Current status of the facility instruments at the Large Binocular Telescope Observatory

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ABSTRACT

We present an overview of the current status of facility instruments at the Large Binocular Telescope (LBT). These include Optical and Near-Infrared instruments: the prime-focus optical Large Binocular Cameras (LBCs); the optical Multi-Object Double Spectrograph (MODS); and the LBT Near-IR Spectroscopic Utility with Camera Instruments (LUCIs). Each side of the telescope contains one of the aforementioned instruments. We detail the recent move to “all binocular all the time” science operations, including the use of multi-mode Adaptive Optics with the LUCIs (diffraction limited over a 30′′ × 30′′ field of view or enhanced seeing over a 4′ × 4′ field of view). Binocular science has three configurations: Duplex mode, with identical configurations on both sides, providing an effective collecting area of 11.9 meters; Fraternal Fraternal Twin or Mixed mode (same instruments with different setups or different instruments on each side, respectively), which is effectively two 8.4 meter telescopes; or interferometry with a 22.6 meter baseline.

Keywords: ELT, Observatories, Instrumentation, Binocular, Spectroscopy, Imaging

1. INTRODUCTION

The Large Binocular Telescope (LBT) is part of the Mount Graham International Observatory (MGIO), which includes the 1.8 meter Vatican Advanced Technology Telescope, and the 10-meter Sub-millimeter Telescope. MGIO is located on Emerald Peak on Mount Graham, at an elevation of 3,192 meters. Mount Graham is part of the Pinaleño Mountains located in southeastern Arizona, near the city of Safford. Access to MGIO is restricted annually from approximately November 15th through April 15th due to the combination of unpaved roads and winter weather conditions. Access requires the use of four-wheel drive vehicles during this period. Over the last year the observatory has moved to a model where visiting astronomers (assisted by LBT staff astronomers) operate the scientific instruments on the telescope from a remote observing room at LBT headquarters in Tucson, Arizona. The observatory operates from September 1-July 10 each year. Between July 11-August 31 the observatory closes for monsoon season in southern Arizona. This down-time is used for telescope and instrument maintenance, upgrades, and for one primary mirror to be aluminized and the other washed.

The LBT is an international partnership which includes public universities in Arizona (25% share of time) comprising the University of Arizona, Arizona State University and Northern Arizona University; Germany or LBT Beteiligungsgesellschaft (25% share of time), which includes the German institutes of Landessternwarte Königstuhl, Leibniz Institute for Astrophysics Potsdam (AIP), Max-Planck-Institut für Astronomie, Max-Planck-Institut für Extraterrestrische Physik, and Max-Planck-Institut für Radioastronomie. German federal funding requires that some of this time is available to other public universities within Germany; Italy or Instituto Nazionale di Astrofisica (25% share of time) which is responsible for offering access to the Italian community to LBTO; the Ohio State University (12.5% share of time); and the Research Corporation for Science and Advancement (12.5% share of time) which coordinates the participation of four universities (Ohio State University,

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University of Notre Dame, University of Minnesota, and University of Virginia).

Time on LBT is also available through the National Optical Astronomy Observatory (NOAO) via the Telescope System Instrumentation Program (TSIP). A total of 39 nights are allocated for semesters 2017B through 2019B. Currently, applications for TSIP time may only request use of the three facility instruments in integral increments of 0.5 nights. This does not include access to the Adaptive Optics (AO) modes with the near-infrared imager & spectrograph. TSIP observations are scheduled classically each semester and the observing programs are executed by LBT staff.

In this conference proceeding, we present a summary of the capabilities of the LBT scientific facility instruments that are available for partner science observations. It is an update to the review of Rothberg et al. (2016). In the last two years, LBT has moved to routine nighttime binocular operations for all three facility instruments, as well as the availability of adaptive optics (AO) and enhanced seeing mode (ESM) to improve the image quality of the facility near-infrared instrumentation.

2. THE LARGE BINOCULAR TELESCOPE

2.1 Overview

The Large Binocular Telescope houses two 8.4 meter primary mirrors, separated by 14.4 meters (center-to-center). Due to the fast f/1.14 focal ratio, these mirrors are affixed to a single compact altitude-azimuth mount housed in a co-rotating enclosure, see Hill et al. (2004), Ashby et al. (2006), Hill et al. (2006), and Hill et al. (2010) for more details. The unique design of LBT allows for its use in three configurations: 1) “Twinned” or Duplex mode in which each mirror has identical instrument configurations yielding an effective collecting area of 11.8 meters; 2) Interferometric mode, which uses the baseline from edge to edge of the two primary mirrors to create an effective aperture of 22.6 meters; and 3) “Heterogeneous” mode, in which the 8.4 meter primary mirrors are each configured with different instrument configurations (i.e. optical imaging on one side, near-infrared spectroscopy on the other side) and operate as two independent telescopes with a common mount. In this mode, the two mirrors can move independently of each other up to the “co-pointing limit” (∼ 40″).

The binocular telescope design is combined with four Bent Gregorian focal stations (three with instrument rotator bearings) and one Direct Gregorian focal station for each side of the telescope. In addition, each mirror contains swing arms which holds an instrument at prime focus. All instruments (whether facility or otherwise) are always mounted on the telescope. Switching among the focal stations housing the different instruments is done by moving various swing arms which hold the prime focus optical cameras, or secondary and tertiary mirrors. The transition between prime focus and Gregorian instruments takes ∼ 20 minutes, while transitions between different Gregorian instruments can take ≤ 10 minutes. For brevity, the left-side of the telescope is denoted as SX and the right-side is denoted as DX. Figure 1 shows a layout of the LBT, including locations of all currently installed instruments.

2.2 Co-Pointing & Telescope Movement

With the recent move to “all binocular all the time” for night-time science operations, operating the LBT as a truly binocular telescope requires a different approach to understanding how the telescope can move and the limitations and advantages of having two mirrors capable of independent motion. This is especially important when each side may be required to move independently to acquire or center on targets of interest. The two sides are not required to have precisely the same target or position angle for binocular mode to work. The telescope mount points near the the mid-point between the two sides and the telescope software “knows” to avoid presets or small offsets that would violate the co-pointing limit (Hill et al. 2014). The only restriction is the co-pointing limit which is the maximum physical travel distance allowed between the two mirrors. Currently, the co-pointing limit is ∼ 40″ in diameter. The actual limit on sky varies because it is also affected by the movement and the position of the secondary and tertiary mirrors. Thus, each side can dither as required by the science so long as the two sides together don’t violate the co-pointing limit (see Figure 2).

