Prime Focus Active Optics with the Large Binocular Telescope

J. M. Hill\textsuperscript{a}, R. Ragazzon\textsuperscript{b}, A. Baruffolo\textsuperscript{b}, C. J. Biddick\textsuperscript{a}, O. P. Kuhn\textsuperscript{a}, E. Diolaiti\textsuperscript{c}, D. Thompson\textsuperscript{a} and A. Rakich\textsuperscript{a}

\textsuperscript{a}Large Binocular Telescope Observatory, University of Arizona
933 N Cherry Avenue, Tucson, AZ 85721, USA

\textsuperscript{b}INAF - Osservatorio Astronomico di Padova
Vicolo dell’Osservatorio 5, I-35122 Padova, Italy

\textsuperscript{c}INAF - Osservatorio Astronomico di Bologna
Via Ranzani 1, I-40127 Bologna, Italy

ABSTRACT

The Large Binocular Telescope (LBT) 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. We describe our use of active optics with the honeycomb primary mirrors to provide focusing, collimation and low-order active wavefront correction for the two prime focus cameras now operating on the telescope. We use a custom IDL program, LBCFPIA, to geometrically analyze extrafocal pupils in order to determine focus and wavefront corrections through third-order spherical aberration. We also describe that section of the telescope control system which manages primary mirror collimation and accepts wavefront correction requests from the instrument. We present active optics results obtained during commissioning of the prime focus cameras and during science observations.

Keywords: binocular telescope, honeycomb mirror, active optics, prime focus imaging, extrafocal pupil

1. INTRODUCTION

The Large Binocular Telescope (LBT) Observatory 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. 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. However, the two primary mirrors can also be used independently to obtain seeing-limited images over a wide field-of-view. Monocular prime focus science imaging started in Fall 2006, with regularly scheduled science observations starting in January 2007. Binocular imaging with two co-pointed prime focus cameras began in Fall 2007, and the dark of the moon has been dedicated to imaging science with both cameras since January 2008. Additional information on the Large Binocular Telescope is provided in Hill et al. (2008).\textsuperscript{1} Figure 1 shows the LBT ready for binocular prime focus observing. Here we describe the active optics system used to maintain telescope focus, collimation and wavefront alignment during those imaging observations.

\textsuperscript{1} Further author information: Send correspondence to J.M.H.: E-mail: jhill@as.arizona.edu, Telephone: +1 520 621 3940
2. BASIC ACTIVE OPTICS

Astronomical "active optics" involves the active adjustment of the positions and shapes of optical elements in a telescope to maintain the best possible images in the telescope image plane. These adjustments occur on timescales ranging from tens of seconds to tens of minutes. With the development of 6-10 meter class telescopes weighing hundreds of tons, active optics has become an essential part of the telescope builder's toolkit. Very large optical elements must be held to extremely tight mechanical tolerances in order to achieve sub-arcsecond image quality. The primary mirror weighing tens of tons must be held in collimation position within tens of microns relative to the other optical elements in the presence of more than a millimeter of gravity deflection of the telescope structure. The shape of the primary mirror must be held to tens of nanometers in the presence of forces from the changing gravity vector and from wind gusts. See Noethe (2002)\textsuperscript{2} for a detailed description of all aspects of active optics in astronomy.

The strategy we have adopted for active optics at LBT is as follows. The foundation of all active optics systems are components of the telescope that are as fundamentally stiff and stable as they can practically be. On top of that layer, we add a system of open-loop look-up tables which position the optics to the expected position as a function of telescope elevation angle and temperature. Finally, measurements of the delivered optical wavefront in the science focal plane provide the final correction to deal with variable and non-predicted effects. This "active" correction provides the final adjustment to the telescope optical system to deliver the best possible image quality. Of course, this paper is not talking about adaptive optics which operate at much faster...
3. LARGE BINOCULAR CAMERA

The first scientific instruments to be installed and commissioned on the LBT are the blue-optimized and red-optimized prime focus cameras known collectively as the Large Binocular Camera (LBC). Each camera has four CCD (charge-coupled devices) chips in the focal plane - each with dimensions of 2048x4608 pixels - for a total of 36 megapixels. In front of each CCD array is a set of six fused silica (blue) or BK7 (red) corrector lenses that correct the comatic aberration of the fast primary mirror to make an extended field-of-view (approximately 24 x 24 arcminutes). Each camera contains eight broad-band filters for making deep scientific images. LBC is described by Speziali et al. (2008)\textsuperscript{3} and previously by Ragazzoni et al. (2006).\textsuperscript{4} First light with the camera optimized for blue and near-ultraviolet work occurred in October 2005, and regular science observations started in January 2007 after some commissioning of the telescope and camera. Image quality during science commissioning observations was as good as 0.5 arcsec FWHM in the U-band on nights of good seeing. Performance of the blue camera on sky is discussed by Giallongo et al. (2008).\textsuperscript{5} Figure 2 shows the red-optimized corrector assembly being aligned on the telescope in November 2006. Gentile et al. (2008)\textsuperscript{6} provide additional details on the optomechanical alignment of the red corrector lenses. Science observations using both the blue and red cameras simultaneously began during the dark of the moon in February 2008.

