 at 100 m
- Ground signals & noise both virtually identical (within 0.02 dBA)

Axibody

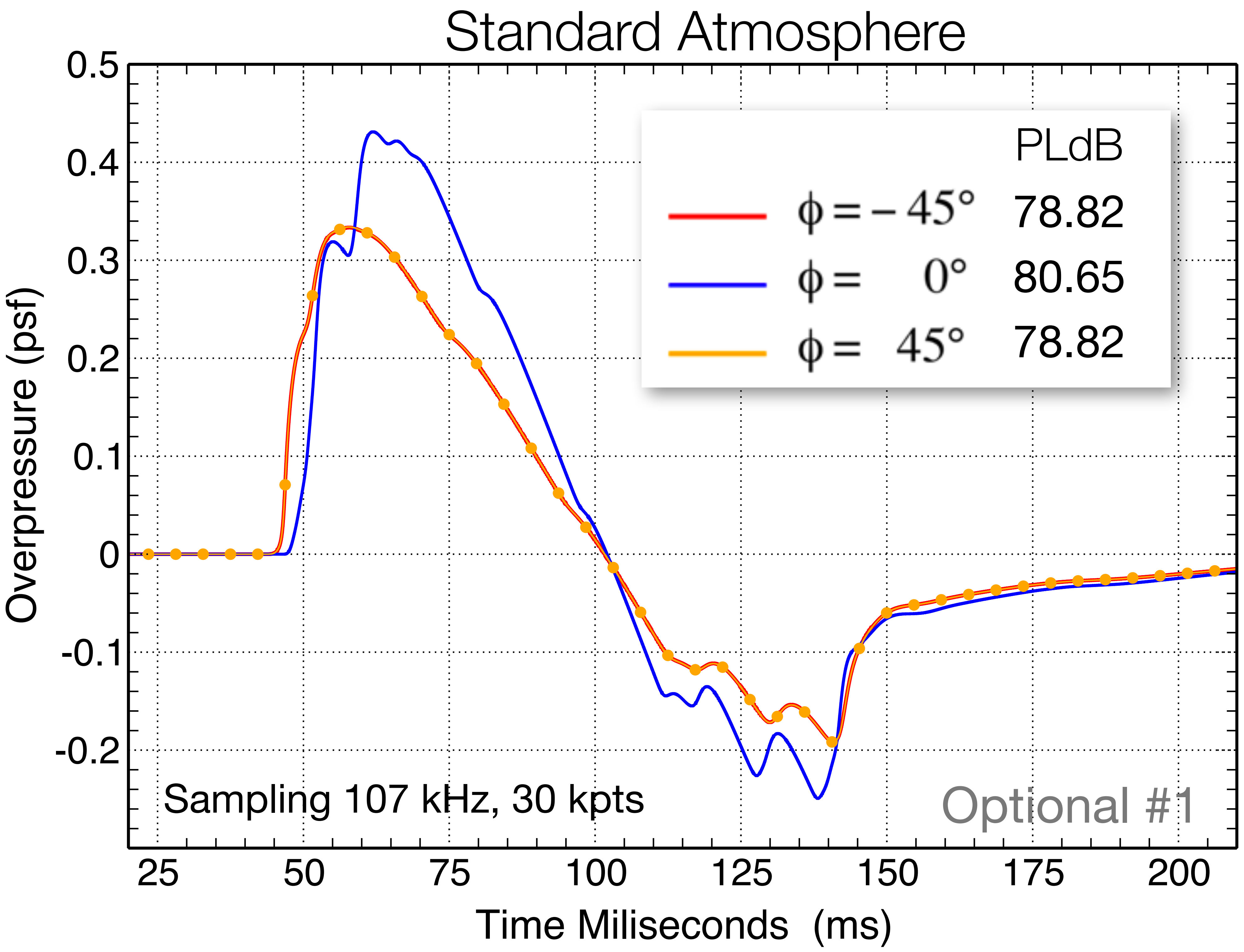
Ground signature – Standard Atm. vs Atmosphere 3, ϕ = {-45°, 0°, 45°}

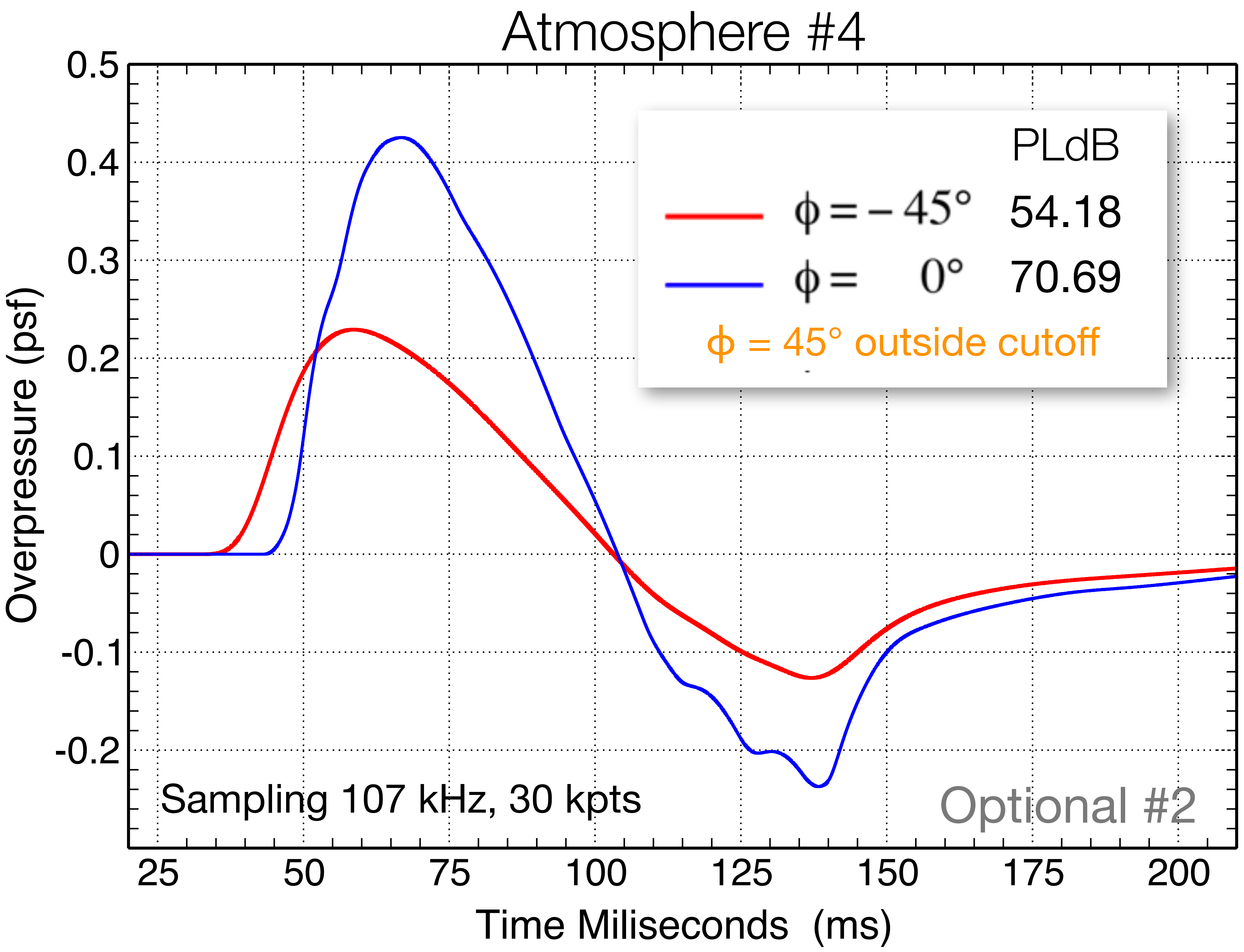


- Atm #3 has slightly more noise on-track
- Propagation time roughly 70 sec @ ϕ=0° & 112–120 sec @ ϕ=45°

Axibody

Ground signature – Standard Atm. vs Atmosphere 4, ϕ = {-45°, 0°, 45°}

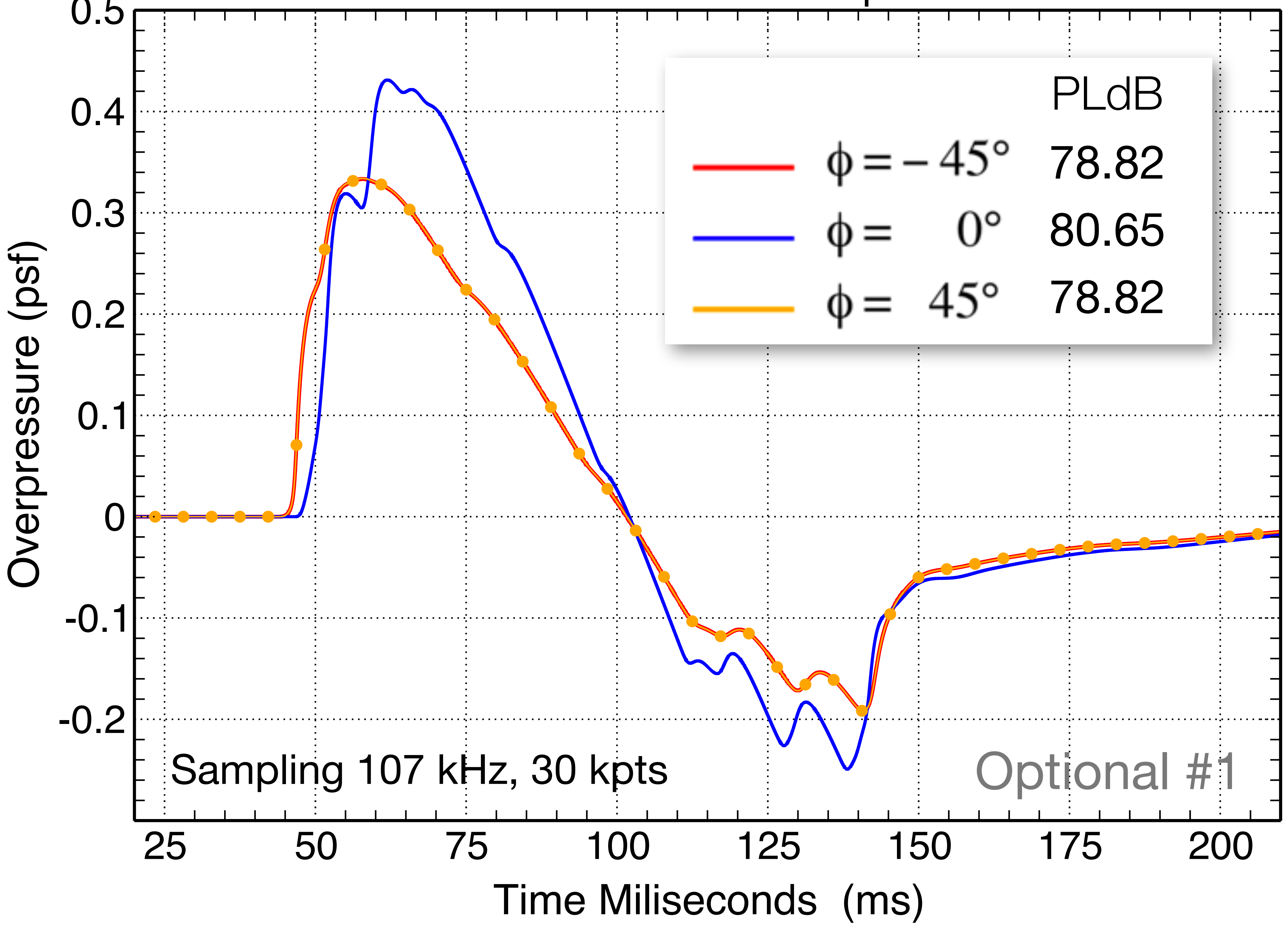




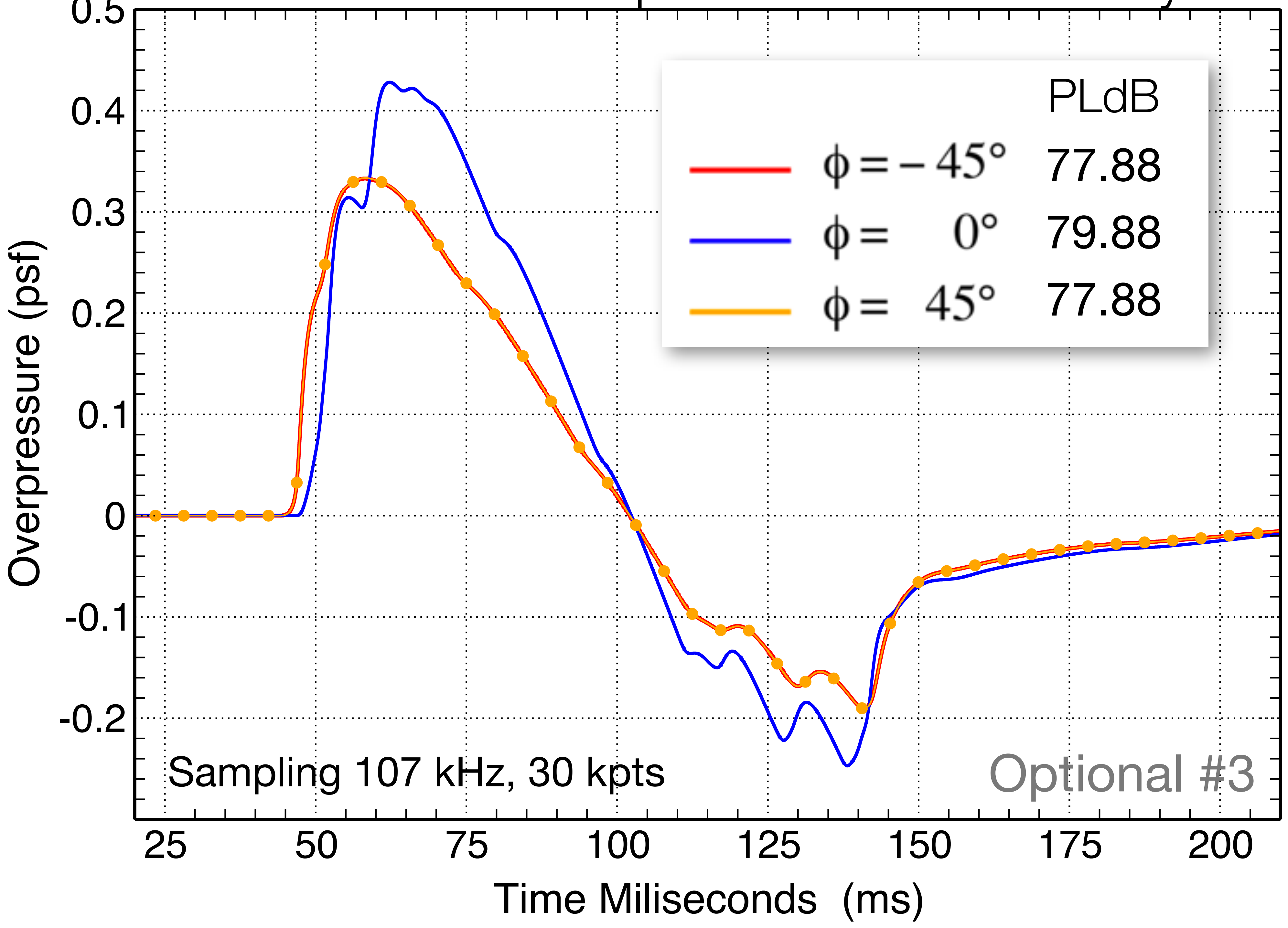
- Atm #4 is a hot, dry day, 10 dB quieter on track
- Atm #4 propagation time roughly identical @ ϕ=0° but ~20sec longer at @ ϕ=-45°
- Atm #4 cutoff before ϕ=+45°

