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A conceptual design for the Thirty Meter Telescope adaptive optics systems

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ABSTRACT

In this paper, we provide an overview of the adaptive optics (AO) program for the Thirty Meter Telescope (TMT) project, including an update on requirements; the philosophical approach to developing an overall AO system architecture; the recently completed conceptual designs for facility and instrument AO systems; anticipated first light capabilities and upgrade options; and the hardware, software, and controls interfaces with the remainder of the observatory. Supporting work in AO component development, lab and field tests, and simulation and analysis is also discussed. Further detail on all of these subjects may be found in additional papers in this conference.

Keywords: adaptive optics, extremely large telescopes

1. INTRODUCTION

The TMT Project[1] is now continuing with its 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 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.

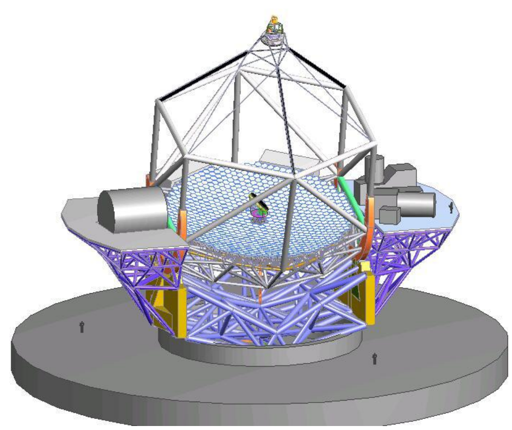

Figure 1: TMT telescope design with instruments, AO systems, and laser guide star facility

The project has recently completed an important set of design milestones. These include conceptual design and feasibility study reviews for a wide range of telescope, adaptive optics (AO), and instrumentation subsystems, followed by the Conceptual Design

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Review for the full project in May of 2006. Progress during the Conceptual Design Phase has included the refinement of system requirements and their allocation to subsystems, the initial formulation and assessment of design concepts for these subsystems, and (in a few cases) subscale hardware demonstrations of key component technologies. This paper provides a brief survey of all of these activities as they relate to the TMT AO systems. Further details may be found in the related papers presented at this conference.[2-21]

2. AO REQUIREMENTS AND DEVELOPMENT APPROACH

The range of instrumentation capabilities proposed for TMT and their associated top-level AO requirements are described elsewhere,[2,22] but will be summarized again here for convenience and to identify changes which have occurred during the Conceptual Design Phase. Table 1 lists the top-level requirements for TMT instrumentation capabilities and the associated AO systems. AO requirements are listed in terms of field of view (FoV), spectral passband, delivered performance, and any additional specialized requirements.[a] The principal changes made in the past year include (i) transfer of responsibility for the 2.9-5.0 μm spectral band from the near IR AO system to the mid IR, (ii) a corresponding tightening of requirements on the performance of the mid IR AO system, and (iii) relaxation of the initial performance requirements for the near IR AO system to allow an RMS wavefront error of about 180 nm RMS.

Instrumentation capability (and AO mode)	Field of View	Spectral passband, μm	AO performance requirements	Special requirements
Narrow field, near-IR spectroscopy and imaging (MCAO)	10-30 arc sec	1.0-**2.5** (goal 0.6-**2.5**)	Delivered RMS wavefront error (WFE) of 122-133 nm **(relaxed to 180 nm at first light)**	--2% differential photometry --differential astrometric accuracy of 1% of image FWHM --Increase the inter-OH background by at most 15%
Narrow field, mid-IR spectroscopy and imaging (MIRAO)	10 arc sec	**2.9**-18 (goal **2.9**-28)	Delivered RMS WFE < **500 nm** (goal **300 nm**)	Increase N band background by at most 15%
Wide field spectroscopy (GLAO)	77 sq. arc min	0.31-1.0 (goal 0.31-1.5)	"Enhanced seeing" to reduce slit widths and integration times for background-limited observations	
Multi-object, near-IR integral field unit spectroscopy (MOAO)	Multiple 2-5 arc sec objects within a 5 arc min region	0.6-2.5	50% enclosed energy with a 0.05 sec square pixel at a wavelength of 1 μm	
High contrast imaging and IFU spectroscopy (ExAO)	2 arc sec	1-2.5	Contrast ratios of 10^6-10^8 at separations of **0.05**-1.0 sec.	IR WFS guide star magnitude m_H < **10**

Table 1: Summary of instrument capabilities and associated top-level requirements for adaptive optics. Changes made in the past year are indicated in **bold.**

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 for each case:

- The needs of near infra-red spectroscopy and imaging are well met by a multi-conjugate AO (MCAO) system that utilizes multiple laser guide stars (LGSs) and deformable mirrors (DMs) to measure and correct

[a] Sky coverage requirements are not listed, but they are sufficiently challenging that laser guide star (LGS) AO systems must be available for all applications excepting high contrast imaging around bright stars.

atmospheric turbulence in three dimensions, thereby providing diffraction-limited image quality over a field-of-view significantly larger than the conventional isoplanatic angle.

- 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 optical path. This mandates a separate mid-IR AO (MIRAO) system.
- Ground-layer adaptive optics, which estimates and corrects low-altitude atmospheric turbulence by averaging wavefront sensor (WFS) measurement from multiple widely-spaced guidestars, is the preferred approach to enhancing atmospheric seeing (and thereby improving observational efficiency) for wide-field optical (and near-IR) spectroscopy.
- Because the five arc minute field specified for multi-object spectroscopy is too large to be corrected by a practical MCAO system, 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.
- Finally, the AO requirements for very-high-contrast imaging and IFU spectroscopy will be addressed by an Extreme AO (ExAO) system combining very high-order atmospheric compensation, a nulling interferometer or similar diffraction suppression system, and an additional second-stage wavefront sensor used for detecting and correcting the systematic errors in the AO system that would otherwise introduce "superspeckles" and degrade the achievable contrast.

The facility and instrumentation AO systems designs which have been developed during the Conceptual Design Phase for each of these applications are described briefly in Sections 3 and 4 below.

