1st AO4ELT conference, 02001 (2010)
DOI:10.1051/ao4elt/201002001

Adaptive Optics Systems for the Thirty Mirror Telescope

Brent Ellerbroek,[a]

TMT Observatory Corporation

Abstract. At first light, the overall AO system architecture for the Thirty Meter Telescope will consist of the Narrow Field Infra-Red AO System (NFIRAOS) and the associated Laser Guide Star Facility (LGSF). NFIRAOS is an order 60x60, dual conjugate, laser guide star AO system designed to obtain diffraction-limited performance in the near IR with high sky coverage. It will provide a delivered wavefront error of 190-200 nm RMS over a central 15-30 arc second field-of-view, and a lesser degree of atmospheric turbulence compensation over a larger 2 arc minute field for multi-object spectroscopy and low order (tip/tilt/focus) natural guide star wavefront sensing in the near IR. The LGSF generates 6 sodium laser guidestars for use with NFIRAOS, using 6 25-watt lasers located in the telescope azimuth structure and a laser launch telescope behind the TMT secondary mirror. In this paper, we review the work to date on requirements derivation, design development, performance analysis, component prototyping, and lab/field tests for these AO systems. The possible options for future MOAO, ExAO, GLAO, and MIRAO systems for TMT are also briefly described.

1 Introduction

This paper provides a very brief introduction to the current status and future plans of the Thirty Meter Telescope (TMT) Adaptive Optics (AO) program. The top-level performance requirements for the first light facility AO system are described in Section 2, and the derived system architecture and subsystem design concepts are outlined in Section 3. Section 4 describes the estimated performance of the system. The AO component development effort is briefly summarized in Section 5, and two important AO lab and field tests are highlighted in Section 6. Section 7 lists some of the possible future upgrades being considered beyond the first light AO system, and Section 8 concludes with a brief summary of the key features and overall status of the AO development program for TMT. Finally, the other papers at this conference which describe all of these subjects in considerably greater detail are listed in the Reference section.

2 Requirements Flowdown

The principal top-level performance requirements for the TMT facility AO system at first light are summarized in Table 1 below. Briefly, these requirements correspond to diffraction-limited wavefront compensation in J, H, and K bands with good sky coverage, a moderately large corrected field, excellent astrometric/photometric accuracies, high observing efficiency, and high reliability.[1]

These top-level requirements already determine many of the basic features of the AO system architecture. Diffraction-limited wavefront compensation on a 30 meter telescope implies a very high order AO system, and the 10-30" corrected field-of-view implies the use of multiple guidestars for atmospheric tomography, together with multiple deformable mirrors for multi-conjugate AO (MCAO). High sky coverage mandates the use of laser guide star (LGS) adaptive optics, but 50% sky coverage at the galactic pole can only be achieved by paying careful attention to the natural guide star (NGS) wavefront sensors, which are still needed to measure the low-order tip/tilt/focus modes. A relatively large (2') patrol field is required simply to acquire these guide stars with adquate probability; wavefront sensing in the near IR (J+H bands) is also required, both because of the higher frequency of red stars and the partial "sharpening" of the guidestar images that will be provided by the MCAO system at these wavelengths. Multiple (at least 3) NGS will be needed to detect the effects of tilt anisoplanatism, which would otherwise blur the time-averaged image of the science object if only a single off-axis tip/tilt guide star was used.

[a] e-mail: brente@caltech.edu

AO for ELT

Table 1. Top-level TMT AO requirements at first light

Requirement	Value
Throughput	> 85% from 0.8 to 2.5 μm
Thermal emission	< 15% of background from sky+telescope at median temperature
Wavefront quality	187 nm RMS on-axis
	191/208 nm RMS average on a 10"/30" field-of-view
Sky coverage	> 50% at the galactic pole
Photometry	2% differential accuracy (10' exposure, 30" field-of-view)
Astrometry	50 μ-arc-second differential accuracy (100" exposure, 30" field-of-view)
Acquisition time	< 5' to acquire a new field (start-to-finish)
Reliability	< 1% unscheduled downtime

