# Adaptive Optics Program Update at TMT

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## ABSTRACT

The TMT first light Adaptive Optics (AO) facility consists of the Narrow Field Infra-Red AO System (NFIRAOS), the associated Laser Guide Star Facility (LGSF) and the AO Executive Software (AOESW). 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 17-34 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, one high order Pyramid WFS for natural guide star AO, up to three low-order, IR, natural guide star on-instrument wavefront sensors (OIWFS) within each client instrument, and up to four guide windows on the science detectors (ODGW). The LGSF system can generate up to four different asterisms as required for NFIRAOS and future AO systems using up to eight sodium lasers.

In this paper, we will report on the important milestones reached by the TMT first light AO systems and their components over the last two years, including the successful final design review for NFIRAOS, the successful production readiness review for the NFIRAOS Real Time Controller, and the completion of the DM prototyping activities followed by the launch of the DM procurement. We will report on the status of the development of the visible wavefront sensor detectors and cameras for NFIRAOS, and the significant progresses done in the development of the algorithms for the Point Spread Function Reconstruction. Finally, we will present a conceptual design study for an Adaptive Secondary Mirror for TMT.

**Keywords:** Adaptive optics program, extremely large telescopes

## 1. INTRODUCTION

The TMT first light Adaptive Optics (AO) architecture has been defined to provide near-diffraction-limited wavefront quality and high sky coverage in the near infra-red (IR) for the first light science instruments IRIS (InfraRed Imaging Spectrograph)[1] and the most recently proposed instrument MODHIS (Multi-Object Diffraction Limited High Resolution Spectrograph)[2]. The AO architecture is a Laser Guide Star (LGS) Multi Conjugate AO (MCAO) architecture consisting of (i) the Narrow Field IR AO System (NFIRAOS), which senses and corrects 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 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 progresses have been made in designing, modeling and prototyping these systems and their AO components over the last two years. NFIRAOS has successfully passed its final design review. The NFIRAOS Real Time Controller has reached its production readiness. The LGSF preliminary design work is progressing with focus on interfaces with the telescope structure and telescope utilities. Major progresses have been made in defining the observation sequences and associated timing requirements[9] as well as in developing the Point Spread Function Reconstructor algorithms for the AO Executive Software.

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In the area of AO components, work is progressing developing the deformable mirrors, the visible detectors, and their cameras. Following the completion of two competitive studies with AOA Xinetics (AOX) and CILAS to develop the final designs of the NFIRAOS DMs, and to fabricate DM prototypes, TMT has selected CILAS as its supplier and has launched the NFIRAOS DMs procurement. The visible detectors are being fabricated and packaging trials of the polar coordinate detectors are being performed. Key requirements have been demonstrated for the visible detectors readout electronics, and the final design of the visible cameras has been started.

Several AO modeling and analysis activities have been conducted to address the high priority AO modeling recommendations of the NFIRAOS final design review[7], and recently to analyze the impacts of failed DM actuators on AO performance. Finally, TMT has supported a conceptual design study for an adaptive secondary mirror to support future generations of TMT instruments.

## 2. TMT FIRST LIGHT AO REQUIREMENTS AND ARCHITECTURE REVIEW

The TMT first light top-level AO science requirements have been very stable for many years. They include high sky coverage at the galactic pole, diffraction limited performance in J, H and K bands, high accuracy astrometry and photometry requirements, high optical throughput and low background requirements. The TMT first light AO systems have been developed to address these requirements.

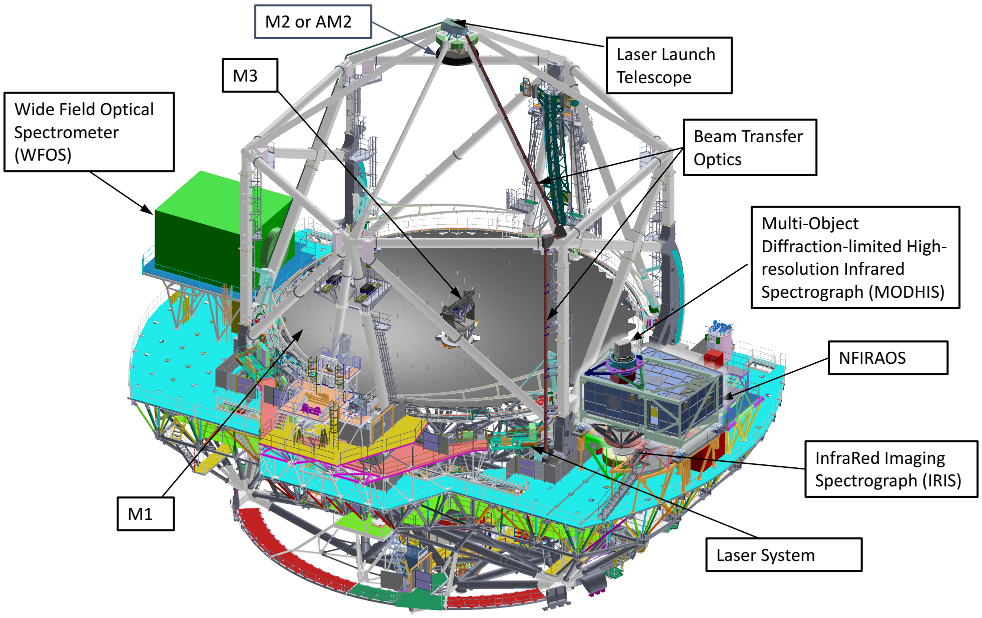


Figure 1: The TMT telescope with the first-light instruments and AO Systems (NFIRAOS and LGSF).

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

- The LGS MCAO System, NFIRAOS, 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. It senses and corrects for wavefront aberrations due to atmospheric turbulence and the telescope at 800Hz. It is cooled at -30°C to meet the low background requirement. Strehl ratios of the order of 70% in K band for LGS MCAO mode, and 80% in K band for NGS AO mode are expected.

