The Large Binocular Telescope

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ABSTRACT

The Large Binocular Telescope (LBT) Project is a collaboration between institutions in Arizona, Germany, Italy, Indiana, Minnesota, Ohio and Virginia. The telescope on Mt. Graham in southeastern Arizona uses two 8.4-meter diameter primary mirrors mounted side-by-side to produce a collecting area equivalent to an 11.8-meter circular aperture. A unique feature of LBT is that the light from the two primary mirrors can be combined to produce phased array imaging of an extended field. This coherent imaging along with adaptive optics gives the telescope the diffraction-limited resolution of a 22.65-meter telescope. The first primary mirror was aluminized in April 2005. First light with a single primary mirror and a prime focus imager was achieved in October 2005. We describe here some of the technical challenges met and solved on the way to First Light. The second of two 8.4-meter borosilicate honeycomb primary mirrors has been installed in the telescope in October 2005 and was aluminized in January 2006. Binocular operation with two prime focus cameras is planned for Fall 2006. The telescope uses two F/15 adaptive secondaries to correct atmospheric turbulence. The first of these adaptive mirrors is now being integrated with its electro-mechanics.

Keywords: binocular telescope, honeycomb mirror, adaptive optics, phased array imaging

1. PROJECT OVERVIEW

The Large Binocular Telescope (LBT) uses two 8.4-meter diameter honeycomb primary mirrors mounted side-by-side to produce a collecting area (110 square meters) equivalent to an 11.8-meter circular aperture. A unique feature of LBT is that the light from the two primary mirrors can be combined optically in the center of the telescope to produce phased array imaging of an extended field. In practice this extended phased field can be of order 1-arcminute in diameter. Adaptive optics has been designed into the telescope from the beginning to augment the high resolution imaging from visible to mid-infrared wavelengths. The main wavefront correctors are the F/15 Gregorian adaptive secondary mirrors. The interferometric focus combining the light from the two 8.4-meter primaries will reimage the two folded Gregorian focal planes to three central locations for phased array imaging. Several of the instruments will implement an additional wavefront corrector at a higher conjugate after the Gregorian focus. This coherent imaging gives the telescope the diffraction-limited resolution of a 22.65-meter telescope. We will be able to produce images with a resolution of 5-milliarcseconds in visible light and 20-milliarcseconds in the near infrared. The binocular configuration leads to a compact and stiff mechanical structure. The short focal ratio primary mirrors help minimize the size of the co-rotating enclosure. The telescope is located at Mount Graham International Observatory in the Pinaleno Mountains of southeastern Arizona at an elevation of 3192 meters. The project through the installation of the first 8.4-meter primary has been described by Hill & Salinari (2004) and references therein.

2. FIRST LIGHT

The suite of facility instruments for LBT includes a pair of wide-field prime focus cameras built in Italy by a collaboration of astronomers centered in Roma and Firenze. These cameras are the first scientific instruments to be used on the telescope. The prime focus imagers are deployed into the optical beam on swing arms so they may be quickly and easily interchanged with the Gregorian secondaries. The first blue-optimized prime

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Figure 1. This negative image is a 300-second Blue integration of the galaxy NGC891 which has been designated the “First Light” image for the left side of the Large Binocular Telescope.
focus camera was installed on the telescope in the summer of 2005. Additional details of the Large Binocular Camera (LBC) prime focus instruments are provided by Ragazzoni et al. (2006). The prime focus cameras are serving as the commissioning test instruments for many of the telescope sub-systems and they will provide the first routine science observations in early 2007.

