Adaptive Optics Program at TMT

Adaptive Optics for Extremely Large Telescopes 4 – Conference Proceedings, 1(1)

Boyer, Corinne

Publication Date
2015

DOI
10.20353/K3T4CP1131715

Adaptive Optics Program at TMT

C. Boyer[*], B. Ellerbroek

TMT Observatory Corp., 1111 S. Arroyo Parkway, Pasadena, CA, USA 91101;

ABSTRACT

The TMT first light Adaptive Optics (AO) facility consists of the Narrow Field Infra-Red AO System (NFIRAOS) and the associated Laser Guide Star Facility (LGSF). NFIRAOS is a 60 x 60 laser guide star (LGS) multi-conjugate AO (MCAO) system, which provides uniform, diffraction-limited performance in the J, H, and K bands over 17-30 arc sec diameter fields with 50 per cent sky coverage at the galactic pole, as required to support the TMT science cases. NFIRAOS includes two deformable mirrors, six laser guide star wavefront sensors, and several low-order, infrared, natural guide star wavefront sensors within each client instrument. The first light LGSF system includes six sodium lasers required to generate the NFIRAOS laser guide stars. In this paper, we will provide an update on the progress in designing, modeling and validating the TMT first light AO systems and their components over the last two years. This will include the final design activities for NFIRAOS, preliminary design activities for the LGSF, final design and prototyping activities for the deformable mirrors, final design and fabrication for the visible detectors, preliminary design activities for the NFIRAOS visible cameras, preliminary design activities for the NFIRAOS Real Time Controller (RTC) and development and tests of prototype candidate lasers. Comprehensive and detailed AO modeling is also continuing to support the design and development of the first light AO facility.

Keywords: Adaptive optics program, extremely large telescopes

1. INTRODUCTION

The first light Adaptive Optics (AO) architecture for the TMT has been defined to provide near-diffraction-limited wavefront quality and high sky coverage in the near infra-red (IR) for the first TMT science instruments IRIS (InfraRed Imaging Spectrograph) and IRMS (InfraRed Multislit Spectrometer). It is a Laser Guide Star (LGS) Multi Conjugate AO (MCAO) architecture consisting of (i) the Narrow Field IR AO System (NFIRAOS)[1], which feeds up to three science instrument ports after sensing and correcting for wavefront aberrations introduced by the atmospheric turbulence and the telescope itself, (ii) the Laser Guide Star Facility (LGSF), which generates multiple LGS in the mesospheric sodium layer with the brightness, beam quality and asterism geometry required by both NFIRAOS and later the second generation of TMT AO systems, and (iii) the Adaptive Optics Sequencer of the AO Executive Software, which automatically coordinates the operations of the AO systems with the remainder of the observatory for safe and efficient observations.

Significant progress has been made in designing, modeling and prototyping these systems and the associated AO components over the last two years. The NFIRAOS team has performed important tradeoffs, developed prototypes and conducted tests of critical AO components, designed and built a MCAO prototype bench dedicated for algorithm testing and is now busy developing the final design. The LGSF team is also conducting important tradeoffs, performing extensive modeling, prototyping components and developing the preliminary design of the LGSF. In house work is being performed to bring the AO Executive Software design to a preliminary design level. On the AO component front, design, prototyping and tests continue for the deformable mirrors, the wavefront sensor (WFS) detectors and associated cameras, the real time controller and the lasers. Finally, several AO modeling and analysis activities have been conducted in the areas of high contrast imaging, high precision astrometry for the galactic center and other observations, and to further support the development of the requirements of the TMT AO systems and AO components.

---

[*] cboyer@tmt.org; phone: 1 626 395 1623; www.tmt.org

2. TMT FIRST LIGHT AO REQUIREMENTS AND ARCHITECTURE REVIEW

The TMT top-level AO science requirements are summarized in Table 1 and have remained very stable since the last AO4ELT conference in 2013.

