Adaptive Laser Compensation for Aero-Optics and Atmospheric Disturbances

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Overview

- Scaled USAFA wind tunnel aero-optical disturbances
- Adaptive optics compensation with classical control
  - Bandwidth limitations for idealized AO
  - Scaling relations, power laws, and compensation frequencies
- Effect of latency on aero-optics compensation
  - Frequency-domain analysis with classical AO error rejection
- Adaptive AO control simulations
  - Aero-optics only
  - Free-stream turbulence only
  - Combined aero-optics and free-stream turbulence

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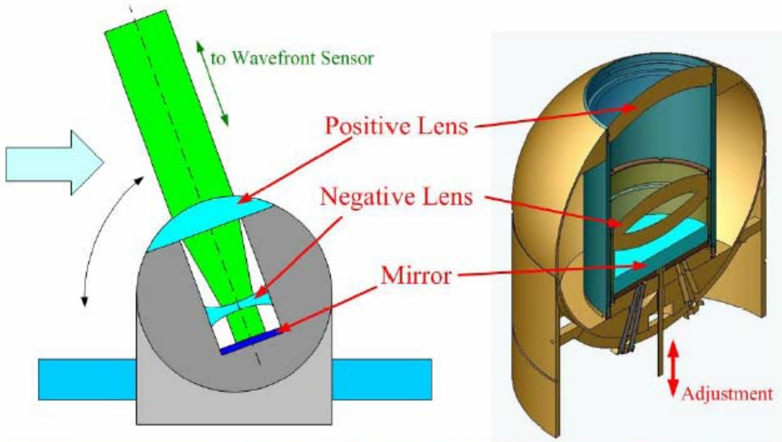
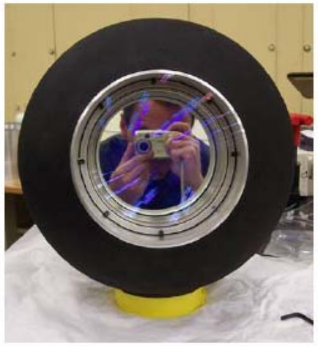
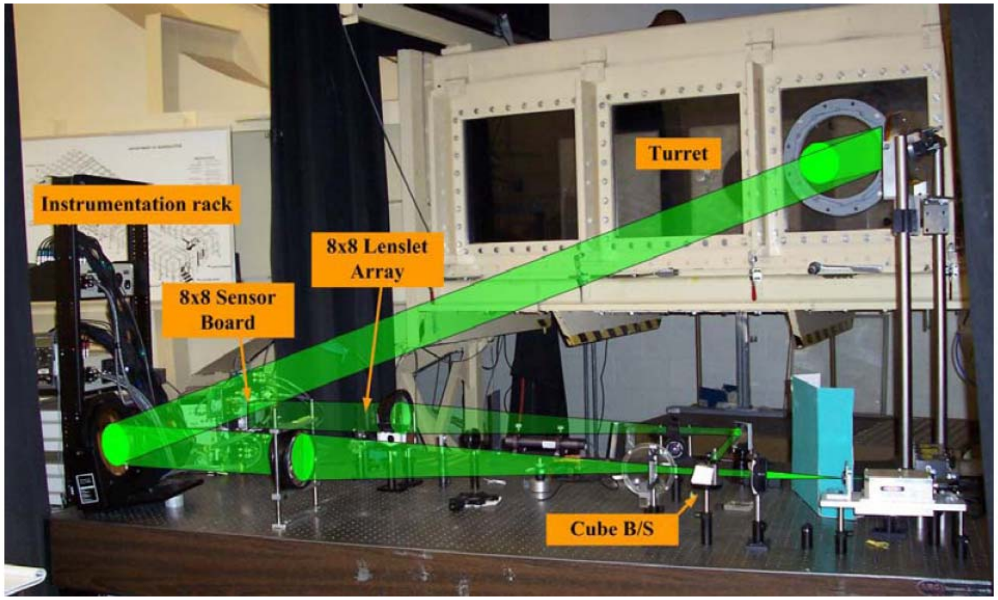
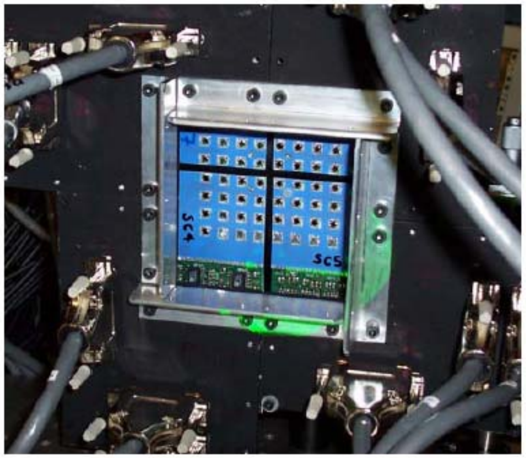
USAFA Wind Tunnel Measurements: 8x8 Wavefront Sensor Data





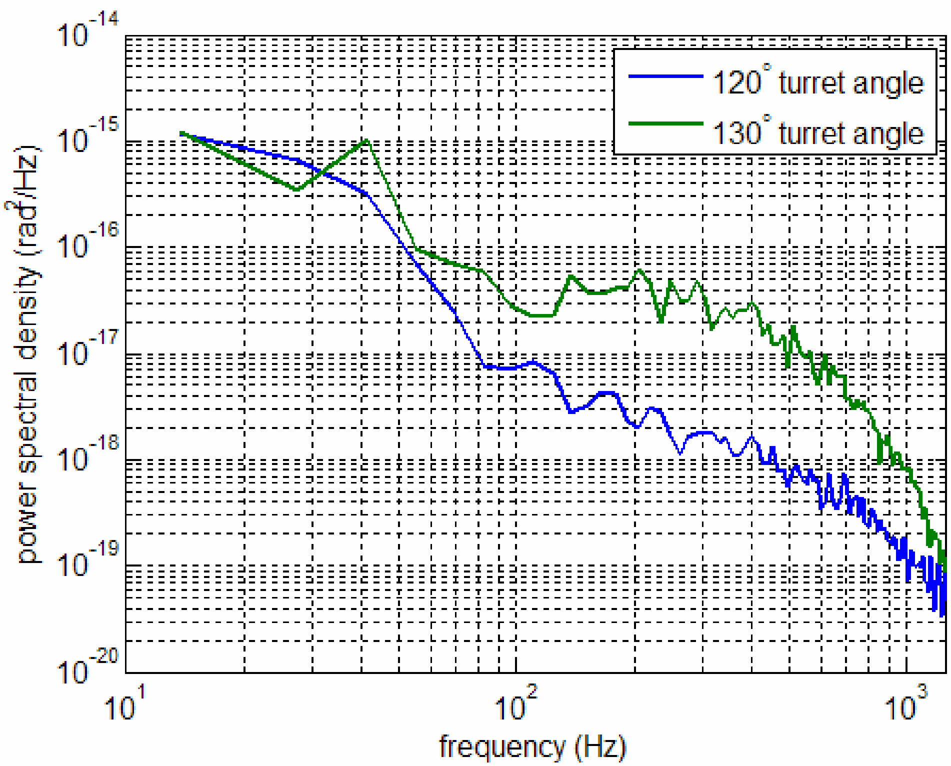
- **12” turret model with 3” wavefront reconstructions**
- **Mounted in USAFA wind tunnel**
- **Optical measurements @ Mach = 0.4**
- **High-bandwidth wavefront sensor**
  - **8x8 subaperture array (moderate-to-low)**
  - **78.125 kHz sample rate (fast)**

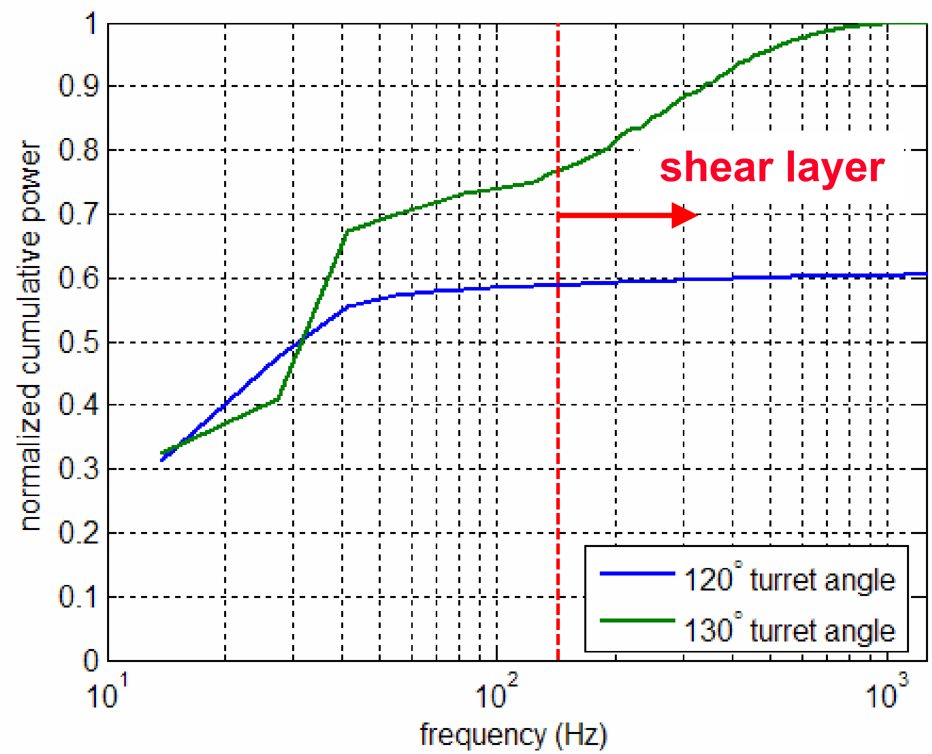




Photos courtesy University of Notre Dame

Aero-Optics Power Spectrum





- Comparison of disturbance power spectrum for 120° and 130° turret angle
- Enhancement in disturbance at 130° primarily at higher frequency