The telescope control system (TCS) accepts and processes requests from the science instruments to move to a target on sky (called a “preset”). When the telescope is configured for binocular operations, the TCS expects a preset from the SX and DX sides of the telescope. If only one preset is sent, the telescope will not move. Once two presets are received by the TCS, the telescope mount will move. In some cases, LBT may be configured...
for monocular operations (i.e., one instrument in an instrument pair is not available), in which cases the TCS expects a preset from only the authorized side of the telescope. A hybrid configuration also exists called “pseudo-monocular” mode, in which one side of the telescope is authorized to move the mount, but once on target, both mirrors may send commands to move their respective mirrors. The Pointing Control Subsystem (PCS) decides and resolves requests to move the telescope or mirrors as needed. These requests may come from the TCS, or the Guiding Control Subsystems (GCS) for each instrument. There are two types of motions, “synchronous” or “asynchronous.” Synchronous motion assumes that both sides of the telescope move at the same time. In cases where the SX and DX side need to move a distance greater than the co-pointing limit (i.e., a blind offset from a
star to a faint target for spectroscopy or dithering to a blank field for near-IR imaging), the command to move must be synchronous. However, synchronous presets can also be sent for small movements that do not approach the co-pointing limits. Asynchronous movement occurs in cases where the SX and DX sides move independently. For example, dithering on one side of the telescope or acquiring a science target in a spectroscopic slit or mask. Asynchronous presets can be made in cases where one side of the telescope encounters a problem or other failure after arriving at a new sky location. A second asynchronous preset can be sent on the side with problem so as not to interfere with observations already occurring on the other side of the telescope. Asynchronous movements are executed one at a time by the TCS as long as they do not violate the co-pointing limits. For more details regarding the philosophy and execution of binocular movements with LBT see De La Peña et al. (2010).

2.3 Types of Instrumentation

There are three categories of LBT scientific instrumentation. The first are facility instruments, which are available for use by anyone within the partnerships (including TSIP). Facility instruments are supported and maintained by LBTO personnel. Although during commissioning phases, facility instruments are still supported by the instrument teams along with LBTO staff. The second type is Principal Investigator instruments. These are maintained and operated by the instrument builders, however, they may be used by LBT partners (although currently not TSIP) for science on a collaborative basis through time exchanges at the discretion of the PI. LBT staff provide technical assistance primarily limited to interfacing with the telescope control systems and infrastructure. Currently, the only PI instrument is the Potsdam Echelle and Polarimetric Spectroscopic Instrument (PEPSI), which uses both primary mirrors. Each mirror feeds light to a focal station which contain a permanent fiber unit (PFU) that feeds non-polarized on-axis and off-axis light via a fiber-train to the spectrograph mounted below the pier of the telescope (see Figure 1). PEPSI also includes non-permanent polarimeters that can be mounted to the direct Gregorian focus to measure Stokes IQUV parameters (two per polarimeter). PEPSI has been used on sky since 2015B and the polarimeters saw first light on September 11, 2017. For more information, see Strassmeier et al. (2008). The third type of LBT instrumentation is Strategic instruments. These are defined as technically challenging, designed to push the limits of astronomical instrumentation, and have a major impact on astronomy. Strategic instruments may be available to the LBT community on a collaborative basis or through time exchanges with the PI. Currently, the only fully operational strategic instrument is the LBT Interferometer (LBTI), which uses both primary mirrors and comprises LMIRCam (3-5 μm) and the NOMIC (8-13 μm) camera. They are currently operational for on sky scientific observations, see Himz et al. (2008), Wilson et al. (2008), Skrutskie et al. 2010, Leisenring et al. (2012), and Hoffmann et al. (2014) for more information. The LBT Interferometric Camera and the NearIR/Visible Adaptive iNterferometer for Astronomy (LINC-NIRVANA) is a multi-conjugate adaptive optics (MCAO) near-IR imaging system that provides both ground-layer and high-layer corrections (Gasserl et al. (2004), for more information. The LBT Interferometric Camera and the NearIR/Visible Adaptive iNterferometer for Astronomy (LINC-NIRVANA) is a multi-conjugate adaptive optics (MCAO) near-IR imaging system that provides both ground-layer and high-layer corrections (Gasserl et al. (2004), and Herbst et al. (2014)). It was installed on to the telescope on September 20, 2016. It is currently in the early-stages of commissioning and closed the loops with both ground and high layer corrections on sky during 2017A. Further discussion of PI and Strategic instruments are beyond the scope of this paper.

3. FACILITY INSTRUMENTS

3.1 Large Binocular Cameras (LBCs)

3.1.1 Instrument Layout

The LBCs are comprised of two wide-field f/1.14 imagers, one optimized for blue wavelengths (0.33-0.67 μm) using fused silica in the lenses which permits better transmittance of light at λ < 0.5 μm, the other optimized for red wavelengths (0.55-1.11 μm) using borosilicate glass (BK7) lenses which are optimized for light at λ > 0.5 μm. Each LBC operates at the prime focus location of their respective mirrors (LBC-Blue at SX and LBC-Red at DX). They are each mounted on a spider swing-arm that can be deployed above the primary mirror and moved into and out of the telescope beam as required. The LBCs were accepted as facility instruments in October 2011. The two instruments were a contribution by INAF to the first generation of LBT instruments. Specific details regarding construction, commissioning, and upgrades can be found in Ragazzoni et al. (2006), Speziali et al. (2008), and Giallongo et al. (2008). The LBCs were the first instruments to make full use of binocular observing at LBT. When used in a binocular
configuration the LBCs dither simultaneously using the mount, rather than each mirror moving independently. The advantages are quicker movement on sky and no need to worry about violating the co-pointing limits. The disadvantage is that with slightly different readout times and filter motions between the two cameras, as well as variations in the exposure times needed between blue and red filters, one side of the telescope can potentially sit idle while the other continues to collect photons before the mount offsets to a new position on sky.

The LBCs each contain six E2V CCD detectors, four of which are used for science. The four science CCDs are E2V 420-90s with \(2048 \times 4608\) (13.5 \(\mu\)m square pixels) are arranged in a mosaic with three abutted next to each other. A fourth CCD is rotated clockwise 90 degrees and centered along the top of the three science CCDs. Each CCD covers \(7.8 \times 17.6\) with a gap of 70 pixels \((18''\) between each CCD. This yields a \(23' \times 25'\) field of view (FOV). In order to obtain an uninterrupted image, dithering is required to fill the gaps between CCDs (and recommended to correct for cosmic rays and bad pixel columns). The un-binned readout time for the full array of science CCDs is 27 seconds. The other two CCDs are used for guiding and tracking collimation and wavefront control (Technical Chip 1, and Technical Chip 2, respectively). They are E2V 420-90 custom made \(512 \times 2048\) (13.5 \(\mu\)m square) pixel CCDs that do not have a shutter mechanism. They are placed on either of the science CCD chips. One is within the focal plane and is used for guiding adjustments, the other is out of the focal plane and uses extra-focal pupil images to maintain collimation and focus. Exposures are taken every 8-32 seconds with the the Tech Chips (depending on the brightness of the stars that fall onto the array). Figure 3 shows the layout of LBC-Blue (similar to LBC-Red) corrected field size), and an example of a \(g\)-sloan image.

