| | |
|---|---|
| ***Publication Year*** | 2024 |
| ***Acceptance in OA*** | 2025-04-02T10:51:46Z |
| ***Title*** | Emerging adaptive optics facility at Large Binocular Telescope Observatory |
| ***Authors*** | Ragland, Sam, Brusa, Guido, Cavallaro, Alessandro, Choi, Heejoo, Guerra, Juan Carlos, Herbst, Tom, Lefebvre, Michael, Miller, Douglas, PEDICHINI, Fernando, Power, Jennifer, Shields, Joseph, Smithwright, Mark, Taylor, Gregory, Veillet, Christian, Zhang, Xianyu, Biasi, Roberto, Conrad, Al, Close, Laird, ESPOSITO, Simone, Gallieni, Daniele, MASCIADRI, Elena, Mechtley, Brandon, Peretz, Eliad, PINNA, Enrico, RAGAZZONI, Roberto, ROSSI, Fabio, AGAPITO, Guido, Bec, Matthieu, BERGOMI, Maria, Bertram, Thomas, Briegel, Florian, FARINATO, JACOPO, Hill, John, Kim, Daewook, MARAFATTO, Luca, PIAZZESI, Roberto, Radhakrishnan, Kalyan, RICCARDI, Armando |
| ***Publisher's version (DOI)*** | 10.1117/12.3019441 |
| ***Handle*** | http://hdl.handle.net/20.500.12386/37003 |
| ***Serie*** | PROCEEDINGS OF SPIE |
| ***Volume*** | 13097 |

# Emerging adaptive optics facility at Large Binocular Telescope Observatory

Sam Ragland*[a], Guido Brusa[a], Alessandro Cavallaro[a], Heejoo Choi[b], Juan Carlos Guerra[a], Tom Herbst[c], Michael Lefebvre[a], Douglas Miller[a], Fernando Pedichini[d], Jennifer Power[a], Joseph Shields[a], Mark Smithwright[a], Gregory Taylor[a], Christian Veillet[a], Xianyu Zhang[a], Roberto Biasi[e], Al Conrad[a], Laird Close[f], Simone Esposito[g], Daniele Gallieni[h], Elena Masciadri[g], Brandon Mechtley[a], Eliad Peretz[i], Enrico Pinna[g], Roberto Ragazzoni[j], Fabio Rossi[g], Guido Agapito[g], Matthieu Bec[a], Maria Bergomi[j], Thomas Bertram[c], Florian Briegel[c], Jacopo Farinato[j], John Hill[a], Daewook Kim[a,b,f], Luca Marafatto[j], Roberto Piazzesi[d], Kalyan Radhakrishnan[j], Armando Riccardi[g]

[a]Large Binocular Telescope Observatory, University of Arizona (USA), [b]Wyant College of Optical Sciences, University of Arizona (USA), [c]Max-Planck-Institut für Astronomie (Germany), [d]INAF - Osservatorio Astronomico di Roma (Italy), [e]MicroGate S.r.l. (Italy), [f]Steward Observatory, University of Arizona (United States), [g]INAF - Osservatorio Astrofisico di Arcetri (Italy), [h]A.D.S. International S.r.l. (Italy), [i]NASA Goddard Space Flight Ctr. (United States), [j]INAF - Osservatorio Astronomico di Padova (Italy); *sragland@lbto.org

## Abstract

The Large Binocular Telescope (LBT) [1] Observatory pioneered Adaptive Optics (AO) technologies such as Adaptive Secondary Mirror (ASM)[2], Pyramid wavefront sensor[3], and Ground-layer AO using Rayleigh lasers[4] at 8-10 m class telescopes. We have initiated an effort to turn LBT AO into a facility-class capability. The effort involves (1) building an AO team with AO development capability, (2) improving the robustness of the AO, (3) developing in-house AO expertise to maintain and troubleshoot the AO systems, (4) automating processes for efficient on-sky operation, (5) tracking performance metrics and cultivating accountability for on-sky AO performance, and (6) minimizing the operational risks for the ASMs. We present the status of these developments.

LBTO continues its efforts to develop innovative technology. We explore the next phase of AO developments, including Agile Extreme Adaptive Optics (AgXAO) on the DX side of the LINC-NIRVANA[5][6] optical bench to overcome the limitation imposed by varying and large atmospheric seeing at Mount Graham. AgXAO implementation includes the development of (1) a high-order, high-sensitivity wavefront sensor, (2) a high-density deformable mirror with 3000 actuators and next-generation ASM with about 950 actuators, (3) active optics integration, (4) vibration and wavefront piston control, (5) atmospheric turbulence measurements and weather forecast integration, and (6) a visible camera and an AO-corrected narrow-field fiber-coupled IFU spectrograph using one of the existing workhorse visible spectrographs. Developing AgXAO on the SX side, too, would enable Fizeau imaging in the visible wavelengths.

AgXAO will also serve as a general-purpose high-contrast (and subsequently a Fizeau imaging) Testbed on LBT to test advanced wavefront control algorithms, including astrophotonics experiments, and machine learning algorithms with minimal impact on routine science operations. We propose developing AgXAO through student projects to train the next-generation scientists and engineers for the extremely large telescope (ELT) era. The ultimate goal is to push large aperture ground-based telescopes to their performance limits and make them competitive with space telescopes in terms of PSF stability and performance to enable breakthrough science.

**Keywords:** adaptive optics, Large Binocular Telescope Observatory, high-contrast imaging and spectroscopy, adaptive secondary mirror, advanced wavefront control, high-contrast AO Testbed, PSF stabilization, hybrid (ground and space) laser-guide star mode

## 1. INTRODUCTION

The Large Binocular Telescope is the first of the emerging generation of extremely large telescopes. It consists of two 8.4 m diameter primary mirrors on a common mount, providing a collecting area equal to a single 11.8 m mirror and interferometric capability with an edge-to-edge baseline of 22.8 m. LBT is a unique large-aperture facility in the northern hemisphere (latitude: 33° N). This latitude gives LBT access to northern declinations that are outside the reach of GMT or E-ELT, yet is far enough south to have some overlap with these telescopes, as well as LSST.

Adaptive Optics Systems IX, edited by Kathryn J. Jackson, Dirk Schmidt, Elise Vernet,
Proc. of SPIE Vol. 13097, 130970L · © 2024 SPIE · 0277-786X
doi: 10.1117/12.3019441

The Adaptive Optics (AO) systems provide diffraction-limited imaging and spectroscopic science capabilities to the first-generation instruments (LUCI[7] and LBTI[8][9]) and second-generation instruments (SHARK-VIS[10], SHARK-NIR[11], and yet-to-be-commissioned iLocater[12]). A brief description of the LBT first- and second-generation instruments is presented elsewhere in this conference[13].

The AO systems provide extreme AO performance in the NIR under excellent seeing conditions. The recent science from the AO instruments includes observations of Io's resurfacing via plume deposition through the highest spatial resolution images of Io ever obtained from a ground-based telescope[14].

This paper provides an overview of the recent LBTO AO**,** emphasizing the AO developments from September 2023 to May 2024. The work could be broadly classified into two categories: (1) Facility-class Adaptive Optics (FCAO) and (2) Agile Extreme Adaptive Optics (AgXAO) developments, which are presented in Sections 2 and 3, respectively.

