The Multi-Object Double Spectrographs for the Large Binocular Telescope

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ABSTRACT

Ohio State is building two identical Multi-Object Double Spectrographs (MODS), one for each of the f/15 Gregorian foci of the Large Binocular Telescope (LBT). Each MODS is a high-throughput optical low- to medium-resolution CCD spectrometer operating in the 320-1000nm range with a 6.5-arcminute field-of-view. A dichroic distributes the science beam into separately-optimized red and blue channels that provide for direct imaging and up to 3 spectroscopic modes per channel. The identical MODS instruments may be operated together with digital data combination as a single instrument giving the LBT an effective aperture of 11.8-meter, or separately configured to flexibly use the twin 8.4-meter apertures. This paper describes progress on the integration and testing of MODS1, and plans for the deployment of MODS2 by the end of 2008 at the LBT.

Keywords: Spectrometers, Large Telescope Instruments, Multi-Object Spectroscopy, Ground-based Astronomy

1. INTRODUCTION

Optical spectrometers are the work-horse instruments of the current generation of 8-10 meter class telescopes. The unique 2-primary design of the twin 8.4-meter Large Binocular Telescope (LBT; see Hill & Salinari 2000) presents particular challenges for the design of such an instrument. Direct beam combination is precluded by the complexity and size of the optics required for the non-interferometric operation given the LBT's configuration; throughput penalties in the complex optical train would obviate the advantages of the combined system's effective 11.8-meter diameter collecting area. The very low readout noise possible with modern CCD detectors suggests that for applications that are largely background or Poisson-noise limited, digital data combination after the fact is a more practical way to achieve the large effective area of the LBT. Cost savings in building two identical instruments for the twin foci of the LBT make this option doubly attractive. While the truly unique property of the LBT is its 27%-filled-aperture interferometric capability, it is notable that the main first-light facility instruments of LBT (Wagner, these proceedings, paper 6269-07) are all dual instruments: the two Large Binocular Cameras (LBC; Ragazzoni et al. 2004), one red and one blue optimized, deployed at the prime foci of LBT; the identical twin LUCIFER Near-Infrared Imager/Spectrometers to be deployed at the interior f/15 bent-Gregorian foci (see Mandel et al., these proceedings, paper 6269-126); and the Multi-Object Double Spectrographs (MODS) to be deployed at the straight-through f/15 Gregorian foci behind each of the LBT's primary mirrors.

As part of its in-kind contribution to the first-light facility instrument suite of the LBT, the Ohio State University began in March 1998 with a concept for a multi-object spectrometer that would operate in the visible band covered by CCD detectors (roughly 320-1100nm wavelength). This concept has evolved from a set of performance and science goals (Osmer et al. 2000) and a high-throughput optomechanical design (Byard & O'Brien 2000) into the twin Multi-Object Double Spectrographs currently under construction. Each MODS spectrograph is an identical copy of the other: a low- to medium-dispersion spectrometer with a 6.5-arcminute field of view and a dichroic beam splitter to direct light into separately-optimized red and blue channels. Each channel has a suite of tuned optics, gratings, filters, and detectors that allows simultaneous operation across the entire CCD-accessible spectrum. An active closed-loop Image Motion Compensation System (IMCS) nulls out both gravity-induced and stochastic flexure in the structure to deliver extremely stable imaging and spectroscopic performance required for long, deep integrations and highly repeatable configuration for high-precision spectrophotometry (see Marshall et al 2006, these proceedings paper 6269-57).

This paper describes the progress to date on the MODS project, focusing on recent integration and testing activities as we prepare the first MODS spectrograph for deployment at the LBT in late 2007. The second MODS spectrograph will proceed in parallel, deployed in late 2008 to complete the full instrument complement. Detailed information, as well as the latest progress reports about MODS can be found on the project website (www.astronomy.ohio-state.edu/MODS)

2. MODS STRUCTURE

The main structure of each MODS is a steel space-frame consisting of a welded upper structure that mounts the main optics and focal-plane mechanisms, connected to the collimator mirror tailpiece via 8 steel tubes. The structures were built by Indian Creek Fabricators of Tipp City, Ohio, along with a large handling and storage cart. The first MODS structure was delivered to OSU in February 2005, with the second delivered in January 2006. A photograph of the MODS1 structure in the OSU high-bay shop space is shown in Figure 1.