The combination of fast focal ratios and prime focus requires a set of refractor corrector lenses to deal with geometric distortions over a large field of i affect the large field of view (FOV). Each LBC uses a similar set of five corrective lens (a 6th lens is the cryostat window with almost no net power). This is based on the Wynne approach of positive-negative-positive lenses (Wynne 1972\(^{19}\)), but with the second and third elements each split

Figure 3: Top Left - the chip layout of LBC Blue (the four science chips and the two technical chips used for collimation and guiding); Bottom Right - a distortion map of LBC-Blue; Right - 3600 sec \(g\)-sloan image of the galaxy IC 342 (observed by B. Rothberg on UT September 04, 2017 and processed by O. Kuhn to remove the distortions and re-sampled to a constant scale of \(0''.224\) pixel\(^{-1}\)).
into two lenses. A filter wheel sits between the 5th and 6th corrective lens (the first lens is defined as closest to the primary mirror). The corrected fields have a diameter of 110 mm and 108.2 mm for LBC-Blue and LBC-Red, respectively, which is an angular field of $\sim 27^\circ$ in diameter (the science detectors cover $\sim 75\%$).

Each of the LBCs houses two filter wheels, and each wheel houses 5 slots. This allows for up to 8 filters to be used on sky for each instrument (one slot in each wheel must always be empty to allow light to pass through). The two LBCs use different filters of different widths. LBC-Blue filters are 159.8 mm in diameter (155 mm opening), and LBC-Red filters are 189.6 mm in diameter (185 mm opening). Currently, LBC-Blue contains only six filters, these are listed in Figure 4 along with their transmission curve. There are currently ten filters available for LBC-Red, although only eight can be used on sky at any given time. The two extra filters are TiO 784 and CN 817 which were purchased and tested in semester 2014B by Landessternwarte Königstuhl (LBTB-Germany) and have been available for use by all partners since 2015A. These filters can be swapped in as needed, but PIs must carefully choose which filters they replace.

![LBCB filters’ transmission](image1)

![LBCR filters’ transmission](image2)

<table>
<thead>
<tr>
<th>LBC Blue Filter</th>
<th>50% Cut-On (μm)</th>
<th>50% Cut-Off (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-Spec</td>
<td>0.330</td>
<td>0.390</td>
</tr>
<tr>
<td>U-Bessel</td>
<td>0.333</td>
<td>0.382</td>
</tr>
<tr>
<td>B-Bessel</td>
<td>0.375</td>
<td>0.469</td>
</tr>
<tr>
<td>Sloan g</td>
<td>0.397</td>
<td>0.550</td>
</tr>
<tr>
<td>Sloan r</td>
<td>0.522</td>
<td>0.666</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LBC Red Filter</th>
<th>50% Cut-On (μm)</th>
<th>50% Cut-Off (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-Bessel</td>
<td>0.493</td>
<td>0.577</td>
</tr>
<tr>
<td>Sloan r</td>
<td>0.555</td>
<td>0.686</td>
</tr>
<tr>
<td>Sloan g</td>
<td>0.572</td>
<td>0.690</td>
</tr>
<tr>
<td>Sloan i</td>
<td>0.597</td>
<td>0.836</td>
</tr>
<tr>
<td>i-Bessel</td>
<td>0.713</td>
<td>0.881</td>
</tr>
</tbody>
</table>

Figure 4: Left - A plot of the transmission curves for the LBC-Blue filters. Right - A plot of the transmission curves for the LBC-Red filters. Below each plot is a table of filters for each LBC. 1Broad width (top-hat) filter response designed to mimic the spectroscopic coverage in this wavelength range. The filter has a bandpass that depends on angle of incidence, with a 10-15 angstrom blueshift from normal to 26° angle of incidence. Filter transmission scans obtained in the summer of 2016 by the NOAO spectrometer show some non-uniformity across the filter. 2The z-sloan filter has no red cutoff and is limited only by the detector quantum efficiency ($\sim 0$ at 1.1μm). 3Medium width filters

### 3.1.2 Collimation

The ability to collimate the LBCs is a critical step to achieving and maintaining good image quality for science observations. The LBCs are particularly sensitive to temperature differences between the ambient temperature in the enclosure and the mirror glass which leads to large aberrations, particularly at the start of the night. Until recently, collimation was achieved only using Focal Plane Image Analysis (FPIA) which measures and analyzes highly de-focused images of stars (pupils). Hill et al. (2008) provides more details. Using a geometrical method described by Wilson (1999) aberration coefficients are derived by measuring the internal and external borders of pupils, and in some cases, their illumination profiles. Empirically determined scaling relations based on these are then used to apply the Zernike corrections (Z4, Z5, Z6, Z6, Z8, Z11, and Z22) needed to remove the aberrations. A small region of Chip 2 just below the rotator center on each LBC is read out in order to speed up the process. The process is repeated until the corrections converge. However, this requires that those
preparing the observations select a field with a sufficient number of bright stars. The method uses as many of
the de-focused stars as possible to measure pupils. If there are too few stars and/or they are faint, then the
algorithm has trouble properly measuring the pupils and determining the appropriate corrections.

Figure 5: Shown here are the WRS panels associated with the WRS process, starting with the Chip 2 collimation
readout (displayed in a DS9 window), the selection of the best pupil, and the comparison between the real and
model pupil.

A new system was tested in September 2016 to overcome a number of deficiencies in the current algorithm.
The Wavefront Reconstruction Software (WRS), developed by INAF, selects the brightest pupils in a field to
measure (Stangalini et al. 2014,22 Stangalini et al. 201523). The pupil must meet a minimum threshold for
signal-to-noise (S/N). This avoids noisy estimates of Zernikes. WRS analyzes the moments of the intensity dis-
tribution of the pupils and from that reconstructs a model of the pupil. The process iterates until the residual
differences between the real and modeled pupils are minimized (Tokovinin and Heathcote 200624). The Zernike
coefficients needed are then computed and applied. The biggest gains with WRS are when significant coma is
present at the start of the night (Z7 and/or Z8) and/or significant temperature gradients which can lead to
spherical aberations (Z11 or Z22). In these cases FPIA has difficulty finding the inner hole of the pupil, and
in extreme cases under- or over-estimates the pupil diameter. Figure 5 shows an example of the WRS process,
starting with the Chip 2 collimation readout, the selection of the best pupil, and the comparison between real
and model pupils. From this, the Zernike coefficients needed to collimate the LBCs are computed.

Since WRS can take significantly longer than FPIA to converge, a new IDL routine DOHYBRID was developed
by John Hill to improve efficiency by first running WRS to deal with coma and spherical aberrations, then
continuing to collimate with FPIA. DOHYBRID should be run at the start of the night, or when the LBCs are first
used during the night. After this, FPIA is run as before (every 30 minute). This requires observers to move
from their science target to a nearby field with a sufficient number of bright stars to land on the section of Chip
2 used for collimation. Once FPIA converges, the observers return to the science field. In addition, Tech Chip
2 can be used for active collimation while science exposures are taken but only if there are bright stars on the
chip. Corrections are computed and applied in between each science exposure.