The main telescope activities during the spring and summer of 2005 included: getting the telescope alt-az mount to properly track stars, getting the left primary mirror support system working at all elevation angles and temperatures, debugging the multi-threaded instrument interface to the telescope control system, mounting and aligning the left prime focus camera, developing a look-up table to manage collimation of the F/1.14 primary, and testing the primary mirror thermal control system. These activities resulted in our obtaining good quality images for the “First Light” observation on the night of 12 October 2005 (UT). The target was an edge-on spiral galaxy (type Sb) in the constellation of Andromeda known as NGC891. We admit that we picked NGC891 because we find it to be a very attractive galaxy. However, NGC891 is of particular scientific interest because a galaxy-wide burst of star formation, inferred from X-ray emission, is stirring up the gas and dust in its disk. There are numerous more distant galaxies in the background of the NGC891 field which are more typical of what a large telescope like LBT will eventually study with longer exposures.

The First Light observation was made through a broadband blue filter (B-Bessel) as a series of ten 30-second exposures. The individual 30-second exposures were each taken with the two axes of the telescope (elevation and azimuth) and the rotator of the camera tracking open-loop according to a pre-calculated trajectory. The telescope trajectory was corrected with a pointing map (Tpoint) which compensates the gravitational flexure of the telescope structure. The Large Binocular Camera has four CCD chips in the focal plane - each with dimensions of 2048x4608 pixels - for a total of 36 megapixels. In front of the CCD array is a set of 6 fused silica corrector lenses that correct the comatic aberration of the fast primary mirror to allow an extended field-of-view. The ten exposures were each offset slightly on the sky so that the seams in the CCD array do not appear in the final combined image. The telescope was focussed and collimated before each set of 5 images that were taken. The primary mirror cell has a look-up table to make tiny corrections to the focus as a function of telescope elevation angle before each individual exposure. After the images were calibrated and registered, they have been combined in the computer to make a single blue image of the galaxy with an exposure time of 300 seconds. The image quality of the individual exposures ranges from 2.9 pixels to 3.6 pixels FWHM where each pixel corresponds to 0.227 arcseconds on the sky. Thus the final stacked image has a resolution of 0.8 arcseconds FWHM which is typical of the wide field imaging which will be obtained with this camera. The angular size of the final image on the sky is about 30 arcminutes across. Figure 1 shows approximately half of the final stacked First Light image.

In parallel to First Light, we also carried out the first experiments with active optics on the primary mirror using extrafocal images, and experiments with guiding the telescope using the LBC technical chips. Neither active figure correction nor guiding was used to obtain the First Light images. This means that the mirror figure and support were stable since it left the Mirror Lab in Tucson two years earlier, and that the telescope was tracking reasonably well (0.25 arcsec rms at that time) without guiding. As we implement active optics and guiding the images should improve down to approximately 0.5 arcsec FWHM where they are limited by seeing and pixel size.

3. PRIMARY MIRRORS

3.1. Polishing

The second of two 8.4-meter borosilicate honeycomb primary mirrors for LBT has been polished at the Steward Observatory Mirror Lab in Tucson during 2004/2005. During 2005 it was tested in its final mirror support cell and then transported to the mountain. These paraboloidal primary mirrors have a focal ratio of F/1.142 (9.6-meter focal length) to allow a very compact and stiff mechanical assembly to be used for the telescope optical support structure. A special computer-controlled “stressed lap” was used to polish this steeply aspheric optical surface (1.4 mm p-v departure). The optical surface is measured using phase-shifting interferometry and a refractive null corrector near the center-of-curvature. The surface figure of the second primary mirror was measured to deviate from the ideal paraboloid by less than 25 nanometers rms in the telescope cell. Martin et al. (2006) describe the polishing, the test setup and the results of active figure adjustment under the test tower.
3.2. Primary Mirror Transport – Design Success

The transportation of the second 8.4-meter mirror from the polishing laboratory to the mountaintop was a cooperative effort between the University of Arizona and Precision Heavy Haul of Phoenix, Arizona. The mirror was transported in a specially designed box which provides multiple layers of spring isolation. The mirror box was transported horizontally down interstate highway 10 between Tucson and Safford, Arizona. The truck with the mirror box travelled at speeds up to 80 km/hour on the interstate highway with a rolling roadblock escort to control traffic. After arriving at the observatory base camp, the box was tilted by 60 degrees and mounted on a Goldhofer trailer for the transport up the 48 kilometers of winding mountain road. Figures 2 and 3 show the second primary cell and the second primary mirror in its transport box on the way up the mountain road during September 2005. The second mirror transport took 3 days of travel to reach the mountaintop site from Tucson. We feel this transportation activity was a particular success because of the excellent cooperation between the university, private industry and local police forces. Davison et al. (2004) provide additional details on the engineering aspects of mirror transportation and mirror handling.

