Evolution of NASA PCBoom: Simulations for the AIAA Sonic Boom Prediction Workshop 3

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Outline

- **Evolution of NASA PCBoom**
  - Numerical enhancements
  - Physics-based enhancements
  - Comparison with a flight dataset

- **SBPW Results**
  - Case 1 and Case 2
  - Ground-ray intersection
  - Carpet width
  - Ray tube area
  - PL Calculations

- **Summary**

Evolution of NASA PCBoom

PCBoom 6.7b (Wyle) → **PCBoom 6.7.1** → **PCBoom 6.7.2**

- ➢ Increased speed of Burgers' equation solver
  - From min to subsecond
- ➢ Accounted for full wind effects
  - Attenuation
  - Nonlinearity Coefficient
- ➢ Modified Schulflat mode for better prediction
  - Ground-ray intersection
  - Carpet width

- ➢ Kinematic ray tracing equations
  - solved using 2nd -order finite difference
  - used a semi-analytical solution for stratified atmospheres
  - replaced the Modified Schulflat mode
    - better prediction of ground-ray intersection
- ➢ Analytical approach for better carpet width prediction
- ➢ Geometrical spreading using 1 ray, via its Jacobian, rather than 4 rays

Kinematic Ray Tracing Equations

- **Ray Path (3 ODEs)** (e.g., Lonzaga, *AIAA Aviation 2019 Forum*, p. 3386. 2019)

$$\frac{dx_\alpha}{ds} = \frac{1}{v_r}\left(v_{o,\alpha} + \frac{{c_o}^2 q_\alpha}{\Omega}\right), \qquad \alpha = 1,2,3$$

Where:

$x_\alpha \rightarrow$ ray position

$v_{o,\alpha} \rightarrow$ wind velocity

$s \rightarrow$ ray path length

$c_o \rightarrow$ sound speed

- **Doppler Shift**

$$\Omega = 1 - v_{o,\alpha} q_\alpha$$

- **Ray Slowness and Wavefront**

$$\frac{dq_\alpha}{ds} = -\frac{1}{v_r}\left(\frac{\Omega}{c_o}\frac{\partial c_o}{\partial x_\alpha} + q_\beta \frac{\partial v_{o,\beta}}{\partial x_\alpha}\right)$$

  - For Stratified Atmospheres, $q_\alpha = q_\alpha(x_\beta)$ are known. **No need to numerically solve this ODE!**

- **2nd -Order Finite Difference (For range-dependent atmospheres)**

$$\frac{df}{ds} = g(s),$$

$$f(s_{n+1}) \approx f(s_n) + \delta s \frac{df}{ds}(s_n) + \frac{\delta s^2}{2}\frac{d^2 f}{ds^2}(s_n), \qquad n \rightarrow n^{th} \text{ step}$$

- **Stratified Atmospheres (No need for finite difference numerical solution!)**

$$x_\alpha(s) = x_\alpha(s_i) + \int_{s_i}^{s} \frac{1}{v_r}\left(v_{o,\alpha} + \frac{{c_o}^2 q_\alpha}{\Omega}\right) ds'$$

Burgers' Equation: Dynamic Ray Tracing

- **Burgers' Equation** **(Using a spectral representation)**

$$\frac{dU}{ds} = \underbrace{\frac{i\omega\tilde{\beta}}{4\pi}\int U(s,\omega')U(s,\omega-\omega')d\omega'}_{\text{Nonlinearity}} - \underbrace{\alpha_t(s,\omega)U(s,\omega)}_{\text{absorption}}$$

- **Spectral representation *U* and the acoustic pressure**

$$p(s,\tau) = p_i^{(p)}B(s)u(s,\tau)$$

- **Effective coefficient of nonlinearity and convection effect**

$$\tilde{\beta} = \frac{\beta p_i^{(p)}B\Omega\chi}{\rho_o c_o^3}, \qquad B = \sqrt{\frac{\rho_o c_o \chi \Omega A_i}{\rho_{o,i} c_{o,i} \chi_i \Omega_i A}}, \qquad \chi = \frac{c_o}{v_r}$$

- **Parameters to be determined : $\boldsymbol{\tilde{\beta}, \alpha_t,}$ and $\boldsymbol{A}$**

- **Numerical solution using a pseudospectral, split-step method**

$$\frac{\partial u}{\partial s} = \tilde{\beta}u\frac{\partial u}{\partial \tau},$$
$$\frac{dU}{ds} = -\alpha_t(s,\omega)U(s,\omega)$$

- Very efficient
- Step size based on absorption consideration

Full Wind Effects: What is new?

- Burgers' equation

$$\frac{dU}{ds} = \frac{i\omega\tilde{\beta}}{4\pi}\int U(s,\omega')U(s,\omega-\omega')d\omega' - \alpha_t(s,\omega)U(s,\omega)$$

- Frequency Doppler Shift and wind convection

$$\alpha_t(s,\omega) \rightarrow \chi\alpha(s,\omega\Omega), \qquad \text{Updated PCBoom}$$
$$\alpha_t(s,\omega) \rightarrow \alpha(s,\omega), \qquad \text{Older PCBoom}$$

  - Older PCBoom, no Doppler shift or convection
  - Updated PCBoom, with Doppler shift and convection

- Effective coefficient of nonlinearity

$$\tilde{\beta} = \frac{\beta {p_i}^{(p)} B\Omega\chi}{\rho_o\, c_o^3}, \qquad \chi = \frac{c_o}{v_r}\ , B = B(v_r)$$

$$v_r = \left|\left|\mathrm{v_o} + \hat{\mathbf{n}}c_o\right|\right| \qquad \text{Updated PCBoom}$$
$$v_r \rightarrow c_o + \hat{\mathbf{n}}\cdot\mathbf{v_o}\ , \qquad \text{Older PCBoom}$$

  - Older PCBoom replaces ray velocity with the effective sound speed approximation.

Geometrical Spreading: Jacobian vs Ray Tube Area

- Dynamic Ray Tracing involves

$$\nabla \cdot \frac{d\mathbf{x}}{ds} = \frac{1}{J}\frac{dJ}{ds}$$

- Jacobian

$$J = \begin{bmatrix} \frac{\partial x_1}{\partial s} & \frac{\partial x_1}{\partial \phi} & \frac{\partial x_1}{\partial t_a} \\ \frac{\partial x_2}{\partial s} & \frac{\partial x_2}{\partial \phi} & \frac{\partial x_2}{\partial t_a} \\ \frac{\partial x_3}{\partial s} & \frac{\partial x_3}{\partial \phi} & \frac{\partial x_3}{\partial t_a} \end{bmatrix}$$

- Older PCBoom (PCBoom 6.7.1 and older, PCBoom 6.7b) replaces *J* with *A,* ray tube area

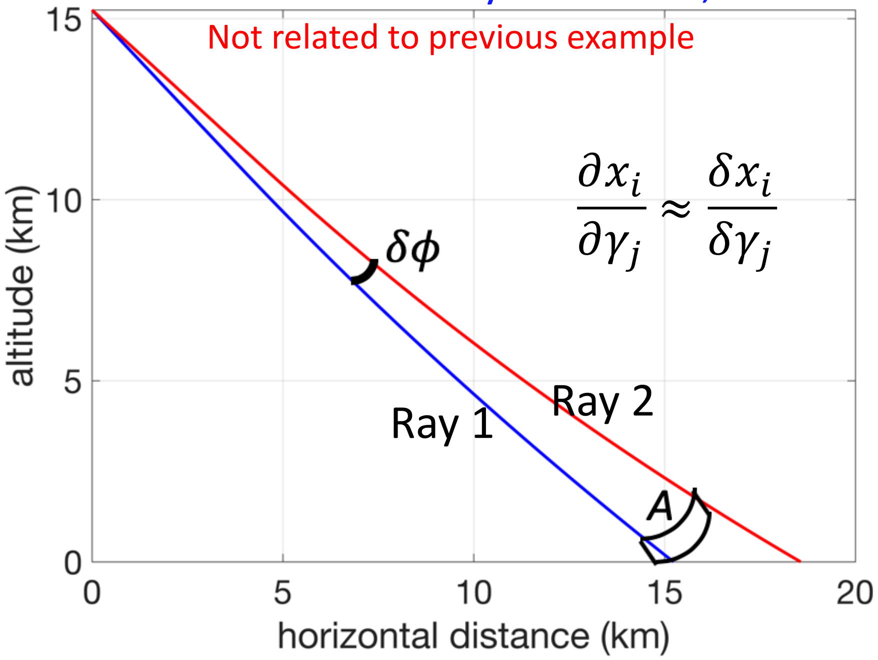
- Updated PCBoom uses the Kinematic Ray Tracing

$$x_\alpha(\gamma) = x_\alpha(\gamma_i) + \int_{s_o}^{s} \frac{1}{v_r}(v_{o,\alpha} + c_o n_\alpha)ds',$$

$$\gamma = \{s, \phi, t_a\}, \qquad \gamma_i = \{s_i, \phi, t_a\}, \qquad \alpha = 1,2,3$$

