

# Updates to PCBoom Sonic Boom Propagation Code: Modeling QSF18 Sonic Thumps



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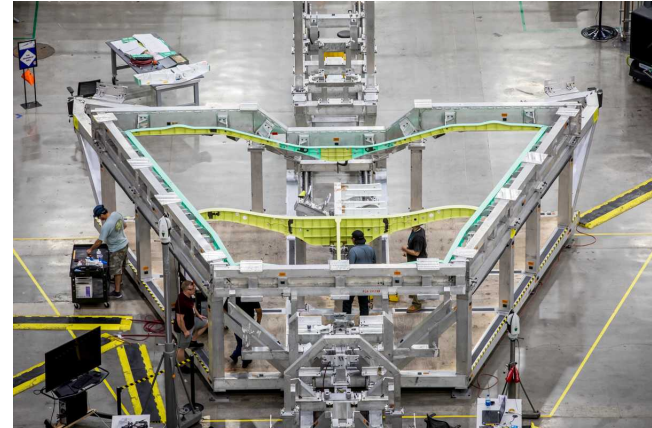


# Background



- Building the X-59 (experimental low boom flight demonstrator)
- X-59 signature validation
- Overflight community test campaign
- Enhancement of sonic boom propagation codes
  - Account for dominant atmospheric effects
  - Better predict the far-field acoustic pressure
- Recent enhancement to NASA PCBoom
  - Increase computational speed and accuracy
  - Better account for wind effects
- **Focus of this presentation**
  - **Enhancement on geometrical spreading**
  - **Ubiquitous turbulence effects on boom propagation**

X-59's wing under construction



Envisioned overflight test



- ❖ Motivation: Statement of the problem
- ❖ Geometrical spreading effects (ray tube area)
  - ❖ Contribution to the predictions
  - ❖ Novel method to compute more accurately
- ❖ Turbulence-scattering-based attenuation model
  - ❖ Development
  - ❖ Application to a subset of QSF18 data
  - ❖ Identification of limitations and assumptions
- ❖ Future Outlook
- ❖ Summary

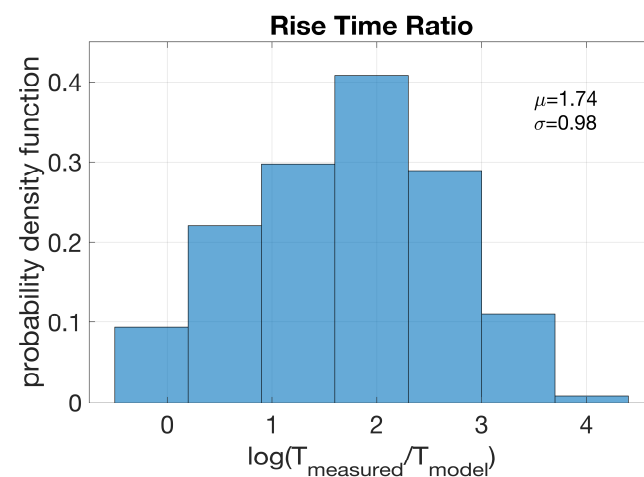
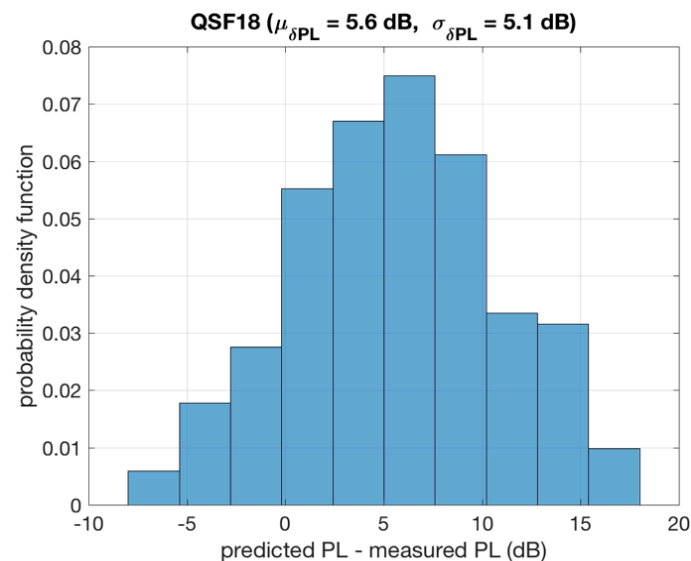


