

Third Sonic Boom Prediction Workshop: An Analysis to the Propagation Cases Using PCBoom



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➤ **3rd Sonic Boom Prediction Workshop**

- About a dozen participants in the propagation session
- Participants from aerospace agencies or laboratories and companies worldwide
- Main takeaways:
 - Simulation results submitted by participants using their sonic boom propagation codes vary
 - Variability increases with lateral distance from undertrack

➤ **Some of the sources of the variability**

- Transformation from CFD reference frame to ground reference frame
 - Conversion of the nearfield signatures to waveforms in the ground reference frame.
- Calculation of the geometrical spreading

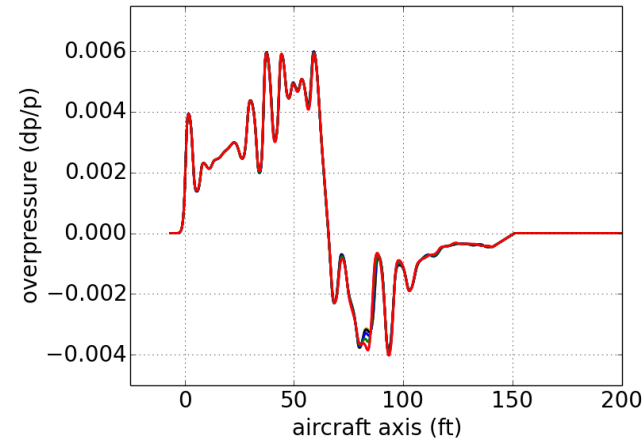
➤ **Validation of the Enhanced PCBoom using an exact solution**

- For the Jacobian or ray tube area
- U.S. Standard atmosphere
- Downward propagating rays (primary sonic boom carpet)