3. FACILITY AO SYSTEMS

The planned facility AO capabilities for TMT include the Narrow Field IR AO System (NFIRAOS), which is an LGS MCAO system intended to provide near-diffraction limited performance in the near IR over a 30" FOV for the near IR instrumentation requirements listed on the first line of Table 1. The artificial laser guidestars required by both NFIRAOS and the additional LGS AO systems described in Section 4 below will be generated by the Laser Guide Star Facility (LGSF), which will use three 50 W, CW solid state lasers to generate and project LGS asterisms of up to 8 guide stars from a laser launch telescope (LLT) located behind the TMT secondary mirror. An adaptive secondary mirror (AM2) will be implemented as a facility AO upgrade that will enable or enhance the performance of the wider field and longer wavelength AO systems described in Section 4 below, and also serve as the low-order, large stroke "woofer" deformable mirror for future AO systems requiring very high order wavefront correction (such as ExAO and a possible NFIRAOS upgrade). These three facility AO systems are described further in the following paragraphs.

3.1. Narrow Field IR AO System (NFIRAOS)

This is the first light TMT Facility AO system, intended for use with up to three near IR (1.0-2.5 μm) scientific instruments.[4] Figure 2 illustrates the overall opto-mechanical layout, which is largely defined by the desire to utilize relatively mature piezostack deformable mirror (DM) technology and minimize the number of optical surfaces. The first order AO design parameters consist of order 61 by 61 and 75 by 75 DMs conjugated to ranges of 0 and 12 km (the former is mounted on a tip/tilt stage), 6 LGS wavefront sensors with 60 by 60 subapertures viewing an asterism with a 35" radius, and an 800 Hz update rate. Although described as a "narrow field" AO system, an MCAO capability is included to both

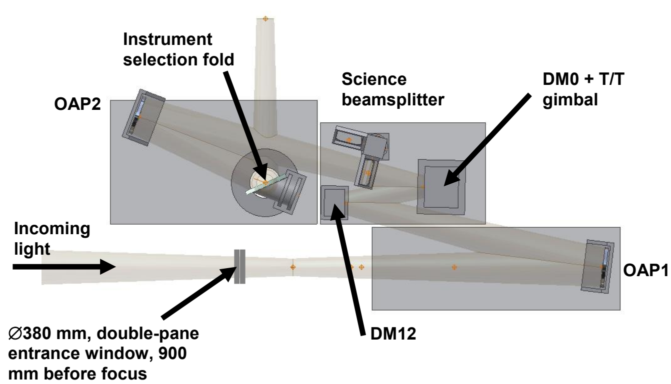


Figure 2: NFIRAOS Science Optical Path

(i) support science instruments with a FoV on the order of 30", and (ii) improve sky coverage by compensating, or "sharpening," the images of IR tip/tilt natural guidestars over the majority of a 2 arc min technical FoV.

Current error budgets predict an on-axis, tilt-removed wavefront error of about 180 nm RMS, including both fundamental AO error sources and implementation effects from the telescope, science instrument, and NFIRAOS itself. The on-axis performance of a future NFIRAOS upgrade is estimated to be about 130-135 nm RMS, assuming that (i) the ground-layer order 61 by 61 DM is replaced by a 121 by 121 mirror, (ii) an adaptive secondary mirror (AM2) is available to provide the low-order, large amplitude correction no longer feasible with the new DM due to the smaller inter-actuator pitch, (iii) the LGS WFSs are also upgraded from 60 by 60 to 120 by 120 subapertures, and (iv) advanced, 50W, pulsed laser systems are available to eliminate wavefront sensing errors associated with the nonzero thickness of the sodium layer (see Section 3.2 below).

Low order tip/tilt/focus wavefront sensing will be provided by the science instruments fed by NFIRAOS. Three separate tip/tilt measurements in different directions within the 2' guide field will enable accurate estimation of the atmospheric tip/tilt in the direction of the science target, largely eliminating the effect of tilt anisoplanatism which would otherwise degrade performance if only a single off-axis tip/tilt guide star was utilized. The use of infra-red stars significantly improves the NGS WFS limiting magnitude and sky coverage because of the diffraction-limited cores of the guide star images in J and H band, which are not significant at shorter wavelengths. The tip/tilt error for 50 per cent sky coverage at the galactic pole is estimated to be about 65 nm RMS wavefront error (including both turbulence-induced tip/tilt jitter and telescope wind shake effects), under the assumption that IR detectors arrays with 5-10 electrons of read out noise at frame rates of approximately 500 Hz will be available.[21]

Unlike most existing AO systems, NFIRAOS does not include a separate steering mirror for tip/tilt compensation. The ground-layer DM is instead mounted on a tip/tilt stage to avoid the additional optical surfaces which would be necessary using the conventional approach. The achievable bandwidth of the tip/tilt stage is likely to be limited by the mass and size of the DM, and a "woofer-tweeter" control algorithm has consequently been developed to compensate the high frequency, low-amplitude component of the tip/tilt jitter using the DM actuators themselves.[9]

One important challenge for the NFIRAOS design is the requirement to limit emissivity to 15% of the inter-OH sky+telescope background. This will require that NFIRAOS be cooled to approximately -30 C, and has implications on DM performance requirements as described further in Section 6.1 below.

