Nonnormality of Sonic Boom Loudness Metrics in the Turbulent Atmospheric Boundary Layer at Large Lateral Distances from the Flight Path

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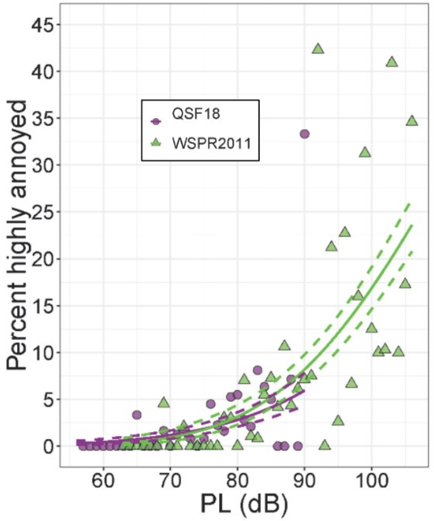
X-59 Flight Test Surveys

- Community response surveys to be conducted with X-59
  - Model dose-response relationship
  - Dose = sonic boom loudness metric (PL, ISBAP, A, B, D, E-SEL)
- Bayesian MLR approach to modeling dose response [1]
- Assumes no uncertainty in noise dose estimate
- Dose uncertainty included by Doebler et al. [2]
  - Estimated PL drawn from normal distribution
  - $\sigma_{dose\ uncertainty}$ estimated from measurements
    - WSPR2011: 3.7 dB
    - QSF18: 4.9 dB
- Turbulence effects are likely a big contributor to noise dose uncertainty



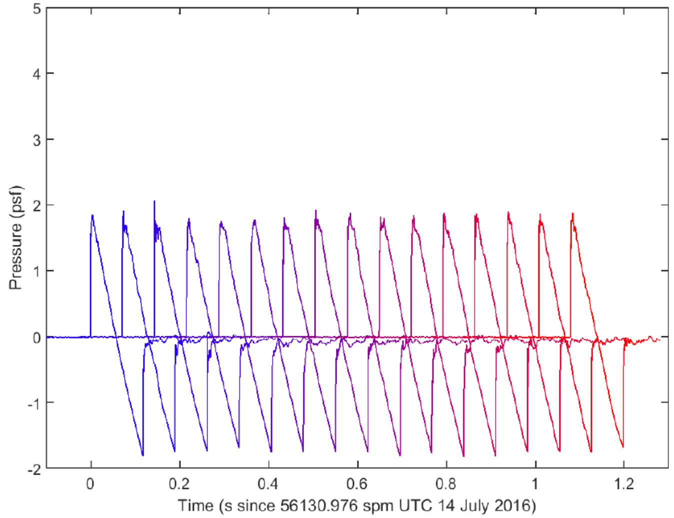
Dose-response relationship computed from BLMR for QSF18 and WSPR2011 [1]. Reproduced with permission [1]. Copyright 2020.

Artist’s illustration of the NASA X-59 aircraft.

Turbulence Effects on Sonic Booms

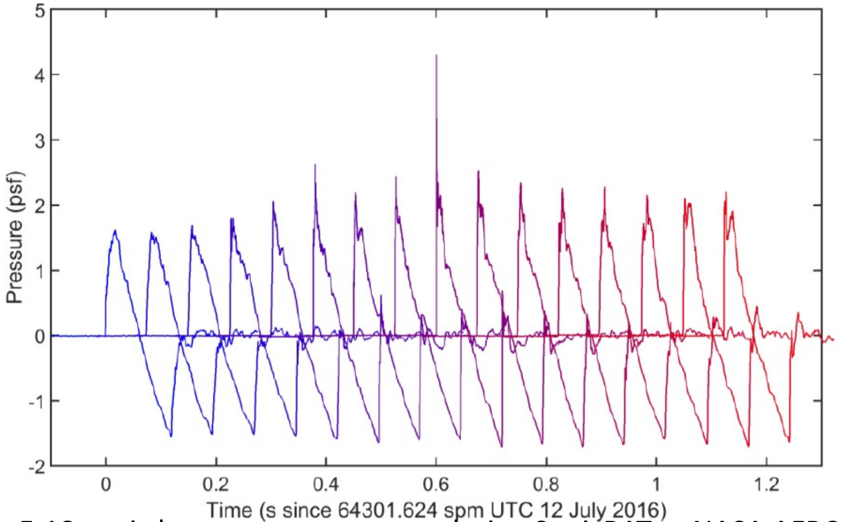
- Atmospheric boundary layer (ABL) turbulence can cause variability in sonic boom waveforms [3,4,5]
- Dose variability may lead to flattening of dose-response curve
- Turbulence effects may be accounted for in simulations (see Refs. [6,7,8,9])
  - Computationally expensive
  - Quick estimates of $\sigma_{dose\ uncertainty}$ likely preferred