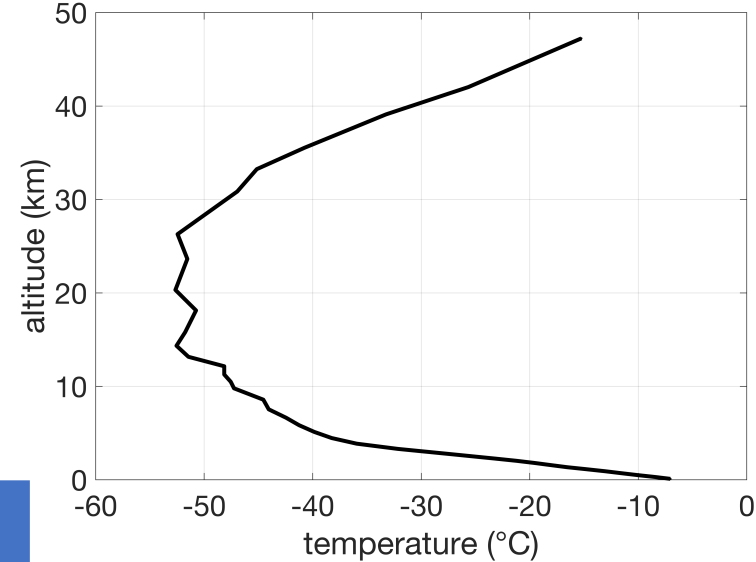
Case 2 and Atmospheres



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

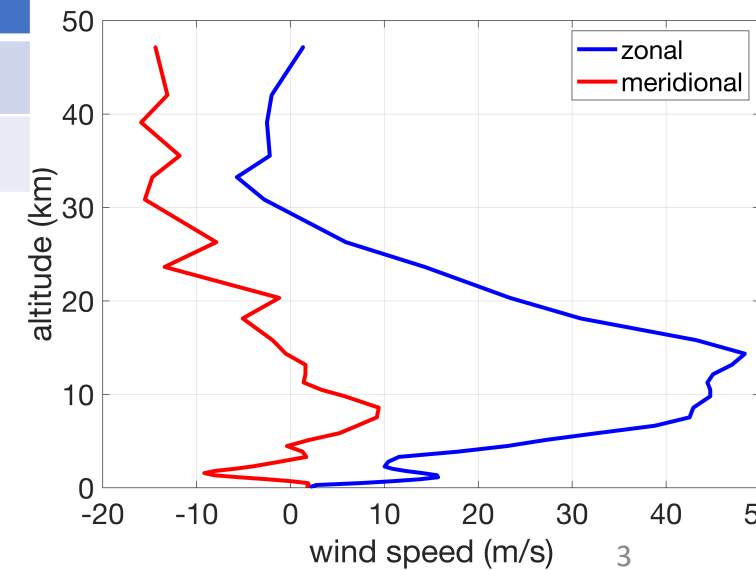


Windy Atmosphere

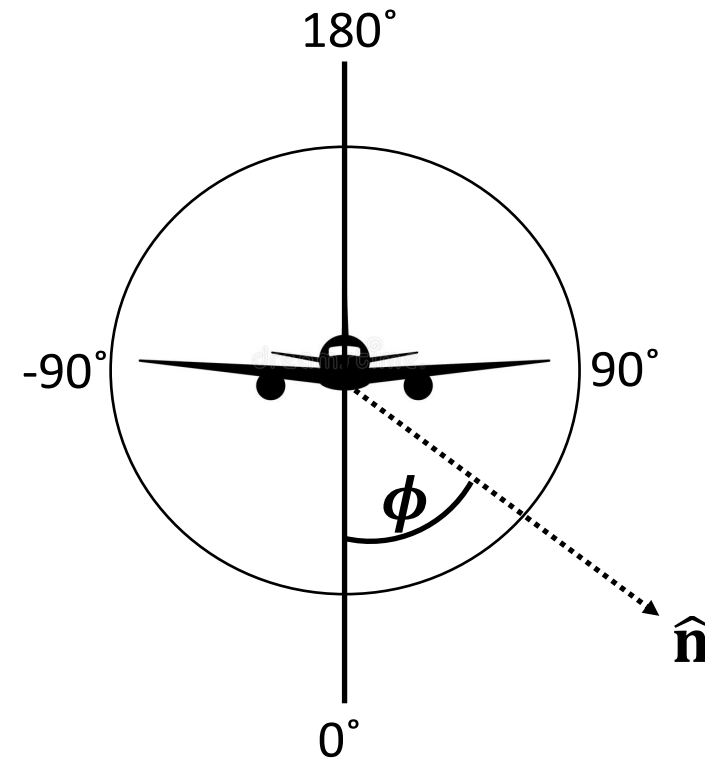
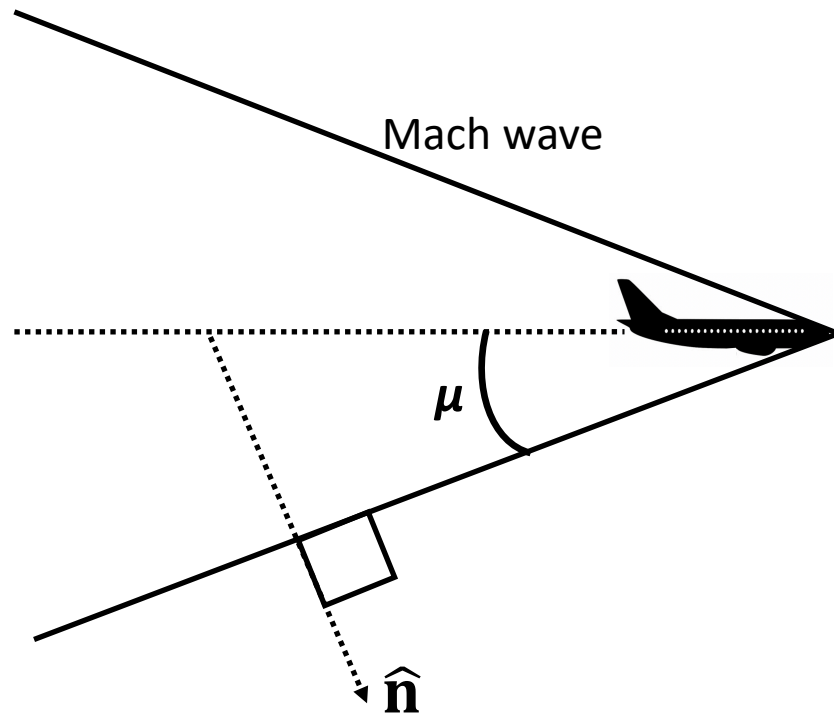


