

Turbulence effects on shaped booms: Finite impulse response filter development

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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

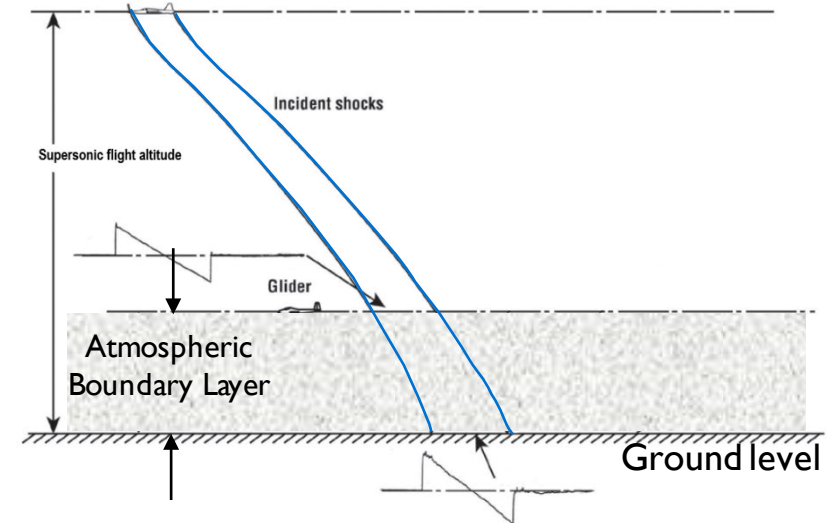
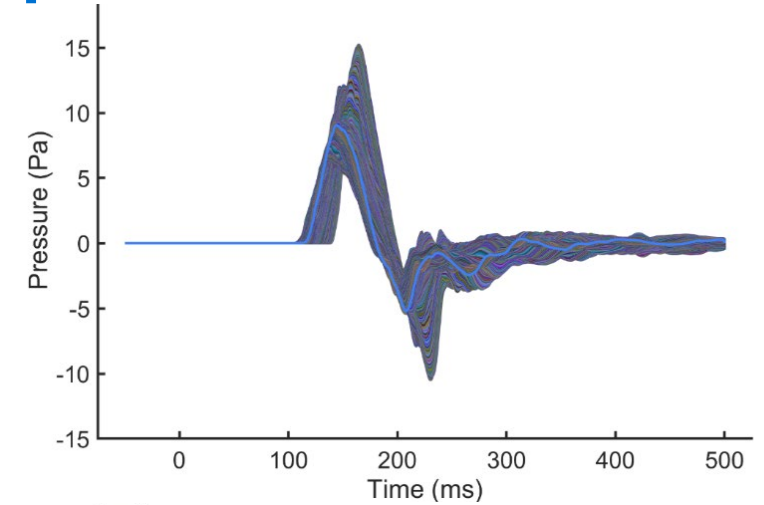
Robert Downs, Michael Barzach, Jacob Klos, Joel Lonzaga, William Doeblor, Peter Parker, Alexandra Loubeau

Outline

- Motivation for improved methods of modeling turbulence effects
- Finite impulse response (FIR) filters: general methodology and current implementation
- FIR filter testing: circular check and verification simulations
- Summary
- Ongoing work: Enhanced FIR filtering approach

