



Tools for simulating atmospheric turbulence effects on supersonic X-59 acoustic pressure signatures

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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 Doebler
- 2. 1pPA4 Turbulence effects on shaped sonic booms using finite impulse response filter banks**
Joseph Fletcher, Robin Downs, Jacob Klos, William Doebler, 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 Doebler, Alexandra Loubeau

Presentation outline



- **NASA X-59 research and atmospheric turbulence effects**
- **Previous NASA models and limitations**
- **Current methods for quick estimation of turbulence effects**

NASA X-59 research



- X-59 is a piloted supersonic aircraft designed and built to demonstrate quiet supersonic flight
- Key data will be gathered on public perception of quiet supersonic flights in several cities across the nation

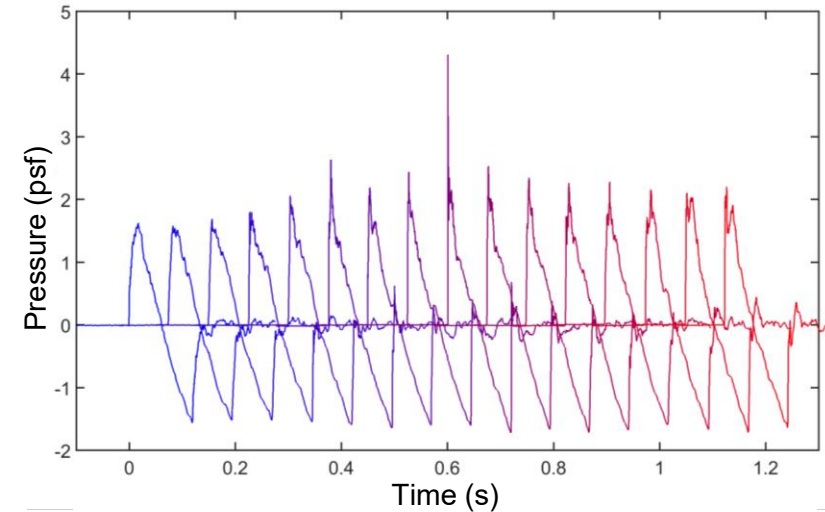


Background on measured atmospheric turbulence effects



➤ **Atmospheric turbulence is one source of variability in levels observed at the ground from sonic boom propagation through the atmosphere**

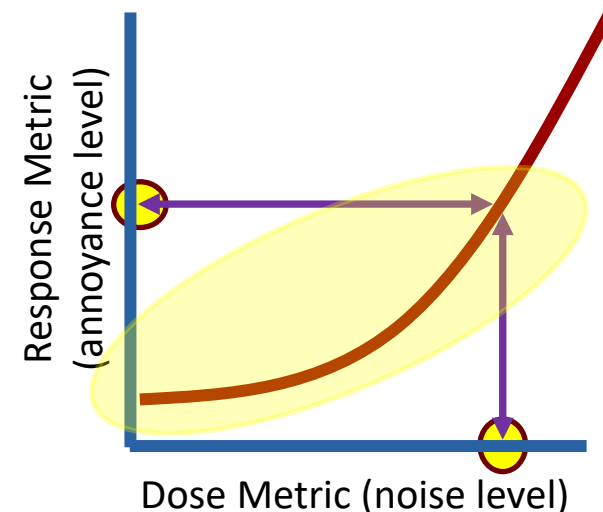
- Observed in several flight tests
- Waveforms and perception metric levels vary



Bradley et al., NASA/CR-2020-220509 (2020)

➤ **This poses challenges for accurately estimating noise dose during X-59 community testing**

- Noise dose and uncertainty are needed for correlating survey and acoustic data

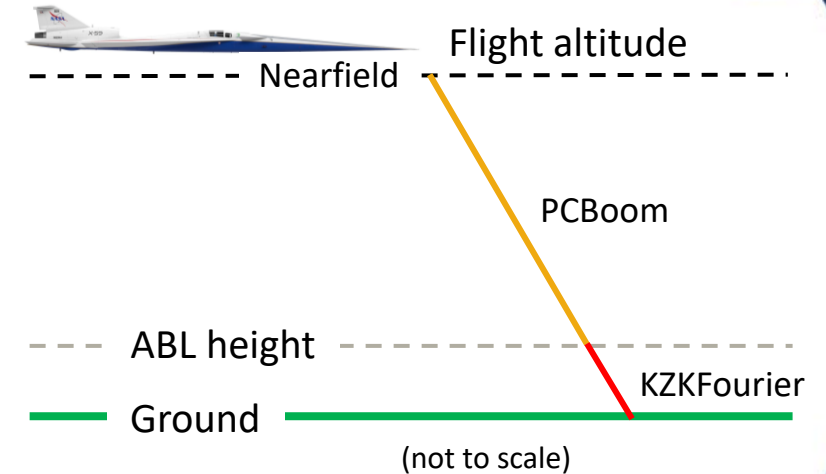


Previous models of atmospheric turbulence effects



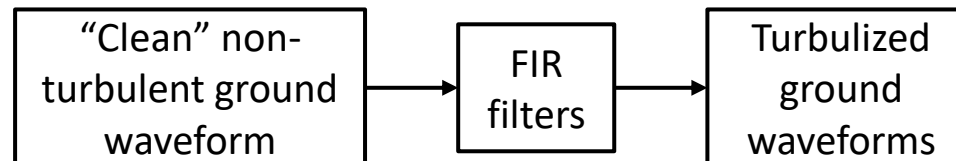
➤ KZKFourier

- Lossy nonlinear propagation simulation tool that includes diffraction due to atmospheric turbulence (KZK equation)
- Applied only in the Atmospheric Boundary Layer (ABL)
- Turbulence modeled as fields of velocity and temperature fluctuations
- Turbulence fields are frozen



