Invited Paper

An overview and the current status of instrumentation at the Large Binocular Telescope Observatory

R. Mark Wagner, Michelle L. Edwards, Olga Kuhn, David Thompson, and Christian Veillet

Large Binocular Telescope Observatory
933 North Cherry Avenue, Tucson, AZ 85721 USA

ABSTRACT

An overview of instrumentation for the Large Binocular Telescope (LBT) is presented. Optical instrumentation includes the Large Binocular Camera (LBC), a pair of wide-field ($24' \times 24'$) mosaic CCD imagers at the prime focus, and the Multi-Object Double Spectrograph (MODS), a pair of dual-beam blue-red optimized long-slit spectrographs mounted at the left and right direct F/15 Gregorian foci incorporating multiple slit masks for multi-object spectroscopy over a $6'$ field and spectral resolutions of up to 2000. Infrared instrumentation includes the LBT Near-IR Spectrometer (LUCI), a modular near–infrared (0.9–2.5 μm) imager and spectrograph pair mounted at the left and right front–bent F/15 Gregorian foci and designed for seeing-limited (FOV: $4' \times 4'$) imaging, long-slit spectroscopy, and multi-object spectroscopy utilizing cooled slit masks and diffraction limited (FOV: $0'.5 \times 0'.5$) imaging and long-slit spectroscopy. Strategic instruments under development that can utilize the full 23 m baseline of the LBT include an interferometric cryogenic beam combiner with near–infrared and thermal-infrared instruments for Fizeau imaging and nulling interferometry (LBTI) and an optical bench near–infrared beam combiner utilizing multi-conjugate adaptive optics for high angular resolution and sensitivity (LINC-NIRVANA). LBTI is currently undergoing commissioning and performing science observations on the LBT utilizing the installed adaptive secondary mirrors in both single–sided and two–sided beam combination modes. In addition, a fiber-fed bench spectrograph (PEPSI) capable of ultra high resolution spectroscopy and spectropolarimetry (R = 40,000–300,000) will be available as a principal investigator instrument. Installation and testing of the bench spectrograph will begin in July 2014. Over the past four years the LBC pair, LUCI1, and MODS1 have been commissioned and are now scheduled for routine partner science observations. Both LUCI2 and MODS2 passed their laboratory acceptance milestones in the summer of 2013 and have been installed on the LBT. LUCI2 is currently being commissioned and the data analysis is well underway. Diffraction–limited commissioning of its adaptive optics modes will begin in the 2014B semester. MODS2 commissioning began in May 2014 and will completed in the 2014B semester as well. Binocular testing and commissioning of both the LUCI and MODS pairs will begin in 2014B with the goal that this capability could be offered sometime in 2015. The availability of all these instruments mounted simultaneously on the LBT permits unique science, flexible scheduling, and improved operational support.

Keywords: Optical and infrared instruments, imaging cameras, spectrographs, interferometers, Large Binocular Telescope

1. INTRODUCTION

The Large Binocular Telescope Observatory is located in southeastern Arizona near Safford in the Pinaleno Mountains on Emerald Peak at an altitude of 3191 m. The binocular design of the Large Binocular Telescope (LBT) has two identical 8.4 m telescopes mounted side-by-side on a common altitude-azimuth mounting for a combined collecting area of a single 11.8 m telescope. The entire telescope and enclosure are very compact by virtue of the fast focal ratio (F/1.14) of the primary mirrors. The two primary mirrors are separated by 14.4 m center-to-center and provide an interferometric baseline of 22.8 m edge-to-edge. The binocular design, combined with integrated adaptive optics utilizing adaptive Gregorian secondary mirrors to compensate for atmospheric phase errors, provides a large effective aperture, high angular resolution, low thermal background, and exceptional

Further author information: Send correspondence to R. M. Wagner, E-mail: mwagner@lbto.org, Telephone: +1 520 6263006, Fax: +1 520 6269333

Ground-based and Airborne Instrumentation for Astronomy V, edited by
Suzanne K. Ramsay, Ian S. McLean, Hideki Takami, Proc. of SPIE Vol. 9147,
914705 · © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2056787

sensitivity for the detection of faint objects. The LBT is an international collaboration of the University of Arizona, Italy (INAF: Istituto Nazionale di Astrofisica), Germany (LBTB: LBT Beteiligungsgesellschaft), The Ohio State University, and the Tucson–based Research Corporation representing the University of Minnesota, the University of Virginia, and the University of Notre Dame.

The observatory continues to operate in a challenging mixed mode of telescope and instrument commissioning on one hand and partner science observing on the other. Currently, approximately 70% of the available time is scheduled for partner science observations. A telescope configuration change during the night to facilitate the use of two different instruments is available to the LBT community thus improving efficiency and productivity and mitigating instrument technical downtime. In addition, both partner science observations and some technical time are now both flexibly scheduled improving both efficiency and progress. The overall current status of the LBT is summarized in these proceedings by Hill et al.[1] and references therein. The challenges of contemporaneous commissioning, the transition to regular partner science operations, and the short–term development plan of the observatory are discussed in these proceedings by Veillet et al.[2]

During the past two years, the observatory and partnership achieved several important milestones. In late 2013, the observatory took delivery of the last two remaining facility instruments that were under development by the partners. Now, all three pairs of the optical wide field imagers (LBC), optical spectrometers (MODS), and infrared imager/spectrometers (LUCI) are attached to the LBT and available for regular science observations or are in commissioning at the present time. A detailed description of these instruments is presented herein as well as the two interferometers and high resolution fiber–fed spectrograph. In late 2013, the first propagation of the ARGOS Rayleigh laser guide star system was successfully completed. ARGOS users a pair of three Rayleigh laser guide star constellations from each side of the LBT to provide ground layer adaptive optics corrections for the two near–infrared LUCI spectrometers. ARGOS is described in these proceedings by Raab et al.[3] Finally, the first stabilized fringes of the two 8.4 m telescopes and nulling interferometric observations were obtained with the LBT Interferometer (LBTI) in December 2013 and January 2014 respectively and are described in these proceedings by Hinz et al.[4] and Defrère et al.[5]

In this contribution, we present a summary of the scientific instruments for the LBT that have been commissioned for partner science observations and are now in regular use, those instruments that are being commissioned at the present time, or are currently under development in partner laboratories for the LBT.

2. LBT INSTRUMENTATION SUITE

LBT instruments are distributed in three categories. Facility instruments are available for use by anyone in the partnership and are supported and maintained by the LBTO. Principal investigator instruments are private instruments and are supported and maintained solely by the builders with limited technical assistance from the LBTO. Strategic instruments are technically challenging developmental instruments which are considered crucial to the long term scientific success of the LBT. Strategic instruments may be unique and are expected to have a major impact on astronomy as a whole. These instruments may be available to the general LBT community on a collaborative basis or through time exchanges. They may become facility instruments in the future at the discretion of the LBT Corporation (LBTC) Board of Directors.

Three facility instruments, two strategic instruments, and one major principal investigator instrument are under construction for the LBT. The instruments are as follows:

1. Facility Instruments (separate telescopes)
    - Large Binocular Camera (LBC)
    - Multi-Object Double Spectrograph (MODS)
    - LBT NIR-Spectrometer (LUCI)
2. Strategic Instruments (combined telescope)
    - LBT Interferometer (LBTI) with both 8–14 μm (NOMIC) and 3–5 μm (LMIRcam) cameras

- LBT INterferometric Camera and the Near–IR/Visible Adaptive iNterferometer for Astronomy (LINC-NIRVANA)

3. Principal Investigator Instrument

   - Potsdam Echelle and Polarimetric Spectroscopic Instrument (PEPSI)

The LBC is a pair of blue–red optimized prime focus imagers with a field of view of almost $0\overset{\circ}{.}5$. MODS is a pair of dual–beam, blue–red optimized, optical spectrographs incorporating long–slit, custom multi–slit, and direct imaging modes. LUCI is a pair of near–infrared (hereafter NIR) imagers and spectrographs that can be used in both seeing– and diffraction–limited modes by virtue of interchangeable cameras for direct imaging, long–slit spectroscopy, and customized multi–slit spectroscopy. In addition, both 1–2.5 μm (LINC-NIRVANA) and 3–14 μm (LBTI) interferometers are under development or conducting science commissioning. PEPSI is a fiber–fed echelle spectrograph for ultra-high resolution optical spectroscopy and spectropolarimetry. The basic parameters of LBT instruments are summarized in Table 1.

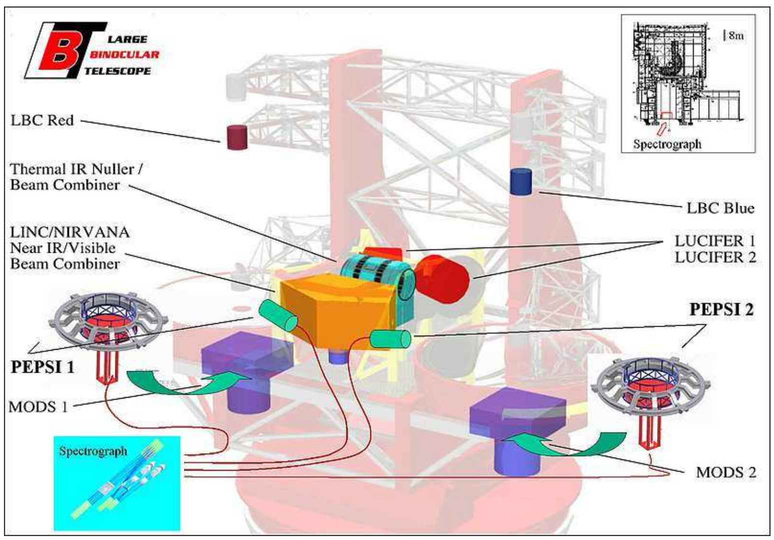

Figure 1. LBT focal station allocation. The locations of the LBC, MODS, LUCIFER, LBTI, and LINC-NIRNAVA are shown. Focal stations for the PEPSI fiber bundles and the location of the spectrograph chamber in the bottom of the telescope pier are shown schematically as well. Illustration courtesy of K. Strassmeier.