Calm Atmosphere



F-18 sonic boom measurements during SonicBAT at NASA AFRC in a calm atmosphere [4].

Turbulence Present



F-18 sonic boom measurements during SonicBAT at NASA AFRC in an atmosphere with turbulence present [4].

Objectives

Problems

- $\sigma_{dose\ uncertainty}$ will depend on turbulence conditions and propagation distance
- Dose uncertainty may not follow a normal distribution

Objectives

- Quantify dose uncertainty for N-waves and shaped booms (X-59)
- Examine normality of dose uncertainty

Method

- Past investigations simulate with KZK or FLHOWARD Eqns. (see Refs. [6,7,8,9])
- Present investigation: FLHOWARD type approach, but retain more terms

Outcome

- Approximate model of dose uncertainty based on simulation data
- Depends only on meteorological conditions, waveform, and metric

Simulation Approach

- Steps:
  1. Use PCBoom [11] to obtain input waveforms at z_i
  2. Simulate through computational domain with inhomogeneous ABL turbulence (using FLHOWARD-type equation, see Refs. [8,10])
  3. Compute $\sigma_{dose\ uncertainty}$ and sonic boom metric distributions along the propagation direction

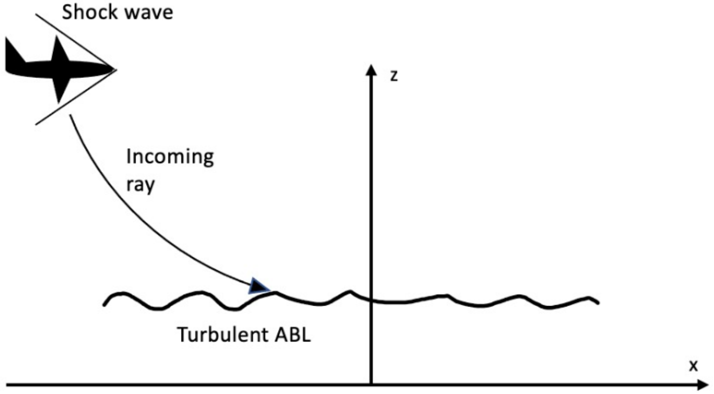
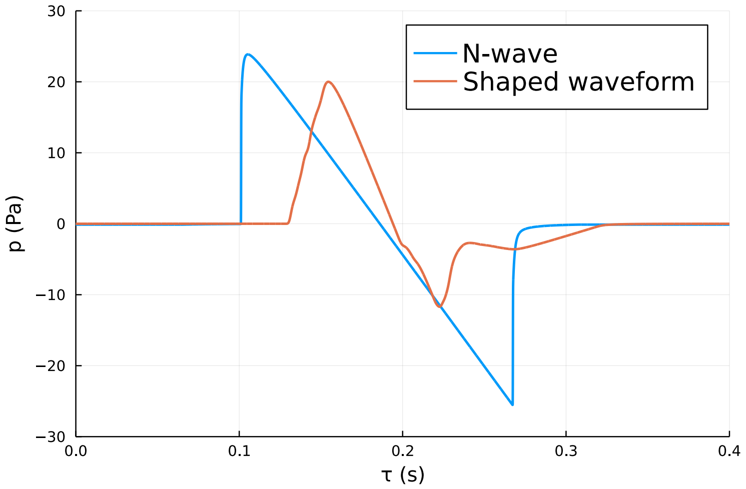
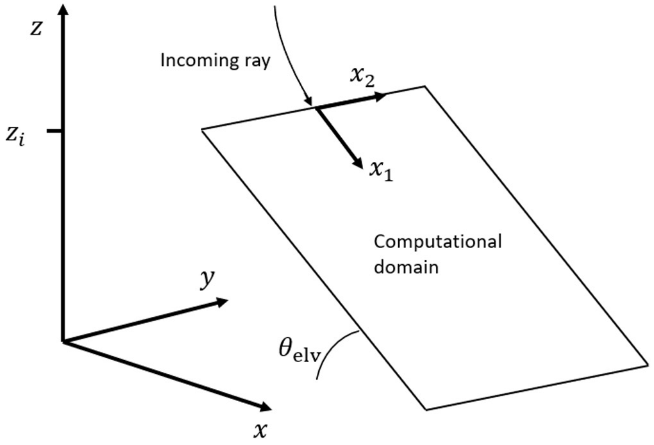