3.2. Laser Guide Star Facility (LGSF)

The basic opto-mechanical design concept for the TMT LGSF has been derived in part from the LGS system designs developed for the Gemini North (Altair) and Gemini South (MCAO) telescopes.[10] The basic elements of the concept are illustrated in Figure 3. As with the Gemini design, the TMT LGSF consists of four primary subsystems. The Laser Enclosure housing the sodium guidestar lasers is mounted on the primary mirror (M1) structure. The Beam Transport Optics (BTO) then direct the laser beams up the telescope truss to a position behind the secondary mirror, where the BTO Optical Bench (BTOOB) is located. The BTOOB consists of the optics that format the LGS asterisms, feed the beams into the

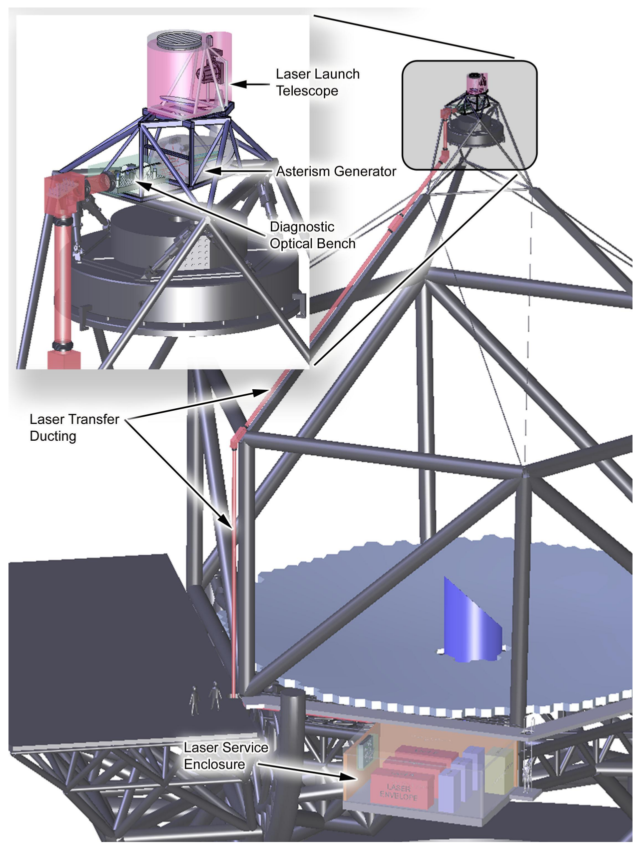


Figure 3: Laser Guide Star Facility (LGSF) implementation on TMT. The Laser Enclosure is the room attached to the M1 support structure, and the Laser Launch Telescope is located behind the M2 assembly.

LLT, maintain the asterism orientation on the sky, and evaluate beam quality and pointing. Finally, the LLT itself is located behind the TMT secondary (M2) on the axis of the telescope.

The TMT LGSF must project four different LGS asterisms for NFIRAOS and the remaining TMT AO modes, provide an ability to switch quickly from one to another, and output a total laser power of 150 W to match the LGS signal level requirements derived for NFIRAOS and the remaining TMT AO systems (about 25 Watts per beacon are needed to satisfy the NFIRAOS error budget during times with low sodium column density, roughly a factor of 2.5-3 larger than required on an 8- to 10-m class telescope due to the impact of guidestar elongation). The baseline LGSF uses three 50 W, continuous wave (CW) sodium lasers to achieve this total power level; in fact, two lasers producing 100 W of total power will provide a reasonable level of performance for most LGS AO operating modes under most operating conditions. A robust proof-of-concept 50 W CW laser has recently been demonstrated by the USAF Research Laboratory at the Starfire Optical Range,[23] and a somewhat similar system is now under development by Lockheed Martin Coherent Technologies (LMCT) for delivery to Gemini South in early 2007. These systems have been used to place bounds on the basic mass, volume, and power requirements for the TMT Laser Enclosure.

Several potential upgrades to the TMT LGSF were considered as part of the conceptual design process. The use of hollow-core fibers to transport the laser beams could result in significant simplification of the BTO relay system and even permit the Laser Enclosure to be located off the telescope. This approach has now been adopted for several 10 Watt class CW lasers on 8 meter telescopes, but further progress towards the transmission of higher peak powers over longer path lengths must be demonstrated before this can be considered a viable option for TMT.

A second possible upgrade is the use of sodium lasers producing short (2-3 μs) pulses approximately 1 km in length, as required by a LGS wavefront sensing concept referred to as "dynamic refocusing.[24,25]" This upgrade would eliminate LGS elongation due to the finite thickness of the sodium layer, thereby reducing laser power requirements for TMT AO systems by about a factor of about 2.5-3. Such an upgrade would also eliminate or significantly alleviate several sources of calibration errors associated with dynamic, random variations in the sodium layer profile. Additionally or alternatively, lasers producing somewhat longer (200-400 μs) pulses or pulse trains would eliminate Rayleigh backscatter interference between separate laser beacons ("fratricide") and significantly reduce the impact of thin cirrus upon the performance of LGS AO systems. We intend to monitor the progress towards these pulse format options, and make a final decision on the baseline laser system in 2009 at the start of the TMT construction phase.

3.3. Adaptive Secondary Mirror (AM2)

The 3.6 m adaptive secondary mirror that would be required by TMT represents a very dramatic advance over existing adaptive secondary mirrors on 6.5- to 8-m class telescopes,[26] and is consequently not currently planned as a first light AO capability. The TMT AO development plan still calls for the implementation of AM2 as one of the earliest AO upgrades because of its many potential benefits. These include: (i) reduced emissivity for Mid-IR AO (MIRAO) systems, (ii) significantly simplified implementation of ground-layer AO (GLAO) for wide-field scientific instruments, (iii) a significant reduction in DM stroke requirements for all remaining AO modes, and (iv) a greatly enhanced active optics capability for all seeing-limited instruments and observations.

All of the above requirements can be met using a mirror with approximately 1800 actuators that control somewhere between 250 and 600 modes. The proposed design concept consists of 6 identical wedge-shaped segments, supported by balanced voice coil actuators mounted on a light-weighted reaction and reference structure. Further information on the status of the design effort can be found in Section 6.2 below.

4. INSTRUMENT AO CAPABILITIES

AO system requirements and conceptual designs have also been developed for the four additional TMT instrumentation capabilities listed in Table 1, and are described briefly in the following paragraphs. They are listed in their approximate order of technical sophistication, from a mid-IR AO system which is a candidate for first-light operation to an ExAO system requiring order 128 by 128 wavefront correction, pyramid wavefront sensing, and a nulling interferometer.