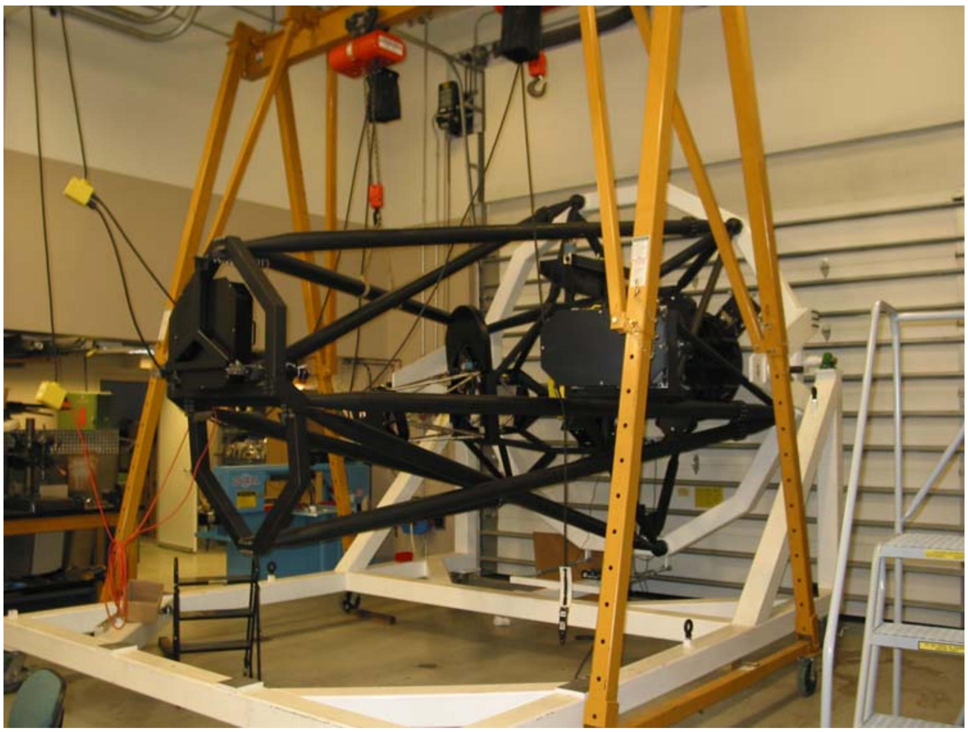

Figure 1: MODS1 structure on its handling cart in the OSU Astronomy shop during preliminary fitting and alignment of the optomechanical subsystems. The collimator tailpiece is in the foreground with the blue collimator mirror cell shown above (the red collimator space is empty). The blue camera structure is visible in the foreground, and the red camera structure in the background.

The overall MODS structure is approximately 4.5 meters long, and 2.4-meters in diameter at the widest point near where it mounts to the f/15 Gregorian instrument rotator of the LBT. When fully equipped and enclosed in its light-tight shrouding, each MODS will have a rotationally-balanced moving mass of approximately 2700kg.

The MODS1 structure is in our main shop in McPherson Laboratory on the OSU campus where we are carrying out the main assembly, integration, and testing of the instrument. The MODS2 structure is housed in a high-bay space we lease on West Campus, where we can perform basic work more or less in parallel with MODS1. When MODS1 is shipped to Mt. Graham, MODS2 will move into our main shop for final integration, testing, and preparation for shipping. Having both facilities allows us to reduce the time between deployment of MODS1 and MODS2, as well as making appropriate parallel changes to MODS2 as we learn with MODS1 what minor rework is required.

