

Turbulence effects on shaped booms: propagation simulations using KZKFourier

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Turbulence effects on shaped booms

1. 4pPA1 Central composite design of modeled atmospheric turbulence parameters for sonic boom propagation

William Doeblor, Peter Parker, Robert Downs, Alexandra Loubeau

2. 4pPA2 Propagation simulations using KZKFourier

Robert Downs, Michael Barzach, Will Doeblor, Peter Parker, Alexandra Loubeau, Joel Lonzaga

3. 4pPA3 Finite impulse response filter development

Robert Downs, Michael Barzach, Jacob Klos, Joel Lonzaga, William Doeblor, Peter Parker, Alexandra Loubeau

Outline

- Background and motivation for modeling turbulence effects
- Methodology: Penn State KZKFourier code and simulation matrix design
- Execution of KZKFourier simulations
- Results and empirical model
- Further work

Background and motivation

- Atmospheric turbulence introduces large variations in ground levels in a way that is not feasibly deterministic
- Simulations by Penn State (Stout and Sparrow) of F-18 sonic booms (N waves) used to develop filters for estimating turbulence effects in PCBoom
- Limitations of SonicBAT N-wave filters
 - Turbulence parameter limits
 - Apparent unsuitability for use with shaped boom waveforms

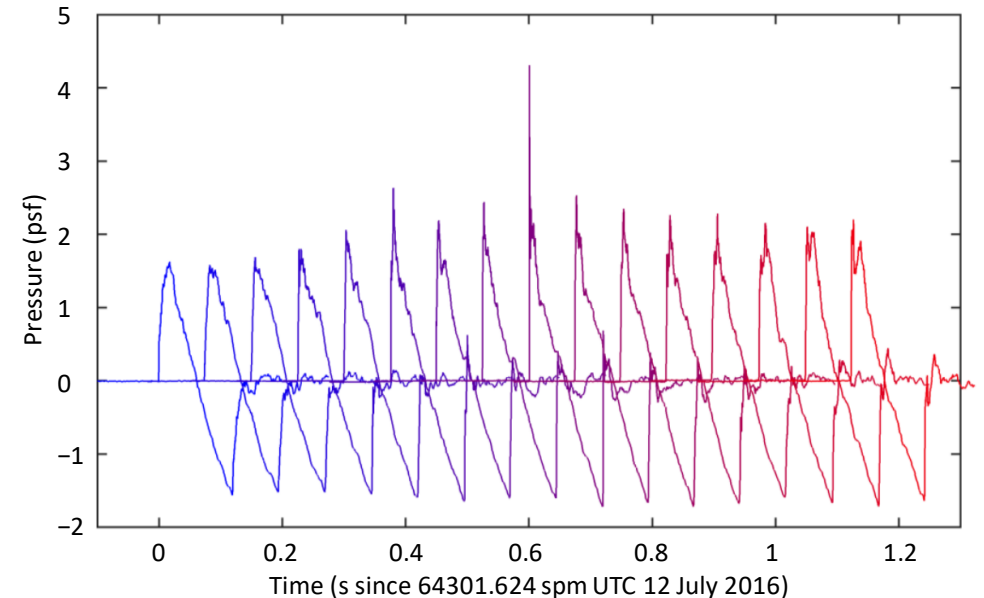


Figure 48. Recording of BAT004 on primary array.
Signatures overlaid on same plot with channel 1 starting at left in blue through channel 16 at right in red.

Source: NASA/CR-2020-220509 (2020)

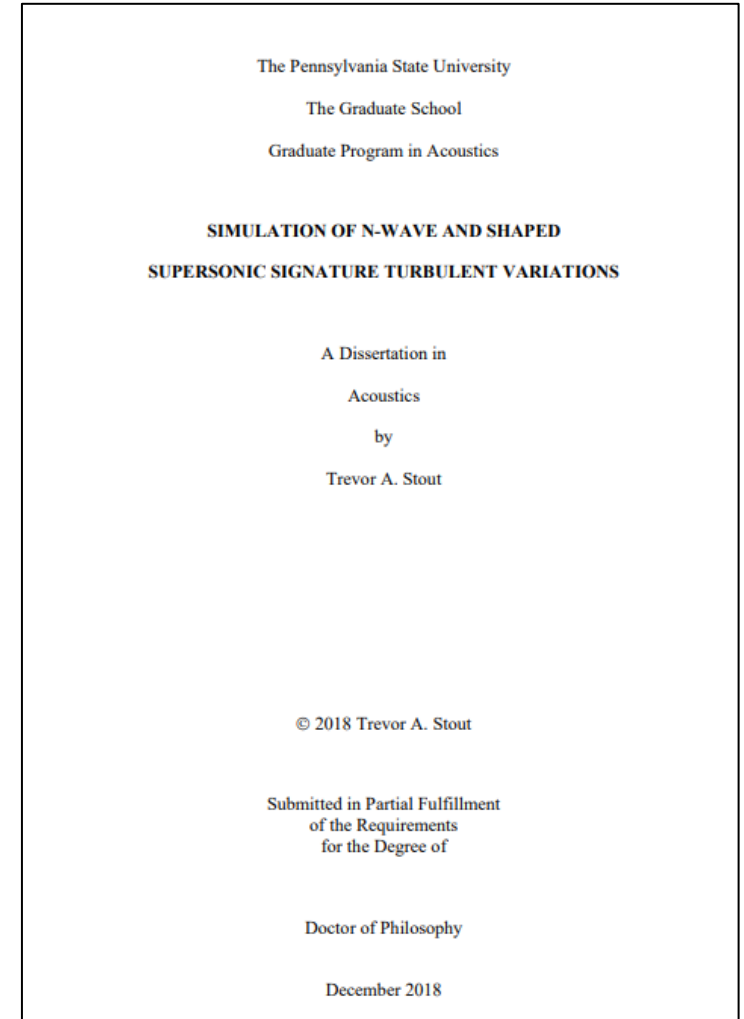
Methodology: KZKFourier code

- KZKFourier code developed by Penn State in conjunction with SonicBAT
- Propagation model is the KZK equation
 - Models diffraction effects, thermoviscous absorption, molecular relaxation, nonlinearity, and includes temperature and velocity fluctuations
- Turbulence modeled as fields of velocity and temperature fluctuations
 - Turbulence spectra follow forms given by Ostashev and Wilson model
 - KZKFourier code represents spectra as sums of Fourier modes with random phase and direction