The original plan for LBC active optics was to use small glass blocks on the technical CCDs used for guiding to produce a pair of extra- and intra-focal pupils. Unfortunately, a design error lead to these pupils being vignetted, and therefore useless for traditional curvature sensing of the wavefront. Our solution born out of practical necessity has been to move the primary mirror down (along the optical axis) -0.8 mm in order to produce 60-pixel diameter pupils on the science CCD arrays. These extrafocal pupils are then analyzed to focus and collimate the telescope correcting Zernike terms through Z11. We elected to use single extrafocal pupil images since the time required to collect these was two times less than collecting both intra- and extra-focal pupils in sequence. Preparing, acquiring, reading out, analyzing the image and sending the results to the telescope takes 2 minutes per iteration with one or two iterations required when the telescope moves to a new target field. The remainder of this paper describes the active optics system used by the LBC to optimize the image quality during observations.

4. GEOMETRICAL ACTIVE OPTICS

When an extrafocal pupil image has zero aberration it appears perfectly uniform (looks just like the entrance pupil of the telescope). Aberrations in the LBC corrector and/or the primary mirror cause distortions in the shape and intensity of the pupil image. We can use these distortions to measure and improve the focus, collimation and shape of the primary mirror. We use the size of the pupil (at a given extrafocal offset) to indicate the departure from the ideal focus. This allows us to measure the focus with a single CCD exposure. We use the centration of the central obstruction to indicate the mis-collimation coma. Severe coma alters the light distribution across the pupil and causes the pupil to look like a crescent moon. Ellipticity of the pupil is used to indicate astigmatism which can be corrected by bending the primary mirror. The relative size of the central obstruction compared to the outer diameter is used to indicate spherical aberration. We use the instrument rotator angle to relate the orientation of the aberrations on the pupil to the primary mirror. Figure 4 shows a cribsheet we have developed to allow making the active optics corrections by manually inspecting the telescope pupils. Authors Baruffolo and Ragazzoni have written an IDL program to automatically analyze the extrafocal pupils and compute low-order corrections to send to the primary mirror. Some details of that program’s operation are described below.

5. LBCFPIA (LARGE BINOCULAR CAMERA FOCAL PLANE IMAGE ANALYSIS)

The determination of low-order aberrations for the LBC camera is based on the geometrical method described by R. N. Wilson (1999).\textsuperscript{7} Highly defocussed images of stars (pupils) are analyzed and the aberrations are derived from quantitative measurements of their external and internal borders.

At the highest level of abstraction, the procedure for computing the aberration coefficients is composed of three steps:
Figure 2. Authors Diolaiti and Hill access the red-optimized prime focus corrector in front of the right primary mirror during alignment activities in November 2006. The telescope is horizon-pointing in this view. The corrector assembly is supported by a swing arm which can move the assembly out of the beam for observing with the Gregorian secondary mirror. Photo by Ray Bertram.
Figure 3. This 16-second $r'$ image from 28-May-2008 shows the extrafocal pupils from the center of the LBC-Red camera field which are used for focussing and collimation. This field is at low galactic latitude, so there are many more stars than seen in a typical field. This image is 2304 x 1408 pixels (8.6 x 5.3 arcminutes) from the center of the science array. The pupils marked with boxes are those selected for the active optics analysis with LBCFPA. In this field, selecting pupils which are not contaminated by adjacent stars was a non-trivial exercise. The highlights at the inner and outer edges of the pupils are the ellipse fits which are used to determine the geometrical shapes of the pupils.

- identification of candidate pupils to be analyzed;
- calculation of aberration coefficients from the candidate pupils;
- filtering and “sanity check” of results.

In the first step, a low order, two-dimensional polynomial is fitted to the background and subtracted from the image, then all pixels below a pre-defined threshold are set to zero. The resulting image is searched for “cells” of connected pixels. A simple test on the size and shape of these cells rejects those that cannot be single pupil images.

