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Adaptive Optics for the Thirty Meter Telescope

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ABSTRACT

Adaptive Optics (AO) will be essential for at least seven of the eight science instruments currently planned for the Thirty Meter Telescope (TMT). These instruments include three near infra-red (NIR) imagers and spectrometers with fields of view from 2 to 30 arc seconds, a mid-IR echelle spectrometer, a planet formation imager/spectrometer, a wide field optical spectrograph, and a NIR multi-object spectrometer with multiple integral field units deployable over a 5 arc minute field of regard. In this paper we describe the overall AO reference design that supports these instruments, which consists of a facility AO system feeding the first three instruments and dedicated AO systems for the remaining four.

Key design challenges for these systems include very high-order, large-stroke wavefront correction, tip-tilt sensing with faint natural guide stars to maximize sky coverage, laser guidestar wavefront sensing on a very large aperture, and achieving extremely high contrast ratios for the detection of extra-solar planets and other faint companions of bright stars. We describe design concepts for meeting these challenges and summarize our supporting plans for AO component development.

1. INTRODUCTION

The TMT Project is now proceeding with a Design and Development Phase (DDP) towards the long-term goal of constructing and operating a 30-meter-diameter optical/infra-red telescope for research in astronomy. The project is a partnership consisting of ACURA, the Association of Canadian Universities for Research in Astronomy; AURA, the Association of Universities for Research in Astronomy; the California Institute of Technology; and the University of California. The prime objectives of the DDP are to organize and staff the project, collect survey data to select a telescope site, develop requirements and complete a preliminary design of the telescope and its associated instrumentation, and establish a confident cost estimate and complete a readiness review.

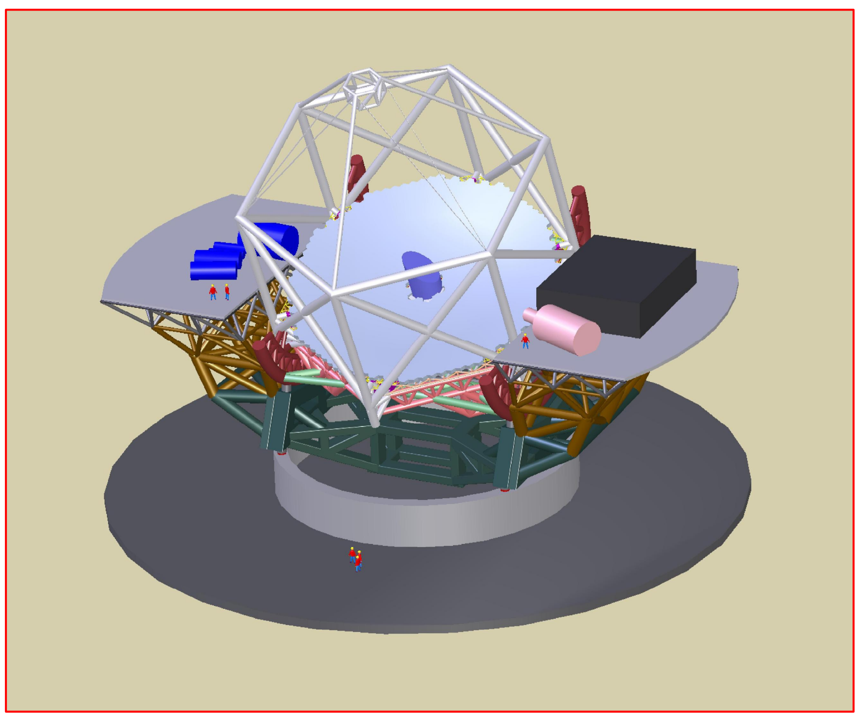

Figure 1: TMT Reference Design

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Fig. 1 illustrates the telescope reference design that has been synthesized from previous studies by the individual partners.[1,2,3] The Gregorian optical design consists of a 30m, f/1, parabolic primary mirror (M1) and a 3.6m concave, ellipsoidal secondary (M2). The output focal ratio is f/15, and the design has been optimized for a 20 arc minute field-of-view (FOV). The primary is composed of 738 hexagonal segments which are approximately 1.21m corner-to-corner. The telescope elevation access is located above the primary mirror, allowing the flat tertiary mirror (M3) to direct the beam to multiple instrument locations located on the two large Nasmyth platforms.