Diagram of ray propagation from source to ABL height.



Initial waveforms at ABL height computed from PCBoom.



Computational domain of simulations.

Atmospheric Boundary Layer Conditions

- Convection level expresses relative importance of buoyancy effects to mean shear
- Will consider 3 different convection levels
  - Weak convection: $\log(-z_i L_o^{-1}) \leq 0.5$ (KSC)
  - Moderate convection: $0.5 < \log(-z_i L_o^{-1}) < 1.5$ (KSC)
  - Strong convection: $\log(-z_i L_o^{-1}) \geq 1.5$ (AFRC)
- Obukhov length, L_o, is a measure of production of TKE due to shear and buoyancy effects

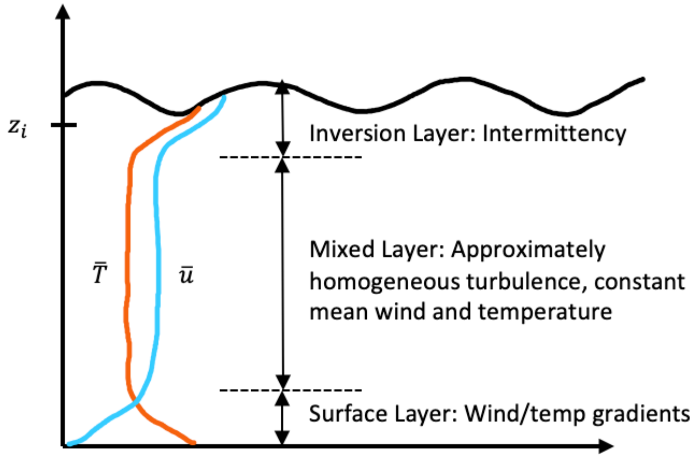


Illustration of daytime ABL.

Turbulence statistics in the mixed layer.

Flight No.	σ_T (K)	L_T (m)	σ_u (m/s)	L_u (m)	z_i (m)	$\log(-z_i L_o^{-1})$
KSC20	0.044	68.30	0.67	78.30	411.6	0.115
KSC1	0.086	71.20	0.78	89.20	457.3	0.451
KSC12	0.199	94.10	1.10	129.8	640.2	0.885
KSC6	0.406	65.20	1.11	96.70	457.3	1.342
KSC17	0.354	69.10	1.01	105.0	487.8	1.571
AFRC1	0.385	141.5	1.50	215.8	1000.0	1.601
AFRC2	0.341	189.4	1.52	297.4	1347.0	1.968
AFRC3	0.327	188.4	1.41	302.6	1344.0	2.459

Turbulence Generation

- Inhomogeneous: statistics vary with altitude
- Turbulence statistics model (Ostashev and Wilson [14])
- Temperature fluctuations

$$\frac{\sigma_T^2(z)}{T_*^2} = \frac{4}{(1-10\zeta)^{2/3}} \qquad \frac{L_T(z)}{z} = 2\,\frac{1\ -7\zeta}{1\ -10\zeta} \qquad (1)$$