## 2. FACILITY-CLASS ADAPTIVE OPTICS DEVELOPMENT

We initiated an effort to develop LBTO AO into a facility-class capability and spent about 1.75 FTE during the past nine months. We summarize the developments in this section.

### 2.1 Team development

The development of facility-class adaptive optics (FCAO) started by forming an AO Group at LBTO in September 2023. The group consists of eight core members: five scientists (including the AO Group Head) and three engineers or senior technicians. In addition, the AO group has over a dozen extended members from the other groups at LBTO (Engineering, Software, Science Operation, Mountain operations) and members from Wyant College of Optical Sciences and partner institutions.

The first major task undertaken by the core AO group, besides supporting AO science operations, is FCAO development. We initiated a handful of R&D projects to develop in-house technical expertise to troubleshoot problems promptly. We encountered four significant AO failures during the past nine months, three involving wavefront sensors (loose pyramid, loose OCAM2K, and detached pyramid modulator tip/tilt mirror) and one involving one of the adaptive secondary mirrors (a temperature-dependent failure of the DX adaptive secondary mirror (ASM)). The team was successful in troubleshooting all these issues and promptly mitigating or fixing all but one problem. The open issue, the detached tip/tilt mirror, is the most recent incidence requiring bringing the wavefront sensor to the lab for regluing and the science schedule does not allow for a quick fix.

We made some changes to the team members' roles and demonstrated significant efficiency improvements. We utilized the freed-up resources to advance the FCAO developments further. We will soon use some freed-up resources for AgXAO development (Section 3).

The AO group is presenting the following six papers at the 2024 SPIE AO conference.

- Emerging adaptive optics facility at the Large Binocular Telescope Observatory, Ragland et al, #13097-20
- Adaptive secondary mirrors at the Large Binocular Telescope recent updates, Brusa et al., #13097-95
- Enhanced Seeing Mode at the Large Binocular Telescope Observatory, Miller et al., #13097-222
- On-sky performance metric parametrization@LBTO pyramid WFS, Guerra et al., #13097-243
- AO functionalities improvements with the adaptive secondary mirrors at the Large Binocular Telescope, Zhang et al., #13097-264
- Turbulence monitoring at the Large Binocular Telescope: Current status and ongoing developments, Veillet et al., #13097-310

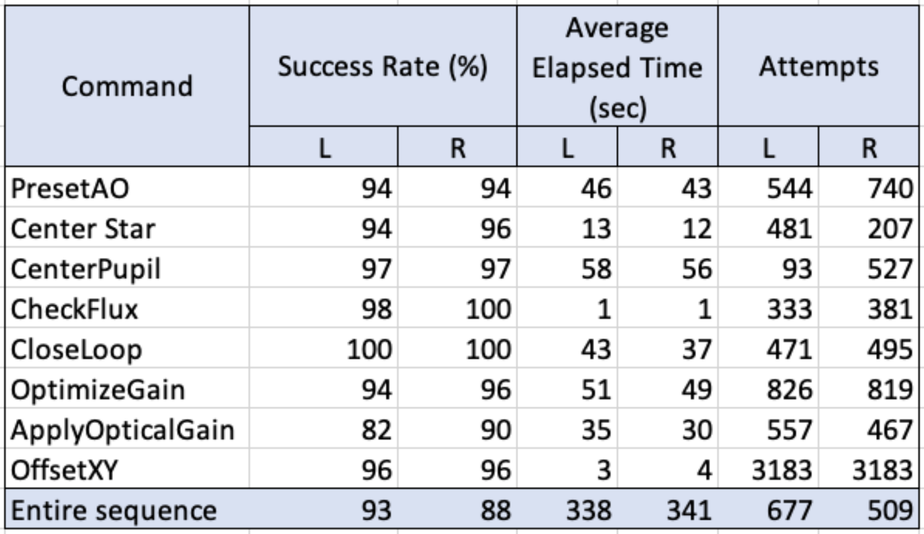
### 2.2 Robustness improvement

We have undertaken a few projects that we expect to improve the AO operations in the upcoming observing semester (semester 2024B). The main ones are (1) observing sequencer upgrade, (2) IssueTrak backlog, and (3) documentation & cross-training (DCT).

### 2.2.1 Observing Sequencer improvements

As a precursor to making improvements, we took baseline performance metrics for the different steps of the observing sequencer and set the target metric for upgrading the current implementations. Table 1 shows the success rate and the average elapsed time of the sequencer tasks, including the entire sequence, for the LUCI wavefront sensors (WFS) in 2023. We focus on the loop gain and optical gain optimization processes to reach the target success rate of 95% and within the target elapsed time of 300 seconds for the entire target acquisition sequence. The effort involves (1) improving the robustness of the associated state machines of the sequencer, (2) implementing monitoring functions, and (3) implementing auto-recovery features to minimize the AO downtime.

*Table 1: The success rate and the average elapsed time of the AO observing sequencer tasks, including the entire sequence, for the LUCI WFSs in 2023.*



| Command | Success Rate (%) | | Average Elapsed Time (sec) | | Attempts | |
|---|---|---|---|---|---|---|
| | L | R | L | R | L | R |
| PresetAO | 94 | 94 | 46 | 43 | 544 | 740 |
| Center Star | 94 | 96 | 13 | 12 | 481 | 207 |
| CenterPupil | 97 | 97 | 58 | 56 | 93 | 527 |
| CheckFlux | 98 | 100 | 1 | 1 | 333 | 381 |
| CloseLoop | 100 | 100 | 43 | 37 | 471 | 495 |
| OptimizeGain | 94 | 96 | 51 | 49 | 826 | 819 |
| ApplyOpticalGain | 82 | 90 | 35 | 30 | 557 | 467 |
| OffsetXY | 96 | 96 | 3 | 4 | 3183 | 3183 |
| Entire sequence | 93 | 88 | 338 | 341 | 677 | 509 |

### 2.2.2 Addressing IssueTrak backlog

LBTO AO uses the IssueTrak (IT) system for AO operators to issue tickets for AO problems. Over the years, there has been a significant buildup of open IT tickets, which has contributed to the system's frailty. We spent substantial resources to address the IT backlog. Still, more work remains.

In September 2023, there were 280 open ITs out of 657. By April 2024, we had reduced the number to 153 out of 678. During this period, 21 new ITs were added (657 + 21 = 678). The closed ITs include 52 from the ASM subsystem that are classified as design issues in the second-generation ASM but do not have safety concerns. Hence, we closed them without resolving them. We plan to restart this effort in late 2024 to address the remaining ITs. We aim to reduce the open items to below a dozen by the summer of 2025 and maintain this at this level.

### 2.2.3 Improvements to the AO maintenance program

We are working toward developing in-house technical skills to operate and maintain the four WFSs and training summit personnel for urgent intervention and annual maintenance. We established a preventive maintenance program, scheduled maintenance tasks, and consolidated the spare list. The related efforts include (1) documenting the maintenance tasks for the WFSs, (2) identifying areas requiring more information, (3) Reorganizing/updating the WFS operational procedures, (4) Creating a summary of interventions, troubleshooting actions, and lessons learned, (5) identifying the operational risks, including obsolescence, and (6) developing a risk mitigation plan, and 7) identifying potential future minor upgrades. We plan to expand this program, incorporating the ASMs.