3. MODS OPTICAL SYSTEMS

All of the MODS small optics and most of the large optics of MODS are now in hand. We are only awaiting delivery of the Red and Blue Camera Corrector lenses from the Steward Observatory Mirror Lab (SOML) and the two dichroics to complete the optics. As described by Byard & O'Brien (2000), light first passes through a field lens behind the slit plane, then through a dichroic beam splitter that divides the light into red and blue channels with a "notch" wavelength of 550nm (this is the nominal design specification, the exact notch will be measured from the delivered optics). Each "arm" of MODS has a single reflective collimator mirror, and a 4-position turret with gratings, prisms, or imaging flats in the pupil plane that feed into off-axis Maksutov-Schmidt re-imaging cameras with integrated shutters and filter wheels. A field-flattening lens immediately in front of the CCD detector also serves as the CCD dewar window.

3.1 Collimator Mirrors

The 4 MODS collimator mirrors are identically figured HEXTEX blanks polished into the required parabolic shape by Sagem/REOSC. All collimators were delivered on time and exceed our specifications. These are installed in a 3-actuator tip/tilt/focus mechanism at the tail of the spectrometer. The blue collimators will be coated with aluminum, and the red collimators with overcoated silver, both optimized for their respective wavelength regions.

3.2 Camera Optics

The MODS cameras consist of an off-axis spherical primary mirror, an off-axis aspheric corrector lens, and a field-flattener lens. The camera primaries are 4 identically figured HEXTEX blanks figured by the SOML. We have 3 of the 4 camera primary mirrors as of March 2006. The aspheric off-axis corrector lenses are the most challenging optics in MODS and are still being figured at SOML. A key milestone for 2006 will be the completion of the corrector lenses.

3.3 Gratings

The baseline configuration of MODS will have medium-dispersion red and blue diffraction gratings (R=2000) manufactured by Newport Spectra-Physics (formerly Richardson Grating Laboratory). We are fortunate that we can use stock large rulings from their catalog. The red gratings are 250 grooves/mm blazed at 673nm (Catalog nr. 53999ZD01-271) delivering a nominal resolution of R=1730 (4 pixels) with a 0.6-arcsec slit in first order. The blue gratings are 400 grooves/mm blazed at 400nm (Catalog nr. 53999ZD01-584) with a nominal resolution of R=1640 (4 pixels) with a 0.6-arcsec slit in first-order. All have been delivered along with measured blaze curves.

3.4 Double-Pass Prisms

MODS will use double-pass 8-degree glass prisms with back reflective coatings to provide a low-dispersion, high-efficiency spectroscopic mode. The blue prism is made of fused silica and coated with aluminum on the back, delivering a resolving power that varies smoothly from R=400-100 (4 pixels) from 300-550nm wavelength. The red prism is made of Ohara TIH6 and coated with silver on the back, delivering resolving powers of R=600-100 (4 pixels) from 500-1000nm. The resolution curves are shown in Figure 2.

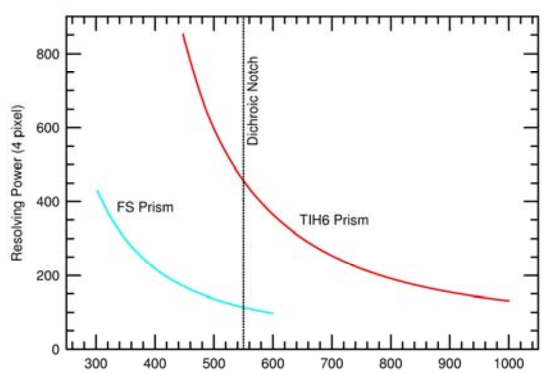

Figure 2 – Resolution curves for the MODS double-pass prisms.