- The On-Instrument wavefront sensors (OIWFS) are located in the NFIRAOS instruments and are dedicated for tip/tilt/focus sensing in the near IR (IRIS provides three OIWFS and MODHIS only one), and the four On-Detector Guide Windows (ODGW) are located in IRIS and are serving as truth tip/tilt sensors.
- 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, (TMT intends to implement Toptica/MPBC lasers as its baseline for sodium lasers), ii) the beam transfer optics optical path, which transports up to 8 laser beams in a square pattern (with no central beam) 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 Adaptive Optics Sequencer of the AO Executive Software automatically coordinates the operations of NFIRAOS, the OIWFS/ODGW and the LGSF with the remainder of the observatory for safe and efficient observations.

MODHIS is the most recently proposed first light instrument. It is dedicated to exoplanet science and is based on the latest diffraction-limited single-mode fiber injection, detector, multiplexing, and calibration (Laser Frequency Comb) technologies. It is a diffraction-limited near-infrared (0.95µm-2.4µm) high-resolution (R ~100,000 to 180,000) spectrometer that offers a baseline multiplex of four objects (with a goal of more) with a field of view for each multi-object unit of 2 arcsec. The instrument consists of two parts i) the front end and fiber injection unit, which efficiently transmits the light to the spectrograph and 2) the spectrograph. MODHIS will be mounted on the NFIRAOS top port.

## 3. FIRST LIGHT AO SYSTEM DESIGN PROGRESS

### 3.1 Narrow Field IR Adaptive Optics System (NFIRAOS)

Since the last AO4ELT Conference in 2017, the NFIRAOS team at NRC Herzberg in Victoria (Canada) has successfully passed its final design review end of June 2018[3]. The NFIRAOS Final Design phase was kicked off in April 2014. To involve more of the Canadian community in TMT, and in particular in NFIRAOS, NRC-HAA subdivided NFIRAOS into subsystems and subcontracted the final design of many of these subsystems to Canadian industry while keeping the overall responsibility for system performance, technical design, system engineering, delivery and acceptance of sub-systems, fabrication of other elements, and overall assembly, integration, verification and calibration. A total of five Canadian industrial partners were involved in the final design of eight major NFIRAOS subsystems. Some sample images of the NFIRAOS design[6] are provided in Figure 2 to Figure 4.

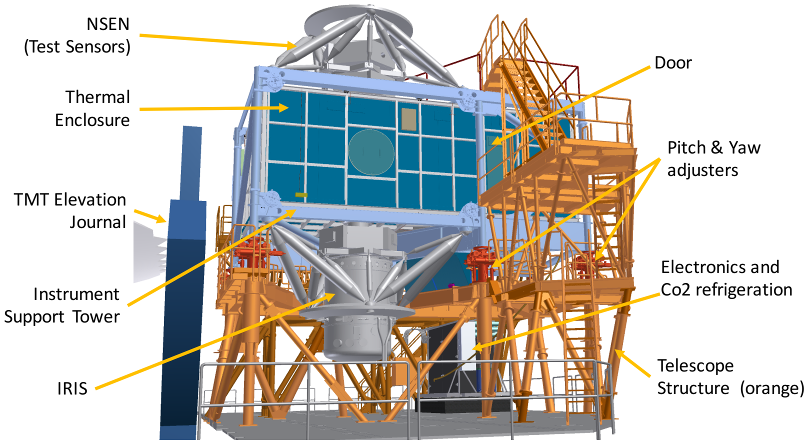


Figure 2: NFIRAOS (blue) installed on the –X Nasmyth platform with the first light instrument IRIS suspended below and the NFIRAOS test instrument mounted on the top port.

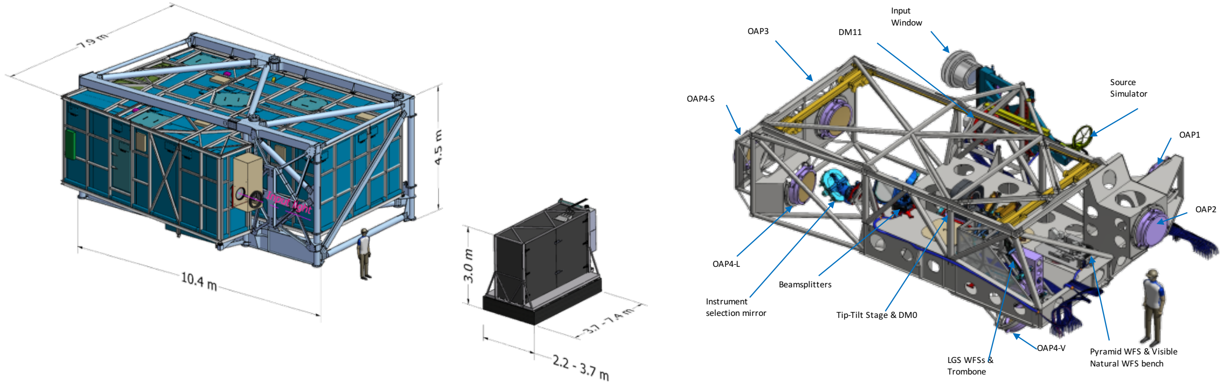


Figure 3: NFIRAOS optical enclosure designed by Quantum and electronics enclosure designed by NRC (left). NFIRAOS optical table fully populated with NFIRAOS optical assemblies (right).