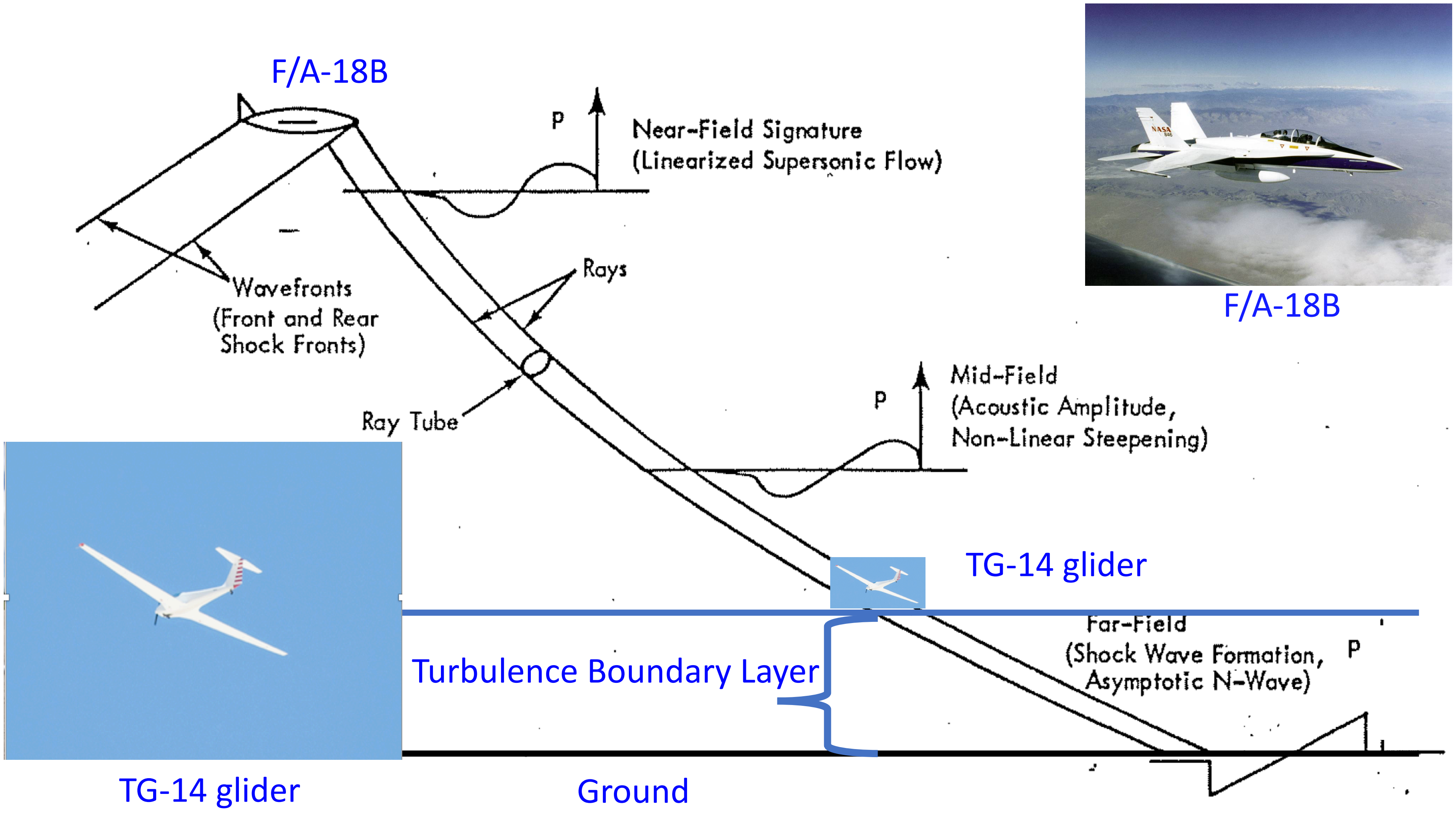
$$\frac{\partial x_\alpha}{\partial \gamma_\beta} = \frac{\partial}{\partial \gamma_\beta} x_\alpha(\gamma_i) + \frac{\partial}{\partial \gamma_\beta} \int_{s_i}^{s} \frac{1}{v_r}(v_\alpha + c_o n_\alpha)ds'$$

Illustration: Ray tube area, *A*



- Older PCBoom depends on the accuracy of neighboring rays
  - Requires 3 or 4 rays
- Updated PCBoom purely depends on the medium properties.
  - Requires only the ray of interest

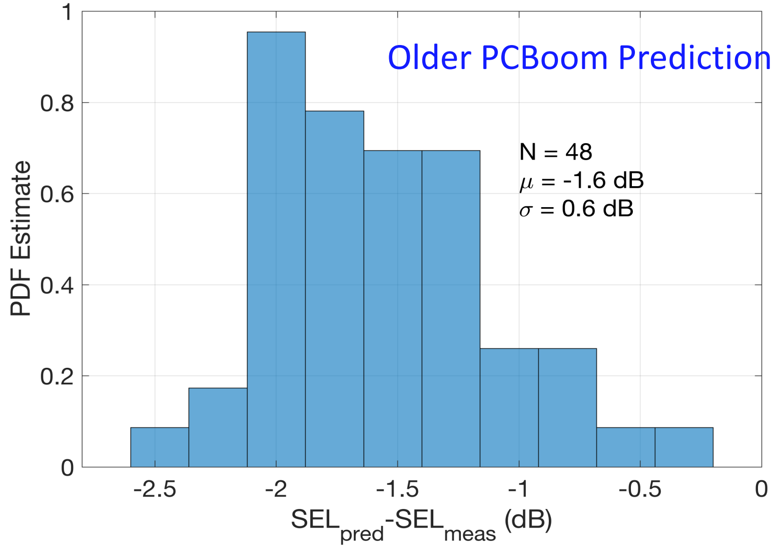
Comparison of Models With SonicBAT Data

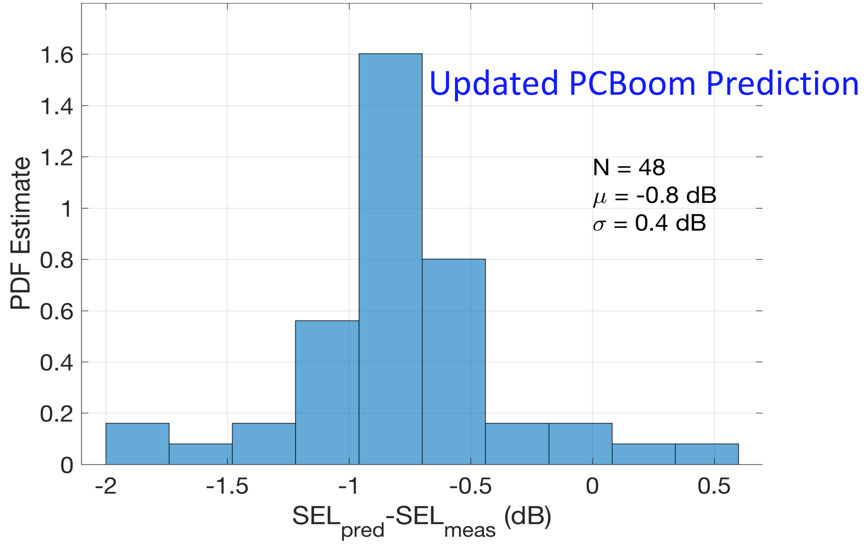


SonicBAT dataset recorded aloft can be used to validate other sonic boom propagation codes too.

Unweighted Sound Exposure Level (SEL) Comparison

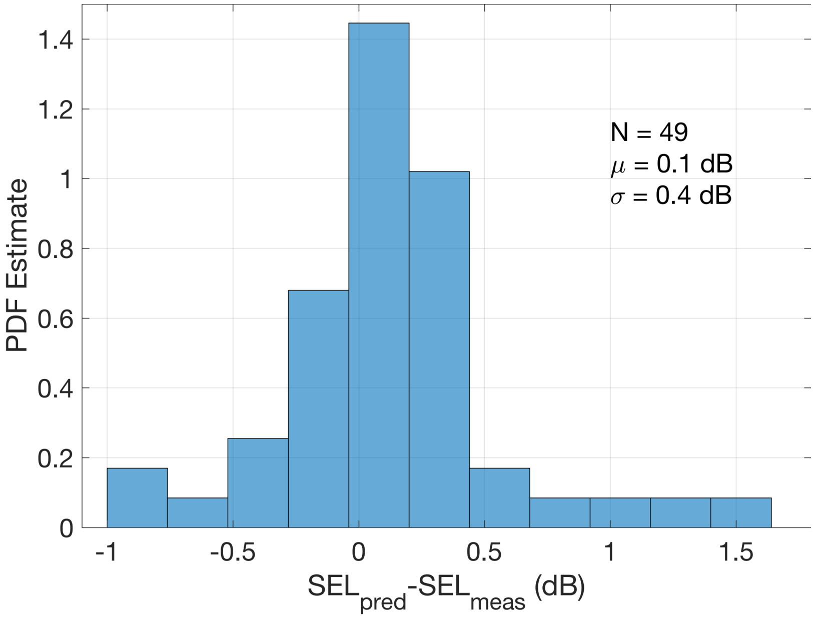
PCBoom Near-Field Approximant





CFD Near-Field Solutions

Updated PCBoom Prediction



- Updated PCBoom agrees better with measurement than older PCBoom
- CFD near-field solutions lead to better agreement with measurements
- No older PCBoom prediction using CFD. Code breaks down due to complicated signature