Table 1: TMT top-level first light AO requirements

Requirements	**Implied AO design requirements**
High sky coverage (50% at the galactic pole)	• Laser guide star (LGS) AO. • Natural guide stars (NGS) in NIR to sense tip/tilt/focus • Multi-conjugate AO with 2 deformable mirrors (DMs) to sharpen guide star images over a large field of view.
Diffraction limited performance in J, H, and K bands (187nm RMS on axis; 191nn RMS on 17” FoV; 208nm RMS on 30”; zenith with median seeing)	Laser guide star (LGS) Multi-Conjugate AO: • Multiple (6) LGS and tomographic reconstruction to defeat the cone effect. • Two DMs for wide-field wavefront correction • High spatial (60x60) and temporal (800Hz) sampling to minimize the wavefront errors due to DM fitting and servo lag. • Bright lasers (20W or more) to minimize the wavefront sensor noise error.
Astrometry (50μarc sec over 30” in H band for a 100 second exposure) Photometry (2% over 30” at λ=1μm for a 10 minute exposure)	• Multi-conjugate AO with PSF reconstruction. • Distortion-free optical system.
High optical throughput (85% over 0.8-2.5μm with goal of 90% over 0.6-2.5μm) Low background (15% of ambient sky and telescope)	Cooled (-30°C) AO system with strong requirement to minimize the number of optical surfaces.
Output ports (3 ports, f/15 with a 2’ FoV)	Multi-conjugate AO with 2 instruments at first light.

The first light AO architecture for TMT (Figure 1) consists of the following major systems:

- NFIRAOS, which is located on the TMT Nasmyth platform and relays light from the telescope to 3 science instrument ports after sensing and correcting for wavefront aberrations introduced by atmospheric turbulence and the observatory itself. NFIRAOS includes two DMs conjugated at 0km (63x63) and at 11.8km (76x76) with the DM conjugated to the ground mounted on a tip/tilt stage to reduce the number of optical surfaces. It also includes six 60x60 LGS WFS (one on-axis, and five in a pentagon with a radius of 35 arcsec), a 60x60 NGS WFS for operation without laser and operates at 800Hz.
- The LGSF generates multiple LGS in the mesospheric sodium layer with the brightness, beam quality, and asterism geometry required by both the first light AO system (NFIRAOS) and later the second generation of TMT AO systems. It includes: i) the lasers, which are attached to the inside of the –X elevation journal facing the TMT primary mirror, ii) the beam transfer optics optical path, which transports up to 9 laser beams in a square pattern along the telescope elevation structure to the telescope top end, iii) the LGSF top end, which formats and launches the laser asterisms (up to 4 different asterisms) to the sky from the laser launch telescope, and iv) the laser safety system.

- The On-Instrument wavefront sensors (OIWFS) of the two NFIRAOS instruments dedicated for tip/tilt/focus sensing in the near IR (IRIS employs up to three OIWFS[2] and IRMS only one) and up to four On-Detector Guide Windows for IRIS only serving as truth tip/tilt sensors.
- The Adaptive Optics Sequencer of the AO Executive Software, which automatically coordinates the operations of NFIRAOS, the OIWFS and the LGSF with the remainder of the observatory for safe and efficient observations.