Stout, T.A., "Simulation of N-Wave and Shaped Supersonic Signature Turbulent Variations," Ph.D. Dissertation, The Pennsylvania State University, State College, PA, 2018

Stout, T.A., Sparrow V.W., and Blanc-Benon, P. "Evaluation of numerical predictions of sonic boom level variability due to atmospheric turbulence", J. Acoust. Soc. Am. 149 (5), May 2021

Stout, T.A. and Sparrow V.W., "Atmospheric turbulence effects on shaped and unshaped sonic boom signatures", J. Acoust. Soc. Am. 151 (5), May 2022



Methodology: simulation regions

Steady level flight at altitude 52,026 ft, $M = 1.4$

(not to scale)

Ambient atmosphere

- Temperature and pressure profiles from ICAO 7488/3
- RH profiles from ISO 5878 Addendum 2 - 50 deg N annual median up to 8 km, ISO 9613-1 Annex C above 8 km
- No wind

ABL (varies)

7-factor simulation design:
 $ABLH, u_*, w_*, T_*, RH, p_0, T_0$

No turbulence

Vector and scalar
turbulence

Ground

(varies, based on surface pressure)

X-59 C612A nearfield pressures

PCBoom Enhanced Burgers

KZKFourier

Clean waveform

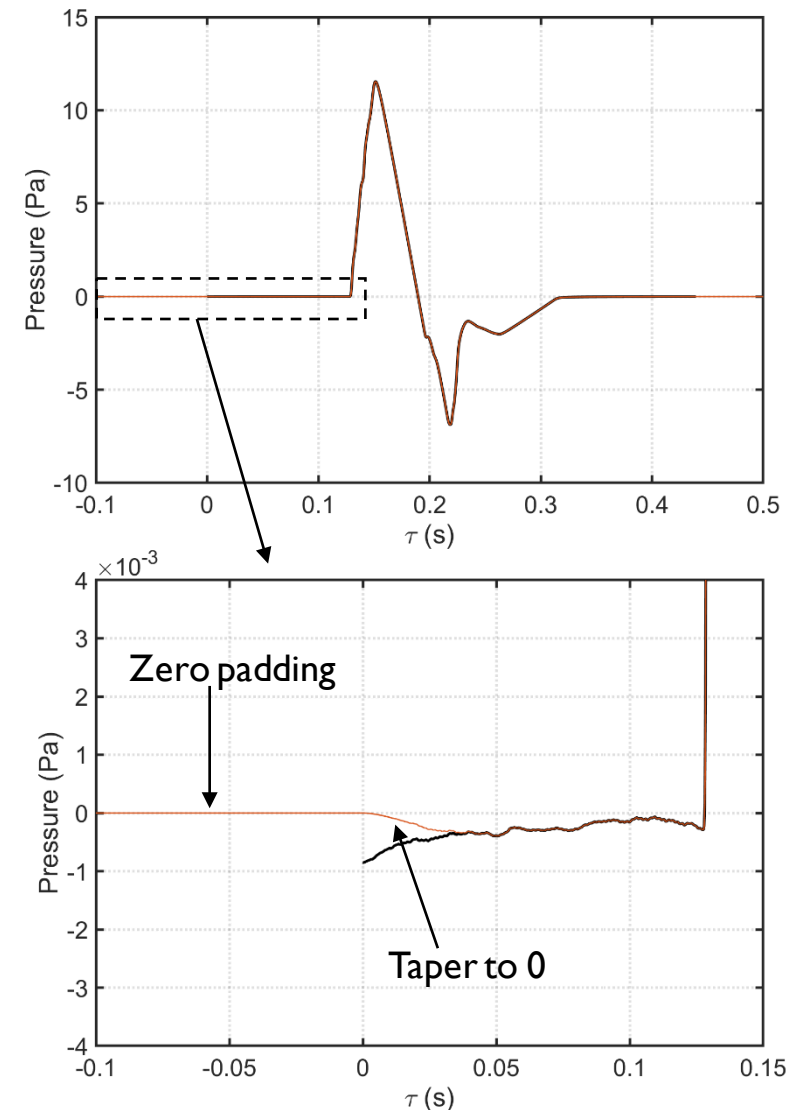
PCBoom Enhanced Burgers

KZKFourier

Turbulized waveforms

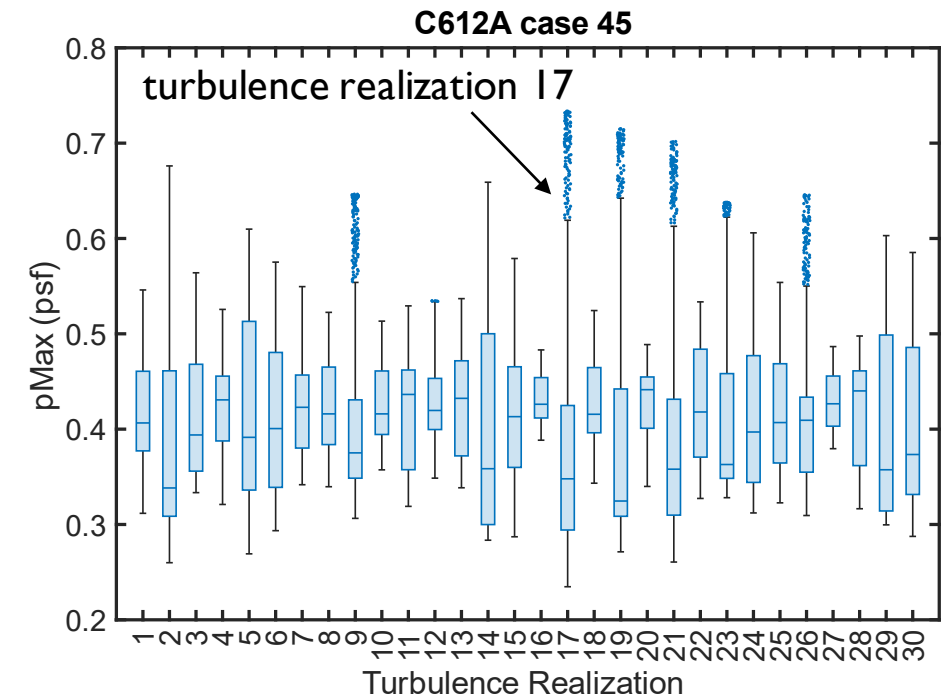
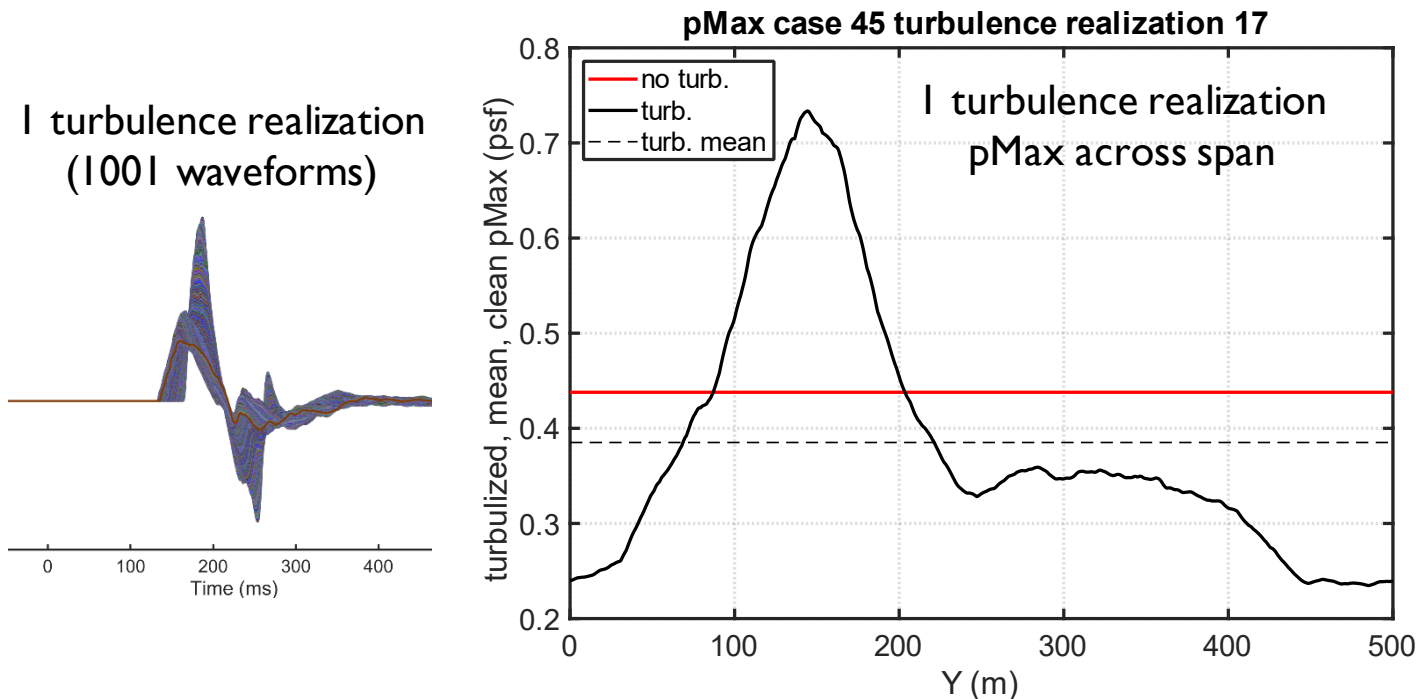
Execution of KZKFourier simulations

- High resolution near-field pressure data propagated to top of ABL (reflection factor 1.0) using PCBoom 7.2 enhanced Burgers solver
- Preparation of waveform at top of ABL:
 - Waveform resampled to uniform 64 kHz
 - 10% Hann-window taper applied at each end
 - Tapered waveform zero-padded at each end



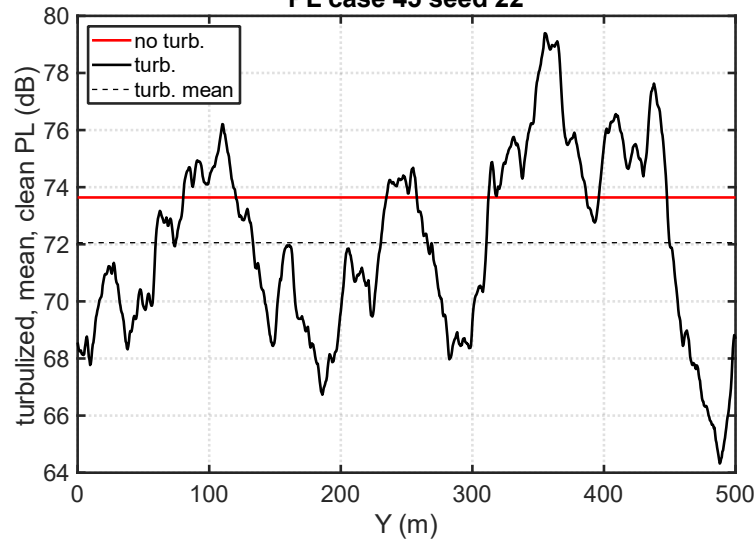
Execution of KZKFourier simulations

- 45 cases $\times$ 1 turbulence realization $\approx$ 1128 hours, 3 cores/simulation
- For each of 45 cases ran 30 simulations using different turbulence realizations