Case	Mach Number	Flight Altitude (km)	Prop Init Dist from AC (m)	Ground Altitude (m)
1	1.6	15.7600	100.584	264.069
2	1.4	16.4592	82.296	110.011

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



Mach Angle and Ray Coordinates

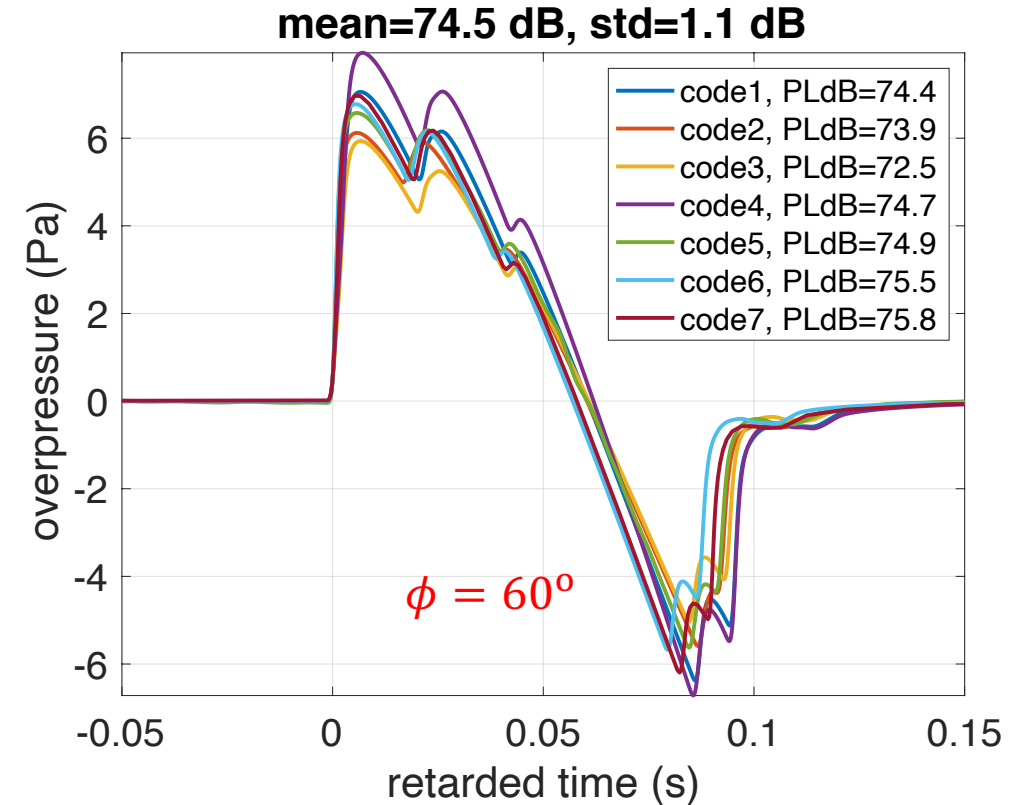
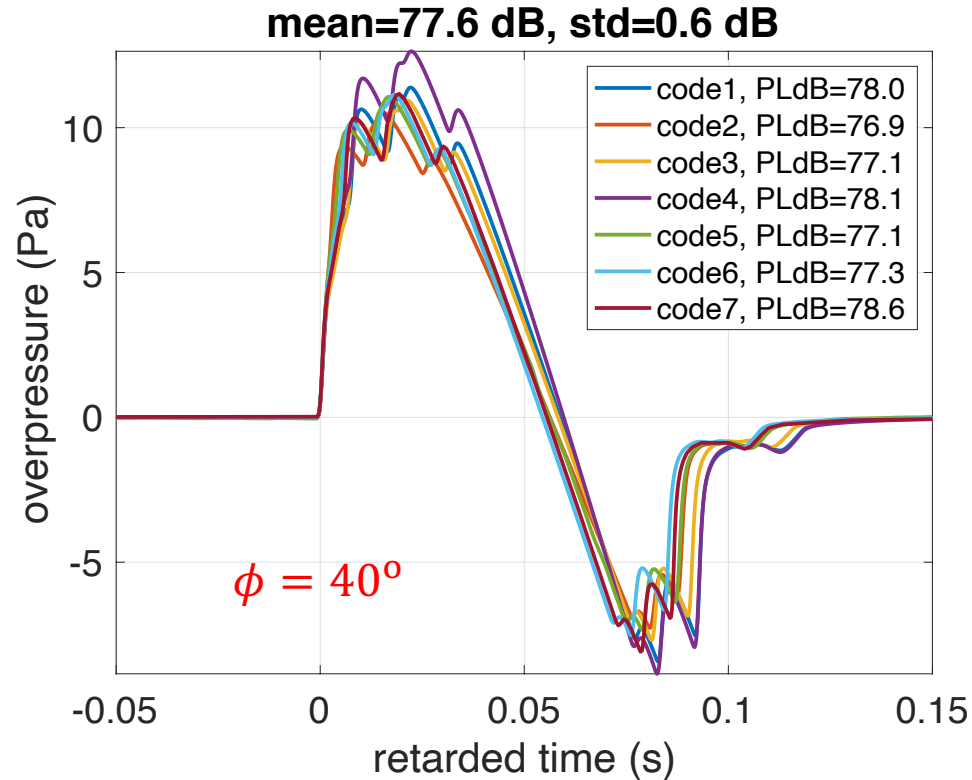