Overview of FIR filter approach

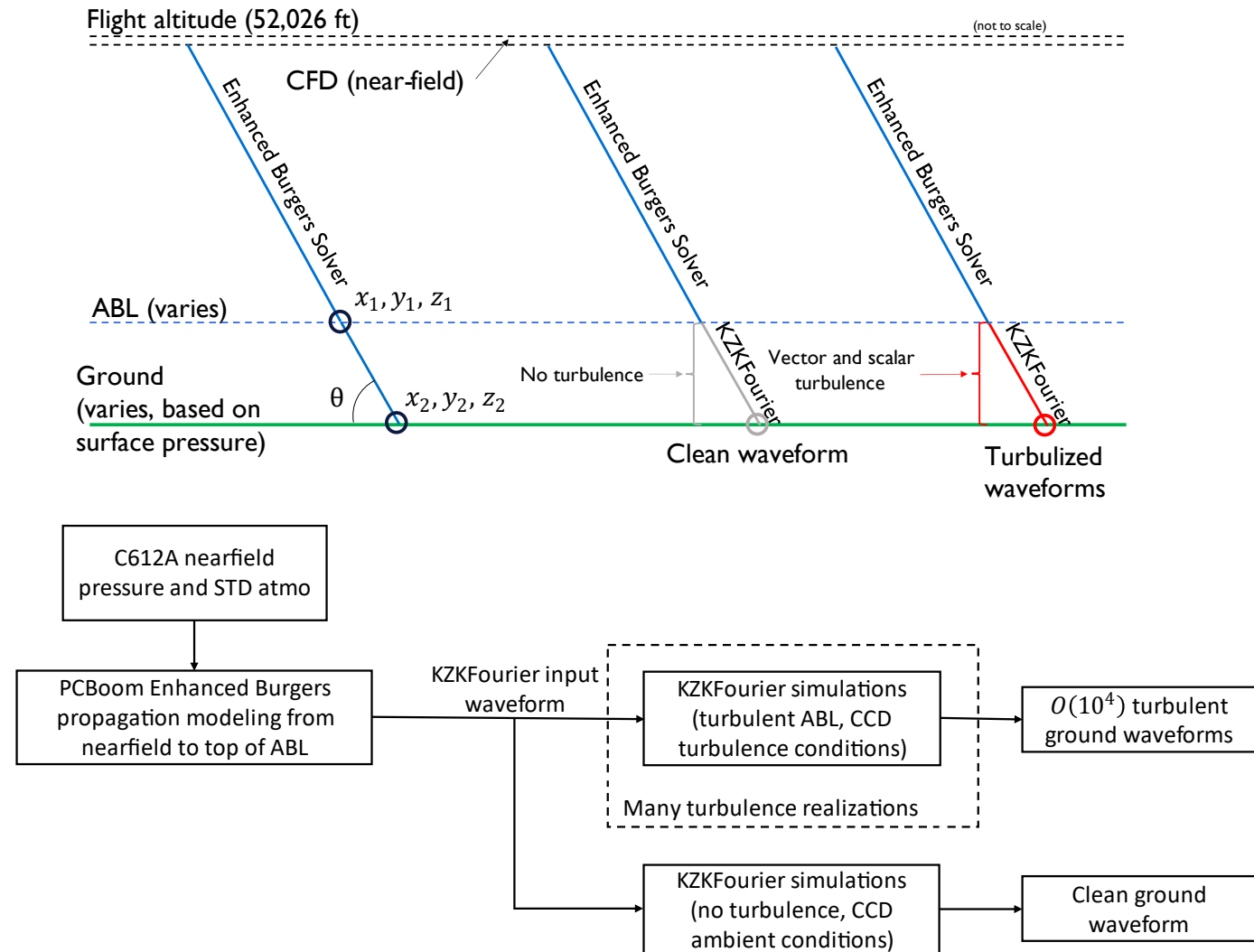
- Simulation tools such as KZKFourier (Stout and Sparrow) can be used to model turbulence effects, but are computationally expensive
 - Plotted simulation results required wall time of approx. 46 hours
- Concept of using a filter function to quickly model atmospheric turbulence effects in ABL was demonstrated by Locey and Sparrow using SSBE data
- Assumes turbulence effects limited to within Atmospheric Boundary Layer (ABL)
- Locey and Sparrow (2008): developed 6 filters implemented in PCBoom based on N wave with Taylor shocks (6 turbulence conditions)
- Stout and Sparrow (2018): developed 2,016 filters implemented in PCBoom based on measured F-18 N wave (96 points $\times$ 7 metrics $\times$ 3 statistics)



Graphic adapted from figure 2.22 of "Sonic Boom: Six Decades of Research", Maglieri et al., NASA/SP-2014-622, 2014.