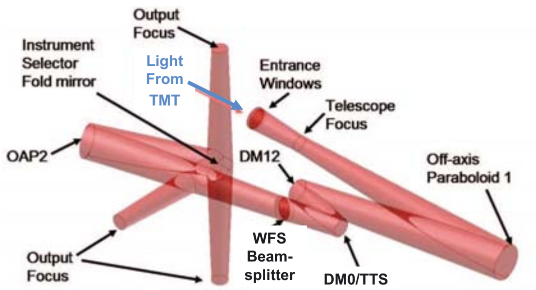

Fig. 1. NFIRAOS science optical path

Excellent photometric and astrometric accuracy imply a spatially uniform and well-characterized point spread function (PSF), which in turn implies a need for accurate PSF reconstruction and (yet again) MCAO. The requirements for high optical throughput and low thermal emission motivate the choice of an optical design form with a minimum number of surfaces, highly transmissive/reflective optical coatings, and a cooled optical path. High observing efficiency requires a highly automated control system for target and guide star acquisition, closing and optimizing control loops, and collecting science exposures (e.g., while dithering) with a minimum of overhead. Finally, high reliability can be achieved through the use of demonstrated and/or near-term system architectures and component technologies whenever possible, with understood risk and managed system complexity.

3 Subsystem Designs

The overall first light AO architecture developed from the above exercise consists of three major subsystems. These are the Narrow Field IR AO System (NFIRAOS), the Laser Guide Star Facility (LGSF), and the AO Executive Software (AOESW) system. The first two of these subsystems are briefly described in the following paragraphs.

The LGS MCAO system *NFIRAOS* will be mounted on the TMT nasmyth platform, with output ports for two vertically mounted and one horizontally mounted science instruments.[2] The basic optical design form (see Fig. 1) is a 1-1 off-axis parabola relay, which provides a coliminated beampath including the surfaces for the two deformable mirrors and the beamsplitter for the visible wavefront sensing channels (LGS, higher order NGS, and calibration). An instrument selection fold mirror then directs the IR output beam into one of the three science ports or the NFIRAOS acquisition camera. To minimize the number of optical surfaces in the science path, field (or pupil) derotation will be performed using a rotation bearing located that the NFIRAOS-to-instrument mechanical interface. As their name implies, the IR on-instrument wavefront sensors (OIWFSs) used for low-order (tip/tilt/focus) NGS wavefront sensing are also located in the science instruments.[3] Finally, the NFIRAOS science optical path will be cooled to -30 Celsium to reduce thermal emission.[4]

The current design for the *Laser Guide Star Facility* employs a relatively conservative approach based upon existing LGS facilities such as Gemini North and South.[5] The laser system is located in the telescope azimuth structure to maximize the available space, provide a fixed gravity orientation for the lasers, and minimize the potential for vibration coupling and heat dissipation from the lasers into the TMT primary mirror. The system will consist initially of 6 25W class solid state, CW laser devices with one spare.

The laser launch telescope (LLT) is located on-axis, behind the TMT secondary mirror. This location reduces the maximum separation between the launch telescope and any WFS subaperture location, which directly determines to the magnitude of LGS elongation for a CW laser beam. On account of the long path length and relatively high laser power levels, a mirror-based beam transfer optics system is envisioned to transmit the laser beams from the laser location to the LLT. This system includes diagnostics to measure the alignment, power, and beam quality of the laser beams at the telescope top end, as well as steering mirrors to compensate for the effects of telescope misalignments and fast tip/tilt jitter. Note that the laser beams must be transferred from the telescope azimuth to elevation structures along the telescope elevation axis. This segment of the beam transfer optics path must be "deployable" to enable a seeing-limited instrument to utilize this stretch of the nasmyth platform when NFIRAOS is not in use.

4 System Performance Analysis

At first light, NFIRAOS is required to obtain an on-axis wavefront error of 187 nm RMS at zenith, under median observing conditions, and with 50% sky coverage at the galactic pole. This value represents the wavefront delivered to the science focal plane, with all error sources included. Detailed modeling and performance analysis predict that this requirement can be met. These estimates are based upon high fidelity time-domain AO simulations, accounting for a range of factors including: (i) physical optics and LGS elongation effects upon wavefront sensing, (ii) the modeled and budgeted wavefront aberrations in the telescope, NFIRAOS, and science instrument, (iii) the actual RTC algorithms specified for WFS pixel processing and tomographic wavefront reconstruction, and (iv) wavefront disturbance statistics based upon a combination of TMT site measurements,[6] sodium LIDAR data, and telescope modeling. Finally, the use of the so-called "split" tomography algorithm enables the simulation of 100's of randomly selected NGS asterism in order to estimate expected performance at 50 per cent sky coverage.[8, 9]