- Cumulative power 120° and 130° turret angle—normalized to power @ 130°
- Increase above ~100 HZ attributed to shear-layer

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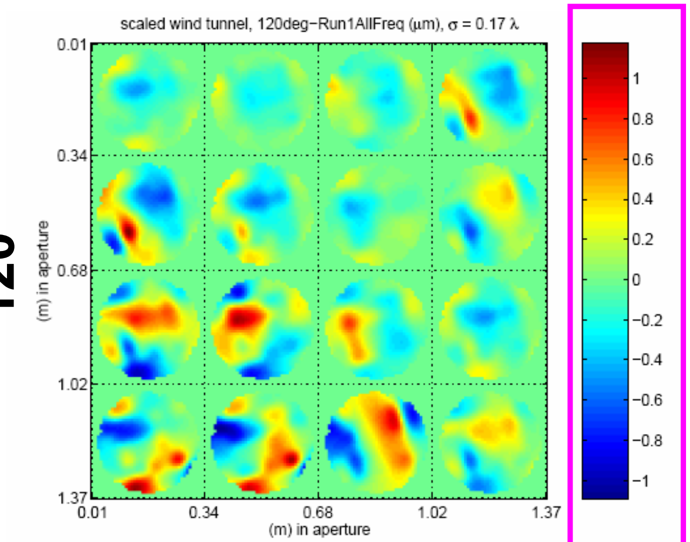
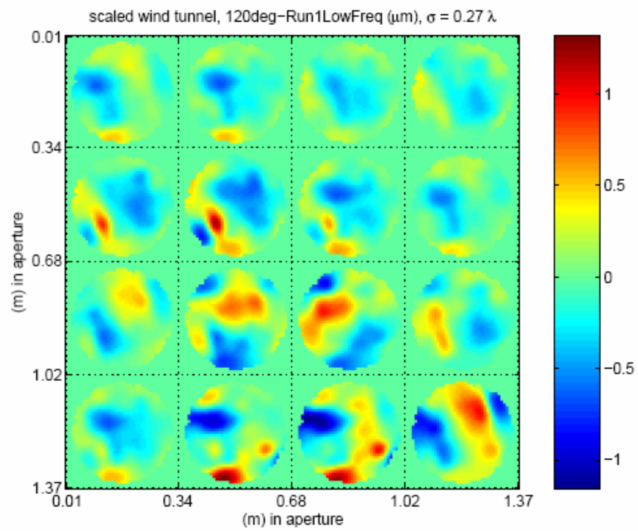
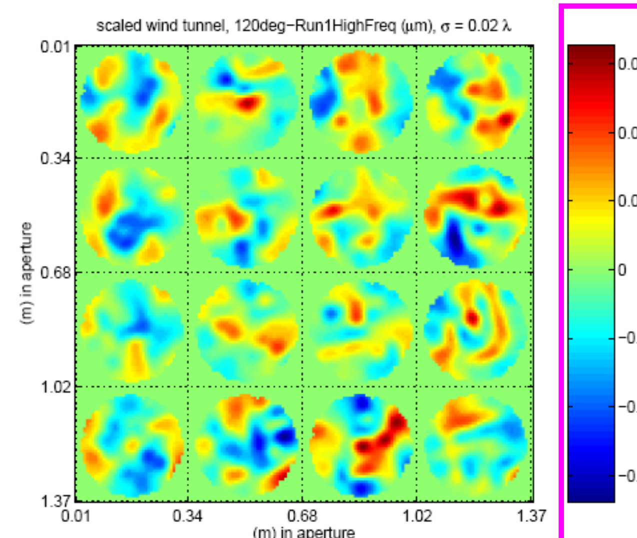
Wavefronts Scaled for Flight Conditions: D_t = 1.27 m, v_p = 0.3 Mach, h_p = 10kft

UNFILTERED | **LOW FREQUENCY (< 144 Hz)** | **HIGH FREQUENCY (> 144 Hz)**

120°

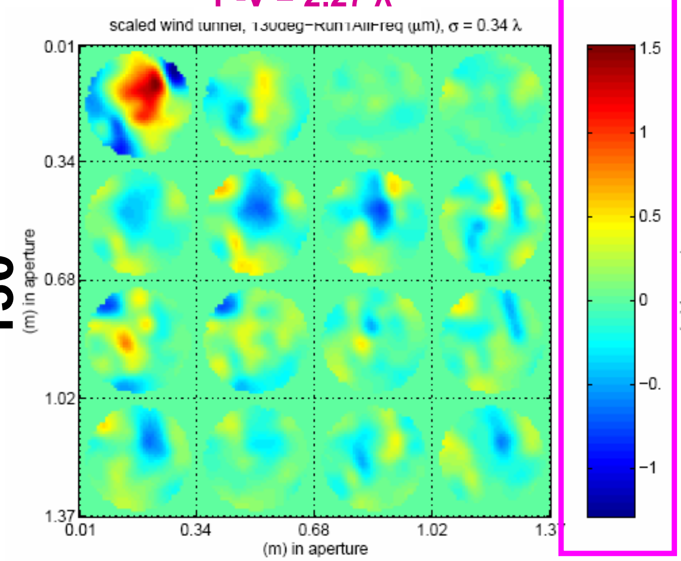


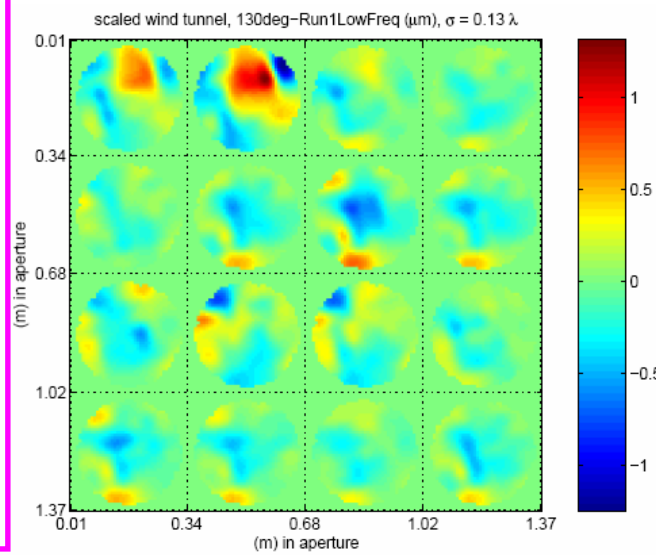


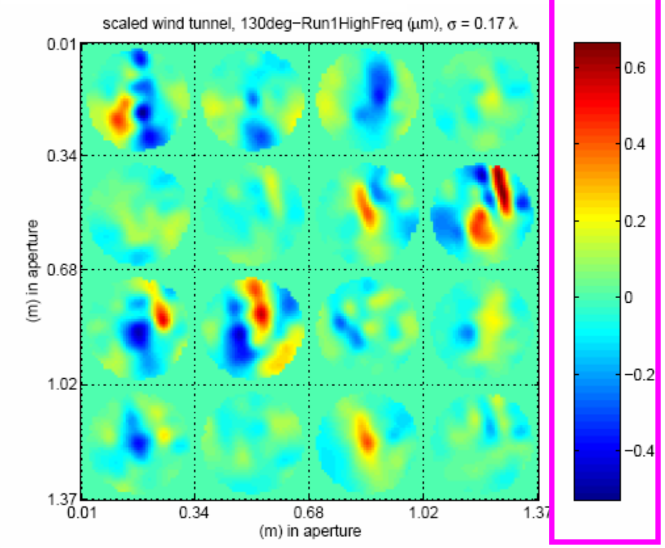


P-V = 2.27 λ | **P-V = 0.13 λ**

130°

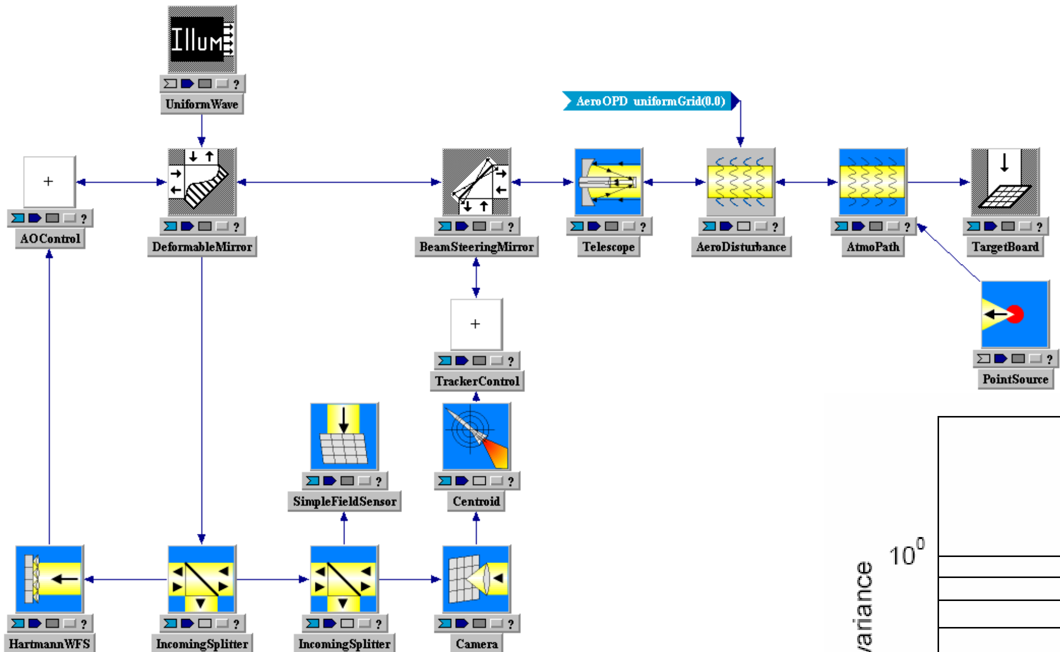






P-V = 2.81 λ | **P-V = 1.20 λ**

Simulation & Controller Characteristics



- **Closed-loop tracking and higher-order sensing/compensation**
- **Simple integrator control**