➤ PCBoom

- Nonlinear numerical propagation tool includes methods for estimating turbulence effects
 - Investigated and implemented several methods
- Includes (“plug-in”) filters that quickly estimate atmospheric turbulence effects in ABL
 - Filters created from (N-wave) measurements or simulations



Limitations in modeling atmospheric turbulence effects



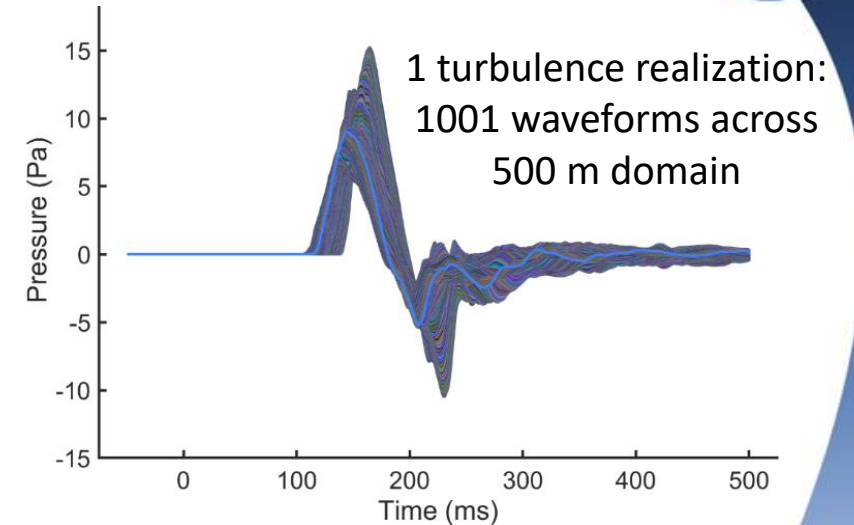
➤ Simulation tools such as KZKFourier are computationally expensive

- Need to run multiple realizations for convergence of results
- Plotted simulation results required wall time of multiple days of CPU hours
- Not suited to rapid turnaround times needed for X-59 analyses

➤ FIR filters that quickly estimate atmospheric turbulence effects in ABL were originally developed for N-waves

- Issues observed with applying filters to shaped signatures
- Limited range of atmospheric conditions
 - Developed for turbulence parameter ranges corresponding only to two US locations (for validation with measured data)

➤ Need for a quick estimation method that is relevant for X-59 signature analysis



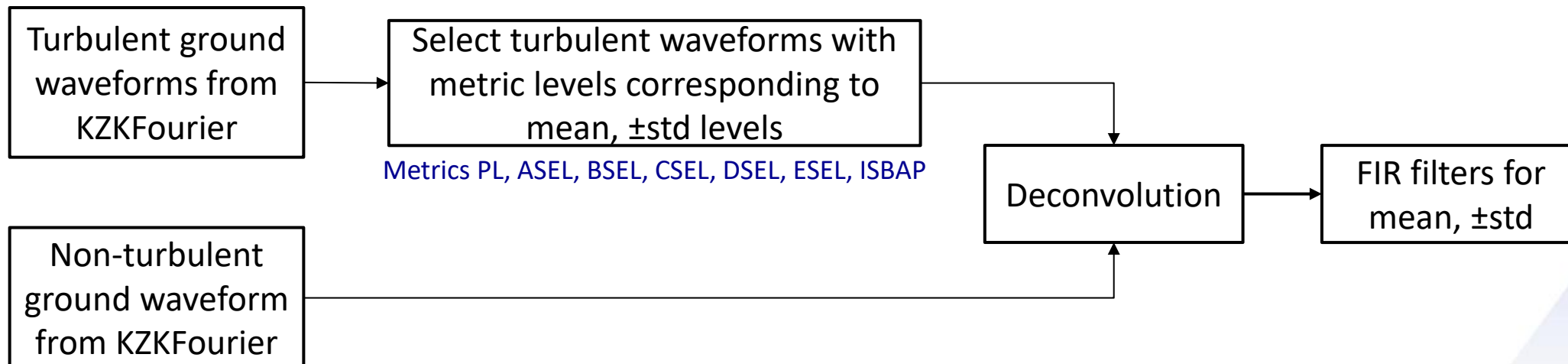
Locey and Sparrow, "Modeling Atmospheric Turbulence as a Filter for Sonic Boom Propagation," NCEJ 55, 2007.

Stout and Sparrow, "Atmospheric turbulence effects on shaped and unshaped sonic boom signatures," JASA 151 (5), 2022.