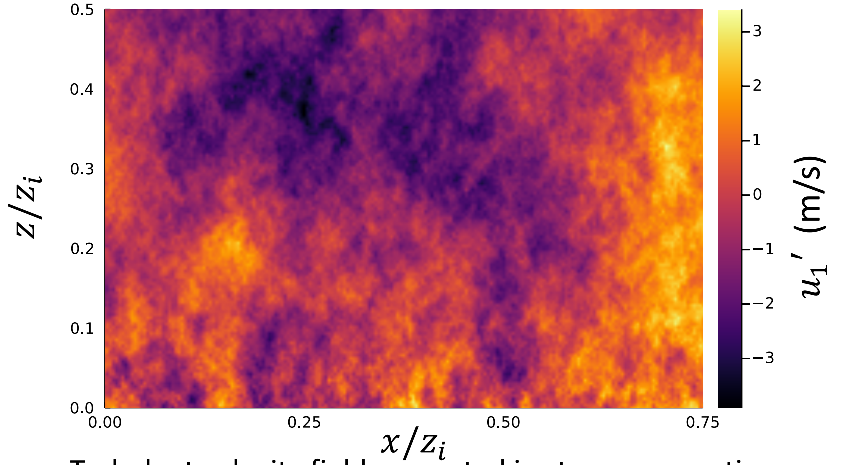
- Shear driven

$$\frac{\sigma_s^2}{u_*^2} = 3.0 \qquad \frac{L_s}{z} = 1.8 \qquad (2)$$

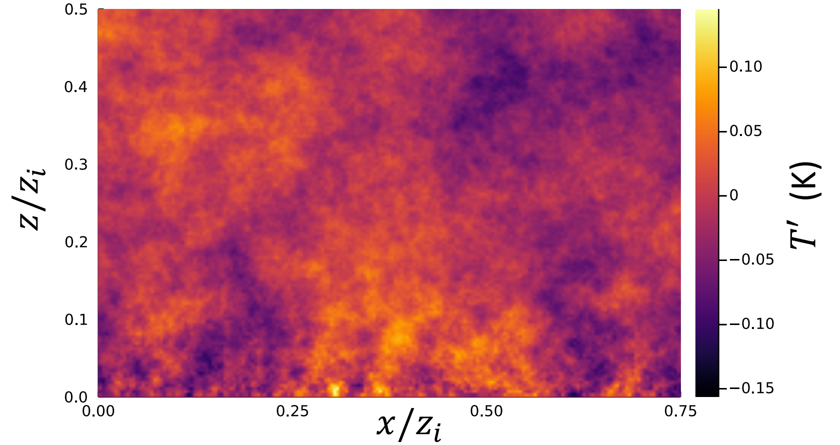
- Bouyancy driven

$$\frac{\sigma_b^2}{w_*^2} = 0.35 \qquad \frac{L_b}{z_i} = 0.23 \qquad (3)$$

- Turbulence generated with Generalized Random Phase Method (see Wilson [15])



Turbulent velocity field generated in strong convection conditions.



Turbulent temperature field generated in strong convection conditions.

Analogous Focal Length of Turbulence

- Index of refraction

$$n = 1 + \frac{u' + c'}{c_0} \tag{4}$$

- In the absence of humidity fluctuations, $c' c_0^{-1} = 0.5 T' T_0^{-1}$
- Effective focal length

$$\ell_f = \frac{C_1}{2} \mathcal{L} \frac{1 + \sigma_u c_0^{-1} + 0.5\, \sigma_T T_0^{-1}}{\sigma_u c_0^{-1} + 0.5\, \sigma_T T_0^{-1}} \tag{5}$$

- $\mathcal{L}/2$ is radius of curvature of equivalent "lens"
- Approximated as variance weighted average of L_T and L_u

$$\mathcal{L} = \frac{(\sigma_u c_0^{-1})^2 L_u + (0.5\, \sigma_T T_0^{-1})^2 L_T}{(\sigma_u c_0^{-1})^2 + (0.5\, \sigma_T T_0^{-1})^2} \tag{6}$$

- Empirical correction: $C_1 = 0.743 + 0.2087 \log(\mathrm{z_i})$

ℓ_f for each ABL setpoint.

	KSC20	KSC1	KSC12	KSC6	KSC17	AFRC1	AFRC2	AFRC3
ℓ_f	3890 m	3540 m	2948 m	2369 m	2763 m	2565 m	2724 m	3014 m