4.1. LGS Mid-IR AO (MIRAO) for a Mid-IR Echelle Spectrograph (MIRES)[6]

Scientific operations at longer IR wavelengths (potentially 2.9-28 μm for TMT) require an AO system with a minimum number of warm optical surfaces to limit the emissivity which may otherwise become the dominant source of background noise. For the TMT aperture, adequate wavefront compensation over a narrow FoV can be achieved at these wavelengths by a 31 by 31 DM and 3 LGS, which are arranged in a 140" diameter asterism and "picked off" via fold mirrors to avoid the requirement for a warm dichroic beamsplitter that would increase emissivity. The LGS WFS design will be borrowed from NFIRAOS, since this will reduce design costs, simplify sparing and maintenance, and there is no penalty in utilizing 60 by 60 subapertures when adequate laser power is provided by the LGSF.

The first light version of the system would utilize a conventional 31 by 31 piezostack DM (on a tip/tilt stage) in a 3-mirror optical relay very similar to existing AO system designs. This relay and an additional fold mirror would be removed once AM2 becomes available. This reduces the number of warm optical surfaces before the MIRES dewar window from 7 to 3, and improves overall observing efficiency by approximately 50 per cent.

4.2. LGS Ground Layer AO (GLAO) for a Wide Field Optical Spectrograph (WFOS)[16]

As their name implies, GLAO systems are intended to correct low-altitude atmospheric turbulence, and thereby provide "enhanced seeing" over fields-of-view dramatically wider than can be provided by either conventional AO systems or even MCAO. "Enhanced seeing" is expected to significantly reduce integration times for many background-limited observations, and thereby appreciably improve the overall observing efficiency of TMT. The estimate of the low-altitude component of atmospheric turbulence is obtained by simply averaging WFS measurement from multiple, widely-spaced natural- or laser guide stars. The preferred wavefront corrector is an adaptive secondary mirror, since the design of an AO relay becomes very difficult for an instrument with a large FoV.

The TMT Wide Field Optical Spectrograph is a challenging application for a GLAO system, however, on account of the wavelength range of interest (UV to visible) and the relatively large FoV of 77 square arc minutes. Both of these parameters reduce the thickness of the ground layer which can be successfully corrected using a single DM. However, detailed simulations indicate that GLAO still measurably improves seeing at wavelength of 0.8 μm over the full WFOS FoV, thereby enabling narrower slit widths which reduce the required integration times by factors of 15 to 25 per cent for background-limited observations of point sources. This improvement is certainly non-trivial when the operations costs for a 30 meter class ELT such as TMT are taken into account. These results are achieved with 4 sodium laser guide stars and order 30 by 30 wavefront compensation, although GLAO performance is a relatively weak function of either of these parameters.

4.3. LGS Multi-Object AO (MOAO) for an Infra-Red Multi-Object Spectrograph (IRMOS)[3,5]

The term "MOAO" describes a system in which multiple, independent wavefront corrections are applied to compensate many small objects within a larger overall field-of-view, using a tomographic wavefront estimate obtained from multiple wavefront sensors observing either natural- or laser guide stars. In principle, MOAO can be coupled to integral field unit (IFU) multi-object spectrographs with fields-of-view that are too large for practical MCAO systems, but the concept requires open-loop control of high-order MEMS wavefront correctors and is therefore considered too challenging for TMT first light. The current design parameters for the TMT MOAO system include 8 laser guide stars and order 64 by 64 wavefront sensing and correction using some combination of high-order, low stroke MEMS and low-order, large-stroke "woofer" DMs. Either AM2, a conventional piezostack DM, or multiple bimorph mirrors (one per MEMS) could possibly be used for this latter role.

Simulations indicate that the enclosed energy values of up to 50% within a 50 mas pixel may be feasible for J, H, and K band observations of multiple small targets distributed within a 5 arc minute FoV, although implementation error sources such as non-common path aberrations and uncorrectable telescope aberrations have not yet been fully taken into account. Sky coverage is estimated to be quite large with either visible or near IR tip-tilt sensing, since the RMS tip/tilt jitter allowed with 50 mas IRMOS IFU pixels is relatively large.

4.4. Extreme AO (ExAO) for a Planet Formation Instrument (PFI)[7]

In comparison with nearer-term ExAO systems planned for smaller ground- and spaced-based telescopes, the TMT aperture diameter provides a unique capability to detect and characterize the young, Jupiter-sized planets to be found in the nearest star-forming regions. The anticipated contrast ratio of $\sim 10^{-6}$ for this science case is among the least stressing for applications of ExAO to high contrast imaging, but the typical star-to-planet separation (0.05") and stellar magnitude (H=8-10) will require both the high angular resolution associated with a large aperture and an ExAO system design optimized for relatively low WFS signal levels. At the same time, surveys of older, nearby field stars will require very high-order, high bandwidth wavefront correction to achieve contrast ratios of $\sim 10^{-8}$ at larger separations from brighter (I=6-8) stars. Both scenarios demand exquisite calibration and real-time control of quasi-static wavefront errors associated with the telescope and the AO system.

The ExAO design concept developed for PFI addresses these requirements in three stages. The front end AO system will include a 128 by 128 MEMS DM driven at up to 2-4 kHz by an I-band pyramid wavefront sensor of equivalent order, and is expected to obtain H band Strehls of 0.9 on bright stars.[20] This first AO system is followed by a interferometric nuller to suppress the diffracted light scattered by the TMT pupil, and then by an IR "back wavefront sensor" to detect and correct the quasi-static speckles induced by chromatic effects, non-common path wavefront aberrations, and other calibration errors which might otherwise be mistaken for planets.[18] On dimmer stars, the front-end AO system will provide partial correction at lower bandwidths while the back IR WFS controls the final wavefront. This two-stage approach yields additional rejection of atmospheric turbulence, allowing PFI to reach contrast of 10^{-6} to 10^{-7} on H = 10 magnitude young stars and better than 10^{-8} on brighter nearby targets.