Shaped boom filters developed applicable to X-59



- Regular filters followed method of Stout and Sparrow
- PCBoom + KZKFourier run with X-59 shaped signature input
- Variety of atmospheric conditions spanning expected range across U.S.
- FIR filters developed corresponding to metric mean and mean $\pm$ std
 - 45 design points $\times$ 7 metrics $\times$ 3 statistics = 945 filters
- Filters can then be applied to new non-turbulent shaped waveforms to quickly estimate turbulence effects



Simulation matrix design covers range of conditions

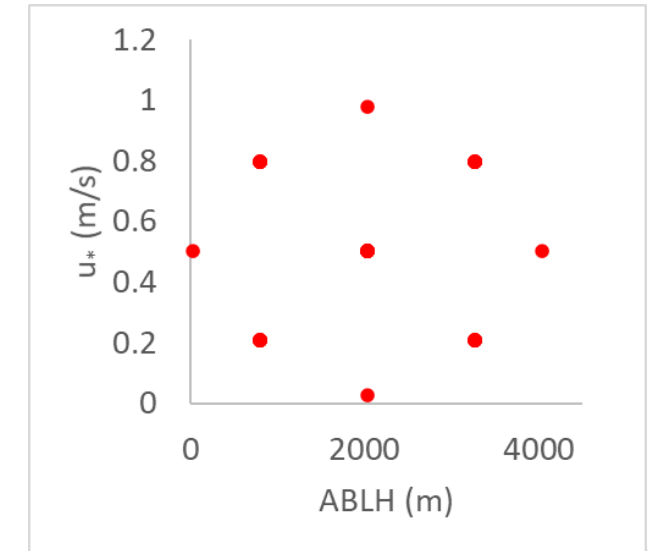


➤ Design of Experiments approach: Central Composite Design

- Minimize computation time to cover high-dimension parameter space

Parameter	Values
Turbulence strength	$u_* = 0.03, 0.21, 0.50, 0.80, 0.98$ m/s $w_* = 0.10, 0.82, 1.96, 3.11, 3.83$ m/s $T_* = 0.21, -0.21, -0.87, -1.54, -1.96$ K
ABL height	24, 797, 2030, 3262, 4035 m
Relative humidity	5, 23, 52, 82, 100%
Surface pressure	0.83, 0.87, 0.93, 0.98, 1.02 atm
Surface temperature	256, 269, 291, 313, 327 K
Propagation angle	Not directly varied; 35–37°
Propagation distance through ABL	Not directly varied; 0.04 – 6.70 km
$\sigma_{vec} = \sqrt{3u_*^2 + 0.35w_*^2}$	Not directly varied; 0.06, 0.87, 1.16, 1.45, 1.46, 1.87, 2.06, 2.30, 2.42 m/s

Example of two parameters



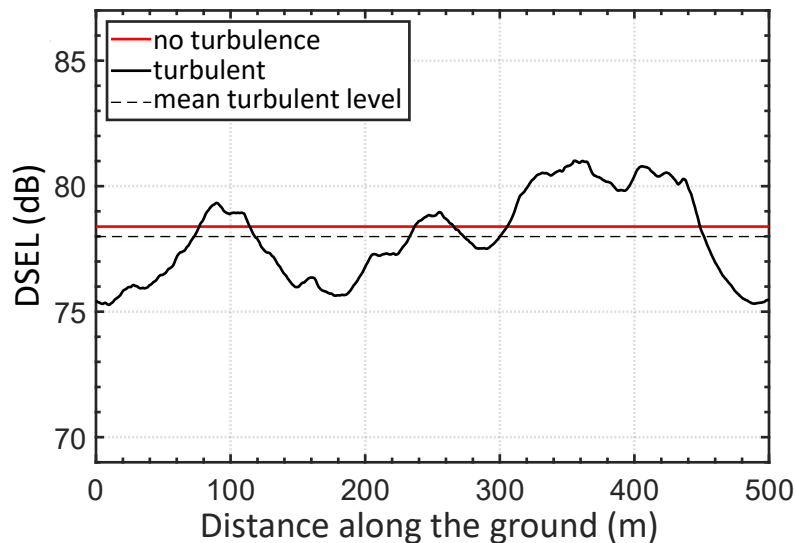
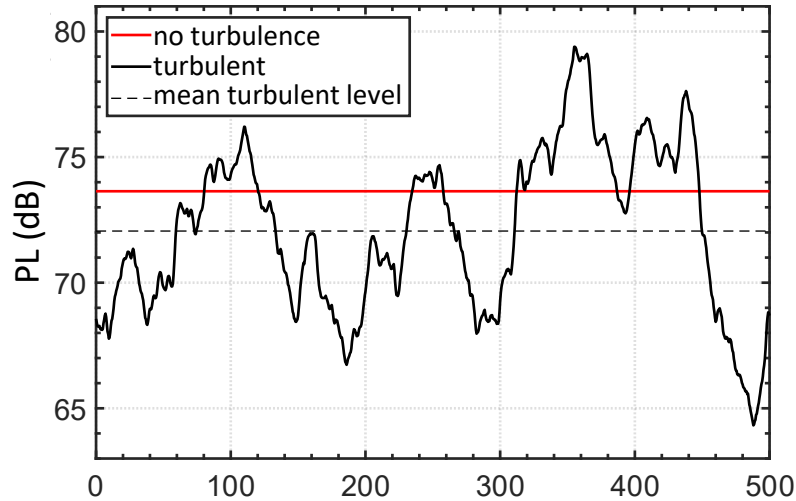
➤ Parameter space includes 5 levels of 7 design factors

➤ 45 unique design cases

➤ Ranges of parameters

- Ranges of each factor based on 10-year meteorological datasets for 19 airfields across U.S.