Axibody

Ground signature – Standard Atm. vs Standard Atm. + 70% Relative Humidity



Standard Atmosphere



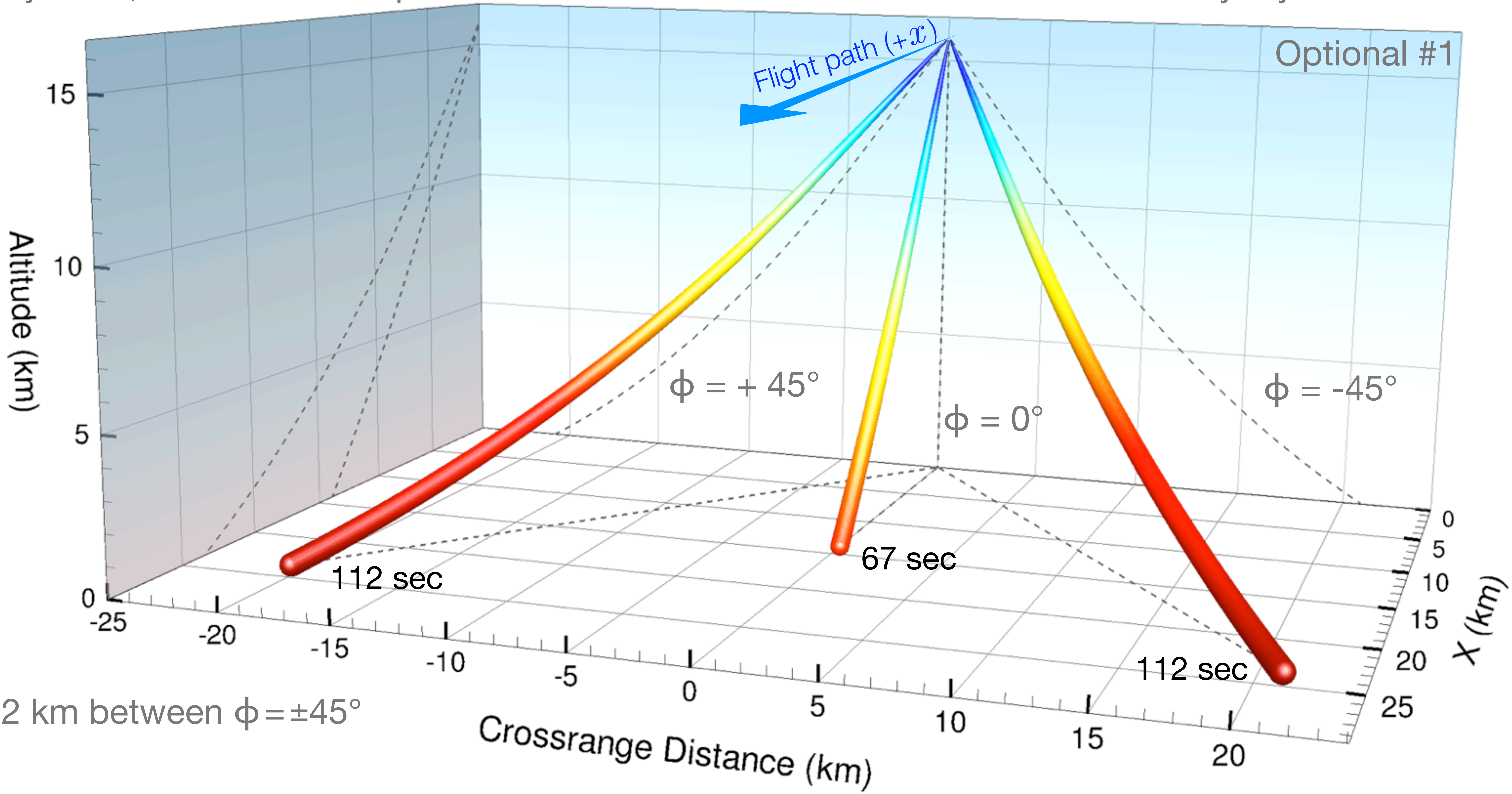
Standard Atmosphere + 70% Humidity

- Optional #3: constant relative humidity of 70%
- Results with 70% RH are ~1dB quieter
- Seems counter intuitive, usually humidity improves propagation (louder)