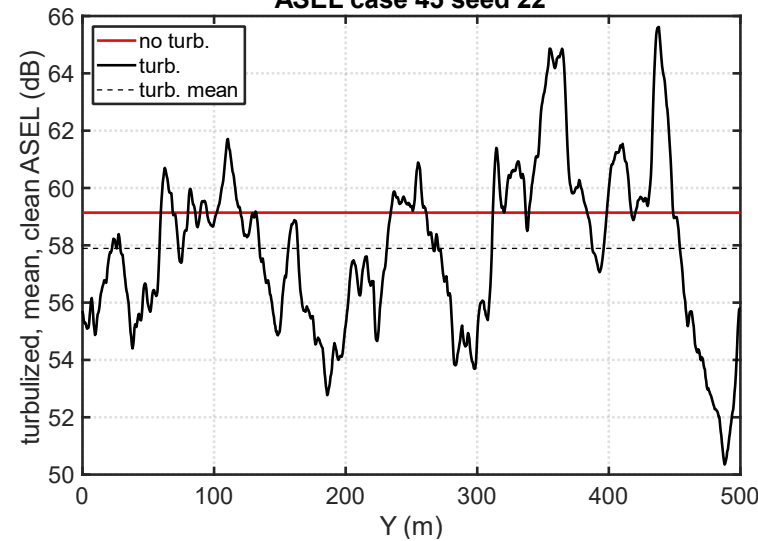


Results: example ground metrics for one simulation

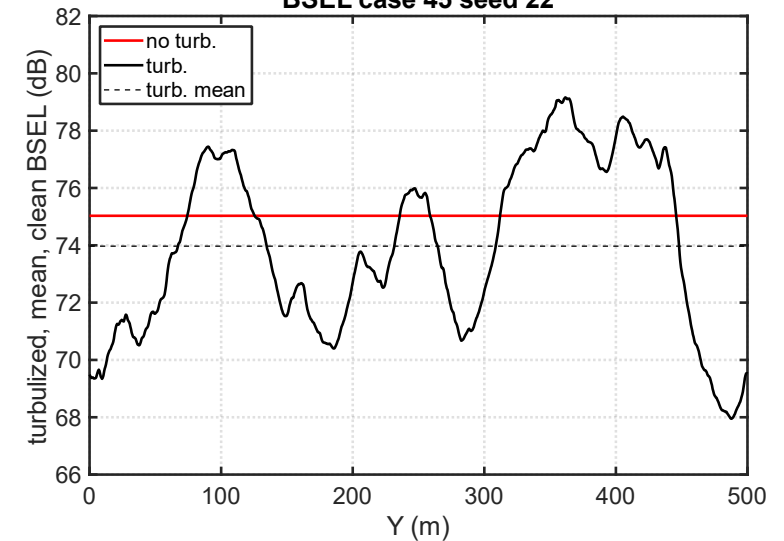
PL case 45 seed 22



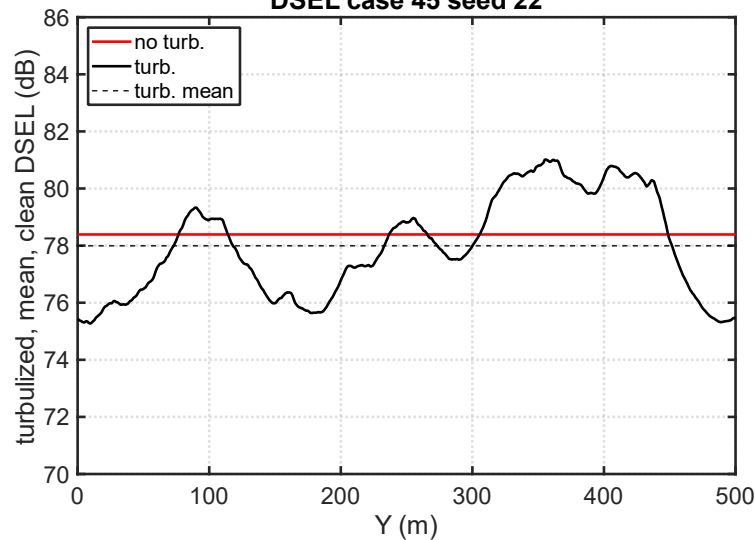
ASEL case 45 seed 22



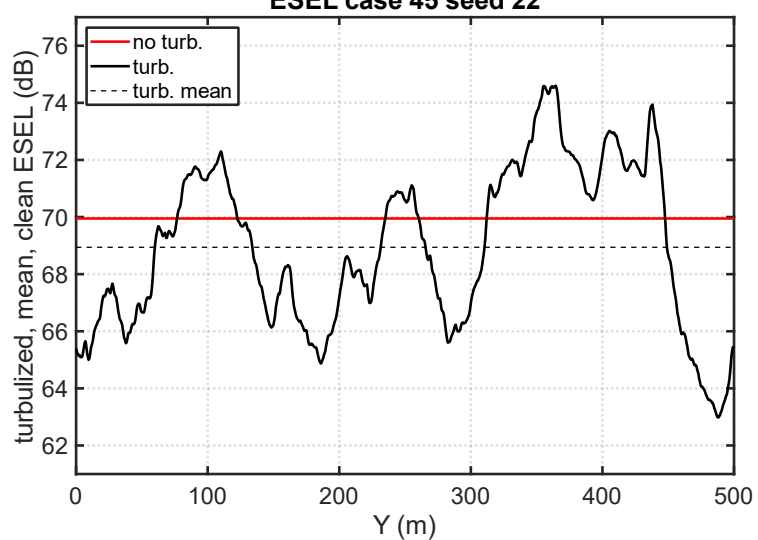
BSEL case 45 seed 22



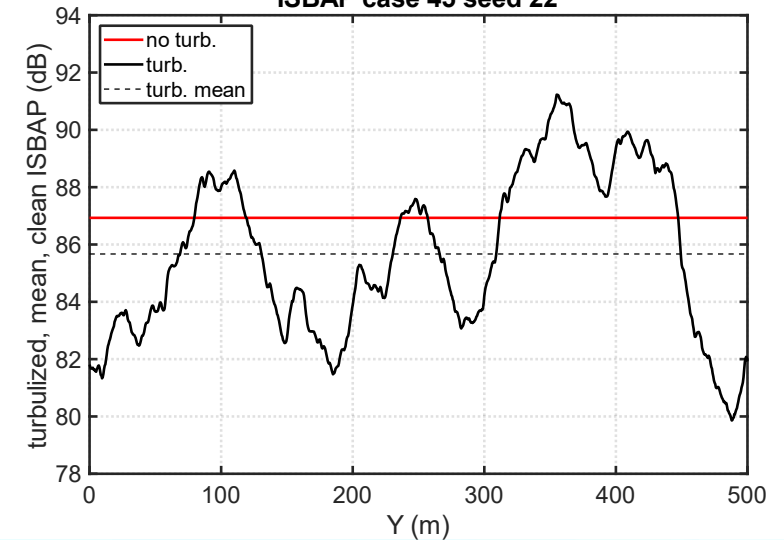
DSEL case 45 seed 22



ESEL case 45 seed 22

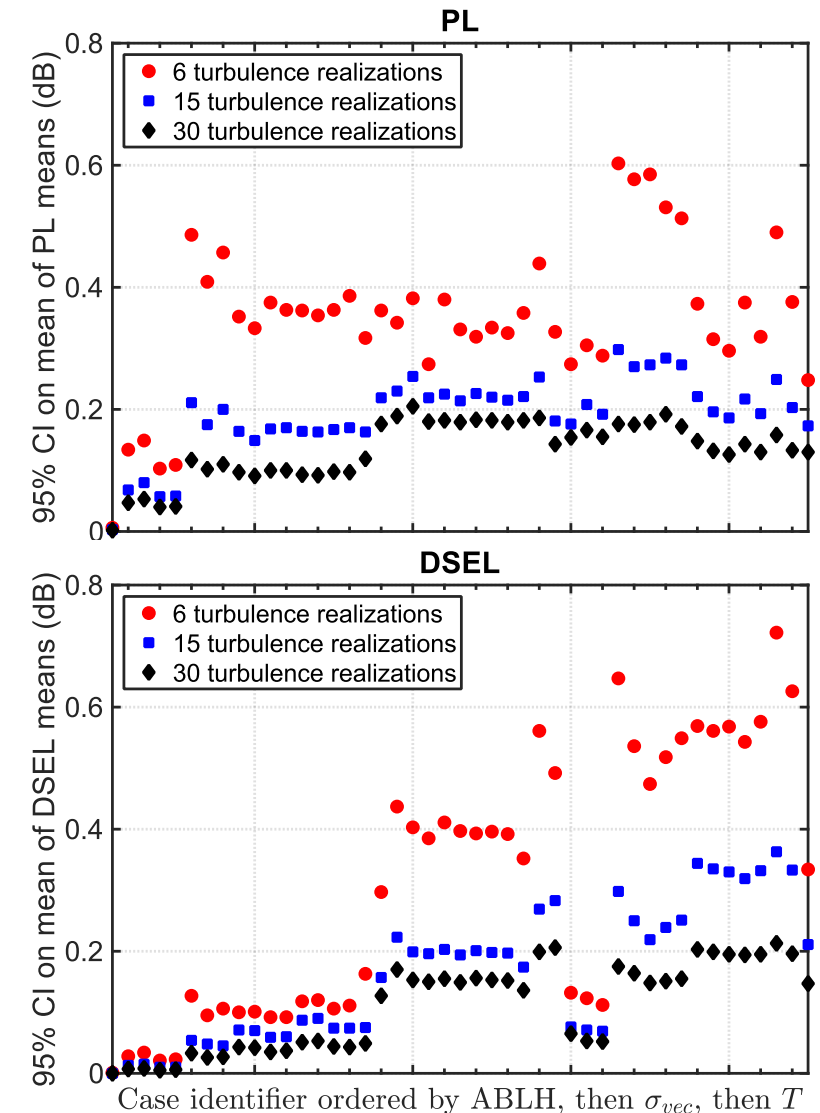