Example ground waveform metrics for one simulation

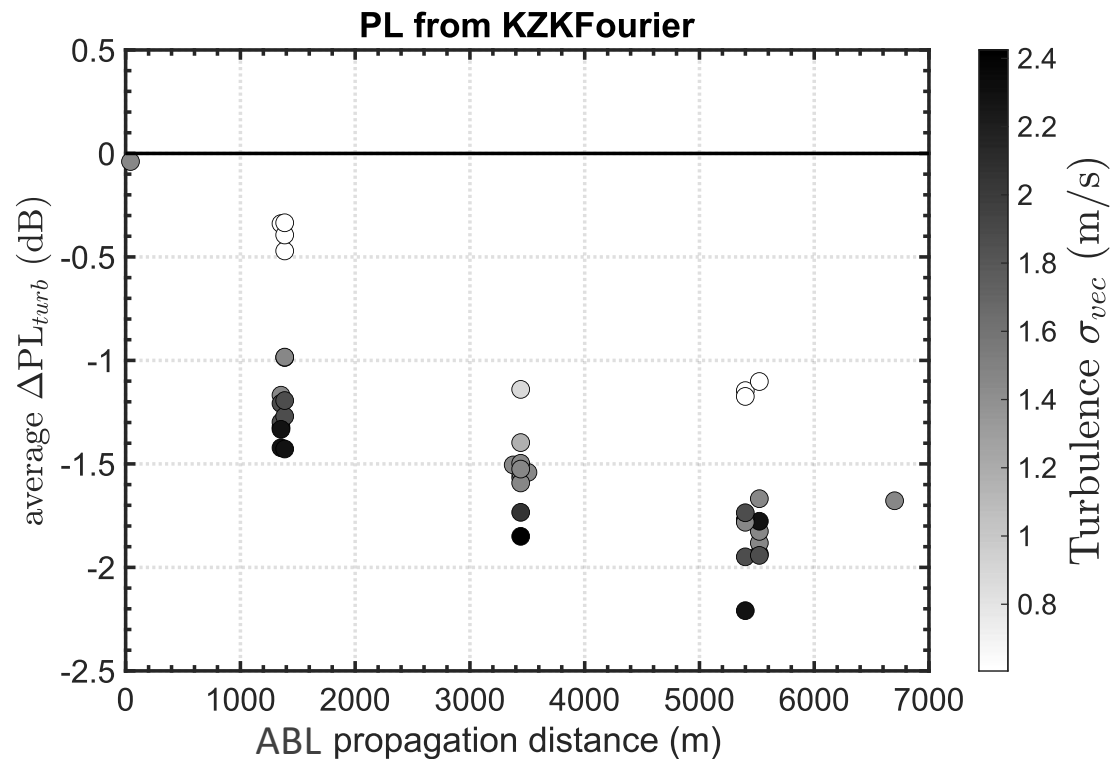


- **1 case, 1 turbulence realization**
- **1001 waveforms (virtual mics) along 500 m domain**
- **PL varies ± 7 dB about the mean**
- **Mean level for turbulent waveforms falls below no-turbulence case**
- **Same overall trends for all metrics**
 - PL varies more than other metrics
 - PL mean reduction is larger than for other metrics

KZKFourier results indicate most important factors



- For all cases considered, mean metric levels < no-turbulence metric levels

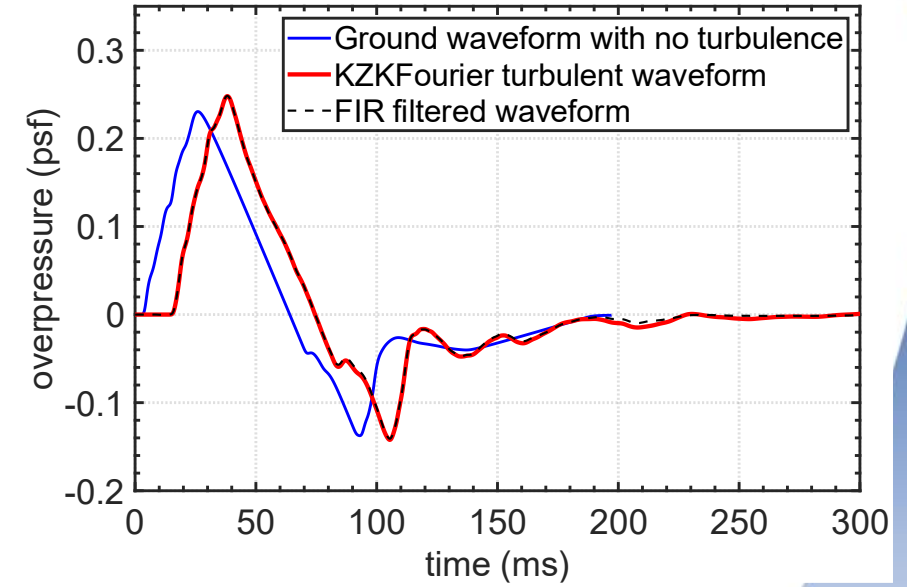


- Empirical model analysis to identify relative sensitivity of metrics to simulation factors. Most significant factors:
 - ABL height
 - $\sigma_{vec} (= \sqrt{3.0u_*^2 + 0.35w_*^2})$
 - (ABL height)²
 - Surface temperature
- Increasing ABL height or σ_{vec} generally reduces mean metric level

Verification testing of FIR filters vs. KZKFourier benchmark



- Circular check quantifies how well FIR filtered waveform metrics match KZKFourier results for same test case
- Verification testing uses different near field pressures, ambient atmospheric conditions, and turbulence conditions
- Although results are more accurate than when using N-wave filters, a newer method was developed for even greater accuracy
 - Regular filter limited by definition to specific metrics and statistics
 - Potential limitation on performance for a different input waveform
 - May not reproduce same point on distribution of levels for a different input waveform