3.5 Small Optics

The four field flatteners are all in hand: the blue lenses were fabricated from fused silica by JML Optical Industries, and the red lenses were fabricated from Schott NZK7 by SOML. All optics are on specification, and have been given MgF_2 anti-reflection coatings. We also have the fused silica field lenses from JML, and numerous smaller pieces, including laser beam splitters, folding flats, the calibration system re-imaging lenses, acquisition/guide pickoff prisms, and guide and wavefront sensor camera reimaging optics. The only remaining small optics are the dichroic beam splitters which we expect to receive later in 2006 once the coating specification is finalized with the thin-film vendor. Quotes have been received for the anti-reflection coatings for lenses and reflective coatings for mirrors, and will proceed during 2006.

4. MECHANICAL SYSTEMS

Design and manufacture of most of the MODS mechanical parts is complete, and over the last few months we have found our shelves quickly filling with a large number of small bits of precision-machined metal, all anodized a stylish matte black. Most of the main subsystems of MODS have been assembled at least once and given an initial fitting on the MODS1 structure (Figure 3). The main tasks ahead are the full integration of these systems with motors and sensors, bench testing of each component with the computer control systems, and then installation and wiring into their final configuration.

The largest MODS components, the cameras and grating turrets, have heavy-duty custom-built handling carts with special articulated fixtures that permit easy service and testing off the instrument, and mounting systems that recapitulate the mounting surfaces on the instrument proper. Smaller components are mounted on light-weight carts with no special fixtures. These allow us to easily transport them between lab and shop areas, and to store them out of the way when not in use (while designed to mount compactly on MODS, off-instrument they consume a substantial amount of floor space).

4.1 Focal Plane Systems

The MODS focal plane is a crowded space occupying the core of the upper space-frame and home to the instrument dark slide, calibration system, Acquisition, Guiding, and Wavefront (AGW) camera stage, and the slit mask storage and insert/retract mechanism. Each constitutes a major subsystem. Both dark slides have been assembled, tested, anodized, and hung on the wall out of the way. The MODS1 calibration system has been mounted on the instrument and is being fitted with its integrating sphere at this writing. A similar fitting with MODS2 will proceed once we figure out the first one. The MODS1 slit mask system has been installed on the MODS1 frame where it is currently holding the laser alignment system, while the MODS2 slit mask system is assembled on a cart for testing the motor control system, shown in Figure 4. Tests with this system show we can remove a slit mask from the science field, stow it in the 24-position cassette, and deploy a second mask into the science field in approximately 20 seconds. The AGW camera stage mounts to this structure, and is being re-assembled after some minor rework. The AGW stage is a 4-axis system (X, Y, Focus, and Filter) and will be the next multi-axis system integrated in the lab with the prototype motion-control system.

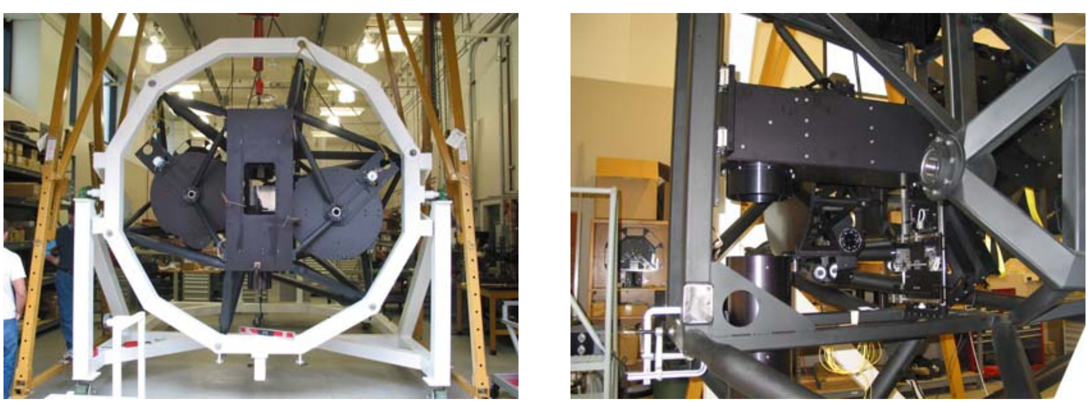

Figure 3 – MODS focal plane during initial fitting. **Left**: front of MODS looking into top of the focal plane assembly showing the dark slide (open), and the two grating turrets (blue at left, red at right). **Right**: side view of the crowded focal plane after the red grating turret has been removed, showing the calibration tower in the in-beam position (calibration light feeds from the tube below, shown without its integrating sphere and connecting baffle).