ISBAP case 45 seed 22



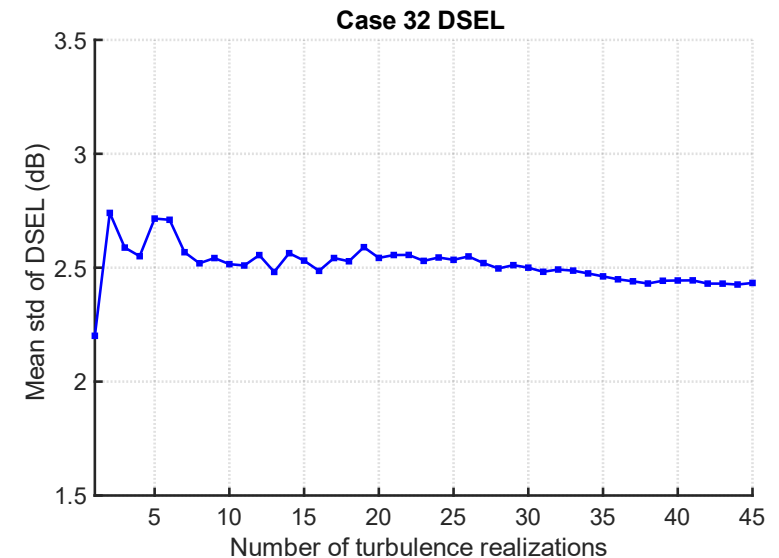
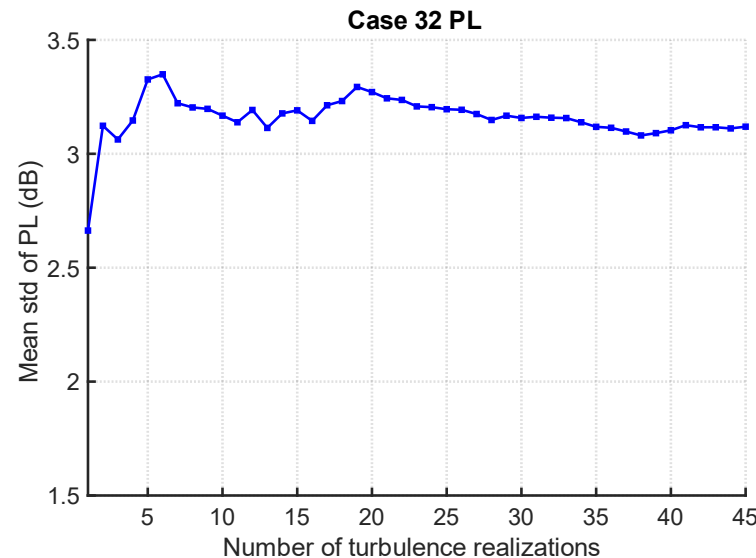
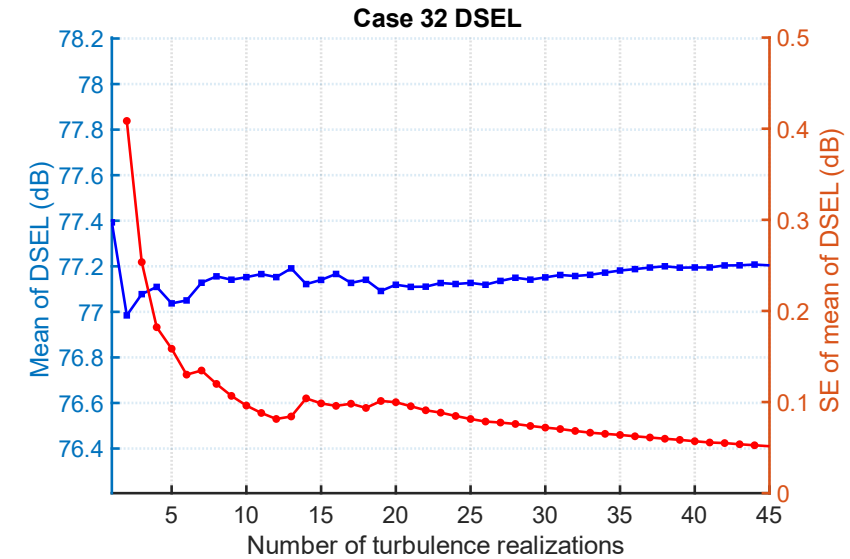
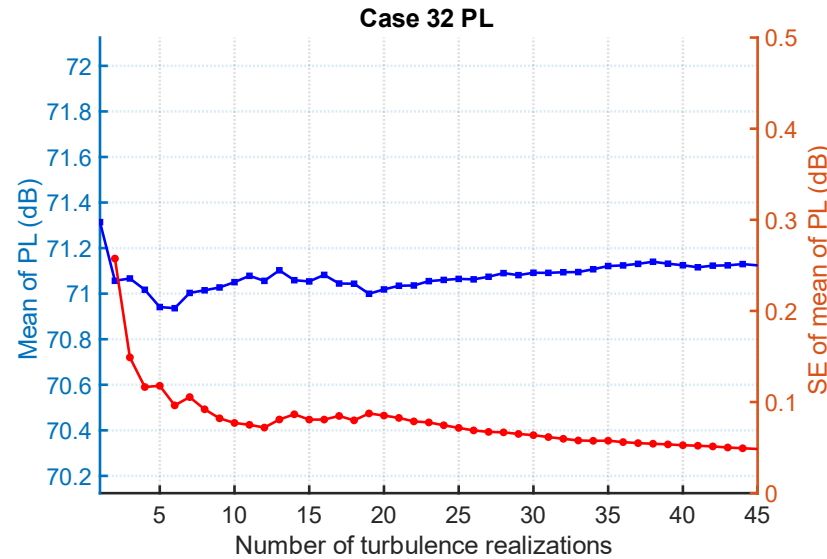
Results: evaluating convergence

- Goal: determine how many turbulence realizations are needed to ensure set of results are representative of underlying distribution
- Approach:
 - For each of 30 turbulence realizations (1001 – 2001 ground waveforms) calculate mean metrics
 - For sets of turbulence realizations, calculate
 - 95% confidence intervals on mean of mean levels
- Using 30 turbulence realizations produces 95% CI < 0.22 dB for all metrics
 - Max 95% CI = 0.20 dB for PL, 0.17 for ASEL
 - Shorter propagation distance → smaller confidence interval for same number of turbulence realizations