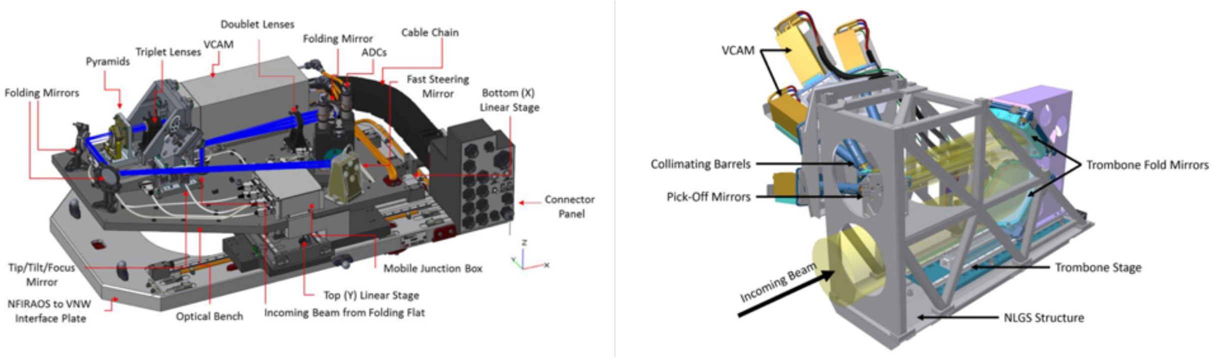


Figure 4: Final Design of the visible NGS wavefront sensor subsystem designed by ABB and INO (left) and LGS wavefront sensor subsystem designed by NRC.

The NFIRAOS team has now entered a final design update and production readiness phase, i) to address the action items of the final design review, ii) to complete the design of a few non-critical items, iii) to update the overall cost and schedule, and iv) to complete the components and sub-systems production readiness.

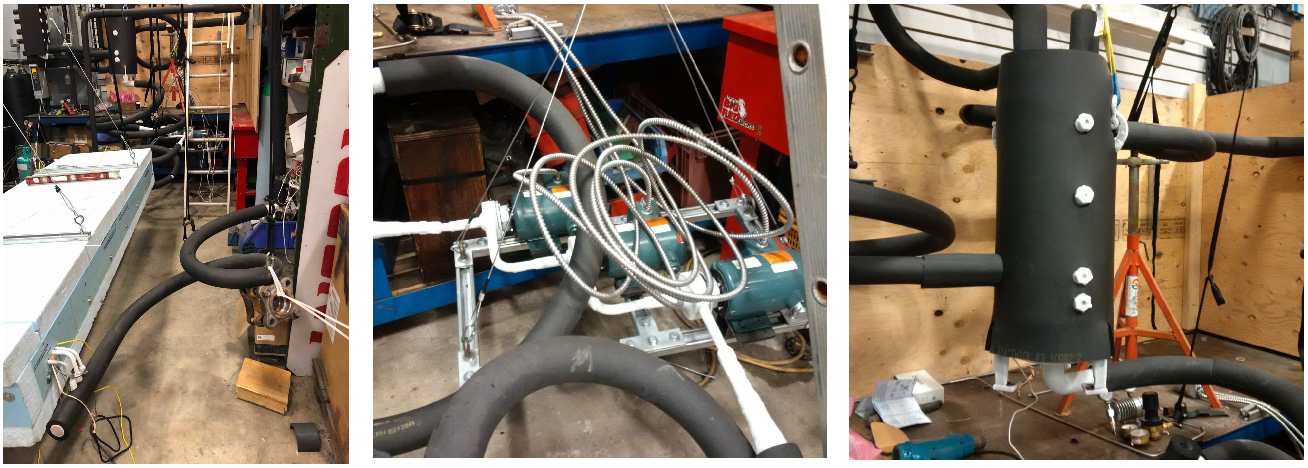
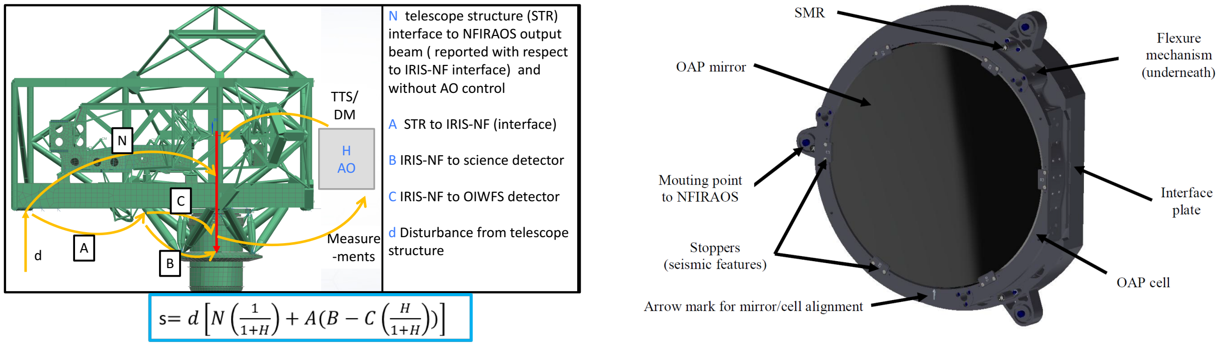


Figure 5: Left: Prototype of the enclosure panel tested for vibrations. Middle and Right: Prototype of the prototype cooling system which includes 3 pumps working in series (middle) and a circulation $CO_2$ tank (right).

The AO calibration plan has been further detailed to address the comments from the NFIRAOS Final Design Review[4].

The design of the NFIRAOS optical enclosure has been updated for the new TMT baseline $CO_2$ refrigerant. In addition of updating the design, the team has built and tested a prototype of the cooling system and of the enclosure panels. Figure 5 illustrates some of this prototype hardware developed with NFIRAOS' industry partner Quantum Technology and its sub-contractor Accent Engineering. The purpose of the prototype work was to demonstrate the feasibility of a closed-loop $CO_2$ cooling system for the NFIRAOS optical enclosure, to assess the vibration of the enclosure panels, and to verify NFIRAOS compliance to its vibration requirement. The tests were successful. The $CO_2$ prototype cooling system ran as expected, and under nominal flow conditions, the vibration of a single panel was measured to be 0.090 N rms, which corresponds to 0.7 N rms total for the complete NFIRAOS enclosure versus a 1N rms total requirement. Extensive work was performed to estimate the NFIRAOS + IRIS end to end performance in the presence of various vibration disturbances, such as telescope vibrations, internal Laser Guide Star Mechanism vibrations due to sodium layer tracking, tip-tilt stage reaction forces, and cooling system vibrations from thermal enclosure[8]. A new model called NFIRAOS/IRIS Frequency Domain Integrated Modeling (NFIDim) was created as part of this effort. This new model has been validated through testing and comparison with several time domain transient analyses for NFIRAOS only, and will be now used to perform the end-to end performance analysis for NFIRAOS and IRIS.