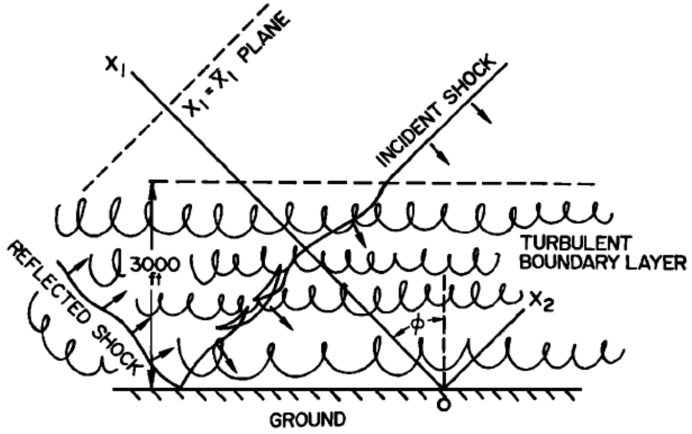


Illustration of turbulence effect on sonic boom wavefront. Reproduced with permission [16]. Copyright 1972.

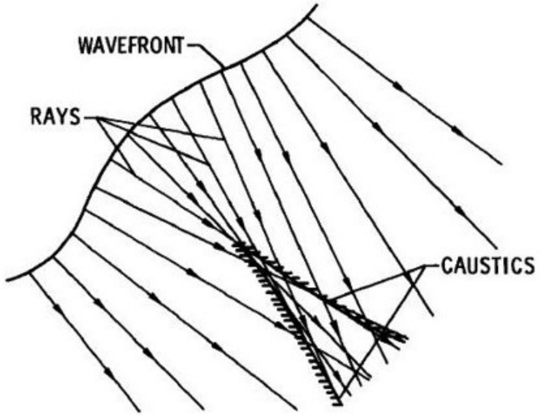
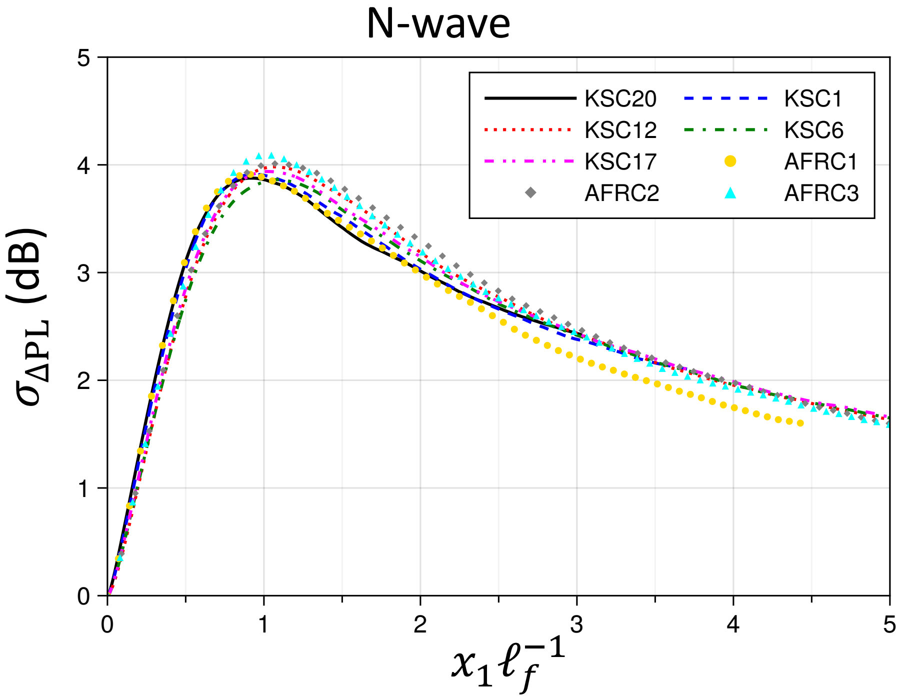


