

Turbulence effects on shaped sonic booms using finite impulse response filter banks

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Turbulence effects on shaped sonic booms

1. **1pPA3** Tools for simulating atmospheric turbulence effects on supersonic X-59 acoustic pressure signatures

Alexandra Loubeau, Robin Downs, Joseph Fletcher, Jacob Klos, William Doeblner

2. **1pPA4** Turbulence effects on shaped sonic booms using finite impulse response filter banks

Joseph Fletcher, Robin Downs, Jacob Klos, William Doeblner, Alexandra Loubeau, Joel Lonzaga

3. **1pPA5** Using finite impulse response filters to model turbulence effects across a range of propagation distances

Robin Downs, Joseph Fletcher, Jacob Klos, William Doeblner, Alexandra Loubeau

Outline

- Introduction and motivation for Finite Impulse Response (FIR) filter approach to estimating turbulence effects on sonic booms
- New ensemble* FIR filters concept vs regular FIR filters concept
- Filter testing:
 - Ensemble filters circular check
 - Filter verification cases
 - Comparison of results among N-wave filters, regular shaped boom filters, and ensemble shaped boom filters
- Summary

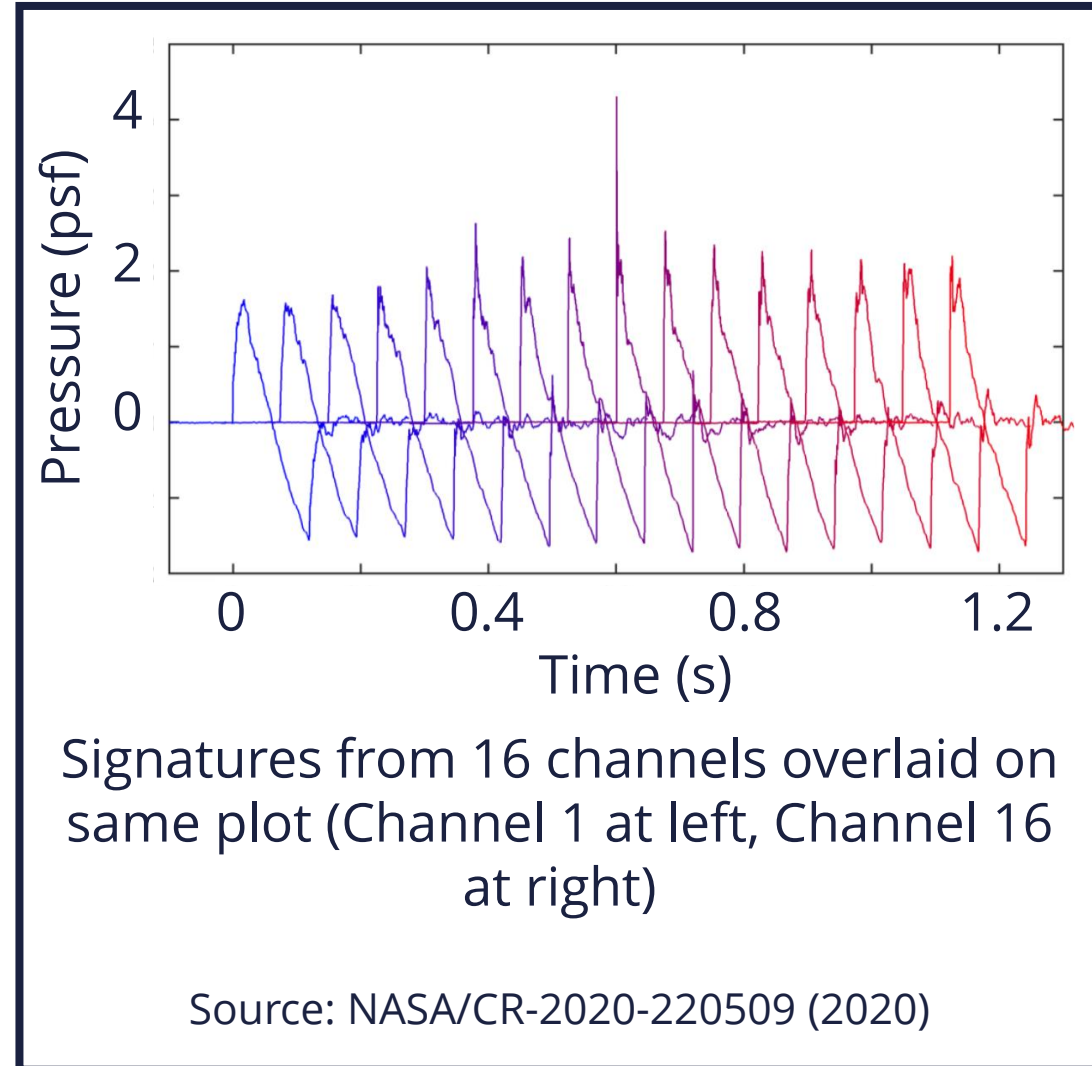
Ensemble shaped boom filters are available in PCBoom version 7.5