μ is Mach angle

ϕ is emission azimuthal angle

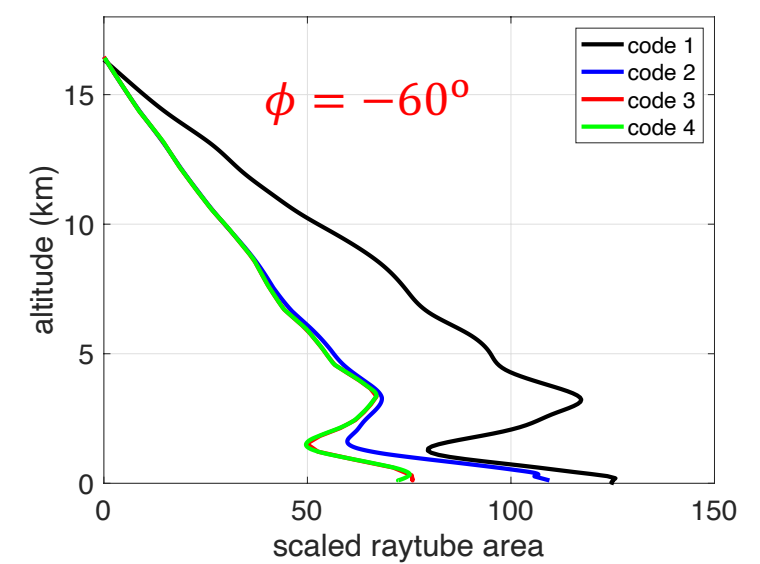
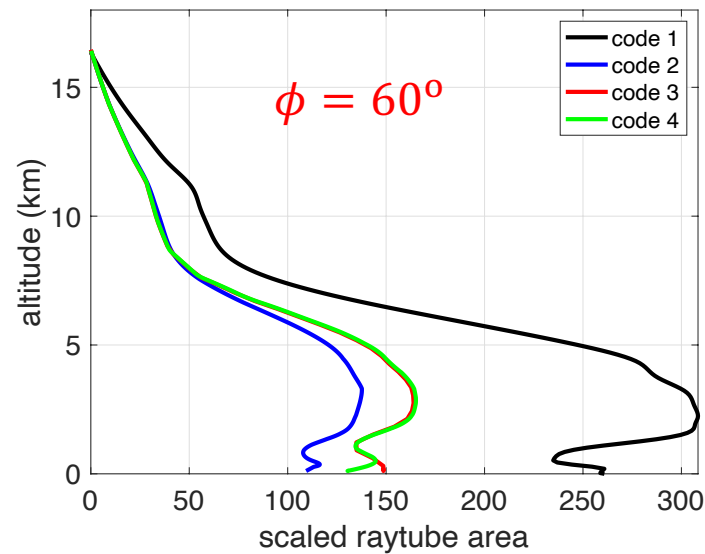
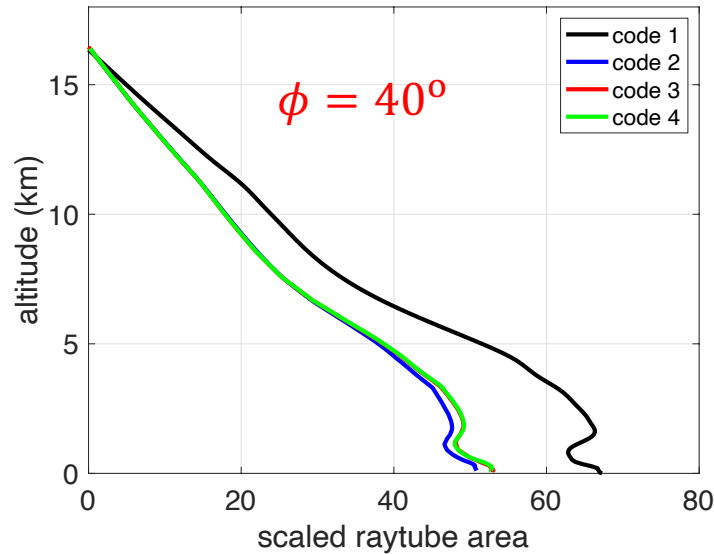
$\hat{n}$ is unit vector normal to the Mach wave