# Motivation: Propagation Prediction Problem During QSF18



- ❖ Predicted PL much larger than recorded PL
  - Forecasted weather
  - As-flown trajectory
  - Accounting for aircraft weight
  - Unexpected loss mechanism
- ❖ Difficulty in the survey design
  - Meeting the designed PL distribution
  - Dose-annoyance analyses
- ❖ Shifting of dive points
  - mitigate the unexpected loss mechanism
- ❖ PCBoom prediction includes
  - Thermo-viscous dissipation
  - Molecular vibrational relaxation
- ❖ **The loss mechanism is attributed to**
  - **Scattering from turbulence**
    - **Large observed rise times**

## Prediction Using As-flown Trajectory and Measured Weather Conditions



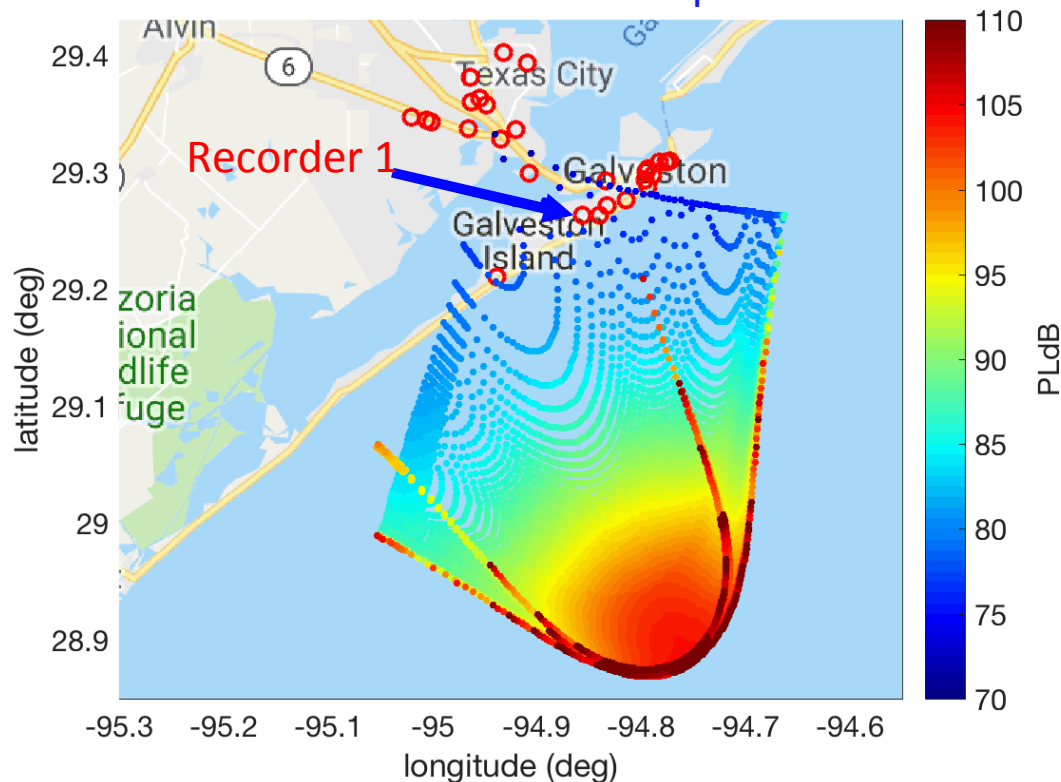
# Flight 4 Pass 1: Atmosphere, Boom Carpet, & Measurement