4.2 Grating Turret and Tilt Mechanisms

All 4 grating turrets have been completed and anodized preparatory to final assembly on their handling carts. The first two have been installed on MODS1, validating our handling methods with this large mechanism, and showing where some minor rework was needed in the frame to make the tight fit. The first turret is complete and installed on MODS1 in the blue channel position for testing of the IMCS. Early bench testing of the first turret showed that our belt-drive concept was not workable, so we rebuilt the front face of the turret to incorporate a direct gear drive, like that used in our filter wheels. This system has proven far better and more reliable. Bench tests demonstrate that we can change between gratings in around 20 seconds. Assembly of the more intricate tilt mechanisms is proceeding on schedule.

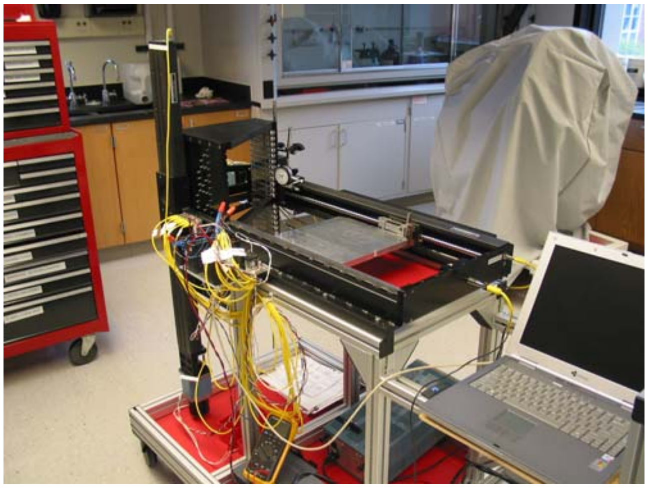

Figure 4 – MODS mask storage cassette and insert/retract mechanism on its handling cart with the prototype motion control system and a dummy (aluminum plate) mask. This system was used to help qualify our motor control component choice.

4.3 Camera Structures

Mechanical parts for all 4 MODS cameras are complete and two of the cameras have been assembled and installed on their handling carts. Both the red and blue camera structures for MODS1 have been fitted on the MODS1 structure and basic mechanical alignment completed, also validating our procedures for installing and removing the camera assemblies from MODS. The MODS1 Blue Camera has been installed in MODS1 for use in IMCS testing, using the first camera primary mirror with a temporary silver coating and no corrector lens or filter wheel (Figure 5).

Figure 5 – MODS1 Blue Camera mounted for IMCS testing. Note the temporary silver coating in the center of the mirror. The camera is mounted without its filter wheel, CCD, corrector lens, or light-tight enclosure.

4.4 Collimator Mirror System

The first of the collimator mirrors has been bonded to its invar mounting flexures and installed in MODS1 on its 3-actuator tip/tilt/focus system (Figure 6). A temporary silver coating has been applied to the surface for IMCS testing. This is the first multi-axis mechanism tested on MODS with the prototype motion-control system.

Figure 6 – MODS1 blue collimator assembly, showing the three tip/tilt/focus actuators and the collimator mirror. A temporary silver coating has been applied for alignment and IMCS testing activities.

5. CCD DETECTORS

The first-light MODS1 system will be deployed with 4096×4096 commissioning CCDs. These devices are monolithic 15μm pixel backside-illuminated CCDs made by Semiconductor Technology Associates (STA0500A) that have been thinned and mounted by Mike Lesser of the Steward Observatory Imaging Technology Laboratory. These will be operated with an OSU-built controller designed by Bruce Atwood. We have these detectors in hand and are building the control electronics at this writing. The same basic device will be used on the red and blue channels.