The locations of these instruments on a rendering of the LBT at the various foci are shown in Figure 1. The LBC is mounted at the prime focus on swing–arm spiders just inside the location of the Gregorian secondary mirror. MODS is attached at the direct F/15 Gregorian focus and is accessed by swinging the LBC out of the beam and inserting the secondary into the beam. LUCIFER, LBTI, and LINC–NIRVANA are mounted at the front, center, and back bent F/15 focal stations respectively and are accessed by a rotating tertiary mirror. The PEPSI spectrograph is located in the base of the LBT pier in an environmentally controlled chamber. Optical fibers running from a fixed location behind LINC–NIRVANA for integral light spectroscopy and from polarimeters mounted in place of MODS at the direct F/15 foci for spectropolarimetry are connected to the spectrograph. In addition, a separate solar–feed telescope directs integrated sunlight through an optical fiber to the PEPSI spectrograph for daily ultra–high resolution solar spectroscopy and study of the solar–stellar connection.

These instruments are mounted on the telescope simultaneously and can be available for use during the night to take advantage of exquisite but rare observing conditions, flexible scheduling, mixed-mode observing programs, and targets of opportunity, as well as mitigating instrument unavailability or technical downtime. In these proceedings, Reynolds et al.[6] describe in detail the technical and operational support of LBT facility instruments including maintenance, spare parts, and trouble–shooting as well as our reliability goals and current progress. The overall operational efficiency of the LBT and its instruments are discussed by Veillet et al.[2] in these proceedings.

Table 1. LBT Instrument Parameters

Instrument	Focal Station	Modes	Spectral Coverage (μm)	Spectral Resolution	Field of view	Pixel scale
LBC-Blue LBC-Red	Prime	Direct CCD	U,B,V, g,r V,R,I,r,i,z,Y	4-50	$27' \times 27'$	$0''.228$
LUCIFER	Front-Bent	Imager, Longslit, MOS AO	z, J, H, K, K_s J, H, K, K_s	2000-8500 $\sim$30,000	$4' \times 4'$ $30'' \times 30''$	$0''.12$-$0''.25$ $0''.015$
MODS-Blue MODS-Red	Direct F/15	Imager, Longslit, MOS	0.32-0.65 0.55-1.1	100-1540 100-1730	$6' \times 6'$	$0''.125$
LBTI	Center-Bent	Nulling/Fizeau Interf Fizeau Interf	8-14 1.5-5	100 350	$12''$ $20''$	0.018 0.011
LINC NIRVANA	Rear-Bent	Fizeau Interferometer	J, H, K_s	5-20	10-$20''$	0.006
PEPSI	Rear-Bent Direct F/15	Spectroscopy Spectropolarimetry	0.39-1.1	40,000 to 300,000	$0''.5$-$1''.4$	0.165

3. FACILITY INSTRUMENTS

3.1 The Large Binocular Camera (LBC)

The LBC consists of a pair (LBC blue + LBC red) of wide-field mosaic optical CCD imagers at the F/1.14 prime focus of each 8.4 m primary mirror (Figure 2). Each camera is mounted on a swing-arm spider attached to the elevation structure of the telescope so that the cameras can be swung into and out of the telescope beam at any time and be ready for observations. The blue camera is optimized for the UB bands while the red camera is optimized for the VRIZ bands. Commissioning of the blue and red cameras was completed in December 2007 and January 2008 respectively. Originally, the LBC was a project of INAF. The LBC was accepted as a facility instrument in October 2011 after several upgrades and is now maintained by the LBTO with assistance from the LBC team for detector and software support. A description of the LBC and its performance is given by Speziali et al.[7] and Giallongo et al.[8] and references therein.

A five–element refractive corrector was designed separately for each camera to produce superb images over a corrected field of view of about $30'$ in diameter in their respective wavelength bands. Facility science filters include Bessel U, B, V, R, and I and SDSS g', r', i', and z'. In addition, there is a wide and high-throughput UV filter in blue channel and both a Y filter and an intermediate band (20 nm FWHM) filter centered at 972 nm in red channel for cosmological investigations.

Each science array consists of four three-side buttable CCDs (2048 $\times$ 4608, 13.5 μm square pixels) which cover about 75% of the corrected field. They are mounted in a spherical bi-metallic dewar sitting on a field de-rotator assembly. Two frame transfer technical CCDs (512 $\times$ 2048, 13.5 μm square pixels) are located inside the corrected field on each side of the science array. One of these detectors coincides with the science focal plane and is used for guiding adjustments which are then sent to each primary mirror while the telescope tracks along the mean position. The other technical CCD is located 800 μm below the science focal plane and provides extra-focal pupil images suitable for the measurement of optical aberrations to optimize and maintain focus and image quality. Superb collimation of each telescope and co-alignment of the telescope pair are essential if excellent image quality is to be achieved when using the LBC.

Recently, there have been a host of enhancements to both LBCs to increase their efficiency and reliability. These include several software upgrades to improve error logging and recovery, rotator trajectory tracking, and GUI usability.[9] The observatory has implemented regular filter and lens cleaning schedules and is in the process of producing spare filter cells to accommodate user provided speciality filters.

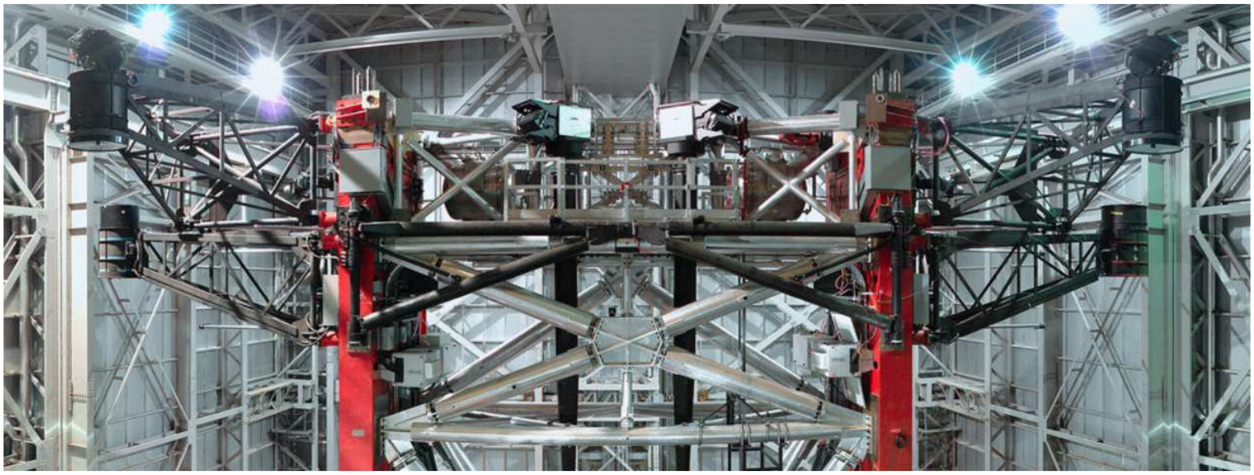

Figure 2. Picture of the top end of the LBT showing the prime foci, deformable adaptive secondary mirrors, and the ARGOS laser launch optics. The LBC blue channel imager (left–center) and red channel imager (right–center) are shown with the respective left and right secondary mirrors mounted above them. Photo by Ray Bertram.

A major upgrade of all four detector controllers (two science and two technical CCDs) will occur in the summer of 2014. Both the sequencer and controller interface board will be replaced by a SkyTech SPC_A600 sequencer board with a piggy-backed embedded Linux processor board. This will result in significant changes to both the LBC hardware and software architecture. The upgrade is expected to significantly speed up instrument start-ups and reboots, decrease the instance of communication errors, and reduce the number of control computers, limiting the potential for hardware failure as discussed in these proceedings by Summers et al.[9]

Delivering on the promise offered by the LBC requires continual efforts to optimize the performance of the instruments and telescope. This is especially true with regards to optical imaging quality, which is difficult to maintain at the fast prime focus. New temperature dependent terms have now been included in the collimation model of the telescope and a process known as range balancing[10] keeps the primary mirrors close to the midrange of their travel as successive corrections are applied after a preset to a new target and each telescope subsequently optimizes collimation and co–pointing.

LBTO is also pursuing new avenues for collimation with the goal of improving both the range of conditions under which collimation can be achieved (the "keyhole") and the final quality of the fit. Testing has started of a new routine developed by INAF that uses improved pupil detection and key components of the wavefront reconstruction scheme described by Tokovinin and Heathcote[11] to address weaknesses in the current algorithm. Experimentation with new techniques will continue throughout 2014. In addition, other on–going work seeks to resolve intermittent problems with the delivered PSF in which point sources may appear elongated (ellipticity ~ 0.1) across the entire FOV at times. This may result from a small amount of binodal astigmatism but it is currently under investigation.

3.2 The Near–Infrared Imager and Spectrograph (LUCI)

LUCI (formerly known as LUCIFER) consists of a pair (LUCI1 + LUCI2) of cryogenic NIR imagers and spectrographs mounted at the bent–front F/15 Gregorian foci of each LBT telescope (Figure 3). LUCI is project of the LBTB. A technical description of LUCI has been presented by Seifert et al.[12] A summary of the on–sky testing and science commissioning of LUCI1 was presented by Seifert et al.[13] and Ageorges et al.[14] respectively. A recent update, including the commissioning of LUCI2 and the status of its adaptive optics and binocular modes is presented by Buschkamp et al.[15] in these proceedings.