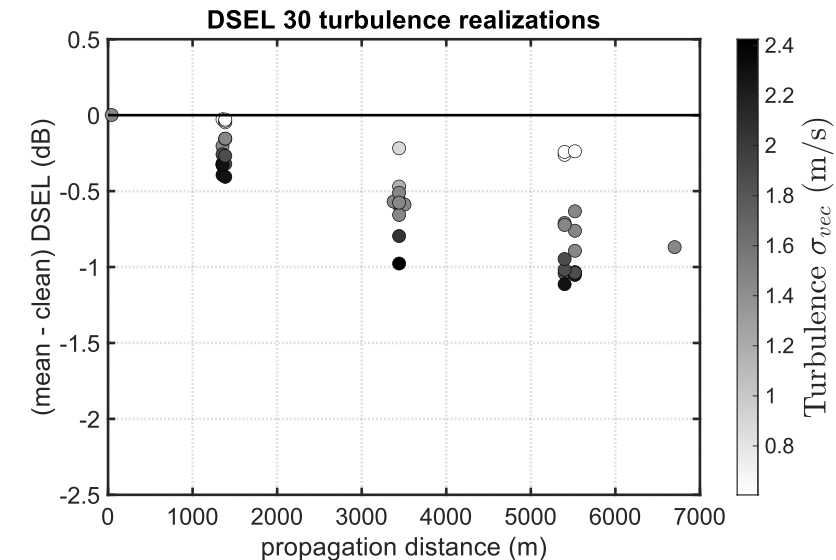
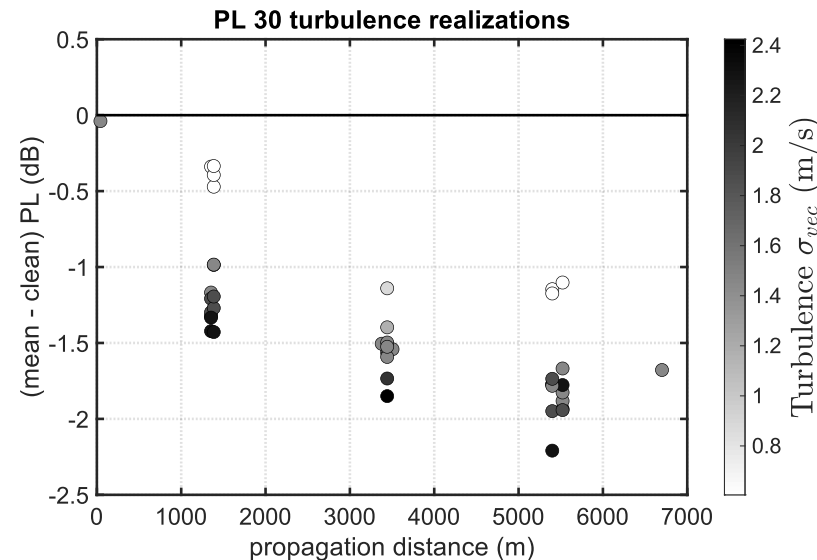
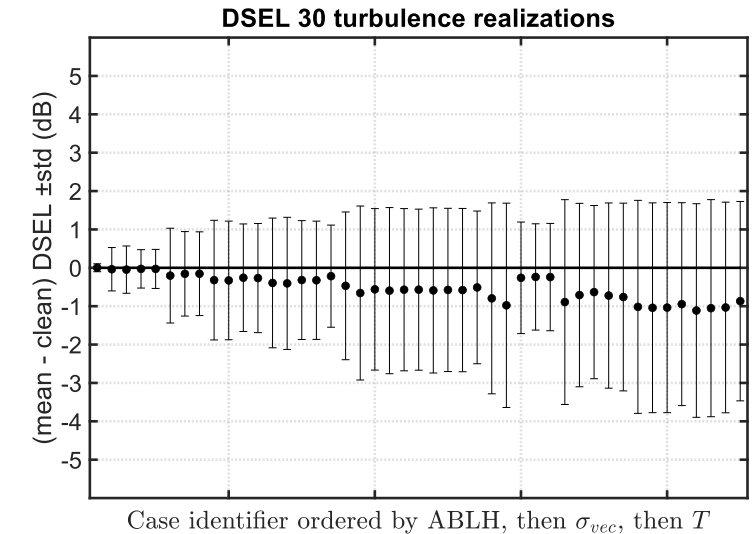
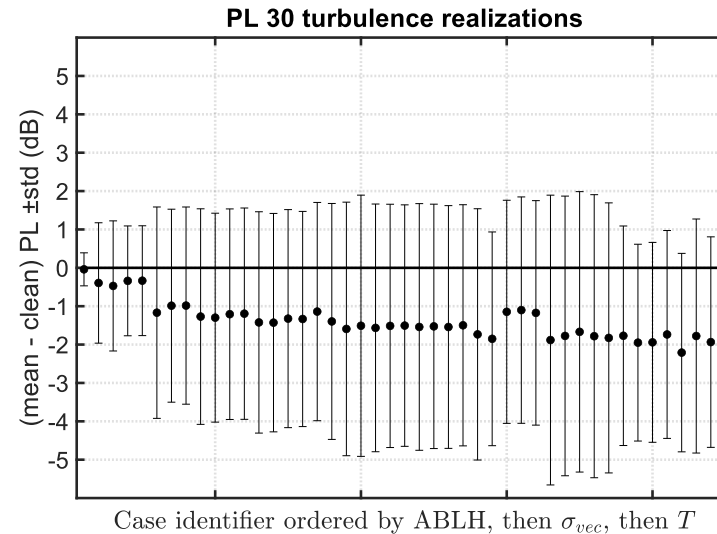
Results: cumulative means and standard deviations

- For sets of turbulence realizations, calculate
 - cumulative mean of turbulence realization means
 - cumulative mean of turbulence realization standard deviations
- Two example cases run with 45-60 turbulence realizations
- Metric means and standard deviations fairly stable with 30 realizations



Results: mean metrics and σ relative to no-turbulence levels

- Metric means and standard deviations generally correlate with propagation distance: longer propagation $\rightarrow$ larger reduction in mean level compared with no-turbulence level
- For all cases considered, mean metric levels $<$ no-turbulence metric levels within standard error of the mean



KZKFourier results: empirical models

- Empirical model analysis applied to simulation results
- Motivations:
 - Identify relative sensitivity of metrics to simulation factors
 - Quality check – results should make sense in the context of physical relationships and related modeling work