Waveform Comparison: Realistic Atmosphere



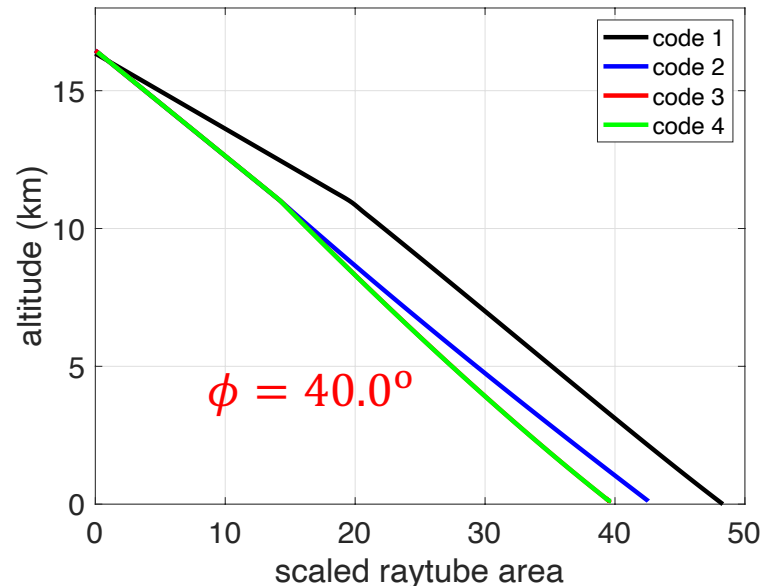
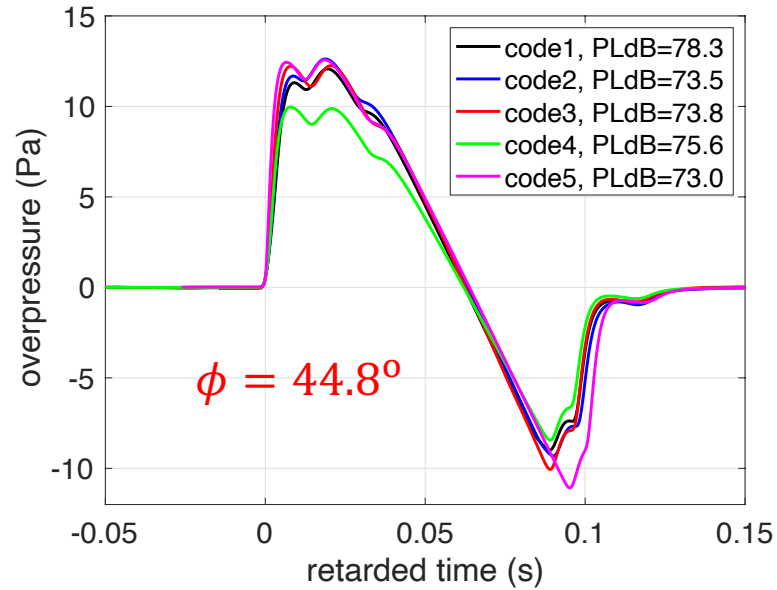
- Results for azimuthal angles of 40 deg (left) and 60 deg (right)
- Submitted by 7 participants who are power users who develop or maintain codes
- Standard deviation of Perceived Level (PL) increases with azimuthal angle