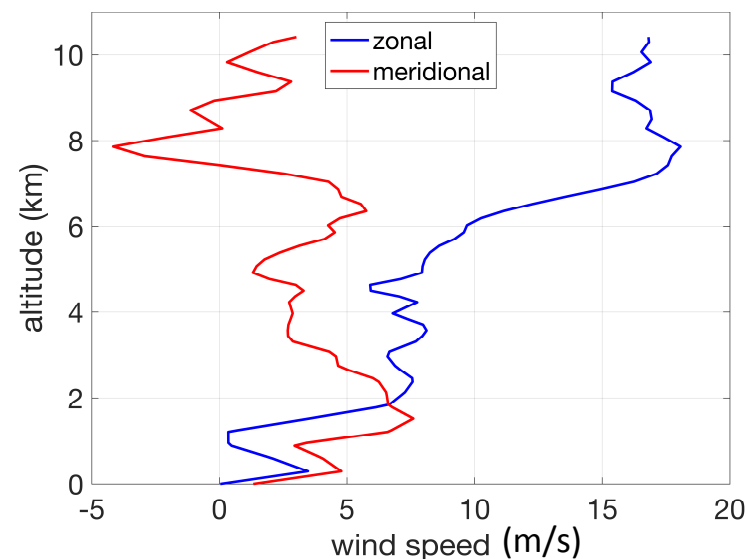
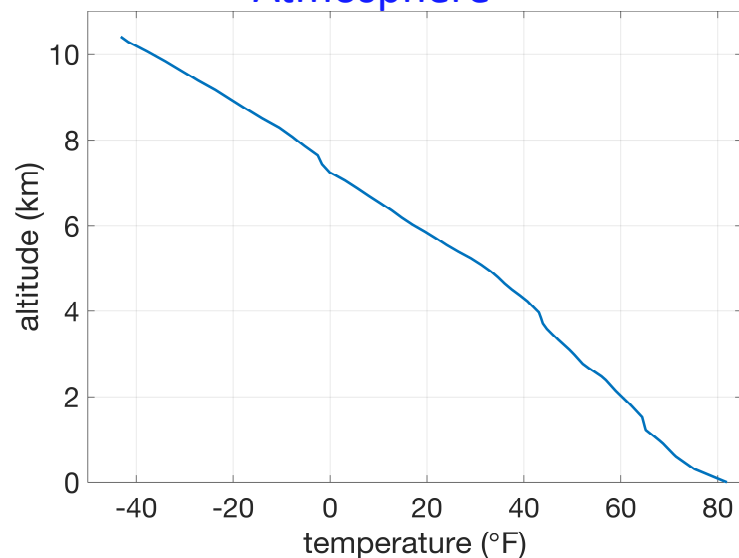
At recorder 1 (Scholes Airport)

- Predicted PL = 76.6 dB
- Measured PL = 66.0 dB

## Sonic Boom Carpet



## Atmosphere



# Significance of Geometrical Spreading



## ❖ Waveform amplitude

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

$$B = \sqrt{\frac{\rho_o c_o \chi \Omega A_i}{\rho_{o,i} c_{o,i} \chi_i \Omega_i A}}$$

- $B$ : amplitude scaling parameter
- $A$ : ray tube area
- $p_i^{(p)}$ : initial peak overpressure
- $u$ : scaled acoustic pressure
- $s$ : ray path length,  $\tau$ : retarded time
- $\rho_o$ : air density,  $c_o$ : sound speed
- $\chi$ : convective index,  $\Omega$ : Doppler shift

## ❖ Cumulative nonlinear effects (ignoring losses)

$$u(s, \tau) = u_o \left( \tau + u_o \int_{s_o}^s \tilde{\beta} ds' \right),$$

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

- waveform
  - Stretching
  - Steepening
- $\beta$ : coefficient of nonlinearity
- $\tilde{\beta}$ : effective coefficient of nonlinearity