Axibody

Raytubes, standard atmosphere

Colored by raytube area

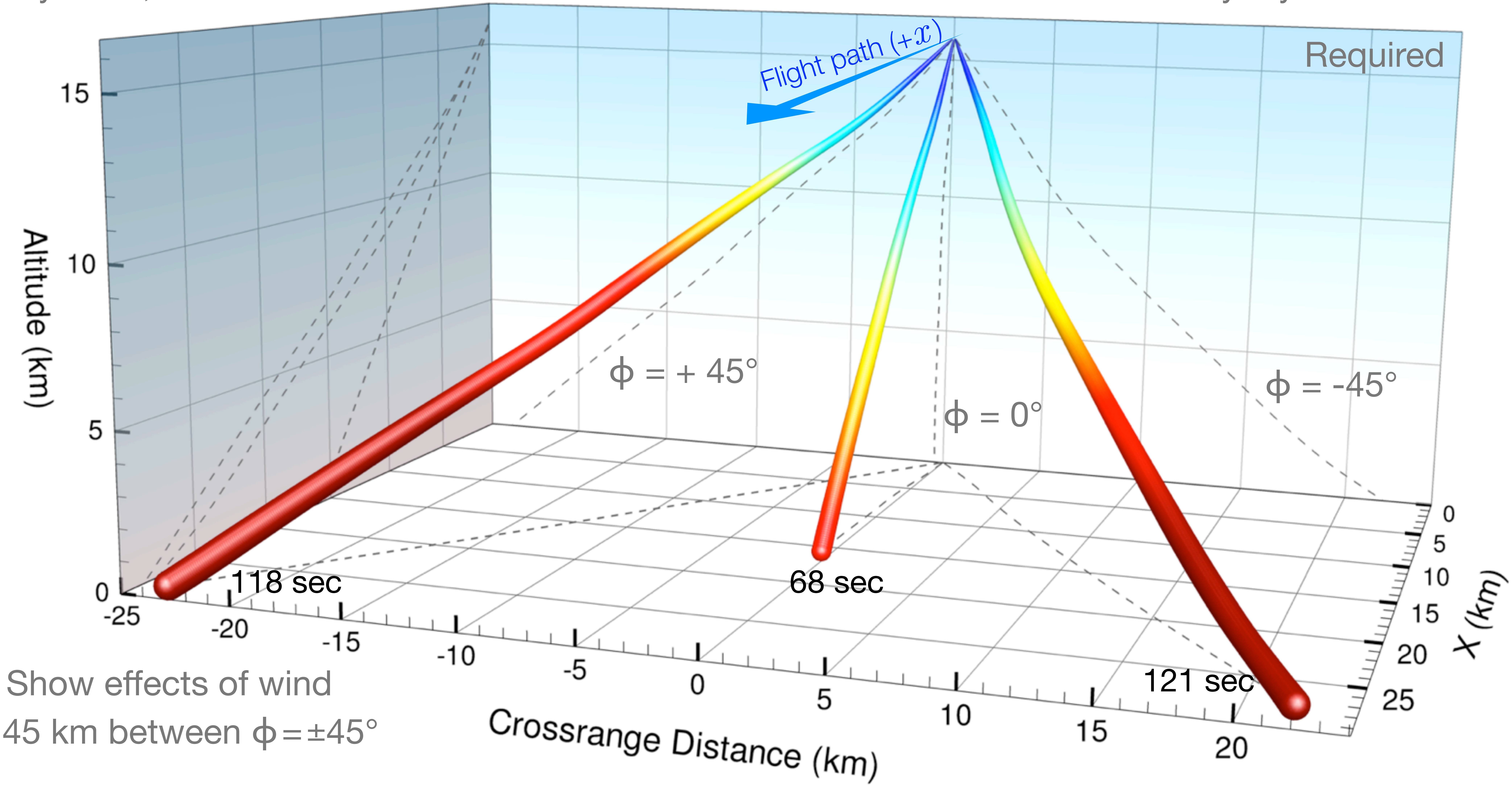


42 km between ϕ=±45°

Axibody

Raytubes, Atm #3

Colored by raytube area



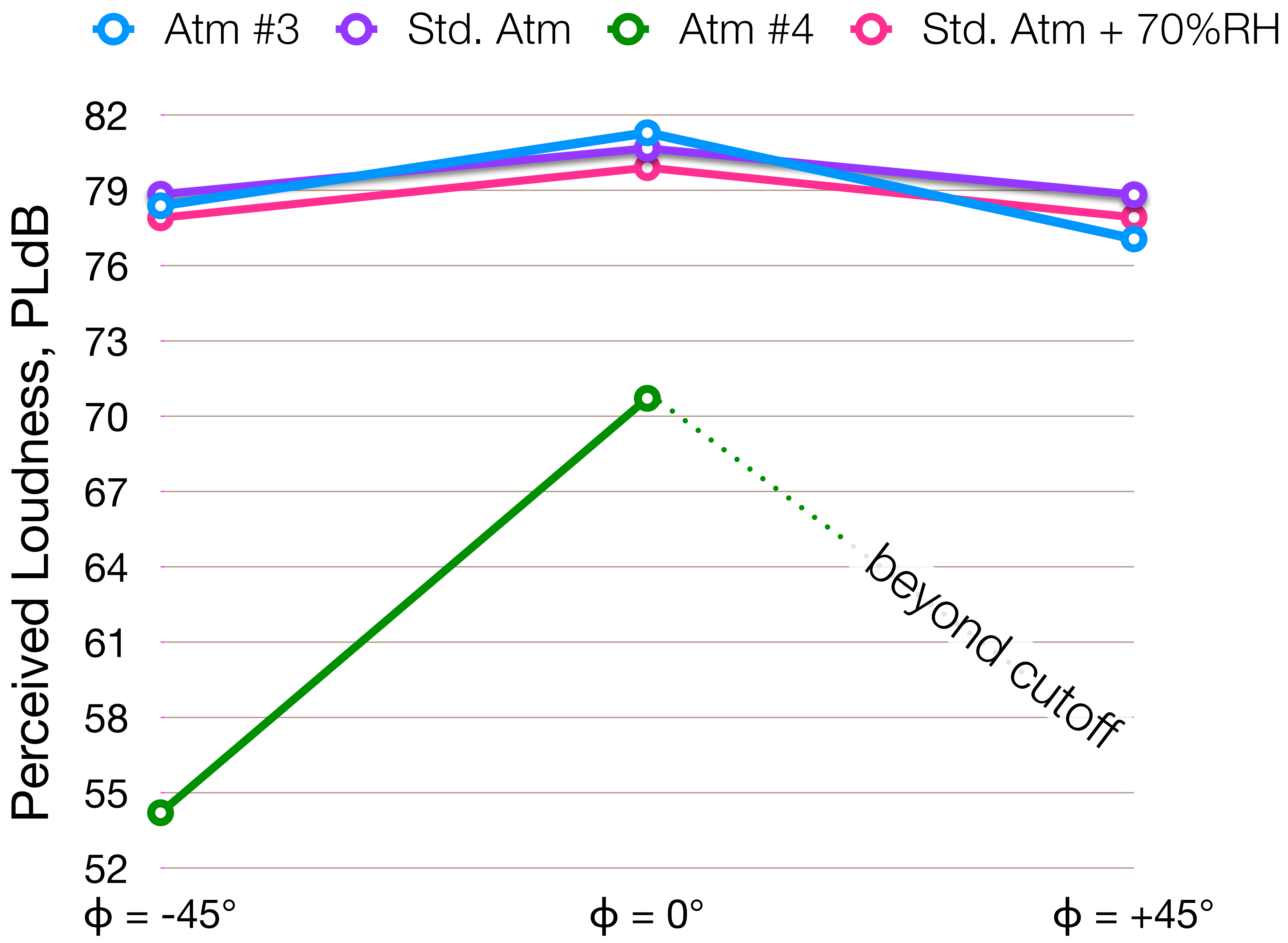
Show effects of wind

45 km between ϕ=±45°

Axibody

Perceived loudness at ground level

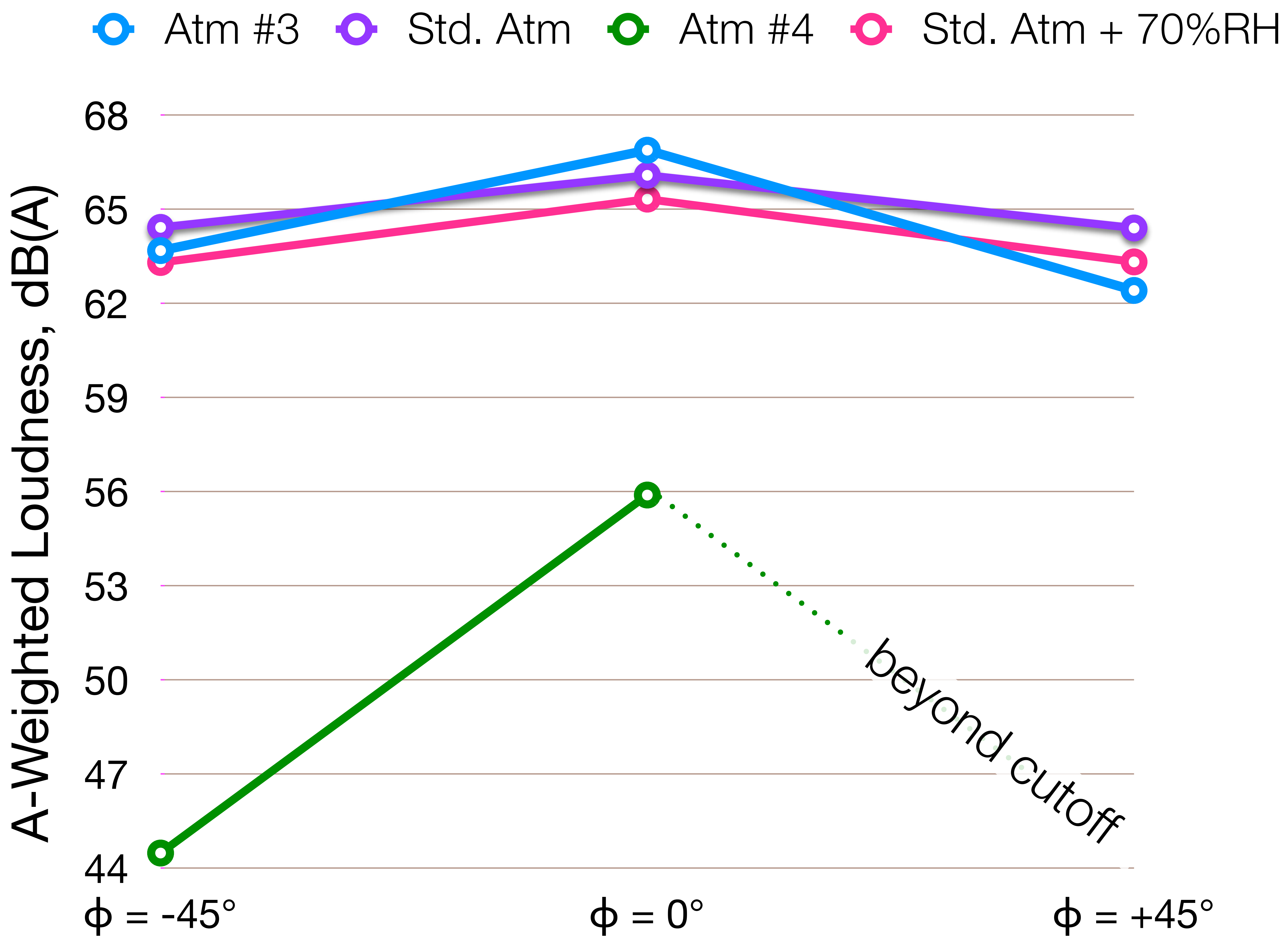
- Atm #3 loudest on-track
- other metrics show similar trends.
- Atm #4 off track very close to cutoff at ±45°
- Atm #4 cutoff before ϕ=+45°



Axibody

dB(A): A-Weighted loudness at ground level

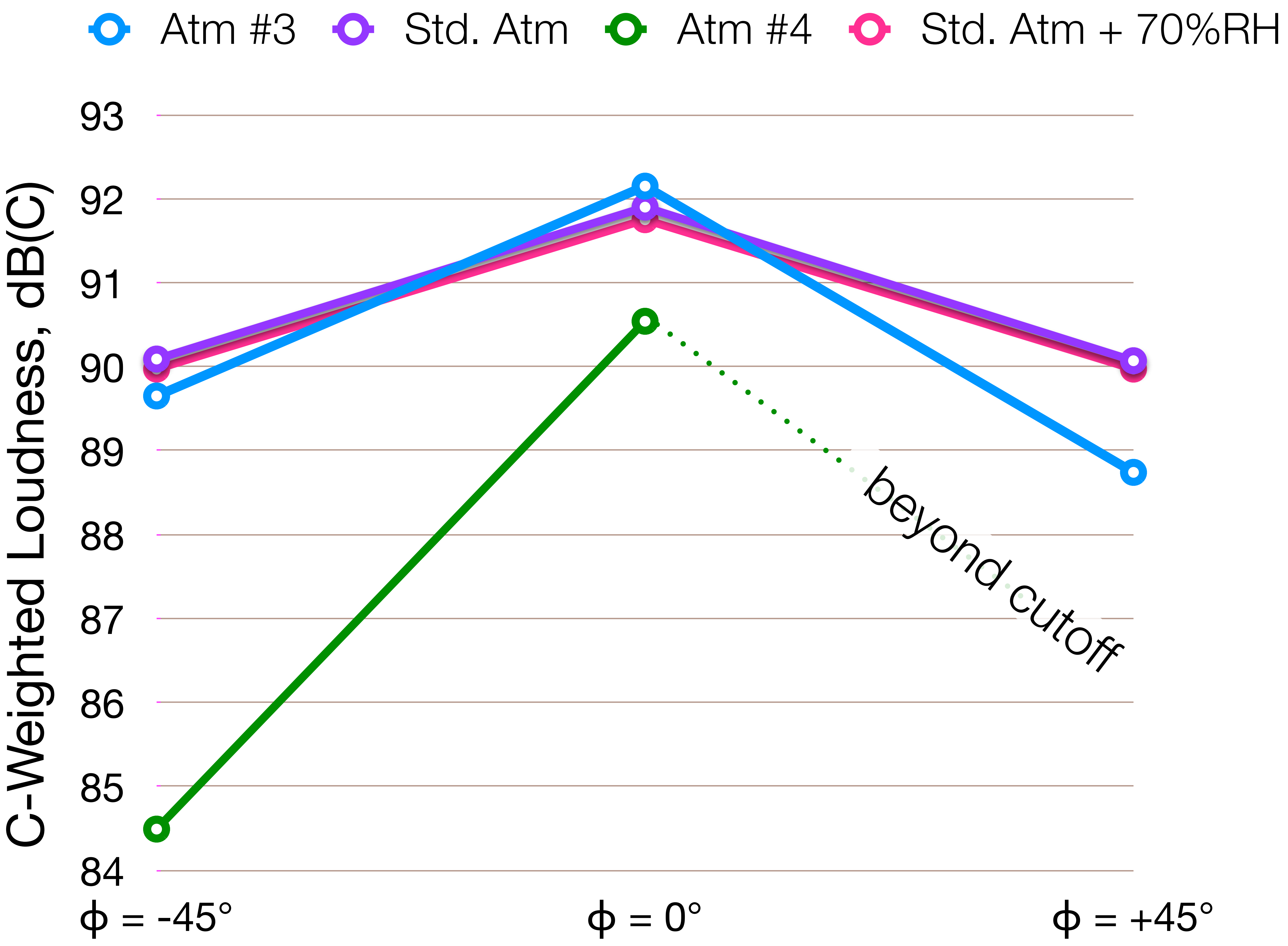
- Atm #3 loudest on-track
- other metrics show similar trends.
- Atm #4 cutoff before ϕ=+45°



Axibody

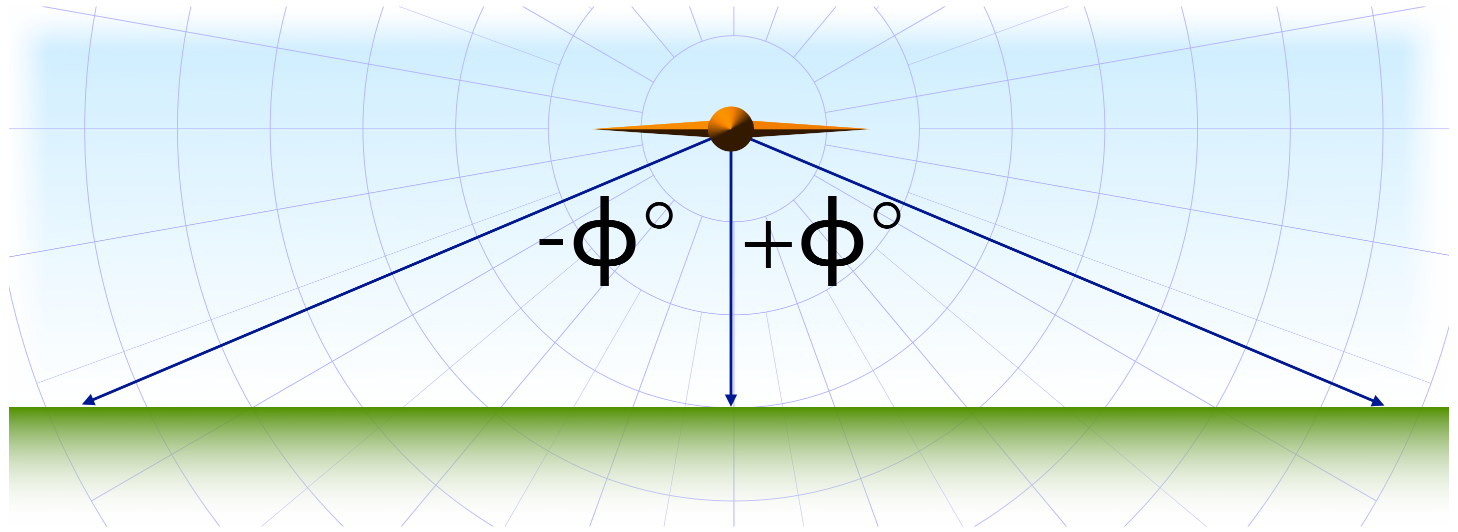
dB(C): C-Weighted loudness at ground level

- SEL(C) shows most variation with azimuth angle
- Also shows least variation between Atm #4 and others



Axibody

Signal cutoff

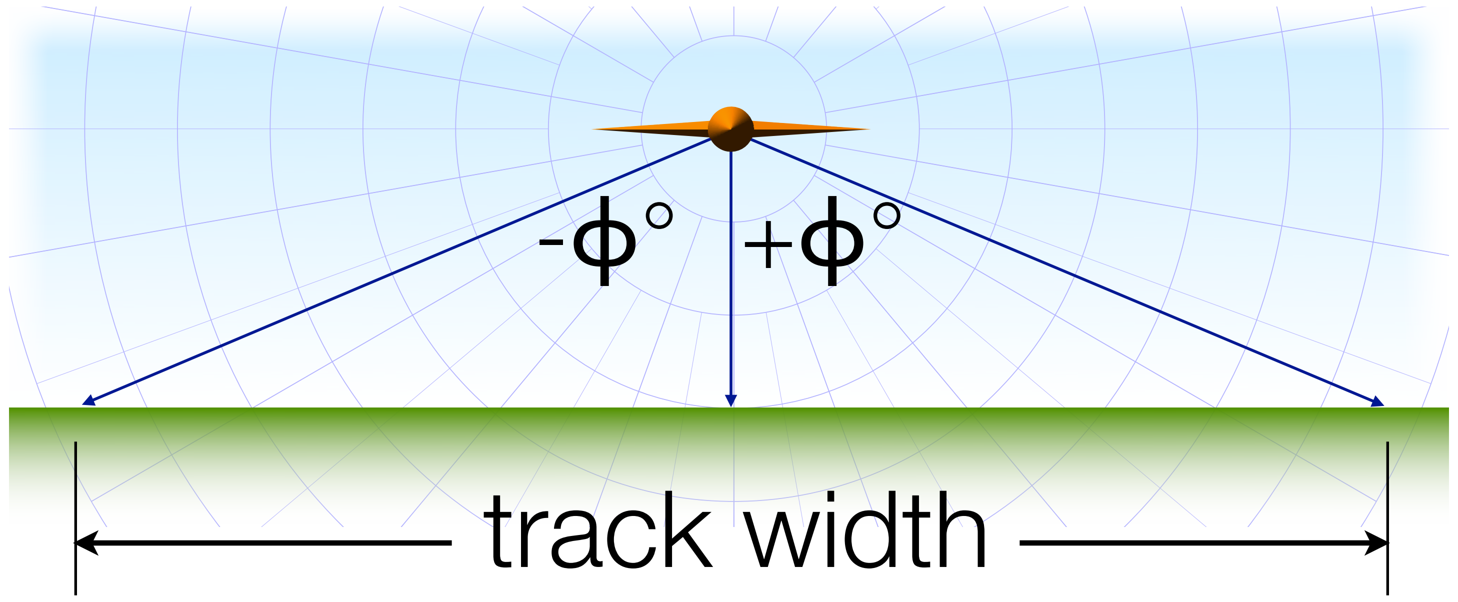


- Propagation time near cutoff around 3-4 mins

Atmosphere Profile	Cutoff ($-\phi°$) (x, y) km	Cutoff ($+\phi°$) (x, y) km
Atm # 3	**-50.28°** **(44.1, 39.3) km**	**53.08°** **(48.5, -46.1) km**
Std. Atm	-53.38° (35.9, 34.5) km	53.38° (35.9, -34.5) km
Atm # 4	-46.70° (44.9, 40.8) km	43.89° (35.9, -30.7) km
Std. Atm + 70% humidity	-53.38° (35.9, 34.5) km	53.38° (35.9, -34.5) km

Axibody

Signal cutoff

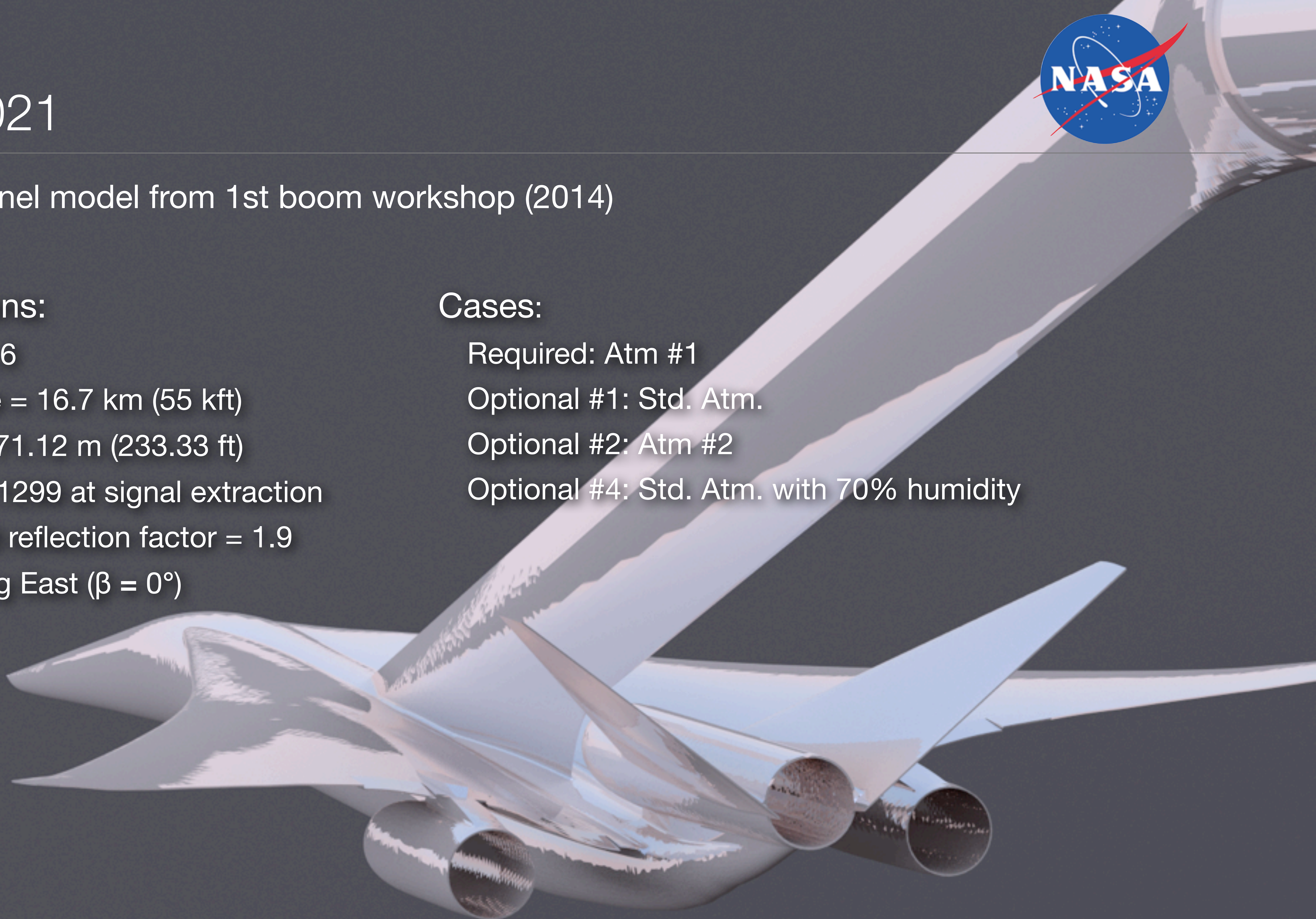


- Propagation time near cutoff around 3-4 mins
- Winds generally increase track width (from 70 to ~85 km)