This telescope design has at least four important consequences for any AO system that will be implemented. Firstly, the Nasmyth platforms will support large instruments and AO systems with an orientation that is fixed with respect to the direction of gravity. The secondary mirror is conjugate to a range of about 300 m above the telescope, which is an attractive location for implementing groundlayer and/or low-order wavefront corrections via an adaptive mirror. The image of the telescope pupil will rotate on the Nasmyth platform, including any wavefront aberrations induced by the primary mirror segments and the obscurations caused by the secondary mirror support struts. These struts are expected to be 0.3 to 0.5 meters in width. Finally, the large aperture diameter implies that telescope dynamics, as well as atmospheric turbulence, will contribute to control bandwidth requirements for tip/tilt and possibly other low-order modes of the wavefront.[4,5]

2. INSTRUMENTATION CAPABILITIES AND ADAPTIVE OPTICS MODES

The range of scientific applications proposed for TMT has been outlined previously.[6] Table 1 presents a top-level summary of the derived requirements for scientific instrumentation and the associated AO systems. AO requirements are listed in terms of FOV, spectral passband, delivered performance, and any additional specialized requirements. The requirements for sky coverage are not listed, but are sufficiently challenging that laser guide star (LGS) AO systems must be available for all applications excepting faint companion detection around bright stars.

Instrumentation Capability	FOV	Passband, μm	AO Performance Requirement	Special Requirements
Narrow field, near-IR spectroscopy and imaging	10-30 sec	0.6-5.0	Delivered RMS wavefront error (WFE) of 122-133 nm	-- 2% differential photometry -- differential astrometric accuracy of 1% of image FWHM -- Increase the inter-OH background by at most 15%
Multi-object, near-IR integral field unit spectroscopy	Multiple 2-5 sec objects within a 5 min region	0.6-2.5	50% enclosed energy within a 0.05 sec pixel at a wavelength of 1 μm	
Wide field spectroscopy	77 sq, min	0.31-1.0 (goal 0.31-1.5)	“Enhanced seeing” to reduce slit widths and integration times for background-limited observations	
Narrow field, mid-IR spectroscopy and imaging	10 sec	8-18 (goal 3-28)	Delivered RMS WFE < 750 nm (goal 350 nm)	Increase N band background by at most 15%
High contrast imaging and IFU spectroscopy (for faint companion detection and characterization)	2 sec	1-2.5	Contrast ratio of 10^6-10^8 at separations of 0.03-1.0 sec	IR WFS Guide star magnitude $m_H < 11$

Table 1. Summary of instrument capabilities and associated top-level requirements for adaptive optics

The AO performance requirements listed in Table 1 are qualitatively very different for each class of TMT instrumentation, and different AO system concepts (or "modes") are most suitable in each case:

- The needs near infra-red spectroscopy and imaging are well met by a single multi-conjugate AO (MCAO) system[7] that utilizes multiple laser guide stars (LGSs) and deformable mirrors (DMs) to measure and correct atmospheric turbulence in three dimensions, thereby providing diffraction-limited image quality over a field-of-view significantly larger than the conventional isoplanatic patch.[*]
- The five arc minute field specified for multi-object spectroscopy is too large to be corrected by a feasible MCAO system, however. Multi-object AO (MOAO) is proposed as a means of providing separate wavefront corrections for multiple small scientific fields based upon a three dimensional atmospheric turbulence estimate obtained using multiple laser guide stars.[8]
- Ground-layer adaptive optics, which estimates and corrects low-altitude atmospheric turbulence by averaging wavefront sensor (WFS) measurement from multiple widely-spaced guidestars,[9] is proposed as method of enhancing atmospheric seeing and thereby improving observational efficiency for wide-field optical (and near-IR) spectroscopy.
- The degree of atmospheric turbulence compensation required for observations in the mid-IR is comparatively modest, but system emissivity must be reduced by minimizing the number of warm surfaces in the mid-IR AO (MIRAO) optical path.
- Finally, the AO requirements for very-high-contrast imaging and IFU spectroscopy will be addressed by an Extreme AO (ExAO) system combining a high-order atmospheric compensation, a precision coronagraphic mask, and an additional post-coronagraph wavefront sensor used for detecting and correcting the systematic errors in the AO system that would otherwise introduce "superspeckles" and degrade the achievable contrast.[10]

This broad range of AO systems will face a common set of very dramatic challenges in spite of their obvious differences, including:

- High sky coverage requirements mandate that extremely dim natural guide stars must be used for tip/tilt (and tilt anisoplanatism) sensing in LGS AO systems;
- Stringent requirements on the delivered wavefront quality in a system with a very large value of D/r_0 imply very high order wavefront sensors and correctors, computationally intensive wavefront reconstruction algorithms, and powerful lasers for generating sodium laser guidestars.
- The large value of D/r_0 also implies large-stroke wavefront correction, with tip/tilt-removed mirror figure adjustments of approximately 10 μm required with 1 arc second seeing and a 60m outer scale.

Our proposed approach to addressing these challenges is summarized in the following section.