Two new ways to improve collimation and reduce associated overheads are underway. The first is to apply
WRS to the de-focused stellar images collected from Tech Chip 2. This would permit robust collimation cor-
rections to be applied without moving from the science field. However, Tech Chip 2 is vignetted, which would
produce non-circular pupils that are difficult to model. The largest problem is that WRS (and the current scheme) relies on there being bright stars on Tech Chip 2. Science programs must be planned carefully to make sure that the best position angles and dithers are used to put sufficiently bright stars onto the Tech Chip. In cases where observations are made with filters at $\lambda < 0.4\mu m$ and/or at high or low galactic latitudes, there may be insufficient stars available within the science field. The second method employs telescope metrology (ultra-high accuracy measurements of the mirrors) using a multi-channel absolute distance measuring fiber-interferometer system which can measure the motions and vibrations of objects with accuracies to a few tenths of a micron. The system was installed on the LBT primary mirrors and LBCs during summer 2017. It is able to measure the semi-absolute (not the actual optical surfaces) distance between the primary mirror and prime focus corrector to a level of $1\mu m$ r.m.s.. This includes multi-line measurement errors, primary mirror positioning errors and dome seeing. The goal is to account for all motions between the LBCs and primary mirrors and be able to collimate without interrupting science observations and moving the telescope. The tests are part of a collaboration between the Giant Magellan Telescope Organization and LBT (see Rakich et al. 2018 - 10700-59 this conference).

3.1.3 Example of the Power of the LBCs
In September 2017, the Origins Spectral Interpretation Resource Identification Security - Regolith Explorer spacecraft (OSIRIS-REx) returned to Earth as part of a gravity assist (or slingshot) to put it on course for its sample-return mission to the near-Earth asteroid Bennu (1999 RQ36). The date of closest approach was September 22, 2017. However, before ground-based telescopes had even begun to prepare to capture images of OSIRIS-REx on closest approach, the LBT focused both of its LBC cameras to directly image the spacecraft nearly three weeks before closest approach. Figure 6 is a time-series of three $V$-Bessel exposures showing the movement of OSIRIS-REx.

Figure 6: Left - Time series LBC images obtained with the $V$-Bessel filter on UT Sep 02, 2017. Each exposure is 300 seconds. OSIRIS-REx is shown highlighted by the red boxes. Images were obtained by B. Rothberg, O. Kuhn, J. Hill, A. Conrad, and S. Allanson. The astrometry and processing were done by C. Veillet.

3.2 Multi-Object Double Spectrograph (MODS)

3.2.1 Instrument Layout
The Multi-Object Double Spectrographs (MODS) are a pair of identical instruments, each capable of imaging, or spectroscopy using longslit and user-designed multi-object slit (MOS) masks. Each MODS is mounted at the direct Gregorian $f/15$ port (MODS-1 on SX and MODS-2 on DX, see Figure 1). The MODS were designed and built by The Ohio State University as part of its contribution to the first generation of LBT instruments. Specific details can be found in Pogge et al. (2006), (2010) and first light results are presented in Pogge et al. (2012). MODS-1 was installed in 2009 and became available for partner science in 2011B. MODS-2 was installed in 2014A and commissioned from 2014B-2015B. Both MODS have been used for on sky science since semester 2015B and have been used together regularly in binocular mode since 2016.
The MODS employ reflective optics to achieve high-throughput from 0.32 μm-1.05 μm. The MODS house separate blue- and red-optimized channels that use custom-built E2V CCD231-68 back-side illuminated CCDs with 3072 × 8192 pixels (15 μm square). The blue channel is standard silicon with E2V Astro-Broadband coating and the red channel is 40 μm thick deep depletion silicon with extended-red coating (E2V Astro-ER1). This provides increased performance long-wards of 0.8 μm, with significantly reduced fringing relative to other optical spectrographs and imagers. The CCD can be read out in different sizes depending on the observing mode.

MODS has two observing modes: direct imaging; and spectroscopy using curved focal plane masks. The optical layout of MODS incorporates a dichroic beam splitter below the focal plane that splits light into separate, but optimized blue and red only channels. There is a cross-over at 0.565 μm that results in a drop in flux in a small region (∼0.005 μm centered on this wavelength). For some science cases, users may choose to employ blue- or red-only observations. The dichroic is replaced with no optic in the beam for blue-only mode and replaced with a flat mirror for red-only mode (imaging and spectroscopy). Direct imaging is achieved by replacing the grating with a plane mirror and is used for target acquisition for spectroscopy. The standard acquisition is to read out a smaller 1K×1K region of the CCD to reduce overheads during the acquisition (readout ∼ 40 sec). Direct imaging can also be used for science programs. MODS includes a full complement of sloan filters: u, and g for the Blue channel; and r, i, and z for the Red channel. The usable FOV is 6′ × 6′ but with degraded image quality at radii > 4.5′. In the case of direct imaging for science, the CCDS are read out in 3K×3K mode.

MODS has two spectroscopic modes: a medium resolution diffraction grating optimized for blue and red spectral regions with \( R \sim 2300 \) and 1850 (assuming a 0′.6 wide slit), respectively. The resolution scales with slitwidths; and a double-pass 8′ glass prism with back reflective coating that produces a low-dispersion spectroscopic mode with \( R \sim 420-140 \) in the blue, and \( R \sim 500-200 \) in the red. The grating dispersion uses the full 8K×3K CCD, while the prism mode uses a 4k×3K readout mode. Longslit and multi-object slit masks are made available through a mask cassette system with 24 positions. Each mask is matched to the shape of the Gregorian focal plane. The first 12 positions in the cassette contain permanent facility and testing masks. The facility science masks include: 0′.3, 0′.6, 0′.8, 1′.0, 1′.2, and 2′.4 × longslit segmented masks (each contains five 1′ long slits each separated by 3′ segmentation braces); and a 5′ wide × 60′ longslit single segment mask used primarily for spectro-photometric calibrations. The remaining 12 mask slots are available for custom designed MOS masks (discussed later).

The acquisition, auto-guiding and wavefront-sensing systems (AGW) are a part of MODS and located above the instrument focal plane, but within the unit itself. The patrol field of the AGW is 5′×5′ and overlaps with the bottom half of the MODS science field. The guideprobe can potentially shadow the science field or science mask if a guidestar is not chosen carefully. MODS uses an infrared laser (\( \lambda = 1.55 \mu m \)) closed-loop image compensation system (IMCS) to provide flexure compensation due to gravity, mechanical, and temperature effects. The IMCS can null motion to within an average of ±0.6 pixels for every 15″ for elevations of 90° -30°. More information about the IMCS can be found in Marshall et al. (2006).28 MODS also houses the calibration system internally. It consists of continuum (fixed intensity Quartz-Halogen and variable intensity incandescent) used for calibration imaging and spectroscopic flats; and emission-line lamps (arc lamps) used for wavelength calibration of grating and prism spectroscopy.