3.3. Mirror Cells and Active Optics

The second primary mirror has been mounted on the telescope in its support cell during October 2005 to complete the binocular telescope optics in the largest sense. Figure 4 shows the mirror being installed in its cell...
Figure 3. This photo shows the second primary mirror in its transport box on the way up the mountain road. The trip up the winding mountain road takes 2 days with a typical speed about 3 km/hour. Photo by Ron Smallwood.

off the telescope after transport to the mountain. The mirror cell contains 160 pneumatic actuators which float the mirror against the force of gravity in order to preserve and adjust its accurate shape. Each actuator has an internal servo loop which regulates its air pressure to deliver the commanded force as measured by a loadcell in the actuator. Both axial and lateral forces are applied only to the backplate of the glass honeycomb. Loadspreaders are glued to the backplate in order to distribute the forces to the honeycomb structure. Figure 5 shows some of the 160 pneumatic actuators mounted in the lower portion of the mirror support cell. Six “hardpoints” arranged as a Stewart platform provide the mechanical stiffness to control the position of the mirror in the cell. The force on these stiff hardpoints is measured with a set of loadcells and used to adjust the overall set of force commands to the actuators. The mirror support concept was described by Gray et al. (1994). Air entrainment devices are used to circulate air through the cell and the glass honeycomb in order to keep the mirror in thermal equilibrium at a temperature close to nighttime ambient temperature.

3.4. Oscillation of the Active Mirror Support System – Challenge

When the left primary mirror support system was tested at room temperature in Tucson, it was stable and fairly well-behaved. When the same system was tested on the mountain in 2004, we discovered that it wanted to oscillate when the hardpoints were adjusted to collimate the mirror position in the cell. This oscillation was eventually found to be temperature dependent. At the same time, we also had some intermittent serial
communication errors between the support actuators and the mirror cell control computer. We also saw large jumps in the forces that were being readback from the actuator loadcells. The serial communication errors and the force jumps were fairly quickly isolated to connectors on the actuator servo cards. The connectors were prone to work loose under the weight of dangling cables in the changing gravity field of the telescope causing an intermittent connection. This problem was solved in the short term by more carefully tying down the cables in the cell, and was solved in the long term by changing to a more robust type of connector. However, considerable effort studying the vibration and stiffness properties of the hardpoints which position the mirror failed to reveal any cause of the observed oscillation.

Eventually, the cause of the mirror oscillation was traced to the support force actuators. Once the temperature got below freezing, the group of actuators would oscillate spontaneously without any motion of the hardpoints, and without the hardpoint force feedback loop running. During the summer of 2005 while also testing the right mirror cell in the lab, we identified at least three problems with the force actuators: 1) the dual-axis actuators had received an incorrect integrator feedback resistor in the servo loop which regulates the force/pressure in the actuator; 2) the particular air cylinder design resulted in an asymmetric air volume on either side of the piston when the mirror was in its nominal position – this lead to an asymmetric force response between the push and pull directions of the actuator; and 3) the vacuum grease in the actuator cylinders was observed to become quite stiff as the temperature approaches freezing. The resistor was replaced with the correct value. The volume was balanced by inserting a plastic plug inside the unused volume of the air cylinders. The cylinders were re-lubricated with a different brand of vacuum grease that was better suited for the low temperatures. Individual actuators were measured to have improved frequency response (6 Hz), and to be more stable against oscillation by a factor of 20 at temperatures as low as -7 degC. These tests were carried out with the actuator position fixed on the actuator calibration stand.