3. DESIGN APPROACH AND AO SYSTEM ARCHITECTURE

Possibly the most demanding and essential requirement for the TMT AO program is to provide a meaningful degree of atmospheric turbulence compensation for the first-light science instruments within the first one to two years of observatory operations. This mandates a phased implementation approach to AO, with an initial objective of scaling the performance of existing (and near-term) astronomical AO systems to the TMT aperture diameter with a minimum dependence upon speculative components and system concepts. The initial AO system architecture consequently avoids reliance upon an adaptive secondary mirror, MEMS deformable mirrors, extremely high order wavefront sensing and correcting elements, and laser systems with power levels or pulse formats dramatically different from what has been demonstrated to date. All of these more advanced components figure prominently in plans for later AO system upgrades, however.[†]

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[*] Even for narrow-field observations, MCAO improves the sky coverage of LGS AO systems by "sharpening" the images of tip/tilt guide stars and enabling fainter stars to be used for tip/tilt wavefront sensing over a significant FOV.
[†] Cryogenic DMs are currently not under consideration, since the adaptive secondary mirror provides an alternatives approach to minimizing the emissivity of the MIRAO system.

In spite of the above philosophy, a number of important innovations in AO component technology will still be required for the initial TMT AO systems. The scientific payoff of maximizing sky coverage is so great that we have decided to baseline near-IR NGS tip/tilt wavefront sensing, since the sharpening of the guide star images in J band yields a significant improvement in limiting magnitude.[‡] Sodium laser guidestar elongation due to the thickness of the sodium layer becomes important at the TMT aperture diameter, and it appears that a radial CCD geometry is one possible approach to achieving the required levels of LGS WFS measurement accuracy with feasible laser powers and CCD pixel rates.[11] New, innovative implementations of near-optimal wavefront reconstruction algorithms will be required, since the computation rates associated with the classical vector-matrix multiply (VMM) implements are unrealistic even considering extrapolation by Moore's Law. Finally, the simultaneous requirements for large-amplitude and high-bandwidth wavefront corrections suggest the use of a woofer-tweeter control architecture; this includes tip/tilt compensation, where telescope resonances excited by windshake may occur at relatively high frequencies.

Section 5 below outlines some of the ongoing and planned R & D activities that address the above component issues. The principal stages of the phased AO implementation strategy are summarized in Tables 2-5 below.

The **first light AO architecture** is described in Table 2. This configuration provides atmospheric turbulence compensation for one or more (relatively narrow field) near-IR instruments using the MCAO system NFIRAOS (for Narrow Field Infra-Red AO System[12]), and one or more mid-IR instruments using MIRAO.

AO Mode	Deformable Mirrors (and technology)	Guidestars and Sensors
NFIRAOS (MCAO)	Order 60x60, h=0 km, 8-10 μm stroke, (piezo) Order >30x30, h=12km, >4 μm stroke, (piezo)	6-9 LGS, order 60x60, 17-25W power 1-3 tip/tilt or tip/tilt/focus IR NGS
MIRAO	Order 15x15 to 30x30, ambient, (piezo)	1-3 LGS, order 60x60 17-25W power 1 tip/tilt/focus IR NGS

Table 2: First light AO architecture summary

NFIRAOS is a MCAO system utilizing two deformable mirrors and 6-9 sodium laser guidestars. The baseline design is limited to order 60x60 compensation on account of the anticipated capabilities (and costs) of wavefront sensors, deformable mirrors, and sodium guidestar lasers that will be procured beginning in the 2009-10 time frame. This order of correction corresponds to a density of two actuators per meter in the plane of the TMT primary mirror, and yields error budgets with a delivered wavefront error in the range of 150 to 200 nm RMS.[12]

The NFIRAOS MCAO configuration is expected to provide atmospheric turbulence compensation over roughly a two arc minute diameter field of view, which is sufficient for acquiring IR guidestars for tip/tilt wavefront sensing at the galactic pole. DM stroke requirements for tip/tilt removed wavefront compensation are estimated to be 8-10 μm for 6-sigma compensation of atmospheric turbulence with r_0=10 cm and a 60m outer scale.[13] This will require moderate improvements over existing piezostack deformable mirrors.

The laser guide star requirements for NFIRAOS are achieved using 150W of total laser power, projected in 6-9 beacons of 17-25W each from a single laser launch telescope located behind the TMT secondary mirror. On account of laser guidestar elongation, these laser power requirements are approximately 70 per cent greater than would be required for an LGS AO system on an existing 8 to 10m astronomical telescope. Significantly more pixels per subaperture will also be required (8x2 or 16x4 vs. a 2x2 quadrant detector) to implement noise-optimal wavefront sensing methods.[14,15] Three facilitized copies of an existing laser system would suffice to meet our requirements for total laser power,[16] and a pulsed laser system does not appear to be necessary to achieve adequate wavefront sensing measurement accuracy. The baseline wavefront sensing detector for NFIRAOS is the radial format CCD array currently under development via the AO Development Program (AODP),[11] which would offer improved measurement accuracy and reduced pixel rates with or without a pulsed laser.

[‡] The increase in WFS measurement noise due to the thermal background is negligible due to the short integration times and the small angular subtense of the diffraction-limited core of the guide star image.