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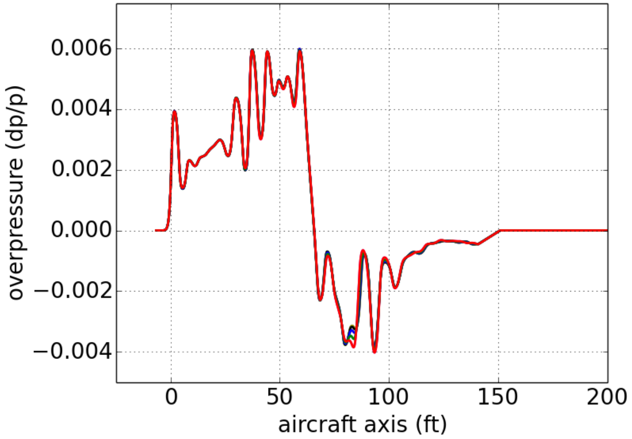
- **SBPW Results**
  - Case 1 and Case 2
  - Ground-ray intersection
  - Carpet width
  - Ray tube area
  - PL Calculations

Case	Mach Number	Flight Altitude (km)	Prop Init Dist from AC (m)	Ground Altitude (m)
1	1.6	15.7600	100.584	264.069
2	1.4	16.4592	82.296	110.011

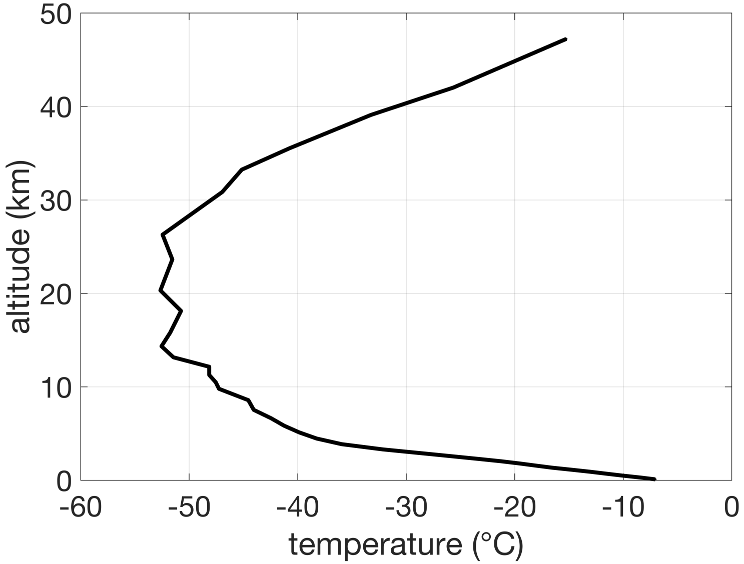
Aircraft Heading: East
Atmospheres: Standard and Windy Atmospheres as provided
Ground Refl. Coef: 1.9

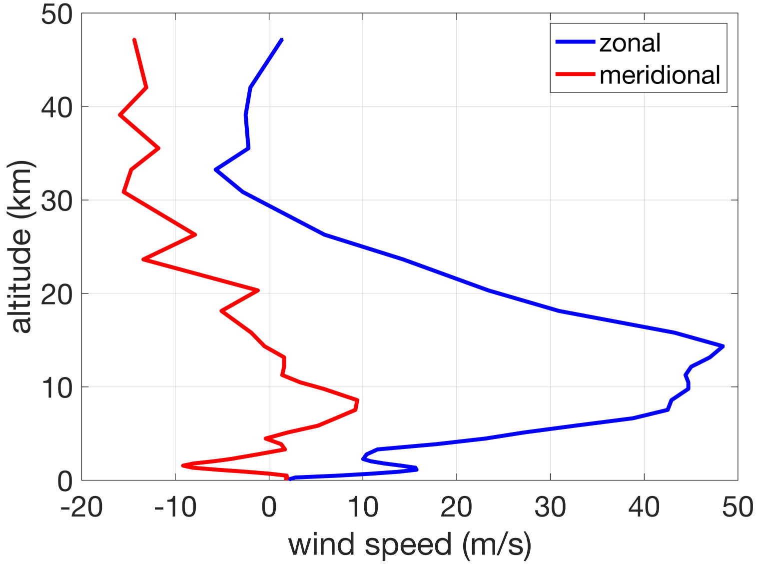
Case 2 and Atmospheres

- ➢ **Initial Signatures**
  - ➢ **X-59 C609 version**
- ➢ **Atmospheres**
  - ➢ **Standard**
  - ➢ **Measured windy**

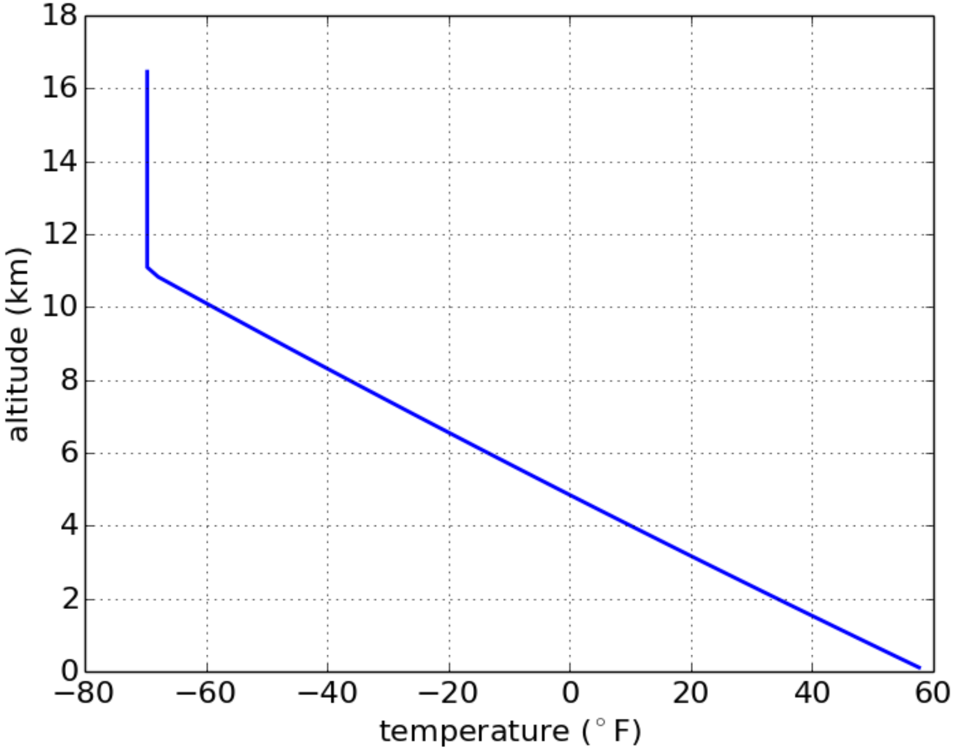


Windy Atmosphere





Standard Atmosphere



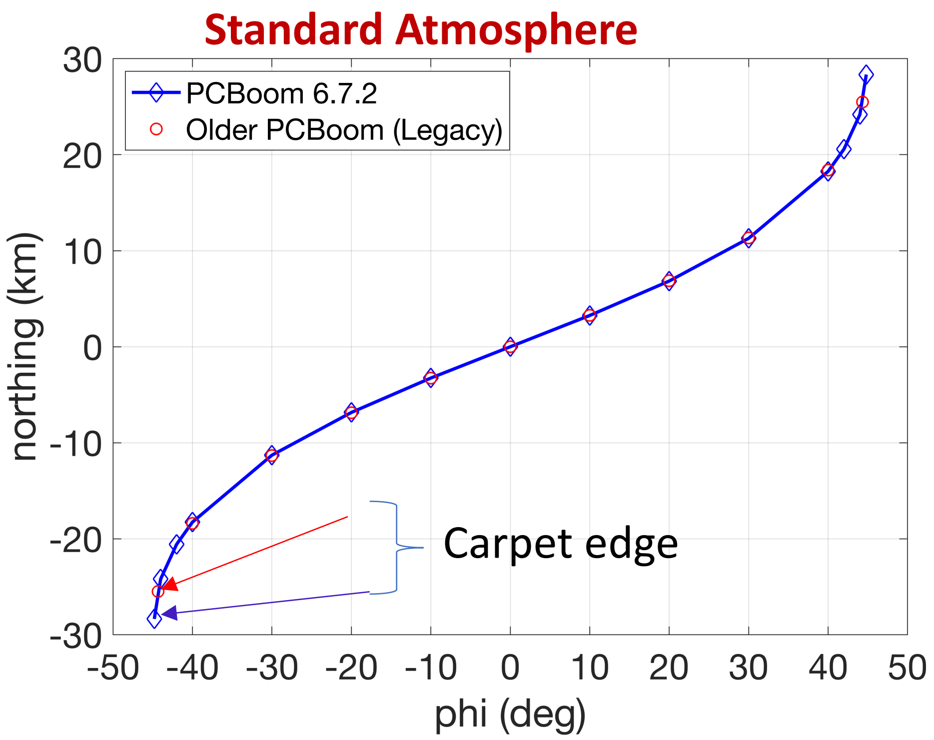
Ground-Ray Intersection and Carpet Width