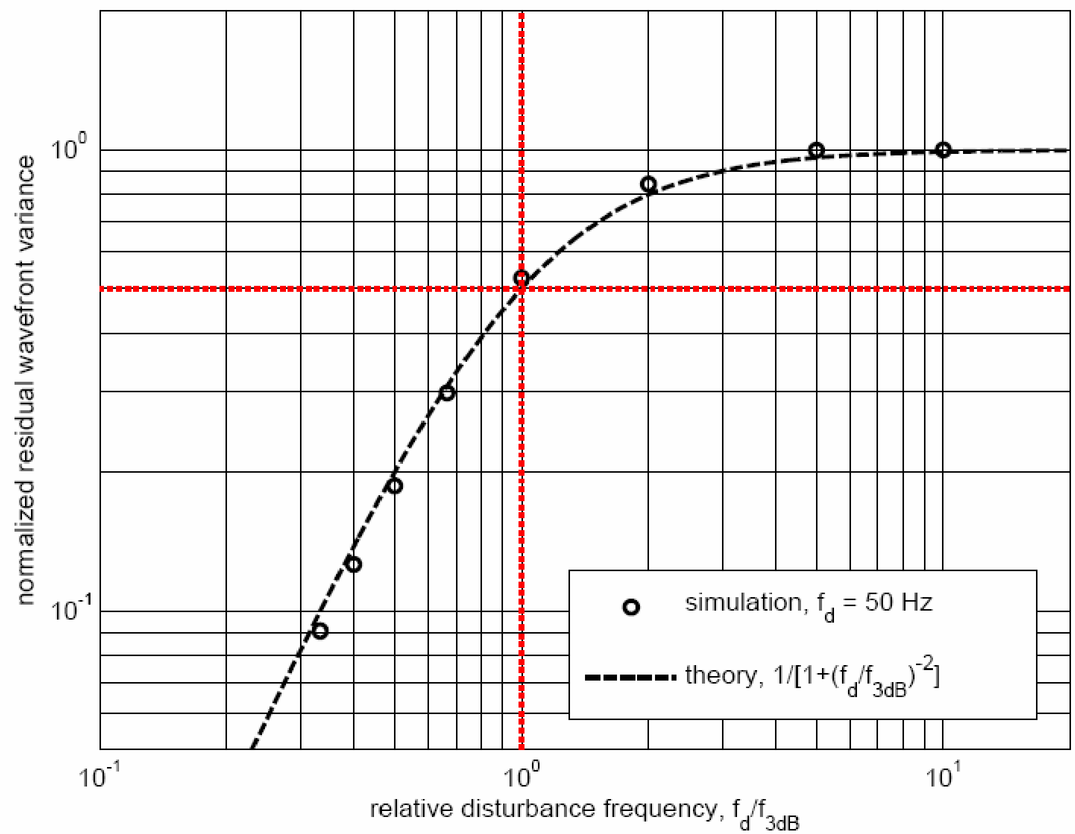
$$c(t_{k+1}) = c(t_k) + \beta\epsilon(t_k)$$

- **With 0 latency in the simulation, error rejection is given by**

$$ERJ(f) = \left[1 + \left(\frac{f}{f_{3dB}}\right)^{-2}\right]^{-1}$$

$$f_{\text{3dB}} \equiv \frac{\beta f_s}{2\pi}$$

- **Simulation & theoretical error rejection compare favorably**



Compensation Results with Variable AO Bandwidth

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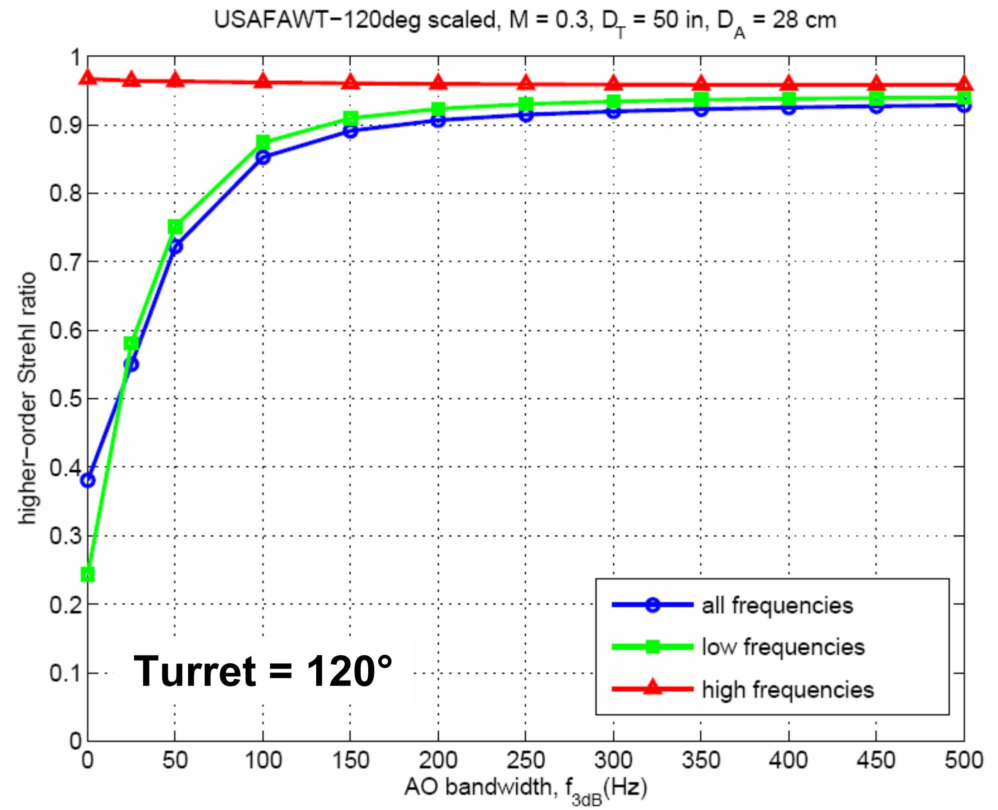

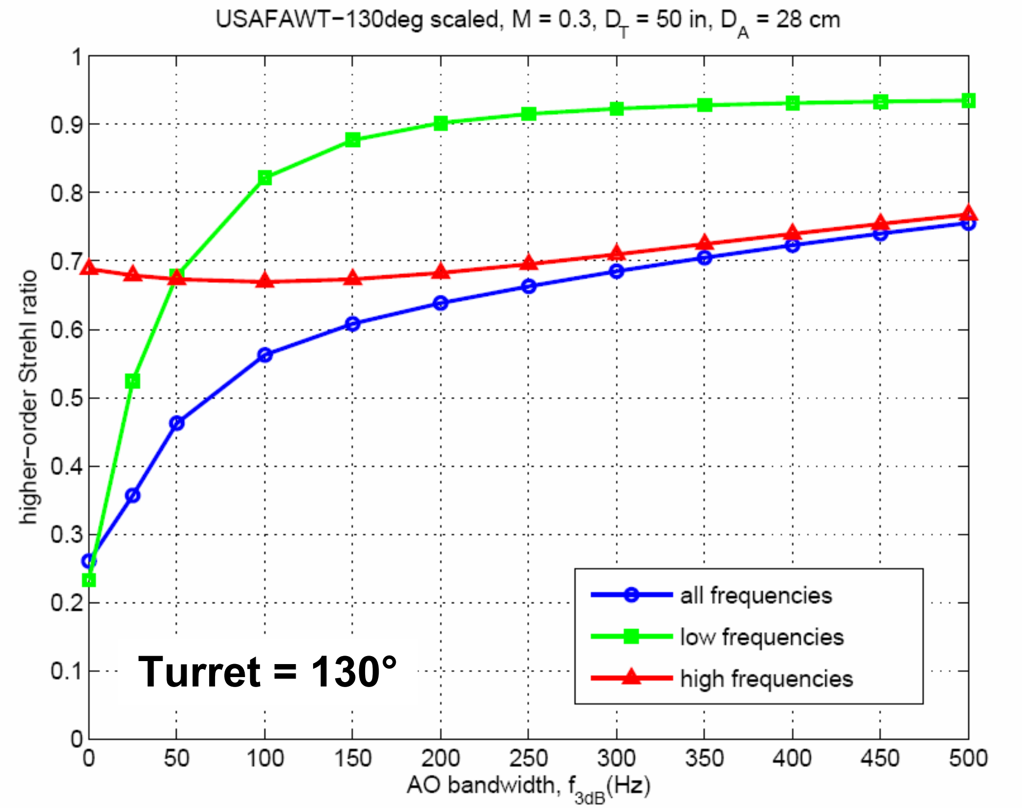

- **Open loop Strehl ratio = 0.38, closed-loop @ 500 Hz bandwidth = 0.93**
- **Shear-layer disturbance is negligible**
- **Compensation performance governed by low-frequency disturbances**