The two instruments are capable of seeing–limited imaging, long-slit and multi-object spectroscopy over a $4' \times 4'$ field of view, as well as diffraction–limited imaging and long-slit spectroscopy over a $30'' \times 30''$ field-of-view. These modes can be selected by the choice of three different cameras mounted on a rotating turret giving image

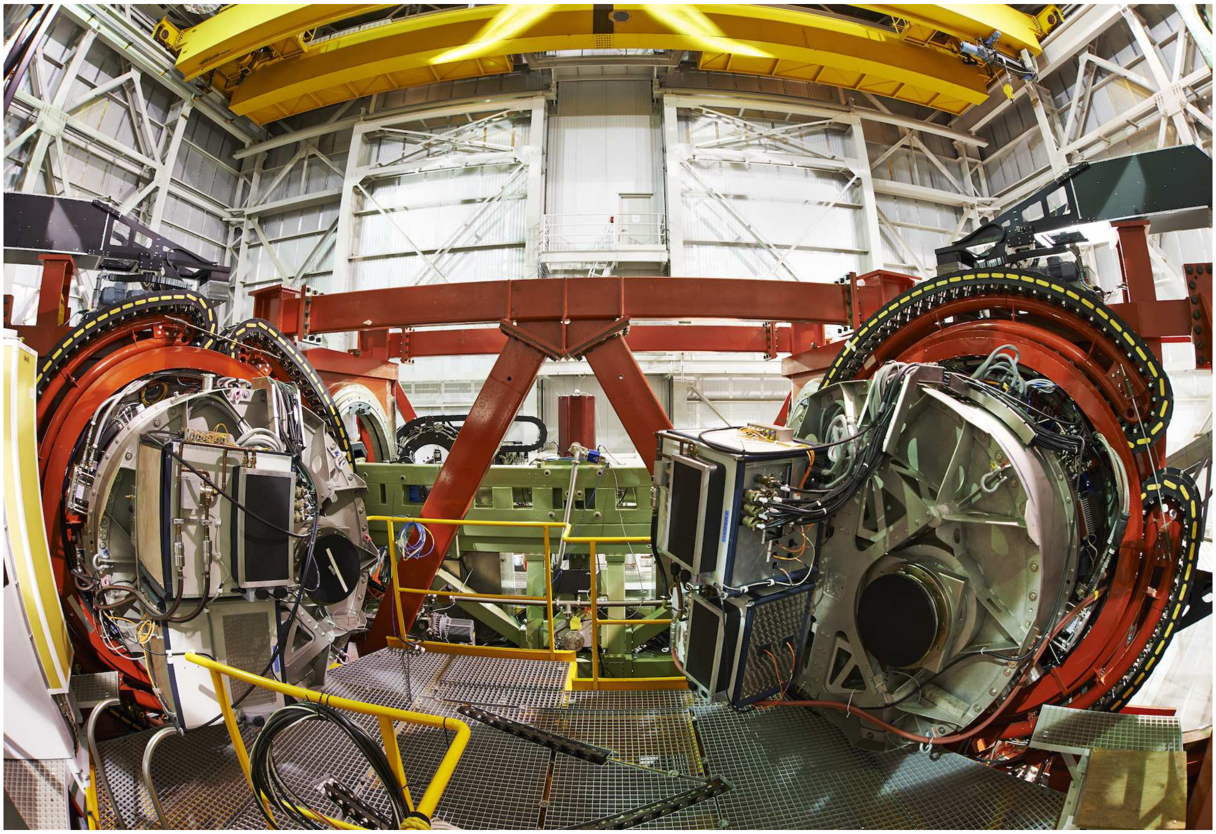

Figure 3. LUCI1 (right) and LUCI2 (left) attached to Gregorian instrument rotators and Acquisition–Guide–Wavefront Sensing units of the LBT. The black–colored circular port to facilitate cryogenic mask cassette exchanges can be seen on both instruments. Photo by Enrico Sacchetti.

scales per pixel of $0''.25$ (F/1.8), $0''.12$ (F/3.75), and $0''.015$ (F/30) for spectroscopy, imaging, and adaptive optics respectively. The pixel scale in the diffraction-limited mode was selected to optimally sample (2 pixels) the Airy disk in the J-band (FWHM = $0''.031$). At present, neither instrument is equipped with the high resolution F/30 AO camera since the diffraction–limited imaging performance continues to be characterized and optimized in laboratory tests in Heidelberg. We anticipate installation of the first F/30 camera into LUCI2 in the fall of 2014 with testing and commissioning to begin shortly thereafter.

Due to the unfortunate loss of the original detector in LUCI1 in September 2011, the original LUCI2 detector was moved to LUCI1 and a pair of Teledyne HAWAII-2RG (H2RG) 2K × 2K pixel HgCdTe detectors were procured. The original LUCI2 detector now in LUCI1 has acceptable sensitivity across the entire 0.9–2.5 μm spectral range with quantum efficiencies of ∼50-55% across all bands. The H2RG detectors will provide a significant increase in sensitivity for both instruments, with quantum efficiencies above ∼80%. The first of the new H2RG detectors is currently installed in LUCI2, while the second H2RG will be retrofitted into LUCI1 sometime in 2015.

Both instruments have an identical complement of filters mounted in two filter wheels located in the converging beam. A set of broadband zJHKK$_s$ filters, order-sorting H+K and z+J filters for spectroscopy, and a number of narrow-band atomic–line and molecular band filters such as Brγ 2.17 μm, H_2 2.12 μm, Fe II 1.65 μm, and OH 1.1 μm are available. In addition to a plane mirror used to select direct imaging mode, the grating assembly has three diffraction gratings providing (1) single–order coverage of the zJHK bands at a resolution of ∼7000 (210 gpm used in 2nd order at K through 5th order in z), (2) simultaneous coverage of the H+K or z+J bands at a resolution of ∼2000 (200 gpm), and (3) coverage of the K–band between 1.9–2.3 μm at a resolution of about 4150 (150 gpm). The latter grating may be replaced with a new grating for the diffraction–limited mode that

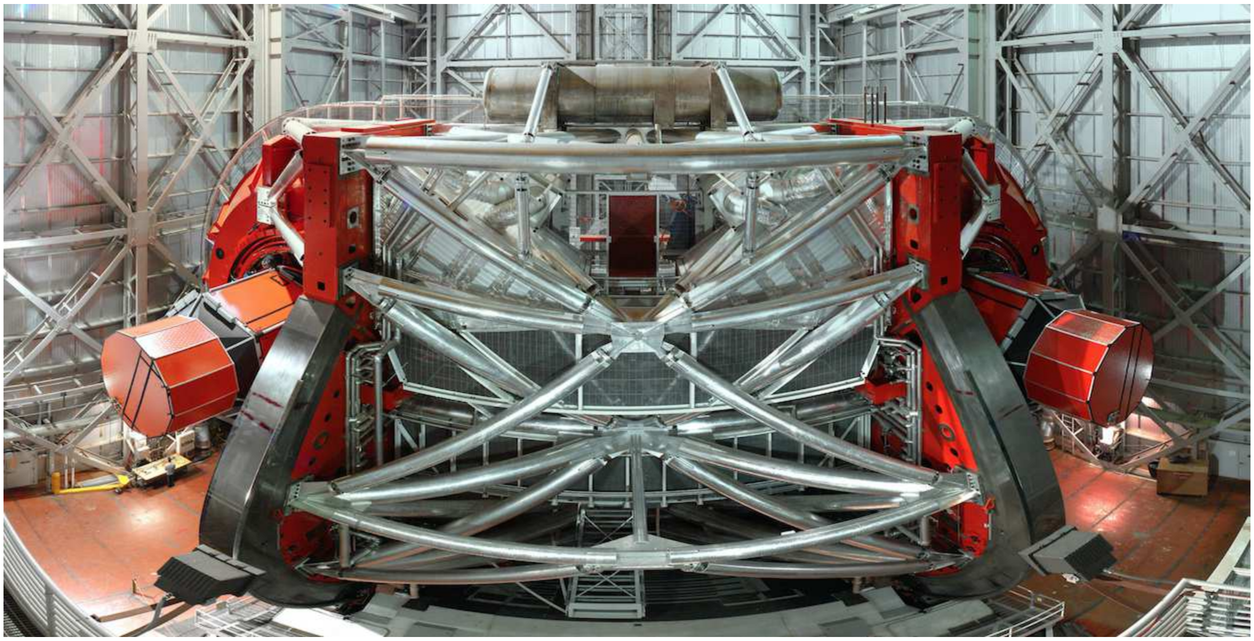

Figure 4. Panorama of the LBT pointed at horizon showing MODS1 (left–center) and MODS2 (right–center) attached to the direct F/15 Gregorian foci. MODS1 has been available for partner science since the 2011B semester. MODS2 commissioning began in May 2014. Photo by Ray Bertram.

allows full-band coverage similar to the 210 gpm grating but using the F/30 camera.

The most complicated LUCI mechanical subsystem is the cryogenic MOS Unit.[16,17] Multi–object NIR spectroscopy has become the most frequently used observing mode of LUCI1 allowing large samples of high redshift extragalactic objects to be studied simultaneously. The MOS Unit consists of a storage unit that is comprised of an exchangeable cassette holding 23 custom masks plus another 10 masks consisting largely of the permanent long–slits, a focal plane unit (FPU) that positions the mask in the LUCI focal plane with high positional accuracy and repeatability, and a mask handling robot that carries the individual masks between storage and the FPU, all of which operate in a vacuum at cryogenic temperatures. The exchange of a slit mask cassette holding the individual custom masks is also performed at cryogenic temperatures using a pair of evacuated and cooled auxiliary cryostats through a port on the rear of the instruments. Electronically activated gate valves on both LUCI and the auxiliary cryostat maintain a vacuum and provide a clean environment for the exchange. The fabrication of custom LUCI masks and the cryogenic exchange process is described by Reynolds[18] in these proceedings.