The first NFIRAOS production readiness review for the NFIRAOS optics is scheduled end of July 2019. During the production readiness phase, the NFIRAOS team has confirmed the requirements and optical budgets, demonstrated that the surface specifications are achievable, developed the optical manufacturing drawings, refined the testing procedures, and finalized the integration and optical alignment plans. Following the review, the NFIRAOS team is expected to launch the procurement of the glass of the first article OAP[5].



$$s = d\left[N\left(\frac{1}{1+H}\right) + A\left(B - C\left(\frac{H}{1+H}\right)\right)\right]$$

Figure 6: Model developed for the NFIRAOS + IRIS end to end performance analysis (left). OAP design (right).

### 3.2 Laser Guide Star Facility (LGSF)

The Institute of Optics and Electronics (IOE) team in Chengdu, China, is developing the LGSF preliminary design with the support of the TMT AO team. Since the last AO4ELT conference, work has focused on developing the mechanical design for the top end and detailing the interfaces with telescope structure and services. The LGSF wavefront error budget has been tightened for the low order aberrations to minimize the LGS spot size and improve AO performance. In particular, the laser launch telescope wavefront error has been reduced to a total of 20nm RMS for low aberrations and discussions have been started with vendors to review manufacturing feasibility.

The design of the top end is progressing as shown in Figure 7. Next steps include finite element analysis for the top end for flexure and seismic disturbances and update of the top end support structure as needed based on the finite element analysis results.

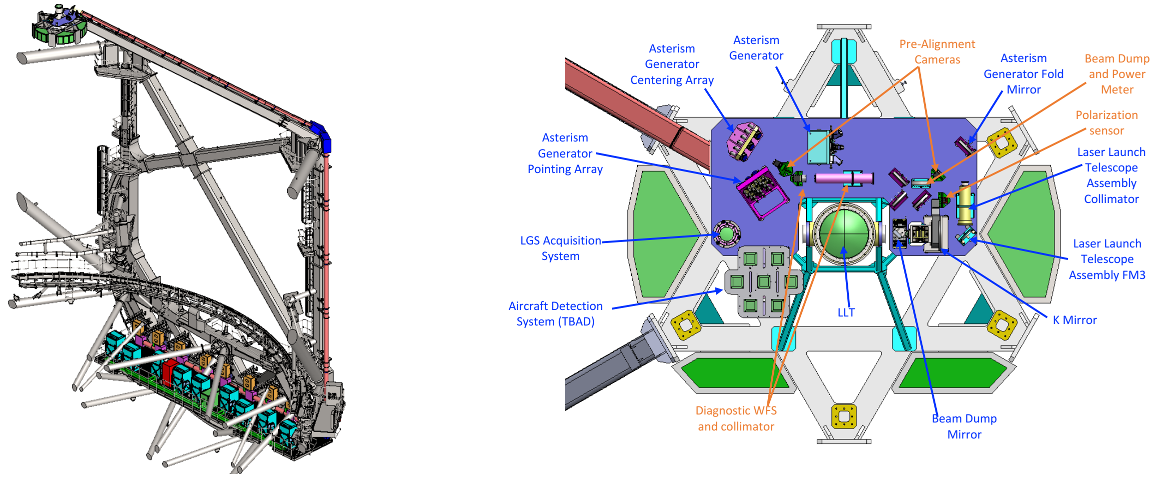


Figure 7: LGSF mounted on the telescope structure (left). Updated LGSF Top end design (right)

### 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.

Since the last AO4ELT conference, the TMT AO team has focused on developing the LGS MCAO PSF Reconstructor algorithms[12].

A top level PSF Reconstruction block diagram is provided in Figure 8. Three different algorithms have been studied to estimate the Optical Transfer Function (OTF) of the atmospheric turbulence:

- The classical algorithm ($Est_0$) estimates the turbulence OTF as a product of three filters computed from AO telemetry and simulation models.
- The simulation-based algorithm ($Est_1$) estimates the turbulence OTF directly from a high-fidelity end-to-end simulation model taking into account the mesosphere, the atmosphere, the telescope and the AO system.
- The hybrid algorithm ($Est_2$) estimates the turbulence OTF as the product of the simulation science OTF by an OTF ratio computed from system and simulation AO telemetry.

Best results have been obtained with the hybrid algorithm ($Est_2$)[12]. These results were presented at a PSFR Algorithm Review early January 2019. The reviewers recommended to now focus on estimating the OTF due to static and implementation errors to check the robustness of the algorithm. Finally, the plan is to eventually test the algorithm on published observatory data.

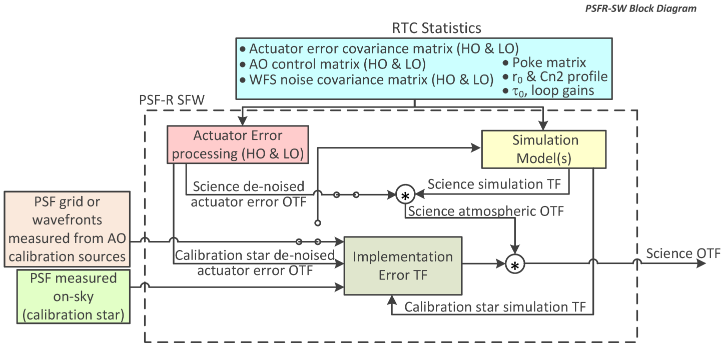


Figure 8: PSF Reconstructor Block Diagram.