- **Open loop Strehl ratio = 0.26, closed-loop @ 500 Hz bandwidth = 0.76**
- **Disturbance is dominated by low-frequency components**
  - **Well-compensated with 200 Hz AO loop**
- **High-frequency OPD limits compensation**

Compensation Scaling Analysis

- **Compensation data tested for power-law scaling behavior**

$$\frac{\varepsilon_\phi^2}{\sigma_\phi^2} = K \cdot f_{3dB}^{-\gamma}$$

- **Linear fit of natural log of normalized phase variance to natural log of compensation bandwidth gives power-law fitting parameters**
- **Compensation power-law can be written in the following form:**

$$\varepsilon_\phi^2 = \frac{1}{2}\sigma_\phi^2 \left(\frac{f_A}{f_{3dB}}\right)^\gamma \rightarrow S_h \simeq \exp\left[-\frac{1}{2}\sigma_\phi^2 \left(\frac{f_A}{f_{3dB}}\right)^\gamma\right]$$

- **Aero-optics compensation scaling frequency f_A gives bandwidth at which disturbance is reduced by a factor of 2**
- **Analogous to scaling law for compensation of free-stream turbulence**

$$S \simeq \exp\left[-\left(\frac{f_G}{f_{3dB}}\right)^{5/3}\right]$$

Compensation Scaling Results
130° Turret Angle

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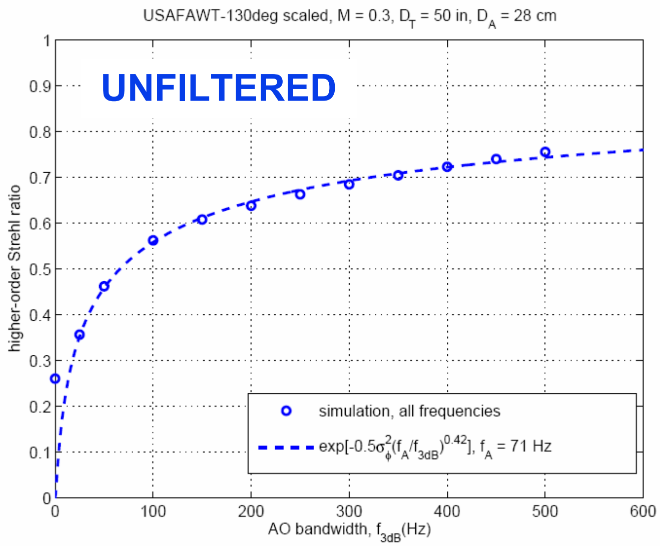
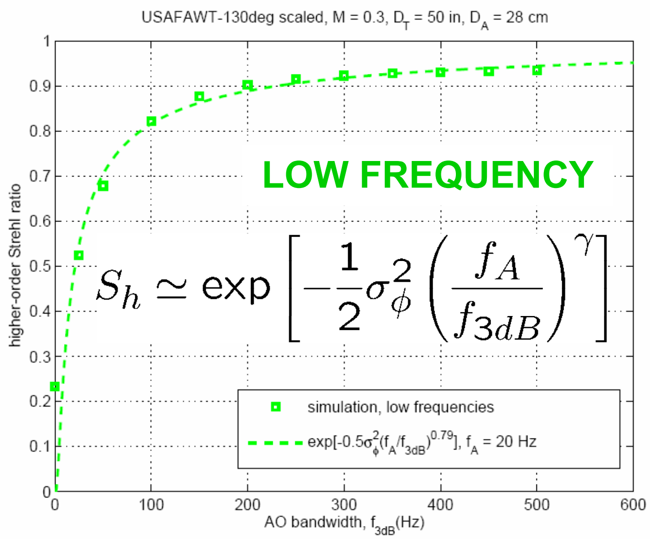
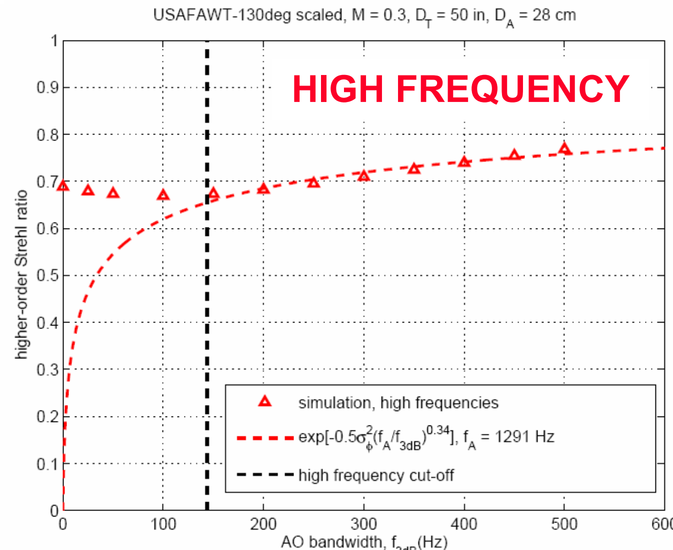




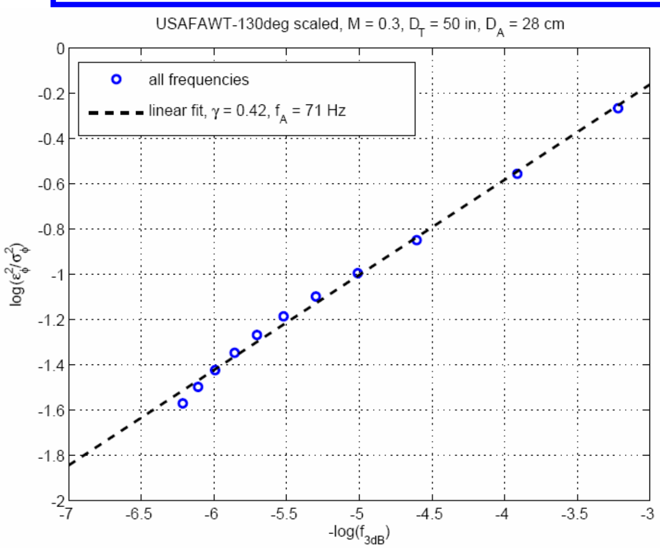
$$S_h \simeq \exp\left[-\frac{1}{2}\sigma_\phi^2\left(\frac{f_A}{f_{3dB}}\right)^\gamma\right]$$

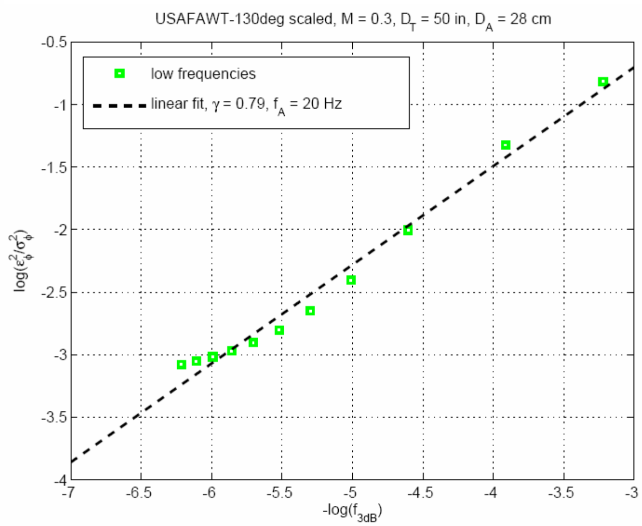


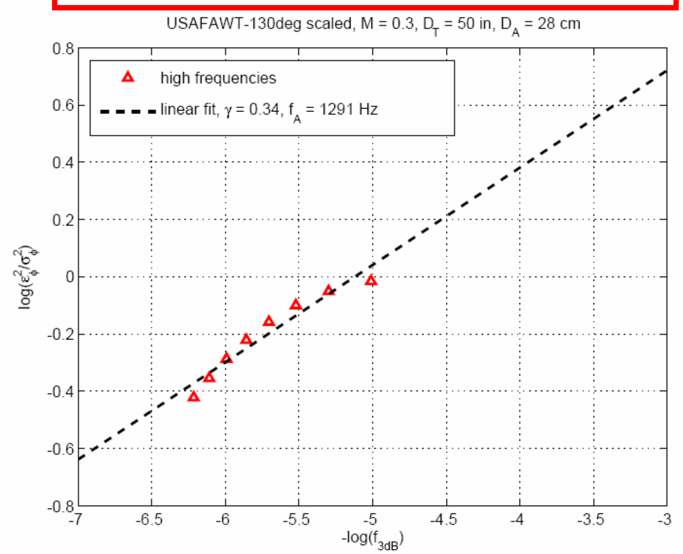
$$\sigma_\phi = 0.19\ \lambda$$
$$\gamma = 0.42,\ \ f_A = 71\ \text{Hz}$$