LUCI1 has been used for regular science observations by the LBT partnership since January 2010. Incremental improvements of the various mechanisms, the MOS Unit, electronics, and software have been performed by the LUCI team and LBTO to improve reliability. Laboratory acceptance of LUCI2 in Heidelberg was completed in June 2013. The instrument was then disassembled and shipped to Mount Graham where it was reintegrated and tested in the mountain clean room facility in September and October respectively. Science commissioning of the seeing–limited modes of LUCI2 began in November and was completed in January 2014. Reduction and analysis of these data is in progress by the LUCI team, the LBTO, and support from Steward Observatory. We anticipate offering LUCI2 for seeing–limited science to LBT community in the 2014B or 2015A semester as commissioning of both AO imaging and spectroscopy modes continuing in parallel.

3.3 The Multi–Object Double Spectrograph (MODS)

MODS consists of a pair (MODS1 + MODS2) of identical double–beam blue–red optimized optical spectrographs attached to the straight–through F/15 Gregorian focus of each 8.4 m primary mirror (Figure 4). MODS is a project of The Ohio State University. The recent status of MODS is summarized by Pogge et al.[19]

For acquisition, guiding, and active optics, a modified version of the standard facility guiding and wavefront–sensing system was constructed as part of MODS itself above the instrument focal plane. The optical layout incorporates a dichroic beam splitter below the focal plane and reflects red light into the red channel collimator through a fold mirror. The optical design provides broad spectral coverage and high throughput by incorporating an off-axis Maksutov-Schmidt camera and optimized coatings on the optics and detectors. The useable field-of-view is about $6' \times 6'$ but with slightly degraded image quality beyond $4'$. A grating turret mechanism in each channel holds up to 3 dispersers plus an imaging flat mirror. Each channel utilizes a medium-dispersion diffraction grating manufactured by Newport Spectra-Physics and optimized for the blue and red spectral regions respectively each giving a resolution of about 2000. In addition, a double-pass 8° glass prism with a back reflective coating and optimized for the blue and red spectral regions has been implemented in each channel to provide a highly efficient low-dispersion spectroscopic mode with smoothly varying resolutions of 300–100 across the blue spectrum and 450–100 across the red spectrum. MODS utilizes a closed-loop image motion compensation system (IMCS) to adjust for flexure due to gravity, temperature fluctuations, and mechanical effects. The IMCS has proven to be extremely reliable, robust, and accurate minimizing image shift to within 0.6 pixels while tracking through an elevation change of 15°.

MODS incorporates the new E2V CCD231–68 monolithic backside–illuminated 8K × 3K pixel CCD detectors optimized for the blue and red spectral regions and operated using the OSU MkIX detector controllers. The red–optimized detector is a 40 μm–thick deep–depletion device with a proprietary Astro–ER1 coating resulting in a peak quantum efficiency of about 97% at 650 nm and superior performance long–ward of 800 nm and no fringing. The RON is $\sim$2.5 e^- RMS for these devices. Full-frame readout takes approximately 72 s. Smaller frames and consequently faster readouts are selectable through various windowing options and/or binning for the direct imaging mode and target acquisition.

MODS has three observing modes: direct imaging, long–slit, and multi–slit using curved focal plane masks. The direct imaging mode of the spectrograph can be implemented by retracting a slit mask from the focal plane and replacing the grating with a plane mirror. Direct imaging mode is used to perform precise target acquisition on long–slits or multi–slit focal plane masks as well as for science programs that may require simple direct imaging observations. A set of SDSS filters are available both channels. This mode has been particularly advantageous and popular for combined photometric and spectroscopic monitoring programs. In long–slit mode, a single $6'$ long slit provides spatial coverage across a slice of the MODS field-of-view and can be oriented at any angle by the instrument rotator assembly. Six long–slits of varying widths between $0.3''$ and $5.0''$ are available. In multi–slit mode, a curved slit mask matched to the shape of the Gregorian focal plane is used to precisely locate a series of small and precisely positioned slits or apertures centered on targets within the MODS field-of-view. As many as 72, $5''$ long slitlets can be accommodated in the design across a $6'$ field. Each MODS spectrograph can accommodate up to 24 slit masks stored near the MODS focal plane in the cassette assembly and exchange mechanism. A description of the curved MODS focal plane masks and their fabrication is described by Reynolds[18] in these proceedings.

MODS1 began regularly scheduled partner science observations in the 2011B semester after commissioning and science verification were completed earlier in May. MODS2 passed its laboratory acceptance milestone in Ohio in August 2013. Reintegration and testing in the mountain clean room facility was completed the following March and the instrument was subsequently installed on the LBT at the right–direct F/15 Gregorian focal station on April 9. Commissioning of the MODS2 guiding and active optics system was completed in early May by both LBTO and MODS team personnel. In addition, the MODS2 direct imaging astrometric and photometric portions of the science commissioning plan were completed as well. Spectroscopic science commissioning will begin in earnest in the fall of 2014.

4. STRATEGIC INSTRUMENTS

The LBT was designed as an interferometric platform with exceptional sensitivity because the individual telescopes are mounted on a single steerable mount. This design eliminates the need for long delay lines, contains fewer warm optical elements, has a fixed entrance pupil geometry for wide–field Fizeau beam combination, and the high angular resolution direction is always parallel to the horizon and perpendicular to the parallactic angle. The telescope provides a single baseline of 14.4 m for pupil-plane beam combination and a 22.8 m baseline in the Fizeau or image-plane configuration. Two strategic interferometric instruments are under development for the LBT that make use of these modes.

The University of Arizona and the Research Corporation partners are currently commissioning the NASA–funded LBT Interferometer (LBTI) for both nulling interferometry and Fizeau imaging in the 3–14 μm spectral region. The beam combiner provides a combined focal plane from the two LBT primaries and maintains phase coherence and overlap of the two beams. Science goals for LBTI include (1) a sensitive nulling survey of nearby stars in the 8-14 μm band to search for debris disks and zodiacal light (HOSTS: Hunt for Observable Signatures of Terrestrial Planetary Systems), (2) a survey of the same stars covered by HOSTS but at 3.8 μm for the direct imaging detection of extrasolar planets (LEECH: LBTI Exozodi Exoplanet Common Hunt), and (3) a search for resolved structure in nearby protostar accretion disks, mass losing stars, AGN and quasars. In addition to these science goals, concurrent technical efforts are underway to develop nulling interferometry techniques including active phase control and observing strategies, provide a test–bed for nulling interferometry techniques with application to future space missions, and provide a combined-beam focal station for thermal infrared Fizeau interferometry imaging cameras and high contrast coronagraphy. A recent description of LBTI and its status is presented by Hinz et al.,[4] Defrère et al.,[5,20] and Bailey et al.[21]

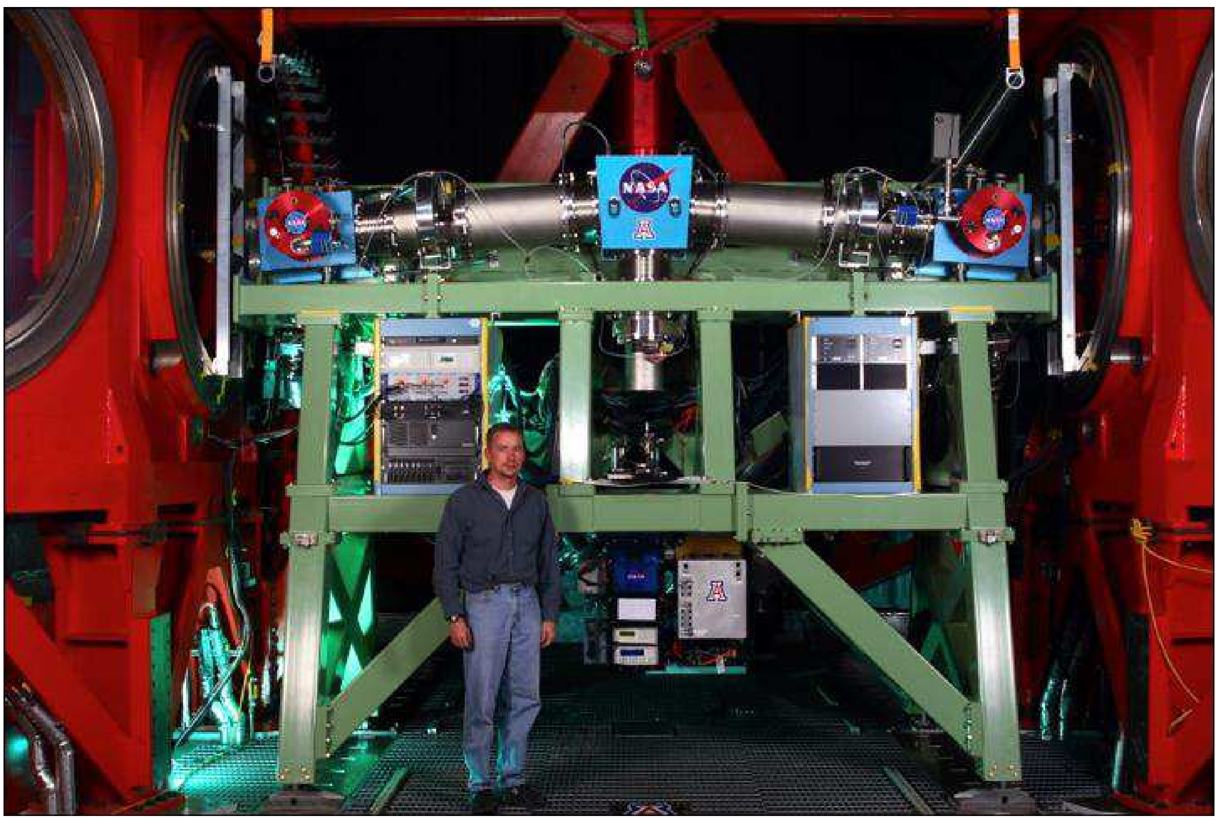

Figure 5. LBTI attached to the bent–center focal station of the LBT. The UBC is visible at the top of the instrument as well as the fast and slow image compensation optical housings visible on each end. The detector is mounted below the instrument. Photo courtesy of Phil Hinz and the LBTI team.