Software available on request from NASA: <https://software.nasa.gov/software/LAR-19926-1>

*Ensemble filters were previously referred to as enhanced filters in the PCBoom Version 7.5 User's Guide

Motivation for modeling turbulence effects

- Prediction of large variations in ground waveforms and metric levels introduced by atmospheric turbulence requires time-intensive calculations
- Concept of using a filter function to quickly model atmospheric turbulence effects in the atmospheric boundary layer (ABL) was demonstrated by Locey and Sparrow (2007)
- Assumptions:
 - Turbulence effects limited to within ABL
 - Turbulence and nonlinearity in ABL can be accounted for separately
 - Second-order effect of the two combined can be neglected



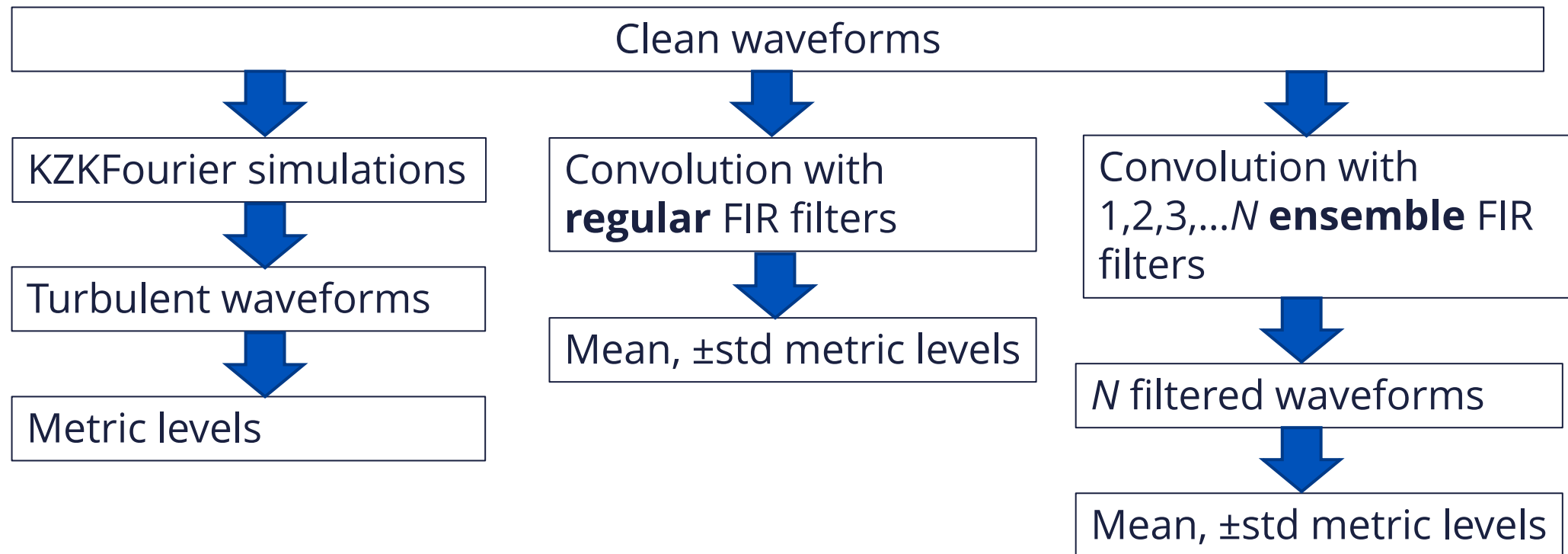
Regular FIR filters

- Finite Impulse Response (FIR) filters were generated through matrix deconvolution [1] of non-turbulent (clean) and turbulent shaped boom ground waveforms
- Ground waveforms generated using PCBoom to propagate from the flight vehicle nearfield to the top of the ABL, then KZKFourier to propagate to the ground
- FIR filters convolved with novel clean ground waveforms to produce output waveforms with turbulence effects (i.e. “turbulized” waveforms)
- Initial FIR filter concept developed by PSU uses a single filter to represent a specific loudness metric statistic (e.g., mean, mean + 1 std, or mean – 1 std)
- Two limitations to the regular FIR filter concept
 1. FIR filters limited to specific metric and statistic
 2. No guarantee that filter output will lie at same point on distribution of all loudness levels when applied to a novel waveform

[1] L. L. Locey, "Sonic Boom Postprocessing Functions to Simulate Atmospheric Turbulence Effects," Ph.D. Dissertation, The Pennsylvania State University, State College, PA, (2008).