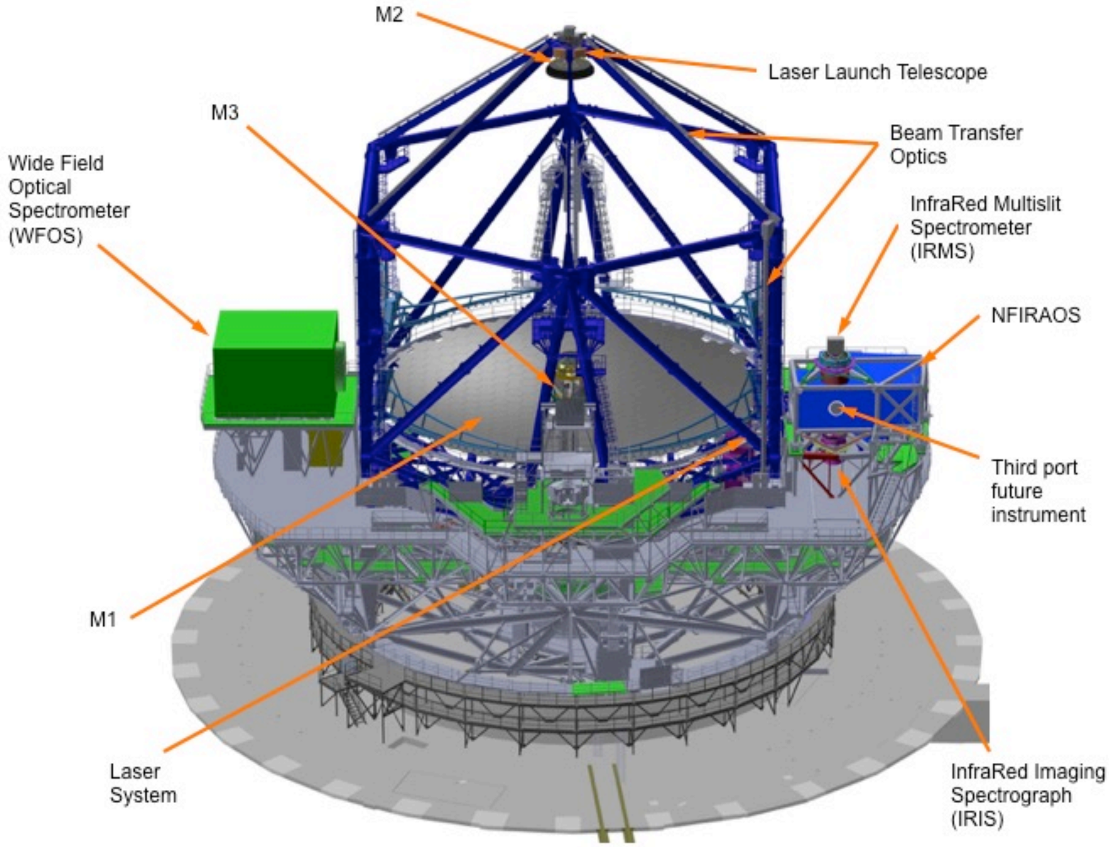


Figure 1: The TMT telescope with the first-light instruments and AO Systems (NFIRAOS and LGSF).

3. FIRST LIGHT AO SYSTEM DESIGN PROGRESS

3.1 Narrow Field IR Adaptive Optics System (NFIRAOS)

Since the AO4ELT Conference in 2013, the NFIRAOS team at NRC Herzberg in Victoria has been busy developing the final design. The main activities conducted by the NFIRAOS team are summarized below:

- Developed and tested a DM Electronics prototype and tested the CILAS DM Breadboard at ambient and cold. The CILAS DM Breadboard test results at -30°C were encouraging showing a total of 16μm stroke before flattening, very low hysteresis and creep, very good linearity, and a residual surface error of 7nm RMS for the working areas of the DM Breadboard, while leaving more than 10μm of stroke after flattening.
- Performed a DM common size trade study with the goals of minimizing the risks associated with DM failure, and DM manufacturing while reducing the DM sparing costs. The conclusion of the study was to keep the baseline configuration (Two different DMs: 63X63 DM0 and 76x76 DM11) with the possibility to mount the

large 76x76 DM11 onto the tip-tilt stage in case of the 63x63 DM0 failure. A single 76x76 spare DM will be sufficient for NFIRAOS.

- Developed a MCAO test bench for tests of wavefront sensing, wavefront reconstruction, calibration algorithms (such as non-common path aberrations calibration through phase diversity), and PSF reconstruction algorithms[4],[5].
- Performed a NGS WFS trade study to select whether to use a Shack Hartmann or a Pyramid WFS. The high order NGS WFS is used for NGS mode and potentially high-contrast imaging, or as a truth WFS to track the changes in the sodium layer profile in LGS mode. The conclusion of the study was to use a Pyramid WFS to improve the performance of the NGS mode while keeping the design impact minimum[3].
- Developed the final design of NFIRAOS. The overall design, system engineering, software and electronics designs are performed at NRC, while the main components final design is sub-contracted to Canada Industry. A total of fifteen sub-contracts will be placed by early 2016[6],[7].

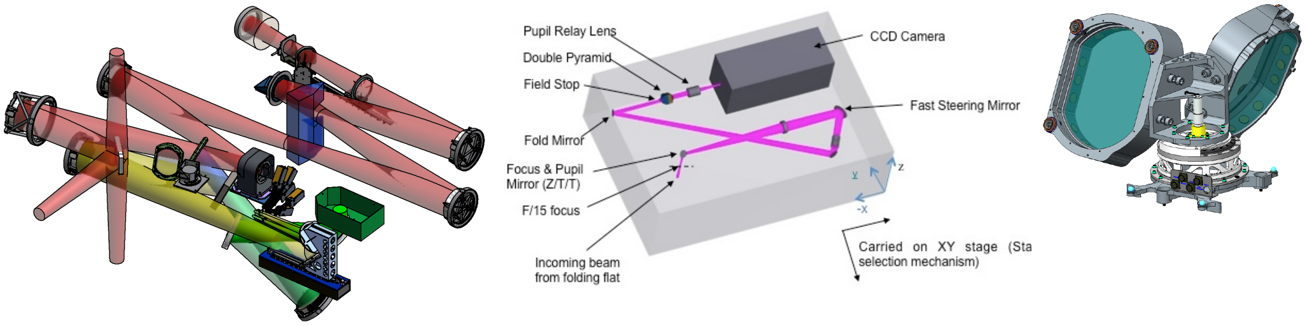


Figure 2: NFIRAOS opto-mechanical layout (left). NGS WFS bench updated for the Pyramid WFS (middle). Final design of the NFIRAOS Beam Splitter (right).