The second strategic interferometric instrument under development for the LBT is a NIR image-plane beam combiner with multi-conjugate adaptive optics (LINC-NIRVANA). The instrument is a project of the LBTB and INAF. LINC-NIRVANA is a Fizeau–mode interferometer like LBTI and combines the light of the two 8.4 m primary mirrors of the LBT in the image plane. LINC-NIRVANA is a general purpose imaging instrument suitable for a wide variety of astrophysical problems requiring high angular resolution imaging in the NIR. Key science problems include supernova cosmology beyond $z \sim 3$, the structure of star-forming regions and circumstellar disks, galaxy formation and resolved extragalactic stellar populations, and the detection of Jupiter-mass extrasolar planets as well as the imaging of planetary surfaces and atmospheres in our solar system. The current status of LINC-NIRVANA is summarized by Herbst et al.[22,23] in these proceedings.

4.1 LBTI

LBTI consists of a cryogenic, all-reflective, beam combiner (UBC: Universal Beam Combiner) located at the center–bent Gregorian focal station of the LBT (Figure 1) and a set of instrument ports that can accommodate three separate cameras (Figure 5). The instrument was designed to conduct surveys of nearby stars for the direct detection of extra–solar planets and debris disks using both high–contrast Fizeau interferometric imaging between 3–14 μm and nulling interferometry in the N–band (8–14 μm). The UBC combines the light from the two individual 8.4 m telescopes into a single focal plane with an F/15 envelope and is designed to provide high throughput, a wide-field of view, and excellent on–axis image quality over the 0.5–20 μm spectral region. The 14.4 m center–to–center baseline produces a fringe pattern that is well matched to the size of the habitable zones and zodiacal disks of nearby stars. The design includes a PZT-mounted mirror for fast tip-tilt and phase compensation adjustments as well as a simple adjustable mirror for slower tip, tilt, and path-length adjustments. A cold pupil spot is incorporated for optimum infrared sensitivity. The calculated optical performance of the UBC shows that the design delivers $\geq$90% Strehl ratio over a 40$''$ diameter field-of-view at a wavelength of 3.8 μm and $\geq$98% Strehl ratio at a wavelength of 11 μm.

The precise overlapping and phasing of the beams takes place in the Nulling Infrared Camera (NIC) designed and optimized for nulling interferometry. NIC is currently the only camera occupying one of the three instrument ports. NIC consists of two different science channels housed in a single cryostat: a long wavelength channel covering the 8–14 μm region (NOMIC: Nulling Optimized Mid–IR Camera) and a short wavelength channel covering the 3–5 μm region (LMIRcam: L & M IR Camera). In addition, the long wavelength channel can be diverted to an auxiliary set of optics for nulling (NIL: Nulling Interferometer for the LBT).

The long wavelength detector for NOMIC is a Raytheon Aquarius 1K $\times$ 1K Blocked Impurity Band (BIB) hybrid array with 30 μm pixels and an image scale of 18 mas/pixel and an unvignetted field-of-view of about 9$''$. λ/D for a monocular aperture is 0.27$''$ at 11 μm and for Fizeau interferometry with the binocular telescope it is 0.10$''$which corresponds to 5.5 pixels on the detector. LMIRCam is a separate project of the Research Corporation partners (Universities of Virginia, Minnesota, and Notre Dame) and the University of Arizona. The short wavelength detector chosen for LMIRcam is a Hawaii-2RG detector with 18 μm pixels at a fine image scale of 10.4 mas/pixel to avoid saturation of the detector for M–band imaging. Currently, only half of the array can be read out with the current electronics resulting in a field-of-view of approximately 10$''$. The baseline filter set for LMIRcam includes L-band, M-band, PAH-on (at 3.3 μm), PAH-off, Brα, and the H_2O ice feature. A grism is available for low resolution (R $\simeq$ 350) spectroscopy. In addition, a vector–vortex coronagraph and non–redundant aperture masks are also available. More information about both cameras and the design of NIC can be found in Hinz et al.[24] and Skrutskie et al.[25]

LBTI was installed on the LBT in September 2010 and on-sky testing began. During this initial testing effort, phasing of the interferometer and first fringes were obtained at 4.8, 10.6, and 12 μm with short exposures of the coherently combined beams. LMIRcam was integrated into the instrument for the first time in May 2011 with the goal of conducting single-aperture adaptive optics. A Strehl ratio of 95% was obtained at 4.8 μm and some science programs were conducted with the camera through the end of 2011. In April 2012, experiments were conducted for the first time to phase LBTI with the dual–aperture telescope in which both adaptive secondary loops were closed and phased images of the overlapping pupils were obtained at 4 and 11 μm.

The first fringe–tracked observations were obtained in December 2013. Fringe tracking is performed in the NIR of NIC using a PICNIC array. The optics can be configured to create different but flexible setups for sensing both tip–tilt and optical path length difference. To this point, fringe sensing has been performed using an image of pupil fringes. The system separates tip–tilt and phase variations by a Fourier transform of the detected light. The magnitude of the transform gives a measurement of the tip–tilt component while the phase of the transform provides a measurement of the optical path delay. To this point, fringe tracking has been performed at 1 kHz. Current work is investigating extending the sampling rate up to 4 kHz.

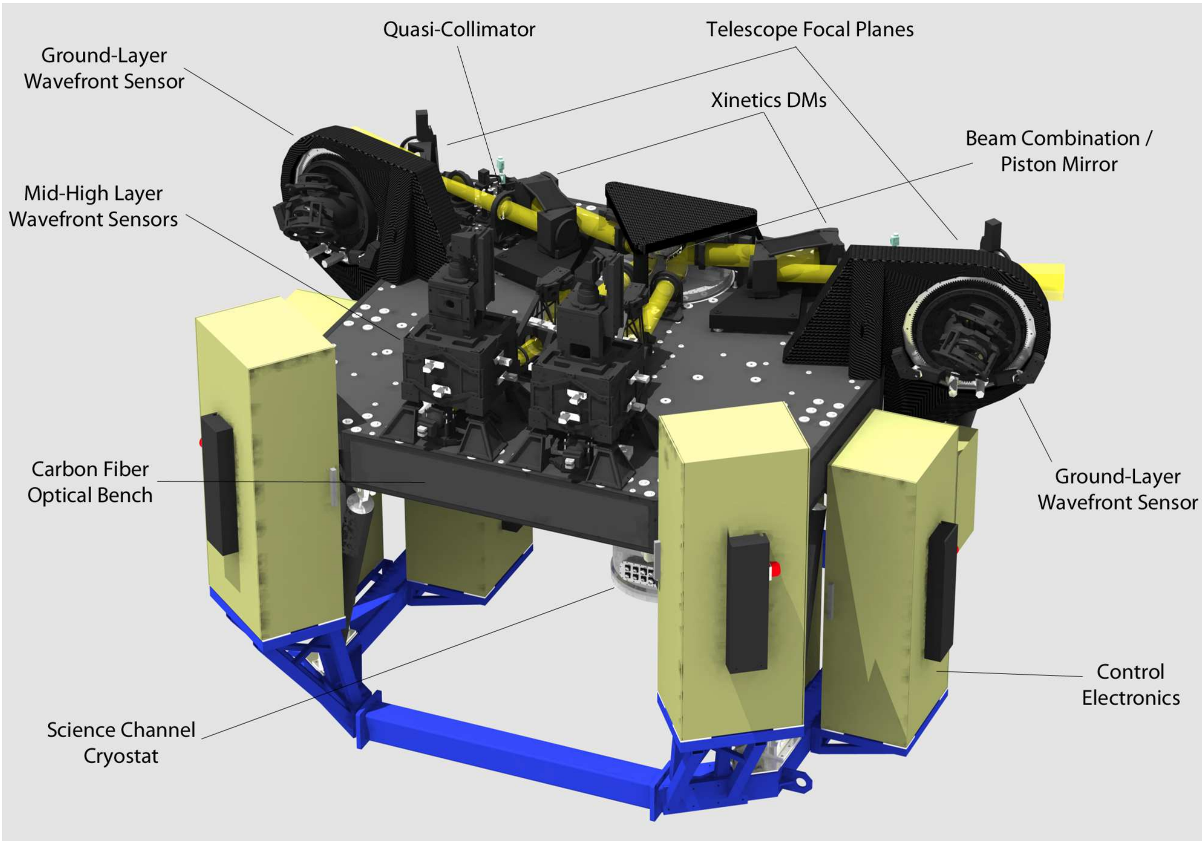

Figure 6. Assembly diagram of LINC-NIRVANA showing the main components and subsystems. Illustration courtesy of Tom Herbst and the LN team.

The first nulling interferometric observations were obtained in September 2012 without fringe and tip–tilt stabilization and in this case the null measurements were fluctuating in and out of destructive interference following the atmospheric phase errors. In December 2013 as described above, the first fringe–tracked nulling interferometric observations were performed with the LBT in the N–band on several bright stars in an effort to test null stabilization rather than optimize null depth. Over a four minute observation, a sustained peak null of 5% was obtained. Currently, the efforts are centered on implementing precise phase tracking and improving the null depth contrast ratio and its stability.