Atmosphere Profile	Cutoff $(-\phi^\circ)$ (x, y) km	Cutoff $(+\phi^\circ)$ (x, y) km	Track Width
Atm # 3	**-50.28°** **(44.1, 39.3) km**	**53.08°** **(48.5, -46.1) km**	**85.4 km**
Std. Atm	-53.38° (35.9, 34.5) km	53.38° (35.9, -34.5) km	69.0 km
Atm # 4	-46.70° (44.9, 40.8) km	43.89° (35.9, -30.7) km	71.5 km
Std. Atm + 70% humidity	-53.38° (35.9, 34.5) km	53.38° (35.9, -34.5) km	69.0 km

LM 1021

Wind tunnel model from 1st boom workshop (2014)



Conditions:

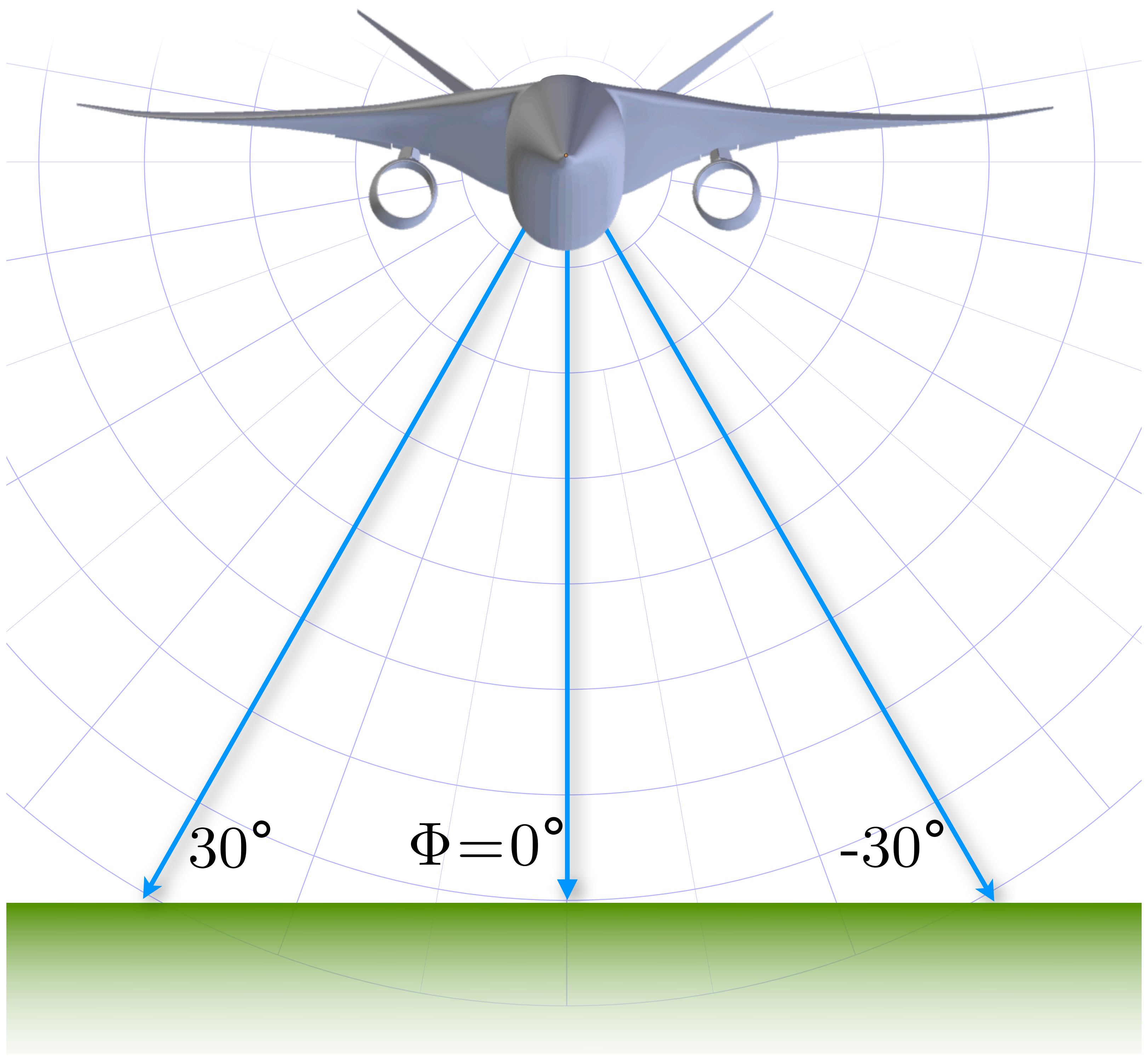
- $M_\infty = 1.6$
- Altitude = 16.7 km (55 kft)
- *Lref* = 71.12 m (233.33 ft)
- r/L = 3.1299 at signal extraction
- Ground reflection factor = 1.9
- Heading East (β = 0°)

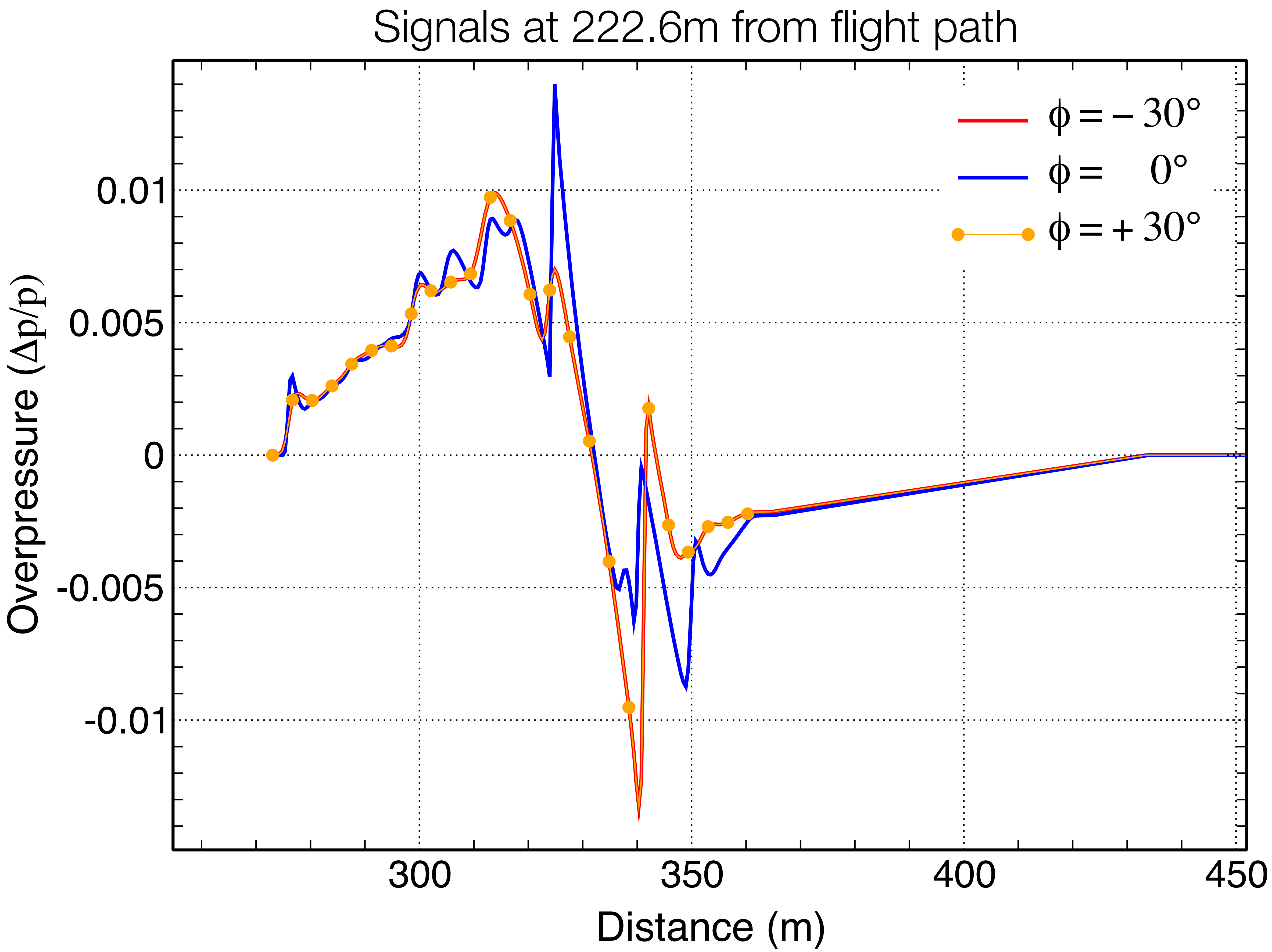
Cases:

- Required: Atm #1
- Optional #1: Std. Atm.
- Optional #2: Atm #2
- Optional #4: Std. Atm. with 70% humidity

LM 1021

Near Field Signatures





Signals closed with a linear ramp to 435 m

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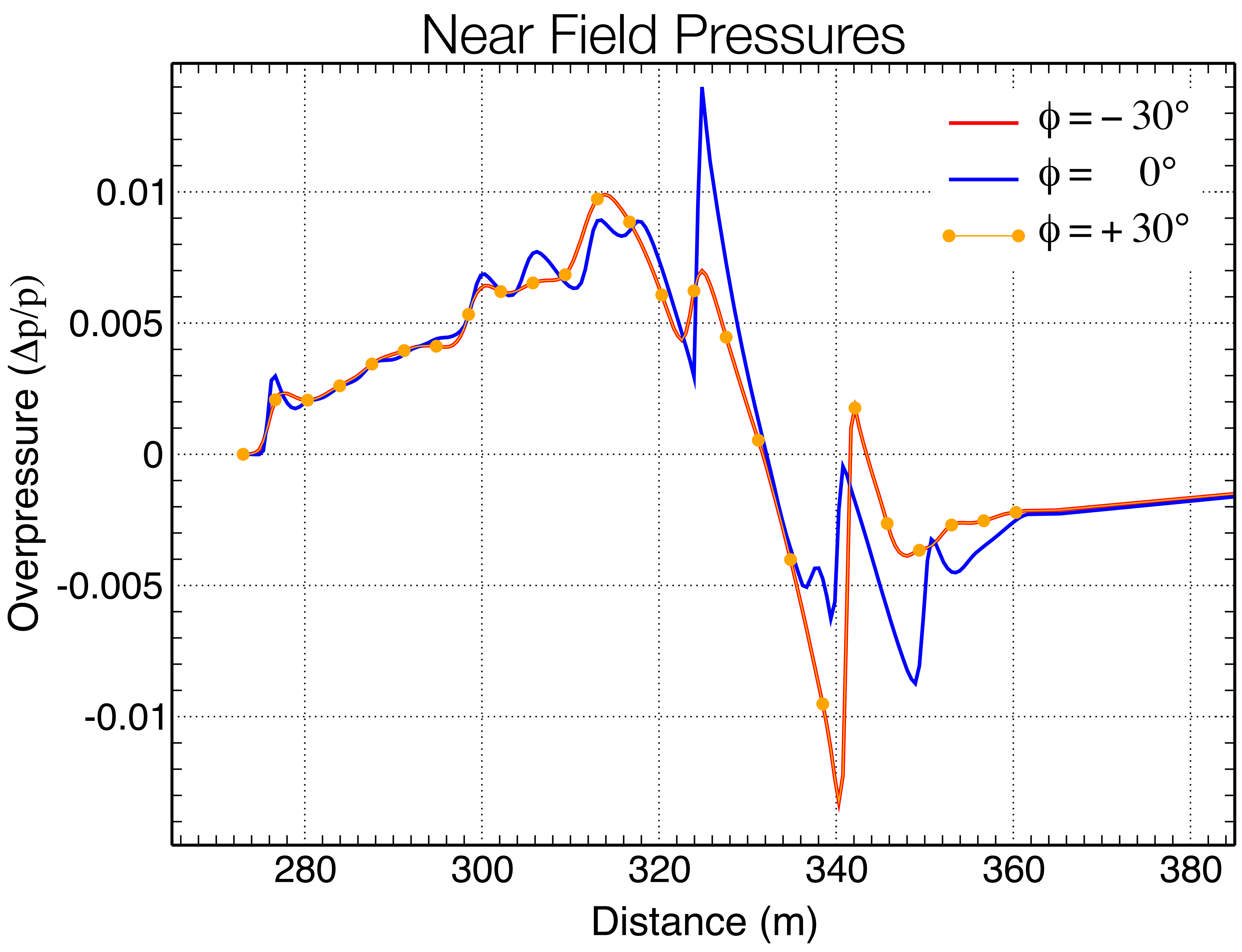
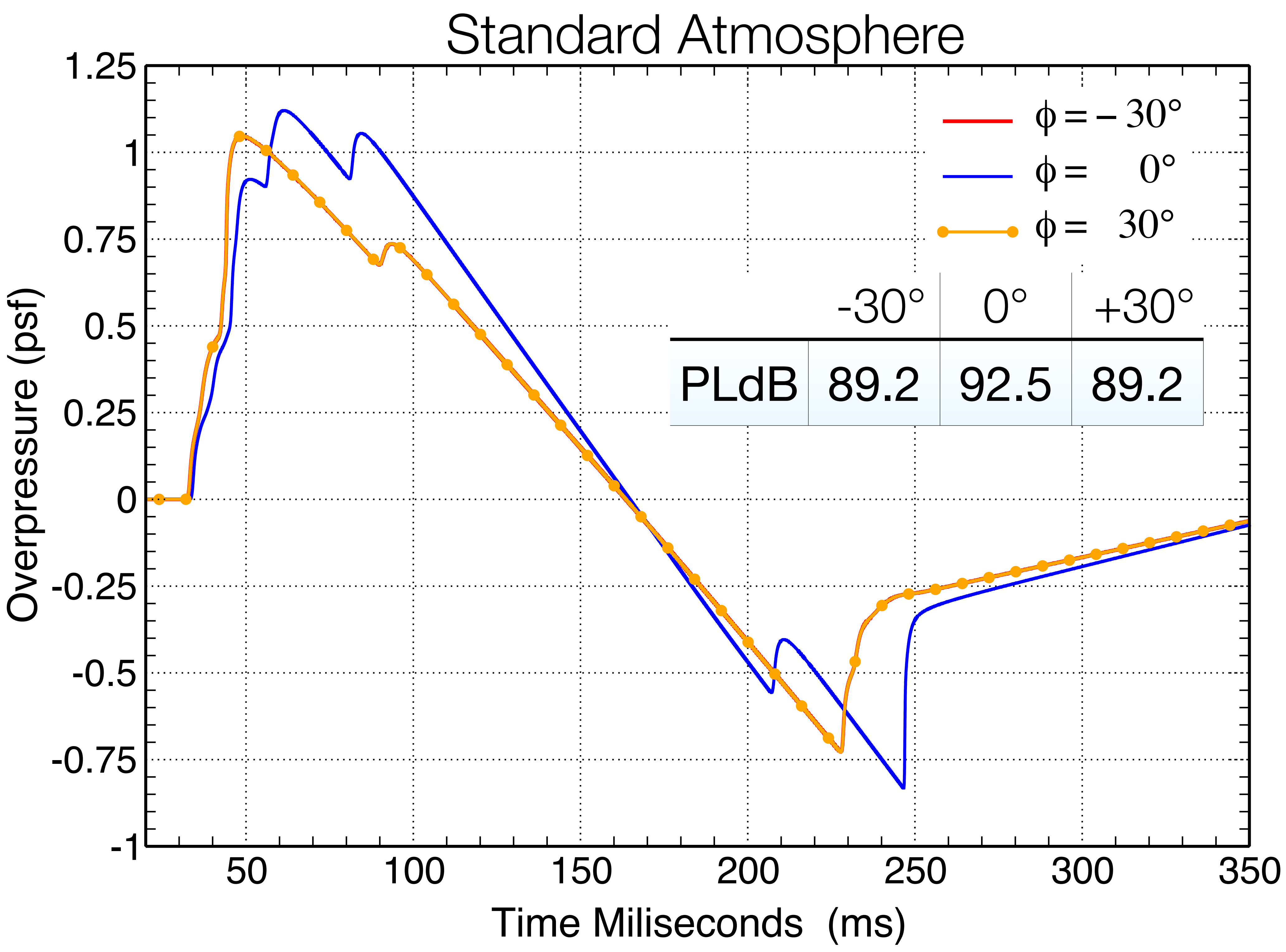
Ground signature: Standard Atmosphere, ϕ = {-30°, 0°, 30°}