### 3.2.2 MODS-1 & MODS-2 Binocular Operations

Binocular observations with MODS-1 & MODS-2 have become routine for nighttime operations since mid-fall of 2016. Currently, MODS-Binocular observations can be run in either duplex mode, where the observing script is “twinned” and the same instrument configuration is used with both MODS (i.e. same imaging filters, same longslit mask and grating, or same MOS mask), or “fraternal twin” mode, where each MODS uses a different MOS mask, or a combination of imaging on one side and spectroscopy on the other. The only constraint is that each MODS must use the same position angle (PA) and same pointing center. This is to avoid violating the co-pointing limit during observations. Future improvements should allow for different PAs and pointing centers to be used.

The filters, gratings, facility longslits, and overall efficiency of MODS-1 & MODS-2 were designed to be virtually identical. Observations with the same instrument configuration used for both MODS is effectively a single MODS observation obtained with an 11.9 meter diameter mirror. To date, the only known variation between the two MODS are the intensity of the internal lamps used for calibrations (flats and arcs). Figure 7
shows an example of observations made with the same instrument configuration for MODS-1 & MODS-2. The data from each MODS have been fully “reduced” (bias-subtracted, flat-fielded, rectified, wavelength calibrated, and collapsed into a one-dimensional spectrum), flux calibrated (using a spectro-photometric star of known brightness to remove the instrumental signature and determine the flux measured for the science target), and corrected for both extinction from the Earth’s atmosphere and along the line of sight through the Milky Way Galaxy, and finally, corrected for the Earth’s motion around the Sun and the redshift of the galaxy. The final data from each MODS are plotted in the top panel of Figure 7 (Red is MODS-1, Blue is MODS-2) and include errors (lighter colors). The object observed is an Ultraluminous Infrared Galaxy (ULIRG) that is suspected of being a late-stage merger between two gas-rich spiral galaxies. ULIRGs emit 10^{12} L_⊙ integrated over 8-100 μm and contain anywhere from 10^{9}-10^{10} M_⊙ of molecular gas, which provides fuel for forming new stars and growing super-massive central black holes (SMBH) that power Active Galactic Nuclei (AGN). The most powerful AGNs are quasars (QSOs) and reside in massive elliptical galaxies. In the local Universe, ULIRGs are known as the progenitors of QSO host galaxies (e.g. Sanders et al. 1988, Rothberg et al. 2013). This ULIRG shows evidence of strong emission lines indicative of a powerful QSO residing in the core of the galaxy (i.e. high-excitation lines). The final spectra from each MODS match each other within the errors. As an additional quantitative check, the flux, velocity broadening, and equivalent width of [OII] (λ = 0.5006 μm) was measured in each spectrum and are shown in the two panels at the bottom of Figure 7.

### 3.3 LBT NIR Spectroscopic Utility with Camera Instruments (LUCI)

#### 3.3.1 Instrument Configuration

The two LBT Utility Camera in the Infrared instruments (LUCI, formerly LUCIFER), are a pair of cryogenic near-Infrared (NIR) instruments, with imaging and spectroscopic (longslit and MOS) capabilities. LUCI-1 is mounted at one of the f/15 Bent Gregorian focus on the SX side and LUCI-2 is similarly mounted on the DX side (see Figure 1). The LUCIs can operate at wavelengths from 0.89 μm (LUCI-1) or 0.95 μm (LUCI-2) through 2.4 μm in one of three modes: seeing limited (SL), Enhanced Seeing Mode (ESM), or diffraction limited AO. Unlike MODS, the guiding and wave-front sensing in seeing limited modes (and initial collimation in ESM and AO modes) are done using external AGW units. The LUCI calibration units also differ from MODS in that they are external to the instruments, residing on mounts located above the LUCIs that swing in front of the entrance windows when needed. Additional information regarding design, construction, and on-sky commissioning can be found in Seifert et al. (2003), Ageorges et al. (2010), and Buschkamp et al. (2012).

The LUCIs are cooled using closed cycle coolers which are monitored to maintain the correct temperatures needed for optimal operation. LUCI-1 was installed at LBT in September 2008 and LUCI-2 as installed at LBT in July 2013. A series of repairs in 2011 and upgrades in 2015 were undertaken to match the capabilities of the two LUCIs with each other. Both are now equipped with 2K × 2K Hawaii 2RG detectors and have the same set of cameras: an f/1.8 (N1.8) camera which delivers a 0″.25 pixel\(^{-1}\) plate scale; an f/3.75 (N3.85) camera with a 0″.12 pixel\(^{-1}\) plate scale; and an f/30 (N30) camera with a 0″.015 pixel\(^{-1}\) plate scale. The N1.8 camera is primarily used for seeing-limited spectroscopy; the N3.75 camera is used for seeing-limited imaging and delivers ~ 4″ × 4″ FOV. The N3.75 camera can also be used for spectroscopy with 2× better resolution and half the wavelength coverage achieved with the N1.8 camera. The N30 camera is used for AO imaging with both LUCIs, delivering a 30″ × 30″ FOV. The N30 camera in LUCI-2 can also be used for diffraction limited spectroscopy due to the presence of a diffraction limited grating (which is not installed in LUCI-1). Both LUCIs also house the same complement of broad and narrow-band filters (see Table 1).

However, there are differences between the available spectroscopic gratings for the two LUCIs. Tables 1 & 2 provide an overview of the capabilities available for both LUCIs. Unlike MODS, the grating tilt is not changeable by the user, the LUCIs offer a wide range of configuration possibilities that can be achieved with various tilts (i.e. central wavelengths or λ_c), gratings, slits, and cameras. Using the N1.8 camera, low resolution grating (G200) permits nearly complete coverage of the near-IR window with only two settings. The high resolution grating (G210) with the N1.8 camera allows for nearly full wavelength coverage of each filter (i.e. z, J, H, and K-band). Users also have the flexibility to combine cameras, gratings, slits, and λ_c in different ways to achieve a wide range of scientific goals (i.e. higher spectral resolutions over shorter wavelength ranges).

Unlike MODS, flexure compensation is currently achieved in a passive mode. A lookup-table of motor values, based on empirical data taken at different elevations and rotations, are used to apply corrections before an
Figure 7: Top - Spectra of $z \sim 0.69$ ULIRG obtained simultaneously with MODS-1 & MODS-2 using a 0''6 wide slit (R $\sim 2000$) with the dual grating. The total integration time for each MODS was 3600 seconds. MODS-1 data are plotted in red, MODS-2 data are plotted in blue. Prominent emission lines are identified in the rest-frame spectra. The bottom two panels show the rest-frame [OII] emission line from each spectra. Fits were made separately to each spectrum to determine the (rest-frame corrected) integrated flux of the line, velocity broadening of the line, and the equivalent width of the line. The measured results from each MODS are consistent with each other. These data are part of a program by B. Rothberg to study the kinematic, star-formation, and AGN properties of $0.4 < z < 1$ ULIRGs.

exposure is taken. The corrections are applied to the last fold mirror in the optical train (FM4), which lies in front of the instrument’s internal pupil. An active flexure compensation (AFC) system has been developed for use with both diffraction- and seeing-limited observations. These corrections are applied during a science exposure (see Pramskiy et al. 2018 - 10702-106 this conference). Successful on-sky tests have been conducted over the last year for both variants of AFC. Updates to software and observing script preparation scripts are currently being undertaken by LBTO staff.