4.2 LINC–NIRVANA

LINC–NIRVANA (hereafter LN) is a 1.0–2.4 μm beam combiner and Fizeau interferometer for the LBT and will be mounted at the back or rear bent focal station (Figure 1). LN will initially use the single, on-axis, adaptive optics system of the LBT to produce interferometric images with the sensitivity of an 12 m telescope but with the spatial resolution of a 23 m telescope (11 mas at J and 20 mas at K) over a science field of view of 10″. LN will require several observations of targets at different projection angles to fill in the (u,v) plane in the same manner as LBTI to produce images free of the LBT PSF and with full 23 m spatial resolution. The performance of LN suggests that reconstructed point sources as faint as $\sim$26 mag with a S/N ratio of 5 can be detected in one hour in the K–band.

LN will be the largest instrument to be deployed at the LBT and consists of an optical bench 6 m wide $\times$ 4.5 m deep by 4.5 m high (Figure 6). Light enters the instrument from the two LBT tertiary mirrors. An annual mirror near each telescope focal plane directs the light from the outer 2-6′ diameter field into the ground-layer wavefront sensor which measures the wavefront using up to 12 natural guide stars and corrects this component using the LBT adaptive secondary mirrors. Light from the central 2′ then enters into the instrument where it is collimated before reaching the mid-line of the instrument. At this point the optical design of LN includes deformable mirrors conjugated to an altitude of 8–15 km and driven by a sophisticated sensor system and wavefront computer. This design will allow simultaneous correction of multiple atmospheric layers resulting in a larger corrected field-of-view. The returned light finally enters the science channel cryostat situated below the optical bench where a Cassegrain telescope images through various filters a 10 × 10 arcsecond field at a scale of 5 mas per pixel onto a Hawaii-2 detector. A dichroic beam splitter separates one band for science and another band for fringe and flexure tracking. The large optical bench support structure is undergoing assembly, integration and testing of the wavefront sensors, optics, and detectors in Heidelberg. A recent picture of the laboratory assembly effort is shown in Figure 7.

In preparation for the full LN installation and commissioning on the LBT, an experiment called LN Pathfinder was installed at the right back bent Gregorian focus in February 2013. Pathfinder consists of a ground-layer wavefront sensor identical in design to the actual LN wavefront sensor, an annular transfer mirror, and an infrared test camera. The design includes a control electronics rack and a mechanical mounting assembly to the telescope. LN Pathfinder verified communication with both the telescope and the AO secondary system, seek to understand wavefront sensor calibration strategies, field acquisition, and the rotating interaction matrix, and studied the impact of flexure and thermal effects. The experiment will help lead to a commissioned focal station in advance of LN arrival as well as gain valuable on–sky experience. LN Pathfinder achieved first light in November 2013 and successfully closed the loop on off–axis rotating reference stars one month later.

The overall LN development effort was re–evaluated in mid–2013, leading to a phased approach to the deployment of the instrument. The first phase, designated Lean MCAO, is dedicated to monocular Multi-Conjugate Adaptive Optics. The MCAO is a 2-layer system, with 12 NGS for GLAO and 8 NGS for high-layer AO. The deformable mirrors have 672 (ground) and 349 (high) actuators, offering a field of view 10.5 (110 square arcsec). The point source sensitivity (5σ in 1 hour) will be in J-band: 25.6, assuming 20% Strehl Ratio, in H-band: 25.0, assuming 40% Strehl Ratio, and in K band 24.7, assuming 60% Strehl Ratio. The first part of the optical components on one side of the LN bench has been successfully aligned in the lab and the optical performances are so far well within specifications. The preliminary acceptance in Europe of Lean MCAO is scheduled for the spring of 2015 and the LN bench should be installed on the telescope before the following winter.

5. PRINCIPAL INVESTIGATOR INSTRUMENT (PEPSI)

One principal investigator instrument is under development and construction for the LBT. The Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI) will provide high and extremely high spectral resolution full-Stokes four-vector spectropolarimetry. The unique design of the spectrograph and large effective aperture of the LBT will combine to allow the simultaneous observation of linear and circularly polarized light with both high spectral and temporal resolution. The key science driver for PEPSI is to better understand the structure and dynamics of stellar magnetic fields. Other problems in solar, stellar, and extragalactic astronomy which can make use of ultra-high spectral resolution are contemplated as well. For integral light spectroscopy, PEPSI on the LBT will be the most sensitive high resolution spectrograph in the world for the foreseeable future with a radial velocity stability of order 1 m/s over an observing season in integrated light. PEPSI is a project of the Astronomical Institute in Potsdam. The design and status of PEPSI was most recently summarized by Strassmeier et al.[26]

The fiber-fed echelle spectrograph is designed to yield spectral resolutions of 40,000 ($2''.2$ aperture), 130,000 ($1''.5$ aperture), and 310,000 ($0''.75$ aperture). The R=40,000 mode allows high resolution spectroscopy at the LBT even in poor seeing conditions. In addition, binning in the dispersion direction can be used for R=20,000 spectroscopy. Given the current instrumental performance estimates, PEPSI is expected to achieve a S/N ratio of about 10 for a $V = 19$ mag star at R=130,000 in $0''.7$ median seeing in a 1 hour integration. Full four-Stokes polarimetry between 450–1050 nm can be obtained at $R = 130,000$ as well. A polarimetric accuracy between 10^{-4} and 10^{-2} is expected to be reached for point sources brighter than about 17th magnitude.

Two focal station pairs for PEPSI will be implemented (see Figure 1 for locations). The PEPSI polarimeters will be installed at the straight-through F/15 Gregorian foci when MODS is dismounted from the telescope. For

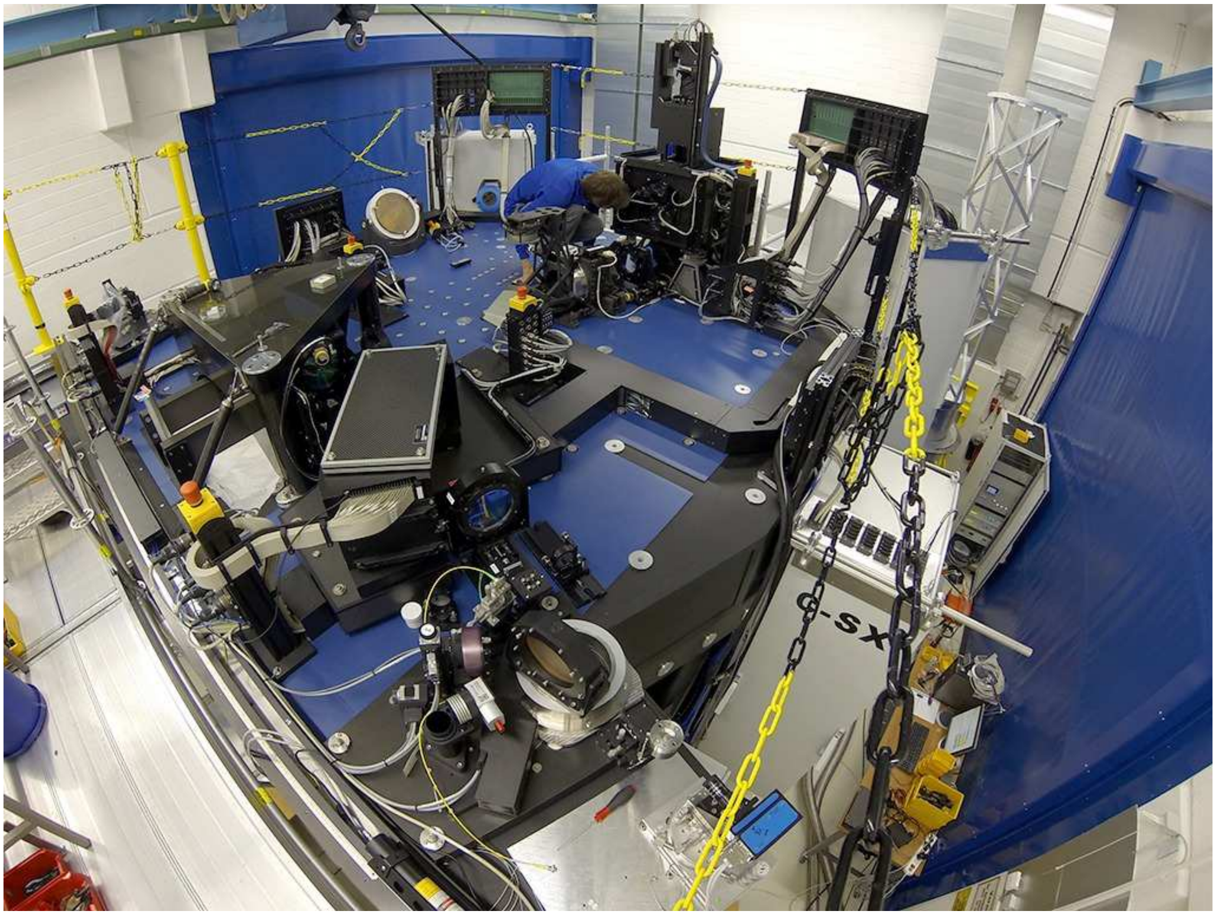

Figure 7. Picture in the integration hall at the MPIA in Heidelberg of the LN optical bench (reversed from left to right compared to Figure 6) showing recent progress in the assembly. Photo courtesy of Tom Herbst and the LN team.

non-polarimetric spectroscopy when MODS is mounted on the telescope, a permanently mounted fiber focus will be implemented to the rear of LINC-NIRVANA and will be accessible by the rotating tertiary mirror. This capability permits high resolution spectroscopy target of opportunity observations. The spectrograph itself is housed in a climate-controlled enclosure in the base of the telescope pier. Light is dispersed by a R4 31.6 grooves per mm Echelle grating mosaic and split into two arms through dichroic beam splitters. The two arms are optimized for the 390–550 nm and 550–1050 nm spectral regions and consist of transfer collimators, VPH grism cross-dispersers, and optimized dioptric cameras. Each science camera will be equipped with back-illuminated and thinned 10.3K $\times$ 10.3K 9 μm pixel CCDs.