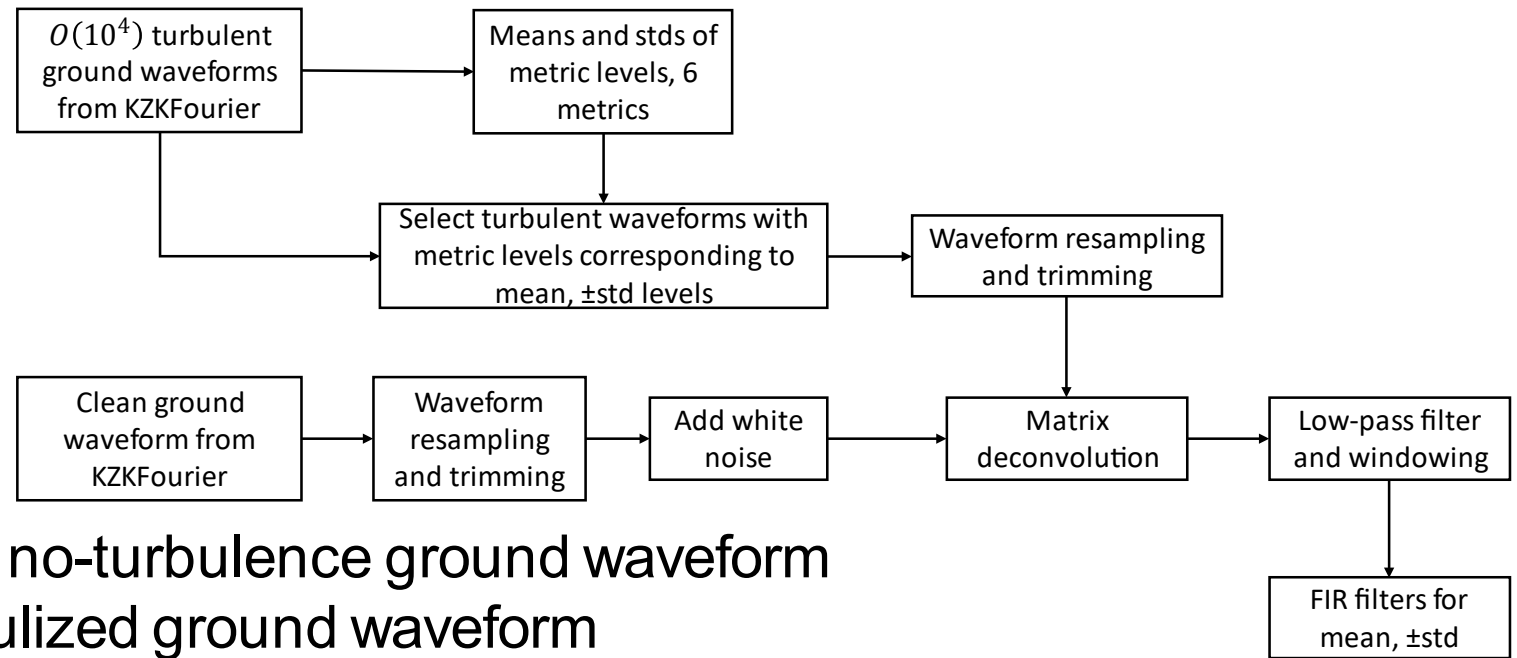
KZKFourier simulations for FIR filters

- Observed issues with applying PCBoom SonicBAT filters to shaped booms include inaccuracy > metric standard deviation
- Recent KZKFourier simulations with C612A waveforms used as inputs to develop shaped-boom FIR filters
- Clean and turbulized ground waveforms produced by combination of PCBoom and KZKFourier modeling
- Same 2D version of KZKFourier used as Stout and Sparrow (2018)