$$\sigma_\phi = 0.19\ \lambda$$
$$\gamma = 0.79,\ \ f_A = 20\ \text{Hz}$$

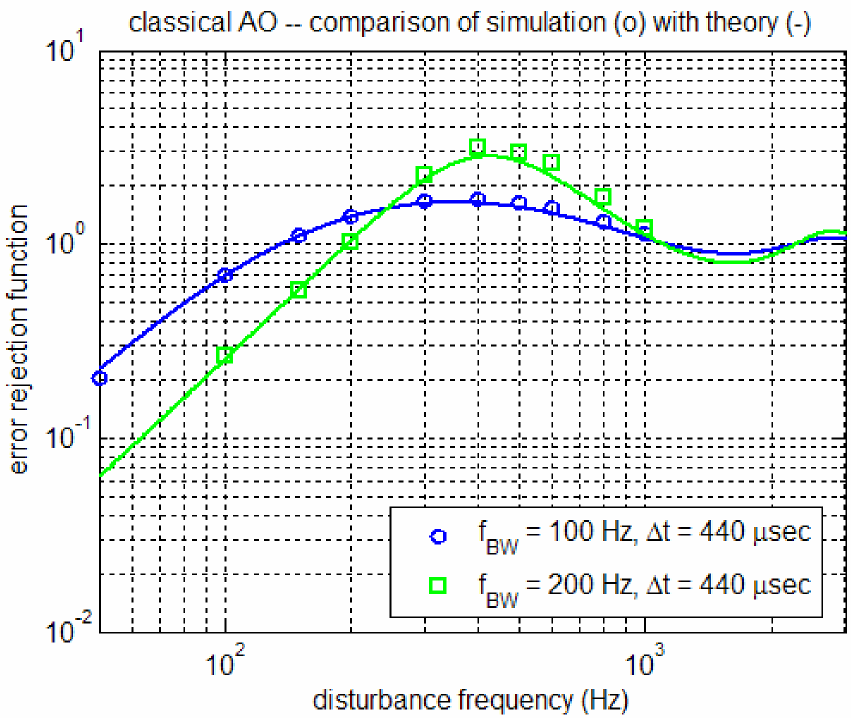
$$\sigma_\phi = 0.10\ \lambda$$
$$\gamma = 0.34,\ \ f_A = 1291\ \text{Hz}$$







AO Latency: Implications to Aero-Optics



- **Practical AO systems suffer degradation due to net latency**
  - **Sensor integration, read-out, reconstruction/processing, DM response, etc.**
- **Error rejection takes on more general form under these conditions**

$$ERJ(f) = \left[1 + \left(\frac{f_{BW}}{f}\right)^2 - 2\left(\frac{f_{BW}}{f}\right)\sin(2\pi f \Delta t)\right]^{-1}$$

- **Incorporate this model directly in aero-optics compensation analysis**

$$\varepsilon_{res}^2 = \int_0^\infty ERJ(f; f_{BW}, \Delta t)\Phi_d(f)\, df \rightarrow S_{h,aero} \simeq \exp(-\varepsilon_{res}^2)$$

- **Can consider this as a composite of low-frequency and high-frequency phenomena**

$$S_{h,aero} = \exp(-\varepsilon_{res:\ low}^2)\exp(-\varepsilon_{res:\ high}^2)$$

$$S_{h,aero} = S_{h,aero:\ low} \cdot S_{h,aero:\ high}$$

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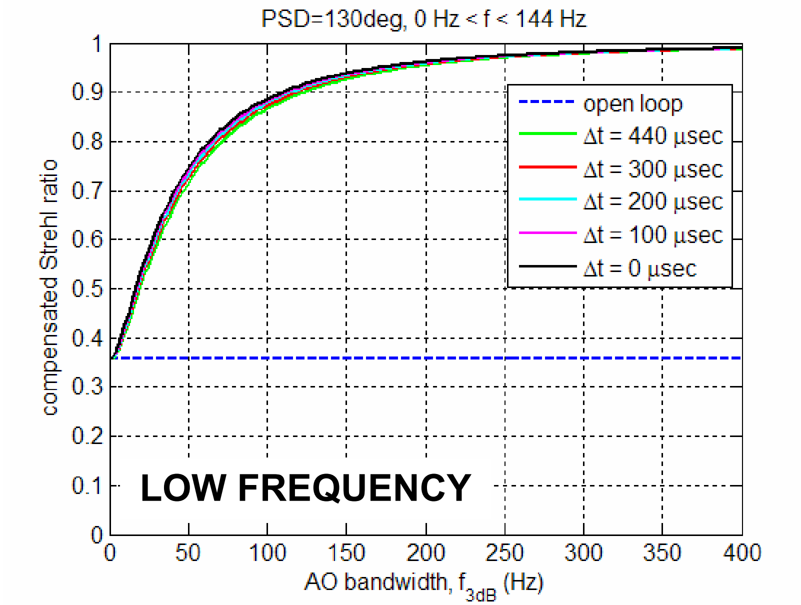
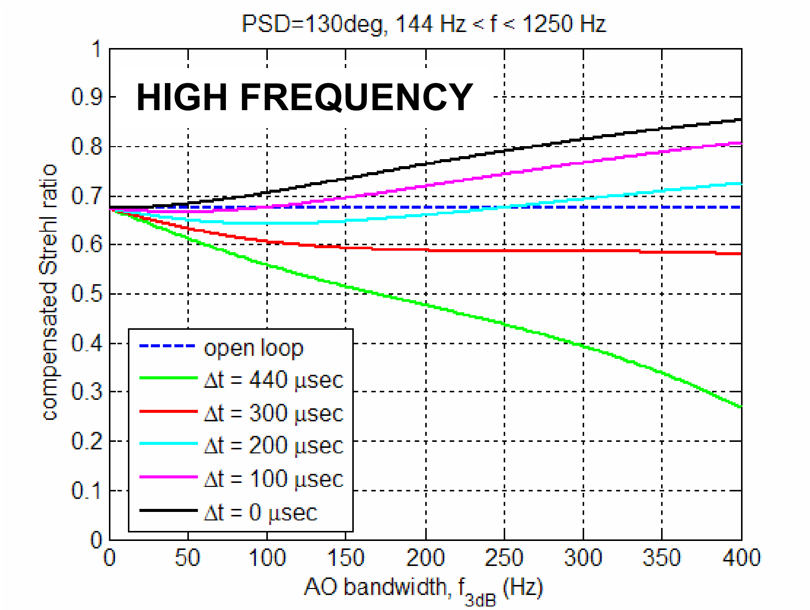
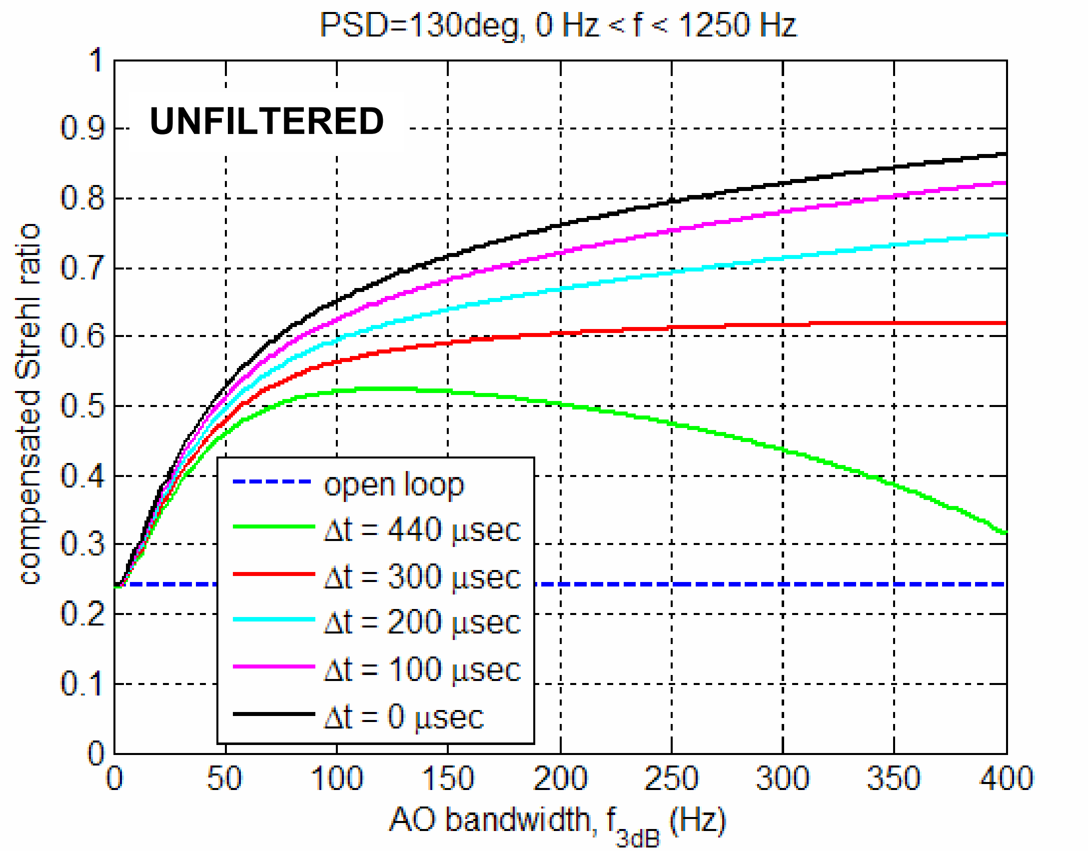
Effect of AO Latency: 130° Turret Angle