# 4. FIRST LIGHT AO COMPONENT DEVELOPMENT

## 4.1 Deformable Mirrors

The requirements for the NFIRAOS DMs includes two mirrors of order 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.

Following the completion of the two competitive studies with AOA Xinetics (AOX) and CILAS to develop the final designs of the NFIRAOS DMs, and to fabricate and test new prototypes, TMT has selected CILAS to supply the NFIRAOS DMs. The CILAS DM Prototype[11] utilizes 616 piezoelectric actuators, which provide large stroke with low non-linearity and hysteresis, low dependence to environment and temperature, and very fast response. The CILAS DM Prototype also includes a metallic optical head to allow large inter-actuator stroke and a rigid baseplate to achieve the dynamic performance. The following sample results were obtained with the CILAS DM Prototype at CILAS using CILAS electronics and at NRC-HAA using the NRC-HAA DM Electronics Prototype:

- Measured maximum stroke: 16.1 µm PV at -30° C (versus TMT requirement of 10 µm PV after flattening, leaving plenty of stroke to flatten the DM)
- Measured inter-actuator stroke: 6.4 µm PV at -30° C (versus TMT requirement of greater than 1.98 µm)
- Measured linearity and hysteresis: 2.8 percent PV (versus TMT requirement of less than 15 percent with a goal of less than 5 percent)
- Best flat: 8.5 nm RMS at -30° C (versus TMT requirement of less than 15 nm RMS with a goal of less than 10 nm RMS)

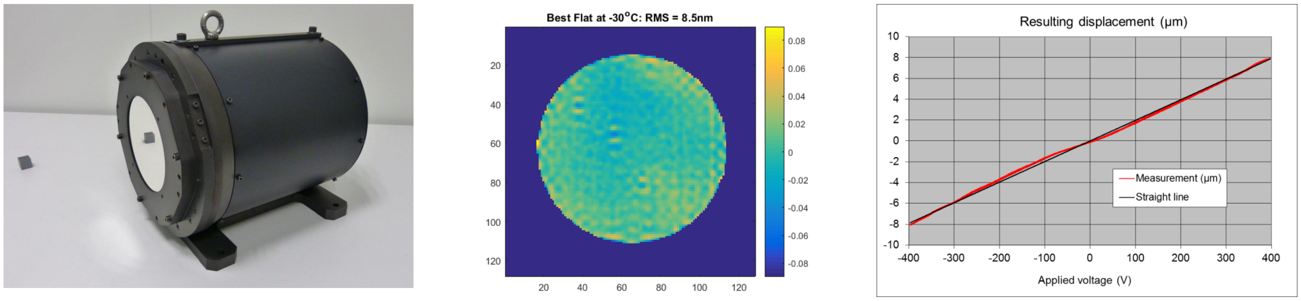


Figure 9: Left: CILAS 28x28 DM Prototype. Middle: Best flat obtained at NRC-HAA showing 8.5nm RMS flatness at -30° C. Right: Linearity response of central actuator in a group of 3x3 actuators while applying a +/-400V cycle showing maximum stroke of ~16 µm and an average hysteresis of less than 5% at ambient.

The new contract with CILAS has been launched and includes a delta design phase to account for interface changes, the fabrication and test of all the actuators, and the manufacturing, assembly and tests of the DMs. The tests at CILAS will be limited to test the actuators at ambient and cold, and to test the DMs at ambient. The DMs will be fully tested at cold at NRC using the NRC cold chamber, metrology bench, high resolution wavefront sensor and the NRC DM electronics.

TMT has revisited its analysis to assess the penalty of failed actuators onto the WFE. Two types of actuator failures have been considered:

- Electrical connection problem within the DM (either permanent or repairable). In this case, a failed actuator is expected to stick at neutral position
- Failed amplifiers in the DM electronics. In this case, a failed actuator is expected to stick at +/- maximum stroke

The modeling results show that up to 10 total actuators stuck at neutral position and randomly distributed on the 2 DMs are tolerable. However, actuators stuck at +/- maximum stroke are not acceptable. It is possible, however, to mechanically detach non-repairable stuck actuators from the optical head. CILAS has developed and tested a prototype of such a tool. Once actuators are mechanically detached, they become floating actuators and NFIRAOS is fairly tolerant to randomly distributed floating actuators. Incremental WFEs due to stuck actuators at neutral position, and due to floating actuators are given in Figure 10.

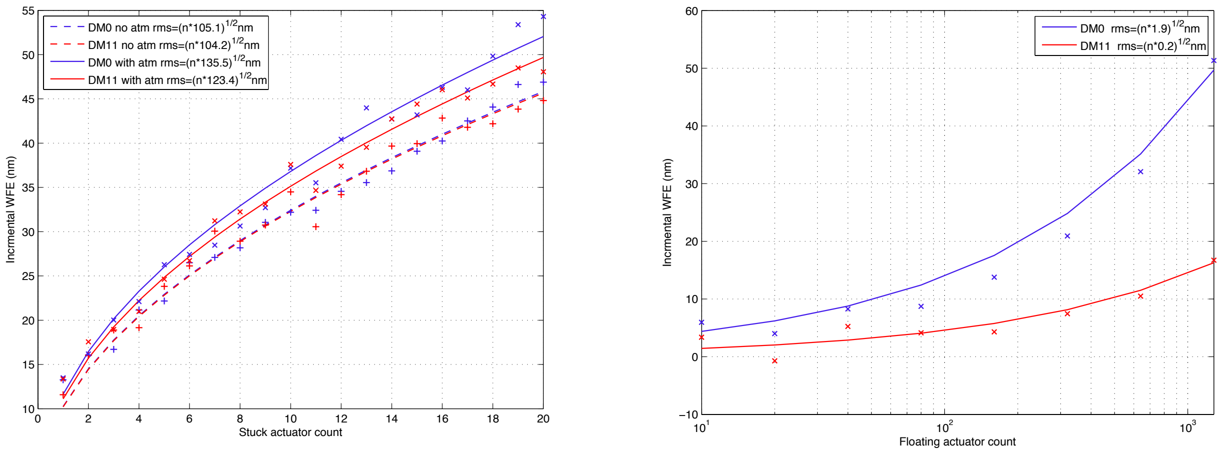


Figure 10: Left: Incremental WFE for stuck actuators at neutral position. Right: Incremental WFE for floating actuators.