	-30°	0°	+30°
PLdB	89.2	92.5	89.2

Sampling Frequency = 75.6 kHz, 40 kpts

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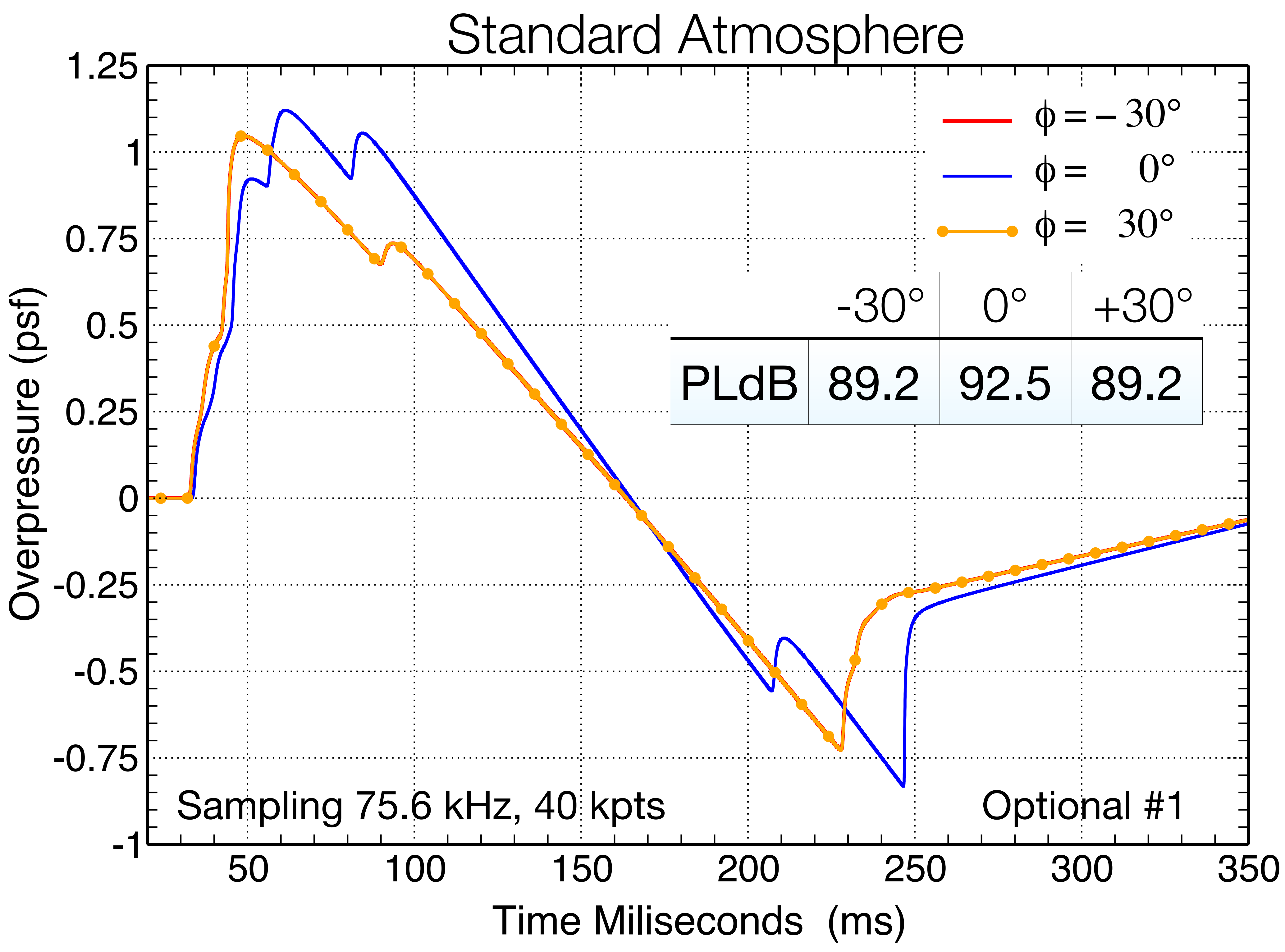
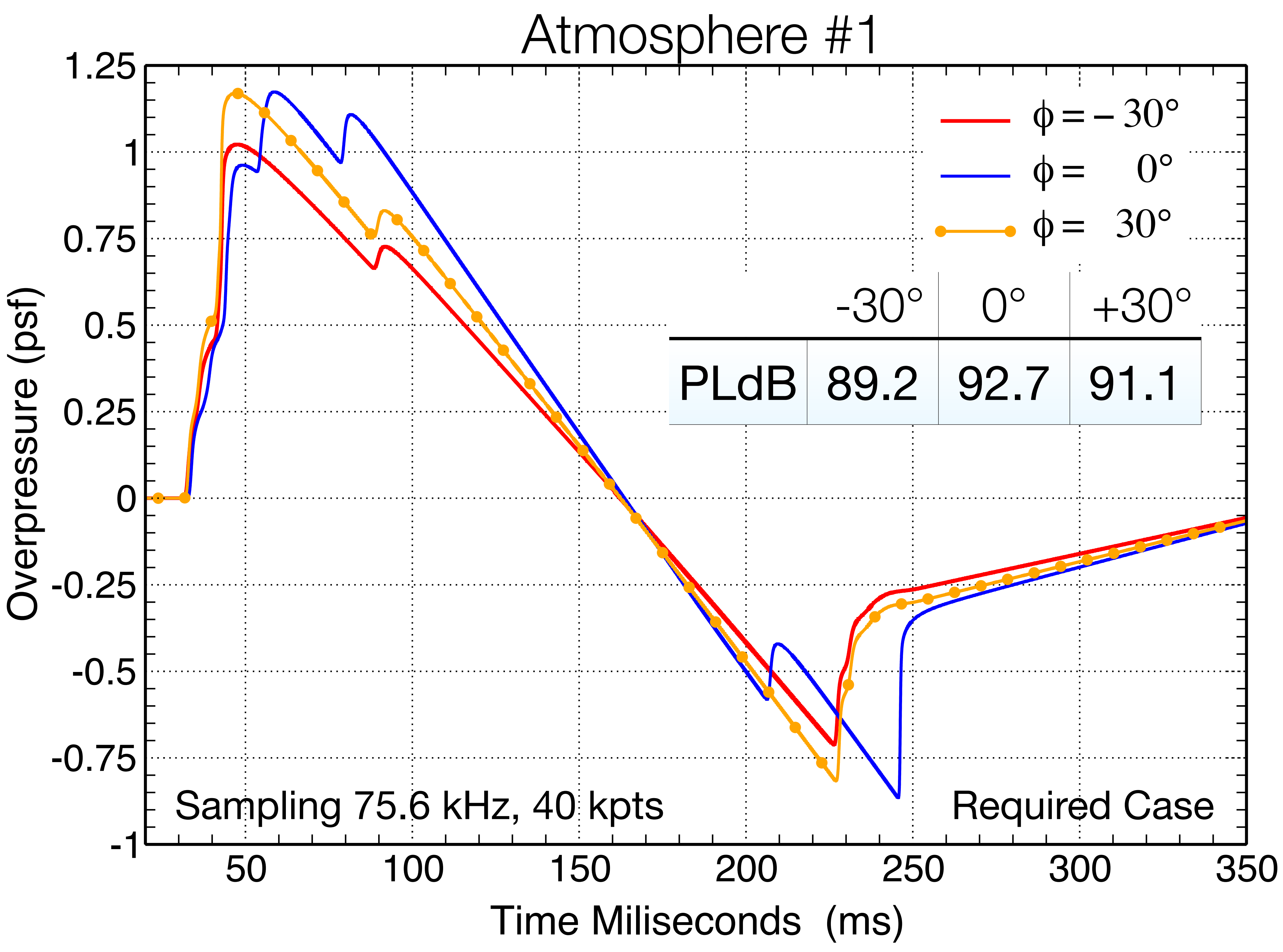
Ground signature – Atmosphere #1, ϕ = {-30°, 0°, 30°}