5. OBSERVATORY INTERFACES

Preliminary opto-mechanical and controls interfaces have been defined between the AO systems described above and the remainder of the TMT observatory. The opto-mechanical interfaces between the LGSF and the telescope structure are illustrated in Figure 3 above. The Laser Enclosure is mounted on the M1 structure, and the Beam Transport Optics (BTO) direct the laser beams up the telescope truss to the Laser Launch Telescope located behind the TMT secondary mirror. The interface between the AM2 and the telescope structure is based upon the same hexapod mount and mirror cell designs used for the first-light conventional secondary mirror (CM2). NFIRAOS will be located on one of the Nasmyth platforms, with input- and output opto-mechanical interfaces with the telescope tertiary mirror (M3) and up to three instruments mounted on two vertical and one horizontal output ports. These instruments are responsible for providing their own image derotation, natural guide star tip/tilt/focus wavefront sensing, and atmospheric dispersion compensation (if and when necessary). Finally, the instrumentation AO systems described in Section 4 above are integral opto-mechanical components of the corresponding science instruments.

Preliminary controls interfaces have also been defined with a variety of the remaining observatory software systems.[8] Most of these interfaces are coordinated by the AO Sequencer (AOS). The AOS receives commands and transfers status to and from the Observatory Control Software (OCS) to control and monitor AO system operations as part of overall science observing sequences. The AOS also interfaces with the Telescope Control System (TCS) to offload low-order, persistent wavefront aberrations from the deformable mirrors (including AM2) to M1 and M2, and to receive commands for driving the NGS WFS probe positions. The real-time controller (RTC) for NFIRAOS will interface with each of its science instruments to receive NGS WFS pixel data for tip/tilt/focus wavefront sensing,[b] and the RTC for each AO system will also interface with the associated instrument controller to monitor (or adjust) field derotation as a function of the elevation angle. Additional software interfaces will transfer AO performance measurements to the Science Data System for point spread function estimation and image post-processing, and archive AO telemetry to the Engineering Data System as required for system commissioning, performance characterization, and trouble-shooting. Finally, the AOS will interface with the Observatory Safety System (OSS) to receive emergency stop signals as needed.

6. PROGRESS IN AO COMPONENT DEVELOPMENT

The broad range of TMT AO systems described in Sections 3 and 4 above will face a common set of very dramatic technical challenges in spite of their obvious differences. High sky coverage requirements mandate that extremely dim natural guide stars must be used for tip/tilt (and tilt anisoplanatism) sensing in the LGS AO systems. Stringent

[b] This is formally an internal AO interface, since the tip/tilt/focus WFSs are considered to be AO components.

requirements on the delivered wavefront quality in an ELT with a very large value of D/r_0 imply the use of 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 60 m outer scale. Finally, the large aperture diameter also implies that sodium guidestar elongation will be a serious challenge for LGS wavefront sensing.

Table 2 summarizes the baseline AO components that will be used to address these requirements for each TMT AO system. As described previously,[22] our strategy for meeting these challenges emphasizes incremental improvements to existing and near-term components whenever possible, with reliance upon piezostack DM technology and CW, solid-state guide star lasers for the first light LGS AO system NFIRAOS. Longer-term systems may utilize more advanced and innovative components, including AM2, MEMS wavefront correctors, and/or pulsed lasers to defeat sodium laser guidestar elongation. Advances in detector technology for both LGS and IR NGS wavefront sensors are assumed in the baseline designs for all of the TMT AO systems, although fallback options based upon more conventional detectors have also been formulated.

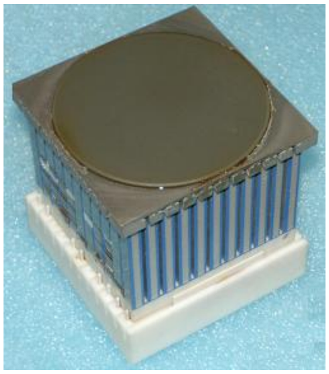
<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">NFIRAOS</th><th colspan="2">MIRAO</th><th rowspan="2">GLAO</th><th rowspan="2">MOAO</th><th rowspan="2">ExAO</th></tr>
<tr><th>1st Light</th><th>Upgrade</th><th>1st Light</th><th>Upgrade</th></tr>
<tr><td rowspan="2">Deformable Mirrors</td><td>“Tweeter”</td><td rowspan="2">61x61 and 75x75 piezostacks</td><td>121x121 and 75x75 piezostacks</td><td rowspan="2">31x31 piezostack</td><td rowspan="2">AM2</td><td rowspan="2">AM2</td><td>64x64 MEMS</td><td>128x128 MEMS</td></tr>
<tr><td>“Woofer”</td><td>AM2</td><td>AM2, piezostack, or multiple bimorphs</td><td>AM2 or bimorph</td></tr>
<tr><td colspan="2">Higher-order LGS WFS detectors</td><td colspan="6">AODP “Polar Coordinate” CCD array with 60x60 subapertures
(120x120 subapertures for NFIRAOS upgrade)</td><td>NA</td></tr>
<tr><td colspan="2">Higher-order NGS WFS detectors</td><td colspan="2">AODP “Polar Coordinate” CCD array with 60x60 subapertures</td><td colspan="2">128x128 IR detector arrays with 5-10 noise electrons/pixel/read at 500 frames/sec</td><td>Visible CCD (current tech.)</td><td>TBD</td><td>128x128 visible and IR arrays</td></tr>
<tr><td colspan="2">Tip-tilt-focus WFS detectors</td><td colspan="4">128x128 IR detector arrays with 5-10 noise electrons/pixel/read at 500 frames/sec</td><td colspan="2">Visible CCD (current technology)</td><td>NA</td></tr>
<tr><td colspan="2">Guidestar lasers</td><td colspan="6">Three 50 W CW solid state lasers generating 3-8 guidestars @ 17-25W each
(6 50W pulsed lasers for NFIRAOS upgrade)</td><td>NA</td></tr>
</table>

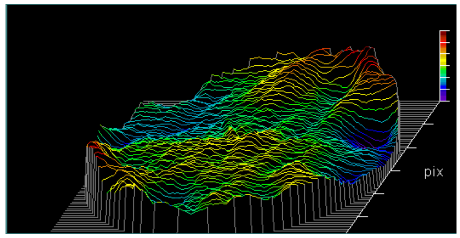
Table 2: Component technology summary for TMT AO systems.