### 2.2.4 Documentation & cross-training (DCT)

We have initiated a project to improve the documentation and minimize single points of failure across the board. The main areas are AO calibrations, WFS maintenance, ASM monitoring, ASM power on/off processes, and ASM handling for thin shell removal and reintegration with the reference body. The WFS documentation includes system functionality and hardware description and the generation of a spreadsheet listing the differences between wavefront sensors. We plan to complete documentation tasks by July 2024 and perform necessary cross-training in August/September 2024.

We consolidated the troubleshooting pages and assigned one of the AO scientists to keep them current. We have made notable changes to the AO nightlog format and scheduled an AO scientist each day to review the AO nightlog from the previous night and take necessary actions, including performing essential data analysis and preparing a report. We are working to incorporate AO downtime tracking into this operation.

## 2.3 AO automation

We initiated an AO automation project to develop new AO operations tools to improve operational efficiency and transition to a single AO expert running both the SX and DX sides in the short term, which non-AO expert operators will subsequently operate. The AO experts will still be scheduled for on-call AO operations support round the clock in parallel to their support role in the AO development projects.

The main modules of AO automation tools are (1) unification of the four WFS operations, (2) visualization package, (3) calibration tools, (4) data logging improvements, including efficiency tracking, and (5) troubleshooting features. As a first step, we created and demonstrated a prototype web-based Monitoring GUI to visualize loop states for any or all of the WFSs in a single interface. The demonstration tested the software platform, including developments in REDIS with Web components in the LitElements framework, which is an addition to the Data Mining System (DMS) framework currently used at LBTO. We target to release some changes for science operations for the upcoming 2024B semester.

## 2.4 Seeing estimation

Seeing estimation during AO observations is crucial to utilize the science data maximally. A Differential Image Motion Monitor (DIMM) instrument mounted high up on the right side of the telescope structure is used to measure the atmospheric seeing. DIMM riding on the telescope means the observable targets are limited to the sky seen through the right slit of the telescope enclosure, and the seeing estimation contains both the atmospheric- and a part of the dome-seeing components.

The DIMM sensitivity suffered over the years due to camera noise issues and is currently limited to an R magnitude of < 3. Sometimes, a suitable bright target is unavailable during science observations, or the measurements are noisy due to low flux. We plan on replacing the DIMM camera in late 2024 or early 2025.

We tested an AO-based seeing estimation tool on on-sky data. The results are encouraging, but more work is needed, especially for observations carried out with limited KL modes. We have also conducted a feasibility study for the Ring-Image Next Generation Turbulence Sensor (RINGSS), an alternate turbulence profiler[15].

## 2.5 ASM risk mitigation

LBT AO uses second-generation ASMs that have challenges. All known issues have been addressed in the third- and fourth-generation ASMs. While a workaround exists for all known issues at LBTO, the aging hardware and obsolescence are of significant concern. We are working to address both the near-term (up to 5 years) and long-term (> five years) operational risks. The short-term risk mitigation includes (1) carrying out a service mission for the DX ASM and (2) Building a hot spare ASM using the decommissioned Magellan ASM. The long-term risk mitigation includes replacing the LBTO ASMs with state-of-art ASMs. We present the short-term risk mitigation effort in this section.

### 2.5.1 DX ASM service mission

The DX ASM has at least twelve known issues. All but one are relatively minor, meaning they don't prevent the ASM from operating for science. Still, some problems, such as failed actuators and detached magnets, negatively impact AO performance. The critical issue is the DX low-temperature crate#1 failure that prevents us from operating the ASM when the chamber temperature is below -6ºC.

In addition, we have identified two preventive maintenance tasks: (1) replacement of glycol hoses and (2) replacement of the vibration isolators for the crates. We have also identified two safety upgrades: (1) new covers for the ASMs and (2) UPS installation for the ASMs. Most of these issues have been known for years but have been unaddressed due to associated risks. We prioritize addressing these issues in July-August 2024 with support from MicroGate for a sub-set of tasks. We will consider a similar service mission for the SX in July-August 2025.

### 2.5.2 Magellan ASM refurbishment

The Magellan ASM was originally Unit #1 developed for LBTO but was rejected as it failed to meet the specifications. The unit was modified to work with the Magellan Telescope with a smaller telescope secondary and was subsequently decommissioned.

The Magellan ASM unit is identical to LBTO's two ASMs, except for the thin shell, and is the only other second-generation unit. The electronics are similar and are direct replacement parts for the LBTO units. The thin shell is a smaller version, and there is no outer row of actuators; however, the reference body is full-sized and is ready to accept both outer actuators and a full-size thin shell. We will use our spare thin shell (TS4) with the refurbished Magellan unit.

We have retrieved the unit from Las Campanas Observatory, Chile, to be shipped and refurbished to be used as a hot spare for LBTO. The unit is packed and ready to be shipped to the ADS once the government paperwork is complete. Meanwhile, we have started the refurbishment process. Figure 1 shows a picture of the Magellan ASM mounted on a stand and subsequently packed in a large wooden box.

We will fabricate the outer actuators through MicroGate and ADS. The work started in May 2024, with the hardware delivered in September 2024. Efforts are underway to recoat the front and rear sides of TS4 in February 2025. We have designed and fabricated two fixtures through ADS to handle the thin shell for recoating—one for front-side recoating and the other for rear-side recoating. We plan to recoat the thin shell in-house at Steward Observatory with support from ADS for mirror handling to minimize the risks.

*Figure 1: Magellan ASM mounted on the stand (left) and packed in a large wooden shipping box with spares in a small box (right).*

We are negotiating a contract with ADS to refurbish the reference body starting Sep 2024. We plan to upgrade the actuator contact points by beveling the actuator holes (to be performed by LBTO at ADS) and replacing the actuator inserts. The reference body surface will be stripped and gold-coated, as the unit suffered a glycol leak in 2016. The optomechanical integration of the unit, including the actuators, will be performed at ADS, and the unit will be shipped to Tucson with new power backplanes. Due to these upgrades, we expect the refurbished Magellan unit to be more robust and easy to maintain than the existing LBTO ASMs. We are considering adding a couple of minor upgrades, such as replacing the retention ring, central hub interface, etc.

The current plan is to have the refurbished reference body shipped to Tucson in May 2025. We are developing an integration plan to be reviewed in Sep. 2024. The integration and testing of the reference body with the thin shell (TS4) is planned for the second half of 2025. Currently, the SX and DX ASM are not interchangeable and must be addressed to have the refurbished Magellan ASM as a hot spare for the LBTO ASMs. We will implement hardware and software interface upgrades to make the SX and DX ASMs compatible with one another. The work primarily involves replacing a damaged cable and streamlining the software configuration. We expect the refurbished Magellan ASM to be ready for on-sky tests by the end of 2025.