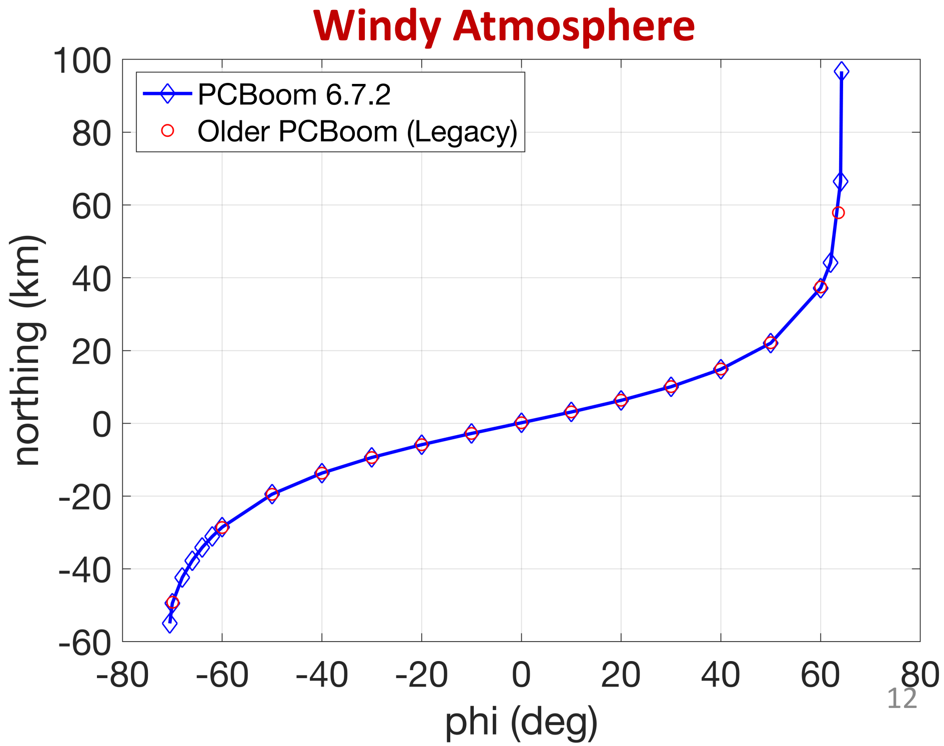
Left figure:

- Standard atmosphere
- Ground-ray intersections
  - updated PCBoom
  - older PCBoom
  - excellent agreement
- Carpet edges differ by 4 km (~2.5 miles)
  - Analytical solution used by updated PCBoom

Right figure:

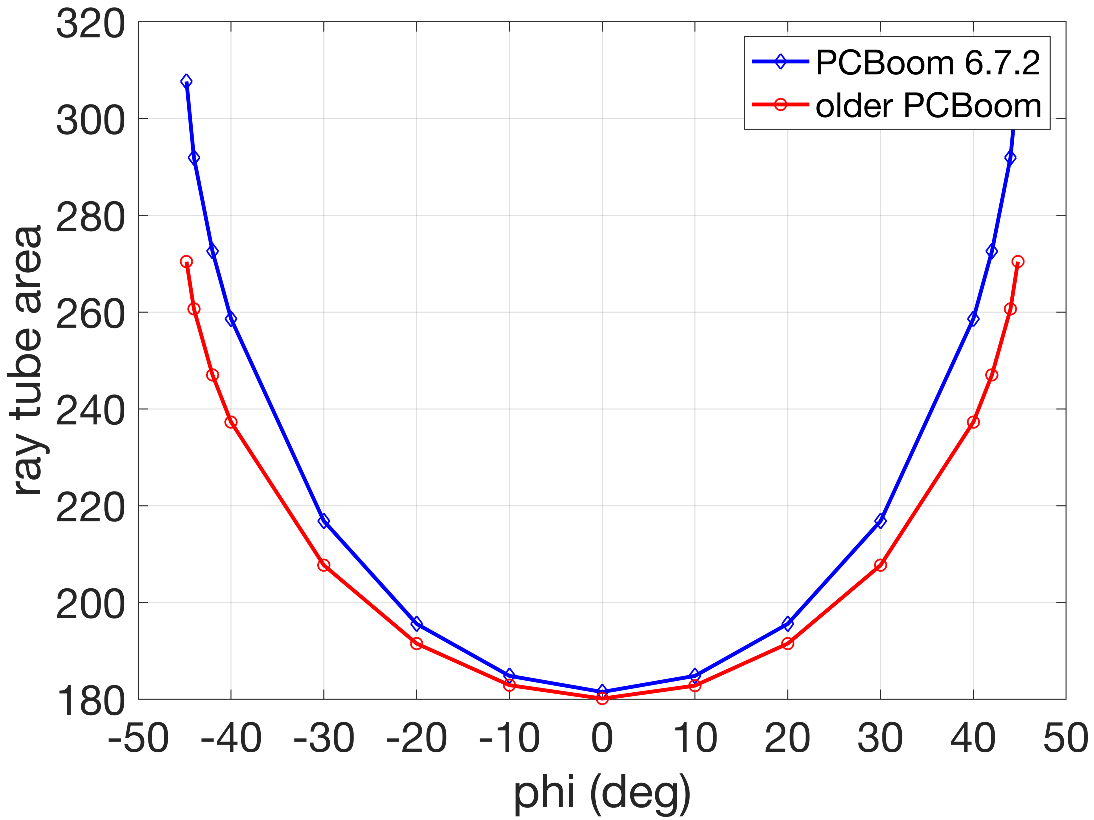
- Windy atmosphere
- Ground-ray intersection using
  - updated PCBoom
  - older PCBoom
- Carpet edges differ by
  - 5 km (~3 miles) to the south
  - 40 km (~25 miles) to the north

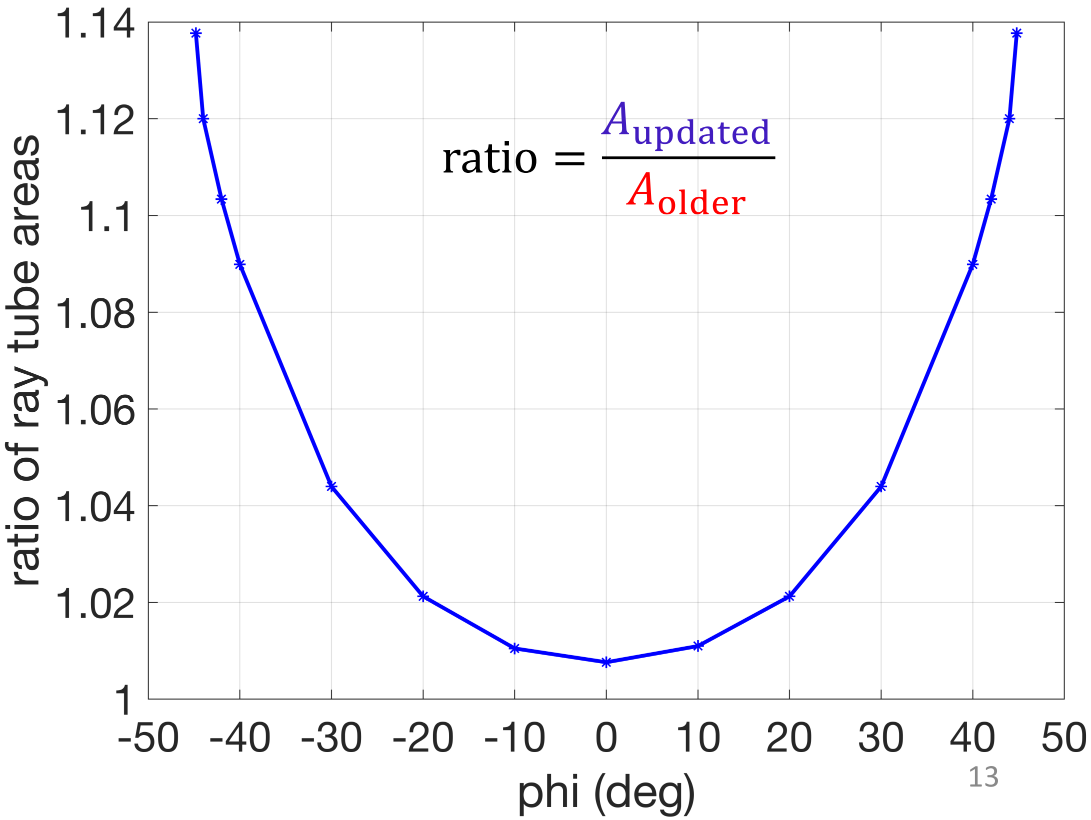




Geometrical Spreading: Standard Atmosphere

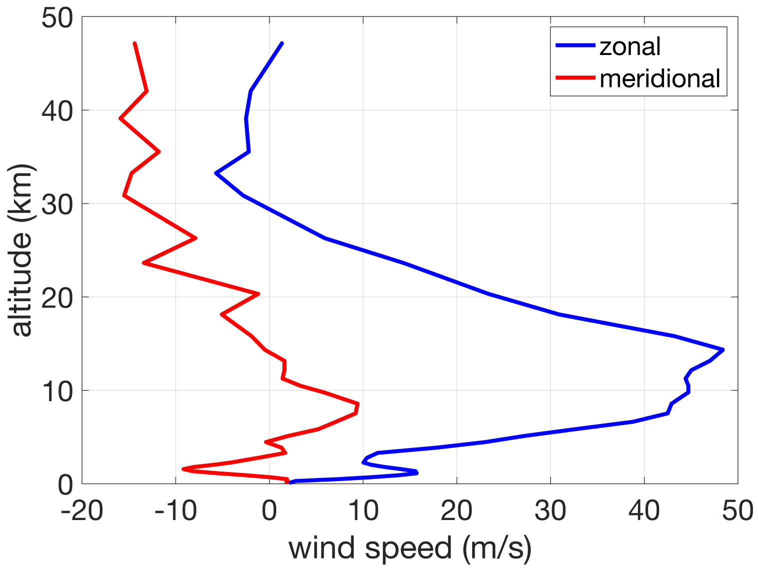
- Ray tube areas using updated and older PCBoom versions
- Nearly identical ray tube areas at phi=0
- Larger ray tube areas predicted by the updated PCBoom for off-track propagation