3.3.2 LUCI-1 & LUCI-2 Binocular Observations

Since 2017A LUCI-1 and LUCI-2 have been available for binocular observations. As noted in Rothberg et al. (2016),1 the LUCI software has been completely revised to incorporate binocular capabilities. Currently, the LUCIs can be configured in “twinned mode” (same pointing center, position angle, and configuration on both sides) or “fraternal twin” mode (same pointing center and position angle, but with a mixture of instrument configurations, including imaging and spectroscopy). Near-IR observations require frequent dithering to remove
Table 1. LUCI-1 & LUCI-2 Filters Available for Science

<table>
<thead>
<tr>
<th>Filter</th>
<th>( \lambda_C ) (( \mu m ))</th>
<th>FWHM (( \mu m ))</th>
<th>Filter</th>
<th>( \lambda_c ) (( \mu m ))</th>
<th>FWHM (( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( z )</td>
<td>0.957/0.965</td>
<td>0.195/0.196</td>
<td>He I</td>
<td>1.088</td>
<td>0.015</td>
</tr>
<tr>
<td>( J )</td>
<td>1.247/1.250</td>
<td>0.305/0.301</td>
<td>Paschen-( \gamma )</td>
<td>1.097/1.096</td>
<td>0.010</td>
</tr>
<tr>
<td>( H )</td>
<td>1.653/1.651</td>
<td>0.301/0.291</td>
<td>OH 1190</td>
<td>1.194</td>
<td>0.010</td>
</tr>
<tr>
<td>( K_s )</td>
<td>2.163/2.161</td>
<td>0.270</td>
<td>( J ) low</td>
<td>1.199</td>
<td>0.112</td>
</tr>
<tr>
<td>( K )</td>
<td>2.194/2.199</td>
<td>0.408</td>
<td>Paschen-( \beta )</td>
<td>1.283/1.284</td>
<td>0.012</td>
</tr>
<tr>
<td>( zJ ) spec</td>
<td>1.175</td>
<td>0.405</td>
<td>( J ) high</td>
<td>1.303</td>
<td>0.108</td>
</tr>
<tr>
<td>( HK ) spec</td>
<td>1.950/1.953</td>
<td>0.981/0.998</td>
<td>FeII</td>
<td>1.646/1.645</td>
<td>0.018</td>
</tr>
<tr>
<td>( Y1 )</td>
<td>1.007</td>
<td>0.069</td>
<td>( H_2 )</td>
<td>2.124/2.127</td>
<td>0.023</td>
</tr>
<tr>
<td>OH 1060</td>
<td>1.065</td>
<td>0.010</td>
<td>Brackett-( \gamma )</td>
<td>2.170/2.171</td>
<td>0.024</td>
</tr>
<tr>
<td>( Y2 )</td>
<td>1.074</td>
<td>0.065</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Note, in cases where two values are listed in an entry, the first corresponds to LUCI-1 the second to LUCI-2.

Table 2. Overview of Installed LUCI-1 & LUCI-2 Gratings

<table>
<thead>
<tr>
<th>Grating</th>
<th>Band</th>
<th>( \lambda)-Range (( \mu m ))</th>
<th>Spectral Width (( \mu m ))</th>
<th>Resolution (0&quot;.5 slit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G210</td>
<td>( z )</td>
<td>0.85-1.02(^a)</td>
<td>0.124</td>
<td>5400</td>
</tr>
<tr>
<td>G210</td>
<td>( J )</td>
<td>1.15-1.35</td>
<td>0.150</td>
<td>5800</td>
</tr>
<tr>
<td>G210</td>
<td>( H )</td>
<td>1.50-1.75</td>
<td>0.202</td>
<td>5900</td>
</tr>
<tr>
<td>G210</td>
<td>( K )</td>
<td>2.06-2.40</td>
<td>0.328</td>
<td>5000</td>
</tr>
<tr>
<td>G200</td>
<td>( zJ )</td>
<td>0.90-1.25(^a)</td>
<td>0.220</td>
<td>2100-2400</td>
</tr>
<tr>
<td>G200</td>
<td>( HK )</td>
<td>1.40-2.40</td>
<td>0.440</td>
<td>1900-2600</td>
</tr>
<tr>
<td>G150(^b)</td>
<td>( K_s )</td>
<td>1.95-2.40</td>
<td>0.533</td>
<td>4150</td>
</tr>
<tr>
<td>G040(^b)</td>
<td>( z, J, H, ) or ( K )</td>
<td>same as G210</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

\(^a\)Note that the dichroic at the entrance window to each LUCI affects the \( z \)-band transmission. The dichroic on LUCI-1 cuts off at \( \lambda = 0.85 \) \( \mu m \) and cuts off at \( \lambda = 0.95 \) \( \mu m \) on LUCI-2; \(^b\)Available on LUCI-1 only; \(^c\)This is diffraction limited grating available on LUCI-2 only, however it is currently not available for on-sky use. Resolution scales down as slitwidth increases. If using the N3.75 camera multiply \( \Delta \lambda \) by 0.48, and if using the N30 camera multiple by 0.06.

Sky emission from the data. This can take the form of small dithers within the same field or large dithers to a blank sky for science fields containing large, resolved objects (i.e. galaxies) or crowded fields (i.e stellar or galaxy clusters). The mirror co-pointing limits can have a significant impact on planning and optimizing near-IR observations, especially in fraternal twin mode. Although for longslit and MOS acquisitions each mirror is moved asynchronously, the software currently uses a synchronous mount offset for binocular observations like dithering.

### 3.4 Multi-Object Spectroscopic (MOS) Masks

A unique capability among the spectroscopic facility instruments (MODS and LUCI) is the capacity to use multi-object spectroscopic masks designed by users. These masks allow the placement of multiple slits, including straight, angled, and curved, in the focal plane. Now that the LBT facility instruments operate in full binocular mode, the MOS capabilities include the ability to duplex observations (same MOS mask for each side) or to allow two different masks to be used for the same science field (with the caveats noted earlier). MODS and LUCI MOS masks are designed using similar software. For MODS, it is called MMS (MODS Mask Simulator).
Currently, a user’s manual and quick-help can be found at [www.astronomy.ohio-state.edu/~martini/mms/](http://www.astronomy.ohio-state.edu/~martini/mms/). The LUCI version is called LMS (LUCI Mask Simulator) and manuals and additional information can be found at [https://sites.google.com/a/lbto.org/luci/preparing-to-observe/mask-preparation](https://sites.google.com/a/lbto.org/luci/preparing-to-observe/mask-preparation). MMS and LMS use the European Southern Observatory SkyCat tool to visualize the focal plane projected on the sky. The software allows users to load any fits image file with a valid world coordinate system (WCS) or access archival images from the Digital Sky Survey or 2MASS (2 Micron All Sky Survey) and place slits of user-defined length and width within the field of view of MODS or LUCI. Figure 8 shown an example image loaded into the LMS software. The galaxy is the Antennae (NGC 4038/4039), an early-stage merger was observed with Hubble Space Telescope (HST) using the Advanced Camera for Surveys (ACS) with the F550M filter (Whitmore et al. 2010). Each of the objects for which a slit is overlaid represents a young stellar cluster detected with HST at multiple wavelengths. This demonstrates the ability to fit a large number of slits within the focal plane. The image on the right in Figure 9 show the mask design. It is a Gerber (gbr) file which is sent for fabrication with a laser cutting machine located at the University Research Instrumentation Center (URIC) at the University of Arizona. For more information about fabrication and materials see Reynolds et al. 2014. There is a single deadline each semester for the submission of MODS and LUCI masks to LBTO. The masks are then reviewed by the LBTO Mask Scientist to ensure there are sufficient alignment boxes, no overlapping slits, a suitably bright guide-star, etc. As of March 2018 the LMS software has been transferred to LBTO for maintenance and future upgrades. The software will soon be updated to allow LUCI MOS masks to make use of AFC to improve the stability of the spectra taken over long integration times.