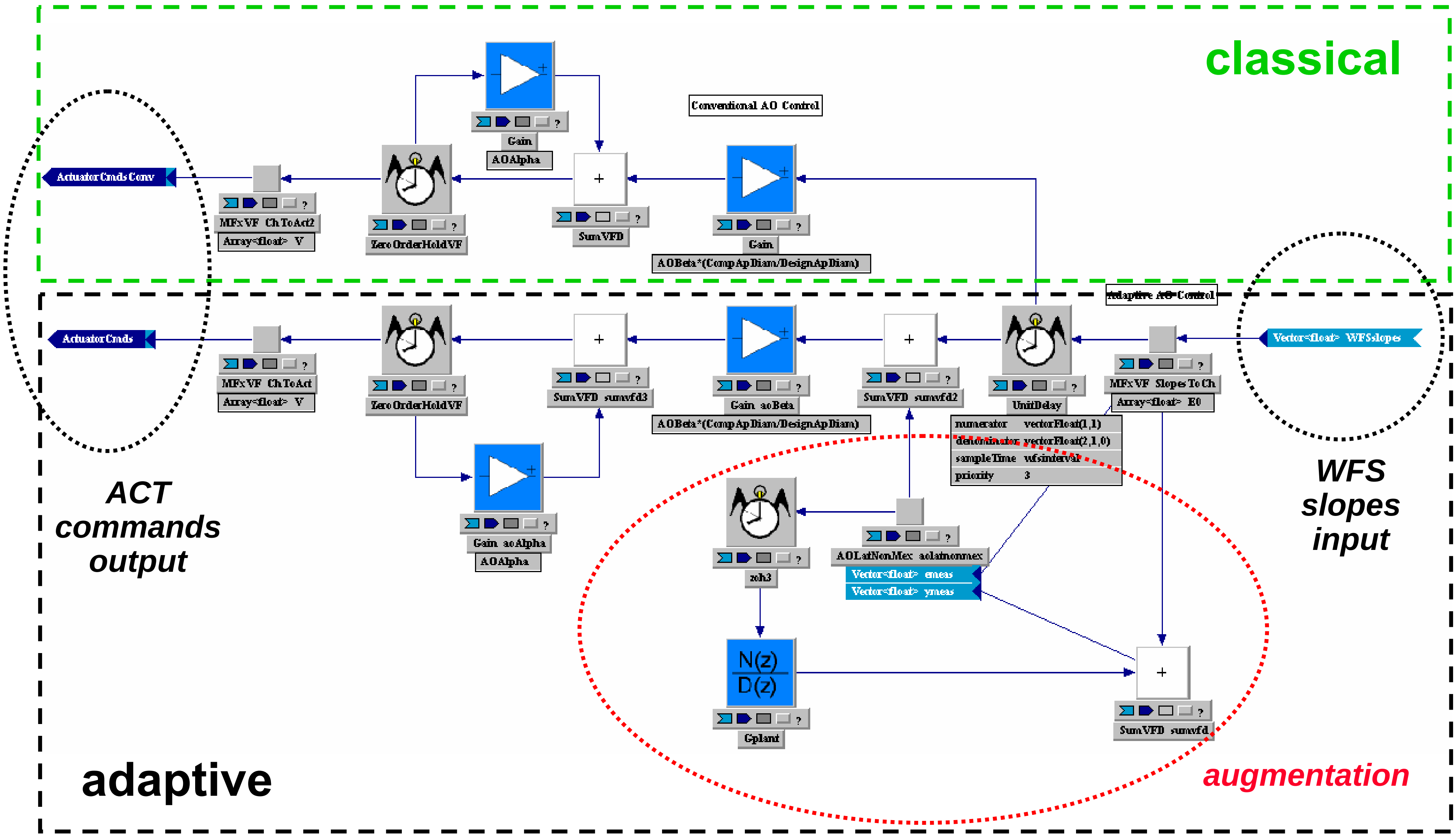






- **Error rejection with latency used with disturbance PSDs to quantify residual Strehl**
- **Degradation with AO latency is driven by presence of high-frequency aero-optics**
- **Shear-layer compensation requires high-bandwidth, low-latency control**

WaveTrain Adaptive Controller Implementation



AO Simulation Results: Aero-Optics Only

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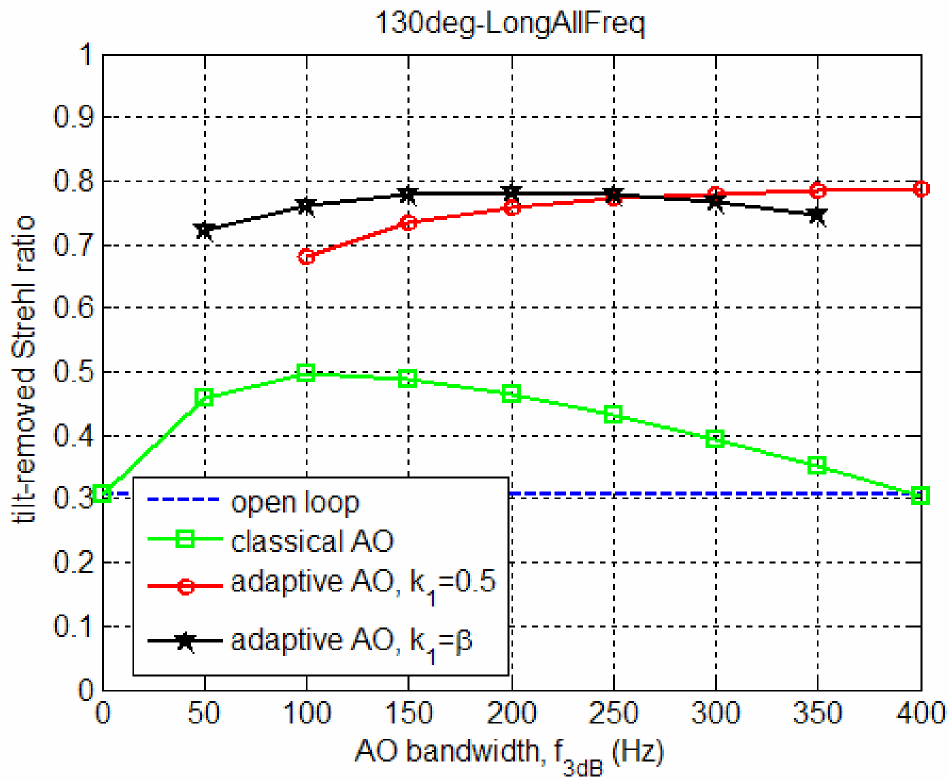

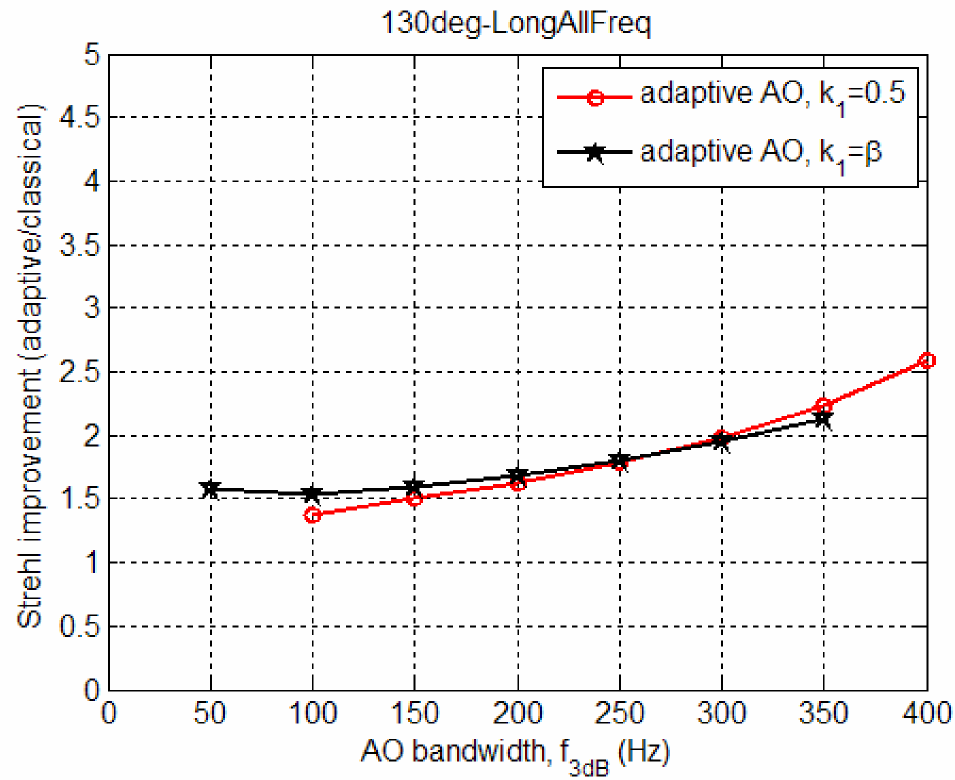

- **<u>Unfiltered</u> aero-optics disturbance**
- **Classical AO control optimized for 100 Hz – 150 Hz bandwidth**
- **Adaptive control reduces degradation due to latency and limited bandwidth**
- **Performance improvement with adaptive control**
- **1.5x – 2.5x depending on bandwidth**