The MODS science CCDs will ultimately be 3072×8196 format 15μm pixel monolithic CCDs built specially for MODS by E2V Technologies. The blue channel CCDs will be made of standard 16μm thin silicon with the E2V Astro-Broadband coatings. The red channel CCDs will be made of 40μm thick deep depletion silicon with E2V Astro-ER1 coatings, giving superior red response, especially long-ward of 800nm, and no fringing. These devices will first be deployed with MODS2. Estimated spectroscopic performance of MODS with these detectors is shown in Figure 7.

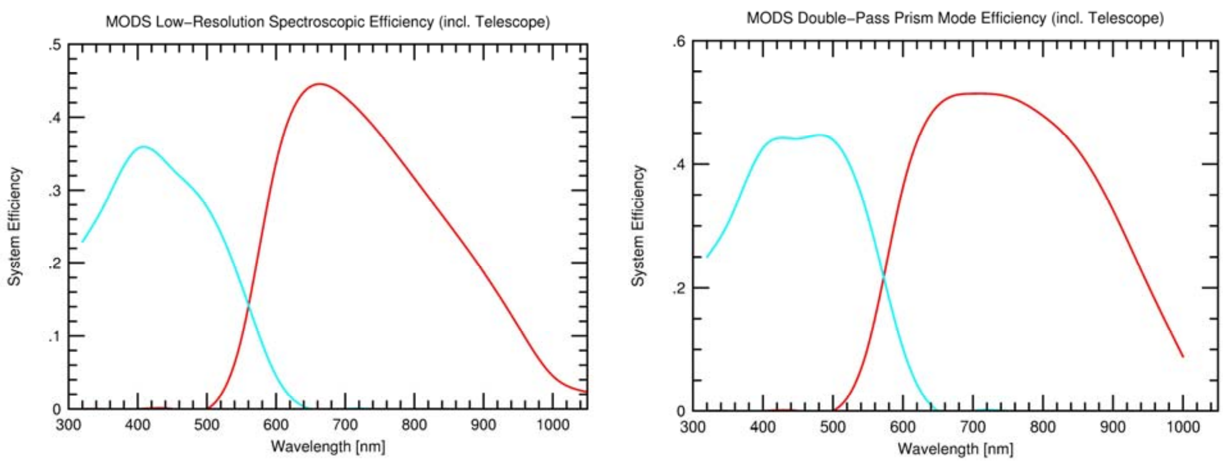

Figure 7 – Estimated spectroscopic performance of MODS with the E2V CCDs and (left) R=2000 gratings and (right) double-pass prisms. Calculations include the optics, dichroic response, and the LBT telescope mirrors.

Each MODS CCD dewar will be mounted on the camera as shown in Figure 8. The dewars' LN_2 reservoirs, shields, and outer shells were fabricated by Meyer Tool and delivered in December 2005. The detector mount section has been rough designed, with the final design awaiting the final mechanical specification from E2V.