This performance modeling is an ongoing process, but our most recent simulations predict an RMS wavefront error of 178 nm in the high-order modes corrected using the LGS WFS measurements.[7] This breaks down further (in quadrature) into a wavefront error of 127 nm RMS for fundamental atmospheric turbulence errors and WFS measurement noise, 97 nm RMS for imperfections in the AO components, and 79 nm RMS for opto-mechanical error sources. In comparison, the tip/tilt error at 50 per cent sky coverage is 47.4 nm RMS, and the total wavefront error in all of the low-order modes controlled by the OIWFS measurements is 63.4 nm RMS. The total error in both the LGS and NGS modes at 50 per cent sky coverage currently sums (in quadrature) to about 25 nm RMS more than the requirement of 187 nm RMS, which is achieved at approximately *45* per cent sky coverage. But performance evaluation and optimization is still ongoing. Further changes are expected on account of (i) new noise measurements for the baseline OIWFS detector (see below), (ii) the modestly larger isoplanatic angle at the (now selected) Mauna Kea site, and (iii) further fine-tuning of the algorithms used for OIWFS pixel processing and the servo loop compensation of the OIWFS-controlled wavefront modes.

5 AO Component Development

The critical AO hardware components for the TMT first light AO systems include sodium guidestar lasers, wavefront correctors, wavefront sensing detectors, and the real-time controller (RTC) electronics. Existing design approaches and near-term technologies have been selected for these components when possible. The most important performance parameters and the selected design choices are summarized very briefly below.

At first light, the TMT LGSF will require 7 lasers (including 1 spare) to generate the NFIRAOS LGS asterism. Their power and sodium coupling efficiency must be sufficient to obtain a signal level of 900 photodetection events per NFIRAOS subaperture at a 800 Hz sampling rate under median conditions; accounting for the round-trip throughput, this can be achieved with an average power of

Fig. 2. Prototype version of the NFIRAOS tip/tilt stage

25W and a coupling efficiency of about 130 photons-m^2/s/W/atom. This power level has now been demonstrated by several different CW and mode-locked CW laser designs based upon sum-frequency generation or simple harmonic generation of the sodium D_{2a} line at $\lambda = 0.589\,\mu$m.[10] The coupling efficiency requirement also appears to be feasible by modulating a CW laser to produce multiple lines and/or simultaneous excitation of the sodium D_{2a} and D_{2b} lines.[11] Other laser requirements include good beam quality, high reliabilty, ease of use, modest mass and size, and (as a goal) operability with a variable gravity vector orientation. TMT is an active partipant in the current round of guidestar laser design and development contracts, which appear to be on track to satisfying these requirements using designs derived from the prototype systems referred to above.

The NFIRAOS wavefront correctors include two high order deformable mirrors and one tip/tilt stage (TTS). The key requirements for the former include (i) 63x63 and 76x76 actuators on a 5.0x5.14 mm pitch, (ii) 10 μm stroke and 5 per cent hysteresis at temperatures from 20 to -30 Celsius, and (iii) an RMS surface error of 15 nm RMS after "flattening." Requirements (ii) and (iii) have been successfuly demonstrated by CILAS in a 9x9 actuator (and 5 mm pitch) subscale prototype DM, using the same piezostack actuator technology and very comparible design parameters as their 41x41 DM developed for the SPHERE ExAO system.[12] Next, the NFIRAOS TTS serves as the mount for the smaller of these two DMs, which has a mass of about 32 kg and major axis of 319 mm. A full scale prototype version of the TTS has also been fabricated by CILAS and successfully tested; in particular the prototype achieved a small stroke bandwidth of 90 Hz at -30 Celsius with a dummy DM payload and its simulated wiring, well in excess of the 20 Hz requirement.

The most challenging NFIRAOS wavefront sensor detectors include the NGS WFS detector, the LGS WFS detectors, and the OIWFS detectors. To support order 60x60 wavefront sensing on faint natural guidestars, the NGS WFS detector is a 256x256 pixel CCD with red-optimized quantum efficiency and one- or sub-electron read noise at frame rates from 10 to 800 Hz. The design is an upgraded version of the 160x160 CCID-56 detector, already fabricated and tested at MIT Lincoln Laboratory under an Adaptive Optics Development Program (AODP) grant. It obtains its low detector read noise using the so-called planar JFET amplifier. The LGS WFS detector design features the more specialized "polar coordinate" geometry, with small patches (6x6 to 15x6) of pixels aligned under each of the 60x60 WFS subapertures to properly match the length and orientation of the elongated LGS image. By minimizing the number of detector pixels, the polar coordinate design reduces pixel read rates and consequently also reduces detector read noise; 3 noise electrons are predicted using the same planar JFET amplifier as described above.[13] Plans call for a wafer run at MIT/LL later this year to fabricate prototype versions of both the NGS and LGS WFS detectors, with processing and frontside testing early in 2010.

