Laser Tomographic Adaptive Optics on Simulated 10-m and 30-m Telescopes at Red Optical Science Wavelengths

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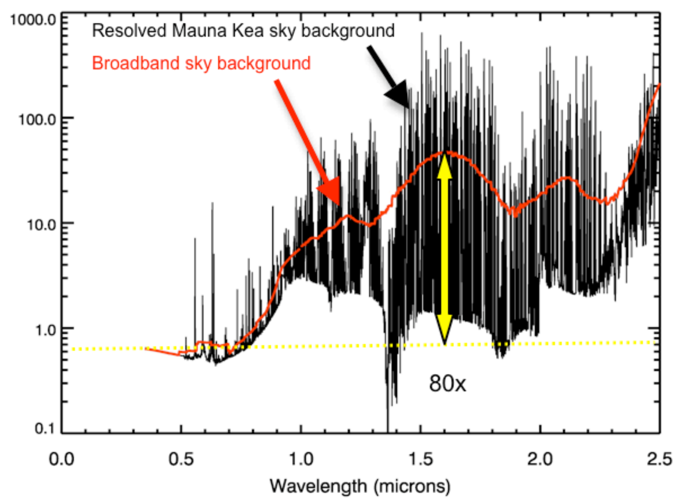
Abstract

We perform high-order Laser Tomographic Adaptive Optics for simulated 10-meter and 30-meter telescopes with the multi-guide star LTAO/MOAO testbed at UCSC. For the ELT experiment, eight Sodium Laser Guide Stars (LGSs) are sensed by 99x99 Shack-Hartmann wavefront sensors over 75". The AO system is instantaneously diffraction-limited at a science wavelength of 800 nm (S ~ 6-9%) over a field of regard of 20" diameter. Open-loop WFS systematic error is observed to be proportional to the total input atmospheric disturbance and is nearly the dominant error budget term (81 nm RMS), exceeded only by tomographic wavefront estimation error (92 nm RMS). On a simulated 10-meter aperture, the system is diffraction-limited at blue wavelengths (425 nm). The total residual wavefront error for this experiment is comparable to wide-field tomographic adaptive optics systems of similar wavefront sensor order and LGS constellation geometry planned for Extremely Large Telescopes.

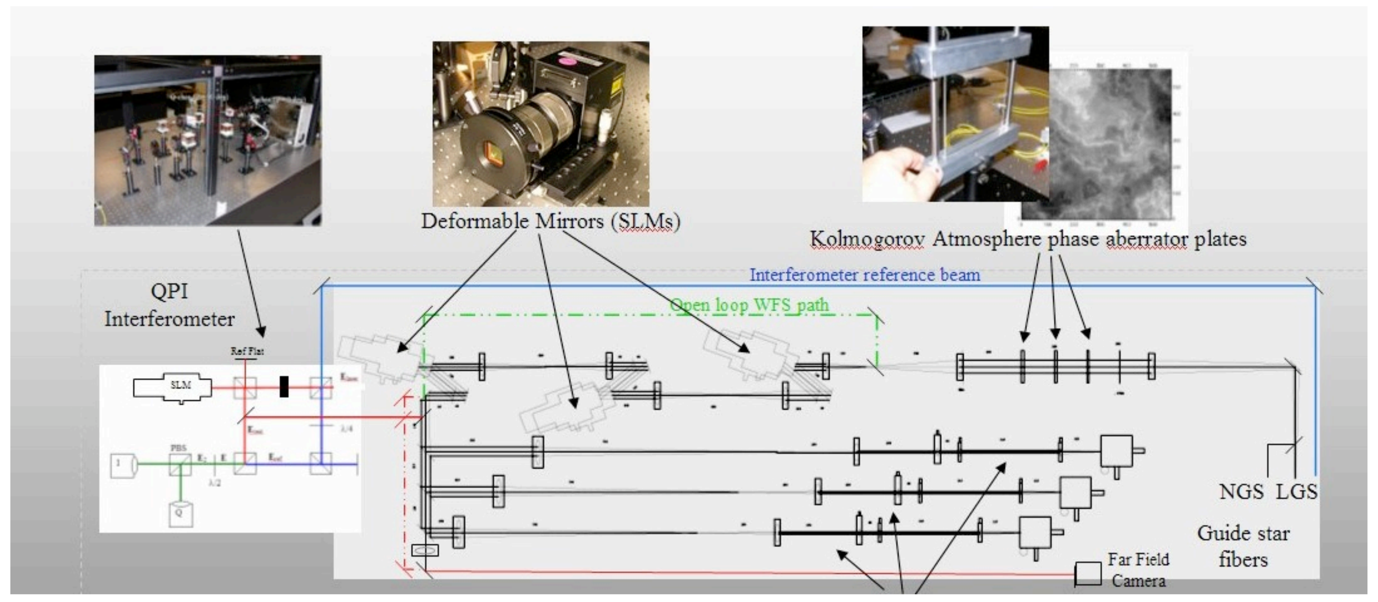
Achieving the diffraction-limit at visible wavelengths can enhance an ELT's imaging sensitivity to faint, compact sources by nearly 5 magnitudes.[1]