Ensemble filters address limitations in FIR filter method

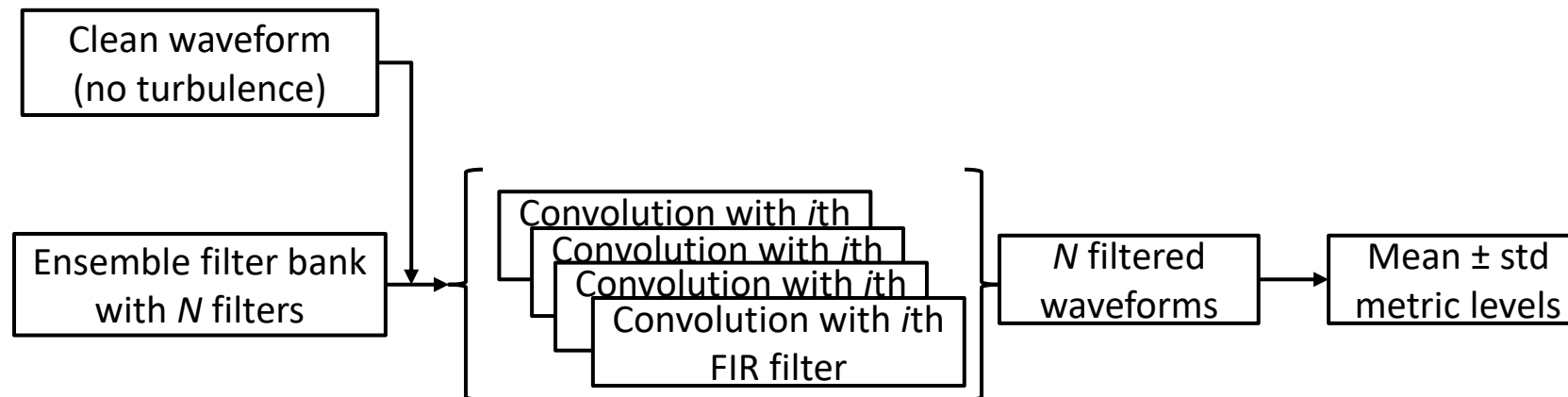


➤ Ensemble* filtering approach

- Use ensemble of FIR filters to form metric statistics
- No longer uses a single exemplar turbulized waveform to represent a specific loudness metric statistic
- More relevant for cases with different starting signatures
- Longer filter length gives more accurate results
- Still orders of magnitude faster than KZKFourier simulations

➤ Verification cases show decrease in error for ensemble filters

- Average errors across 19 verification cases decrease from 0.53 dB (regular) to 0.17 dB (ensemble)

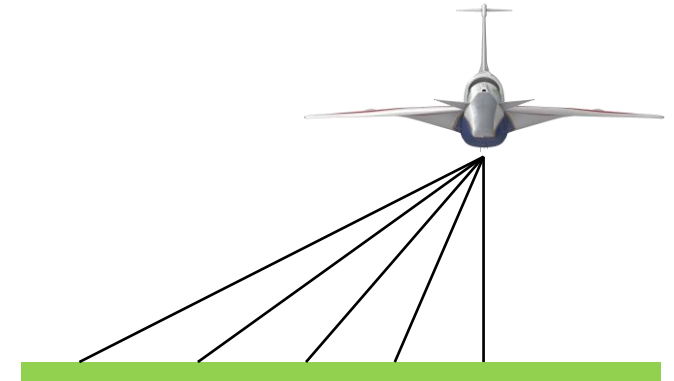


*Ensemble filters were previously referred to as enhanced filters in the PCBoom Version 7.5 User's Guide

Great! But...I want to run cases with longer prop distances



- **Maximum ABL propagation distance was 6.7 km**
 - Based on 95th percentile ABL height across US and undertrack propagation angle
 - Off-track angles will result in longer propagation distances, especially close to lateral cutoff
- **Errors increase outside of propagation distance range that was modeled**
- **Interpolation method implemented in PCBoom finds 4 closest design points and calculates inverse distance-weighted levels**
 - There is no valid extrapolation of values beyond parameter space
- **Filters not appropriate for ABL propagation distances greater than 6.7 km**