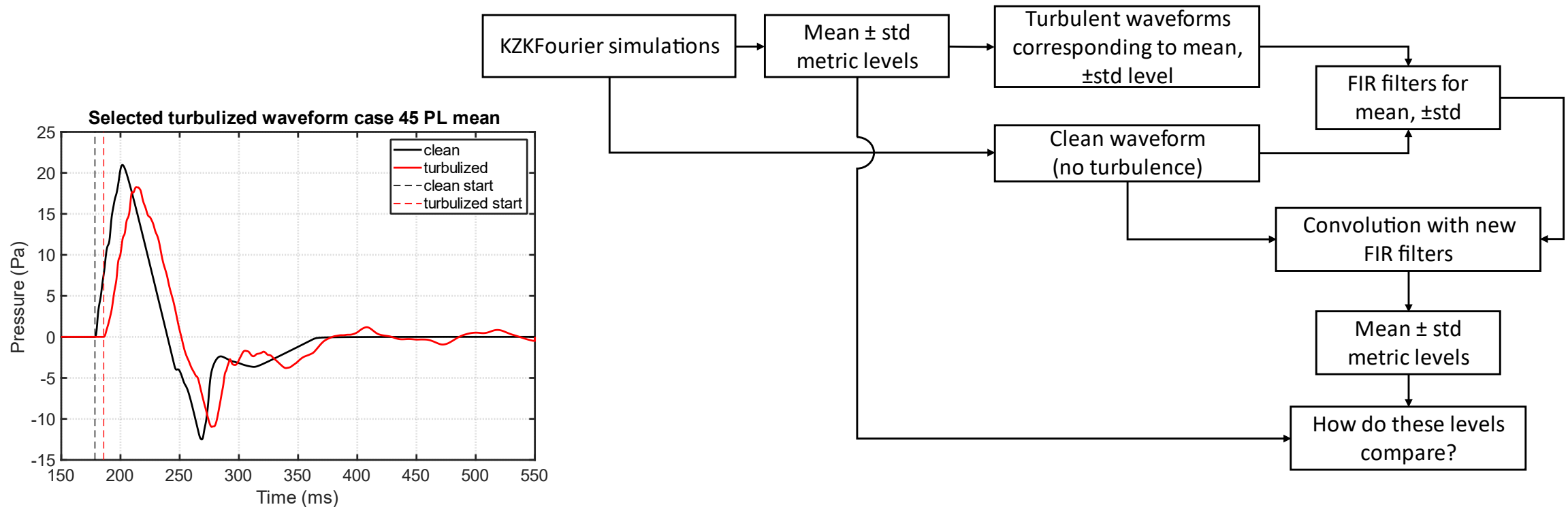
Filter calculation process

- Basic approach: use filter production simulations to generate 810 FIR filters for PL, ASEL, BSEL, DSEL, ESEL, and ISBAP
 - 45 Central Composite Design cases $\times$ 6 metrics $\times$ 3 statistics (mean-std, mean, mean+std)
- Follow general procedure developed by Stout and Sparrow for SonicBAT filters
- Matrix deconvolution process from Locey (2008):
 - Input waveform is a clean, no-turbulence ground waveform
 - Output waveform is a turbulized ground waveform

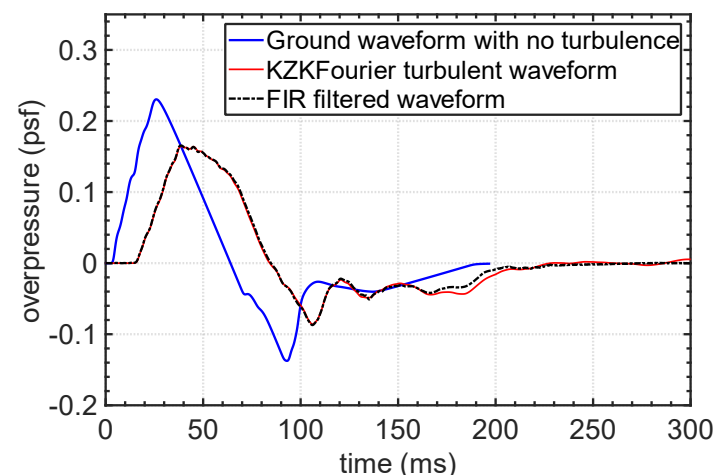
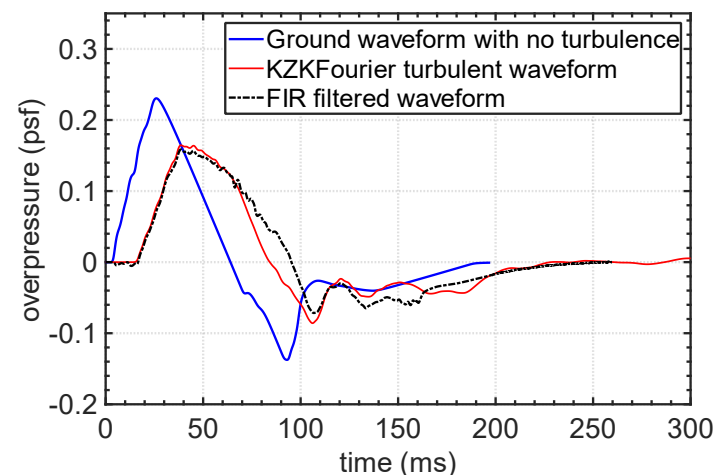


Filter testing: circular check

Goal of the filter circular check: quantify how well FIR filtered waveform metrics match the template turbulence waveform metrics