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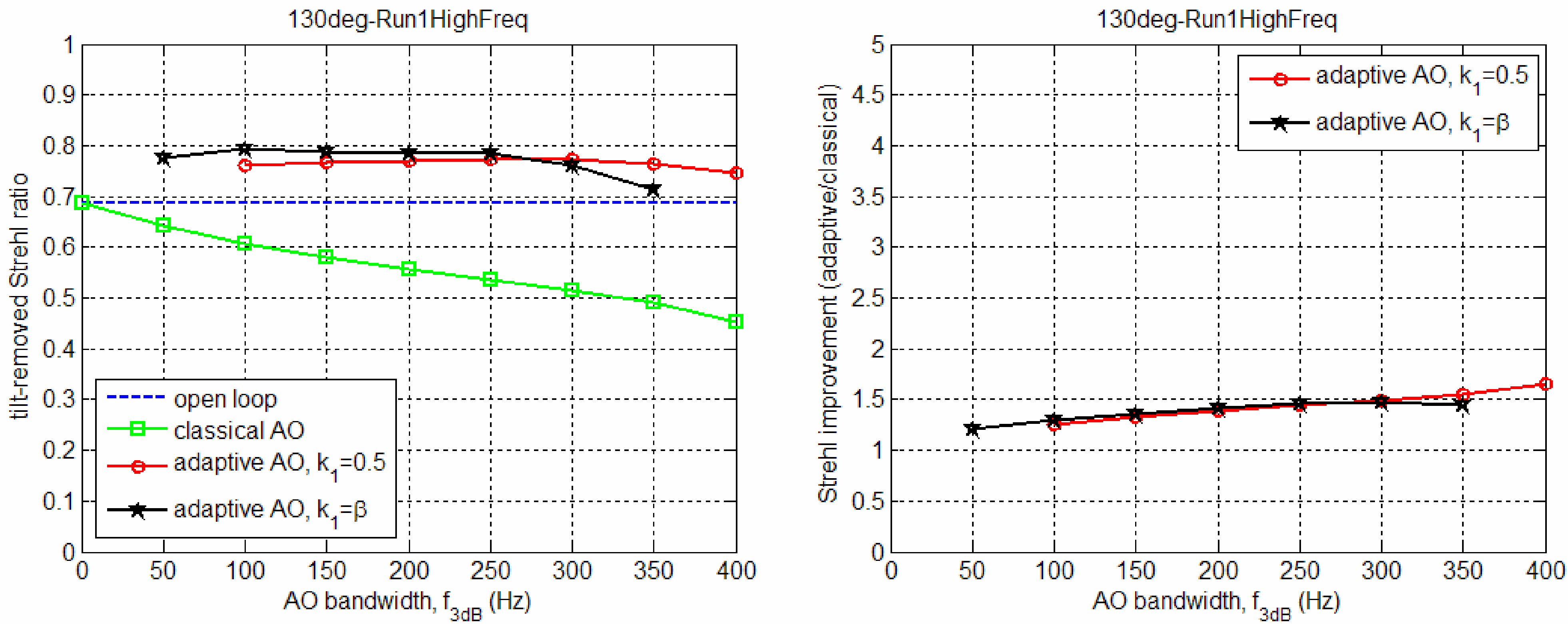
AO Simulation Results: Shear-Layer Only



- **<u>Filtered high-frequency</u> shear layer**
- **Classical AO with 440 μsec latency degrades compensation of shear layer**
- **50 Hz bandwidth + latency with adaptive control similar to 500 Hz classical control with 0 latency**
- **Performance improvement with adaptive control**
- **1.25x – 1.5x increase in compensated Strehl ratio**

AO Simulation Results: Free-Stream Turbulence Only

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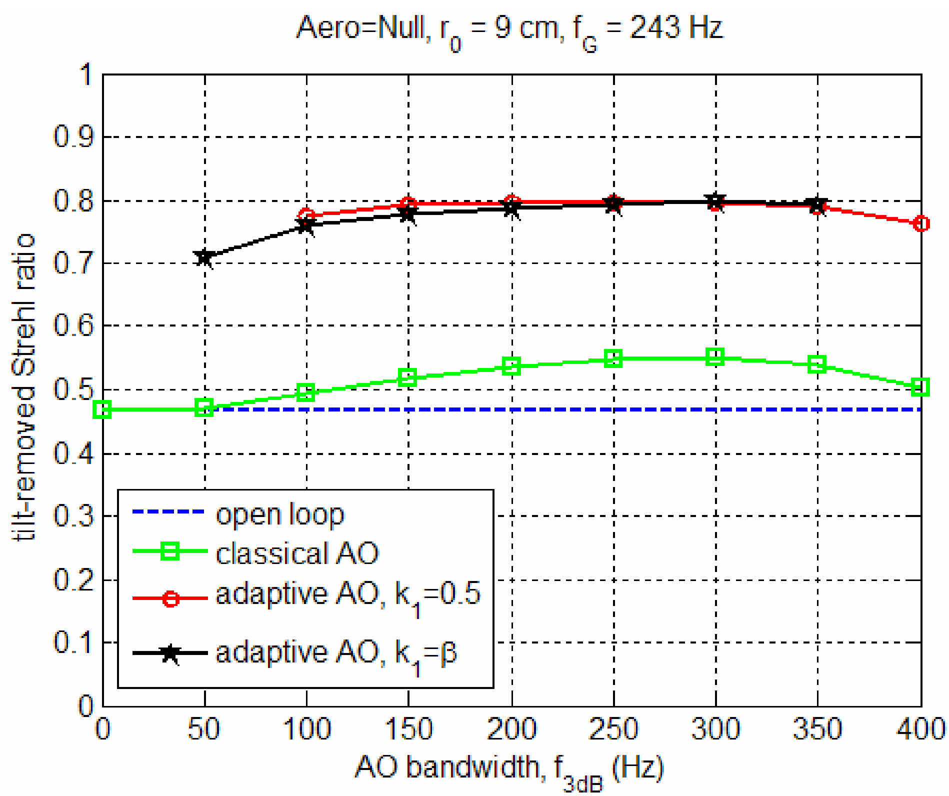

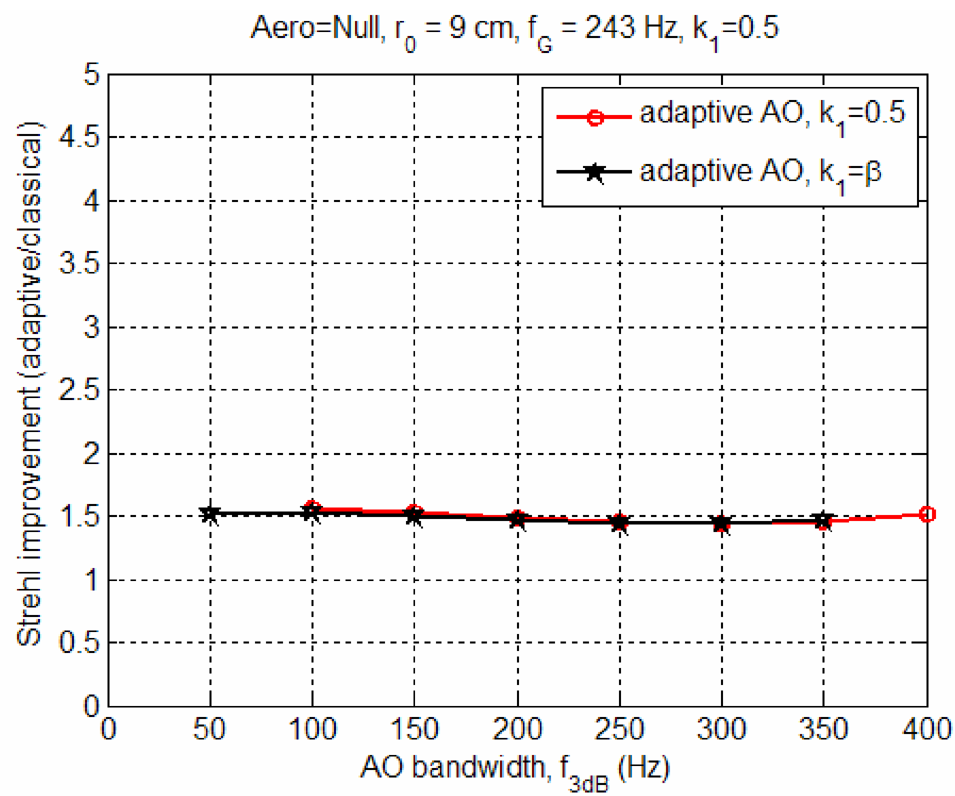

- **Free-stream turbulence only**
- **D/r0 = 3, f_G = 243 Hz**
- **Classical AO control optimized for ~300 Hz bandwidth**
- **Performance improvement with adaptive control**
- **~1.5x increase in compensated Strehl ratio over full range of bandwidths**