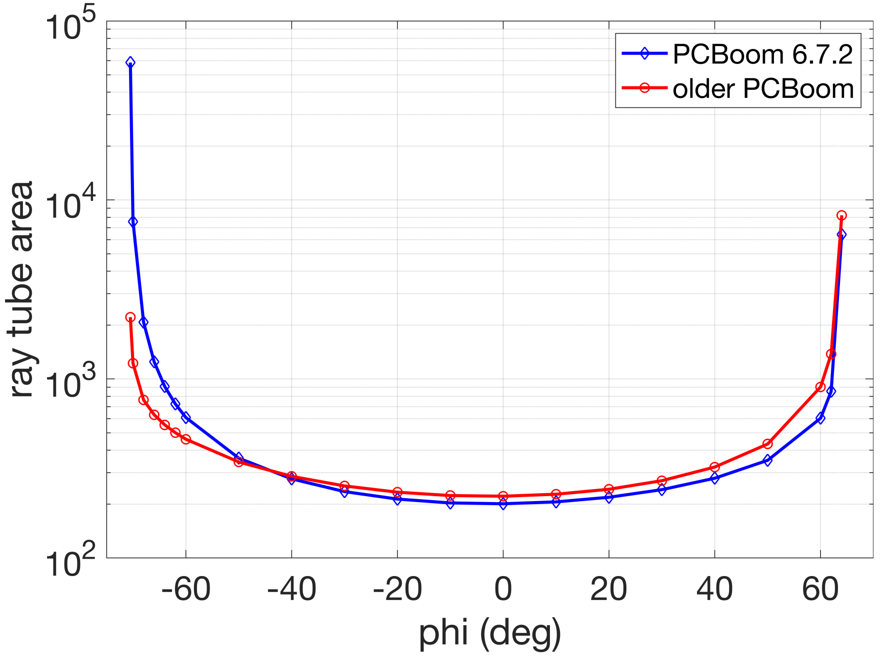


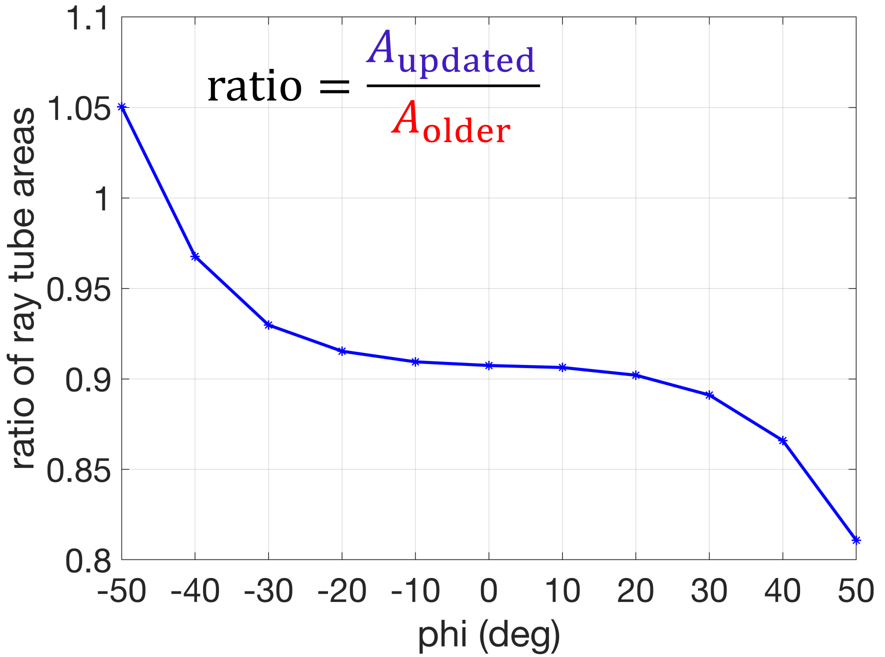


Geometrical Spreading: Windy Atmosphere

- Ray tube areas using updated and older PCBoom versions
- Smaller ray tube areas predicted by updated PCBoom except near the south carpet edge
- Potentially caused by crosswind blowing to the south near the surface with strong wind shear
- Ray tube areas could be main cause of potential differences in the SBPW3 noise metric results



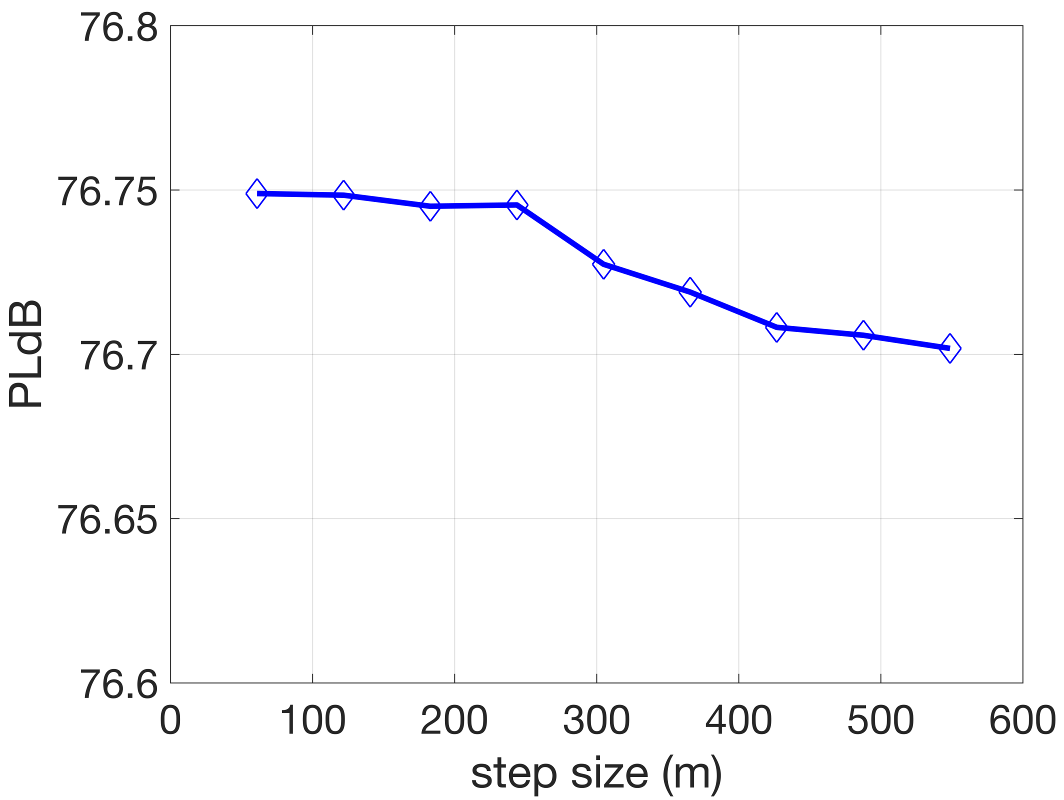


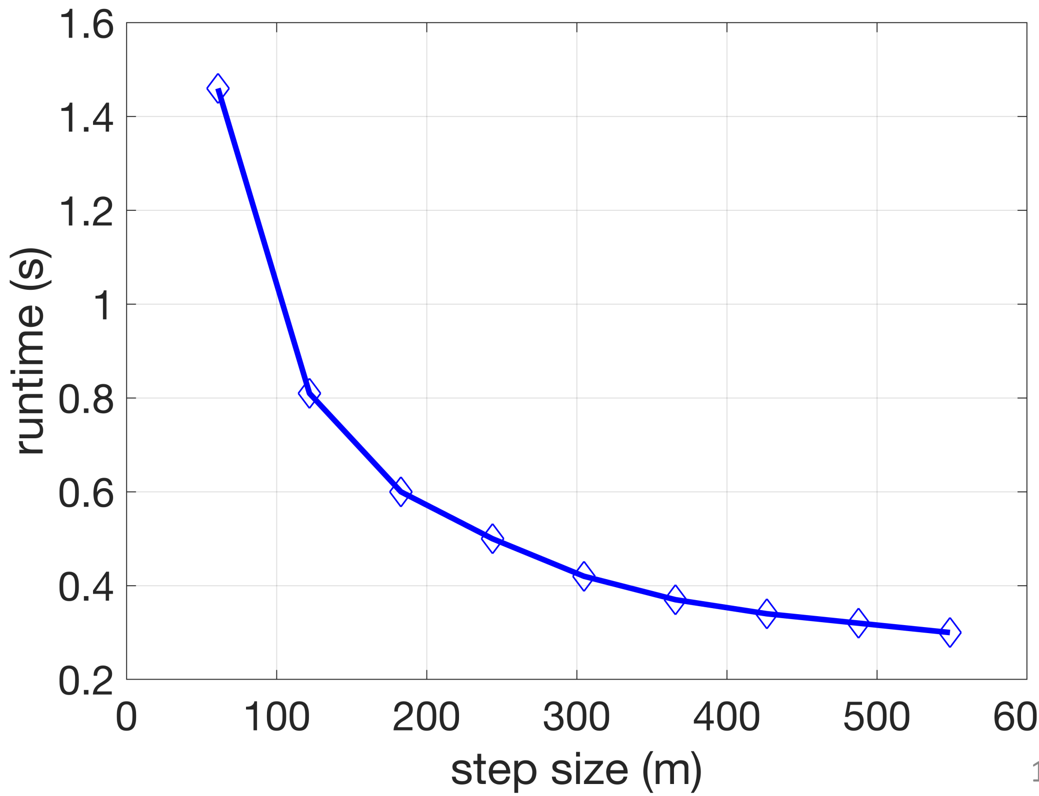


Convergence, Step Size and Runtime: Windy Atmosphere

- **Left figure:**
  - solution convergence at 76.75 PLdB
  - Step size of [50,550] meters,
  - PL band is very narrow, within 0.05 dB