3.2 Laser Guide Star Facility (LGSF)

The Institute of Optics and Electronics (IOE) team in Chengdu China is actively developing the LGSF preliminary design.

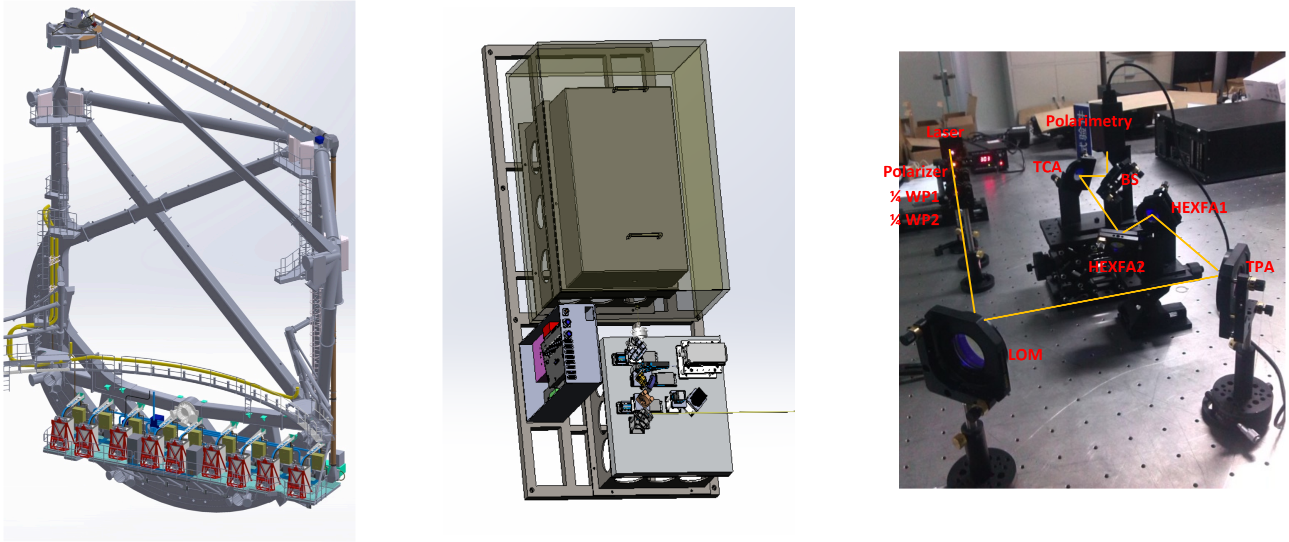


Figure 3: LGSF system. Detailed interface of the LGSF with the telescope structure (left). Details of the laser heads and laser benches mounted on the elevation structure (middle). Polarization test bench (right).

The main design activities performed by the IOE team are summarized below:

- Develop the detailed interface to the telescope structure.

- Perform extensive optical modeling and finite element modeling of the system.
- Conduct several tradeoffs for the location of the optical path, the Laser Launch Telescope (LLT) design (off axis reflective design versus refractive design), and the flexure compensation system (individual beam control versus common control at the different nodes of the optical path).
- Develop prototyping and test setup for the up link fast correction control and the beam polarization control (Two quarter wave plates per beam are necessary to ensure a circular polarization).

3.3 Adaptive Optics Executive Software

The AO Executive Software is composed of three sub-systems: i) the AO Sequencer, which coordinates the actions of the AO systems, ii) the Reconstructor Parameter Generator (RPG), which computes the AO parameters needed by the NFIRAOS Real Time Controller, and, iii) the Point Spread Function (PSF) Reconstructor, which post-processes the AO-corrected PSF from the NFIRAOS WFS and DM telemetry data.

A fully automated AO Sequencer is required due to the complexity of the interactions between AO systems and the TMT requirement for high observing efficiency. This software system will be central to performing AO-assisted observations. It will perform the control and monitoring of the NFIRAOS sub-systems, LGSF sub-systems, On-Instrument WFSs and On Detector Guide Windows of the NFIRAOS instruments. The AO Sequencer components will be dynamically created and composed to execute the startup, test, calibration, observation and shutdown sequences. The observation sequences also include sub-sequences for acquisition, nodding and dithering, non-sideral object tracking, calibration and recovery after a laser safety event or AO/telescope fault.

In house work to further update these sequences, formulate algorithms for the RPG and PSF Reconstructor, and complete the preliminary design of the AO Sequencer and RPG sub-systems is progressing and will be completed by mid 2016.