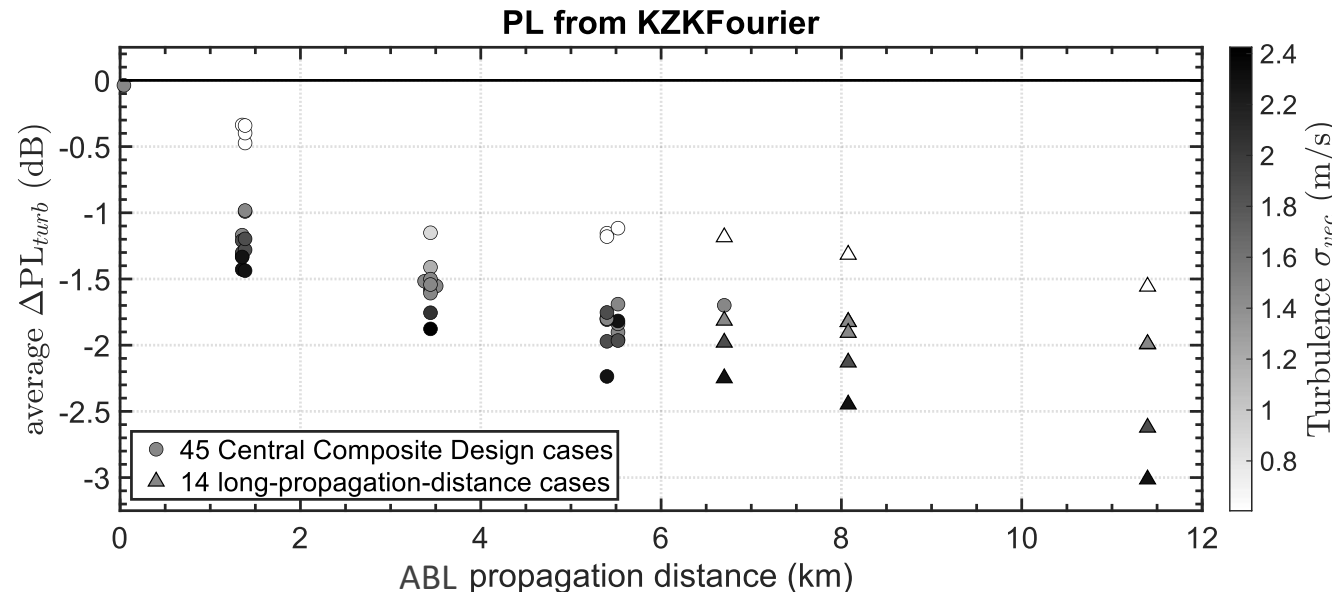


Additional filter design points to extend parameter space



- **KZKFourier runs conducted for ABL propagation distances up to 11.4 km**
 - 14 new cases, for total of 59 cases
 - Different turbulence conditions at 3 different larger ABL heights
- **New filters calculated**
 - Longer filter length required
- **Implementing an improved approach to increase accuracy and computation speed**
 - Split low- and high-frequency ranges into separate FIR/IIR filters
 - For all ensemble filters

Currently under development



Summary of current tools for atmospheric turbulence effects



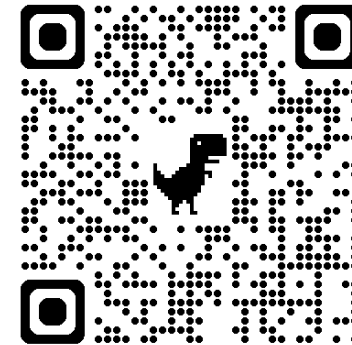
➤ KZKFourier

- Highest accuracy, longest computation time

➤ PCBoom version 7.5 filters for faster computations

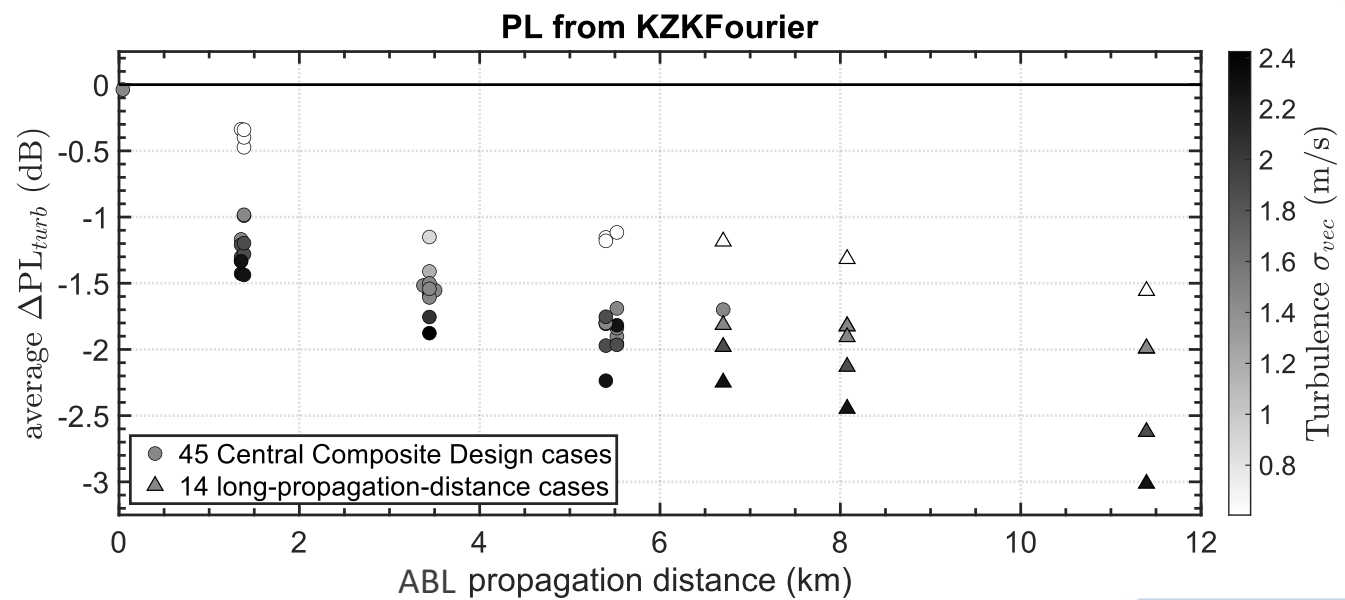
- Regular N-wave FIR filters
 - Not appropriate for X-59 signals
 - Limited range of valid atmospheric conditions
- Regular shaped boom FIR filters
 - Shortest computation time for X-59 signals
- Ensemble shaped boom FIR filters
 - More accurate than regular filters
 - Limited to ABL propagation distances ≤ 6.7 km