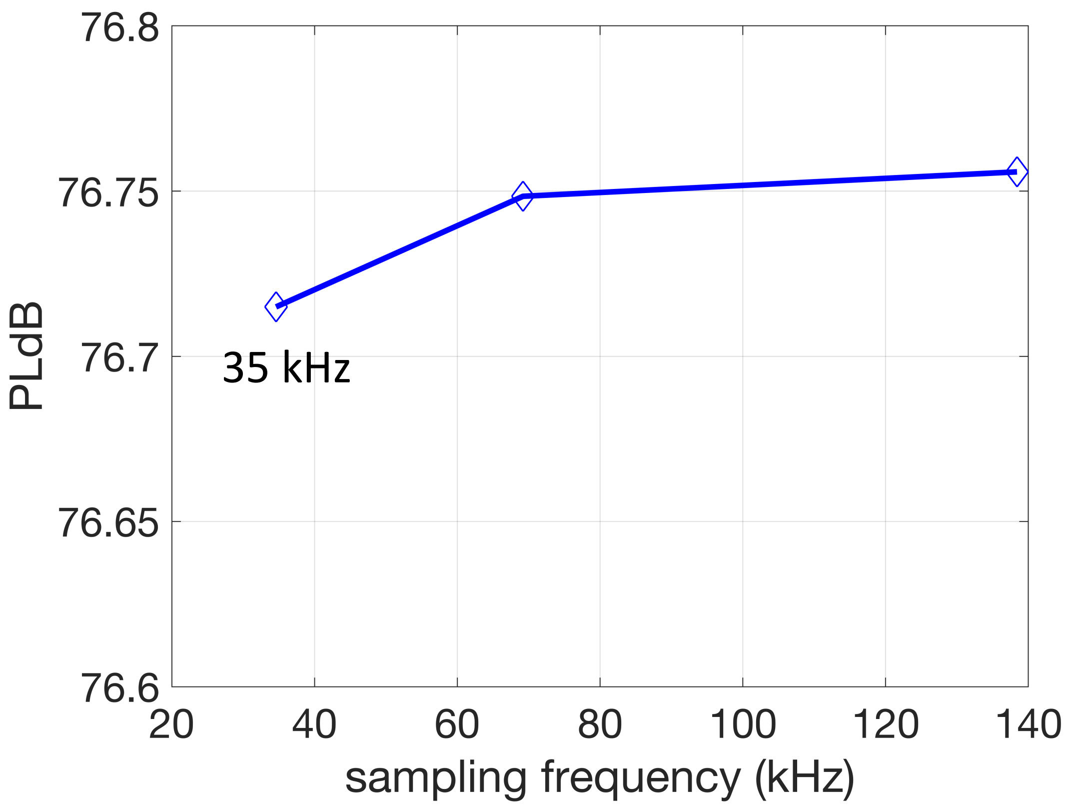
- **Right figure:**
  - Runtime on the order of sec and subsecond

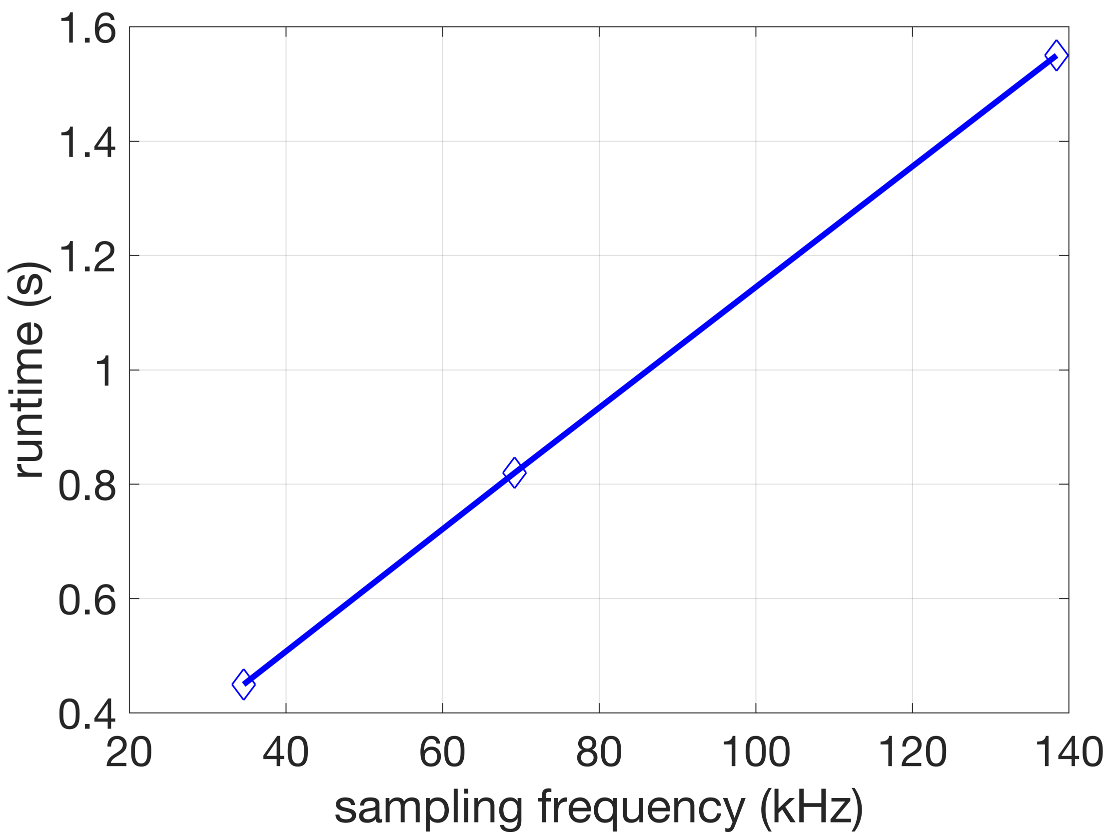




Convergence, Sampling Frequency and Runtime: Windy Atmosphere

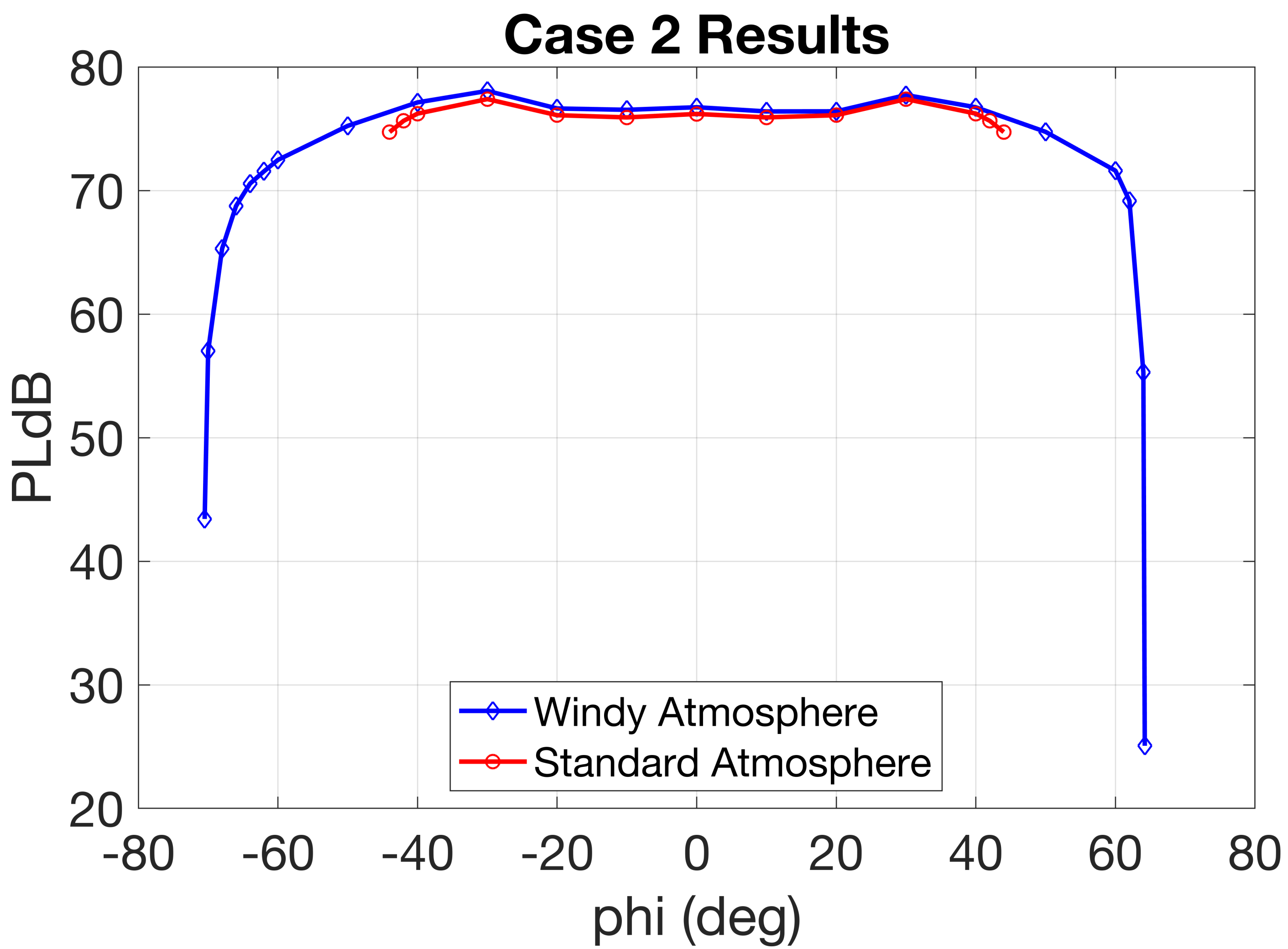
- **Left figure:**
  - Solution nearly unaffected by sampling frequencies
- **Right figure:**
  - Runtime approximately increases linearly with sampling frequency