Results using different filter lengths



Collected results: 810 filters, 62.5 ms filter length

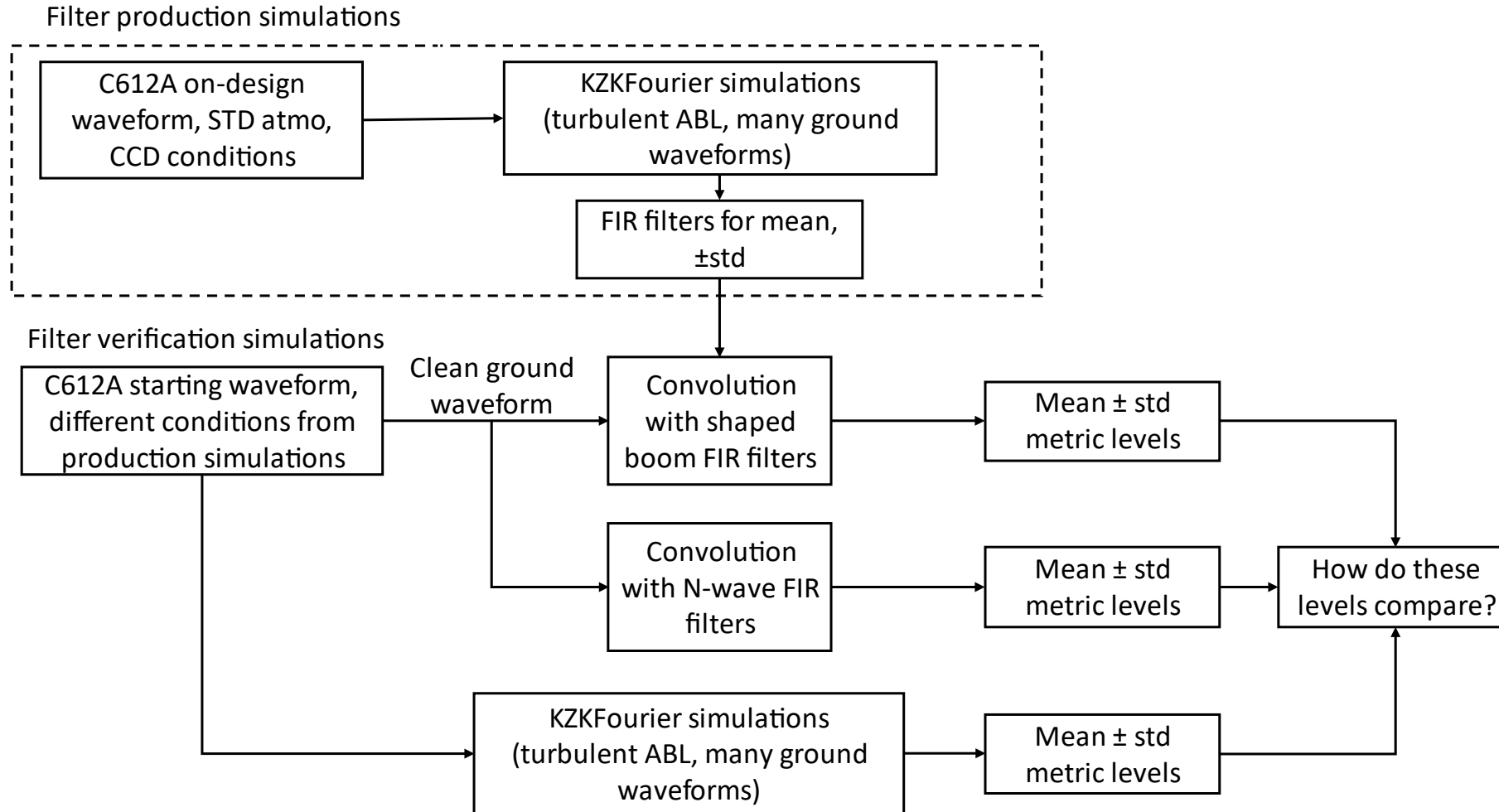
Filter errors (dB)	PL	ASEL	BSEL	DSEL	ESEL	ISBAP
Mean bias	2.11	2.20	0.41	0.15	0.77	0.83
Standard deviation of errors	3.27	3.35	1.63	0.76	1.87	1.53
Mean absolute error	2.18	2.25	0.54	0.32	0.89	0.90

Collected results: 810 filters, 130 ms filter length

Filter errors (dB)	PL	ASEL	BSEL	DSEL	ESEL	ISBAP
Mean bias	0.15	0.13	0.00	-0.01	0.06	0.16
Standard deviation of errors	0.25	0.24	0.15	0.12	0.18	0.27
Mean absolute error	0.18	0.16	0.07	0.05	0.10	0.20