# Ray Tube Area Calculation: 1-Ray vs 4-Ray Methods



- Dynamic Ray Tracing involves

$$\nabla \cdot \hat{n} = \frac{1}{J} \frac{dJ}{ds}$$

- 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

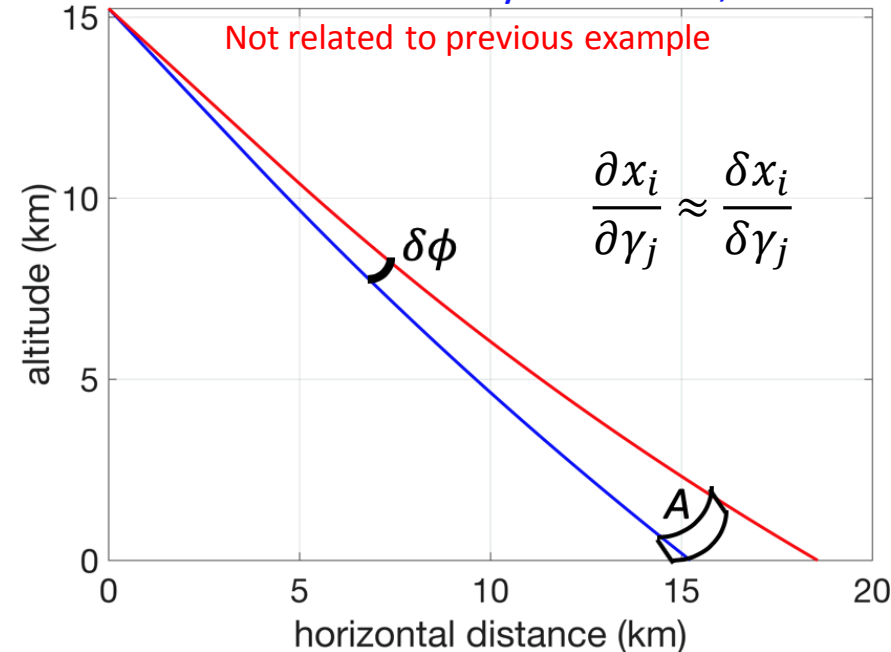
$$x_i(\gamma) = x_i(\gamma_0) + \int_{s_0}^s \frac{1}{v_r} (v_i + c_o n_i) ds',$$

$$\gamma = \{s, \phi, t_a\}, \quad \gamma_0 = \{s_0, \phi, t_a\}, \quad i = 1, 2, 3$$

$$\frac{\partial x_i}{\partial \gamma_j} = \frac{\partial}{\partial \gamma_j} x_i(\gamma_0) + \frac{\partial}{\partial \gamma_j} \int_{s_0}^s \frac{1}{v_r} (v_i + c_o n_i) ds'$$

## Illustration: Ray tube area, $A$

Not related to previous example



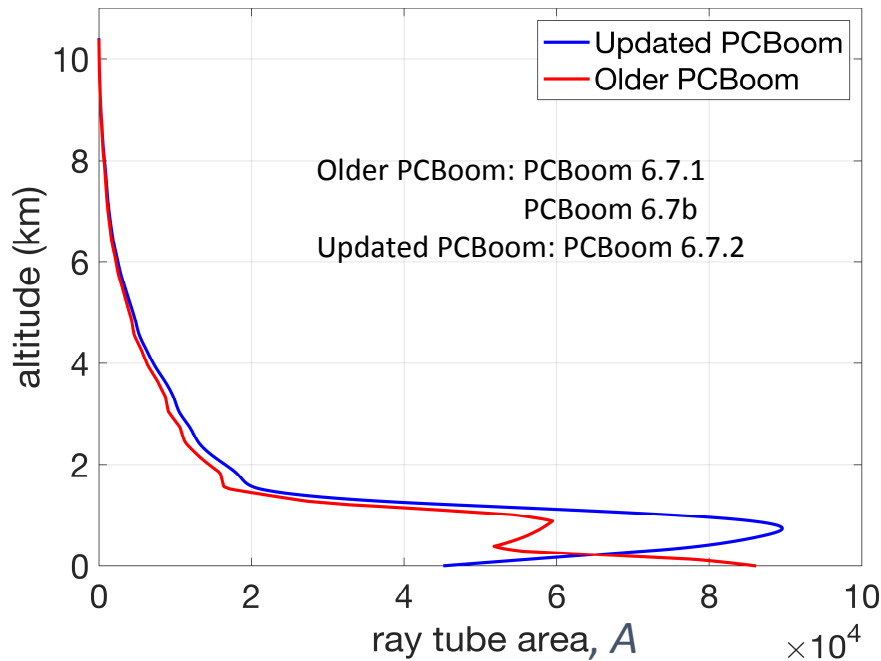
- Older PCBoom depends on the accuracy of neighboring rays
  - Requires 3 or 4 rays
- Updated PCBoom purely depends on the medium properties.
  - Requires only the ray of interest