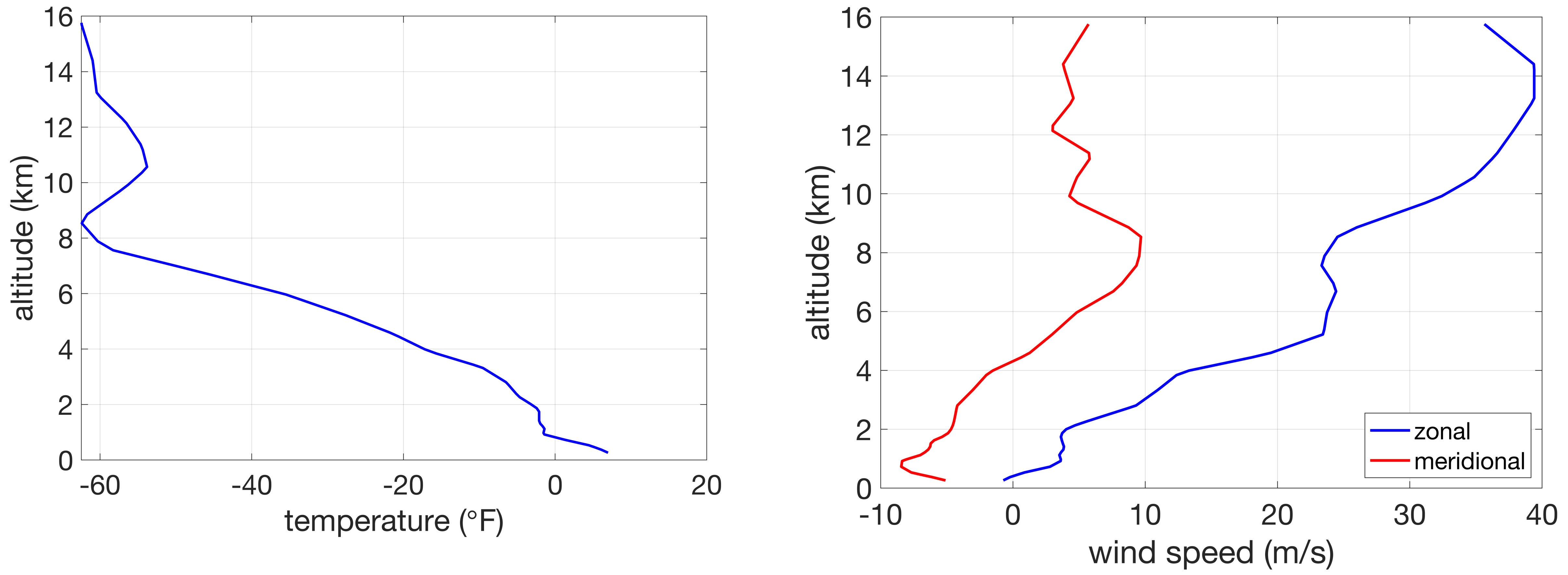


Case 2: Submitted Waveforms and PL Calculations

- **Results submission**
  - 70 kHz sampling frequency
  - ~120 m (400 ft) step size
- **Calculation of PL using NASA's LCASB (MATLAB)**
- **Undertrack and near undertrack PLs are comparable, 75-78 dB**
- **Windy atmosphere**
  - Larger carpet width
  - Larger PL range across the carpet
    - > 25 dB vs ~3 dB
    - Inaudibility with 50 dB



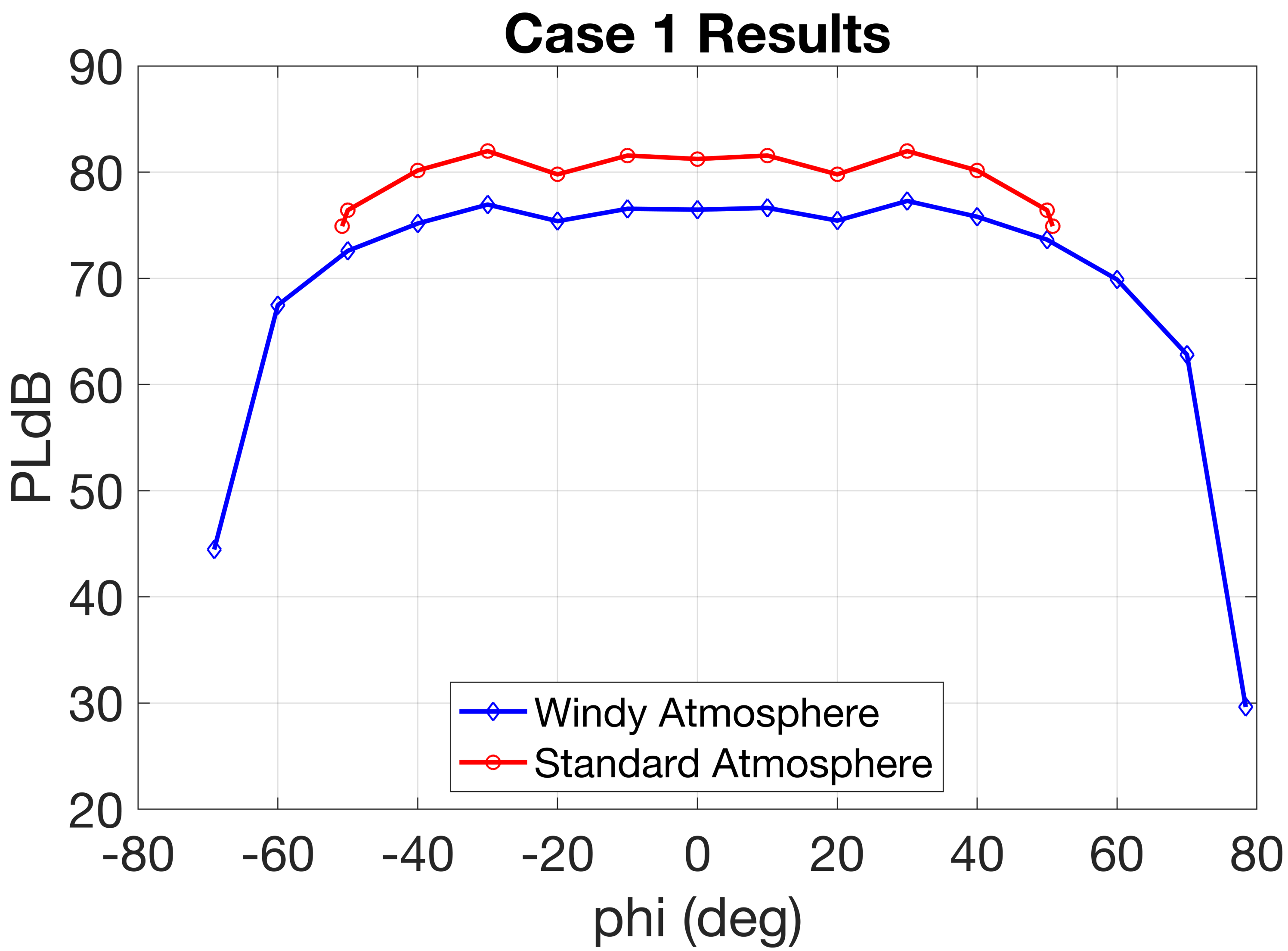
Case 1 Windy Atmosphere



Case 1: Submitted Waveforms and PL Calculations

- Undertrack and near undertrack PLs are not comparable
  - Difference of ~3 dB
  - Warrants further investigation