## 3. AGILE EXTREME ADAPTIVE OPTICS DEVELOPMENT

A significant challenge to High-contrast science at LBTO is the varying and large atmospheric seeing. Figure 2 shows the projected cumulative residual wavefront distribution for bright AO guide stars (R ~ 10) using the DIMM seeing statistics[15] in conjunction with on-sky SOUL performance data in the H-band[16]. As readily seen, the system performs as (or near) XAO at the 25th percentile and as SCAO at the 75th percentile. The objective is to push the system to perform as XAO at the 50th percentile. The statistics do not account for weather loss. The MiniQ used by some partners and policy solutions such as the disruptive observing program help partially mitigate the issue. However, such solutions are less effective for short time-scale variability of tens of minutes.

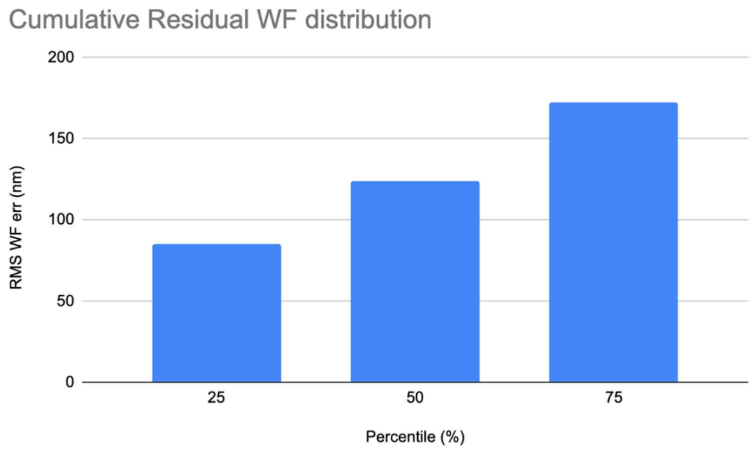


*Figure 2: Projected cumulative residual WF distribution for bright guide stars (R < 10) using LBTO DIMM and H-band Strehl ratio measurements.*

We propose developing Agile Extreme Adaptive Optics (AgXAO) technologies to mitigate the varying and large seeing limitations and well-position LBTO for the ELT era. The system will provide an additional ~ 85 nm wavefront corrections on bright targets with respect to the current performance. The proposed AO development is "Agile" in many dimensions. The proposed system's agility includes the ability to:

- operate under fast-varying seeing (in minutes)
- operate up to 2" seeing
- account for beam-train vibrations
- measure relative wavefront piston errors
- operate under a wide range of guide star magnitudes, R ~ -2 to 19, partly by adding a near-infrared wavefront sensor
- easily switch AO instrument modes/configurations
- have a fast turnaround for AO developments from the laboratory (in Tucson) to the sky (Mt. Graham) in a matter of days

The following section summarizes the significant components of the AgXAO system.

### 3.1 AgXAO components

#### 3.1.1 High-order wavefront sensing

The system has a high-order, highly sensitive visible pyramid WFS with a pupil sampling of 64 pixels across the pupil, operating at up to 3kHz, and a coarse pupil sampling option (30 pixels and 20 pixels across) implemented by optical means to reach fainter magnitude limits. However, accomplishing this by pixel binning is becoming an attractive option, given the availability of low-noise visible cameras.

We propose non-modulated pyramid (NMP) wavefront sensing to improve the sensitivity. The non-linear response of the NMP is a known challenge[17]. We aim to address this by performing interaction matrix calibration with added residual turbulence without modulation. In addition, we plan to incorporate machine learning into the wavefront reconstruction process to mitigate the non-linearity limitation. Another aspect we will investigate is operating the WFS with or without modulation based on the observing conditions. Implementing an improved optical gain tracking tool is another critical element of Agile AO development. Also, we plan to perform end-to-end AO simulations to understand the available options better.

#### 3.1.2 High-order wavefront correctors

There are several benefits to upgrading the current 672-actuator Adaptive secondary mirror (ASM) with a high-density ASM (HDASM; ~ 3,000 actuators) for high-order wavefront corrections. The existing first- and second-generation AO instruments would benefit from such an upgrade. The requirements for the new ASM, besides increasing the actuator count by nearly a factor of four, include: (1) doubling the actuator stroke, (2) reducing the response time by a factor of two and (3) enabling finer wavefront control.

It is challenging to fulfill all these requirements with a single deformable mirror. There are three potential technologies for ASM development: (1) voice-coil-based actuators approach from AdOptica, (2) voice-coil-based actuators with modified cold fingers (the in-house MMT AO exoPlanet characterization System (MAPS) at the Steward Observatory), and (3) hybrid variable reluctance actuators (TNO). Despite all the recent developments in this area, the technical readiness of the best-case option currently is only around the Technical Readiness Level 5.

We propose opting for new ASMs with ~ 950 actuators (the maximum number that can be fabricated with acceptable risks for a 1-m class ASM) and adding a second-stage post-focal plane high-density deformable mirror (HDDM). One of the tradeoff studies we plan to undertake in late 2024 is designing two XAO systems with 1" and 4" beam sizes, respectively, and comparing the optical tolerance for manufacturing and aligning. The trade-off study will help finalize the options for HDDM.

Besides high-order wavefront sensing and correcting, the AgXAO has a few additional components, such as the integration of the active optics (Section 3.1.3), vibration characterization, mitigation, and control (Section 3.1.4), advanced algorithms (Section 3.1.5), and integration of atmospheric turbulence and weather forecast (Section 3.1.6).

#### 3.1.3 Integration of active optics

The off-axis wavefront sensors are used to collimate the telescopes, and the AO systems offload (feedback) semi-static low-order wavefront errors to the secondary hexapod and the telescope control systems to gain the dynamical range of the ASM. Such blind feedback can potentially introduce drifts in the telescope collimation and low-order aberrations. We propose implementing a feed-forward mechanism involving metrology to know the telescope's primary and secondary positions with respect to the focal plane and its evolution. The relative position information will be used to maintain the telescope collimation and pointing and flexure compensation to the level required for XAO, resolving the wavefront error ambiguity. The metrology implementation (Section 3.3.2) will come in handy to provide distance measurements necessary for coarse (few hundred microns) and fine differential piston corrections (few tens of nanometers), enabling Fizeau imaging in the visible wavelength when AgXAO is implemented on both arms of LBT.

#### 3.1.4 Vibration mitigation, characterization, and control

The AgXAO design will emphasize characterizing, mitigating, and controlling the beam-train vibration in tip-tilt and piston. We will make better use of the existing Optical path difference and Vibration Monitoring System (OVMS)[18],[19] for the project. If necessary, we will implement additional accelerometers at strategic locations to provide feed-forward for the vibration control algorithms and combine the accelerometer measurements with the metrology measurements (Section 3.1.3) for the Fizeau imaging application.

#### 3.1.5 Advanced wavefront control

We investigate implementing an advanced Real-Time Control System, replacing the current FPGA-based system with a GPU- and CPU-based one and implementing advanced wavefront algorithms, such as predictive control, speckle nulling, machine learning, etc. We are in the process of setting up an Adaptive Optics Laboratory at the headquarters in Tucson in collaboration with the Large Optics Fabrication and Testing (LOFT) at the Wyant College of Optical Sciences and have initiated a project to experiment with the cacao framework to test wavefront sensor cameras and deformable mirrors. We have obtained two Andor cameras and two low-order ALPAO deformable mirrors for our experiment. We will involve students in supporting the educational aspects of the AgXAO project.