AO Simulation Results: Aero-Optics + Free Stream

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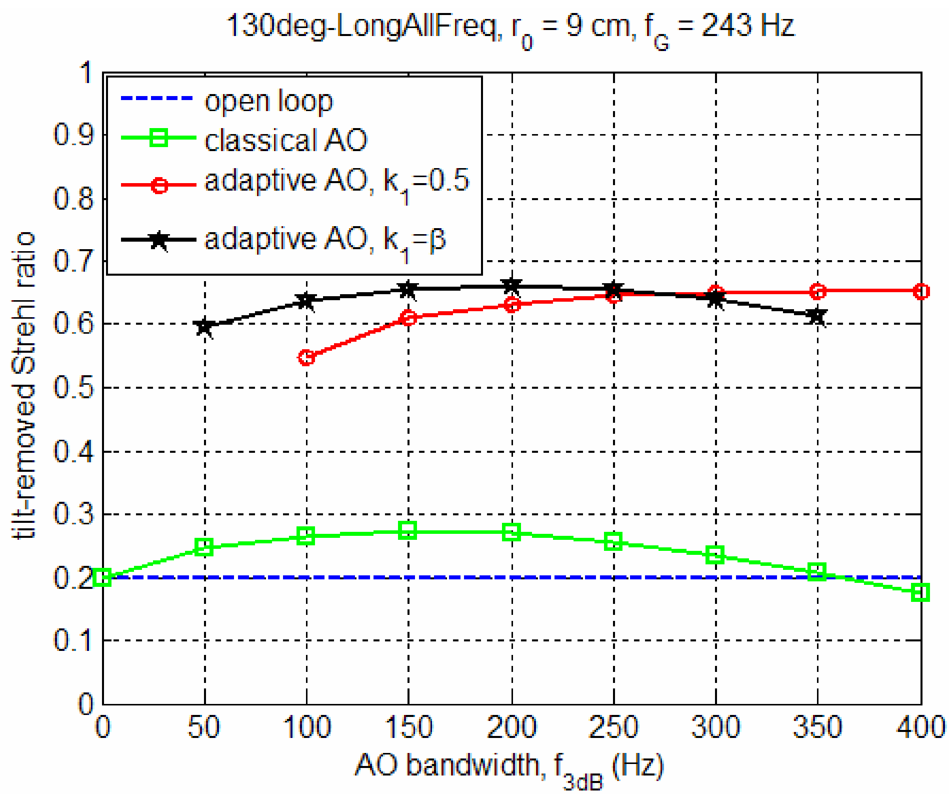

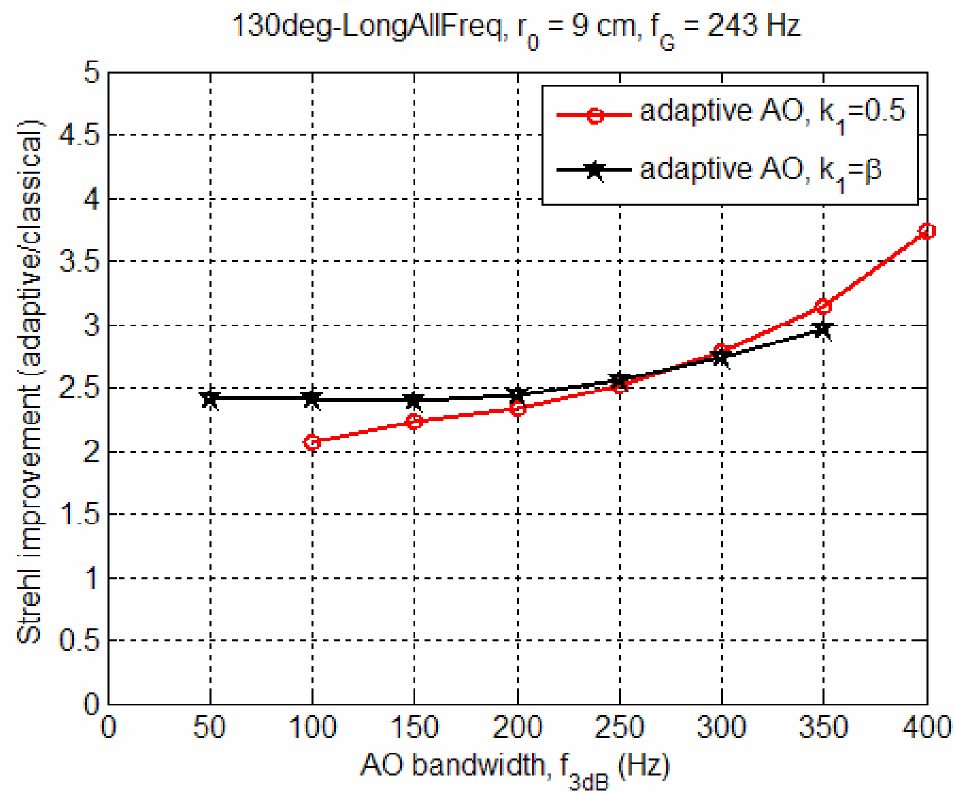

- **Combined aero-optics and free stream turbulence**
- **Classical AO control optimized for 150 Hz – 200 Hz bandwidth**
- **Adaptive control greatly increases compensated Strehl ratio**
- **Performance improvement with adaptive control**
- **2.5x – 4.0x increase in compensated Strehl ratio**
- **Net improvement nearly multiplicative**
  - **Aero-optics improvement x free-stream improvement**

AO Simulation Results: Summary

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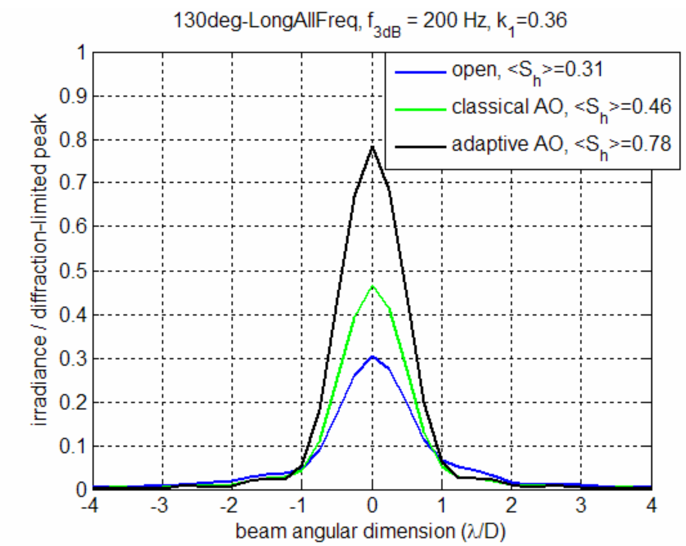
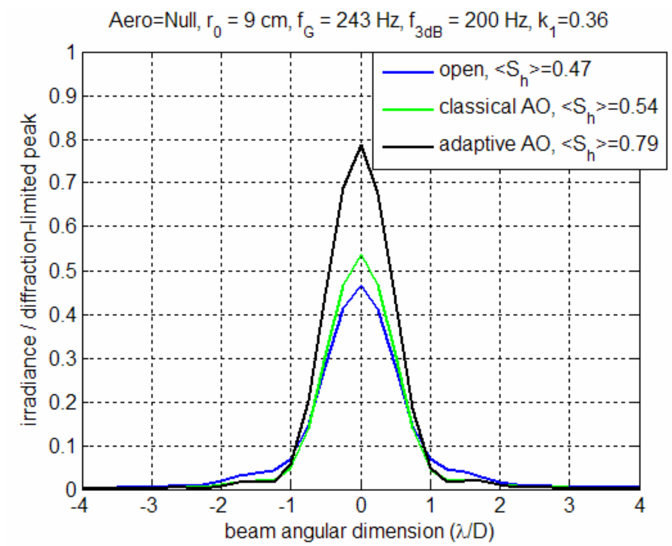
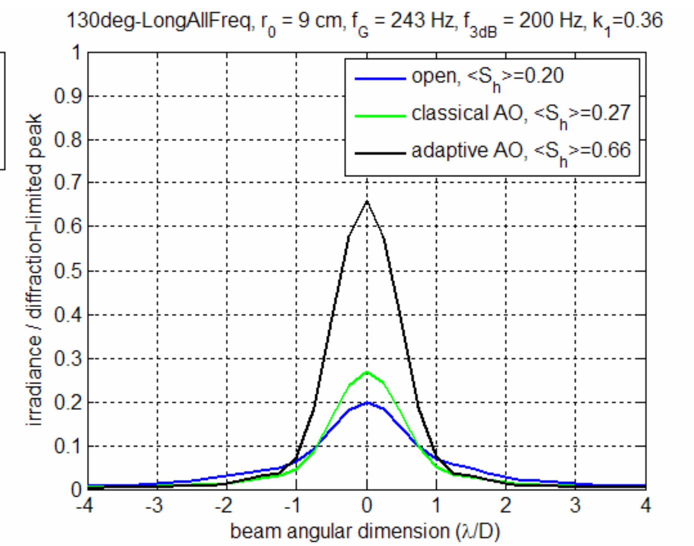


aero-optics only



free-stream only



aero-optics + free-stream

D/r_0	f_G (Hz)	aero sequence	S_h, classical AO	S_h, adaptive AO	Strehl improvement
0	0	130° Long	0.46	0.78	**1.68**
2	158	NULL	0.71	0.84	**1.17**
2	158	130° Long	0.35	0.70	**2.02**
2	296	130° Long	0.33	0.68	**2.06**
3	243	NULL	0.54	0.79	**1.47**
3	243	130° Long	0.27	0.66	**2.44**
3	454	130° Long	0.25	0.64	**2.60**

Adaptive control robust to composite disturbance condition

Conclusions

- **Classical AO compensation effective against low-frequency, large-magnitude disturbances**
  - **Constitute the bulk of aero-optical OPD at the turret angles examined**
  - **Bandwidth requirements achievable with reasonable sensors & standard control (1-2 kHz sample rate, 100-200 Hz error rejection bandwidth)**
- **High-frequency shear-layer disturbances require a high-bandwidth and low-latency control system**
  - **Latency causes AO to amplify shear layer**
- **Adaptive control will help recover high-bandwidth degradations in compensation**
  - **Aero-optics degradation due to shear layer**
  - **Free-stream turbulence with higher value of Greenwood frequency**
- **Adaptive control robust to net disturbance conditions**
  - **Augmentation adjusts to residual from classical loop**
  - **Multiplicative improvement with aero-optics and atmospheric turbulence**

Acknowledgement

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  - Sponsored by the Air Force Research Laboratory