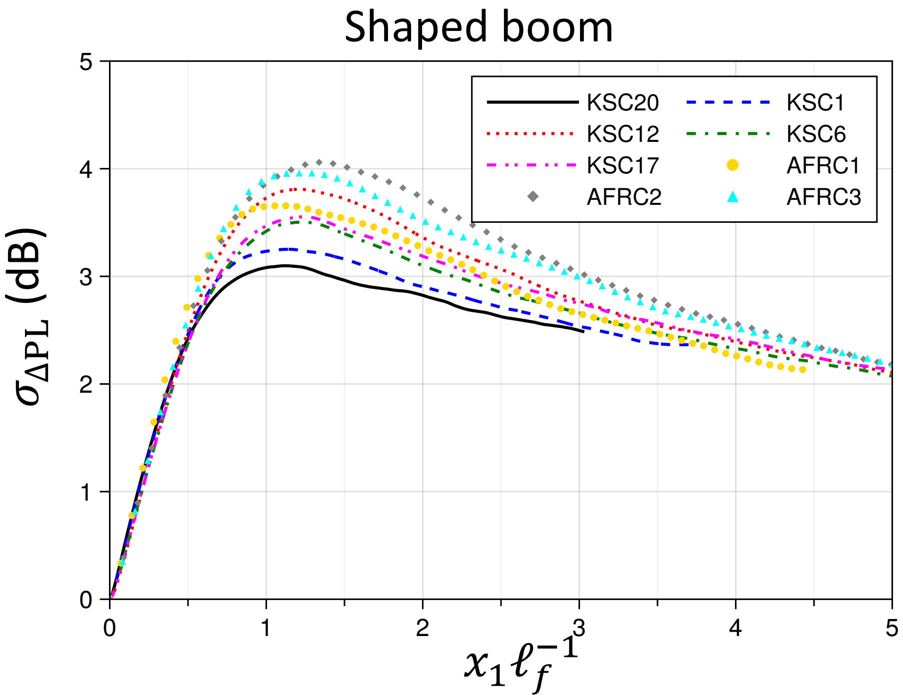
Illustration of caustic formation of a wavefront. Reproduced with permission [16]. Copyright 1972.

Dose Variability

- $\sigma_{\Delta\text{PL}}$ standard deviation of Stevens Perceived level
- Maximum between 3 to 4 dB, similar to WSPR2011 and QSF18
- Linear increase for $x_1 \ell_f^{-1} \leq 0.5$



Standard deviation of PL for the sonic boom N-wave.



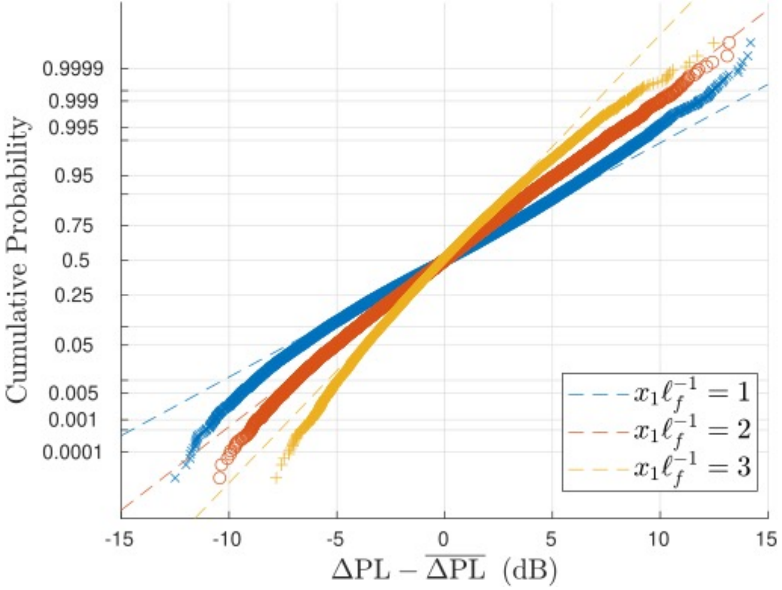
Standard deviation of PL for the shaped boom.

Probability Distributions

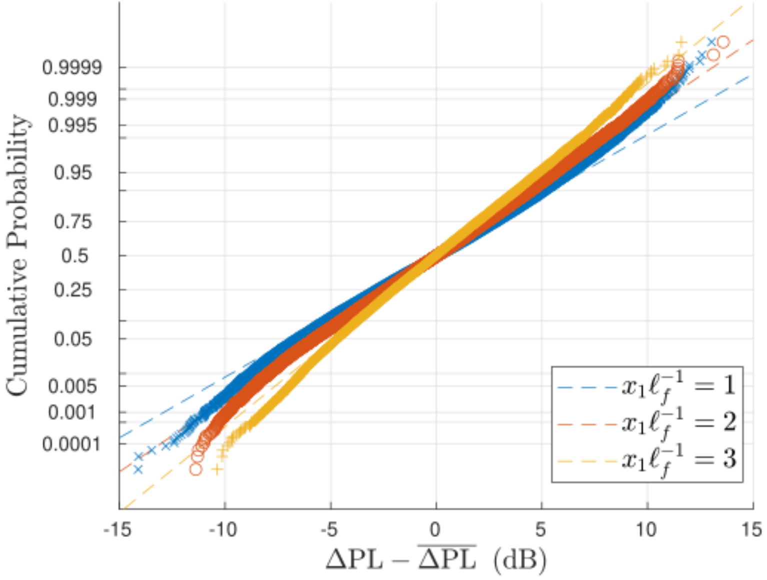
- PL distributions for strong convection
- Dashed line is normal distribution
- Less skewness present in shaped boom
- In general, skewness increases as
  - Lateral distance from flight track increases
  - Turbulence intensity and/or integral scale increases