Ensemble FIR filter concept

- Perform hundreds or thousands of convolutions with bank of filters and calculate loudness metric statistics using the set of all turbulized waveforms
- Expected to be more accurate than regular FIR filter concept but requires more computation time



Generation of FIR filter sets

- Filter sets generated for 45 different turbulence condition cases that varied seven factors following a Central Composite Design (CCD):

Parameter	Values used in cases
ABL height ABLH	24, 797, 2030, 3262, 4035 m
Friction velocity u_*	0.03, 0.21, 0.50, 0.80, 0.98 m/s
Mixed-layer velocity scale w_*	0.10, 0.82, 1.96, 3.11, 3.83 m/s
Surface-layer temperature scale T_*	0.21, -0.21, -0.87, -1.54, -1.96 K
Surface relative humidity RH	5, 23, 52, 82, 100%
Surface pressure p_0	0.83, 0.87, 0.93, 0.98, 1.02 atm
Surface temperature T_0	256, 269, 291, 313, 327 K

- Number of filters N is case-dependent such that standard error of the mean SEM = 0.1 dB; low signal variability requires fewer filters
 - $N = 28$ for case with lowest ABL height
 - $N = 1426$ for case with high intermediate turbulence and ABLH = 3262 m
 - Average $N = 880$, total $N = 39,601$

Filter testing: circular check

- How well do ensemble FIR filtered waveform loudness metrics match the loudness metrics for the KZKFourier turbulent waveforms used in the filter development?

- Mean absolute error calculated as:

Mean(| filtered waveform metrics –

KZKFourier turbulent waveform metrics |)

- Values in table represent average error across all 45 cases

- Filter length:

- First set of filters used 130 ms length
- Filter length increase to 230 ms more accurately reproduced loudness metric levels from large sets of waveforms