Standard Atmosphere

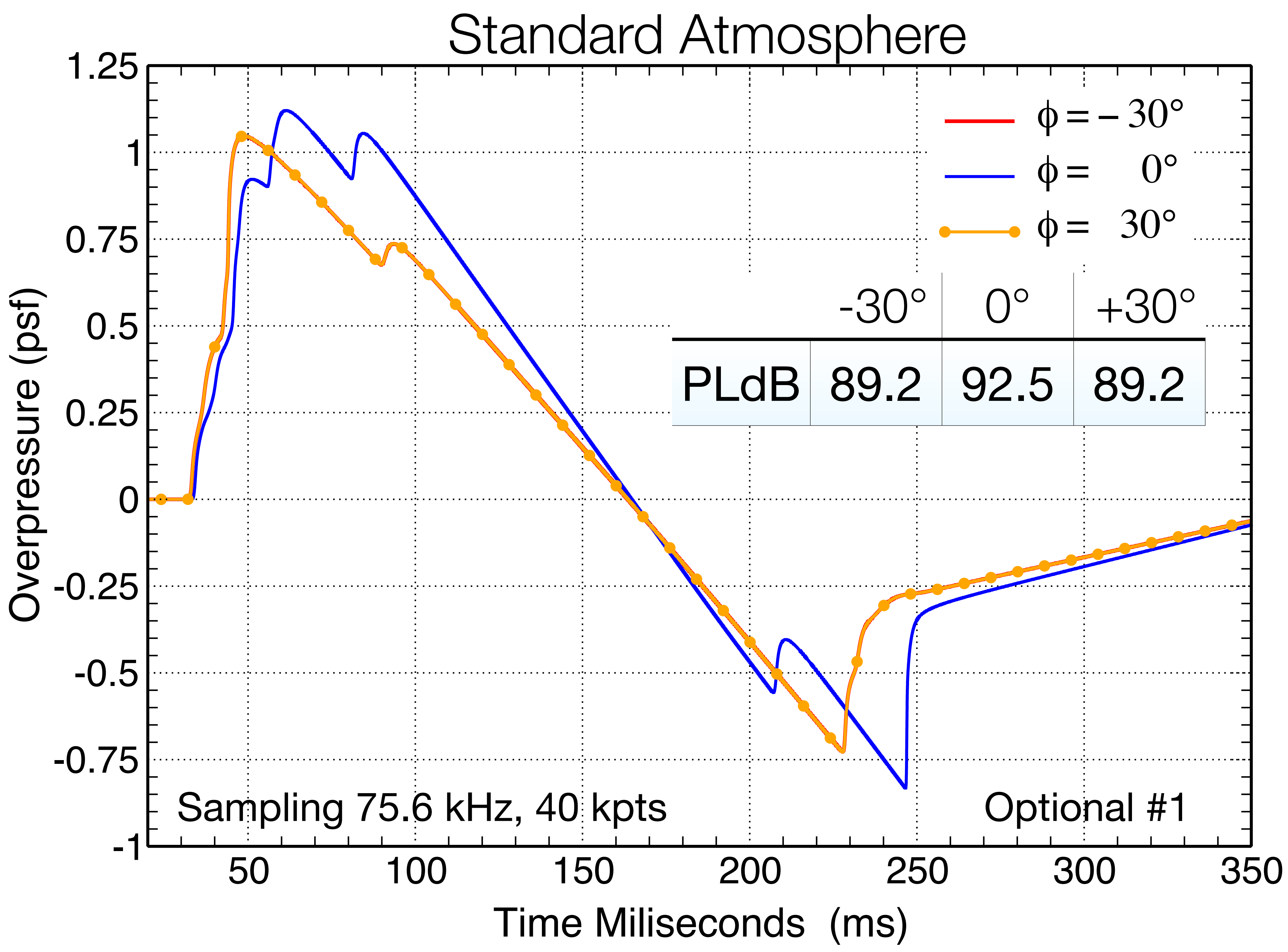
	-30°	0°	+30°
PLdB	89.2	92.5	89.2


Atmosphere #1

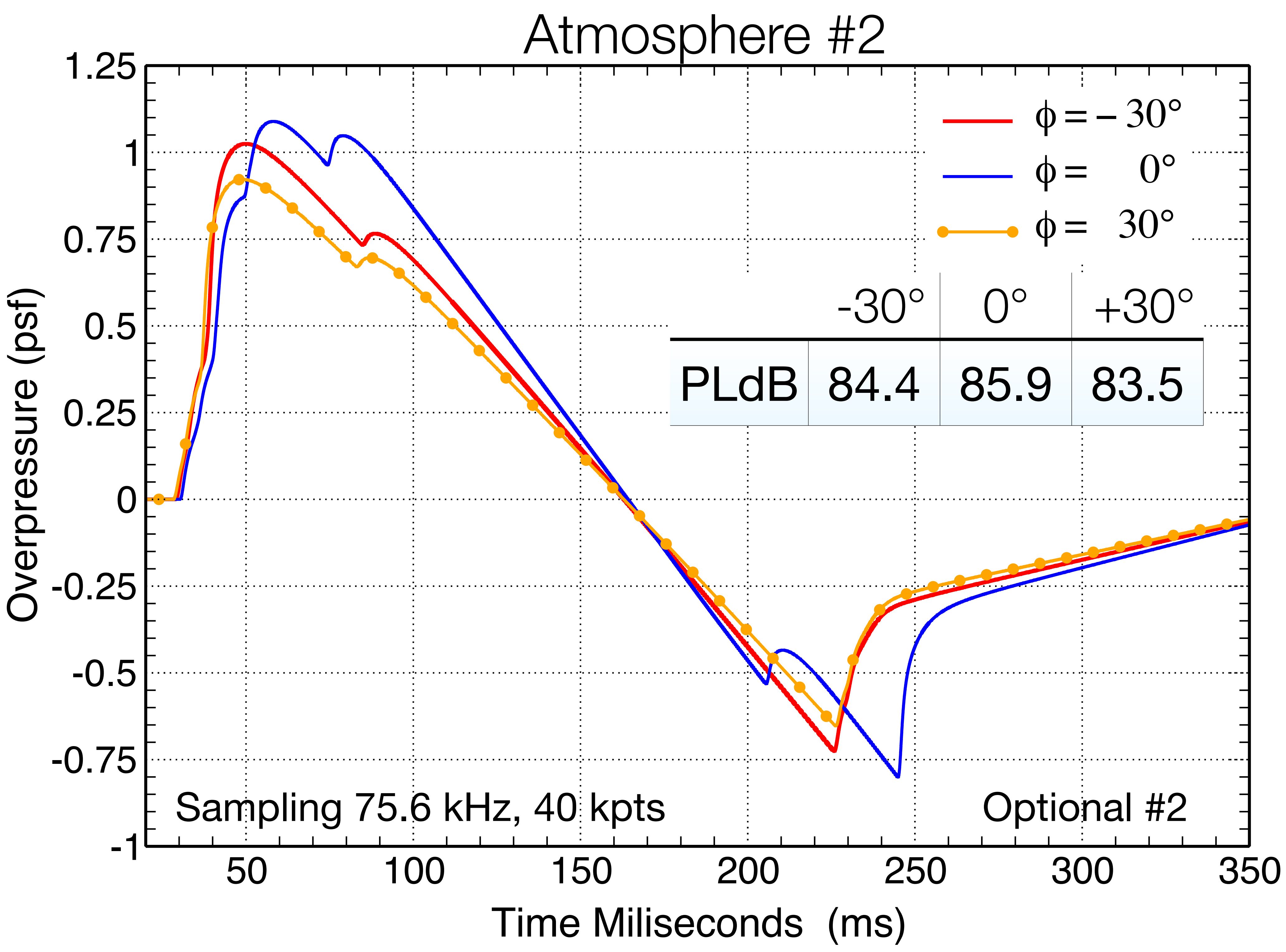
	-30°	0°	+30°
PLdB	89.2	92.7	91.1

LM 1021

Ground signature – Atmosphere #2, ϕ = {-30°, 0°, 30°}


Standard Atmosphere

	-30°	0°	+30°
PLdB	89.2	92.5	89.2


Atmosphere #2

	-30°	0°	+30°
PLdB	84.4	85.9	83.5

Atm 2: dry air, windy day → ~5 dB quieter than Std. Atm. conditions

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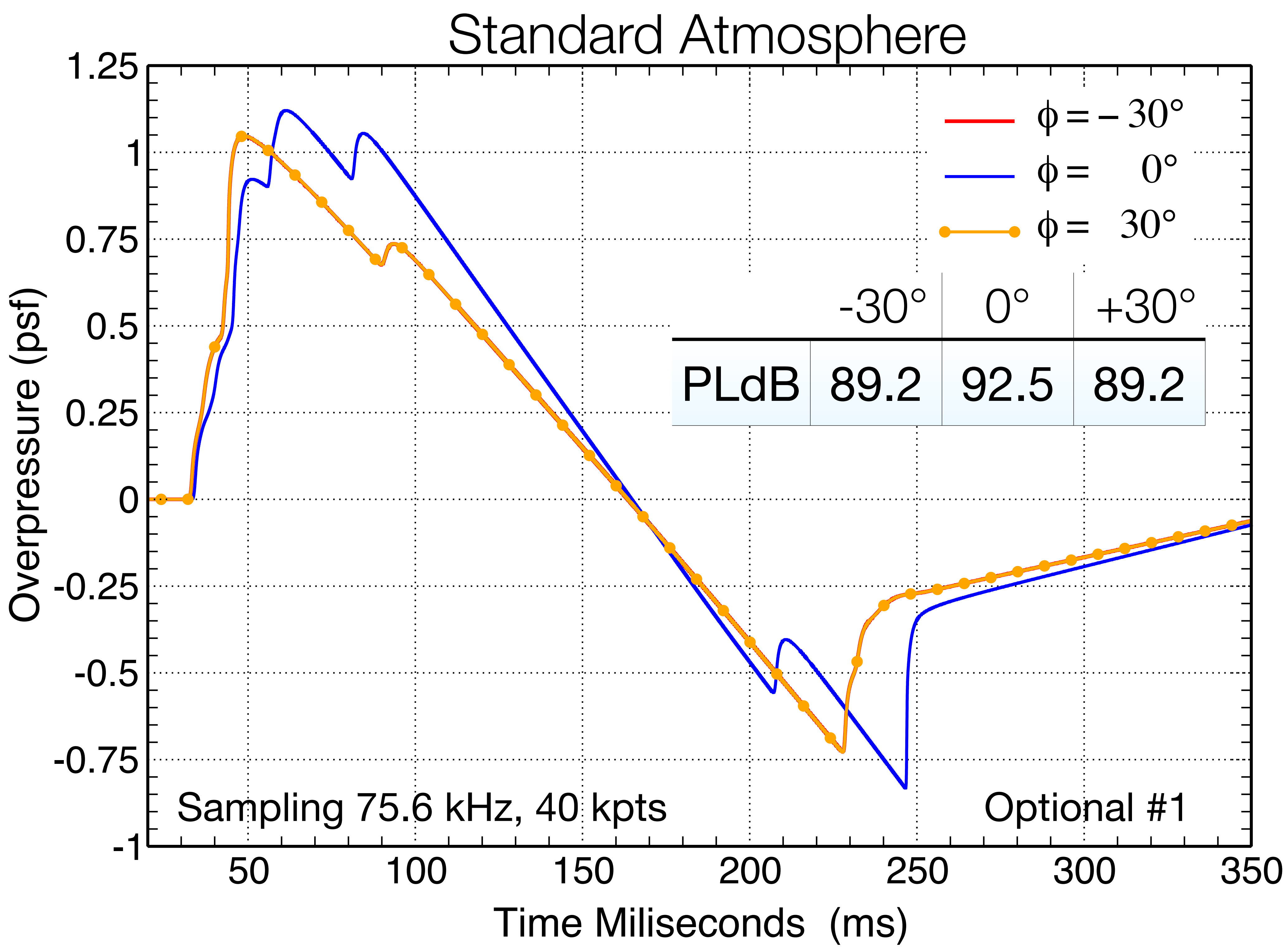
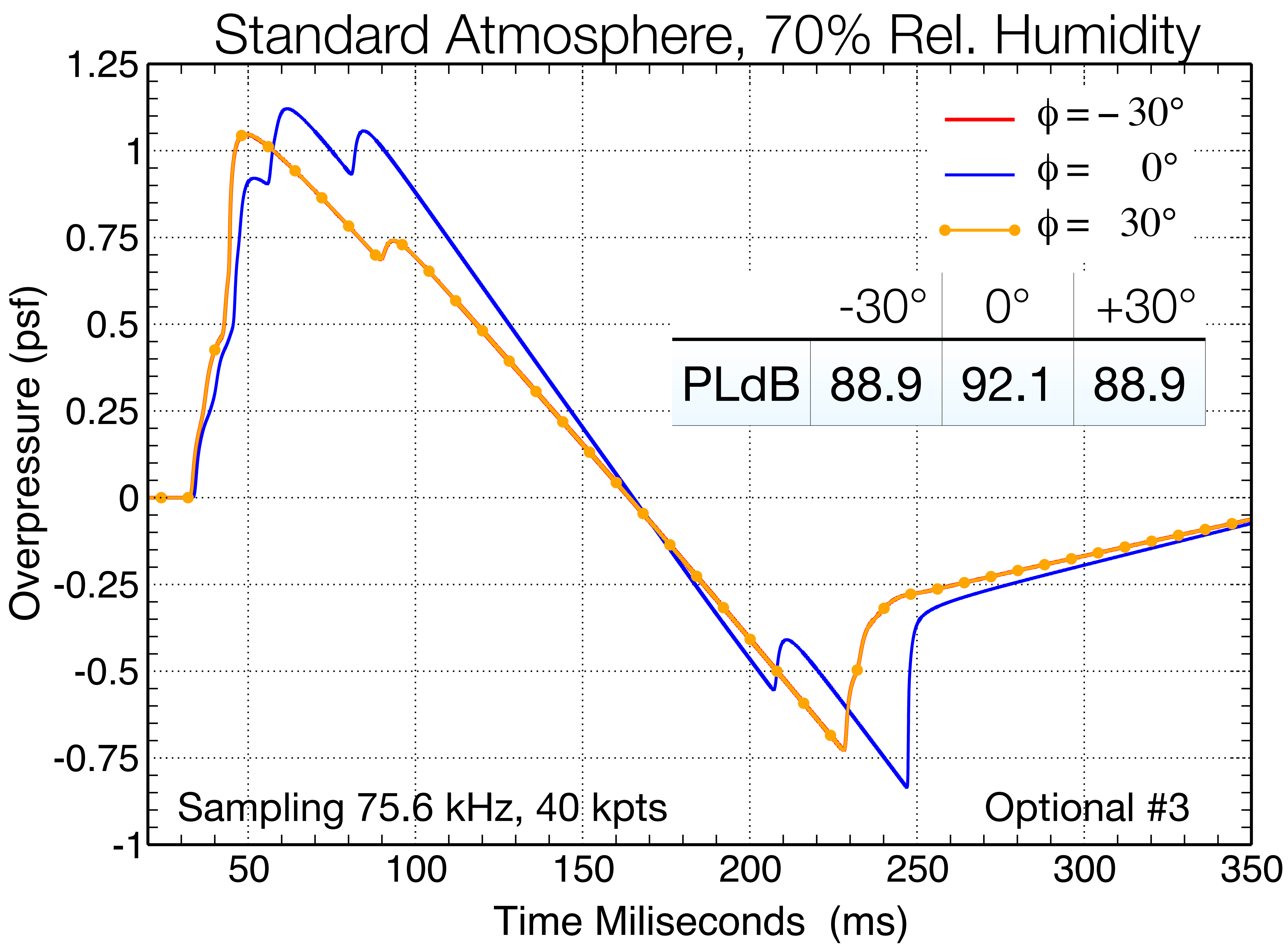
Ground signature – Standard atmosphere +70% relative humidity, ϕ = {-30°, 0°, 30°}



Standard Atmosphere

	-30°	0°	+30°
PLdB	89.2	92.5	89.2



Standard Atmosphere, 70% Rel. Humidity

	-30°	0°	+30°
PLdB	88.9	92.1	88.9

Slightly quieter (0.3-0.4 dB) than in std atmosphere

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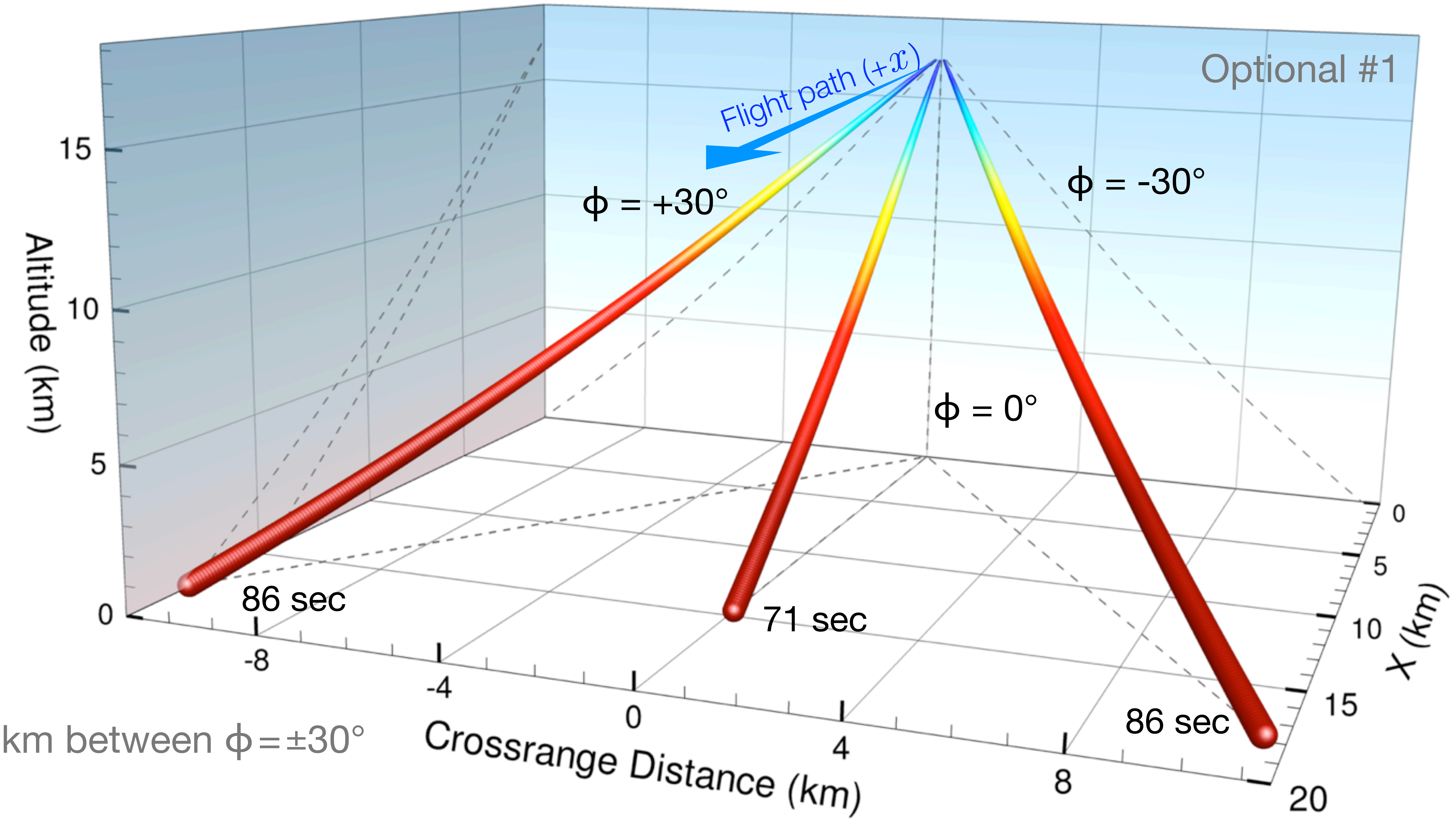
Raytubes, Standard Atmosphere