In the second step of the processing, all the pupil images selected in the first step are analyzed in turn. First an ellipse is fitted to their external border, found by means of the well-known Sobel operator. Then, the interior of the fitted ellipse is searched to find the “hole”, that corresponds to the central obstruction of the pupil. Again the Sobel operator is then used to find the border of the “hole”, which is also fitted with an ellipse. The fitted parameters are then used to derive the aberration coefficients.

Defocus is estimated from the mean external diameter of the pupil compared to the expected defocus from the motion of the primary mirror. Astigmatism from the difference between the major and minor axis of the
ellipse fitted to the external border. Coma from the difference between the position of the centers of the ellipses fitted to the internal and external borders. Spherical aberration from the ratio between the mean diameters of the internal and the external borders. Several coefficients are involved in these computations and have been determined through calibration procedures by applying known aberrations to the primary mirror.

In the final step of the processing, the aberrations computed from all candidate pupils are combined to derive a median value and reject outliers (e.g. resulting from an incorrect fit). A final sanity check is then performed to avoid sending too large corrections to the telescope. For example, we do not try to correct other low-order aberrations until the focus is roughly correct.

The next section describes some of the challenges we encountered to make this active optics program work practically on the sky without expert intervention.

**6. PRACTICAL ISSUES ON SKY**

6.1 Recognizing Aberrated Pupils

One of our earlier challenges was to develop software which could recognize aberrated pupils on an image with multiple stars present in the image. This was particularly a problem in the early days of the instrument when the telescope collimation tables were not well developed and the aberrations could include thousands of nanometers of wavefront focus or coma. The shape rejection described above does a quite good job of rejecting overlapping...
pupils from multiple stars. We are still struggling to find an algorithm that will reliably fit an ellipse to comatic pupils that resemble crescent moons with the dark edge below the detection threshold.

6.2 Seeing Dependence of the Edge Fitting

The next challenge has been to make the edge-fitting algorithm measure a pupil diameter (for focus and spherical) which is independent of the seeing blur. Our solution has been to estimate the seeing using the sharpness of the edge of the pupil, and then use this seeing estimate to apply empirical corrections to the measured diameter. The correction coefficients were calibrated from synthetic pupils that were artificially blurred.

6.3 Spherochromatism

We started focussing with the naive assumption that all extrafocal pupils would be the same diameter regardless of which broadband filter was being used since the broadband platescales were identical to a part in 10000. We quickly discovered that this was not the case. It turns out that residual Spherochromatism (the variation of spherical aberration with wavelength) in the corrector design causes the extrafocal pupil diameters to change significantly even across the wavelength coverage of a single filter. For each of the U, B, V filters, we report below the out-of-focus pupil diameter (in pixels, 0.225 arcsec) computed by Zemax for three different wavelengths: the first half-power point, the peak and the second half-power point. The diameter is computed as the intercept point of the marginal ray for an on-axis point source.

U: 60.25, 60.53, 60.99
B: 59.68, 60.73, 63.23
V: 61.41, 62.39, 63.56

Note that these pupils change diameter from 59.7 to 63.6 pixels over the bandpass of the camera which could lead to a focus error of 27 microns in the position of the primary mirror. Our practical solution to this variation is to always focus the camera in the same filter, and then calibrate conventional filter focus offsets for each of the other filters against this nominal focus position.

6.4 Poor Seeing Infilling the Central Hole

The next challenge is how to respond when the blur from poor seeing fills in the central hole in the pupil and modifies your measurement of spherical aberration. This was particularly challenging because the problem is cross-coupled to each of the previously mentioned challenges. Our first-order solution is to make the expedient choice to not make active correction of spherical aberration when the seeing is worse than 1.6 arcsec. The next solution is to identify that when you do not reliably detect the central hole, that is a sign of negative spherical aberration (bright near the center) that requires a +Z11 correction. We’ve also developed an algorithm that uses the radial distribution of light to estimate the spherical aberration when the fit to the central hole is in doubt.