4. FIRST LIGHT AO COMPONENT DEVELOPMENT

4.1 Deformable Mirrors

The requirements for the NFIRAOS DMs includes two deformable mirrors (63x63 and 76x76) with a 5mm inter-actuator spacing, 10μm of stroke after flattening, 15% hysteresis, less than 2% per time decade creep and an operating temperature of -30°C.

During the last two years, TMT, ESO and CILAS have co-funded a new round of development to improve the manufacturing process of the CILAS actuators and their reliability. In parallel, TMT has sub-contracted AOA Xinetics to develop an actuator, which will meet the TMT stroke requirement at -30°C. Both studies have been successful and TMT has now launched a set of competitive sub-contracts with Northrup Grumman AOA Xinetics and CILAS to develop the final design of the NFIRAOS DMs, and new prototypes[12],[13].

4.2 High-order LGS and NGS Wavefront Sensing

For the six NFIRAOS 60x60 LGS WFS, TMT intends to use the polar coordinate CCDs designed specifically for use with elongated laser guide star images. The polar coordinate CCD reduces the pixel count and total readout rate as opposed to a standard CCD with a conventional rectangular geometry. The requirements for such a detector for TMT include sub-aperture sizes varying from 6x6 pixels at the center to 6x15 pixels at the edge, a quantum efficiency of 90%, and ~3 electrons read noise at 800Hz. A quadrant of the TMT polar coordinate CCD has been designed and fabricated in a wafer run at MIT/LL funded by the TMT, Keck and USAF Research Laboratory. Tests of prototype devices of the polar coordinate CCD have demonstrated fully functional outputs, good yield, uniform CTE, 85% QE, read noise level of 2.7 to 3.7 electrons at 3.5MHz (vs. a 3 electrons requirement) and acceptable dark current at 800Hz[15]. The design of the full-scale detector has been completed by MIT/LL based on the successful prototype quadrant design. The quadrant design was mirrored twice to fill a 360 arc. The design has been also augmented to avoid the gap between the quadrants of the polar coordinate detector. The fabrication has now been launched and the plan is to get the first engineering devices of the polar coordinate detectors by the fall of 2016, and the first science grade devices by the spring of 2017.

For the NFIRAOS Pyramid NGS WFS, TMT intends to use the 256x256 CCD array developed by MIT/LL as part of the polar coordinate prototype effort and successfully tested to achieve the requirements of 80% quantum efficiency, and ~1 electron read noise at 10Hz-800Hz frame rate. Two science grade devices will be packaged for TMT using the same detector package as the polar coordinate detector. The goal is to have the same design for the LGS and NGS WFS cameras.

The preliminary design of the NFIRAOS LGS and NGS WFS cameras and readout electronics has been sub-contracted to Astronomical Research Cameras (ARC) in San Diego with Quartus engineering as a sub-contractor. The main performance requirements of the readout electronics and camera are summarized here:

- Fast pixel data rates for the readout electronics: 128 parallel outputs at 3.5 million pixels per second per output, with a total of ~205,000 pixels for the polar coordinate detector.
- Low noise for the readout electronics (< 3 electrons for the polar coordinate detector and < 1 electron for the NGS detector), requiring the electronics to be packaged close to the detector to avoid long and large interconnections between the detector and the readout system.
- Small volume constraints and less than 0.5W heat dissipation per LGS and NGS camera as they are located within the -30°C NFIRAOS cold enclosure.

Preliminary design activities are progressing well with a preliminary design review anticipated early during the spring of 2016 followed by the development of a full scale prototype for the camera and a 32 channel sub-scale readout electronics prototype.

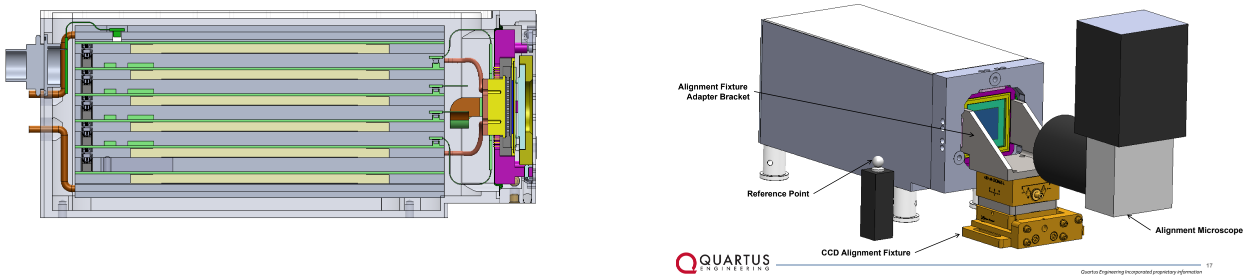


Figure 4: Cross section of the NFIRAOS LGS and NGS visible cameras including the focal plane readout electronics (left). Alignment concept for the NFIRAOS LGS and NGS visible cameras (right).