Colored by raytube area



18 km between ϕ=±30°

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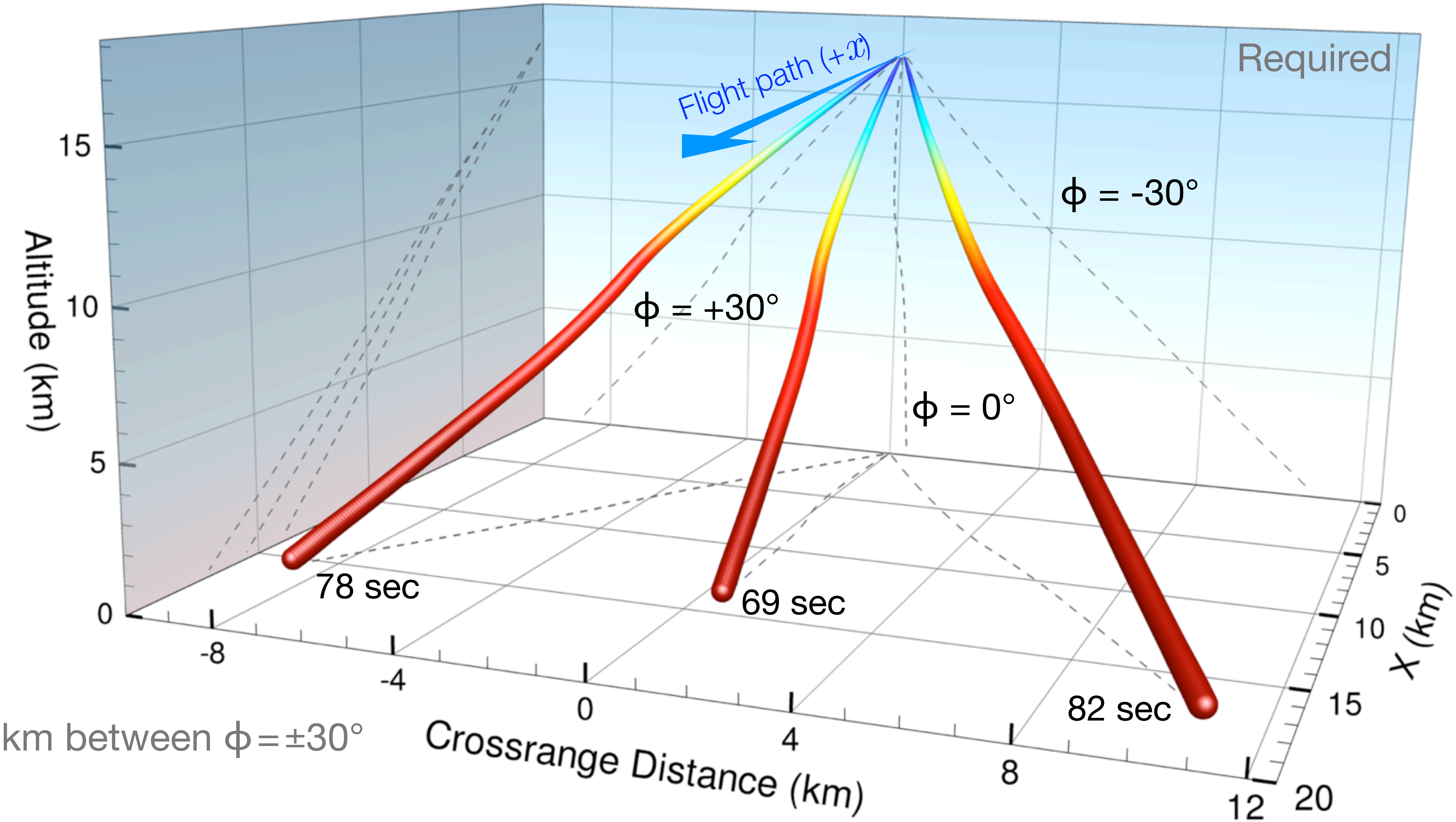
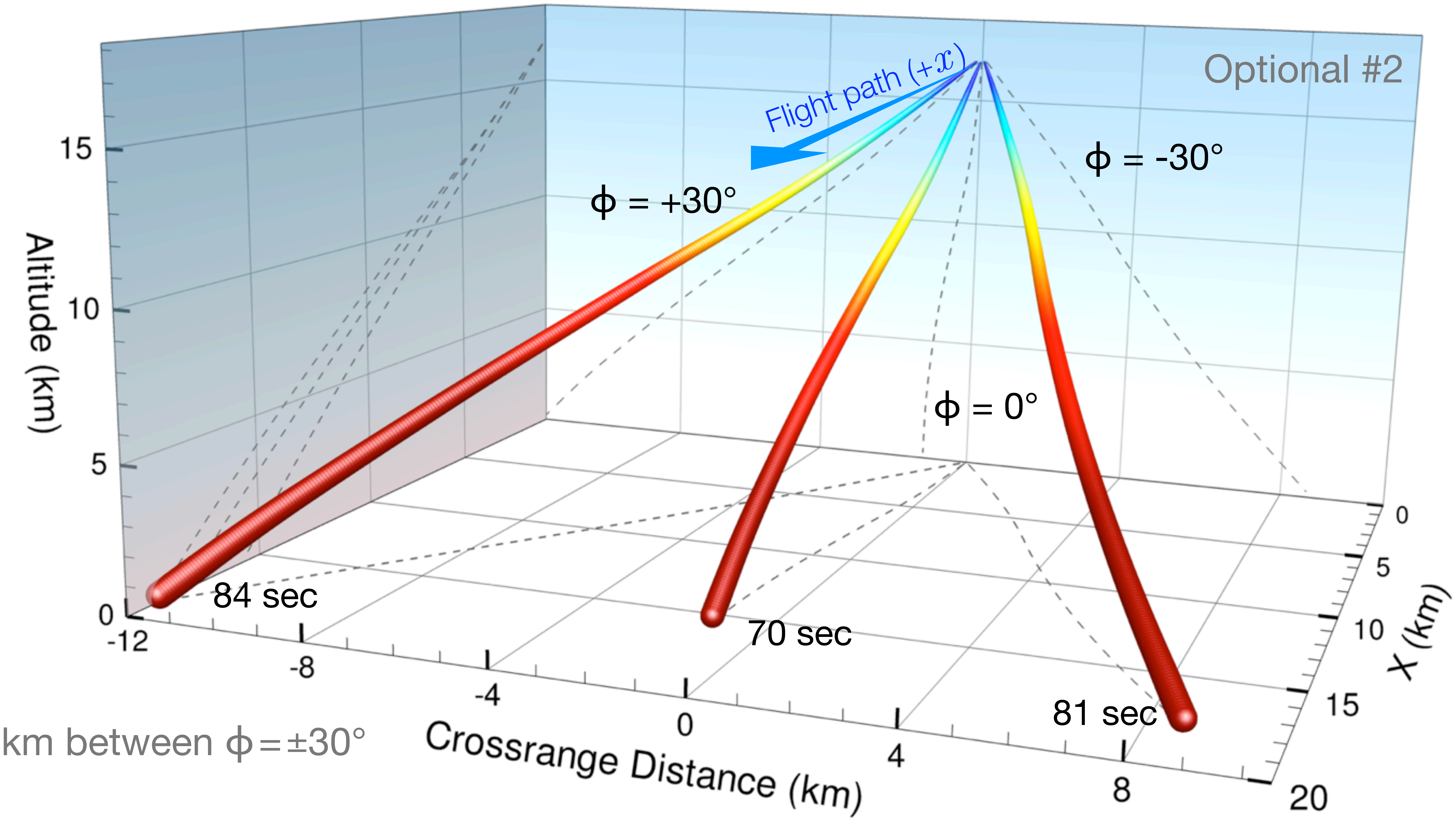
Raytubes, Atmosphere #1