## 4.2 High-order LGS and NGS Wavefront Sensing

For the six NFIRAOS 60x60 LGS WFS, TMT will use the polar coordinate CCDs designed specifically for elongated laser guide star images. The polar coordinate CCD reduces the pixel count and total readout rate by roughly a factor of three in comparison 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 of the array to 6x15 pixels at the edge, a quantum efficiency of 90%, and ~3 electrons read noise at a frame rate of 800Hz.

A one-quadrant prototype of the TMT polar coordinate CCD was successfully designed and fabricated in a wafer run at MIT/LL funded by the TMT, Keck and USAF Research Laboratory. Based on this success, TMT has launched the design and development of the full-scale polar detector at MIT/LL (designated as the CCID87). The design of the full-scale detector is based on the quadrant prototype design. The quadrant design is mirrored twice to fill a 360 arc, and a third metal layer is added to avoid gaps between the quadrants.

A first lot of sixteen, 200 mm wafers of 14 CCDs each, has been fully processed and tested through front illumination[14]. This first lot has been used to optimize the front illumination design and process. Some minor design errors have been corrected and the front illumination yield has been significantly improved. Four wafers from this first lot have been fully processed through back illumination and then tested. Results showed that the anti-reflection coating to form a lightshield around the subaperture framestores was successfully implemented, the yield was high, but the subaperture response to illumination was non-uniform. A second pathfinder run of four wafers of the first lot with four different thicknesses (to address the non-uniformity issue) was then fully processed though back illumination and results showed that the non-uniformity response was reduced to acceptable level for the thinner wafers.

A couple of devices from the second back-illumination run have been selected for testing the packaging process and verifying the noise performance of the detectors. This is work in progress.

A second lot has been fully processed and tested through front illumination and results showed very high yield of more than 40% and very good imager performance in terms of responsivity and dark current. Eight wafers of lot 2 have been selected and will be sent to the back-illumination process once the packaging trial step has been completed.

For the NFIRAOS NGS Pyramid WFS, TMT will use the 256x256 CCD array (designated as the CCID74) developed by MIT/LL as part of the polar coordinate prototype detector effort. This CCD has been successfully tested and achieves the requirements of 80% quantum efficiency and ~1 electron read noise at a 100Hz frame rate. Two science grade devices will be packaged for TMT using the same detector package developed for the polar coordinate detector. The LGS and NGS WFS cameras for NFIRAOS will be based on a common design.

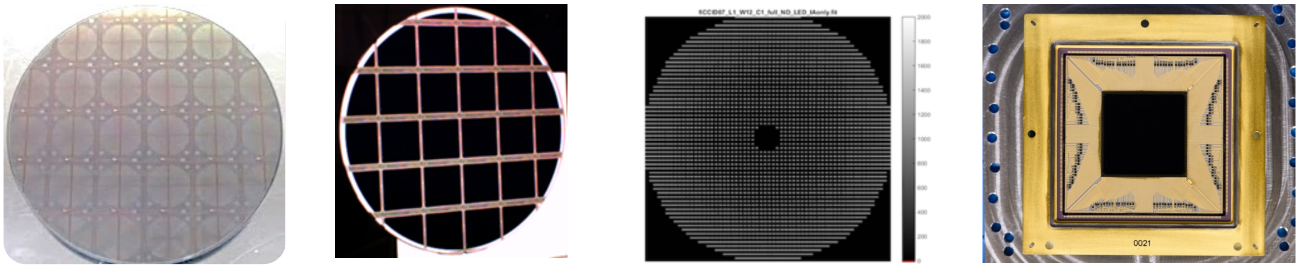


Figure 11: From left to right: 1) Finished front illuminated CCID87 wafer, 2) Finished back illuminated CCID87 wafer, 3) CCID87 front side dark image at 20°C, 4) First CCID87 wire-bonded and installed in package.

The main performance requirements of the readout electronics and camera for the NFIRAOS LGS and NGS WFS 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 read out in 500 µsec for the polar coordinate detector.
- Low noise for the readout electronics (< 3 electrons for the polar coordinate detector at 800Hz, < 1 electron for the NGS detector at 100Hz, and < 1 electron for the readout electronics), requiring the electronics to be packaged close to the detector to avoid long and large interconnections.
- 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.

Astronomical Research Cameras (ARC) in San Diego with Quartus Engineering as a sub-contractor have successfully completed the preliminary design of the cameras and readout electronics (see Figure 12). ARC has also successfully developed a 32 channel sub-scale readout electronics prototype and tested it with an engineering grade NGS WFS 256x256 detector. The readout noise performance has been demonstrated at fast speed (about 4 electrons at 800Hz using the CCID74 - see Figure 12). Based on these results, the expected read noise performance at low speed is about 1.14 electrons.

TMT is now launching the final design of the readout electronics including additional prototyping at ARC. In parallel of the readout electronics design and prototyping, TMT has sub-contracted the Institute National of Optics in Quebec City (INO - Canada) to develop the final design of the opto-mechanical part of the LGS and NGS visible cameras.