No adaptive secondary mirror is currently planned for first light, so no GLAO system will be available for the wide-field optical spectrograph. The initial implementation of the MIRAO system will also require a conventional deformable mirror of order 15x15 to 30x30 and at least two additional mirrors at ambient temperature. From 1 to 3 laser guide stars will be utilized, using the same LGS facility and WFS detector design developed for NFIRAOS.

Table 3 summarizes the system upgrades that are become feasible with an **adaptive secondary mirror**. Our current concept is to utilize a mirror with a somewhat thicker facesheet than current designs,[17] which will reduce fabrication and handling risks at the expense of a diminished order of correction. The adaptive secondary mirror enables the use of GLAO with the wide-field optical spectrograph and improves the performance of the MIRAO system by eliminating the need for the ambient DM and its optical relay.

AO Mode	Deformable Mirrors (and technology)	Guidestars and Sensors
NFIRAOS (MCAO)	Same as Table 2 (first light architecture)	
MIRAO	Order ~50x50 with ~30x30 modes controlled, (adaptive secondary)	1-3 LGS, order 60x60 17-25W power 1 tip/tilt/focus IR NGS
GLAO	Order ~50x50 with ~30x30 modes controlled, (adaptive secondary)	5-8 LGS, order 60x60, 17-25W power 4 tip/tilt/focus visible NGS

Table 3: AO upgrade options with an adaptive secondary mirror

MEMS deformable mirrors of order at least 60x60 would enable an MOAO system for multi-object IFU spectroscopy as outlined in Table 4. The feasible stroke and linearity of these devices remains unknown, so that "woofer" deformable mirrors may be required for large-stroke, low-order wavefront correction. The possibility also exists that MEMS mirrors with a relatively large interactuator spacing of ~1mm could be used in the NFIRAOS design at first light if they are demonstrated within the next several years and provide a significant cost savings over more conventional deformable mirrors.[18]

AO Mode	Deformable Mirrors (and technology)	Guidestars and Sensors
NFIRAOS (alternate)	Order 60x60, h=0 km, 8-10 μm stroke, (MEMS) Order 60x60, h=12km, >4 μm stroke, (MEMS)	6-9 LGS, order 60x60, 17-25W power 1-3 tip/tilt or tip/tilt/focus IR NGS
MOAO (option 1)	Multiple order 60x60, 8-10 μm stoke (MEMS)	8-9LGS, order 60x60, 17-25W power 3-4 tip/tilt or tip/tilt/focus visible NGS
MOAO (option 2)	Multiple order 60x60, 4 μm stoke (MEMS) Order ~50x50 with ~30x30 modes controlled, (adaptive secondary)	
MOAO (option 3)	Multiple order 60x60, 2-3 μm stoke (MEMS) Multiple order ~9x9, 8-10 μm stroke (piezo)	

Table 4: Upgrade options with MEMS deformable mirrors. Three MOAO options are presented, depending upon the stroke achieved by the MEMS and the availability of an adaptive secondary mirror. The MIRAO and GLAO systems are not listed because MEMS will not be used for these AO modes.

Finally, Table 5 summarizes the upgrades that may be feasible given further **advances in AO component technology** which enable wavefront sensors and deformable mirrors with 100x100 or more elements. A NFIRAOS system with order 120x120 components is predicted to meet its requirements for a delivered wavefront error of 122 nm RMS, even allowing a reasonable allocation for telescope, instrument, and calibration wavefront errors. Similarly, an order 120x120 MOAO system could quite possibly satisfy the enclosed energy requirement given in Table 1. Order 100x100 AO components would also enable an ExAO system with a contrast ratio of 10^6 to 10^7, optimized for the detection of young, warm, Jupiter-like planets at small angular separations from young stars in the nearest star forming regions.

The precise implementation of these systems obviously depends upon the specific advances in component technology realized, and Table 5 presents one possible set of examples based upon piezoactuator DMs for NFIRAOS and MEMS for MOAO. Note that such an upgrade to NFIRAOS would also require the use of an adaptive secondary mirror because of the probable stroke limitations of an order 120x120 piezoactuator DM. Either of these upgrades would also require significant increases in laser power beyond the values presented in Tables 2 and 4 for the initial, lower-order implementations of MOAO and NFIRAOS. Pulsed laser formats that enable dynamic refocusing on short pulses as they transit the sodium layer may become an attractive option for the reducing total laser system power and cost.[19]

AO Mode	Deformable Mirrors (and technology)	Guidestars
NFIRAOS	Order 120x120, h=0 km, > 4 μm stroke, (piezo) Order 120x120, h=12km, > 4 μm stroke, (piezo) Order ~50x50 with ~30x30 modes controlled, (adaptive secondary)	6-9 LGS, order 120x120, 40-100 W power 1-3 tip/tilt or tip/tilt/focus IR NGS
MOAO (option 1)	Multiple order 120x120, 8-10 μm stoke (MEMS)	6-9 LGS, order 120x120, 40-100W power 1-4 tip/tilt or tip/tilt/focus visible NGS
MOAO (option 2)	Multiple order 120x120, 4 μm stoke (MEMS) Order ~50x50 with ~30x30 modes controlled, (adaptive secondary)	
MOAO (option 3)	Multiple order 120x120, 2-3 μm stoke (MEMS) Multiple order ~9x9, 8-10 μm stroke (piezo woofer)	
ExAO	Order 100x100, 1-2 μm stroke (MEMS) Order ~30x30, 8-10 μm stroke (piezo or adaptive secondary)	1 IR NGS, order 100x100