Geometrical Spreading: Realistic Atmosphere



- **Raytube areas were later shared by a few power users**
 - Not part of the required submission
- **Calculation of raytube area is as important as numerically solving the Burgers equation**
- **Differences in the raytube area increase with**
 - Propagation distance to the ground
 - Lateral distance from undertrack

Waveform Comparison: U.S. Standard Atmosphere

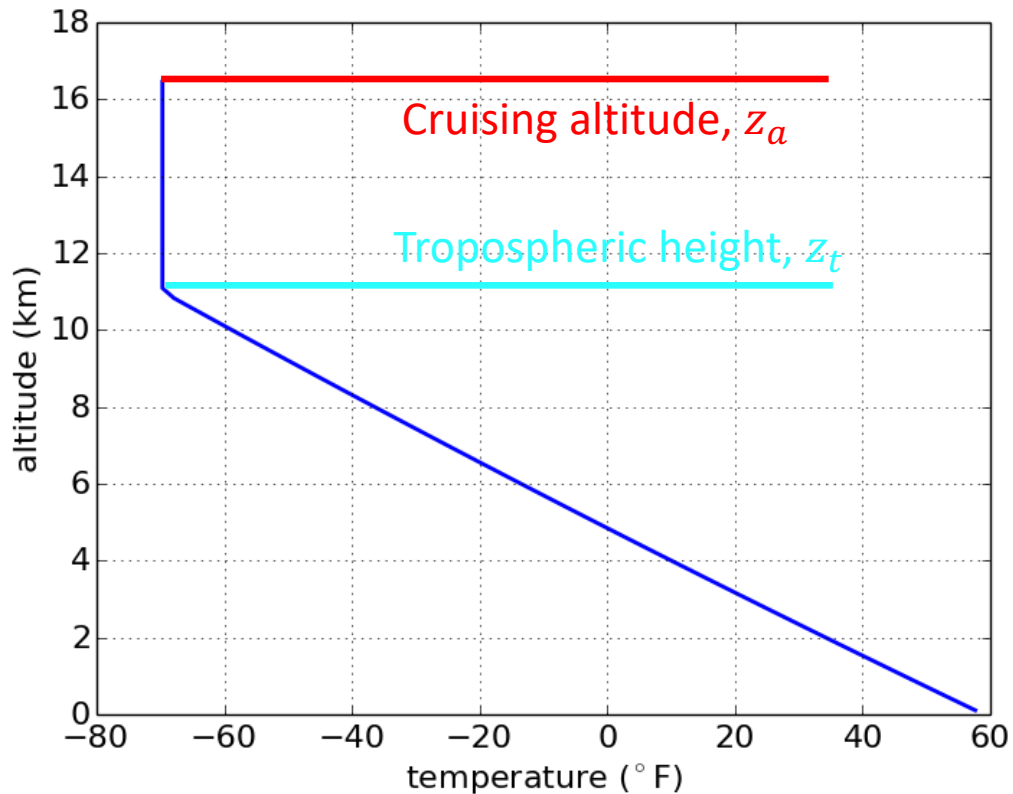


- Comparison similar to the previous waveform comparison
- For U.S. Standard Atmosphere at an azimuthal angle of 44.8° , near cutoff ray
- Raytube area for 40.0° due to limited availability for the 44.8° case
- Significant variability
- Conversion of nearfield signatures a nonissue
- Importance of raytube area