After First Light, all the actuators were removed from the left mirror cell and reworked to address these issues. We were confident that the problems were cured because we were able to reproduce and correct problems in the laboratory in Tucson. In February 2006, the population of actuators was replaced into the left primary cell. We were surprised and disappointed to see that the mirror still oscillated as the temperature approached freezing. Another round of testing on an improved moving test fixture has demonstrated that the fundamental source of the oscillation is stick-slip and friction in the sliding piston seal of the air cylinder. Apparently even the more fluid vacuum grease has not compensated for the relatively poor stick-slip properties when cold. The solution to the problem is to replace the Viton piston seal and shaft seals with a more compliant material. Commissioning work on the telescope is proceeding in summer 2006 with the left primary mirror and the blue prime focus camera since the oscillations are negligible when the ambient temperature is well above freezing.

3.5. In-situ Aluminizing – Design Success

LBT was designed to aluminize the two 8.4-meter primary mirrors in place on the telescope structure. The logic was that it was easier to bring the vacuum belljar to the mirrors, than it was to move the mirrors to the belljar – experience has now confirmed this to be true. At present we are washing and stripping the mirrors manually with long-handled mops while the telescope is at zenith. In the long-term the plan is to build a washing bell which will strip the old coating without requiring humans to be up to their elbows in acids and bases. After washing/striping the telescope is moved to the horizon-pointing position and locked in place. The 25-ton aluminizing belljar is lifted up with the overhead crane and sealed against the corresponding vacuum flange on the mirror cell. Figure 6 shows the belljar mounted over the right primary mirror on the telescope. The technical details and results of the aluminizing system are described by Atwood et al. (2006). The rough vacuum is made with a roughing pump and a Roots blower. Inside the belljar a group of charcoal cryopanels cooled by liquid nitrogen provides the final pumping down to the coating vacuum. Aluminum is evaporated by a set of 28 boron-nitride crucibles heated with tungsten heaters. The LBT system is unique in that each of these 28 source modules contains an integrated transformer mounted with the crucible heater so that the control system supplies 280 VAC at 20 kHz which is then stepped down in voltage and up in current by a factor of 26 at the crucible. Each of the first two primary mirror coatings has been successful. The first coating in March/April 2005 was interesting because we spent several weeks under vacuum chasing down a couple of weld porosity leaks in the primary cell. The second primary mirror was coated in January 2006 with the entire cleaning/coating cycle taking just over a week. We still have some optimization work to do because the initial coatings on the
primary did not cleanly pass the scotch tape test for adhesion even though the witness slides were adhered. Otherwise reflectivity and coating thickness measured on witness slides look good. We believe that selecting in-situ aluminizing was a good choice operationally. The innovative design of the source modules also seems to have been a technical and economical success. The only significant penalty to the telescope design was the need to make the mirror cell a vacuum vessel. This makes the cell weldment somewhat heavy (44 tons), restricts access to the mirror supports in some areas, and requires mechanisms to use vacuum compatible lubrication.

4. TELESCOPE

4.1. Mechanical Structure
The binocular telescope is mounted on an altitude over azimuth mount inside a co-rotating enclosure. Figure 7 shows the binocular telescope with the enclosure open for observing. Hydrostatic bearings operating at 120 bar provide a smooth motion of the telescope with very low friction. The azimuth and elevation drives each have four brushed DC servomotors directly driving pinions (60:1) on common shafts against 14-meter diameter segmented gear sectors. Both the bearings and the motors were designed to preserve the structural stiffness of
Figure 5. This photo shows one of the pneumatic mirror support actuators in the lower portion of the mirror cell. The vertical cylinder (on the right) provides the axial force, and it works in concert with the angled cylinder (on the left) to provide lateral force when the telescope moves away from the zenith. Each cylinder has its own independent analog servo loop with two pressure regulators. Additional actuators appear in the background at the lower edge of the photo.

the telescope. The telescope elevation structure accommodates swing arm spiders which allow rapid (10 minute) interchange of the various secondary and tertiary mirrors as well as the prime focus cameras.