Characteristics of the PL distributions relative to a normal distribution.

Range	Characteristics
$x_1\ell_f^{-1} \leq 1$	Peaked/Skewed Left
$1 < x_1\ell_f^{-1} < 3$	Normal/Slightly Peaked
$x_1\ell_f^{-1} \geq 3$	Skewed Right


N-wave

PL distributions at three non-dimensional propagation locations for the sonic boom N-wave in conditions of strong convection.


Shaped boom

PL distributions at three non-dimensional propagation locations for the shaped boom in conditions of strong convection.

Approximate Model of PL Distribution

- Normal distribution appears to be a good approximation
- Dose uncertainty model

$$\sigma_{dose\ uncertainty} = \frac{A x_1 \ell_f^{-1}}{B + \left(x_1 \ell_f^{-1}\right)^{\alpha}} \tag{7}$$

- A, B, α are parameters determined by regression to simulation data
- Approximate dose uncertainty distribution

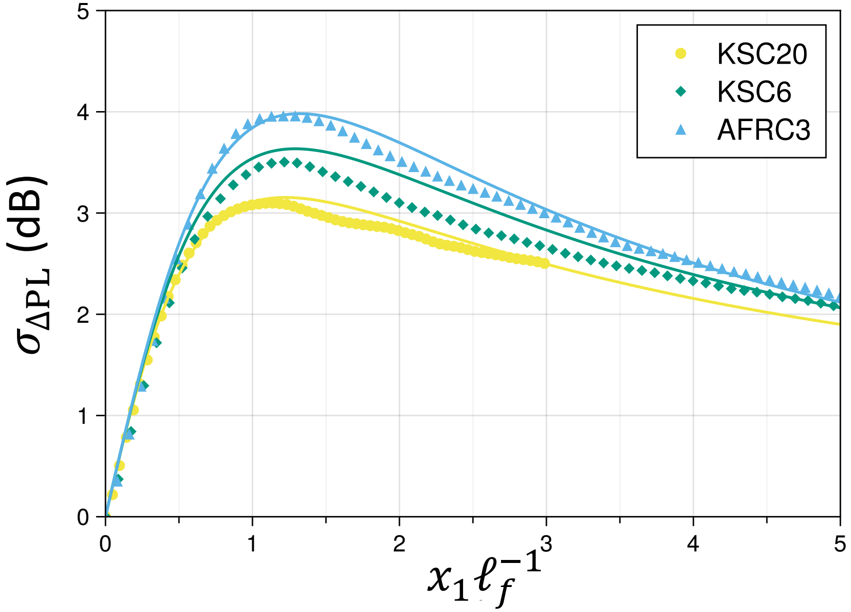
$$f(\Delta\mathrm{PL}) = \frac{1}{\sigma_{\Delta\mathrm{PL}}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\Delta\mathrm{PL} - \mu_{\Delta\mathrm{PL}}}{\sigma_{\Delta\mathrm{PL}}}\right)^2} \tag{8}$$

Approximate Model of PL Distribution

- A, B, α can all be related to $\log(-z_i L_o^{-1})$
- Parameters for X-59 PL, according to regression

$$A \approx 6.32\, B$$
$$B \approx 0.94 + 0.25 \log(-z_i L_o^{-1})$$
$$\alpha \approx 1.68 + 0.94 \log(-z_i L_o^{-1})$$