U.S Standard Atmosphere: Exact Solution



U.S. Standard Atmosphere



Ray paths: Exact solution for downward ray

$$x_j = x_j^{(a)} + n_j s_t + \frac{n_j c_a}{n_h^2 \lambda} (c_o q_3 - n_3), \quad j = 1, 2$$

$$s = s_t + \frac{c_a}{\lambda n_h} \left(\sin^{-1} \left(\frac{n_h c_o}{c_a} \right) - \sin^{-1}(n_h) \right)$$

$$s_t = \frac{z_t - z_a}{n_3}$$

- z_a is aircraft cruising altitude
- z_t is the height of the troposphere
- c_a is sound speed at cruising altitude and
- λ is the absolute value of the sound speed gradient

- Horizontal component of the initial unit vector

$$n_h = \sqrt{n_1^2 + n_2^2}$$

- Vertical Slowness

$$q_3 = - \sqrt{\frac{1}{c_o^2} - \frac{n_h^2}{c_a^2}}$$

Standard Atmosphere: Exact Solution for Downward Rays



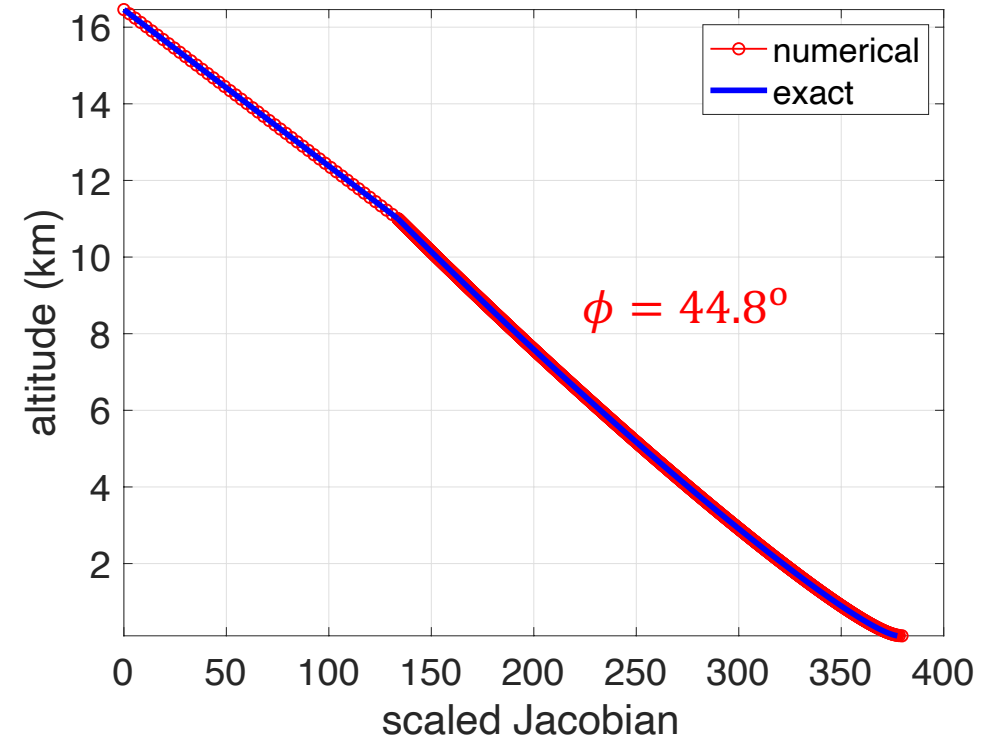
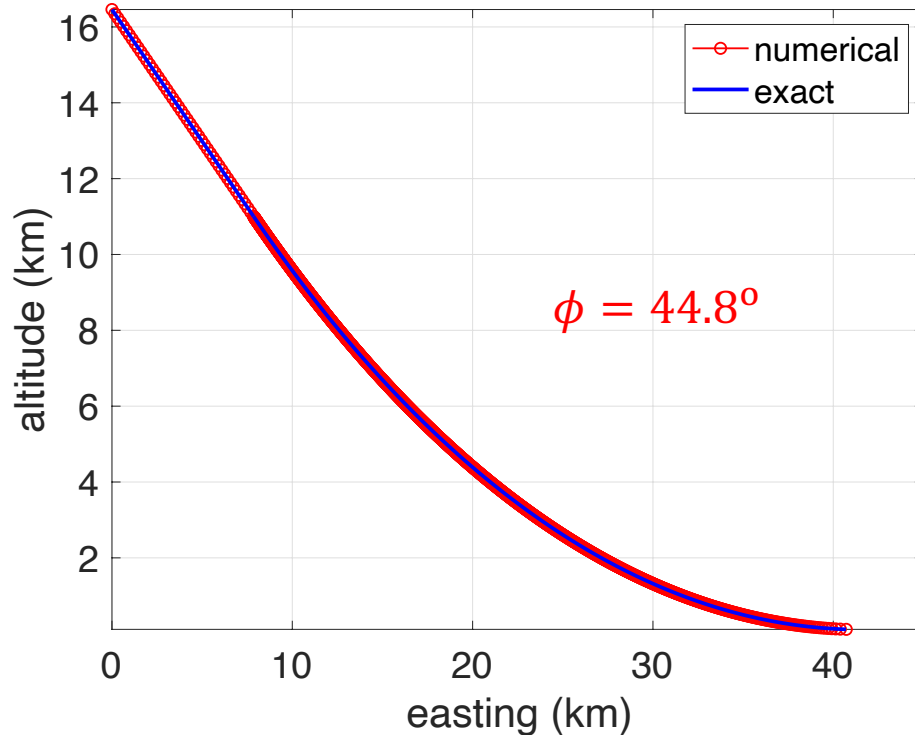
Jacobian: Exact Solution