PCBoom 7.5 is available upon request from NASA:
<https://software.nasa.gov/software/LAR-19926-1>



➤ Newer ensemble filters for longer propagation distances under development

- Higher accuracy, faster computation speed, and faster run time for user



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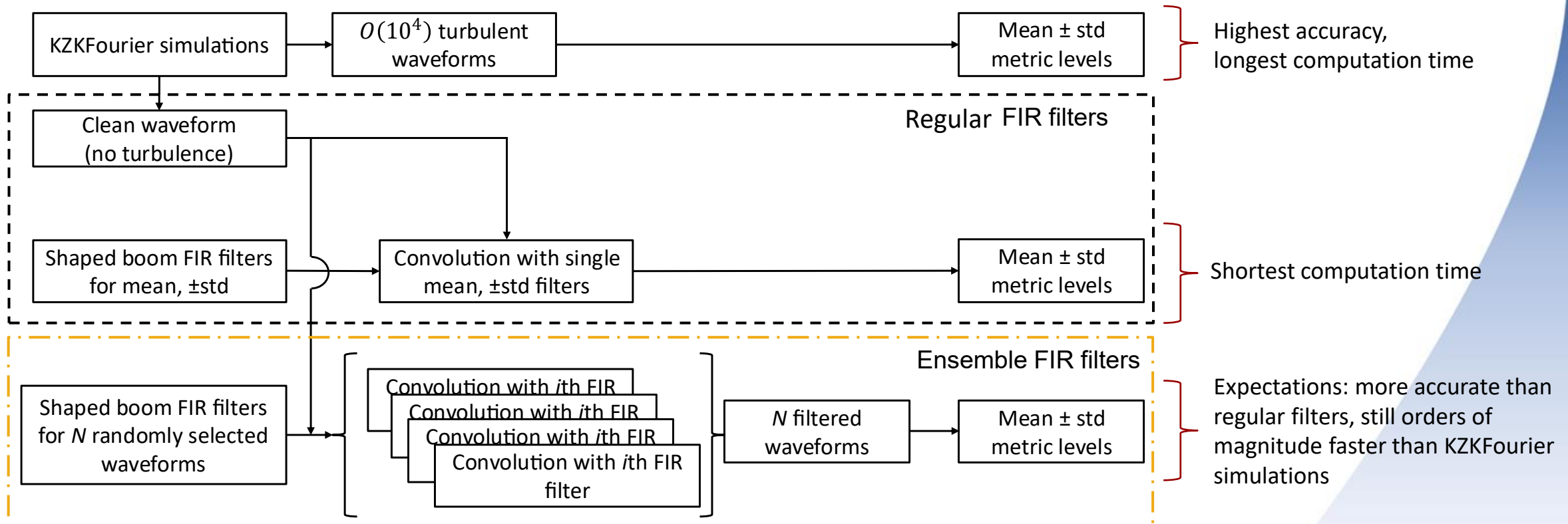


Backup Slides

Regular vs Ensemble FIR filters



- Filter convolution operation is the same: clean no-turbulence waveform in → turbulized waveform out
- Application of Ensemble filter banks requires hundreds or thousands of convolutions



Shaped boom FIR filters developed for faster run times

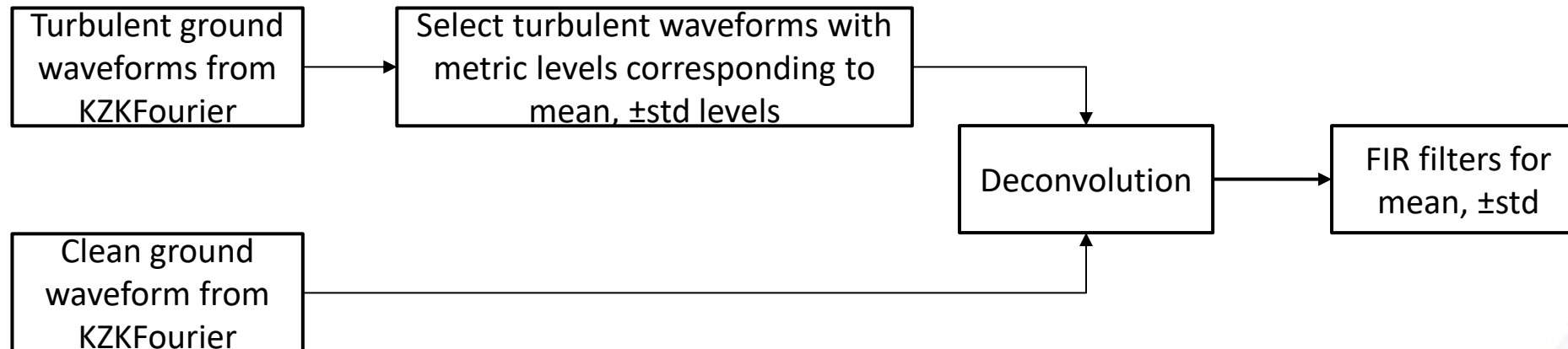


➤ Use KZKFourier production simulations to generate FIR filters

- Metrics PL, ASEL, BSEL, DSEL, ESEL, ISBAP
- 45 design points $\times$ 6 metrics $\times$ 3 statistics (mean-std, mean, mean+std) = 810 filters