Figure 8: Left - The main GUI for the LUCI LMS software (similar to the MODS MMS GUI). The GUI shows a WCS corrected image from HST of the Antennae with the slits overlaid. Note the square $2'' \times 2''$ reference boxes used for alignment Right - a gbr file showing the location of slits and alignment boxes. This file contains the information (location of boxes and slits) used to manufacture the mask at URIC.

Shown in Figure 9 (left) is the MODS MOS mask cassette system. It is located within the MODS housing and accessed through a panel on the side of the instrument. The system houses 12 permanent facility masks, including longslits ranging in width from $0''.3$ to $5''$, as well as specialized masks used for maintenance and checks on the instrument. The cassette system allows up to 12 additional user designed MOS masks to be loaded at any given time. The system grabs a mask (housed within a frame) and inserts it into the focal plane as requested (almost like a music jukebox). During acquisitions, the masks can be removed from the focal plane to take a direct image without having to re-house the mask into its slot. MODS MOS mask exchanges take place the first day of a partner science block. If needed, MODS MOS masks can be exchanged with new masks during the night.
LUCI-1 and LUCI-2 each use a cryogenic MOS unit to house a set of 10 permanent facility longslit masks and up to 23 user designed MOS slit masks (Hofmann et al. 2004\textsuperscript{36} and Buschkamp et al. 2010\textsuperscript{37}). The 10 facility masks include longslit masks ranging in width from 0′.13 (AO-only) to 2′ as well as an N30 fieldstop mask (to block stray light) for AO observations, a blind mask (for taking dark frame exposures) and optic and spectral sieve masks. This main unit houses the focal plane unit (FPU) which places the masks in and out of the LUCI focal plane using a robotic grabber arm (see right image Figure 9). The grabber slides along set of rails to select the requested mask, place it in the FPU, and later place the mask back in its designated slot once it is no longer needed (and another mask is requested). When imaging mode is used, an empty mask holder is placed in the FPU to allow light to pass unobstructed to the detector. Mask exchanges are performed at cryogenic temperatures and require the use of two auxiliary cryostats in order to maintain pressure and temperatures at all times. An auxiliary cryostat holding a secondary cabinet is loaded with the next set of masks to be used for science. It is evacuated and cooled over 24-48 hours before a scheduled exchange. During the exchange, one aux cryostat is attached to LUCI using a set of gate valves controlled by software. Rails connect the aux cryostat to LUCI. The current installed secondary cabinet is moved along the rails into the cryostat. That cryostat is removed and a second cryostat is then attached and a secondary cabinet containing the new masks is placed into LUCI. LUCI MOS masks cannot be extracted and then reinserted back into the MOS unit during the same exchange. The cabinet exchange is all done on the telescope infrastructure itself. This requires the cryostats to be lifted up through large doors in the high bay up and over the telescope and then gently placed on a platform on the telescope (located between the SX and DX mirrors where the bent Gregorian foci are located). Three to four LUCI MOS mask exchanges are scheduled each semester. The number of slots in the auxiliary cabinet is divided up among the partners based on the ratio of the number of science nights each partner has relative to the total number of nights within a block of time serviced by an exchange. Currently MOS mask exchanges for both LUCIs can take up to a week to complete due to the time needed to cool down and warm up the cryostats (i.e. the laws of physics). The addition of a third aux-cryostat would allow mask exchanges to proceed significantly faster.

MODS and LUCI masks are kept in inventory on the mountain. MOS masks can be reused over the course
of multiple semesters. With the move to all-binocular-all-the-time the standard procedure is to fabricate two copies of MODS MOS masks and up to four copies of LUCI MOS masks (in case the same masks are required for back-to-back mask exchanges). PIs are also free to use different MOS masks (some PAs and pointing center) for the same science field.

3.5 Adaptive Optics Observations with LUCI

As noted earlier, the LUCIs can be used in SL mode or enhanced by either the adaptive secondary mirrors or a laser system. Three methods of enhancement are possible. The first is ARGOS (Advanced Rayleigh guides Ground layer Adaptive Optics System) a set of 6 green (λ = 0.532 μm) lasers (3 per side) used to correct for ground layer atmospheric turbulence. ARGOS is designed to be used with the N3.75 camera for either imaging or spectroscopic observations. The system does not provide diffraction limited observations, but can improve the overall image quality to ∼ 0.3-0.3 (based upon on-sky observations to date). More details regarding ARGOS can be found in Rabien et al. 2010, Rabien et al. 2014, and Rahmer et al. 2014.

The next two methods rely on natural guide-stars used with the adaptive secondary mirrors (or AdSecs). The AdSecs have a deformable shell controlled by actuators, which in turn respond to a pyramid wave-front sensor that uses the brightness and observed point-spread function (PSF) of a natural guide-star to determine the appropriate corrections to compensate for atmospheric turbulence. Ideally, the AdSecs can apply up to 400 modes of corrections and can correct for non-common path aberrations (NCPA) using on-axis bright natural guide-stars. The patrol field for the FLAO system is 2’ × 3’ and encompasses the LUCI N30 FOV. This allows each LUCI to reach the diffraction limit with the N30 camera at wavelengths from H-band and redward. Fewer modes of corrections can be applied with guide-stars that are either fainter and/or further off-axis. For more detailed information on construction, commissioning, and operations see Esposito et al. (2010, 2012), Christou et al. (2016), Miller et al. (2016), and Christou et al. (2018 - 10703-10 this conference). LUCI-AO imaging has been available on a shared-risk basis in some capacity at LBT since 2017. In the last year the LBT Observing Tool for generating scripts has been updated to allow users to generate binocular (or binocular) LUCI-AO scripts. LUCI-AO observations have been carried out by some members of the LBT partnership and work continues to better characterize the system. In the summer of 2018, the FLAO system will be upgraded to the next generation Single conjugated adaptive Optics Upgrade for LBT (SOUL). This upgrade will allow for improved corrections and for AO reference stars 1.5-2 magnitudes fainter to be used, thus opening up more of the sky for diffraction limited or AO-enhanced observations (see Pinna et al. 2016 for more information).