130 ms filters more accurately reproduce KZKFourier metric levels than 62.5 ms filters

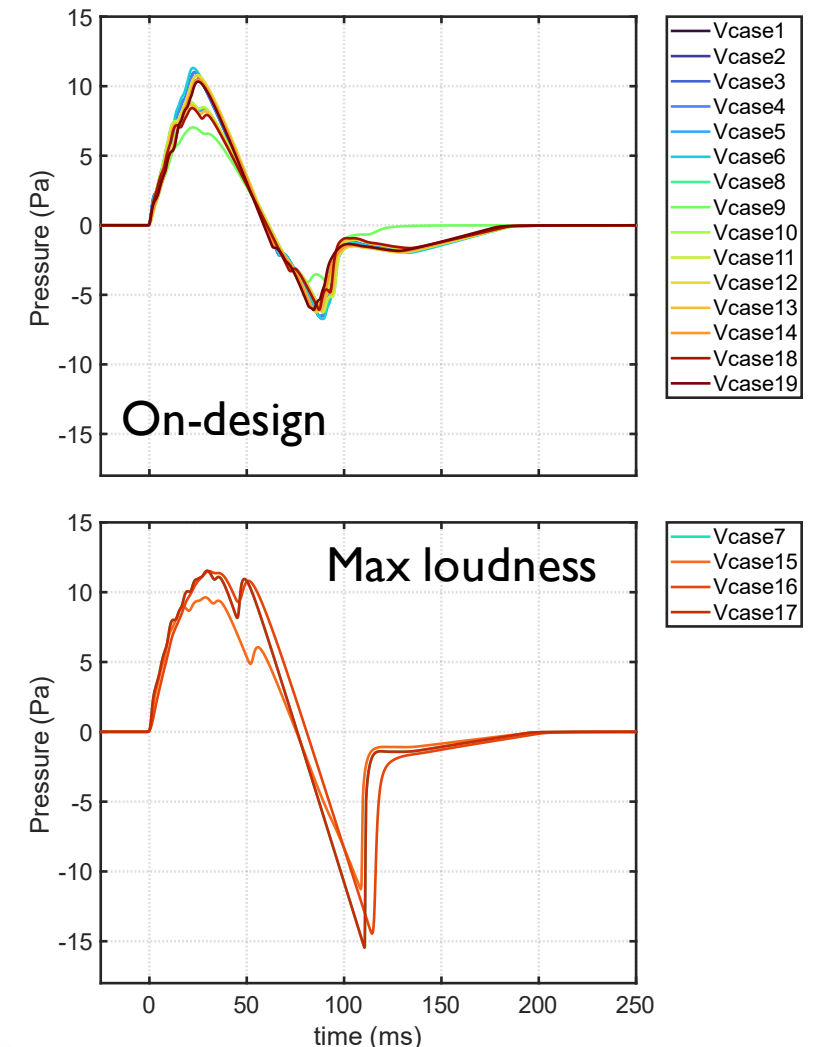
Filter verification testing: KZKFourier benchmark



Filter verification testing: cases

- Executed an additional 19 KZKFourier cases for filter verification, separate from 45 cases used for filter development
- Verification cases:
 - 4 cases used factors values intermediate to the filter development design factors (e.g., different turbulence conditions)
 - 14 cases used different starting waveforms, from either different:
 - ambient atmosphere conditions
 - emission angles
 - Near-field pressures (C609, C612A maximum loudness configuration)
 - 1 case used both a different input waveform and an intermediate factor value