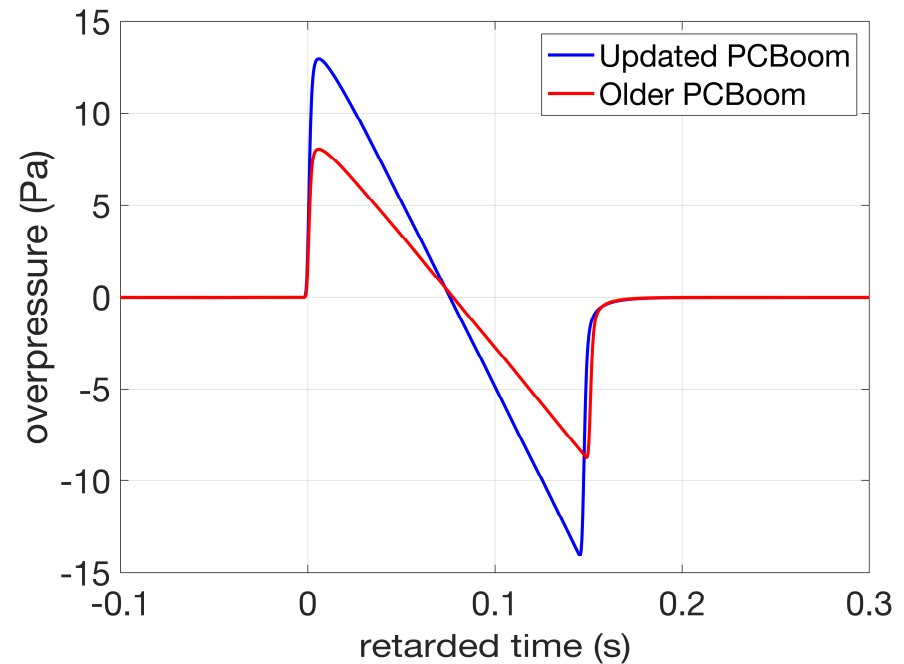
# Flight 4 Pass 1 Event: Geometrical Spreading and Waveform Comparison