#### 3.1.6 Atmospheric turbulence and weather forecast integration

The atmospheric turbulence, from the telescope environment to the upper layers of the atmosphere, is ultimately the limiting factor for the AO systems. Estimating atmospheric turbulence information such as the seeing and vertical profile in real-time is essential to selecting an observing program that best fits the conditions. While crucial to a facility class AO system, it is even more critical when working in an "Agile XAO" environment. A DIMM telescope riding at the top of the telescope has been providing seeing measurements for more than a decade. The seeing data have been a good predictor of the image quality of the science data in seeing-limited and the AO performance in AO mode overall. Unfortunately, it is the only parameter currently available to tune the turbulence profile model run by ALTA for turbulence prediction[20][21][22]. In the context of Agile AO, the real-time characterization of the turbulence profile will become more critical when choosing what to do AO-wise (XAO, SCAO, ESM[23], etc.) and delivering optimal performance.

LBT is therefore moving forward to better characterize its environment and expand its turbulence monitoring capabilities through two main activities: (1) analyzing a wealth of data already available (DIMM, image quality at the prime focus cameras, Shack-Hartman data at the various Gregorian foci, AO telemetry, etc.), and (2) adding a turbulence profiler such as RINGSS, currently tested in campaign mode at the observatory[15], and/or replacing DIMM with a combo Multi-Aperture Scintillation Sensor (MASS)–DIMM instrument, thus providing key information to tune better both the prediction model (ALTA) and the real-time selection of the best science.

Another aspect that AgXAO will address through design requirements is dome-seeing mitigation. We plan to help develop policies to mitigate dome-seeing, such as dome shutter opening time, dome ventilation guidelines, and high-contrast AO scheduling restrictions.

#### 3.1.7 Pathfinder Science Instrument

We propose developing a path-finder science instrument as part of the AgXAO project, in addition to the visible camera used for performance evaluation and initial visible wavelength science. One option is implementing AO-corrected diffraction-limited narrow-field IFU (2" FOV) spectrographs using the existing first-generation non-AO spectrographs, such as the MODS, PEPSI, and LUCI instruments. We propose upgrading one of the visible spectrographs (MODS or PEPSI), adding high-spatial resolution IFU spectroscopic capability to the suite of science instruments at LBTO. The implementation details are presented in Section 3.2.3.

The primary science drivers for the pathfinder instruments are (1) Exoplanet science and (2) Time-domain observations in the Rubin Era: High-spatial and medium/low spectral resolution follow-up of kilonovae and supernovae events.

One technical objective is to demonstrate the agility of the AgXAO in reconfiguring the AO science modes/instruments in under 15 minutes. The other is to gain in-house expertise with fibers for diffraction-limited AO applications. We will design the telescope presets and AO configuration management to enable easy switching between different AO modes and instruments.

### 3.2 AgXAO implementation plan

We propose implementing AgXAO in phases. The following is one potential path forward.

#### 3.2.1 Single conjugate Adaptive Optics (SCAO) NMP Technical demonstration

We propose using the existing LINC-NIRVANA Multi-Conjugate Adaptive Optics (MCAO) infrastructure for the on-sky demonstration of SCAO NMP after making appropriate changes to one of the High-layer Wavefront Sensors (HWS). Figure 3 shows a picture and a drawing of the LINC-NIRVANA optical bench.

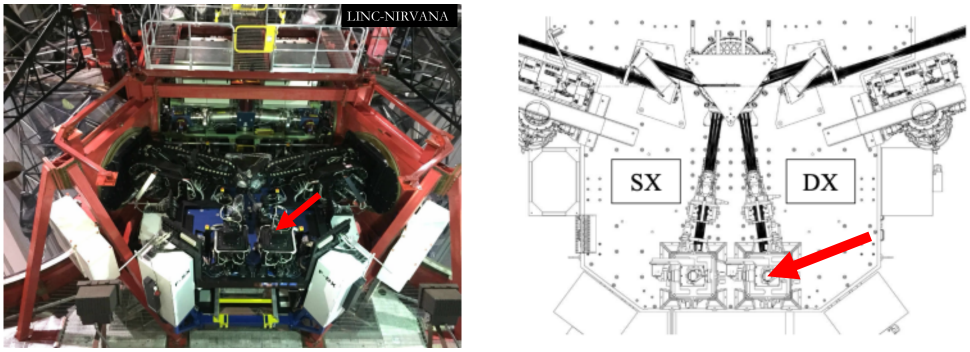
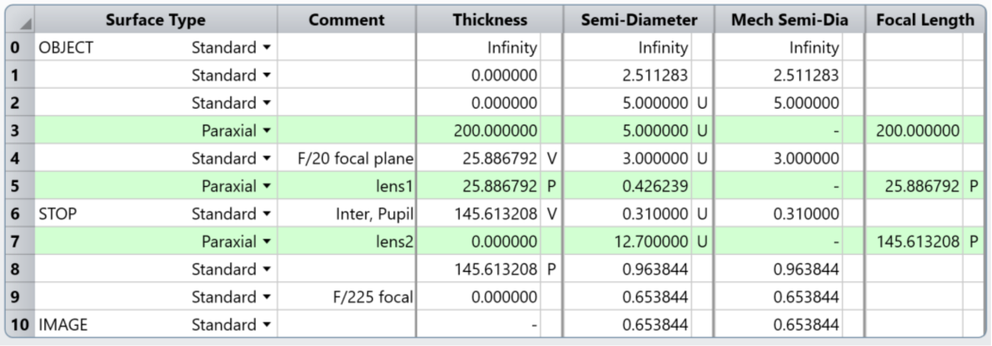


*Figure 3: A picture (left) and a mechanical drawing (right) of the LINC-NIRVANA instrument installed between the two LBT primary mirrors. The DX HWS is pointed with a red arrow.*

Listed below are the required changes to MHWS for the on-sky demonstration of SCAO with wavefront corrections over 600 KL modes.

- Change the conjugation of the MHWS of MCAO to the ground. This task requires no hardware change besides moving the WFS camera away from the pyramid. The camera is on a motorized linear stage with adequate range for this conjugation change. The pupil size is 18 pixels across.
- Modify one of the star enlargers to roughly double the pupil size (38 pixels across). The optical design of the upgraded star enlarger is shown in Table 2.