Table 5: Upgrade options with very high order AO components

4. MODELING METHODS AND SAMPLE SIMULATION RESULTS

Needless to say, simulation and analysis of the TMT AO systems can be quite challenging due to the order of correction required, system complexity, and the range of fundamental and practical error sources that must be considered. For the MCAO and MOAO systems, very high-order wavefront reconstruction algorithms can be evaluated using efficient methods from computational linear algebra as described in previous papers,[20,21,22] and order 120x120 systems with 6 laser beacons and 2 deformable mirrors can in fact be simulated on a single high-performance PC. As an example, the range of trade studies planned to optimize the NFIRAOS design and validate the error budget currently includes:

1. Performance variations vs. the guidestar asterism, the DM conjugate ranges, and the order of correction;
2. Performance variations vs. the AO loop update rate and the LGS WFS measurement noise level;
3. Physical optics effects associated with elongated laser guide stars and partially compensated tip/tilt/focus natural guide stars;
4. The impact of telescope windshake and primary mirror segment alignment and figure errors;
5. Further implementation errors, including actuator hysteresis, actuator dynamic range limitations, DM-to-WFS misregistration,

The first of these studies has been completed as of this writing,[§] study number 2 is ready to begin,[12] and the software upgrades necessary for studies 3-5 are being implemented using prior simulation codes as models.[23]

A variety of auxiliary simulations and analyses are underway to evaluate other aspects of NFIRAOS performance, such as sky coverage,[24] throughput and emissivity,[12] and focus errors associated with imperfectly tracking the range to the sodium layer. Table 6 and Fig. 2 illustrate the work currently in progress on the first and third of these tasks, respectively.

[§] The baseline LGS asterism consists of one on-axis sodium LGS and five more in a regular pentagon with a radius of 35 arc seconds. The DM conjugate ranges are 0 and 12 km. The order of all mirrors and sensors is 60x60 for the first-light system, and 120x120 for the upgraded system.

Wavefront Sensing Band	NGS WFS Architecture	Detector Read Noise Electrons per Frame			
		0	5	10	15
V band (seeing limited)	1 tip/tilt WFS	217	217	219	222
	Multiple tip/tilt WFS	193	195	198	204
	1 tip/tilt/focus WFS	207	210	216	227
J band (Strehl 0.1)	1 tip/tilt WFS	86	95	101	105
	Multiple tip/tilt WFS	22	36	45	52
	1 tip/tilt/focus WFS	36	50	60	67

Table 6: NFIRAOS sky coverage simulation results. This table summarizes the median RMS wavefront error due to atmospheric tip/tilt jitter (in nm) at the Galactic pole for one particular atmospheric turbulence profile, natural guide star model, and LGS asterism. The tip/tilt errors include the impact of measurement noise, servo lag, and tilt anisoplanatism, but the tip/tilt error due to telescope windshake is neglected. Further modeling is in progress, but it is already possible to conclude that J band sensing with partially compensated guide star images is preferred, and that a single tip/tilt WFS is not sufficient due to the impact of tilt anisoplanatism.

The AO modeling requirements for the MIRAO system are comparatively straightforward because the order of correction and the number of laser beacons is appreciably smaller than anticipated for either MCAO or MOAO (see Table 2). The simulation requirements for GLAO are intermediate between these two extremes, and sample comparisons between Monte-Carlo simulations and simpler analytical techniques[25] indicate that the latter may be used for trade studies to determine the LGS asterism and the required order of correction. Fig. 3 illustrates the statistical improvement to the PSF full-width, half-maximum predicted for GLAO for a range of atmospheric turbulence conditions.

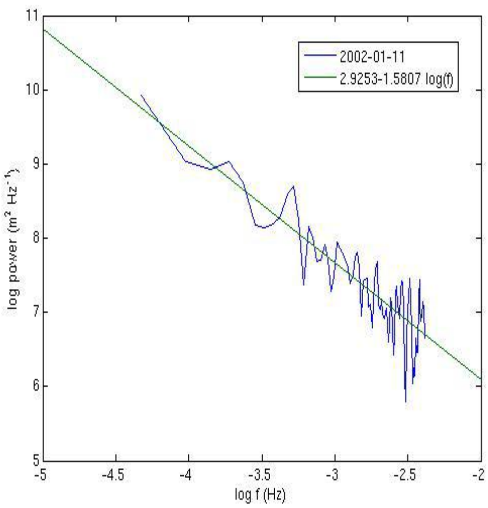


Figure 2: Temporal power spectrum of variations in the mean height of the sodium layer.