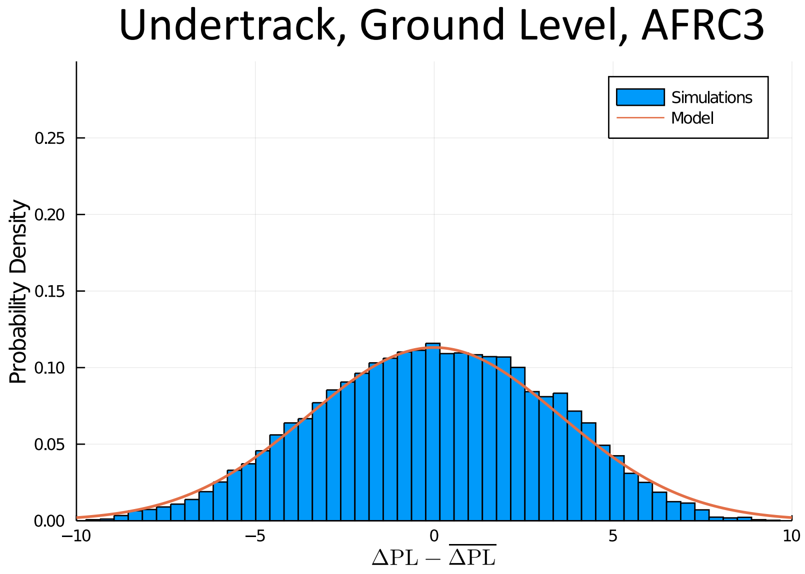
- Will change depending on waveform and metric
- Model approximates $\sigma_{\Delta\mathrm{PL}}$ to within ± 0.25 dB
- Not valid beyond $x_1 \ell_f^{-1} > 5$



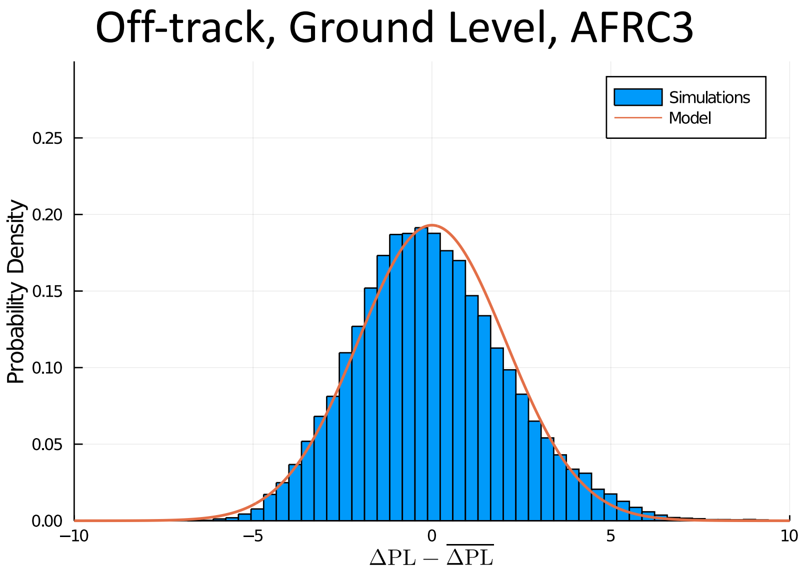
Model of $\sigma_{\Delta\mathrm{PL}}$ compared to simulation results for the shaped boom at three different ABL setpoints.

Comparison to Undertrack PL Simulations

- PDF approximates distributions observed both undertrack and off-track
- Does not capture skewness present in strong convection conditions and large lateral distances from flight path



Probability density function model compared to simulation data at ground level for the shaped boom and ABL setpoint of AFRC3. Elevation angle of 35 degrees.



Probability density function model compared to simulation data at ground level for the shaped boom and ABL setpoint of AFRC3. Elevation angle of 5 degrees.

Summary

- Sonic boom simulations performed to estimate dose uncertainty due to turbulence
- Key outcomes
  - Parameter to collapse $\sigma_{\Delta \mathrm{PL}}$ for $x_1 \ell_f^{-1} \leq 0.5$
  - Model for dose uncertainty distributions
  - In some regions of the sonic boom carpet, normal distribution of dose uncertainty may not be appropriate
- Possible avenues forward
  - Use PCBoom in combination with meteorological data to estimate $x_1 \ell_f^{-1}$
  - Compare dose uncertainty model to measurements

Questions?

Thank you

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