*Table 2: Optical design of the telephoto lens.*



| | Surface Type | | Comment | Thickness | Semi-Diameter | Mech Semi-Dia | Focal Length |
|---|---|---|---|---|---|---|---|
| 0 | OBJECT | Standard ▾ | | Infinity | Infinity | Infinity | |
| 1 | | Standard ▾ | | 0.000000 | 2.511283 | 2.511283 | |
| 2 | | Standard ▾ | | 0.000000 | 5.000000 U | 5.000000 | |
| 3 | | Paraxial ▾ | | 200.000000 | 5.000000 U | - | 200.000000 |
| 4 | | Standard ▾ | F/20 focal plane | 25.886792 V | 3.000000 U | 3.000000 | |
| 5 | | Paraxial ▾ | lens1 | 25.886792 P | 0.426239 | - | 25.886792 P |
| 6 | STOP | Standard ▾ | Inter, Pupil | 145.613208 V | 0.310000 U | 0.310000 | |
| 7 | | Paraxial ▾ | lens2 | 0.000000 | 12.700000 U | - | 145.613208 P |
| 8 | | Standard ▾ | | 145.613208 P | 0.963844 | 0.963844 | |
| 9 | | Standard ▾ | F/225 focal | 0.000000 | 0.653844 | 0.653844 | |
| 10 | IMAGE | Standard ▾ | | - | 0.653844 | 0.653844 | |

- Double the field of view (FOV) of the star enlarger. The current system has a FOV of 1.2". Doubling the pupil size by reducing the f/# by a factor of 2 would increase the field by a factor of 2 to 2.4".
- Replace CCD 39 with the spare OCAM2K camera.
- Implement the interface between OCAM2K and the ASM. A schematic diagram of the electronics interface is shown in Figure 4.
- Implement non-modulated pyramid Interaction Matrix calibrations. We have planned a feasibility study to be performed in the summer of 2024 using the LUCI WFSs.
- Install a visible camera (Forerunner[24]) for performance validation. Investigate the potential of using the LINC-NIRVANA NIR camera, too, for SCAO performance validation but in the near-infrared wavelengths.

We plan to have a design review to implement SCAO NMP in September 2024. The fallback option is to demonstrate low-order corrections (~ 300 modes) using CCD39 without modifying the star enlarger, which is less attractive in terms of the overall AgXAO development.

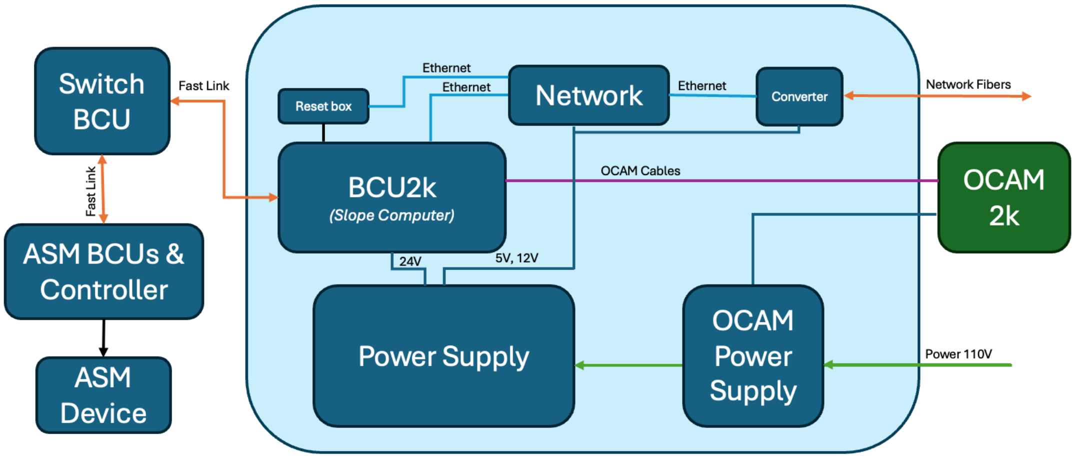


*Figure 4: Schematics of the electronics interface between WFS and the ASM.*

### 3.2.2 Metrology demonstration

We propose installing interferometry-based metrology probes on the LINC-NIRVANA optical bench by upgrading the existing Telescope Metrology System (TMS) [26][27] that ties the primary mirrors to the prime focus instruments, LBCs. We will use the corner cube installed at the center of the adaptive secondary mirror to tie the DX telescope primary to the telescope secondary. We cover the adaptive secondary mirror to the LINC-NIRVANA focal plane path by adding four fiber/collimator pairs and getting the return signals from the retro-reflector at the center of the ASM. Figure 5 shows different subsystems of the TMS. We plan to use fiber splitters and multiplexers to get the necessary metrology channels for the project, making better use of the existing metrology system infrastructure. The goal is to characterize the telescope structure deformation in real-time and apply feed-forward to keep the telescope collimated during science observations. In addition, the metrology will provide wavefront piston measurements. We plan a design review in Dec. 2024.

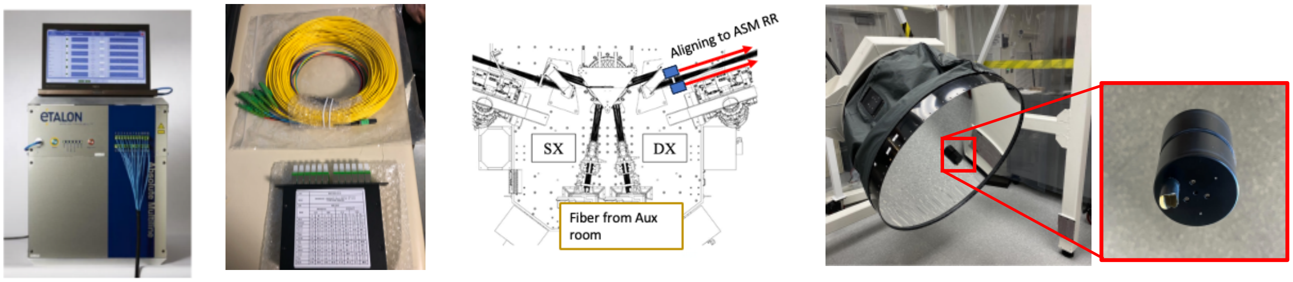


*Figure 5: left to right: TMS machine in Aux room, 70 m routing to the telescope, LINC-NIRVANA optical bench with metrology probe on the DX, and Retro reflector on the ASM.*

### 3.2.3 Pathfinder IFU spectrographs

Young forming giant exoplanets have a typical angular separation and a contrast with respect to the hosting star, respectively, of less than 1 arcsec and down to $10^{-4}$-$10^{-5}$. Therefore, their detection requires combining High Contrast Imaging (HCI) and High-Resolution Spectroscopy (HRS). We exploit this combination by implementing a diffraction-limited Integral Field Unit (IFU) spectrograph, such as ROSES, which is currently integrated at the ADONI lab of the INAF OAR with the proposed AgXAO. The IFU is based on an innovative concept of lenslet array called BIGRE, where each lenslet reduces a portion of the field to a small spot, each of which behaves as an image on the plane of the slit[27].

The BIGRE is substantially a focal reducer, with the reducing factor depending on the ratio between the curvature ratio of the first lenslet array's lenses and the one of the second lenslet array's lenses. The efficiency of a BIGRE is around 70%, with a typical pitch of around 100-200 μm. The advantages of the BIGRE IFU are the larger field-of-view (X5), a more significant number of spectra (X25), and higher efficiency (X3) with respect to the fiber-based IFU. On the other hand, the produced spectra must be shorter to avoid overlapping at the focal plane.

The typical H-alpha lines of accreting exoplanets, being around 100 km/s wide, request a spectral resolution in the range of 1,000 – 5,000 for a good sampling achieved with a volume phase holographic (VPH) grating with a few hundred lines/mm blazed at h-alpha and a pupil of a few millimeters. Figure 6 shows a scheme of the conceptual optical design of ROSES for AgXAO.