4.3 Low-order On-Instrument NGS Wavefront Sensing

TMT presently intends to use Teledyne Hawaii-2RG detectors with 1Kx1K science grade sub-arrays for the low-order On-Instrument WFS detectors in the NFIRAOS instruments. These detectors provide a large enough field of view for initial acquisition, very good quantum efficiency in the J, H and K bands and low read noise for small sub-arrays at frame rates of 10-200Hz. An alternative detector under consideration is the Selex APD. This detector appears to provide superior read noise performance at the required frame rate, although the current device with 256 x 320 pixels is still too small for initial guide star acquisition.

4.4 Real Time Controller

The requirements for the NFIRAOS Real Time Controller include real time pixel processing for the high-order LGS and low-order On-Instrument NGS wavefront sensors, tomographic wavefront reconstruction (requiring to solve a 35k x 8k control problem at 800Hz), calculation of the wavefront corrector actuator commands, and real-time optimization of the algorithms for these processes as atmospheric and observing conditions change. The RTC also acquires wavefront corrector and wavefront sensor telemetry data in order to estimate the science Point Spread Function (PSF) for image post-processing.

The NRC-Herzberg Institute team has just successfully completed the preliminary design of the NFIRAOS Real Time Controller. The RTC architecture is based upon commercial server hardware with a classical Matrix Vector Multiply (MVM) algorithm. Intensive benchmarking have been conducted to support this architecture and have demonstrated that the NFIRAOS RTC performance requirements can be met by using a moderate number of existing off-the-shelf commercial boards, which in addition enable the use of a significantly simpler RTC algorithm (MVM).

The RTC team intends to launch the final design early 2016. The team will continue to survey the processor technology and in particular will check the performance of the next generation of Intel Xeon Phi before selecting the final hardware architecture.

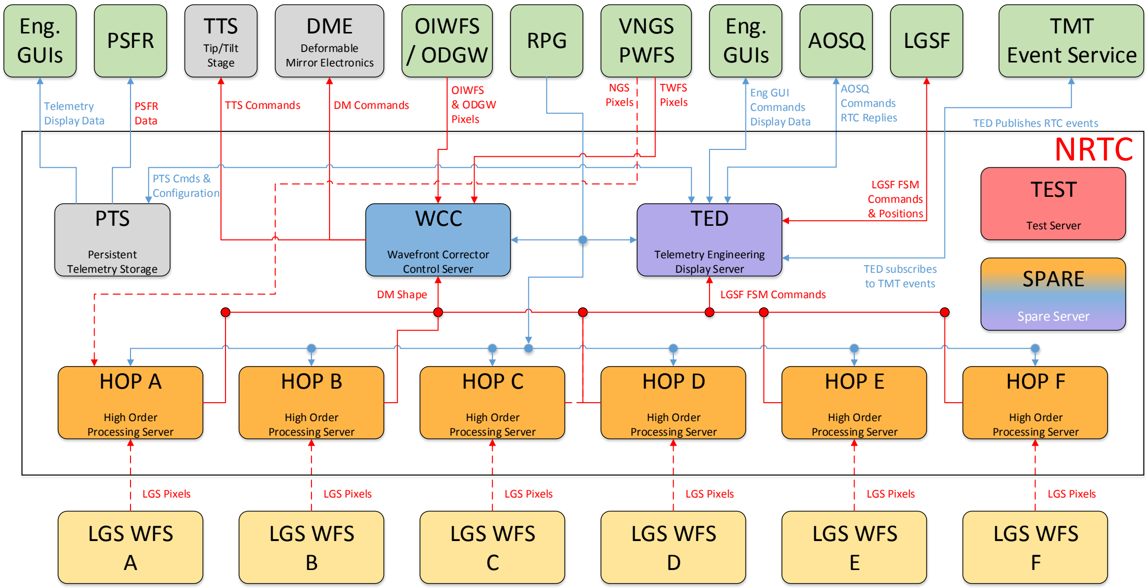


Figure 5: The RTC includes a total of ten servers with one server per LGS WFS, one server dedicated to wavefront corrector control, one server dedicated to telemetry engineering display, a test server and a spare server. Each server includes four high end Intel Xeon CPUs. The connection between the servers, to and from the AO components and other systems is performed through 10/40Gb Ethernet switch with 32 ports.