Over the past several years, the LBT pier has been renovated in preparation for the arrival and installation of PEPSI. In addition, the fixed permanent PEPSI fiber units that include the guiding and active optics modules and the fiber input interface were installed on the telescope structure (Figure 8) near the LINC–NIRVANA focal stations. Installation of the PEPSI spectrograph in the base of the pier will begin during summer shutdown in July and August of 2014. According to the installation schedule, the first spectrum of the Sun using the auxiliary solar–disk–integrated telescope (SDI) mounted on the LBT enclosure could come as early as the end of August. A considerable amount of daytime testing time will be available using the SDI. In order to accelerate commissioning of the PEPSI spectrograph without using valuable LBT on–sky time, a 373 m long fiber has been run from the 1.8 m Vatican Advanced Technology Telescope (VATT) to the LBT pier to direct the light of bright stars into the spectrograph. Commissioning of PEPSI with the LBT itself will follow shortly thereafter. Delivery of the PEPSI direct Gregorian spectropolarimeter units is currently scheduled for the late summer or

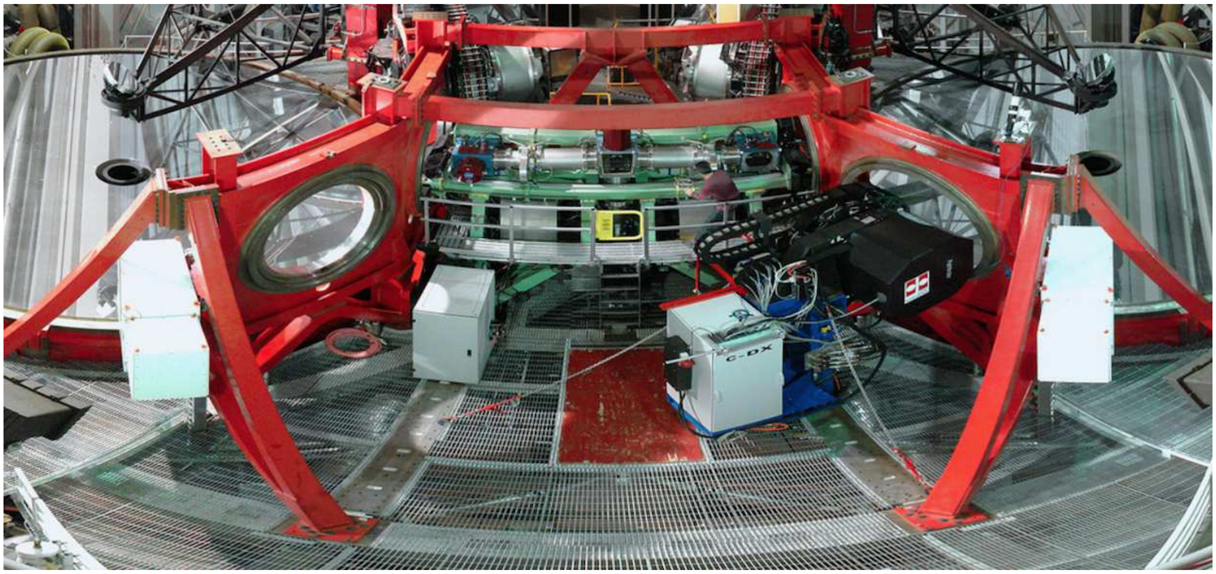

Figure 8. Panorama of the center gallery structure of the LBT showing the permanent PEPSI fiber focal station guiding, active optics, and science fiber focal planes in the white boxes on both the center–left and center–right sides of the gallery. Photo by Ray Bertram.

fall of 2015.

6. INSTRUMENT UPGRADES AND SECOND GENERATION LBT INSTRUMENTATION

With the procurement of the last of the first generation of facility instruments nearing completion and their commissioning underway for deployment in 2015, there has been renewed interest in discussing proposals for second generation instruments for the LBT. With a lead time of at least 10 years between the development of a concept based on a set of science requirements and a commissioned instrument for an 8 m class telescope, detailed planning should indeed begin as soon as possible.

However, the LBTO partnership did not feel comfortable initiating a call for second generation instruments in an observatory where the first generation instruments were not fully operational as yet. Instead, at the end in 2013, the observatory with the support of the LBTC Board and its Science Advisory Committee, solicited proposals aimed at providing to the LBT partnership on a short time scale (in a maximum of three to four years) enhanced or new capabilities on the LBT, with a preference for those making good use of the high spatial resolution performance of the telescope. Eleven proposals were submitted that fell in three categories: improvements in the telescope infrastructure (e.g. AO, laser), upgrades to existing instruments, and new smart and quick instruments. A summary of these proposals as well as the presentations made by the proposing teams at the first LBTO Users Meeting in March 2014 are available on the LBTO web site (www.lbto.org).

Of the eleven proposals that were submitted, five will move forward at various levels and timescales:

LBC–2 (LBC upgrade). LBC–2 aims at maintaining a competitive LBC during the coming decade among the instruments working on 8 m class telescopes through various upgrades leading to better performance. The team will resubmit a new proposal that would also propose a better way to handle active optics collimation and image analysis, which is currently done through dedicated extra–focal imaging using the science detector at frequent intervals, thus decreasing the overall observing efficiency.

SOUL (Single conjugated adaptive Optics Upgrade for LBT). There are currently four Single Conjugated Adaptive Optics (SCAO) systems in routine operation at LBT. They each use an existing Adaptive Secondary Mirror (672 actuators) and a Pyramid Wavefront Sensor (30×30 sub-apertures). SOUL will replace the current wavefront sensor standard CCD with an Electron Multiplied CCD and increase the number of sub-apertures to a 40×40 array. The gain in magnitude for a given Strehl Ratio (SR) offered by SOUL is estimated to be around 1.5–2 magnitudes for all wavelengths and for almost all the range of reference star brightness ($7.5 < m_R < 18$). For example, in terms of the effective correction wavelength, for a reference star with $m_R = 12.5$, a SR of 40% will be achieved at 0.9 instead of 1.2 μm. This will lead to a significant increase in sky coverage, which is one of the limiting factors of natural guide star adaptive optics. The SOUL team is now proceeding with a Phase A proposal and preparing for a Preliminary Design Review for an upgrade of the four current systems (two for the LUCI instruments, two for LBTI, and for the potential new instruments described below).

Upgrading LMIRCam. LMIRCam is described in §4.1 above. This proposal aims at upgrading LMIRCam in three different areas: (1) Replacement of the readout electronics of the HAWAII-2RG array to allow the use of the full array (2048×2048 pixels) to accommodate the full unvignetted field-of-view ($20'' \times 20''$) with an image quality capable of supporting interferometry, (2) Installation of an R∼3000 ruled germanium grism and an R∼50 direct-vision prism to complement the existing R∼300 grism capability, and (3) Development and installation of a 150×150 element pupil-plane lenslet IFU that disperses 20,000 points in a $3'' \times 3''$ field. The development of this upgrade will be phased to accommodate the potential funding schemes currently under consideration.

SHARK (System for coronagraphy with High order Adaptive optics from R to K band). The initial proposed concept is an instrument taking advantage of the existing LBTI AO modules upgraded by the SOUL project described above, which will allow excellent performance in terms of the extreme AO correction. Two channels covering the NIR (0.9–2.5 μm) and a visible one (0.6–0.9 μm), would provide both imaging and coronagraphic modes. Each channel would be installed on one of the two arms of the LBTI structure just after the AO module. LBT lacks a facility instrument that is able to benefit from the amazing performance of its AO systems, something which will be an even greater concern once SOUL has been completed. SHARK could be a solution to this very unfortunate situation. However, the initial proposal will be reformulated and a conceptual design prepared which will present a phased approach aiming at offering sooner rather than later basic capabilities such as NIR imaging while accommodating the extension of the instrument to other interesting modes such as coronagraphy, IFU imaging spectroscopy, and a visible channel.

iLocater (The World's First Diffraction–Limited Doppler Spectrometer). This new instrument is a high-resolution spectrometer that will identify and characterize Earth–like planets orbiting the nearest stars. iLocater is a compact spectrograph that is fed by an optical fiber from the well–corrected ports of LBTI. With input images from the LBT and LBTI that achieve 30× higher spatial resolution than seeing–limited designs (i.e., all radial velocity predecessors), iLocater will simultaneously enable high spectral resolution (R = 110,000), high throughput, and a compact optical design at low cost. The critical element of the instrument is the injection of the AO–corrected beam into the fiber. Tests are planned in the near future to validate the current concept before the instrument development can move forward.

More details on the planning of these developments and their integration in the development plan of the observatory are given in these proceedings by Veillet et al.[2]

7. FURTHER INFORMATION

Further information regarding the LBT and its instruments can be found in the links provided in Table 2.

ACKNOWLEDGMENTS

We wish to thank the LBT instrument team principal investigators, instrument scientists, and personnel including Emanuele Giallongo, Walter Seifert, Roland Gredel, Richard Pogge, Pat Osmer, Phil Hinz, Tom Herbst, and Klaus Strassmeier on behalf of their teams for their continuing efforts to develop, construct, commission, and operate a superb suite of cutting–edge instruments for use at the LBT. In addition, many LBTO personnel and colleagues at one time or another including Richard Green, Joar Brynnel, John Hill, Dave Ashby, John Little, Doug Summers, Robert Reynolds, Kellee Summers, Tom Sargent, John Morris, Elliott Solheid, Jennifer Power, Ray Bertram, and Doug Officer have all played critical roles in the establishment of various interfaces, laboratory testing, mountain reintegration, commissioning, and the early operation and support of LBT instruments. Their efforts are greatly appreciated.