Recent progress towards developing the AO components described in Table 2 has been very encouraging. The following three subsections describe the R & D activities funded directly by TMT, and a final subsection briefly summarizes some of the additional component development work supported by other sponsors.

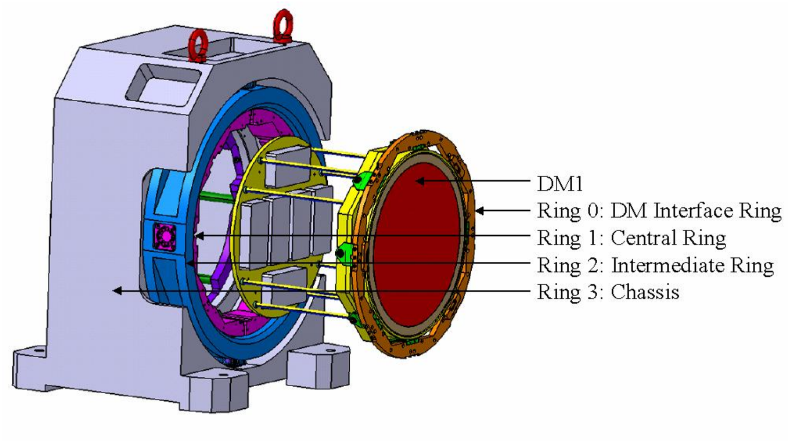
6.1. Piezostack DM conceptual design and feasibility demonstration (CILAS)

Although piezostack DMs have already been used very successfully in numerous AO systems, the DM requirements for NFIRAOS will be exceptional in terms of the size of the DM (75 by 75 actuators), the required stroke (8-10 μm peak-





(a) 9x9 actuator subscale DM (b) Mirror flattened to 13 nm RMS at -35 C



(c) Full scale DM design mounted upon a tip/tilt stage

Figure 4: Sample results from CILAS conceptual design and feasibility study

to-valley surface), operating temperature (as low as -30 Celcius with acceptable hysteresis and surface flatness), and the implementation of the DM on a tip/tilt stage (TTS) able to provide tip/tilt corrections at a closed-loop bandwidth of 20 Hz.

CILAS and the Observatoire de Paris have recently completed a study to develop a conceptual design for the full scale NFIRAOS DM and demonstrate the required level of actuator performance on a subscale prototype with 57 actuators. The subscale prototype, illustrated in Figure 4(a) below, has demonstrated 11 μm of actuator stroke after surface flattening, as well as 5% hysteresis and 13 nm RMS figure quality at a temperature of -35 C. The conceptual design for the full-scale NFIRAOS DM also meets the TMT requirements for mass and volume, and the chances of achieving the tip-tilt-stage requirement for 20 Hz closed-loop bandwidth appear to be very good pending detailed design and prototyping.

6.2. Adaptive secondary mirror feasibility study (SAGEM)

SAGEM has completed a feasibility study of the adaptive secondary mirror concept described in Section 3.3 above. A 5 mm thick Zerodur facesheet with an interactuator spacing of 80 mm will meet all TMT requirements for static figure quality (including gravity-induced actuator print-through), actuator dynamic range for correction of tip-tilt and higher-order wavefront aberrations, wavefront fitting error for a Kolmogorov turbulence spectrum, temporal response, and control loop stability. This relatively thick facesheet (for an adaptive secondary) is expected to reduce fabrication and handling risks. A balanced, reactionless actuator design has been developed which provides adequate force for the required inter-actuator stroke with acceptable power dissipation. Design work on the lightweight reference body is proceeding, although lateral support of the 1.8 m facesheet segments is proving to be one of the most challenging aspects of the design

6.3. Real-time controller (RTC) feasibility and conceptual design study (tOSC)

The TMT RTC is a very challenging system, with processing and IO requirements at least one to two orders of magnitude greater than advanced 8-meter class systems such as the Gemini South MCAO RTC. In collaboration with the TMT project, the Optical Science Company (tOSC) has studied potential algorithm and processor options for the critical real-time RTC processes including WFS pixel processing, atmospheric tomography, and DM actuator command computation.[8] Figure 5 illustrates the signal processing architecture which has been developed. A group of 7 embedded processing boards constitutes the real-time functionality of the RTC. Each board is comprised of either eight DSPs and one FPGA, or eight FPGAs and one DSP. The baseline board concepts are based upon the currently available 500 MHz TS201s DSP from Analog Devices, and the 500 MHz Virtex XC4VX140 FPGA.

LGS and NGS WFS pixel processing is accomplished using two of the DSP boards. The advantage of using DSPs instead of the potentially more powerful FPGAs for this task is that the former are far easier to program and have more of the internal RAM required for proper gain and bias calibration of the WFS pixel intensities. The LGS tomography and DM command calculations tasks are then accomplished by the "A", "B", and "C" FPGA boards. Actuator commands will be sent to the DMs and tip/tilt mirrors using RocketIO ports from each of the "C" FPGAs

We believe that this architecture can provide the NFIRAOS baseline AO system with a complete reconstruction in the range of 300 to 650 μs, which is well within the TMT requirement for the end-to-end latency. Furthermore, this architecture appears to have a potential for growing by adding more boards and could possibly be upgraded to meet the requirements of systems like MOAO and or NFIRAOS upgrade, although requirements for the NFIRAOS upgrade are greater by another order of magnitude.