## Spreading, A (ray tube area)



## Waveforms



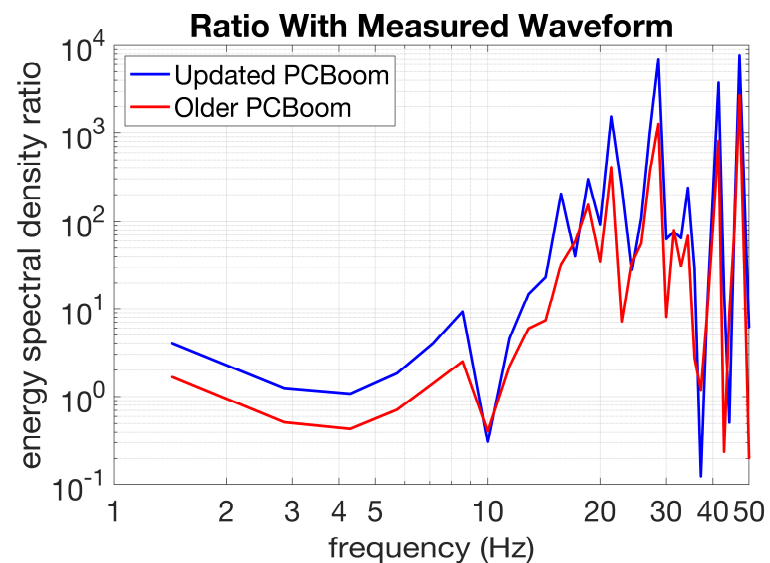
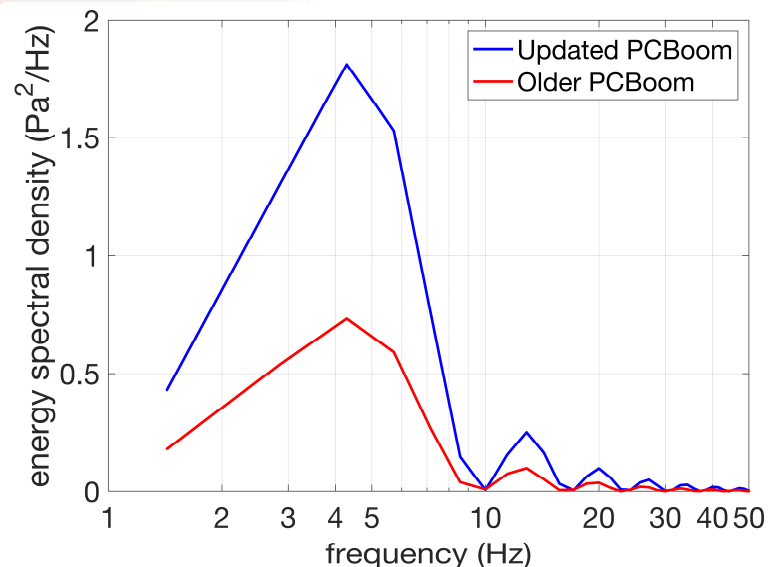
- Left figure: A comparison of the geometrical spreading (ray tube area)
  - Near the ground, the ray tube areas are significantly different
- Right figure: The waveform using the updated PCBoom has much larger peak overpressure



# Comparison Of Models With Measurement



- Same peak frequency,  $\sim 4.3$  Hz, between the models
- The spectral density of the recorded waveform has almost the same peak frequency but with peak spectral density that is nearly the same as that of the updated PCBoom
- Spectral density ratio greater (smaller) than 1 indicates that the medium absorbs (amplifies) the signal
  - Older PCBoom prediction is less plausible
- Wind spectral density is not enough to compensate for the reduced amplitude
- The dips in the ratio at higher frequencies are numerical artifacts; models have vanishing spectral density at those frequencies



# Multiple Scattering-Based Extinction Model



- **Development of extinction (attenuation) coefficient model**
  - Based on multiple scattering theory
  - Using the self-energy formalism

- **Incorporation of the extinction coefficient into Burgers' equation**

$$\frac{dU}{ds} = \underbrace{\frac{i\omega\tilde{\beta}}{4\pi} \int U(\omega')U(\omega - \omega')d\omega'}_{\text{Nonlinearity}} - \underbrace{[\alpha_{tv} + \alpha_{vi}]}_{\text{Absorption}} + \underbrace{\alpha_{ex}}_{\text{Scattering from Turbulence}} U(s, \omega)$$

- **Assumptions of the turbulence fields (statistically)**
  - Isotropic, stationary, and homogeneous
- **Models of the turbulence two-point correlation function**
  - von Karman, Gaussian, and Exponential
$$\alpha_{ex}(\omega) = \alpha_{ex}(\omega; \sigma_c^2, \ell_c, \sigma_v^2, \ell_v)$$
  - Previous presentation on the derivation of the extinction coefficient
- **Negligible impact on the overall runtime of the Burgers' equation solver**