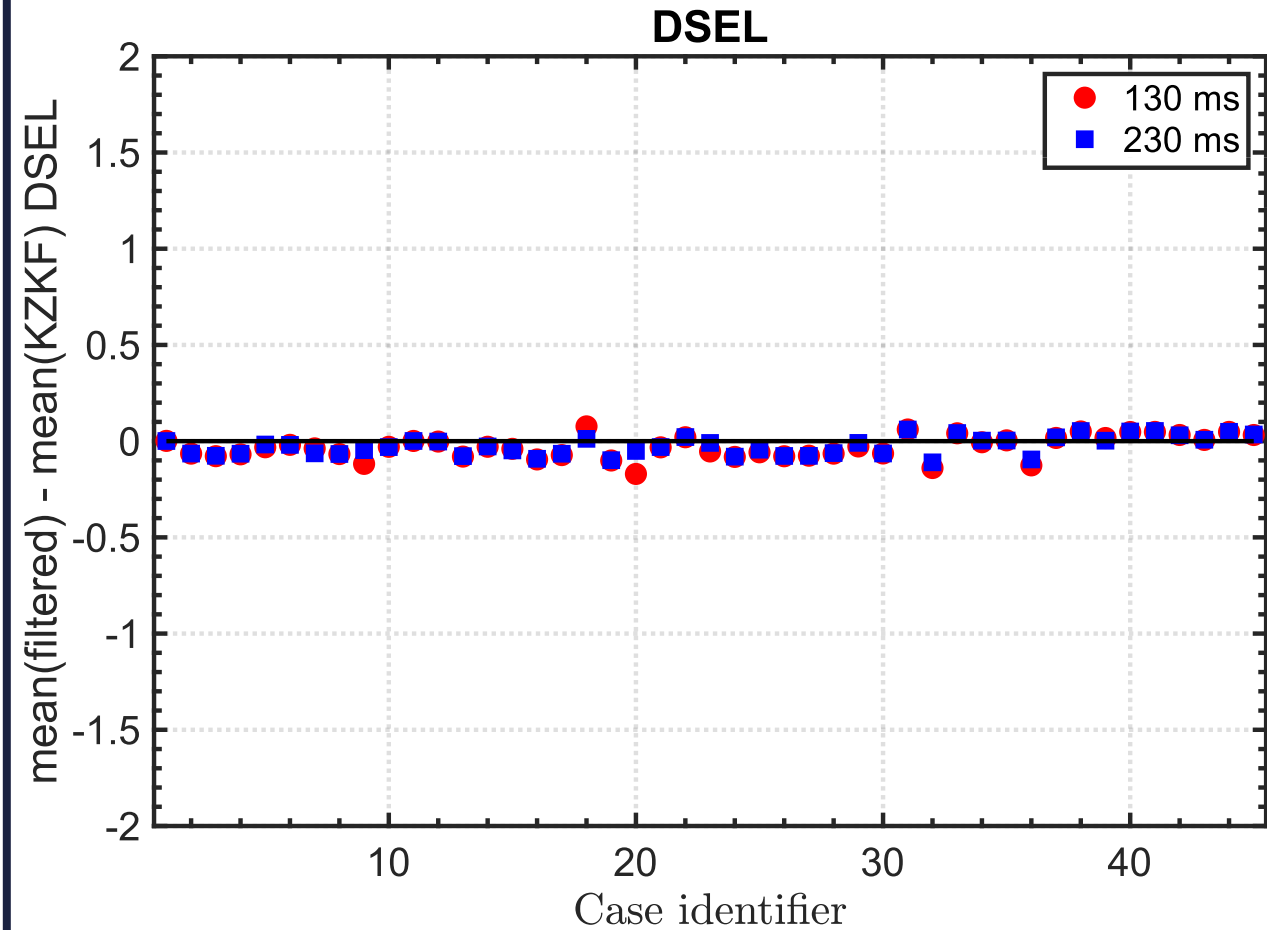