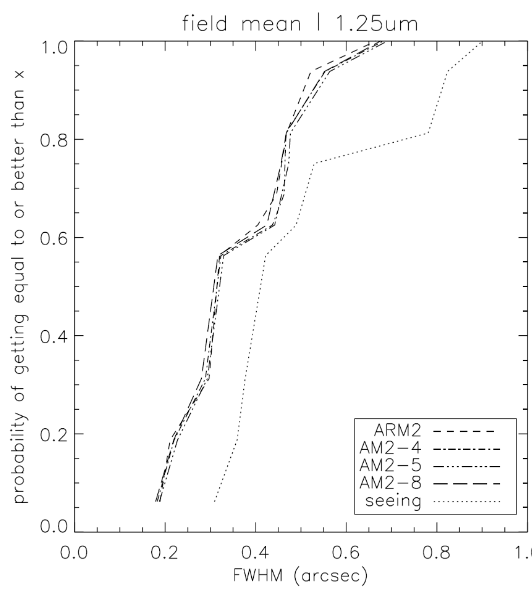
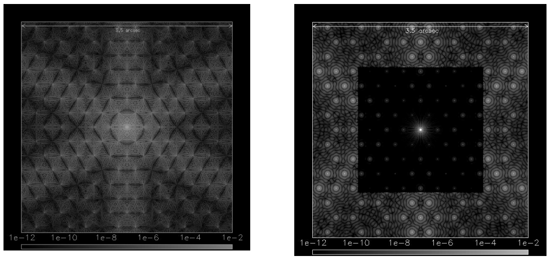


Figure 3: Cumulative probability density functions for the PSF full-width, half-maximum at a wavelength of 1.25 μm for the seeing-limited case (dotted) and a variety of GLAO implementations.

The analysis and simulation effort for ExAO focuses upon those terms of the wavefront error budget which may limit the contrast ratio achieved with even a very high order AO system if they are not properly controlled and calibrated. Some of these issues include (i) the impact of primary mirror segmentation, (ii) spatial filtering to prevent the aliasing of high frequency wavefront aberrations into WFS gradient measurements, and (iii) the detection and correction of systematic errors in the high-bandwidth AO control loop by means of a calibration WFS following the coronagraphic stop. Fig. 4 illustrates a sample analytical result on the first of these three effects.



(a) Raw TMT PSF (b) Apodized for aperture and segment edge effects

Figure 4: The impact of apodization on the diffraction-limited TMT PSF.

5. AO COMPONENT DEVELOPMENT

Full realization of the TMT AO program will require significant investment in AO component development, including work on piezostack DMs, adaptive secondary mirrors, MEMS deformable mirrors, visible and near IR wavefront sensing detectors, sodium guidestar lasers, and real-time control (RTC) electronics and control software. TMT has already initiated development projects in several of these fields, and is closely following the work independently supported by the NSF AO Development Program (AODP) and several other funding sources for the remaining technologies. These projects are briefly outlined in the following paragraphs, which are ordered according to TMT's level of involvement in supporting and directing the work.

Piezostack DMs: TMT has funded a conceptual design study and subscale feasibility demonstration at **CILAS**, the vendor currently under contract to produce piezostack deformable mirrors for the Gemini MCAO and ESO Planet Finder systems. These two mirrors are relatively high order (25x25 and 40x40, respectively), share a common interactuator spacing of 5 mm, and are based upon an actuator design that has demonstrated approximately 7 µm of stroke with roughly 5% hysteresis at a temperature of -25C. Over the next year, CILAS will develop conceptual designs for the baseline NFIROAS deformable mirrors, and also fabricate and test a subscale (order 9x9) deformable mirror that incorporates an improved actuator design intended to achieve the NFIRAOS stroke requirement of 10µm at a temperature of -30 to -35C.

Figure 5: JWST mirror segment demonstration at SAGEM (3mm @ 1.8m)

Adaptive secondary mirrors: TMT has funded **SAGEM** to perform a facesheet feasibility study for the adaptive secondary mirror, and to develop a conceptual design for the mirror's actuators and reaction/reference structure. The feasibility study builds on SAGEM's recent feasibility demonstration of a 1.6 meter hex, 3 mm thick meniscus mirror for the JWST project (Fig. 5). SAGEM will assess designs for both segmented and continuous facesheets fabricated from glass, silicon carbide, or composite materials, and will conduct cost/risk/performance trade studies with respect to mirror diameter, facesheet thickness, and actuator density. The objective of this effort is to define a credible design point for the adaptive secondary facesheet and its associated actuators and reaction structure by the time of the TMT conceptual design review scheduled for Spring, 2006.