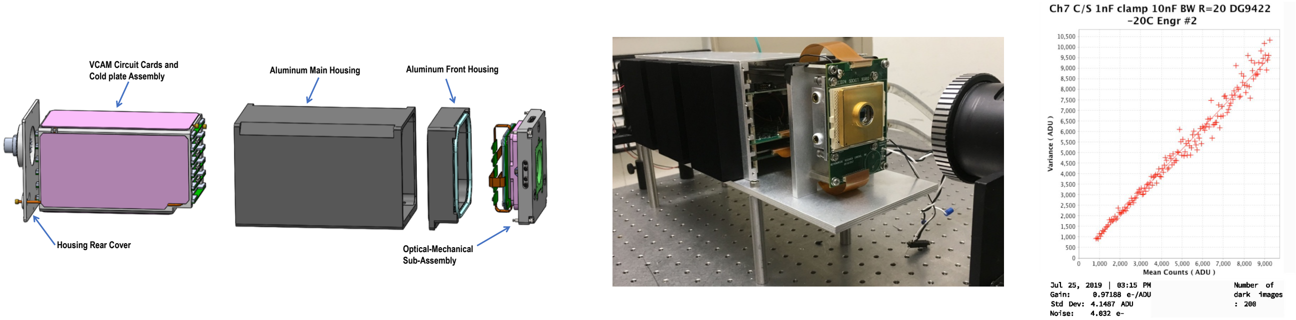


Figure 12: Left: CAD image of the NFIRAOS LGS and NGS visible WFS cameras, including the focal plane readout electronics. Middle: ARC readout electronics prototype. Right: Read noise result of about 4 electrons at 3.5MHz pixel rate

### 4.3 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 and calculation of the wavefront corrector actuator commands (requiring to solve a 35k x 8k control problem at 800Hz), 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 team has successfully completed the production readiness phase of the NFIRAOS Real Time Controller and fabrication is about to start. The system architecture is based upon commercial CPU server hardware with a classical Matrix Vector Multiply (MVM) control algorithm (see Figure 13). The NFIRAOS Real Time Controller resides in the computer room and connection to and from the AO components is done via dedicated 10/40 Gb Ethernet switches[10].

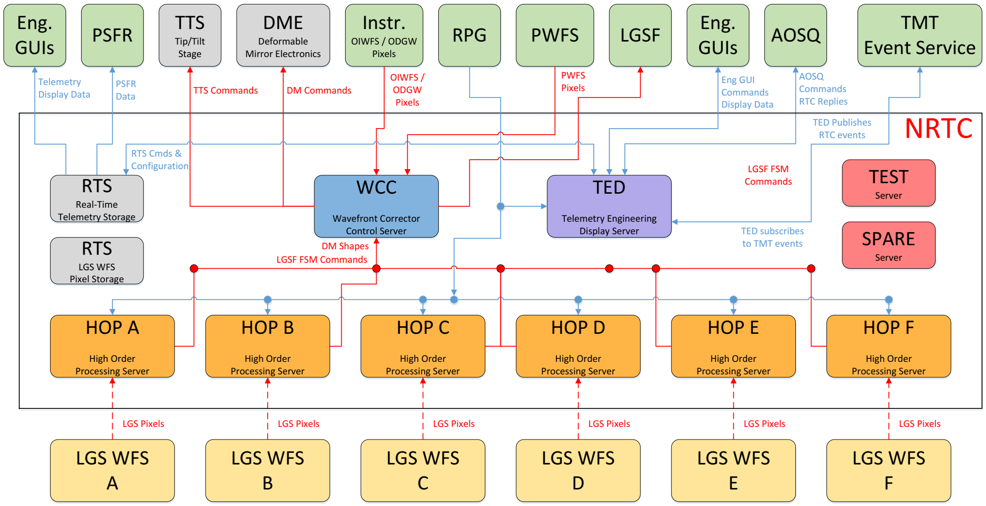


Figure 13: The RTC includes a total of twelve servers with one server per LGS WFS, one server dedicated to wavefront corrector control, one server dedicated to telemetry engineering display, two servers dedicated to real time telemetry storage, a test server and a spare server. Each High Order Processing (HOP) server currently includes quad socket high end Intel Xeon CPUs.

## 5. ADAPTIVE SECONDARY MIRROR CONCEPTUAL STUDY

Since the last AO4ELT conference, TMT has successfully completed a study with ADOPTICA for a 3.1m convex adaptive secondary mirror[13]. The TMT adaptive secondary mirror is intended to support future generations of TMT instruments. The goal of the study was to develop the conceptual design for the mirror and its calibration and test unit, perform the system tradeoffs, identify the risks, analyze the reliability, define the interfaces and develop a project plan.

The design proposed by ADOPTICA consists of a thin segmented shell with 7 segments (6 external petals and one hexagonal segment in the center. The segments are made of Zerodur with a 2.9mm thickness), 3828 voice coil actuators (60x60 order system), a reference body made of Silicon Carbide with the capacitive sensors glued (Bore Silicate tiles) on the reference body. The design and layout for the embedded electronics has been tailored for the TMT reference body and cooling system using $CO_2$ refrigerant. The control boards controlling the actuators are mounted on top of the reference body, while the actuators grouped into mini-bricks are permanently mounted within the reference body as well as a permanently fixed cooling system. The advantages of this concept are less demanding mechanical tolerances for installing the mini-bricks within the reference body and no need for connection/disconnection of the cooling system. The "less" reliable parts which are the control boards are easily accessible and replaceable when the unit is installed on the telescope. The other components (such as the actuators), which have been demonstrated to be much more reliable, will require to remove the unit from the telescope for replacement.