The OIWFS detector requirements include high quantum efficiency (0.8) in J and H band and low read noise (2.5 electrons) on small subarrays at a readout rate of 100 frames per second to achieve the NFIRAOS sky coverage requirement of 50% at the galactic pole. A large format detector (1024x1024 pixels) is also required to simplify guide star acquisition and enable on-chip dithers of 1-2 arc seconds. The current baseline detector for this application in the Teledyne H2RG HgCdTe array. This detector meets the requirements for size and quantum efficiency, and is now approaching the detector read noise requirement in recent tests at Caltech.

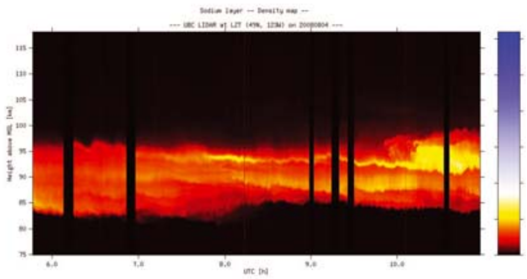

Fig. 3. Time history of the mesospheric sodium layer obtained with the University of British Columbia LIDAR system

Finally, the NFIRAOS RTC must perform the pixel processing for NGS, LGS and on-instrument wavefront sensors, and then solve a 35k x 7k wavefront control problem using the WFS measurements. Both tasks must be performed at a frame rate of 800 Hz, with a requirement/goal of 1000/400 μs end-to-end latency. The RTC must update these algorithms in real time as conditions change, and also store the data needed for PSF reconstruction in post-processing. Using existing hardware designs and control algorithms, the memory and processing requirements for this system would be at least 100 times greater than for an 8m class MCAO system such as Gemini-South. However, two conceptual design studies completed earlier this year by the Optical Sciences Company and the Dominion Radio Astronomical Observatory have provided effective solutions through the use of computationally efficient algorithms and innotative hardware designs based upon DSP and FPGA processors.[14, 15]

6 Lab and Field Tests

Two research projects are currently in progress to demonstrate key features of the NFIRAOS wavefront control architecture, and to characterize the temporal and spatial variability of the mesospheric sodium layer. The *University of Victoria Laser Guide Star Wavefront Sensor Test Bench* is now successfully simulating the full range of real-time algorithms and background optimimization processes proposed for the NFIRAOS LGS wavefront sensing architecture, including: wavefront gradient measurement via matched filtering, real-time updating of the matched filter gains to adapt to sodium layer variations, and real-time updating of the matched filter offsets using a low-bandwidth NGS "truth" (or calibration) wavefront sensor. The performance of the overall system is stable, and can be predicted and optimized based upon the characterized transfer functions of the individual sensors and control laws.[16, 17]

The *University of British Columbia LIDAR system* employs a pulsed, 5W dye laser and a 6m diameter receiver to obtain measurements of the mesospheric sodium layer with a resolution of about 5m at 50 Hz (see Fig. 3). These measurements have confirmed that the power spectrum of the mean range to the sodium layer follows a power law between $f^{-5/3}$ and $f^{-11/6}$ out to a frequency of at least 10 Hz, thereby confirming earlier estimates for the rate at which focus must be updated using an NGS OIWFS for NFIRAOS. This LIDAR system also enables the characterization of "sporadic" micro-meteorite events at levels of resolution which were previously impossible. During the summer of 2009, observations will continue with a new, higher-speed photon counter and a fast steering mirror for the simulation of multi-guidestar asterisms.[18]

7 Upgrade Paths

Beyond first light, the TMT instrumentation plan includes a variety of additional AO systems and instruments as possible "first decade" upgrades. These include mid IR AO (order 30x30 wavefront correction; 3 LGS), multi-object AO (order 64x64 correction using MEMS for 20 deployable IFUs on a 5' field; 8 LGS), ground-layer AO (correction of 400 wavefront modes using an adaptive secondary; 4-5 LGS), and extreme AO (order 128x128 correction, an advanced IR wavefront sensor, and a post-coronagraphic calibration WFS).