Real-time control (RTC) electronics: As of this writing, TMT is evaluating proposals for feasibility studies of the AO RTC electronics required for GLAO, IRMOS, MIRAO, and NFIRAOS. The scope of the study will include the hardware and software elements of an RTC design concept that can be tailored to each of these four systems. Major advances beyond existing real-time control electronics designs for 8-10 meter class AO systems will be required because of the very high order of the TMT LGS AO systems, the use of tomographic wavefront reconstruction algorithms for the control of multiple deformable mirrors, and the use of open-loop and/or woofer/tweeter control architectures for some AO systems. New, computationally efficient wavefront reconstruction algorithms[20,21,22] must be utilized because conventional approaches become impractical, despite the certainty of further advances in signal processing technology according to Moore's law. Advanced processing architectures will also be required, and we expect that these studies will investigate a range of hardware approaches including field programmable gate arrays, DSPs, and arrays of more conventional microprocessors linked via high-speed interconnects.

Sodium guidestar lasers: Progress in this area during the last several years has been highly encouraging, and solid-state sum-frequency guidestar lasers have now generated approximately 50W of CW 0.589 μm radiation with essentially diffraction-limited beam quality at the USAF Research Laboratory.[16] Approximately 35W has been projected onto the sky.[26] A similar solid-state laser producing 12-15W average power has been delivered to Gemini Observatory by Coherent Technologies, Incorporated, and the prospects of scaling this design to the 50W level are good. According to Table 2, approximately 150W of CW laser power will be needed to generate 6-9 17-25W laser beacons for the first light version of NFIRAOS. This power requirement could be met by 3 laser systems using either the AFRL or the (anticipated) CTI design, and the overall mass and volume of either approach is small enough to be mounted on the Thirty Meter Telescope.

The performance of sum frequency fiber lasers is also progressing, including a recent design concept for a pulsed laser that may provide an optimal solution to the guidestar elongation problem.[19] The TMT project intends to monitor all of these ongoing R & D activities, and will begin supporting development of the TMT laser system in the 2009 time frame.

LGS WFS detector arrays: Sodium laser guidestar elongation becomes a serious, but not insurmountable, issue for a 30-meter-class ELT such as TMT. The NSF Adaptive Optics Development Program (AODP) is now funding a project by Rockwell and MIT Lincoln Laboratory to demonstrate a sub-scale prototype of a high-speed, low-noise CCD array with a pixel geometry that has been optimized to reduce the impact of LGS elongation. As illustrated in Fig. 6a, the CCD array pixels grouped into rectangular strips of perhaps 16x4 pixels each which are arranged in one-to-one correspondence with the LGS WFS subapertures, with each strip oriented to match the direction of guidestar elongation on that subaperture. This concept provides two separate options for reducing the impact of LGS elongation on LGS WFS measurement accuracy:

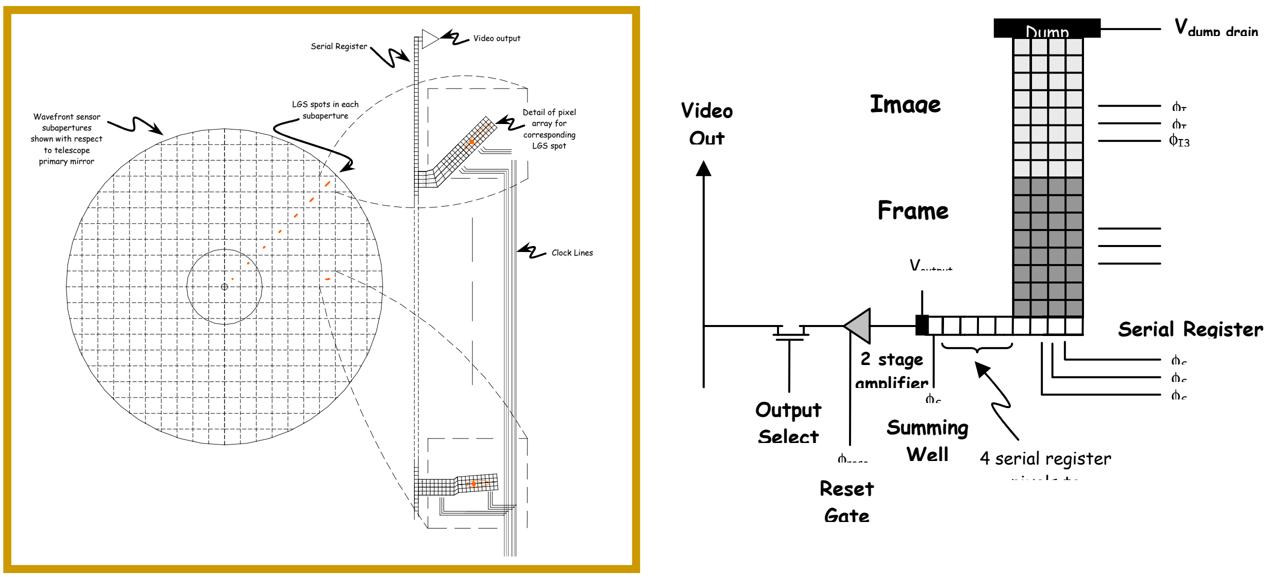
- With the appropriate laser pulse format and proper synchronization, pixel-to-pixel charge transfer may be used to track short pulses (~3 μs, or ~1km in length) as they transit the sodium layer, thereby effectively eliminating LGS elongation at the LGS WFS focal plane. This is one example of the "dynamic refocusing" concept which has been proposed previously using either mechanical or electro-optic techniques.[27,28]
- With more conventional sodium laser pulse formats, this CCD array geometry can still improve LGS WFS measurement accuracy by enabling the use of either "matched filter" or "correlation track" algorithms to detect the displacement of the LGS Shack-Hartmann spots. Similar methods have already been successfully employed in solar adaptive optics,[29] and simulation results based upon sample measurements of the mesospheric sodium layer profile[14] suggest that they will provide substantially better tip/tilt measurement accuracy than either the classical centroid computation or the quadrant detector approach.