4.2. Mount Control System

The brushed DC motors for the telescope azimuth and elevation drives are driven with Copley transconductance power amplifiers. The servo system for the telescope mount is implemented digitally in digital signal processors (DSP) which are hosted in a Linux computer. The computer hardware for the telescope mount control system was provided by Bittware. The system gets position and velocity feedback from Heidenhain incremental encoders mounted on the motor/pinion shafts as well as from Farrand inductosyn strip encoders mounted directly on the telescope axes. Motor encoder and limit switch inputs are interfaced to the DSP clusters through FPGA-based logic. The power amplifier commands and strip encoders are interfaced to the DSP clusters through cPCI analog I/O. A programmable logic controller (PLC) monitors the encoder and limit signals in its role as a safety supervisor. A second PLC manages the motion of the co-rotating enclosure. Additional details on the mount control system are provided by Ashby et al. (2006).
Figure 6. This photo shows the aluminizing belljar mounted on the telescope structure in January 2006 for the coating of the second primary mirror. Note the person for scale standing above the belljar on the mirror cell. Photo by Ray Bertram.
Figure 7. This photo shows the telescope and enclosure with two primary mirrors open to the sky for observing. The left primary mirror (right in the photo) has the LBC-Blue camera in position at prime focus while the right swing arm (left in the photo) is swung out in the maintenance position. Each of the two shutter openings is 10-meters wide. Dead trees on the ridge in the background were burned in the Nuttall-Gibson forest fire in July 2004.
4.3. Stick-Slip of the Elevation Axis – Challenge Met

During telescope testing in October 2004, we encountered a stick-slip phenomenon during slow movements of the elevation axis (below 20 arcsec/sec). Our initial suspicion was friction in the oil pads of the hydrostatic bearings, but spatial repeatability of the sticking caused us to mount a wide ranging exploration. The first problem we discovered was a faulty clock crystal in the DSP card which was running the elevation digital servo. Next we found some misalignment issues with the elevation hydrostatic pads. A noticeable reduction in friction of the elevation axis was made by adjusting the shims behind the lateral restraint hydrostatic pads. We also discovered that the pinion on the right side auxiliary drive was binding against the main gear. These changes improved the telescope performance, but did not remove the stick-slip problem. We implemented an improved servo controller which was better at fighting the stick-slip, but could not eliminate it. In February 2005, we isolated the problem to the main drive motor assemblies. At this point we were scrutinizing the commutator assemblies very carefully for a torque ripple problem because there had been a history of the brush assemblies arcing – the torque turned out to be quite smooth. Finally, we found that three of the four elevation motors had an assembly error which caused the inner and outer races of the bearing outside the pinion to be misaligned so that the rollers overhung the edge of the inner race. This overhang was causing excessive local stress on the components and resulted in small flakes of metal coming off of the inner race – the give away was the sparkling of the metal flakes in the grease. Releasing the preload on this bearing caused the stick-slip problem to go away, but lost some of the deliberate constraint of the shaft holding the motor and pinion. We obtained replacement bearings and reassembled the motors correctly. At this time, we were pleased to see that the elevation lowest eigenfrequency had been increased by nearly 2 Hz compared to the case where the pinion was supported by a single bearing. As we report in the next section, the elevation axis is now tracking quite nicely without any problem of stick-slip even at velocities below 1 arcsec/sec.