Table 2. Further Information

LBT Observatory	http://www.lbto.org
LBT Science Support	http://abell.as.arizona.edu/∼lbtsci/scihome.html
LBC	http://lbc.oa-roma.inaf.it
MODS	http://www.astronomy.ohio-state.edu/MODS/
LUCI	http://www.mpe.mpg.de/ir/lucifer
LBTI	http://lbti.as.arizona.edu
LINC/NIRVANA	http://www.mpia.de/LINC
PEPSI	http://www.aip.de/pepsi

REFERENCES

[1] Hill, J. M., Ashby, D. S., Brynnel, J. G., Christou, J., Little, J. K., Summers, D. M., Veillet, C., and Wagner, R. M., "The Large Binocular Telescope: binocular all the time," Proc. SPIE 9145, [9145–1], (2014).

[2] Veillet, C., Brynnel, J., Hill, J. M., Wagner, R. M., Ashby, D. S., Christou, J. C., Little, J. K., and Summers, D., "LBTO's long march to full operations: step 1," Proc. SPIE 9149, [9149–42], (2014).

[3] Raab, W., Rabien, S., Gaessler, W., Esposito, S., Barl, L., Borelli, J., Deysenroth, M., Gemperlein, H., Kulas, M., and Ziegleder, J., "The ARGOS laser system: green light for ground layer adaptive optics at the LBT," Proc. SPIE 9148, [9148–131], (2014).

[4] Hinz, P., Bailey, V., Defrère, D., Downey, E. C., Esposito, S., Hill, J. M., Hoffmann, W. F., Montoya, M., McMahon, T., Puglisi, A. T., Skemer, A. J., Skrutskie, M., F., and Vaitheeswaran, V., "Commissioning the LBTI for use as a nulling interferometer and coherent imager," Proc. SPIE 9146, [9146–28], (2014).

[5] Defrère, D., Hinz, P. M., Downey, E. C., Hill, J. M., Mennesson, B., Skemer, A. J., Vaz, A., Ashby, D. S., Bailey, V., Brusa Zappellini, G., Christou, J. C., Danchi, W. C., Grenz, P., Hoffmann, W. F., Leisenring, J. M., McMahon, T., Millan-Gabet, R., Montoya, M., and Vaitheeswaran, V., "Co-phasing the Large Binocular Telescope: status and performance of LBTI/PHASEcam," Proc. SPIE 9146, [9146–9], (2014).

[6] Reynolds, R. O., Morris, J., Power, J., Howard, J., Riedl, J., Solheid, E., Wagner, R. M., and Veillet, C., "Maintaining a suite of binocular facility instruments at the Large Binocular Telescope," Proc. SPIE 9149, [9149–41], (2014).

[7] Speziali, R., Giallongo, E., Ragazzoni, R., di Paola, A., Pedichini, F., Baruffolo, A., de Cantis, C., Diolaiti, E., Farinato, J., Fontana, A., Gallozzi, S., Gasparo, F., Grazia, A., Pasian, F., Smareglia, R., and Testa, V., "The Large Binocular Camera: description and performances of the first binocular imager," Proc. SPIE 7014, 158–169, (2008).

[8] Giallongo, E., Ragazzoni, R., Grazian, A., Baruffolo, A., Beccari, G., de Santis, C., Diolaiti, E., di Paola, A., Farinato, J., Fontana, A., Gallozzi, S., Gasparo, F., Gentile, G., Green, R., Hill, J., Kuhn, O., Pasian, F., Pedichini, F., Radovich, M., Salinari, P., Smareglia, R., Speziali, R., Testa, V., Thompson, D., Vernet, E., and Wagner, R. M., "The Performance of the Blue Prime Focus Large Binocular Camera at the Large Binocular Telescope," Astronomy & Astrophysics, 482, 349-357, (2008).

[9] Summers, K. R., DiPaola, A., Biddick, C., Centrone, M., De La Peña, M., Edwards, M. L., Hill, J. M., Kuhn, O. P., Pedichini, F., and Summers, D. M., "LBT prime focus camera (LBC) control software upgrades," Proc. SPIE 9152, [9152–88], (2014).

[10] Rakich, A., Thompson, D., and Kuhn, O. P., "Range–balancing the Large Binocular Telescope," Proc. SPIE 8128, 6-18, (2011).

[11] Tokovinin, A., and Heathcote, S., "Donut: Measuring Optical Aberrations from a Single Extrafocal Image," PASP 118, 1165-1175, (2006).

[12] Seifert, W., Appenzeller, I., Baumeister, H., Bizenberger, P., Bomans, D., Dettmar R.-J., Grimm, B., Herbst, T., Hofmann, R., Jütte, M., Laun, W., Lehmitz, M., Lemke, R., Lenzen, R., Mandel, H., Polsterer, K., Rohloff, R.-R., Schütze, A., Seltmann, A., Thatte, N., Weiser, P., and Xu, W., "The NIR Spectrograph LUCIFER for the LBT," Proc. SPIE4841, 962-973, (2003).

[13] Seifert, W., Ageorges, N., Lehmitz, M., Buschkamp, P., Knierim, V., Polsterer, K., and Germeroth, A., "Results of LUCIFER1 commissioning," Proc. SPIE7735, 77357W1–9, (2010).

[14] Ageorges, N., Seifert, W., Jütte, M., Knierim, V., Lehmitz M., Buschkamp, P., Polsterer, K., "LUCIFER1 commissioning at the LBT," Proc. SPIE7735, 77351L1–12, (2010).

[15] Buschkamp, P., Seifert, W., Polsterer, K., Heidt, J., Lehmitz, M., Rabien, S., Pramskiy, A., and Ziegleder, J., "LUCI2: binocular and LGS/NGS AO modes of LUCI at the LBT," Proc. SPIE 9147, [9147–58], (2014).

[16] Hofmann, R., Gemperlein, H., Grimm, B., Jütte, M., Mandel, H., Polsterer, K., and Weisz, H., "The cryogenic MOS–unit for LUCIFER," Proc. SPIE5492, 1243–1254, (2004).

[17] Buschkamp, P., Gemperlein, H., Hofmann, R., Polsterer, K., Ageorges, N., Eisenhauer, F., Lederer, R., Honsberg, M., Huag, M., Eibl, J., Seifert, W., and Genzel, R., "The LUCIFER MOS: a full cryogenic mask handling unit for the near–infrared multi–object spectrograph," Proc. SPIE7735, 7735791-12, (2010).

[18] Reynolds, R. O., Derwent, M., Power, J., Morris, J., Solheid, E., Wagner, R. M., Kuhn, O., Thompson, D., Edwards, M., and Pogge, R., "The instrument focal plane mask program at the Large Binocular Telescope," Proc. SPIE 9151, [9151–163], (2014).

[19] Pogge, R. W., Atwood, B., O'Brien, T. P., Byard, P. L., Derwent, M. A., Gonzalez, R., Martini. P., Mason, J. A., Osmer, P. S., Pappalardo, D. P., Zhelem, R., Stoll, R. A., Steinbrecher, D. P., Brewer, D. F., Colarosa, C., and Teiga, E. J., "On-sky performance of the Multi-Object Double Spectrograph for the Large Binocular Telescope," Proc. SPIE 8446, 84460G-1-10, (2012).

[20] Defrère, D., Hinz, P., Skemer, A., Arbo, P., Bailey, V., Brusa, G., Connors, T., Downey, E., Durney, O., Eisner, J., Grenz, P., Hoffmann, W., Hill, J., Leisenring, J., McMahon, T., Mennesson, B., Millan–Gabet, R., Montoya, M., Nash, M., Skrutskie, M., Sosa, R., Vaitheeswaran, V., "Update on the LBTI: a versatile high–contrast and high–resolution infrared imager for a 23-m telescope," Improving the performances of current optical interferometers and future designs, Proceedings of Haute Provence Observatory Colloquium (23–27 September 2013), edited by L. Arnold, M. Le Coroller, and J. Surdej, 37–44, (2014).

[21] Bailey, V., Hinz, P., Vaitheeswaran, V., Skemer, A., Defrère, D., Rodigas, T., Esposito, S., Pinna, E., and Puglisi, A., 'The Large Binocular Telescope Interferometer Adaptive Optics System: On-sky Performance and Results," Exploring the Formation and Evolution of Planetary Systems, IAU Symposium, 299, 26-27, (2014).

[22] Herbst, T. M., Ragazzoni, R., Eckart, A., Weigelt, G. P., "The LINC–NIRVANA high resolution imager: challenges from the lab to first light," Proc. SPIE 9147, [9147–57], (2014).

[23] Herbst, T. M., Ragazzoni, R., Eckart, A., Weigelt, G. P., "The LINC–NIRVANA Fizeau interferometric imager: final lab integration, first light experiments, and challenges," Proc. SPIE 9146, [9146–18], (2014).

[24] Hinz, P. M., Bippert-Plymate, T., Breuninger, A. H.., Connors, T., Duffy, B., Durney, O. F., Esposito, S., Hoffmann, W. F., Kim, J., Kraus, J., McMahon, T. J., Montoya, M., Nash, R., Solheld, E., Tozzi, A., and Vaitheeswaran, V., "Status of the LBT interferometer," Proc. SPIE 7013, 7013281-9, (2008).

[25] Skrutskie, M. F., Jones, T. J., Hinz, P. M., Garnavich, P., Wilson, J. C., Nelson, M. J., Solheid, E., Durney, O., Hoffmann, W. F., Vaitheeswaran, V., McMahon, T. J., Leisenring, J. M., and Wong, A., "The Large Binocular Telescope mid-infrared camera (LMIRcam): final design and status," Proc. SPIE 7735, 77353H1-11, (2010).

[26] Strassmeier, K. G., Ilyin, I., Woche, M. F., Dionies, F., Bauer, S.-Marian, Fechner, T., Weber, M., Hofmann, A., Popow, E., and Bartus, J., "PEPSI: the Potsdam Echelle polarmetric and spectroscopic instrument for the LBT," Proc. SPIE7014, 70140N1-12, (2008).