One downside to diffraction limited and AO-enhanced observations is the limitation of 30’’ × 30’’ FOV imposed by the N30 camera. Since 2015, the FLAO system has also included an improved (but seldom used) seeing capability using the larger N3.75 camera. This mode is called “Enhanced Seeing Mode” (ESM) and uses 12 modes of corrections (including tip and tilt) to improve the angular resolution over the full 4’ × 4’ field of view of the N3.75 camera. ESM is designed to improve imaging and spectroscopy (longslit and MOS). During 2018A LBTO staff have worked to better understand the capabilities of ESM. In this paper we present some of the preliminary work characterizing ESM in various conditions.

As part of the more detailed characterization of ESM, observations of the periphery of M92 were obtained under a variety of conditions, including seeing from 0’’ 5-0’’ 0 and with AO reference stars of varying brightness (R = 13.4 and 15.1). Observations were obtained with both LUCI-1 and LUCI-2 with the K-band filter only. ESM was turned on for one set of data, then the observations were repeated under SL conditions (ESM off). Subsequent observations were obtained of several interacting and merging galaxies of varying size to test the ability of ESM to deal with resolved objects. These observations were obtained with K-band, H-band, J-band, and a narrow Brγ filter. The preliminary results for M92 are presented here for LUCI-1 for two epochs with very different seeing conditions. The data were reduced using IRAF. The reduction process includes linearization corrections, bad pixel masking, flat-fielding, and the mosaicing of dithered images into a single image using the IRAF tasks geomap and geotran which correct for shifts, rotation, and any distortions from optics. The IRAF task DAOFTIND was then used to identify stars in the crowded field for each final mosaic image. Non-astronomical objects and stars near the edges of the FOV were removed using an automated TDL routine. The IRAF task radprof was then used to measure a Gaussian full-width at half maximum (FWHM) for every star. For each star the distance to the AO reference star was calculated. Figure 10 shows a plot of the FWHM in angular units of arcseconds plotted against the radial distance from the AO reference star for the two epochs (top row). A
least-squares fit was made to the ESM data plotted in both figures. The red diamonds represent the SL data and the black circles represent the ESM data. Plotted below each panel is the average seeing measured by AGW-1 during the time of the observations (obtained from telemetry). This shows the highly variable and poor seeing conditions on UT 2018-05-05 versus the relatively stable and good seeing on UT 2018-05-16. The preliminary results shown in Figure 10 suggest that ESM can provide a significant improvement in image quality (∼3 ×), particularly in poor conditions (top left panel). This may be of significant benefit to partner science during bouts of poor weather. In the best seeing conditions (top right panel) ESM shows not only a factor of two improvement in image quality, but that the improvement is relatively uniform, with small scatter, up to 150′′ away from the AO reference star. Analysis of this data is ongoing and full results will be presented in an upcoming paper.

Figure 10: Top Left - a comparison of the ESM versus SL data obtained in relatively poor conditions. Top Right - similar to the previous panel, but using data obtained under excellent seeing conditions. Noted in both panels is the range of seeing (zenith corrected) measured by the Differential Image Motion Monitor (DIMM) during the observations. Plotted in the bottom left and right panels is the average seeing measured by the AGW during the observations.

4. MIXED-MODE USE

The goal of LBT is to use the telescope in binocular mode all of the time. While the facility instruments have been designed to work in pairs in binocular mode, the telescope can also be figured to use instruments in a “mixed mode.” These modes could include configurations such as MODS/LBC, LUCI/LBC, and LUCI/MODS. Mixed-Mode use opens up a much wider wavelength range for scientific study (i.e. UV through near-IR simultaneously). As noted earlier, the two sides of the telescope are not required to point at the same exact spot on the sky, and can operate as two independent telescopes as long as they do not violate the co-pointing limits. However, a current limitation of using Mixed-Mode is the ability to pass a binocular preset from two different instruments to the TCS. Since 2014, several combinations of Mixed-Mode have been used on-sky. These primarily have been an LBC with either a LUCI or a MODS. In the case of LUCI/LBC, the telescope can be authorized in binocular
mode. The TCS waits to receive a preset sent from each instrument before moving to the field. Once there, LUCI imaging starts immediately or LUCI spectroscopic acquisitions can begin. The LBC can either stare or begin a dither sequence. The only requirement for the dithering sequence is that the first dither in the sequence be no moves in X and Y. In the case of MODS/LBC, the telescope is set up in a hybrid configuration called “pseudo-monocular.” MODS “drives” the mount, i.e., the preset is sent only by MODS while LBC is “along for the ride.” LBC does not send a preset to the TCS (a value of -90° in the Declination coordinate is used for the LBC script). Once on target, the MODS imaging starts immediately or the spectroscopic acquisitions begin. Just as with LUCI/LBC, the LBC can dither, so long as the first sequence of the dither is no movement in X or Y (0,0). Since Rothberg et al. 2016, we conducted on-sky testing of LUCI/MODS in January 2017. Tests were conducted in full binocular mode and pseudo-monocular mode. Although not successful on-sky, the testing did result in updates to how the LUCI software interacts with the TCS and the non-LUCI side. The net result was a fix which should allow LUCI/MODS to work on-sky in full binocular mode and has been shown to work with a telescope simulator. To date, however, this fix has not been tested on-sky.

5. SUMMARY

Although all of the facility instruments were installed on the telescope by 2014, LBT has not been capable of regular nightly binocular observations with all three facility instruments until recently. With the updates to scripting software, and updates to both the TCS and instrument software, routine binocular observations with pairs of instruments in twinned or fraternal mode are now more commonplace. Work continues to improve mixed mode capabilities, with LUCI/MODS remaining the final configuration to be successfully executed on-sky. However, work remains to make binocular operations more robust. By far, the most important component is a binocular planning tool that can efficiently organize observations so as to take into account co-pointing limits and maximize shutter time for each mirror. Another, is the ability to switch from binocular to monocular observations on the fly in case of instrument or telescope issues. Such capabilities are not yet robust across all three facility instruments. Future binocular possibilities may include mixed mode operations between facility and PI or strategic instruments, particularly in cases of target of opportunity observations.

Since 2016 the use of LUCI+AO has moved from the commissioning phase to a shared-risk availability for our partners (currently this does not include TSIP). LUCI-AO imaging has been conducted in binocular mode, and ARGOS has moved on from a commissioning phase to availability for science observations each semester on a shared-risk basis. LUCI-AO spectroscopy still remains to be fully commissioned and is not available for science operations. The main issue holding back this mode is the current instability in the G040 grating on LUCI-2. The ESM mode for both LUCIs is currently an option for science observations which require a large FOV or for spectroscopy. A full characterization of ESM still remains to be completed, including spectroscopy. The results presented here show ESM has a promising future, not just for the best conditions, but to improve the image quality delivered to each LUCI in mediocre or even poor conditions where AO and ARGOS cannot operate.

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