4.4. Tracking with a Segmented Large Diameter Gear – Design Success

One of the early design debates in the LBT project was what kind and what diameter of drives to put on the telescope. We were particularly concerned to have good stiffness and thus a high structural eigenfrequency as well as a precise and smooth drive for good tracking. We eventually selected a segmented gear design working at a 7 meter drive radius. The large radius reduced the required stiffness and accuracy of the gear sectors. The segmented gear design was an economic choice to avoid the expense of fabricating a 14-meter diameter precision gear. The full circumference of the M6 azimuth rim gears was assembled from 32 segments. Brushed DC servo motors directly drive 23-tooth pinions against the main gears. A higher torque auxiliary hydraulic drive is included in the design for maintenance operations. An error during telescope assembly on the mountain resulted in the auxiliary pinion disengaging and damaging several sectors of the main gear. This proved the important ability to replace several sections of the main gear and regain the original quality.

During the pre-First Light era, we have been tracking the telescope with servo feedback only from incremental encoders on the individual motor shafts. These encoders serve to provide a stable velocity loop for each motor while another strip encoder will eventually provide position feedback directly from the main axes of the telescope structure. This temporary use of the motor encoders for position feedback means that errors in the segmented gears are not corrected by the mount servo. We have been pleasantly surprised that the open-loop tracking performance dominated by these gear tooth errors has been as good as 0.25 arcsec rms. Without the gear errors, the axis servo error is below 0.01 arcsec rms in a 5 meter/sec wind. This gives us great hope for the tracking performance when the main axis strip encoders are deployed. The segmented main axis gears have proved to be an excellent design choice, especially considering that the cost of the gears and their installation was only $100K per axis (not including the machining of the precision mounting surface). Future telescopes have much to gain from this area of technology where individual components are fabricated on precise numerical mills and then assembled into a much larger precision structure.

4.5. Telescope Control System

The mount control system (MCS) is one of a number of sub-systems which make up the overall telescope control system (TCS). The high-level telescope control software interfaces to a dozen sub-systems which control specific activities in the telescope and observatory. These other sub-systems include the adaptive optics system (AOS),
the primary mirror cell (PMC) controls, the enclosure controls (ECS), telemetry (TEL), optical supports (OSS), etc.. These software sub-systems run on Linux servers in the control room and most of them have corresponding hardware interface machines distributed around the telescope and enclosure. For example a real-time VxWorks machine controls each of the primary mirror cells, and Allen-Bradley PLCs control the enclosure, enclosure rotation and some of the telescope safety logic. Each sub-system has ethernet connections for command and control, for reflective memory, and for telemetry and logging. Not all TCS sub-systems have corresponding hardware systems. For example the pointing control system (PCS) which controls telescope tracking passes its trajectories on to the mount control system, and the point spread function (PSF) control system passes collimation information and active mirror figure corrections to the primary mirror cells. Issues related to pointing a binocular telescope are discussed by Terrett (2006).

5. ADAPTIVE OPTICS AND INSTRUMENTS

5.1. Adaptive Optics

The baseline optical configuration of LBT includes adaptive infrared secondaries of a Gregorian design (concave ellipsoidal mirrors rather than the more common convex Cassegrain mirrors). The F/15 secondaries are undersized to provide a low thermal background focal plane which is unvignetted over a 4-arcminute diameter field-of-view. These adaptive secondary mirrors with 672 voice-coil actuators supporting a thin glass shell are now in the final stages of integration and testing in Italy. The 1.6 mm thick, 911 mm diameter thin Zerodur shells for the adaptive secondaries are being polished by the Steward Observatory Mirror Lab at the University of Arizona. Figure 8 shows the second shell after coating the rear surface. The adaptive optics system for the telescope is a cooperative effort between ADS International of Lecco, Italy; Microgate of Bolzano, Italy; and the adaptive optics groups at Osservatorio Astrofisico di Arcetri in Firenze and at Steward Observatory in Tucson. The adaptive secondary units have been described by Riccardi et al. (2004). These adaptive secondaries will update their shape at kiloHertz rates to correct the distortions in the wavefront caused by atmospheric turbulence.