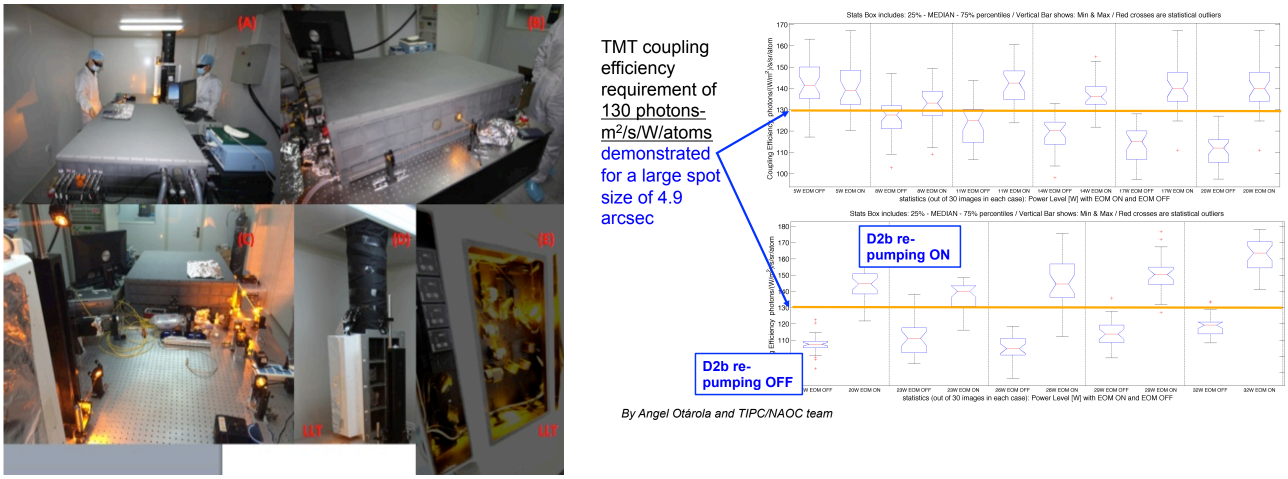
4.5 Lasers

The TMT first light Laser Guide Star Facility will utilize six 25W (20W with the D_2a/D_2b re-pumping option) sodium guide star lasers with high beam quality, high coupling efficiency, high reliability, and a design compatible with a variable gravity vector orientation and the harsh environment of an observatory.

TMT is supporting the design and development of a sodium laser by the Technical Institute of Physics and Chemistry (TIPC) in Beijing, China. The laser design is based upon Sum Frequency Generation (SFG) using 1319nm and 1064nm solid state lasers and has a pulsed format with varying pulse length and pulse repetition frequency.

A total of three TIPC laser prototypes have been built and tested on the sky at the Lijiang and Xinlong Observatories in China and at the UBC LZT site in Canada between 2010 and 2015. The latest prototype meets most of the TMT performance requirements (more than 25W was obtained with a 800Hz pulse repetition frequency). However, the prototype does not meet the beam quality requirement, and the results for coupling efficiency have only been demonstrated with spot sizes equal or larger than 4.9 arcsec. Though significant progresses have been done to reduce the relaxation oscillations of the laser and increase the output power, the TIPC laser concept is not yet fully demonstrated and still has several major challenging engineering requirements to overcome (operation in a variable gravity orientation, reliability, cooling requirements, and vibrations…). The TIPC team is now integrating a new prototype, which should address some of the engineering problems listed above, and in particular the operation in a variable gravity orientation. The new prototype will be thoroughly tested in the lab during the spring of 2016.

Another candidate laser for TMT is the Toptica/MPBC sodium laser developed by ESO, Keck and TMT. The Toptica laser is a Raman Fiber laser and produces the 589 nm beam using second harmonic generation (SHG) conversion of a 1178nm laser[14]. A first unit of the laser has been installed at ESO and meets all the TMT performance requirements[16]. Three additional units are being installed at ESO and another one is being commissioned at Keck at the moment.



TMT coupling efficiency requirement of 130 photons-m^2/s/W/atoms demonstrated for a large spot size of 4.9 arcsec

By Angel Otárola and TIPC/NAOC team

Figure 6: TIPC third prototype laser tested at Xinlong Observatory in China in 2014. Left: on-sky test setup. Right: laser coupling efficiency demonstrated for a spot size of 4.9arcsec.

5. AO MODELING AND PERFORMANCE ANALYSIS

Several AO modeling and analysis activities have been conducted at TMT in particular in the areas of AO requirements definition, high precision astrometry for the galactic center and other observations, high contrast imaging, vibration control and Kalman filtering, and pyramid WFS performance modeling for NGS mode and truth wavefront sensing, and tip/tilt/focus wavefront sensing during acquisition[8],[9],[10],[11]. PSF Reconstruction modeling and experimental analysis will be started again using the NRC-Herzberg MCAO test bench with the goal to refine the algorithms, and later test them with GeMS at Gemini South.