- Windy atmosphere
  - Larger PL range
  - Larger carpet width

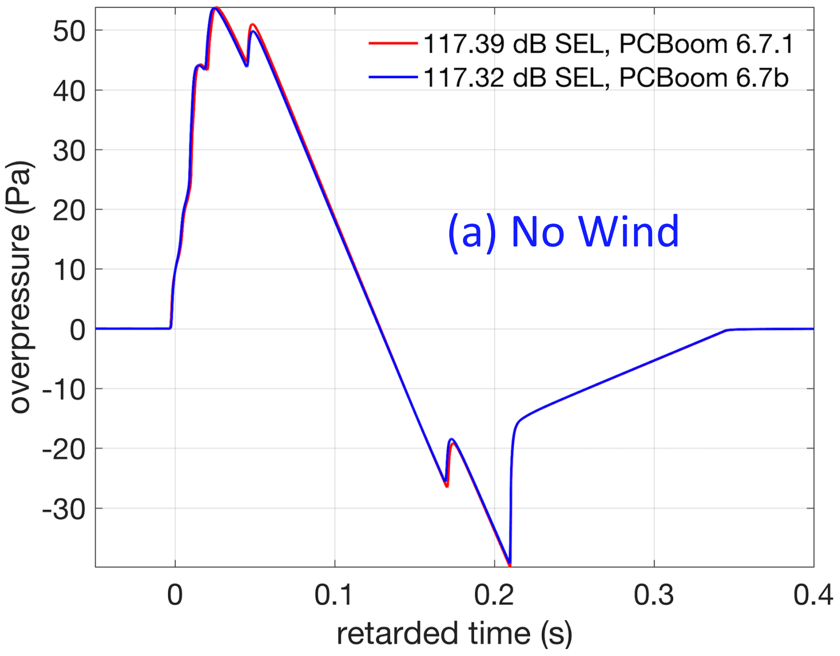


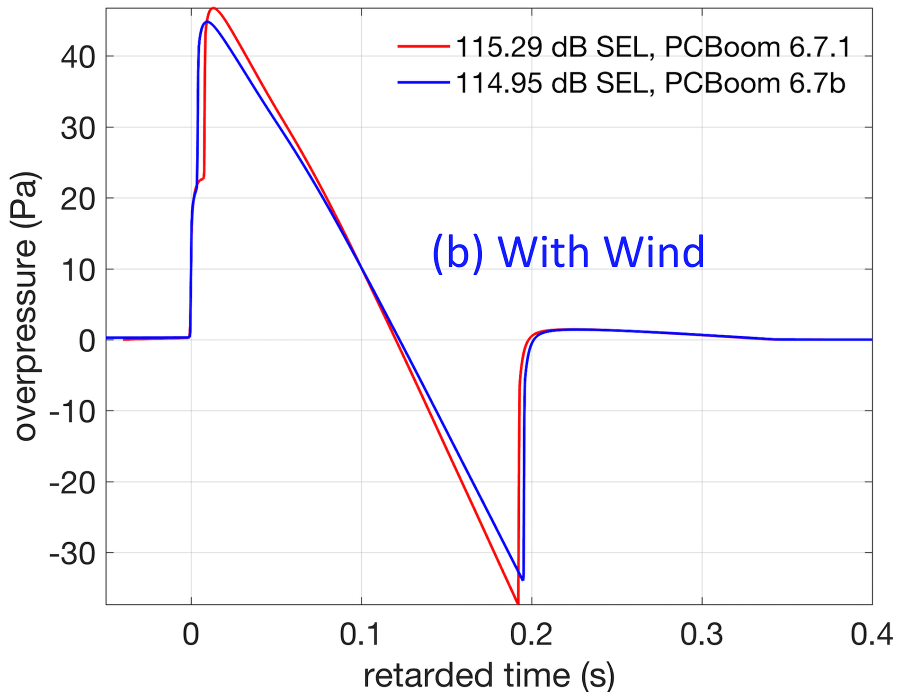
Summary

- Evolution of NASA (updated) PCBoom
    - Numerical enhancements
    - Physics-based enhancements
    - Comparison of predictions with SonicBAT dataset
- Validation of other codes used in SBPW3 using SonicBAT dataset recorded aloft
- Use of updated PCBoom to obtain results using Case 1 and Case 2
- Comparison of the updated PCBoom with the older PCBoom
    - carpet widths
    - ray tube areas
        - Effect of ray tube areas on the potential variability among submitted noise metrics
- Numerical convergence and runtimes
    - step size
    - sampling frequencies

Backup Slides

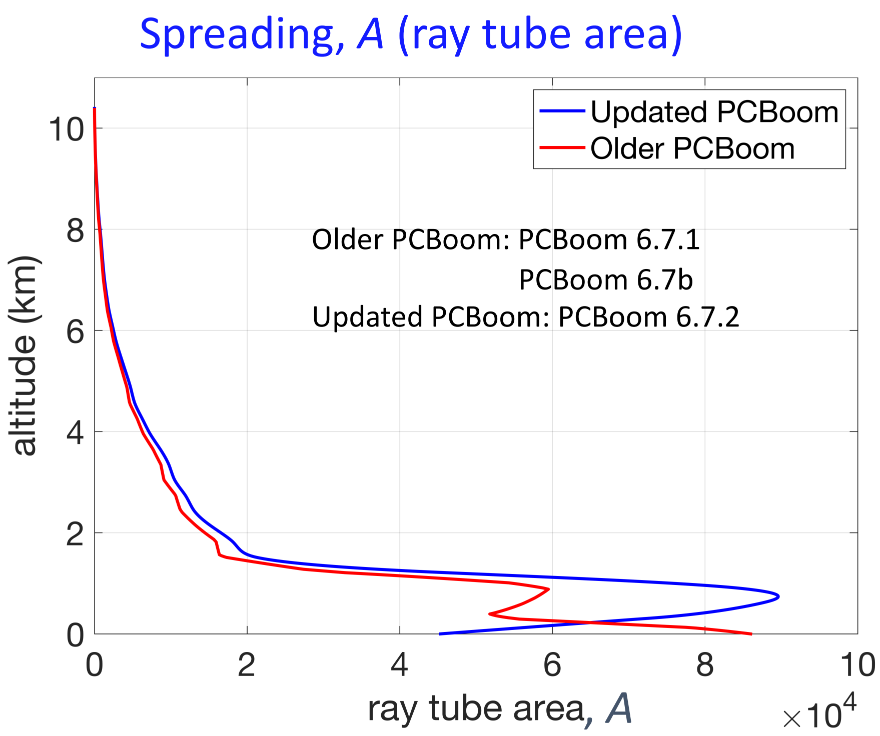
With and Without Wind: Effects on LM N+2 Design

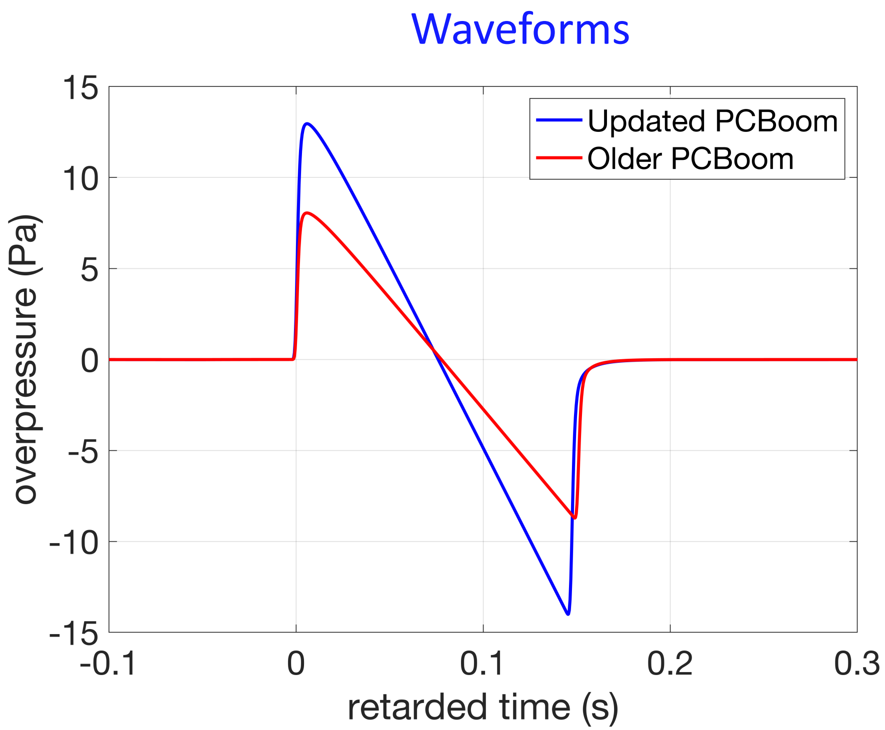




- The LM N+2 design yields near-field signatures with low peak overpressures
- In (a), a LM N+2 waveform was propagated through the U.S. Standard Atmosphere
  - There are no significant differences between the waveforms
- In (b), a LM N+2 waveform was propagated through a windy atmosphere (strong tail wind)
  - There are significant differences between the waveforms
- The differences in the waveforms are mainly caused by the treatment of winds

QSF18 Flight 4 Pass 1 Event: Geometrical Spreading and Waveform Comparison





- Left figure: A comparison of the geometrical spreading (ray tube area)
  - Near the ground, the ray tube areas are significantly different
- Right figure: The waveform using the updated PCBoom has much larger peak overpressure