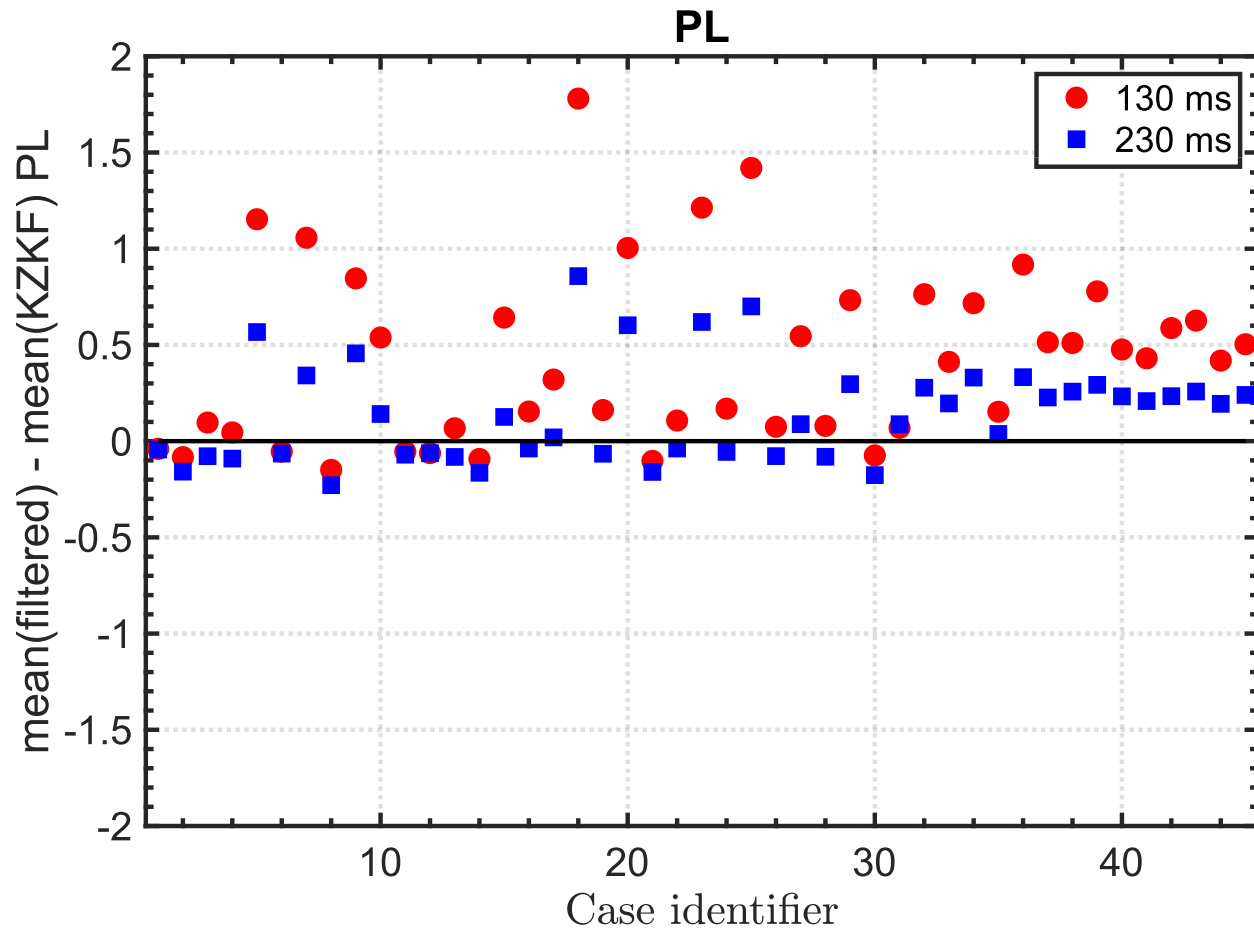
- Application of filters