A variety of possible upgrades to NFIRAOS and its associated science instruments are also possible, such as an "MOAO-light" instrument deploying perhaps6 MEMS-corrected IFUs across the NFIRAOS 2' field. These MEMS would provide a further degree of moderate-field wavefront correction beyond what is feasible using a dual-conjugate AO system, with minimal requirements upon their stroke and open-loop repeatability. MEMS could similarly be incorporated into the on-instrument wavefront sensors to increase the "sharpening" of faint natural guide stars and improve sky coverage.

Finally, a mid-term objective is upgrading NFIRAOS to obtain a wavefront error of 130 nm under median conditions, corresponding to a Strehl ratio of about 0.5 at a wavelength of 1.0 micron. The would require roughly order 120x120 wavefront compensation, implying a new generation of wavefront correctors, sensors, laser guide stars, and real-time controller electronics.

8 Summary

Adaptive optics will be essential to achieving many, if not most, of the major scientific objectives of the Thirty Meter Telescope, and the observatory will be designed from the start to exploit AO. The overall AO architecture and the AO subsystem requirements for TMT have been derived from the AO science requirements: These build upon demonstrated AO concepts and technologies, with low risk and acceptable cost. Conceptual and/or Preliminary Designs have been developed for the AO subsystems, with performance estimate anchored by detailed analysis and simulation. Component prototyping and AO lab/field tests are now underway. The TMT Construction Phase schedule leads to AO first light in 2018, and upgrade paths have defined for improved AO performance and new capabilities during the first decade of operations.

Acknowledgements

The author gratefully acknowledges the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology, and the University of California. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA), and the U.S. National Science Foundation.

References

1. J. Nelson, "Overall science goals and top level AO requirements for TMT," in *Adaptive Optics for Extremely Large Telescopes*, Y. Clenét, J.-M. Conan, T. Fusco & G. Rousset, eds., Paris, 2009.
2. G. Herriot, "NFIRAOS – first light adaptive optics system for TMT," Ibid.
3. D. Loop, "Concept study of on-instrument wavefront sensors for the TMT IRIS science instrument," Ibid.
4. D. Andersen, "Scientific Impact of the Operating Temperature of NFIRAOS on TMT," Ibid.
5. C. Boyer, "The Laser Guide Star Facility for TMT: requirements overview and current status of the design," Ibid.
6. T. Travouillon, "Models of optical turbulence and wind speed for the Thirty Meter Telescope sites," Ibid.
7. L. Gilles, L. Wang& B. Ellerbroek, "Wavefront error budget development for the Thirty Meter Telescope laser guide star adaptive optics system," in *Adaptive Optics Systems*, SPIE Proc. 7015, N. Hubin, C. Max & P. Wizinowich, eds., 2008.
8. L. Wang, "Full Physical Optics Sky Coverage Simulation for MCAO and MOAO Systems on ELT's," Y. Clenét, J.-M. Conan, T. Fusco & G. Rousset, op. cit.
9. L. Gilles, "A Split LGS/NGS Atmospheric Tomography for MCAO and MOAO," Ibid.
10. R. Fugate, "Artifical optical guidestars: prospects for extremely large telescopes," in *Extremely Large Telescopes: Which Wavelengths?*, SPIE Proc. 6986, T. Andersen, ed., 2008.
11. R. Holzlohner et. al, "Optimization of cw sodium laser guide star efficiency," *Astronomy and Astrophysics,* to appear.
12. J.-C. Sinquin, "Recent Progress on Correcting Components at CILAS," Y. Clenét, J.-M. Conan, T. Fusco & G. Rousset, op. cit.
13. S. Adkins et. al, "The design and optimization of detectors for adaptive optics wavefront sensing, in *Advances in Adaptive Optics II*, SPIE Proc. 6272, B. Ellerbroek & D. Bonaccini, eds., 2006.
14. S. Browne, "A Real-Time Controller Architechture for the Multi-Conjugate Adaptive Optics System on the Thirty Meter Telescope," Y. Clenét, J.-M. Conan, T. Fusco & G. Rousset, op. cit.
15. G. Hovey, "An FPGA Based Computing Platform for Adaptive Optics Control," Ibid.
16. R. Conan, "The TMT/NFIRAOS LGS wavefront sensing demonstration bench," Ibid.
17. O. Lardière, "Characterization and mitigation of Laser-Guide-Star aberration," Ibid.
18. T. Pfrommer, "High-resolution results from the UBC-lidar experiment for the Thirty Meter Telescope," Ibid.