The sky brightness in *R*-band from ground-based telescopes is nearly two orders of magnitude darker than the *H*-band background. Thus, extending diffraction-limited correction from *H* to *R*-band with equivalent Strehl can increase a telescope's sensitivity to unresolved sources by more than three AB magnitudes. *An ELT with diffraction-limited resolution at visible wavelengths would be unsurpassed by any other telescope in point source sensitivity.* This capability would enable ground-breaking studies of extragalactic globular clusters, distant quasars, and resolved stars in nearby galaxies.



Mauna Kea sky background vs. wavelength (Mountain et al. 2009). The broadband R-band sky background is darker than the H-band background by a factor of 80.

The LTAO/MOAO testbed at UCSC models a high-order LTAO instrument on an ELT with the goal of reaching the diffraction-limit at visible science wavelengths. Wavefront sensing is performed by multiple Shack-Hartmann sensors with up to 100x100 subapertures. Spatial light modulators are used as deformable mirrors. *The majority of effects that frustrate visible-light correction are modeled, including optical vibration, scintillation, open-loop calibration error, and focal anisoplanatism.* We study the instantaneous performance of high-order atmospheric tomography and exclude most temporal error terms like delay. The equivalent brightnesses of the simulated NGSs are such that the on-axis tip/tilt error is small compared to the diffraction-limited image width of a 30-meter aperture at a science wavelength of 800 nm.