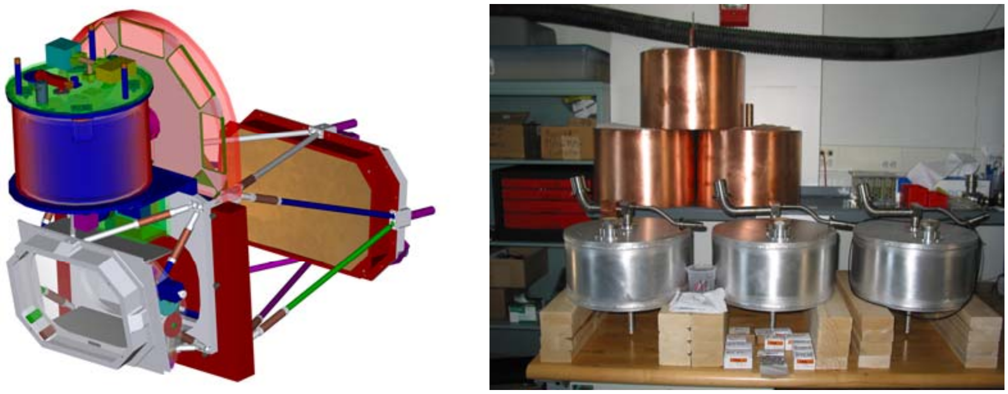

Figure 8 – MODS CCD System. **Left**: Drawing of the dewar assembly and camera. **Right**: Dewar canister parts.

6. INTEGRATION, TESTING, AND DEPLOYMENT

The first major milestone in the integration and testing of MODS was the successful demonstration of the Image Motion Compensation System (IMCS). The MODS1 structure was equipped with all of the components of the blue channel (except for the corrector lens), and the instrument remounted on its cart to place it at the center of balance. A tilt mechanism was used to drive the instrument in altitude from below horizontal to nearly down looking. A detailed description of these tests and their results is presented by Marshall et al. (these proceedings). The tests were an unqualified success, and validated not only the IMCS concept, but provided key tests of prototype MODS control system concepts.

MODS1 is now officially in the assembly, integration, and testing phases. We are aggressively testing all of the main subsystems off instrument in the lab, then integrating them one by one with the motion control system and mounting them onto MODS1. Modules will be assembled in their logical groups, the most complicated of which are 4-axis mechanisms. Two portable 4-axis motor-control systems have been built that will let us test two modules at a time, both on and off MODS proper. As each subsystem is brought online mechanically, its control software is integrated into the overall MODS Instrument Manager system in parallel. This strategy has helped us get ahead of schedule in both areas.

The final phases of MODS1 will be the grand assembly of the entire instrument with all components in place. The MODS camera corrector lenses are currently on the critical path to completion of the grand assembly. Once all the optics are received, mounted, and installed, optical alignment will then proceed.

The optical alignment process begins using a laser alignment procedure to get everything on the same optical axis. This is followed by a fine alignment of the off-axis Maksutov-Schmidt cameras performed by turning the guide camera pickoff optics around to look into MODS (instead of out at the sky), and putting an illuminated pinhole mask in the CCD detector plane. This gives us not only the best camera alignment, but a full front-to-back measurement of alignment. Tests with Code-V have helped us establish our basic optical alignment protocol. After alignment the 4Kx4K commissioning CCDs will be integrated and MODS1 will begin acceptance testing. Details of the acceptance testing protocol are currently being worked out with the LBT Project Office and the LBT Science and Technical Advisory Committee.

MODS1 will then be disassembled, packed up, and shipped to Mt. Graham, where it will be reassembled preparatory to installation at one of the Gregorian foci. The precise schedule for deployment is no sooner than late 2007, driven primarily by the delivery and commissioning schedule of the LBT secondary. Commissioning and science verification activities will then proceed with the 4K×4K commissioning CCDs, followed by early science operations.

MODS2 will meanwhile undergo a similar process, but with a smaller interval of time as we can perform many basic integration tasks in parallel with the MODS1 assembly. The current schedule calls for MODS2 to be commissioned in

2008. MODS2 will be deployed with the 3Kx8K science CCDs, and then MODS1 will be taken offline briefly to install its 3K×8K science detectors. This will allow us to begin full 2-MODS operation with the LBT.

7. ACKNOWLEDGEMENTS

The MODS project has received major support from the U.S. National Science Foundation in the form of NSF grant AST-9987045 and through an award from the Telescope System Instrumentation Program (TSIP). TSIP is funded by the NSF and is administered by the National Optical Astronomy Observatory (NOAO). NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the NSF. This material is based on work supported by AURA through the National Science Foundation under AURA Cooperative Agreement AST 0132798, as amended. Additional support has been provided by the Ohio Board of Regents, The Ohio State University, and David Price.

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