- Timing test showed filter convolution time increases approximately proportional to filter length increase

Filter circular check:
Overall mean absolute
errors (dB)

	130 ms	230 ms
PL	0.56	0.25
ASEL	0.51	0.16
BSEL	0.11	0.03
DSEL	0.06	0.02
ESEL	0.20	0.05
ISBAP	0.34	0.18

Filter accuracy: metric means



Filter testing: verification cases

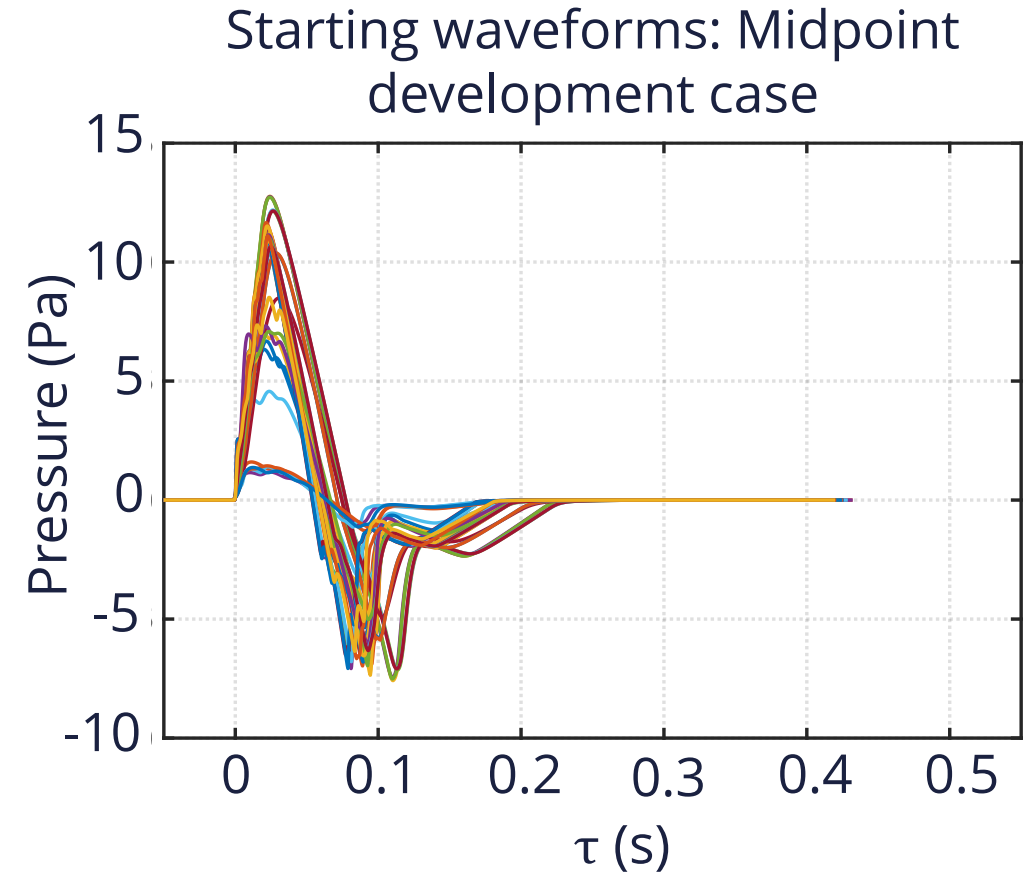
- How does the ensemble FIR filter method perform compared to the other FIR filter designs?
- Additional KZKFourier simulations were run to obtain novel clean waveforms as input to filter methods and turbulent waveforms to use as benchmark. Novel clean waveforms obtained by:
 - using different atmospheric conditions between nearfield and top of ABL, and
 - using nearfield pressures from different azimuth angles
- For atmospheric conditions, 12 ambient conditions were selected to represent median and extrema of 19 US locations $\times$ 365 days $\times$ 4 headings [2]
- For azimuth angle variation, 3 conditions were selected with angles corresponding to undertrack (0 degrees), highest ground PL, and lowest ground PL

[2] W. J. Doeblner and A. Loubeau, "Estimating the noise dose range of the NASA X-59 aircraft in supersonic cruise using PCBoom propagation simulations", JASA Express Letters 3, 053601 (2023).

Batches of verification cases

- Nearfield pressures represent X-59 C612A using simulation data from NASA [3]
- Two sets of 38 verification cases:
 - KZKFourier simulation turbulence factors from the midpoint development case
 - KZKFourier simulation turbulence factors from a case chosen based on similar value of $\Delta PL = PL_{\text{clean}} - PL_{\text{mean}}$ to midpoint case

Case	ΔPL	σ_{vec}	T_*	ABLH	RH
Midpoint	1.53 dB	1.45 m/s	-1.54 K	2029.6 m	52.5%
Higher σ_{vec}	1.43 dB	2.30 m/s	-0.87 K	796.8 m	81.6%



[3] D. L. Rodriguez, M. J. Aftosmis, M. Nemec and W. M. Spurlock, "Adjoint-Based Minimization of X-59 Sonic Boom Noise via Control Surfaces," AIAA Paper 2021-3030, (2021).