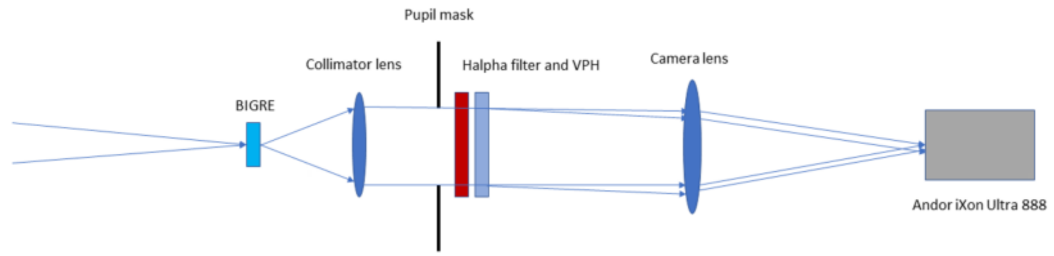


*Figure 6: A schematic diagram of the conceptual optical design of ROSES for AgXAO.*

In addition to ROSES, we propose enabling ~ 250,000 spectral resolution by introducing a fiber split into the existing spectrograph, PEPSI[28]. The implementation involves injecting an AO-corrected image into a 2-D fiber bundle, which is transformed into a fiber slit at the other end. The fiber slit is introduced through a retractable fold mirror placed at the entrance of PEPSI to select the fiber slit for the AO-corrected configuration of this work-horse spectrograph. We propose having a low spatial resolution mode, with a larger FOV of 10", for faint AO guide star fields.

We are considering two potential paths for subsequent XAO developments: (1) SCAO extension (Section 3.2.4) and (2) the Fizeau approach (Section 3.2.5).

### 3.2.4 AgXAO: SCAO extension

The SCAO extension approach involves retaining the LINC-NIRVANA AO hardware to the extent possible and is a continuation of the SCAO demo (Section 3.2.1). The relevant tasks for this approach are listed below.

- Collimate the input beam onto the Xinetic DM by moving lens group 1 away from the telescope focus and removing lens group 2. (In the LINC-NIRVANA configuration, the beam is quasi-collimated on the DM, and lens group 2 is used to subsequently collimate the beam.)
- Move the fold mirror and the DM to get the DM close to the ground conjugation.
- Modify one of the star enlargers to more than triple the pupil size. i.e., 18 pixels to 64 pixels across.
- Replace the CCD 39 with OCAM2K (if not already done for SCAO demonstration (Section 3.3.1)).
- Replace Xinetic DM with HODM (3K).
- Interface OCAM2K to HODM and the ASM through a woofer-tweeter implementation.

### 3.2.5 AgXAO: Fizeau approach

The Fizeau approach involves implementing a new XAO on the DX side and a high-order WFS with the provision of receiving two input beams for potential Fizeau imaging in the visible wavelengths. The relevant tasks are listed below.

- Use an off-axis parabola to collimate the beam.
- Introduce a tip-tilt mirror and an HDDM (3K).
- Introduce a K-mirror for field rotation.
- Have provisions for ADC.
- Introduce a Pyramid WFS close to the HDDM (after the piston mirror) that can take two input beams (64 pixels across each pupil) but start with the DX beam.
- Move the visible camera close to the WFS and modify the fore-optics for lucky Fizeau imaging.

### 3.2.6 AgXAO: Fizeau imaging in the visible

- Implement XAO on the SX.
- Implement the second star enlarger in the WFS. The pyramid will have a larger vertex angle and rotated by 45 degrees. Figure 7 shows the WFS images on OCAM2K for the single-beam and the two-beam configurations.
- Optional: Add star enlarger pairs for coarse pupil sampling (21 pixels & 32 pixels across).
- Implement metrology probes (three channels) for the SX.
- Implement accelerometer feed-forward.
- Explore the feasibility of using the LINC-NIRVANA fringe tracker. If necessary, implement a new NIR fringe tracker.
- Perform Fizeau imaging in the visible wavelengths.

*Figure 7: The pupil from the DX WFS (left) and pupil from both DX and SX (right).*

## 4. SUMMARY

Facility-class AO development is underway at LBTO. We expect to have more robust AO systems and improved operational efficiency and performance by the end of 2024. We will reach facility-class status by the summer of 2025 after six months of on-sky verification. To minimize operational risks, we plan a DX ASM service mission in the summer of 2024 and the Magellan ASM refurbishment projects with a delivery date of the end of 2025.

We have initiated a feasibility study to design and develop the next-generation AO system, the Agile Extreme Adaptive Optics (AgXAO), on the LINC-NIRVANA optical bench. While the initial phases, SCAO and metrology demonstrations, can be performed with limited resources, the XAO developments and the AO-corrected IFU implementation will require external funding. The proposed development has the potential to enable Fizeau imaging in the visible wavelengths – an essential milestone toward ELT development.

## ACKNOWLEDGMENTS

The LBT is an international collaboration among institutions in the United States, Italy and Germany. LBT Corporation Members are: The University of Arizona on behalf of the Arizona Board of Regents; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, The Leibniz Institute for Astrophysics Potsdam, and Heidelberg University; The Ohio State University, representing OSU, University of Notre Dame, University of Minnesota and University of Virginia.

## REFERENCES

[1] Hill, J. M., Green, R. F., Ashby, D. S., Brynnel, J. G., Cushing, N. J., Little, J., Slagle, J. H., and Wagner, R. M., "The Large Binocular Telescope," in [Ground-based and Airborne Telescopes III], Stepp, L. M., Gilmozzi, R., and Hall, H. J., eds., 7733, 77330C, International Society for Optics and Photonics, SPIE (2010)

[2] Riccardi, A. Et al., "Adaptive secondary mirrors for the Large binocular telescope," in Proc. SPIE 5169, pp. 159–168 (2003)

[3] Esposito, S., Riccardi, A., Pinna, E., Puglisi, A., Quir´os-Pacheco, F., Arcidiacono, C., Xompero, M., Briguglio, R., Agapito, G., Busoni, L., Fini, L., Argomedo, J., Gherardi, A., Brusa, G., Miller, D., Guerra, J. C., Stefanini, P., and Salinari, P., "Large Binocular Telescope Adaptive Optics System: new achievements and perspectives in adaptive optics," in [Astronomical Adaptive Optics Systems and Applications IV], Tyson, R. K. and Hart, M., eds., Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series 8149, 814902 (Oct. 2011)

[4] Rabien, S., Angel, R., Barl, L., Beckmann, U., Busoni, L., Belli, S., Bonaglia, M., Borelli, J., Brynnel, J., Buschkamp, P., Cardwell, A., Contursi, A., Connot, C., Davies, R., Deysenroth, M., Durney, O., Eisenhauer, F., Elberich, M., Esposito, S., Frye, B., Gaessler, W., Gasho, V., Gemperlein, H., Genzel, R., Georgiev, I. Y., Green, R., Hart, M., Kohlmann, C., Kulas, M., Lefebvre, M., Mazzoni, T., Noenickx, J., Orban de Xivry, G., Ott, T., Peter, D., Puglisi, A., Qin, Y., Quirrenbach, A., Raab, W., Rademacher, M., Rahmer, G., Rosensteiner, M., Rix, H. W., Salinari, P., Schwab, C., Sivitilli, A., Steinmetz, M., Storm, J., Veillet, C., Weigelt, G., and Ziegleder, J., "ARGOS at the LBT. Binocular laser guided ground-layer adaptive optics," 621, A4 (Jan. 2019)