Waveforms at top of ABL



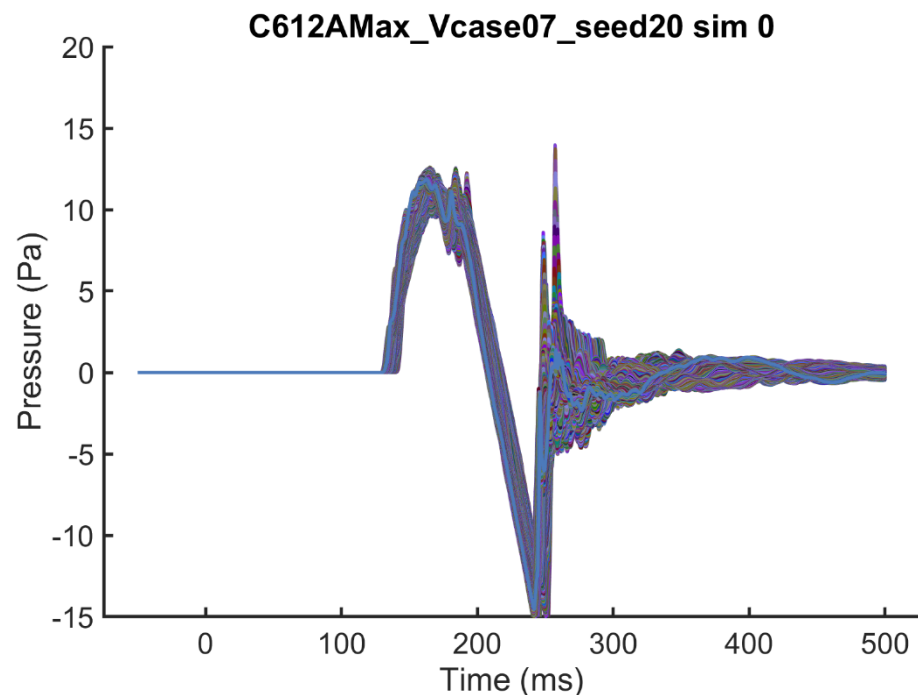
Filter metric comparisons

- Average metric differences (dB) for 19 filter verification test cases
- Benchmark: distributions of turbulent waveform metrics from KZKFourier simulations

	N-wave filters (FiltView)				Shaped boom filters			
	Mean-std filter error	Mean filter error	Mean+std filter error	Overall error	Mean-std filter error	Mean filter error	Mean+std filter error	Overall error
PL	1.24	0.55	1.07	0.95	0.67	0.41	0.44	0.50
ASEL	1.23	0.96	1.02	1.07	0.89	1.38	0.54	0.93
BSEL	1.08	0.63	0.63	0.78	0.39	0.28	0.38	0.35
DSEL	n/a	n/a	n/a	n/a	0.35	0.22	0.32	0.30
ESEL	1.32	0.91	0.71	0.98	1.04	0.42	0.44	0.63
ISBAP	1.09	0.63	0.62	0.78	0.47	0.49	0.35	0.44
Overall	1.19	0.74	0.81	0.91	0.63	0.53	0.41	0.53

Filter metric comparisons, subdivided

- Average metric differences (dB) for filter verification test cases
- Results subdivided into verification cases that used max-loudness waveforms (4 cases) and all others (15 cases)



	C612AMax cases only		Excluding C612Amax cases	
	N-wave filters	Shaped boom filters	N-wave filters	Shaped boom filters
PL	0.52	0.60	1.07	0.48
ASEL	0.74	2.34	1.15	0.56
BSEL	0.58	0.45	0.84	0.32
DSEL	n/a	0.74	n/a	0.18
ESEL	1.09	1.41	0.95	0.43
ISBAP	0.67	0.59	0.81	0.40
Overall	0.72	1.02	0.96	0.39