This AODP project also proposes to demonstrate a JFET amplifier that will reduce detector read noise, perhaps to a level of one electron/pixel/read or less at a read rate 2 Megapixels/second/amplifier. As with the Laser R & D activities described above, the TMT project intends to begin supporting development of TMT-specific designs in approximately 2009, following the conclusion of the current AODP project.

MEMS deformable mirrors: According to Table 3 above, the MOAO system proposed for TMT will initially require MEMS deformable mirrors with 60x60 actuators and at least 2-3 μm of stroke. Other requirements include very high actuator yield and open-loop positioning accuracy of about 20-30 nm RMS. The results obtained to date with order 12x12 and 32x32 actuator MEMS are encouraging,[30] and funding sources including the AODP, the NSF Center for Adaptive Optics (CfAO), and the Lab for Adaptive Optics (LAO) at the University of California, Santa Cruz are continuing to support R & D efforts to demonstrate a prototype mirror meeting TMT's requirements. Once again, TMT expects to continue further development work after the current round of projects is successfully completed.

IR NGS WFS detector arrays: As described in Section 3, tip/tilt sensing in the infrared may appreciably improve the sky coverage of a near-IR LGS AO system such as NFIRAOS, since the "sharpening" of J and H band images by the higher-order adaptive optics allows substantially fainter stars to be used for tip/tilt/focus guiding. For TMT, the diffraction-limited core of a J-band star image will be approximately 60 times smaller than an uncompensated seeing-limited image, and the tip/tilt measurement error due to photon- and background noise will be reduced by a proportional amount assuming that near-diffraction limited image quality can be achieved by the AO system.** Our baseline concept for the IR tip/tilt NGS WFS is based upon relatively small (128^2 to 256^2 pixels), moderately fast (500-1000 frames per second), and relatively low noise (5-10 electrons/pixel/read) detector arrays with a cutoff wavelength of 1.7 µm or greater.

Somewhat faster (1500-2000 FPS) IR arrays will be required for the higher-order wavefront sensor to be used by PFI. For this system, wavefront sensing in the infra-red is preferred to minimize the chromatic aberrations between the science and wavefront-sensing channels. TMT intends to investigate opportunities to support one or more R & D contracts to develop and evaluate arrays meeting these requirements, possibly as part of a larger consortium.



a. WFS subaperture and CCD array pixel geometry b. Subaperture readout schematic

Figure 6. Radial CCD array pixel geometry for minimizing LGS elongation effects on WFS measurement accuracy

6. SUMMARY AND PLANS

Adaptive optical systems form an essential component of the instrumentation planned for the Thirty Meter Telescope. An overall AO system architecture has been defined to support a full range of observing modes, ranging from wide-field optical spectroscopy to faint companion detection at the diffraction limit. The initial AO configuration will utilize existing and near-term AO component technologies whenever possible, while still addressing the issues of sky coverage, sodium LGS elongation, and large-stroke, high-order wavefront correction inherent in developing AO for ELTs. Future advances in AO component technology, including adaptive secondary mirrors and MEMS, can be incorporated, into new and upgraded AO systems, as they become available to provide improved performance and increased scientific capabilities.

The TMT project is now progressing with its design and development phase. AO design work, analysis/simulation studies, and component development contracts are proceeding. The Conceptual and Preliminary Design Reviews for the project are scheduled for May, 2006 and September, 2007, respectively. The Construction Phase of the project is expected to begin in January 2009, pending the submission of successful construction proposals to our sponsors. The current schedule anticipates first light with a phased primary mirror during the second quarter of (calendar year) 2014, with commissioning of the NFIRAOS facility AO system beginning in the first quarter of 2015. Scientific results exploiting the diffraction limit of a Thirty Meter Telescope may then be obtainable by the beginning of 2016.

** Unfortunately, this will not be achieved at visible wavelengths.

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