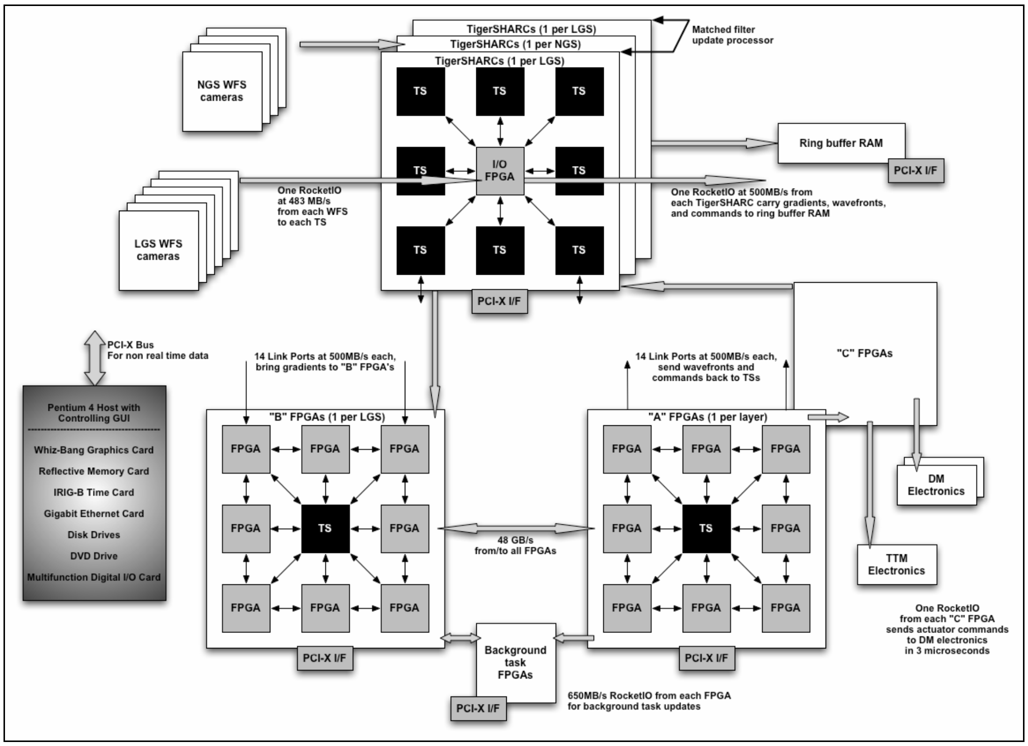


Figure 5: NFIRAOS Baseline RTC processing architecture.

6.4. Separately funded AO R & D activities

These separately funded activities include:

- Solid-state sodium guidestar laser development at the USAF Starfire Optical Range and Lockheed-Martin Coherent Technologies, as outlined in Section 3.2 above;[23]
- Two AODP projects to developed pulsed sodium guidestar lasers, which can conceptually eliminate the impact of sodium LGS elongation via "dynamic refocusing," at Lawrence Livermore National Laboratory and Lockheed-Martin Coherent Technologies;
- An AODP project at MIT Lincoln Laboratory to demonstrate low-noise, polar coordinate CCD arrays optimized for wavefront sensing with (either CW or pulsed) sodium laser guidestars;[27]
- Work supported by the NSF Center for Adaptive Optics, the UCSC Lab for Adaptive Optics, and Gemini Observatory to develop large-stroke, high-order MEMS wavefront correctors suitable for MOAO and ExAO systems; and

- Planned work by Gemini and the European Southern Observatory to develop low-noise, high speed IR detector arrays for both low- and high-order NGS wavefront sensing, as required for tip-tilt-focus NGS wavefront sensors in the TMT LGS AO systems and the IR "back wavefront sensor" in ExAO.

Space prevents us from providing an update on these projects, but additional information is available in the references.

7. LAB AND FIELD TESTS

The TMT project has funded two tests (or "experiments") at Palomar Observatory and the University of Victoria to validate several of the advanced estimation and control concepts proposed for use in TMT AO systems. The Multiple Guide Star Unit (MGSU) at Palomar Observatory consists of 4 Shack-Hartmann sensors, each with 16 by 16 subapertures, which may be used to acquire simultaneous wavefront measurements from four natural guide stars for tests of the tomographic wavefront reconstruction algorithms needed for the NFIRAOS, MOAO, and MIRAO systems. Data reduction and analysis of the first measurements collected in February of this year are now underway, and the initial results are encouraging. In one sample 5-minute data set, wavefront aberrations of 598 nm RMS for the on-axis star were estimated to within an accuracy of 231 nm RMS from the remaining three wavefronts (see Figure 6). It appears that the performance of the tomographic wavefront reconstruction algorithm was limited by WFS camera noise and pupil registration for these initial tests, and work is progress to optimize the reconstruction algorithm and assess the results obtained against predictions based upon analysis and simulation.

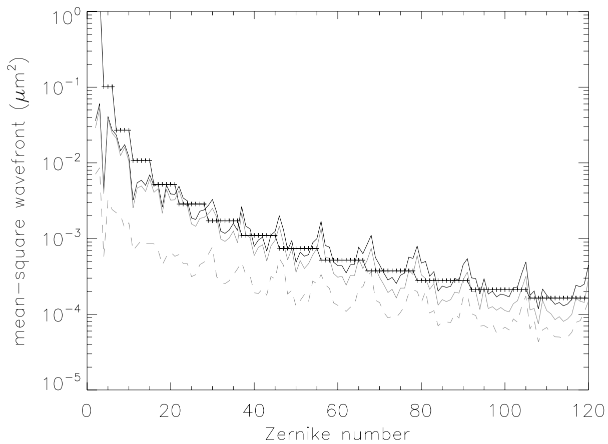


Figure 6: Zernike coefficient summary of preliminary MGSU field test results at Palomar Observatory. This figure plots the RMS Zernike coefficients for the direct reconstruction of the on-axis wavefront (solid black line), the tomographic estimate of this wavefront obtained using the other three wavefronts (solid grey line), and the estimation error between the two (dashed grey line). The theoretical Zernike variances (for an unobscured aperture) are also plotted for comparison (solid black line with pluses).

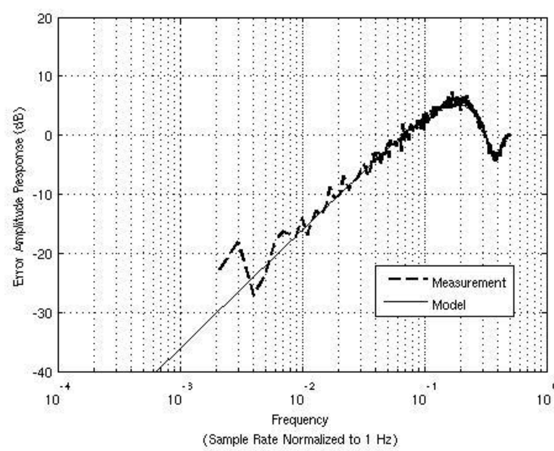


Figure 7: Experimentally measured error rejection ratios for the woofer-tweeter experiment vs. performance predictions.