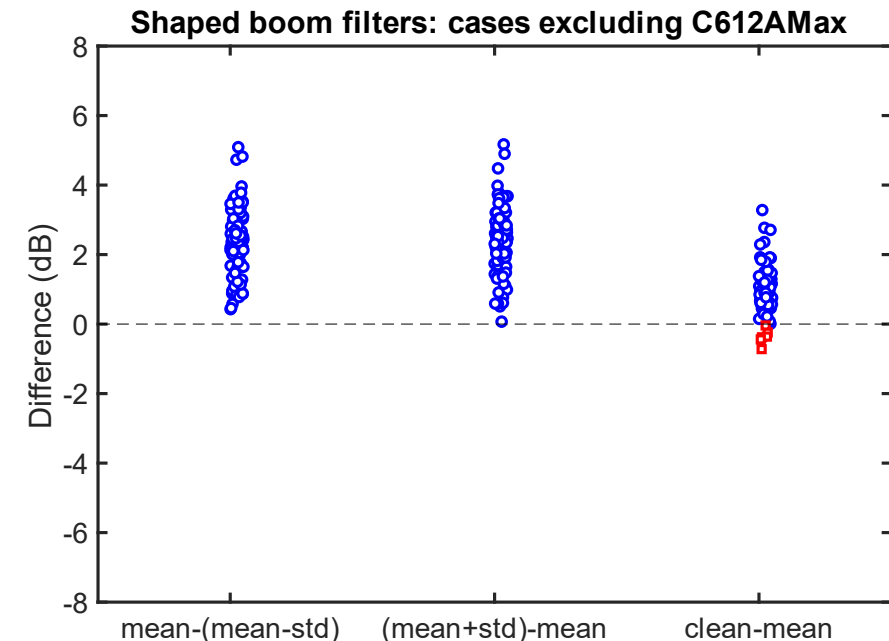
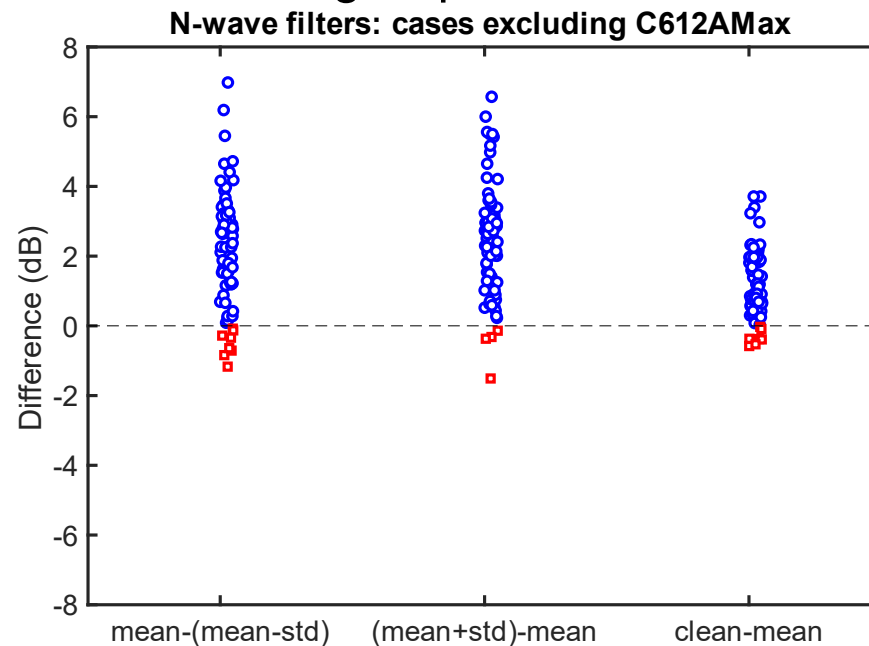
Filter metric comparisons, subdivided

- Average metric differences (dB) for 15 non-max-loudness filter verification test cases
- Results subdivided into verification cases that used undertrack azimuth angle waveforms (9 cases) and all others (6 cases)

	Undertrack waveform cases		Offtrack waveform cases	
	N-wave filters	Shaped boom filters	N-wave filters	Shaped boom filters
PL	1.07	0.42	1.07	0.57
ASEL	1.02	0.60	1.36	0.50
BSEL	0.87	0.21	0.79	0.48
DSEL	n/a	0.18	n/a	0.19
ESEL	1.00	0.30	0.87	0.62
ISBAP	0.91	0.36	0.66	0.45
Overall	0.97	0.35	0.95	0.47

Filter metric statistics

- How often is filter inaccuracy > metric standard deviations? Calculate the following for each verification case and 6 metrics
 - (Mean FIR filter level) – (mean-std FIR filter level)
 - (Mean+std FIR filter level) – (mean FIR filter level)
 - (Clean waveform metric level) – (mean FIR filter metric level)
- Plotted differences are grouped results from all six metrics



Summary and future work

- KZKFourier simulations of shaped boom waveforms used to generate a new bank of 810 FIR filters
 - PL, ASEL, BSEL, DSEL, ESEL, and ISBAP metrics
 - For each metric: mean-std, mean, and mean+std
- Filter accuracy was benchmarked against KZKFourier and compared with PCBoom N-wave turbulence filters developed as part of SonicBAT
 - Results from application of new shaped boom filter have an overall mean absolute error lower than SonicBAT N-wave filters (0.91 dB → 0.53 dB)
 - Subdividing cases by on-design configurations vs max-loudness configuration, mean absolute errors:
 - On-design configurations 0.96 dB for SonicBAT filters vs 0.39 dB for shaped boom filters (15 cases)
 - Max-loudness configuration 0.72 dB for SonicBAT filters vs 1.02 dB for shaped boom filters (4 cases)
- Potential future improvements include
 - Refinement of how filters are applied to produce metric output levels
 - Enhanced filtering approach using an ensemble of filters