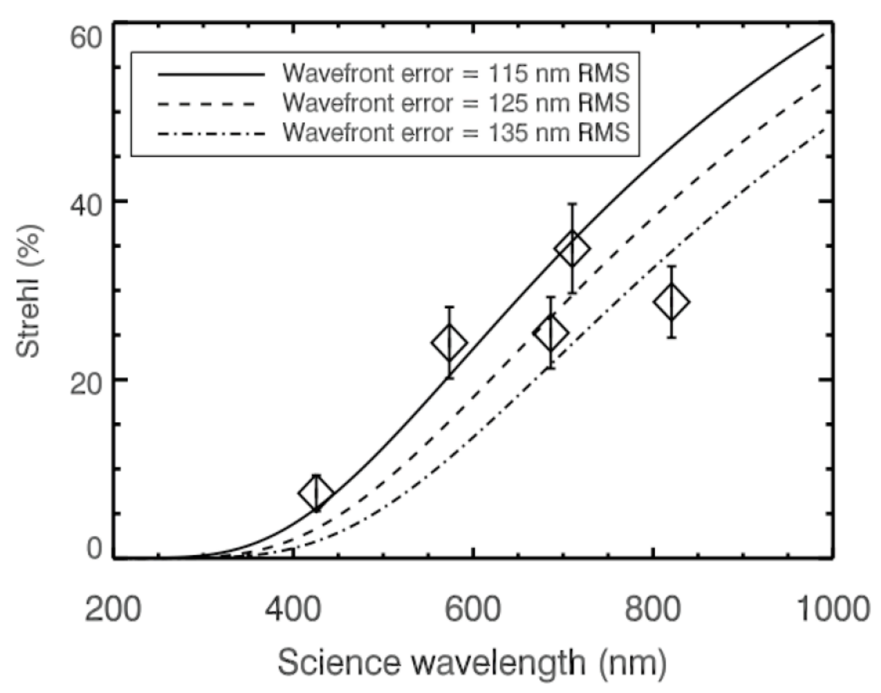


Optical layout of MOAO/LTAO testbed

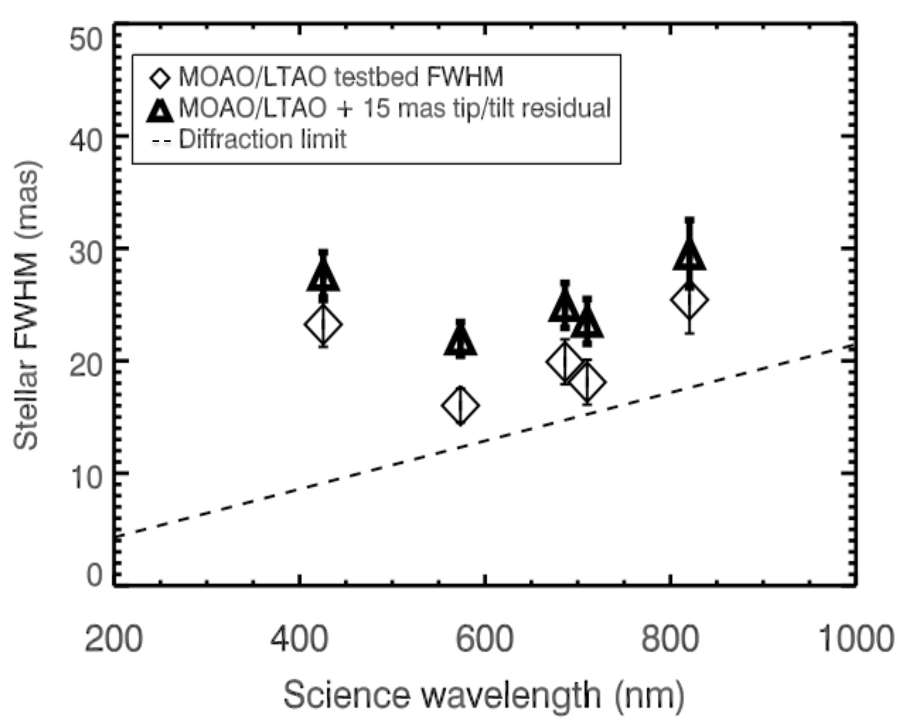
With a 10-meter aperture, 5 LGS's over a 45" field of regard, and high-order 85x85 Shack-Hartmann wavefront sensors, the LTAO testbed achieves the diffraction-limit at blue optical wavelengths.

We simulate different science wavelengths by changing the atmospheric thickness (D / r_0) when the telescope diameter is kept fixed at 10 meters. The atmosphere has a Mauna Kea-like C_N^2 height distribution and wind speeds of 10 m/s. The Shack-Hartmann wavefront sensor has 85x85 subapertures across a 10-m pupil and the deformable mirror has 85x85 actuators. Tomographic processing is performed as described in Gavel (2004). Open-loop wavefront sensing and reconstruction is performed as in Ammons et al. (2010). *The on-axis Strehl for $D / r_0 = 74$ (simulating $\lambda = 425$ nm) is 10% and the off-axis (8-12") Strehls are 5-8% over a 200 millisecond simulation.*

Strehl vs. wavelength with 5 LGS's and 10-meter aperture



FWHM vs. wavelength with 5 LGS's and 10-meter aperture

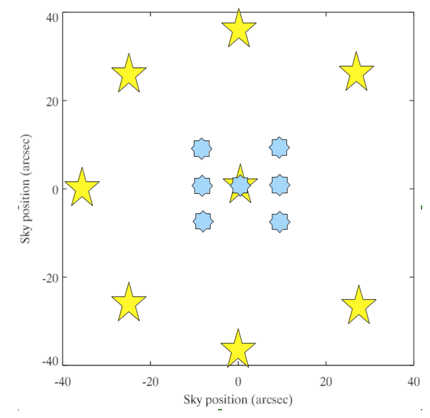


The figures above and to the left show the measured Strehls and image widths as a function of simulated science wavelength. The Strehl data match the Mareschal approximation for a fixed wavefront error of ~125 nm RMS. The FWHM as a function of wavelength reaches a minimum of 16 milliarcseconds at 500 nm. Including an expected tip/tilt residual of 15 milliarcseconds RMS on-sky for bright tip/tilt stars, FWHM's of 20 milliarcseconds may be possible on a 10-meter telescope with an LTAO system of this order.