22 km between ϕ = ±30°

LM 1021

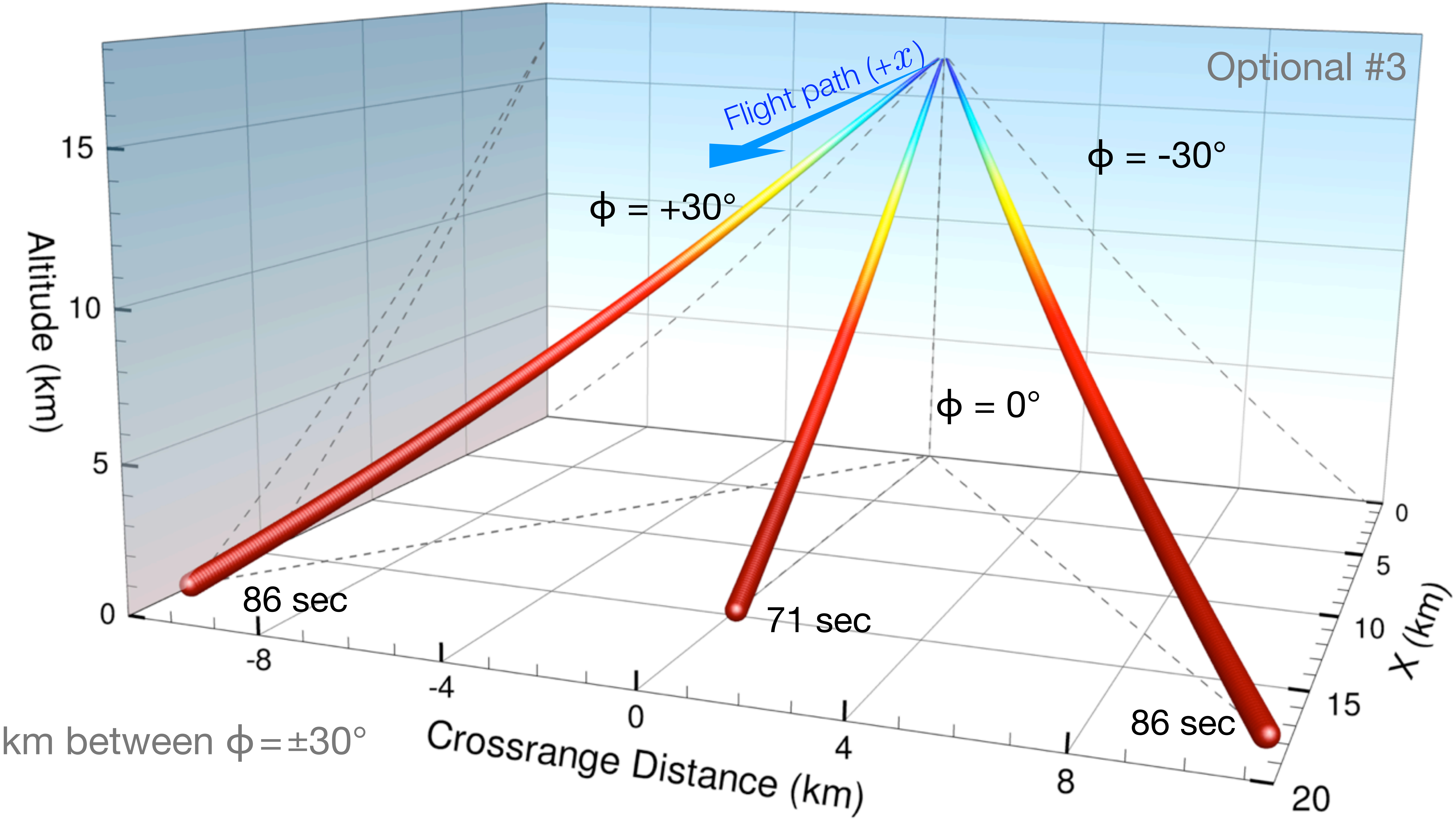
Raytubes, Atmosphere #2



21 km between ϕ=±30°

LM 1021

Raytubes, Standard Atmosphere with 70% relative humidity

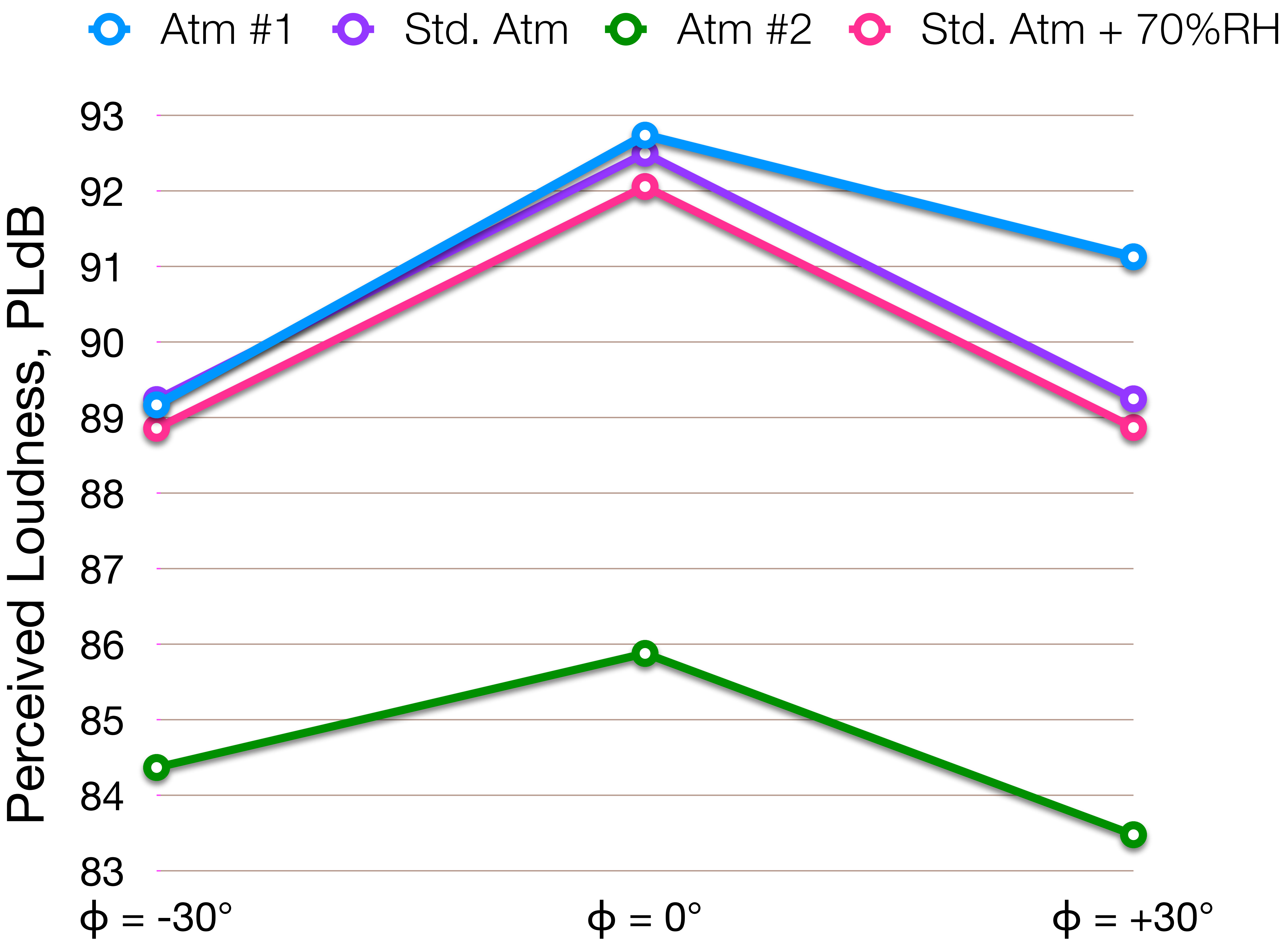


18 km between ϕ=±30°

LM 1021

Perceived loudness at ground level

- Atm #1 loudest on-track
- Asymmetry due to wind
- Atm #2 is 5-7 dB quieter
- Other metrics show similar trends.



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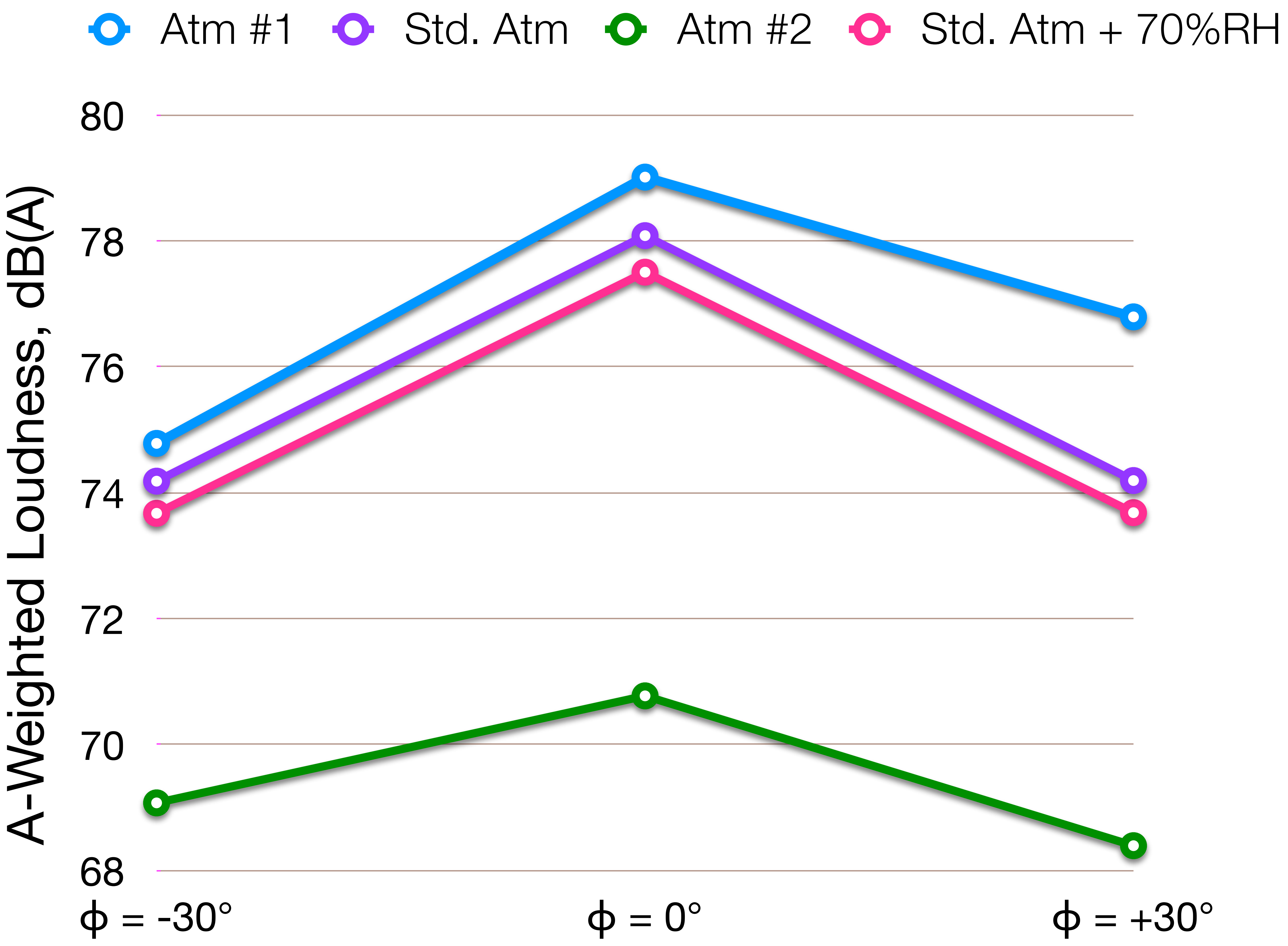
A-Weighted Loudness at ground level

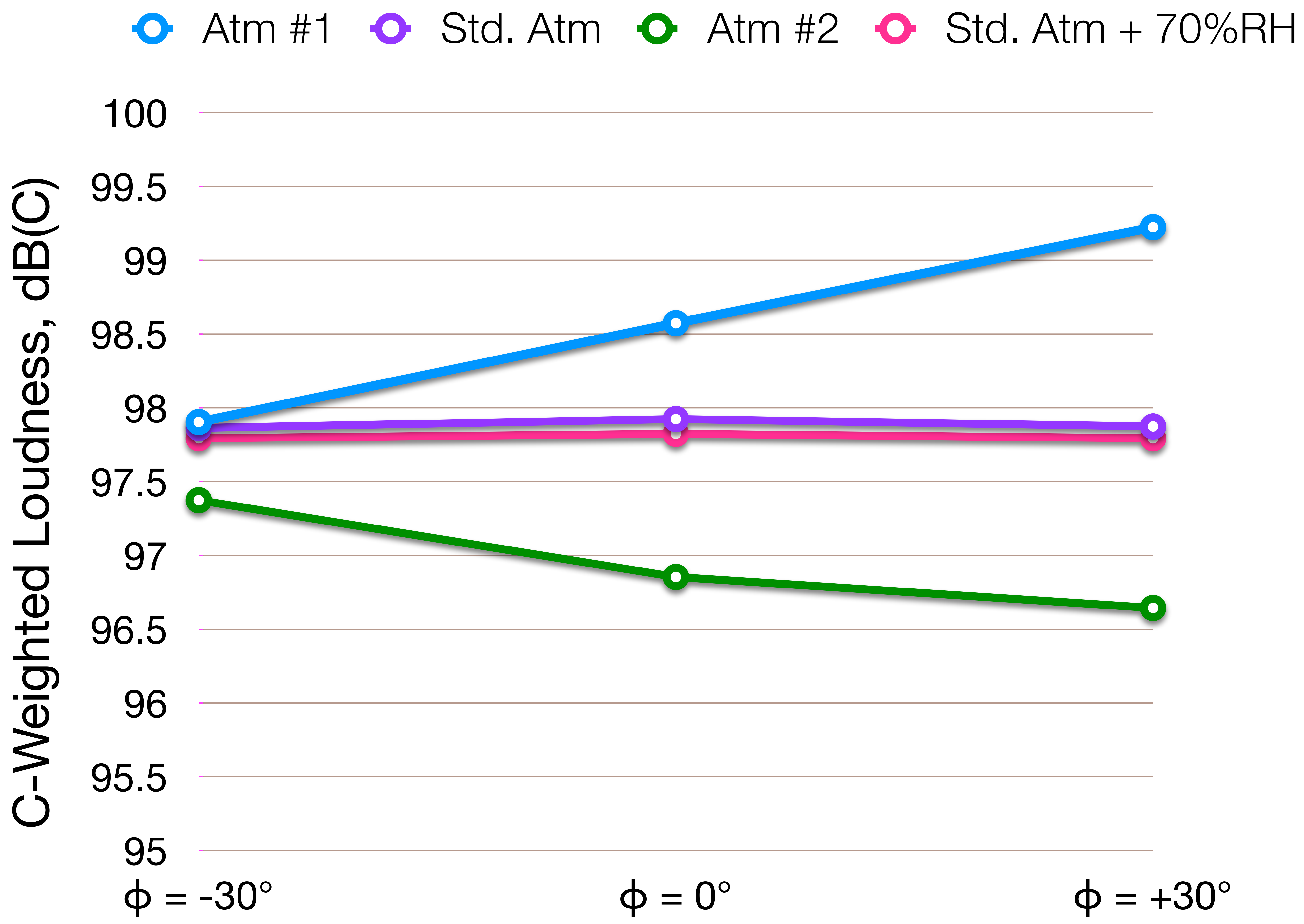
- Atm #1 loudest on-track
- Asymmetry due to wind
- Atm #2 is 5-7 dB quieter
- Other metrics show similar trends.



LM 1021

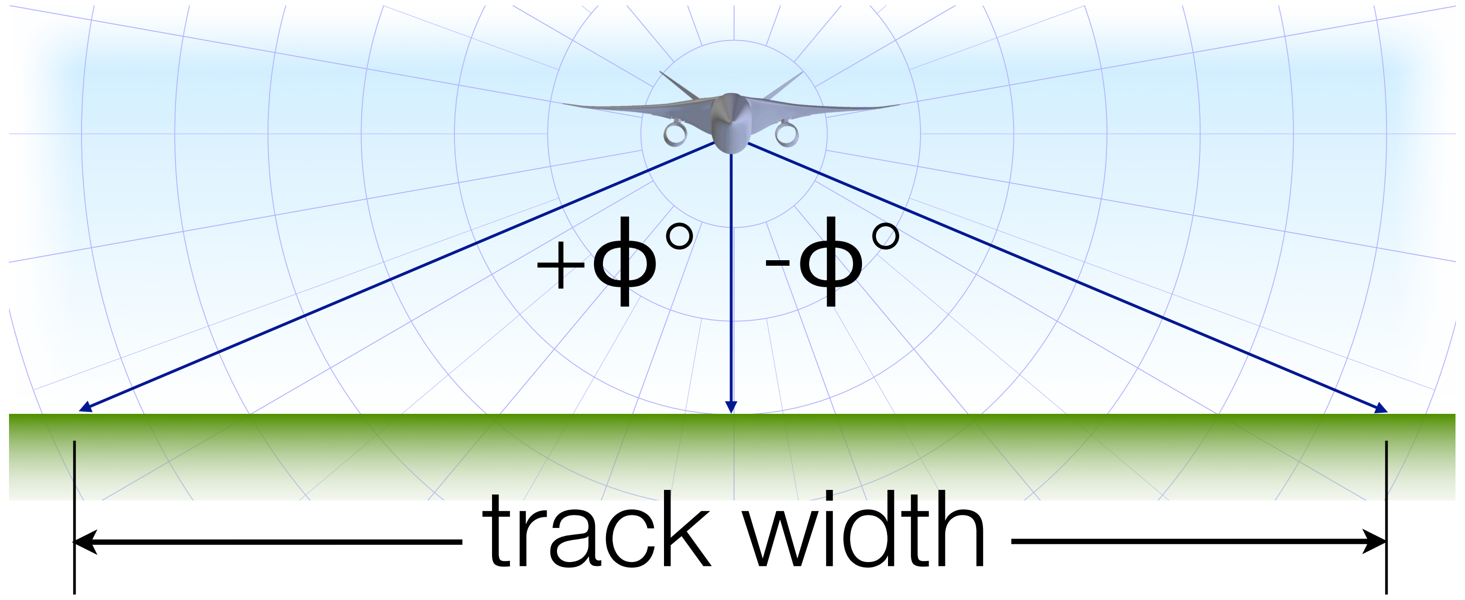
C-Weighted Loudness at ground level

- Windy cases very asymmetric in dB(C)



LM 1021

Signal cutoff



- Track width ~70km in std. atmosphere, but extends to over 110km due to atmospheric variation
- Atm #2 took over 3 mins upwind and 5 mins downwind for signal at cutoff

Atmosphere Profile	Cutoff (−ϕ°) (x, y) km	Cutoff (+ϕ°) (x, y) km	Track Width
Atm # 1	-57° (40.0, 42.3) km	74° (39.4,-44.6) km	86.9 km
Std. Atm	-50.38° (37.0, 35.6) km	50.38° (37.0, -35.6) km	71.2 km
Atm # 2	-64.65° (43.9, 41.7) km	59.35° (67.0, -69.7) km	111.4 km
Std. Atm + 70% humidity	-50.38° (37.0, 35.6) km	50.38° (37.0, -35.6) km	71.2 km

Summary

- Applied sBOOM and LCASB for all required and optional propagation cases
- Mesh convergence study to ensure propagation accuracy of about ± 0.1 PLdB
- Mesh convergence is relatively slow on intricate non-smooth input signals
- Observed atmosphere variation of +2 to -10 PLdB on track, with as much as 20 PLdB of attenuation off-track
- Crosswinds generally increase track width and can result in relatively large cutoff azimuths
- Hot dry days produce the quietest signals and the narrowest track widths
- Raytube visualization shows potential for loud off-track azimuths to be blown back under-track

Questions?