6. SUMMARY

Significant progress has been accomplished in the design, prototyping and modeling of the TMT first light AO systems and AO components. Design and prototyping activities have taken place at the NRC-Herzberg Institute in Canada to advance the NFIRAOS final design effort. IOE in China is working on the preliminary design of the LGSF, and the TMT AO group is developing the preliminary design of the AOESW. Progress in AO components development is also continuing for i) the final design and prototyping of the deformable mirrors, ii) the NFIRAOS WFS, with the fabrication of the full scale polar coordinate detector for the LGS WFS and the preliminary design of the LGS and NGS visible cameras, iii) the completion of the NFIRAOS RTC preliminary design phase, iv) and the prototyping and testing of sodium guidestar lasers.

7. ACKNOWLEDGMENTS

This paper is a summary of the contributions of several TMT staff members, TMT partners and TMT suppliers including: Luc Gilles, Angel Otárola, Tony Travouillon, Lianqi Wang (TMT), David R. Andersen, Jenny Atwood, Peter Byrnes, Kris Caputa, Jennifer Dunn, Joeleff Fitzsimmons, Glen Herriot, Alexis Hill, Dan Kerley, Malcolm Smith, Jean-Pierre Véran (NRC-Herzberg), Sean Adkins(WMKO), Kai Wei, Muwen Fan, Changchun Jiang, Dan Min Li, Xiqi Li, Daoman Riu, Jinlong Tang, (IOE), Terry Bruno, Jeff Cavaco (AOA Xinetics), Hubert Pagès, Jean-Christophe Sinquin (CILAS), Bob Leach (ARC), Kyle Laudner (Quartus), Yong Bo (TIPC).

The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology, the University of California, the National Astronomical Observatory of Japan, the National Astronomical Observatories of China and their consortium partners, and the Department of Science and Technology of India and their supported institutes. 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), the U.S. National Science Foundation, and the National Institutes of Natural Sciences of Japan.

REFERENCES

[1] Herriot, G., et al., "NFIRAOS," AO4ELT4 Proceedings, (2015).
[2] Andersen, D., Dunn, J., "The TMT IRIS On-instrument Wavefront Sensor System," AO4ELT4 Proceedings, (2015).
[3] Véran, J.P., et al., "Pyramid versus Shack-Hartmann: Trade Study Results for the NFIRAOS NGS WFS," AO4ELT4 Proceedings, (2015).
[4] Rosensteiner, M., et al., "Laboratory tests on HeNOS, the MCAO test bench for NFIRAOS," AO4ELT4 Proceedings, (2015).
[5] Turri, P., et al., "The error budget verification of HeNOS, the NFIRAOS test bench," AO4ELT4 Proceedings, (2015).
[6] Lavigne, J.F., et al., "NFIRAOS Off-Axis Parabola Mounts and OAP Testbench Design," AO4ELT4 Proceedings, (2015).
[7] Lavigne, J.F., et al., "NFIRAOS Test Cameras Sub-System Design," AO4ELT4 Proceedings, (2015).
[8] Wang, L., "Optimizing LGS AO Performance in the Context of Evolving Turbulence and Sodium Profiles," AO4ELT4 Proceedings, (2015).
[9] Gilles, L., "Distributed Kalman Filter for Large Scale Adaptive Optics," AO4ELT4 Proceedings, (2015).
[10] Thompson, H., et al., "Progress on measurement of vibration source amplitudes for validation of TMT AO performance vibration budget," AO4ELT4 Proceedings, (2015).
[11] Marois, C., "The 30m Era: High-Contrast Imaging Science with TMT at first light," AO4ELT4 Proceedings, (2015)
[12] Pagès, H., et al., "Recent developments on piezo-stack deformable mirrors for ELTs," AO4ELT4 Proceedings, (2015).
[13] Cavaco, J., Bruno, T., "Deformable Mirror Designs for Extreme AO," AO4ELT4 Proceedings, (2015).
[14] Enderlein, M., et al., "TOPTICA's Robust Sodium Guide Star Laser," AO4ELT4 Proceedings, (2015).
[15] Adkins, S., M., "Measured performance of the prototype polar coordinate CCD array," Adaptive Optics System III Proc. SPIE 8447, 0R1-16 (2012)
[16] Bonaccini, D., "LGS R&D for the ELT: perspective and results", AO4ELT4 Proceedings, (2015).