# Extinction Coefficients Estimation



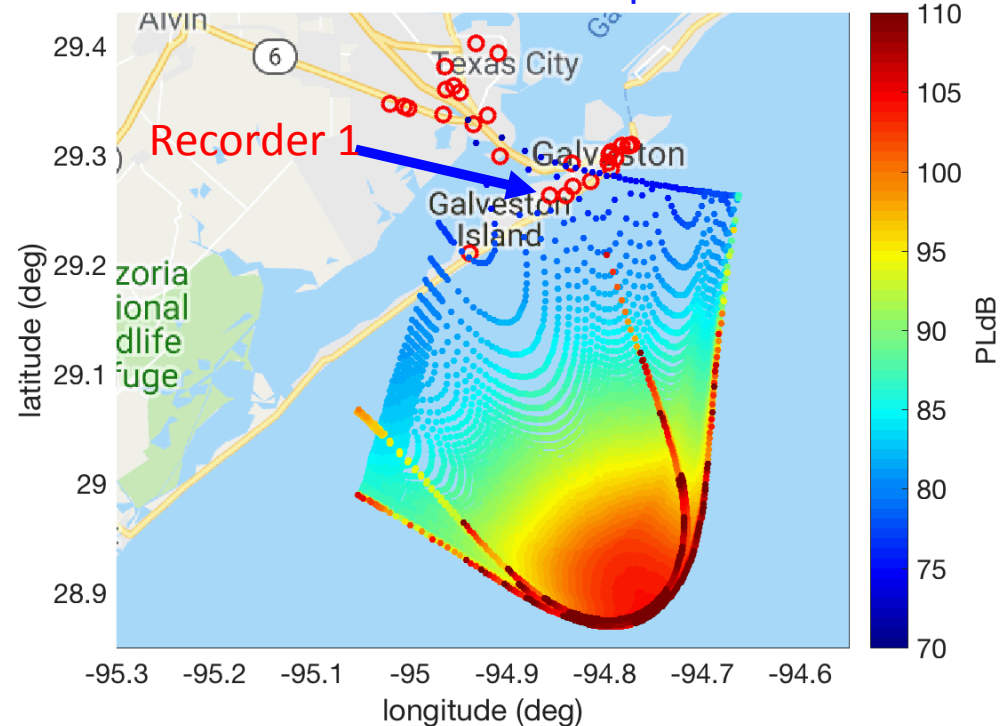
## Inversion Process

- No direct turbulence measurement in QSF18
- No estimation of
  - the variances
  - integral length scales of the fluctuations
- Estimation of the extinction coefficients for each event
  - Using the recorded waveform at Station Alpha (Recorder 1)
  - Using as-flown predicted waveform for that station

## Prediction Enhancements

- Propagate the waveforms for all the other recorders in Galveston Island
- Apply the estimated extinction coefficients to the propagated waveforms
- Repeat the process for all the other events

## Sonic Boom Carpet



## Additional Assumptions:

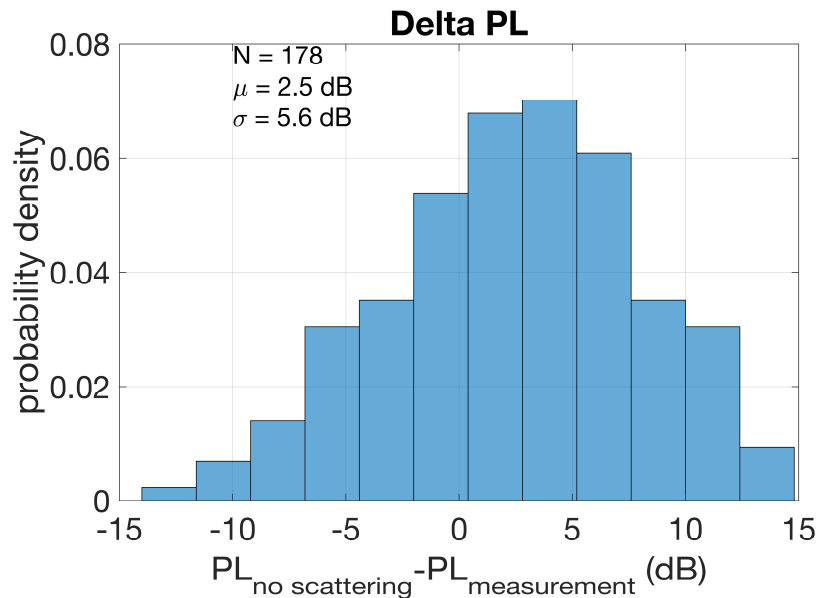
- Minimal height of the turbulence boundary layer (TBL)
- Small variation of the path lengths through the TBL compared to the mean of these path lengths