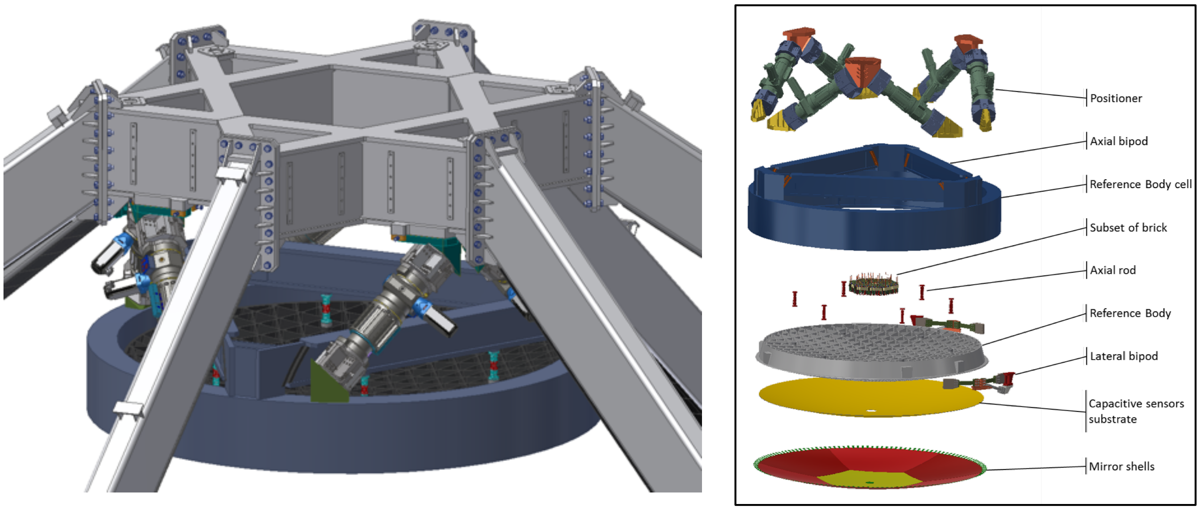


Figure 14: The ADOPTICA Adaptive Secondary Mirror mounted on the TMT top end.

## 6. SUMMARY

Significant progresses have been accomplished in the design, prototyping, fabrication and modeling of the TMT first light AO systems and AO components. NFIRAOS is now updating its final design and progressing toward production readiness. The preliminary design of the LGSF is continuing. TMT has selected CILAS to supply the NFIRAOS DMs and the fabrication of the DMs has been launched. The fabrication of the polar coordinate detectors for the LGS WFS is continuing, and key performance requirements have been demonstrated with the readout electronics prototype for these detectors. TMT has now launched the final design for the readout electronics and for the cameras for the LGS and NGS WFS detectors. The NFIRAOS RTC has successfully passed its production readiness and coding is about to start. Extensive work has also been performed in the area of AO system engineering and modeling to better define and consolidate our design and interface requirements. Finally, TMT has completed a conceptual design study for an adaptive secondary mirror to support future generations of TMT instruments.

## 7. ACKNOWLEDGMENTS

This paper is a summary of the contributions of numerous TMT staff members, TMT partners and TMT suppliers including: Lianqi Wang, Luc Gilles, Melissa Trubey (TMT AO Group), Brent Ellerbroek, Sean Adkins (TMT Consultants), Gelys Trancho, John Rogers (TMT System Engineering), David Andersen, Glen Herriot, Jenny Atwood, Peter Byrnes, Kris Caputa, Ed Chapin, Jeff Crane, Adam Densmore, Jennifer Dunn, Joeleff Fitzsimmons, Kate Jackson, Tim Hardy, Brian Hoff, Dan Kerley, Olivier Lardiere, Malcom Smith, Jonathan Stocks, Jean-Pierre Véran (NRC-Herzberg), Kai Wei, Muwen Fan, Changchun Jiang, Min Li, (IOE), Hubert Pagès, Christophe Landureau, Jean-Christophe Sinquin, Denis Groeninck, Aurelien Moreau, Stephane Vaillant, Richard Palomo, Ronan Wehrle (CILAS), Bob Leach (ARC), James Gregory, Michael Brattain, Daniel O'Mara (MIT/LL), Luc Monat, Christian Proulx, Martin Grenier, Nicholas Desnoyers, Olivier Martin (INO), Roberto Biasi, Mauro Manetti (Microgate), Daniele Galieni, Matteo Tintori (ADS) Wilhlem Kaenders, Bernhard Ernstberger, Frank Lison (Toptica), Claudette Linton, Wallace Clements, Jane Bachynski (MPBC)

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] Larkin J., et al., "The infrared imaging spectrograph (IRIS) for TMT: instrument overview," In Ground-Based and Airborne Instrumentation for Astronomy VII, Proc. of SPIE Vol. 10702, (2018)

[2] D. Mawet, et al. "MODHIS: a multi-object diffraction-limited high-resolution infrared spectrograph for TMT," AO4ELT6 Proceedings, (2019)

[3] D. Andersen, et al. "The Final Design of NFIRAOS," AO4ELT6 Proceedings, (2019)

[4] J.P. Véran, et al. "NFIRAOS AO Calibration Plan," AO4ELT6 Proceedings, (2019)

[5] J. Atwood, et al. "NFIRAOS Pre-Production Optical Design Update," AO4ELT6 Proceedings, (2019)

[6] O. Martin et al. "Assembly, Partial Integration and Tests Philosophy at INO of several components for the Science Path, Calibration, NGS and LGS sub-systems of NFIRAOS, the TMT AO Facility," AO4ELT6 Proceedings, (2019)

[7] G. Herriot, et al. "Stabilizing Plate Scale versus Point Source Sensitivity for MCAO," AO4ELT6 Proceedings, (2019)

[8] J. Fitzsimmons, et al. "Integrated Modelling of NFIRAOS: Characterizing performance in the presence of vibration," AO4ELT6 Proceedings, (2019)

[9] D. Andersen, et al. "Acquisition with NFIRAOS and IRIS on TMT," AO4ELT6 Proceedings, (2019)

[10] D. Kerley, et al. "Herzberg Extensible Adaptive Real-time Toolkit (HEART) Software Architecture," AO4ELT6 Proceedings, (2019)

[11] J.C. Sinquin, et al. "Two large deformable mirrors for TMT," AO4ELT6 Proceedings, (2019)

[12] L. Gilles, et al. "Multi conjugate adaptive optics point spread function reconstruction," AO4ELT6 Proceedings, (2019)

[13] R. Biasi, et al. "TMT Adaptive Secondary Mirror conceptual design study," AO4ELT6 Proceedings, (2019)

[14] Adkins S., et al., "Laser guide star optimized wavefront sensor system for the Thirty Meter Telescope," In AO4ELT5 Proceedings (2017)