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

Where:

- $\frac{\partial x_1}{\partial \phi} = n_1 \Gamma + \frac{2n_2 n_3}{n_h^2} x_1 - \frac{n_1 n_2}{n_3} s_t$
- $\frac{\partial x_2}{\partial \phi} = n_2 \Gamma + \left(\frac{2n_2 n_3}{n_h^2} - \frac{n_3}{n_2} \right) x_2 - \left(\frac{n_2^2}{n_3} + n_3 \right) s_t$
- $\frac{\partial x_3}{\partial \phi} = \frac{n_2 c_o}{n_h^2 \lambda} \left(c_a q_3 - n_3 \lambda q_3 (s - s_t) - n_3 + \frac{\lambda n_h^2 q_3 s_t}{n_3} \right)$
- $\frac{\partial x_1}{\partial t_a} = v_1^{(a)}$
- $\frac{\partial x_2}{\partial t_a} = 0$
- $\frac{\partial x_3}{\partial t_a} = 0$
- $\Gamma = \frac{n_2}{n_h^2 \lambda} \left(\frac{c_o}{c_a} \left[c_a - \lambda n_3 (s - s_t) + \frac{\lambda n_h^2 s_t}{n_3} \right] - c_a \right)$

Validation of PCBoom Using Standard Atmosphere



PCBoom Validation:

- U.S. Standard atmosphere
- Azimuthal angle of 44.8 deg, near the cutoff ray
- Good agreement between Enhanced PCBoom and the exact solutions

Validation of Other Sonic Boom Codes

- Exact solutions can be used to validate other codes, at least for windless case

- Results submitted by the participants of the third Sonic Boom Prediction Workshop were compared
- Comparison showed significant variability of the results
- Variability increased with lateral distance from undertrack
- One potential cause of the variability is the differences in the calculated raytube area
- Exact solutions to the raytube area were derived and
 - were used to validate the Enhanced PCBoom
 - can be used to validate other sonic boom codes