➤ Follow procedure developed by Stout and Sparrow

- For each metric and statistic, select all waveforms with levels ± 0.005 dB of target level $\rightarrow$ approx. 50 waveforms on average
- Select waveform with median rise location in time domain (median advection)
- Signal processing of waveforms input to matrix deconvolution process and FIR filter coefficient outputs
 - Settings adjusted for X-59 signals



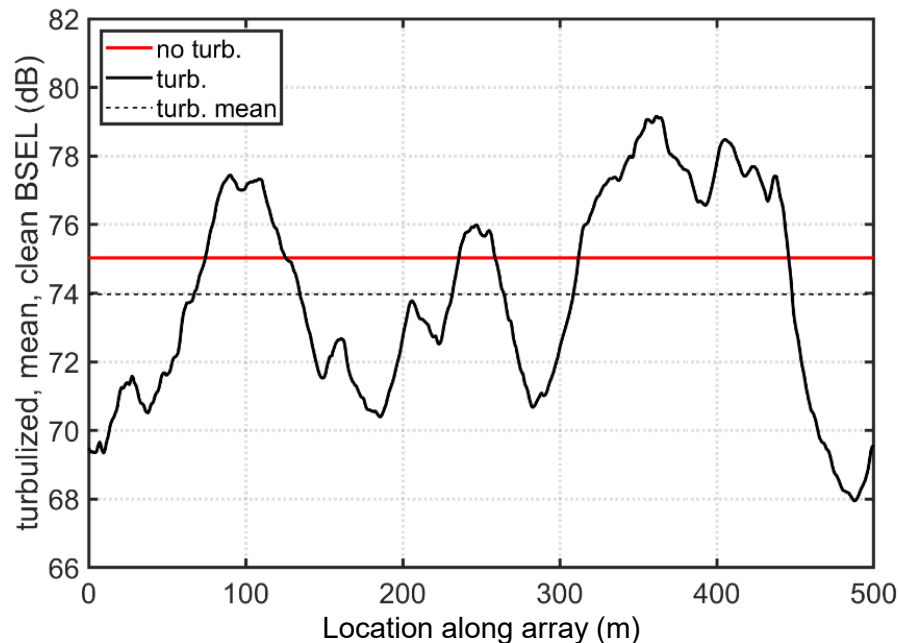
KZKFourier results converge with 30 realizations



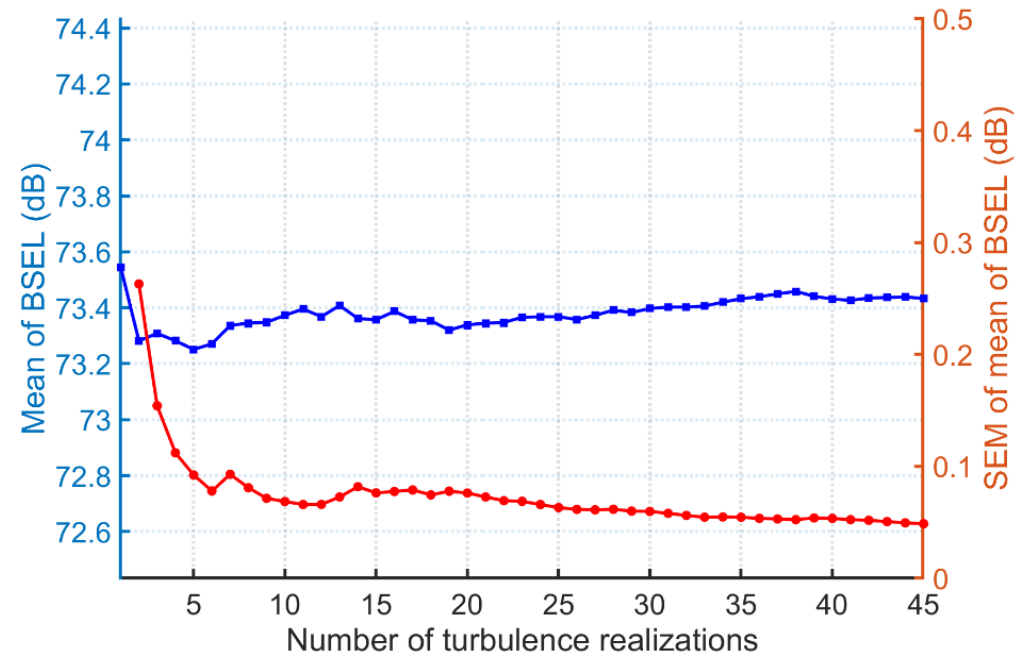
➤ 45 cases x 30 turbulence realizations x 1000 – 2000 ground waveforms

- Used combination of NASA K cluster high performance computing resource and Volpe systems
- Each turbulence realization (45 cases) ~ 1,128 hours
- Evaluated convergence with increasing realizations
- With 30 realizations, 95% CI < 0.22 dB for all metrics

Example ground metrics for one realization



Example convergence for one case



Verification testing of FIR filters vs. KZKFourier baseline



- **Circular check quantifies how well FIR filtered waveform metrics match KZKFourier results for same test case**
 - Overall mean absolute error of 0.1 dB
- **Verification testing uses different near field pressures, ambient atmospheric conditions, and turbulence conditions**
 - 19 verification test cases give overall error of 0.53 dB (error reduces to 0.39 dB for on-design cases)