5.2. Broken Secondary Shells – Challenge

The first two thin shells were damaged during 2005 and are not suitable for scientific use on the LBT. The first shell was fractured in final processing during production in the Steward Observatory Mirror Lab on 2 May. That result is attributable to a failure in process control in the use of a tool for finishing the edge of the fully thinned shell. The shell was still attached to the granite blocking body. The cylindrical tool was used to cut down to make a shelf in the granite exterior to the thin shell. It was then used to cut inward in radius, with the intention of providing a “clean up cut” to the edge of the shell (as well as cutting the supporting granite). A combination of factors apparently led to regions of edge fractures. The choice of tool and diamond grit resulted in a somewhat slow removal rate with higher force than typical. The rate of bringing the tool inward in radius may have been too rapid, given the higher force. Finally, the cooling water or force application debonded the edge of the shell from the pitch in spots, leading to vibration and subsequent fracturing. Changes in procedure led to a successful clean cut during production of the second thin shell. For remediation, a propagating radial crack was drill stopped then sawed to relieve any further stress. The fractured perimeter was cut down (also successfully) to leave a constant but undersized radius. The shell was shipped to ADS in Lecco, Italy, and arrived in the same condition as before packing. This shell is serving as a pathfinder for processing and optical testing, before a science-quality shell is delivered.

The second shell was successfully completed and accepted by LBTO from the Mirror Lab. It was transported to the Sunnyside aluminizing facility, where it was cleaned, masked and aluminized. Design and fabrication errors in the shipping container led to an accident during packing in which the shell sustained an impact fracture to the edge. Damage was not noticed during visual inspection. The combination of compression and accelerations during subsequent shipment caused propagation of a radial crack approaching the central hole of the shell. The damage was discovered during unpacking at ADS in November. The shell is unlikely to be suitable for optical testing.

The shell is packed for shipping in a specially made transport container. The shell is first placed in a naugahyde and fiberglass bowl which is actually formed on the shell during the production process. Foam blocks
Figure 8. This photo shows the second thin shell for the LBT adaptive secondary mirror just after the coating of the armature for the capacitive sensors on the rear (convex) side of the shell. The zerodur shell is 911 mm in diameter and has a mean thickness of 1.6 mm. The front (concave) side optical reflective coating will be applied after the 672 magnets have been glued to the rear surface. A magnet will be glued at each of the spots where the aluminum coating has been masked. Photo by Guido Brusa-Zappellini.

are placed on top. These blocks are constrained in a metal frame, with triangle base and top, with vertical metal posts. When bolts are tightened, the frame puts the foam into compression to restrain any movement of the shell. The machined depression was cut to plan, but the engineer’s drawings erroneously specified the foam to match the exact radius of the shell, requiring centration accurate to a millimeter. The engineer’s original intention was to have the top and bottom foam extend several millimeters beyond the actual radius of the shell. The engineer was called in to inspect this situation but felt with proper centering the shell would be safe. In addition, the vertical posts were erroneously fabricated too short. Aluminum spacer blocks were fabricated to go between the upper triangle and the vertical posts, attached with the clamping screws. As the upper frame was being attached, the packing crew noticed that the shell was decentered by several millimeters. When they raised the upper frame with the crane, one of the spacer blocks became detached from its screw and struck the exposed few millimeters of the edge of the shell, producing a fracture.

It is the conclusion of LBTO that there is nothing fundamental in the manufacture, handling, or shipping of thin shells that makes their ultimate deployment unlikely because of cumulative risk of damage. The thin shell for the MMT adaptive secondary system was successfully shipped to Italy, processed, and deployed at the telescope in Arizona without damage. Strict adherence to carefully developed protocols, handling equipment with large safety margins, and work areas appropriately configured and access controlled should lead to successful
integration and use of thin shells in the LBT adaptive secondary systems. Replacement shells are presently in fabrication. Details of the shell fabrication process are described by Martin et al. (2006). Specific remediation actions now underway include: a redesigned shipping box to relax tolerances and eliminate loose parts, improved and more detailed handling procedures with more of a checklist format, revision of the shell specifications to permit safer production operations, additional training and verification of handling steps with surrogate shells, and the production of a dedicated spare shell.