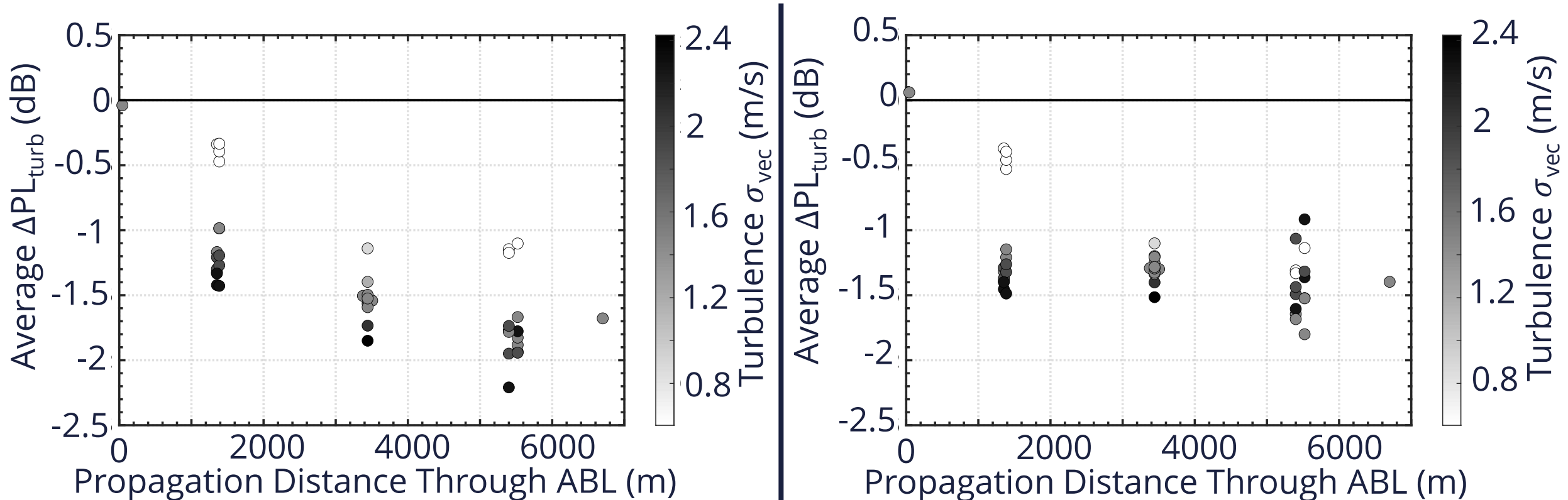
Ensemble filters applied to verification cases

- Comparing turbulence estimation methods using verification cases:
 - Regular N-wave filters
 - Regular shaped boom filters
 - 130 ms ensemble shaped boom filters
 - 230 ms ensemble shaped boom filters
- Values represent average of mean absolute errors across all cases
- Regular N-wave filters generally have the highest overall errors
- 230 ms ensemble shaped boom filters have the lowest overall errors

	Regular N-wave filters (dB)	Regular shaped boom filters (dB)	130 ms Ensemble shaped boom filters (dB)	230 ms Ensemble shaped boom filters (dB)
PL	1.11	0.73	0.47	0.28
ASEL	0.91	1.00	0.50	0.27
BSEL	0.73	0.40	0.15	0.13
CSEL	0.77	0.20	0.10	0.09
DSEL	N/A	0.25	0.11	0.09
ESEL	1.15	0.64	0.23	0.15
ISBAP	0.69	0.52	0.25	0.18
Overall	0.89	0.53	0.26	0.17

Ensemble filters vs KZKFourier

- Comparing turbulence effects on perceived loudness metric across 45 simulation cases
- Left: KZKFourier code, ~1100 hours wall time using 90 CPUs on NASA HPC cluster
- Right: Ensemble filters, ~1.7 hours on circa-2020 laptop workstation



Summary

- A new filter concept was applied to use ensembles of filters to quickly estimate loudness metric statistics for turbulized waveforms
 - Reduced computation time relative to well-resolved KZKFourier simulations enables loudness metric analyses, which require a shorter timeframe
- Ensemble filters are more accurate on average than regular N-wave filters or regular shaped boom filters
- Additional benefits:
 - New loudness metrics (e.g. CSEL) can be added without need for additional filter generation
 - Statistics such as standard deviation and variance are calculated from ensembles of filtered waveforms rather than inferred from mean and mean $\pm$ std filters

Questions

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