[5] Herbst, T.M., 2003, Interferometry with the Large Binocular Telescope, Ap&SS 286, 45

[6] Herbst, T.M., et al., 2018, Proceedings of the SPIE, Volume 10703, id. 107030B 7 pp

[7] Seifert, W., Appenzeller, I., Baumeister, H., Bizenberger, P., Bomans, D., Dettmar, R.-J., Grimm, B., Herbst, T., Hofmann, R., Juette, M., Laun, W., Lehmitz, M., Lemke, R., Lenzen, R., Mandel, H., Polsterer, K., Rohloff, R.-R., Schuetze, A., Seltmann, A., Thatte, N. A., Weiser, P., and Xu, W., "LUCIFER: a Multi-Mode NIR Instrument for the LBT," in [Instrument Design and Performance for Optical/Infrared Ground-based Telescopes ], Iye, M. and Moorwood, A. F. M., eds., Proc. SPIE 4841, 962–973 (Mar. 2003)

[8] Hinz, P. M., Defrère, D., Skemer, A., Bailey, V., Stone, J., Spalding, E., et al. (2016). Overview of LBTI: A multipurpose facility for high spatial resolution observations. In F. Malbet, M. J. Creech-Eakman, & P. G. Tuthill (Eds.), *Optical and infrared interferometry and imaging V* (Vol. 9907, p. 990704). SPIE. https://doi.org/10.1117/12.2233795

[9] Ertel, S., Hinz, P. M., Stone, J. M., Vaz, A., Montoya, O. M., West, G. S., et al. (2020). Overview and prospects of the LBTI beyond the completed HOSTS survey. In P. G. Tuthill, A. Mérand, & S. Sallum (Eds.), *Optical and infrared interferometry and imaging VII* (Vol. 11446, p. 1144607). https://doi.org/10.1117/12.2561849

[10] Pedichini, F., Piazzesi, R., Viavattene, G., Antoniucci, S., Gangi, M., et al. (2022). SHARK-VIS ready for the stars: Instrument description and final laboratory performance test. In L. Schreiber, D. Schmidt, & E. Vernet (Eds.), *Adaptive optics systems VIII* (Vol. 12185, p. 121856Q). https://doi.org/10.1117/12.2629244

[11] Farinato, J. et al., “SHARK-NIR: from K-band to a key instrument, a status update,” Proc. SPIE 9908, paper 116 (2016)

[12] Crass, J., Engelman, M., Sands, B., Pappalardo, D., Johnson, M.C, et al. 2024, #13096-50 (this conference)

[13] Shields, J., Chu, J., Conrad, A., Crass, J., Crepp, J. R., Ertel, S., Ilyin, J. F. I., O.Kuhn, L.Marafatto, Pedichini, F., Piazzesi, R., Pogge, R., Power, J., Ragland, S., Reynolds, R., Riedl, J., Smithwright, M., Strassmeier, K. G., and D.Thompson, “The instrumentation program at the Large Binocular Telescope Observatory in 2024,” in [Ground-based and Airborne Instrumentation for Astronomy X], 13097, 13096–4, International Society for Optics and Photonics, SPIE (2024).

[14] Conrad, A., Pedichini, F., Li Causi, G., Antoniucci, S., de Pater, I., Davies, A. G., et al. (2024). Observation of Io's resurfacing via plume deposition using ground-based adaptive optics at visible wavelengths with LBT SHARK-VIS. *Geophysical Research Letters*, *51*, e2024GL108609. https://doi.org/10.1029/ 2024GL108609

[15] Veillet, C., Guerra, J.C., Masciadri, E., Ragland, S. 2024, Turbulence monitoring at the Large Binocular Telescope: Current status and ongoing developments, #13097-310 (this conference)

[16] Pinna, E., Rossi, F., Agapito, G., Puglisi, A., Plantet, C., Ghose, E., Bec, M., Bonaglia, M., Briguglio, R., Brusa, G., Carbonaro, L., Cavallaro, A., Christou, J., Durney, O., Ertel, S., Esposito, S., Grani, P., Guerra, J. C., Hinz, P., Lefebvre, M., Mazzoni, T., Mechtley, B., Miller, D. L., Montoya, M., Power, J., Rothberg, B., Taylor, G., Vaz, A., Xompero, M., and Zhang, X., 2023, “SOUL at LBT: commissioning results, science and future.,” in [Adaptive Optics for Extremely Large Telescopes 7th Edition], ONERA (June 2023)

[17] Agapito, G., Pinna, E., Esposito, S., Heritier, C.T. and Oberti, S., 2023, A&A, 677, A168

[18] Kurster., M., Bertram, T., Borelli, J.L., Brix., N., Gassler, W. et al, 2010, Proc. 7734, Optical and Infrared Interferometry II, 77342Y

[19] Böhm, M., Pott, J-U, Borelli, J., Hinz, P., Defrère, D., et al., 2016, SPIE 9906E, 2RB

[20] Masciadri, E., Vernin, J., Bougeault, P., 1999, 3D mapping of optical turbulence using an atmospheric numerical model. I. A useful tool for the ground-based astronomy, A&AS, 137, 185-202

[21] Masciadri, E., Martelloni, G. & Turchi, A. 2020. Monthly Notices of the Royal Astronomical Society, Volume 492, Issue 1, p.140-152

[22] Hagelin, S, Masciadri, E., Lascaux, F., 2011. Monthly Notices of the Royal Astronomical Society, Volume 412, Issue 4, pp. 2695-2706

[23] Miller, D., Power, J., Rothberg, B., Thompson, D. & Ragland, S., Enhanced Seeing Mode at the Large Binocular Telescope Observatory, #13097-222 (this conference)

[24] Pedichini, F., Stangalini, M., Ambrosino, F., Puglisi, A., Pinna, E., et al., 2017, High Contrast Imaging in the Visible: First Experimental Results at the Large Binocular Telescope, 2017AJ....154...74P

[25] Rakich, A., Schurter, P., Conan, R., Hill, J. M., Gardiner, M., Bec, M., Kuhn, O., 2018, Proc. of SPIE Vol. 10700, 107001S

[26] Andrew Rakich, Heejoo Choi, Christian Veillet, John M. Hill, Matthieu Bec, Yang Zhang, Trenton Brendel, Breann Sitarski, Michael Gardiner, Dae Wook Kim, Stephanie Rodriguez, "A laser-truss based optical alignment system on LBT," Proc. SPIE 11445, Ground-based and Airborne Telescopes VIII, 114450R (13 December 2020); https://doi.org/10.1117/12.2558013

[27] Antichi, J., Dohlen$^{,}$ K., Gratton, R.G., Mesa$^{,}$ D., Claudi$^{2}$, R.U., Giro, E., Boccaletti, A., Mouillet, D., Puget, P. & Beuzit, J.-L., 2009, *ApJ* **695** 1042**DOI** 10.1088/0004-637X/695/2/1042

[28] Strassmeier, K. G., Ilyin, I., Järvinen, A., et al. 2015, “PEPSI: The high-resolution échelle spectrograph and polarimeter for the Large Binocular Telescope“, AN, 336, 324