The woofer--tweeter experiment at the Adaptive Optics Laboratory of the University of Victoria (UVic AO Lab) has recently achieved successful completion of its first phase.[13] The goal of this experiment is to validate the woofer-tweeter AO control concept, in which two DMs conjugated to the same optical plane are used to achieve both the large stroke and high order of correction required for atmospheric turbulence compensation on an ELT. The two DMs used at UVic are a magnetically-driven mirror manufactured by the Laboratory of Astrophysique of Grenoble with 52 actuators (the "woofer"), and a Boston Micromachines MEMS with 80 actuators (the "tweeter"). The peak-to-valley strokes of the two devices are 25 and 1.2 microns, respectively. The wavefront tip/tilt is compensated by a dedicated tip/tilt mirror, and wavefront measurements are provided by a 9x9 subaperture Shack-Hartmann sensor incorporating a 128x128 pixel

DALSA CCD camera sampled at up to 736 Hz. Finally, a hot-air turbulence generator developed by the UVic AO Lab reproduces the atmospheric Kolmogorov turbulence spectrum.

The woofer-tweeter concept has been successfully tested on the turbulence with a loop rate of 100 Hz, using a control law in which the tweeter commands are off-loaded to the woofer and the tip-tilt mirror to prevent the tweeter from saturating. Stable performance is obtained with this architecture, and the error rejection ratios show an effective compensation of turbulence effects which are in agreement with simulated predictions (See Figure 7). As these very first results look promising, an upgrade of the bench is already planed to implement a 32x32 MEMS tweeter.

8. SIMULATION AND ANALYSIS

Performance analysis for all of the TMT AO systems described in Sections 3 and 4 above is now well past the point of basic error budgeting and standard scaling law formulas. Several time domain simulation codes have been used to model multi-LGS AO systems including MCAO (NFIRAOS), MOAO, MIRAO, and GLAO with wavefront sensing and correction up to order 120 by 120.[12,19] One of these codes (LAOS) features wave-optics modeling of Shack-Hartmann wavefront sensing with sodium laser guidestars, including the effects of uplink propagation with closed-loop tip/tilt correction, guidestar elongation due to the nonzero thickness of the sodium layer, physical optics effects in the Shack-Hartmann WFS, the "polar coordinate" CCD array pixel geometry under development by the AODP, and a variety of spot displacement estimation methods including the standard centroid algorithm and noise-weighted least squares. In addition to modeling the effects of sodium guide star elongation, this LGS WFS model will also be applied to understanding the impact of M1 segment alignment and figure errors on AO system performance in the coming months.

Additional LGS AO modeling capabilities include a Monte Carlo sky coverage simulator for systems which employ multiple tip/tilt natural guide stars such as MCAO and MOAO.[21] This code evaluates the overall tip/tilt error associated with each randomly generated NGS asterism, accounting for the combined effects of anisoplanatism, servo lag, WFS noise, telescope windshake, and any partial "sharpening" of the NGS images provided by the LGS AO system. Low-order (but tip-tilt removed) LGS WFS measurements are also included in the formulation of the tip/tilt estimation algorithm, since these measurements provide additional information on the 3-dimensional turbulence profile which is useful in reducing the estimation error due to anisoplanatism. Some of the finer points of the simulation now include a model for woofer-tweeter control using a combination of fast (small stroke) and slow (large stroke) tip/tilt correctors,[9] and an analysis of the residual errors resulting when noisy, finite bandwidth focus measurements from an NGS WFS are used to keep an LGS WFS focused on the mean range of the sodium layer.[11]

Extensive analysis and simulation work on ExAO systems is also proceeding, including detailed wave-optics end-to-end simulations of the AO architecture described in Section 4.4, as well as studies of the impact of M1 segment alignment, figure and reflectivity errors upon high-contrast imaging.[14,15] These simulations include the front-end AO system with a Pyramid WFS and a 128 by 128 DM, the diffraction suppression system (nuller) and the back-end interferometric WFS with a second 128 by 128 DM located in the nuller. The atmosphere model uses a 7 layer diffractive model to correctly account for the impact from scintillation with a time step of 0.5 msec. Figure 8 shows the contrast on a mI=4.2 star after 1.5 seconds of simulation and extrapolated to a 1 hour exposure. A contrast of 2 x 10^{-8} is achieved even without speckle suppression, which should improve the contrast by

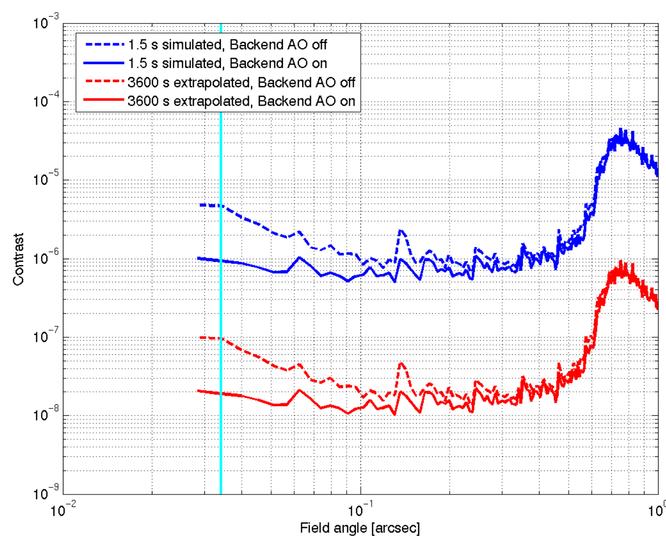


Figure 8: Simulation of ExAO performance on a bright (mI = 4.2) star.

another factor of about 10.

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