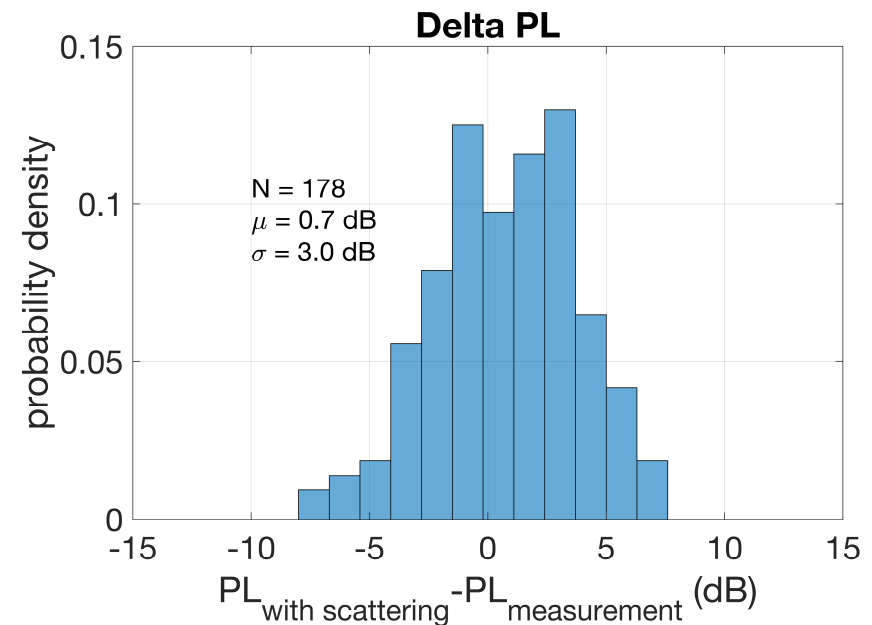
# Improvement to the Predictions Using Perceived Levels (PL)



## No Scattering Effects in Models



## With Scattering Effects in Models



- Inclusion of the scattering effects reduces
  - the mean delta PL from 2.2 to 1.0 dB
  - the std dev from 5.4 to 3.2 dB
- Smaller mean indicates better agreement between models and measurements
- **An improvement to the predictions was achieved!**



## Caveats

- Approach to account for turbulence effects involves simplifying assumptions
  - Violations of these assumptions could explain the residual disagreement between the improved predictions and measurements
- Extinction coefficients were not directly obtained from the turbulence parameters. The procedure used an inversion method.

## Observations/Future Outlook

- Energy reduction is correlated with lateral distance
  - Longer path length through the turbulent boundary layer (TBL)
- PCBoom predictions through the TBL are inadequate without accounting for turbulence-scattering effects
- Scattering models developed must be validated with additional datasets



# Summary

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- ❖ A single-ray method for calculating the geometrical spreading has been developed
  - ❖ Results can significantly differ from those of the 4-ray method
- ❖ Scattering from turbulence has been identified as the plausible source of the large discrepancy between predictions and QSF18 measurements
- ❖ A scattering extinction based on Multiple Scattering Theory has been employed to lessen the discrepancy
  - ❖ Extinction coefficients were determined and applied to other propagated waveforms to improve the agreement between predictions and measurements
- ❖ Waveform rounding due to turbulence-scattering effects is ubiquitous
  - ❖ Could impact future community overflights using the X-59 aircraft