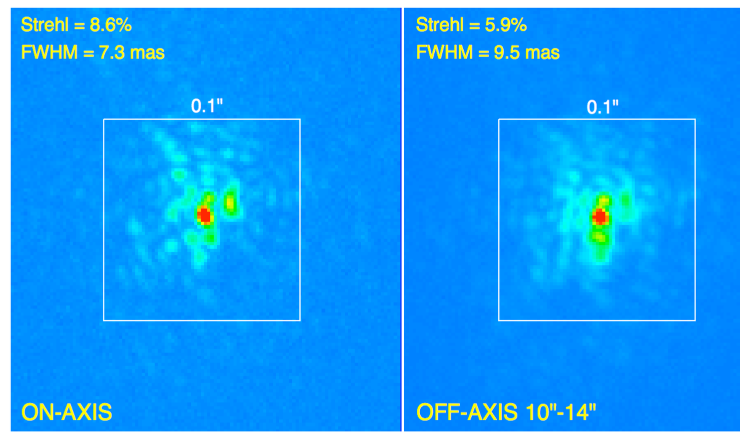
References:
1. Ammons, S.M., et al. 2010, PASP, 122, 573.
2. Gavel, D. 2004, proc. SPIE, 5490, 1356.
3. Mountain, M., et al. 2009, Astro2010: The Astronomy and Astrophysics Decadal Survey, Technology Development Papers, no. 12.

LTAO trades focal anisoplanatism (~300 nm for a TMT) for tomography error (~110 nm on-axis for 8 LGS's on a TMT), enabling diffraction-limited performance below 1 micron. With a 30-meter aperture and 99x99 wavefront sensors, the LTAO testbed achieves ~9% Strehl on-axis at a science wavelength of 800 nm ($D / r_0 = 103$).

We arrange eight LGS's to maximize on-axis Strehl with Laser Tomography (constellation diameter of 75") for a 30-meter aperture. 99x99 Shack-Hartmann wavefront sensors are used with 30 cm subapertures. *Over a 100 millisecond simulation, the on-axis and off-axis PSFs have FWHMs of 7.3 mas and 9.5 mas, respectively (diffraction-limit is 5.7 mas). The on-axis and off-axis Strehls are 8.6% and 5.9%.*



LGS constellation for 30-meter experiment. Yellow stars are LGS's and blue stars are science stars.



On-axis and off-axis PSFs for 100 ms experiment on a 30-meter aperture.

Error Budget Term	On-sky, on-axis	On-sky, off-axis (12."5)	Lab, on-axis (658 nm)
Fitting Error	70.4	70.4	57.9
WFS Aliasing	38.9	38.9	32.0
Tomography Error	112	130	92.0
WFS Systematic error	97.6	97.6	80.3
PPM Lookup Table error	36.5	36.5	30.0
Static Uncorrectable, S=75%	68.3	68.3	56.2
Scintillation	11.8	11.8	9.7
WFS Scintillation	25.0	25.0	20.6
Photon error	18.2	18.2	15.0
WFS zeropoint drift	12.2	12.2	10.0
Linearity calibration drift	12.2	12.2	10.0
Pupil registration drift	9.8	9.8	8.1
Total RMS	189.7	200.9	155.9
Predicted Strehl (%)	10.9	8.3	10.9
Measured Strehl (%)	8.6	5.9	8.6

Error budget for 30-meter experiment for a science wavelength of 800 nm.

Repeatable systematic errors in the WFSs are partially corrected with a linearity calibration (Ammons et al. 2010). Residual systematic error is a result of either non-monotonic nonlinearities in the gain curves or dynamic changes in the WFS optics. *This WFS Systematic error is observed to be proportional to the total atmospheric error with the fitted relation $\sigma_{WFS\ Sys.} = 0.045\ \sigma_{atmos}$.* For the experiment presented here, the open-loop error is measured to be 80.3 nm RMS for depistoned and detilted atmospheres of 1820 nm RMS. The WFS Systematic error is nearly as large as the tomographic error due to blind modes (92 nm in laboratory units).

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[1] comparing seeing-limited and diffraction-limited observations in R-band on a 30-meter telescope, assuming 20% Strehl in R-band, background-limited observations, and 30% lower throughput with LTAO than with a seeing-limited visible-light imager