5.3. AGW Units and Guiding

Acquisition, guiding and wavefront sensing (AGW) units for the Gregorian focal stations are being built in Potsdam. The units provide relatively conventional capabilities for acquisition imaging and off-axis guiding. They also provide off-axis wavefront sensing for focus, collimation and active wavefront correction. Within the same AGW unit housings there are also fast (1 kHz) on-axis wavefront sensors for the adaptive optics system. These modules use a pyramid wavefront sensor with up to 30 resolution elements across the pupil. The on-axis units are being built in Arcetri along with the software for the adaptive optics system. The first AGW unit is undergoing laboratory acceptance tests in Italy. The AGW units have been described by Storm et al. (2004). The overall adaptive optics system for the first adaptive observations with LBT is described by Esposito et al. (2006).

5.4. Additional Instrumentation

A pair of near-infrared spectrographs optimized for wide-field multiobject work and for diffraction-limited observations will be mounted at one pair of the bent Gregorian focal stations in the center of the telescope. These infrared spectrographs described by Mandel et al. (2006) are being built in Germany by a collaboration centered in Heidelberg and Munich. Below the primary mirrors, two large optical-UV spectrographs are mounted at the direct Gregorian focal stations. These two dual-beam spectrographs described by Pogge et al. (2006) are being built in Ohio. Additional details on the LBT facility instruments can be found in Wagner (2006).

The other two pairs of bent Gregorian focal stations will be mainly used for phased array imaging. Two “strategic instruments” are being built to combine the light from both primaries and take advantage of the diffraction-limit from the full 22.65-meter baseline. An instrument emphasizing nulling interferometry in the mid-infrared is being built in Arizona. An instrument emphasizing phased array imaging in the near-infrared with multi-conjugate adaptive optics is being built by a collaboration centered in Heidelberg and Firenze. A more detailed description of the plans for interferometry and phased array imaging on LBT is provided by Hinz & Herbst (2006).

6. PROJECT PARTNERS

The international partners in the Large Binocular Telescope Corporation include Arizona (25%), Germany (25%), Italy (25%), Ohio State (12.5%) and Research Corporation (12.5%). The Arizona portion of the project includes astronomers from the University of Arizona, Arizona State University and Northern Arizona University. The German portion is represented by the LBT Beteiligungsgesellschaft which is composed of Max-Planck-Institut für Astronomie in Heidelberg, Landessternwarte of the University of Heidelberg, Max-Planck-Institut für Radioastronomie in Bonn, Max-Planck-Institut für Extraterrestrische Physik in Munich and Astrophysikalisches Institut Potsdam. National participation in Italy is organized by the Istituto Nazionale di Astrofisica. Partners at individual institutions include the Ohio State University in Columbus, Research Corporation in Tucson, the University of Notre Dame, the University of Minnesota and the University of Virginia. Astronomers and engineers at all of these institutions are involved in building instruments and auxiliary equipment for the telescope.

7. SUMMARY

The mechanical and electrical construction of the Large Binocular Telescope on Mt. Graham is complete. The two 8.4-meter primary mirrors are installed in the telescope and coated. Integration and commissioning of the high level controls and instruments are now in progress. We have described some of the challenges and some successes as the telescope transitions from a construction project into a working scientific instrument.
First light with only the left primary mirror and the blue channel of the “Large Binocular Camera” was achieved in October 2005. The lens assembly of the second prime focus camera will be mounted on the telescope during summer 2006. Commissioning of the adaptive optics system and several spectroscopic facility instruments will be the main tasks for 2007. The plan for LBT operations is described by Green et al. (2006). Recent photos and other news can be found on the LBT web site: http://lbto.org

REFERENCES