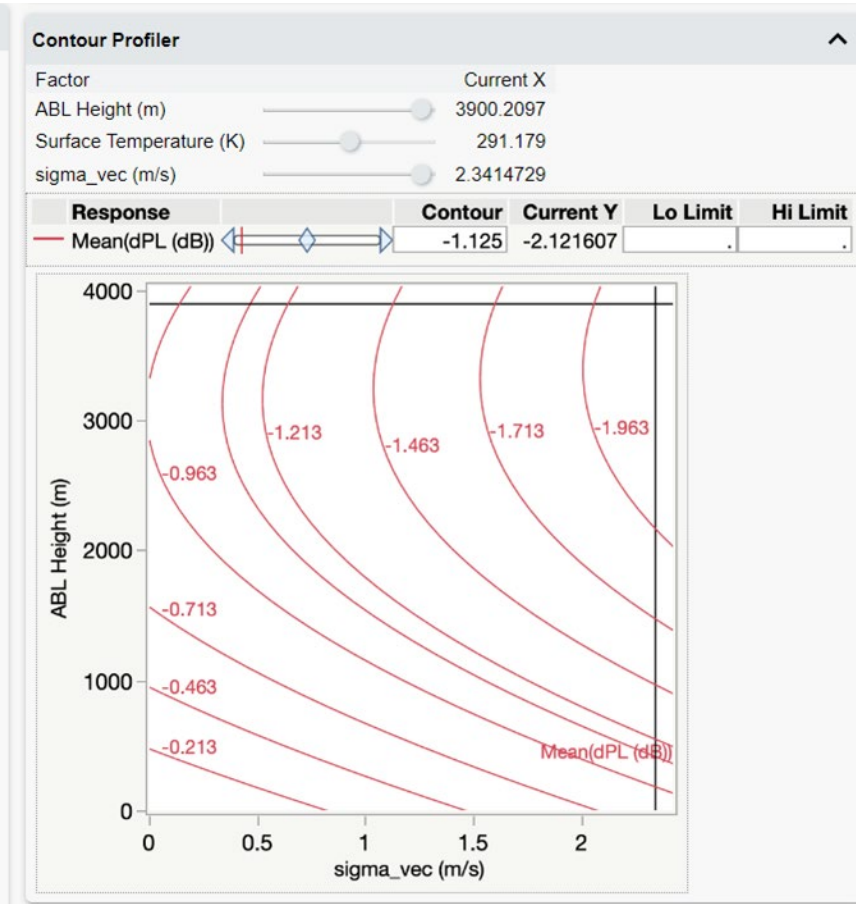
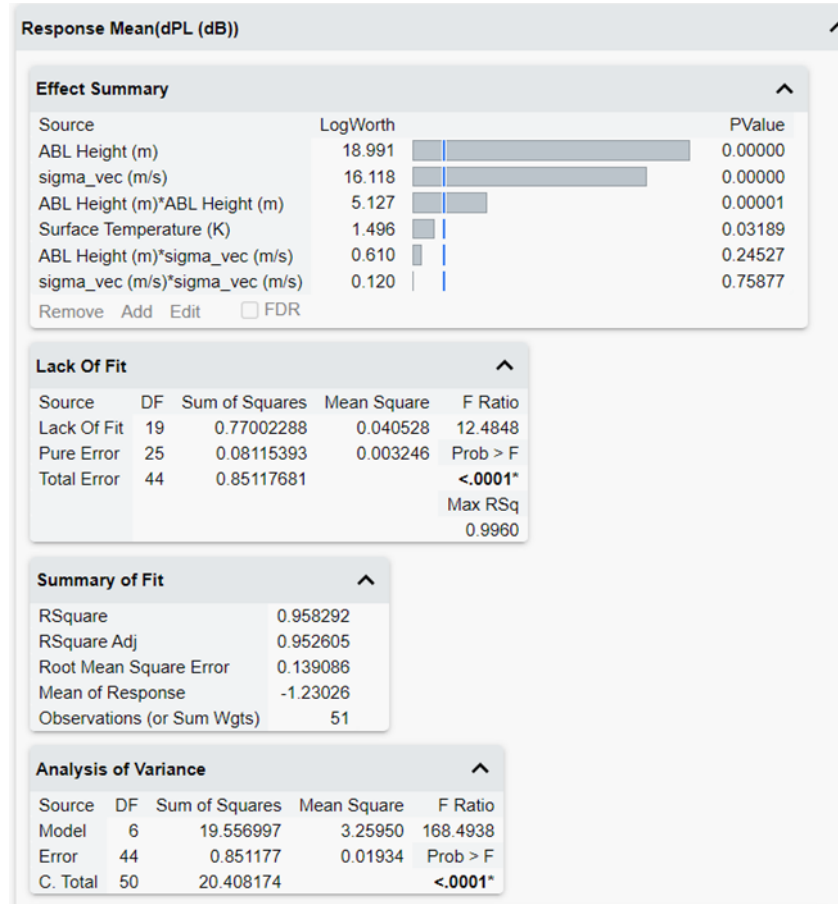
- Multiple models tested using PL metric levels and

$$dPL = PL_{clean} - PL_{mean}$$

- Example:
 - Model 3 fit to means using 28 dPL per case
 - Added physics-based anchor points to 45 cases
 - Anchor points: synthetic points with ABL height = 0, $\sigma_{vec} = 0$, and surface temp = 291 K

KZKFourier results: empirical models

- Model results show that the most significant factors are:
 - ABL height
 - σ_{vec}
 - Surface temperature
- Increasing ABL height or σ_{vec} generally reduces mean PL



Concluding observations and further work

- Propagation simulations executed for 45 sets of conditions, each using 30 realizations of randomly generated numerical turbulence
 - Pooling results from 30 turbulence realizations produces 95% CI < 0.22 dB for all metrics
 - Max 95% CI = 0.20 dB for PL, 0.17 for ASEL
- Shorter propagation distance → smaller confidence interval for same number of turbulence realizations
- Metric means and standard deviations generally correlate with propagation distance: longer propagation → larger reduction in mean level compared with no-turbulence level
- For all cases considered, mean metric levels < no-turbulence metric levels within standard error of the mean
- Further work using results of KZKFourier simulations:
 - 4pPA3: Shaped boom FIR filter development and testing using KZKFourier results