7. LBT ACTIVE OPTICS RESULTS

Using LBCFPIA to make active optics corrections at prime focus allows the low-order Zernike wavefront terms to converge at the rms level of 150 nm per term (Z4, Z5, Z6, Z7, Z8, Z11) in average seeing. The variations can improve to 60 nm per term in the very best seeing conditions when averaging several pupils. These residuals appear to be composed of real variations from the atmosphere (16 second integration time), some known hysteresis of motion in the primary mirror collimation, noise in the mirror force adjustments (1-2 N), and noise from the measurements on the extrafocal pupils. Our experience has been that the figure of the primary mirror is quite stable with time, and that it is sufficient to correct only the low-order Zernike terms from focus (Z4) through spherical aberration (Z11). The largest variation we see overall is focus caused by both gravity deflections and temperature changes. The focus needs to be updated every few minutes using the collimation look-up tables, but adjustments relative to the look-up tables can be done at 30-40 minute intervals. The largest variation we see which is not corrected by the look-up tables is spherical aberration caused by thermal gradients in the mirror when the outside temperature changes rapidly. It takes the mirror ventilation system (45-minute time constant) about 4 hours to bring the mirror back to equilibrium when the outside temperature has changed 5 degreesC relative to the previous night’s observing. A significant change in the ambient temperature also induces
distortions in the telescope steel structure that require coma correction by the active optics system. We have not yet modelled these distortions in a look-up table based on the measured gradients in the structure. The higher-order aberrations of the primary mirror are stable relative to the measurements made under the Mirror Lab test tower before the mirror was brought to the mountain in 2004. Image quality delivered by the prime focus cameras has run the full gamut from 0.4 arcsec FWHM images that are undersampled by the 0.225 arcsec pixels, to really remarkably bad seeing behind a winter cold front of 4 arcsec FWHM.

8. ON-THE-FLY FOCUS AND COLLIMATION

Our original idea was to perform image analysis using one dedicated technical chip which is there near the focal plane of both LBC cameras. When we got to the telescope, however, we discovered that almost all the time the pupils acquired with that chip were unsuitable for analysis (basically, we were "in the caustic"). So we turned to a simpler method (simpler because it is based on "geometrical reasoning") using more defocussed pupils acquired with the science array (the higher defocus brought us out of the caustic). Thus LBCFPIA described above was born.

Considerable experience has been acquired in using LBCFPIA (and quite some efforts to make it work under varied conditions) over the past two years. We are now applying LBCFPIA to pupils acquired with the new technical chip (i.e. the one physically out of focus with respect to the science focal plane, without glass glued on it). Using the science array to measure the focus is tolerable at the beginning of an observation block when the telescope has moved to a new target field. It takes the observer three minutes to displace the primary, acquire an extrafocal image, analyze it, send the corrections, and move the primary back to the nominal focus position. However, interrupting the science observations every 30 minutes to maintain focus and collimation is a big penalty in efficiency. Thus, we are using one of the two technical (guider) CCDs on each prime focus camera to make active optics measurements. We are presently using 16 sec exposures on 20 sec intervals as a compromise between guiding speed and averaging the atmosphere for active optics. This system of active optics with the technical chips is just going into production on-sky as this paper is being written. These technical chips are 0.8 mm below the science CCD chips in the focal plane so they produce pupils which are a factor of 1.4 smaller than the 60 pixel diameter pupils that we typically create on the science array by displacing the primary mirror. Figure 5 shows a sample image of the pupils formed on the extrafocal technical CCDs.

9. PSF SUB-SYSTEM FOR COLLIMATION

At a high level in the Telescope Control System (TCS), active optics, focus and collimation are managed by the Point Spread Function (PSF) sub-system. The IDL program LBCFPIA described above sends the measured Zernike corrections through the Instrument Interface (IIF) to the PSF sub-system. PSF converts the Zernikes into collimation terms for the positioning of the primary mirror(s), and into force changes for the actuators that support the primary mirror(s) using pre-calibrated bending modes. See Martin et al. (2004)8 for details of the calculation and optimization of the support and bending forces. The PSF sub-system then passes the commands on to the PMC Sub-System which directly controls the primary mirror cell by communicating with a real-time VxWorks system attached to the mirror cell. For prime focus observing, the corrector hubs are fixed and all the
Figure 6. This screenshot shows the GUI interface of the PSF sub-system created by author Biddick. This GUI is used to collimate the left primary mirror and to provide feedback on the instrument active optics adjustments to the telescope operator. From the top right, the rows of information on the GUI start with the total collimation target position of the primary. All the rows below are summed to create the top row. These components include: the lookup table for the variation of the collimation with elevation, the variation of collimation with temperature, the active optics collimation corrections sent by the instrument as Zernike terms, instrument collimation offsets (filter offsets), pointing offsets and other terms not used in prime focus observing. The section in the upper left reports information on the position and support forces of the primary mirror. The section in the lower left allows manual input of Zernike terms for active optics in addition to the normal instrument interface for these terms.

Collimation and focus motion is handled by the hardpoints which position the primary mirrors. Tip-tilt, focus and coma can be corrected by either bending the mirror, or by adjustment of the mirror position. The PSF sub-system also manages the look-up tables for the mirror collimation as a function of telescope elevation and of temperature. Figure 6 shows the PSF GUI interface for the primary mirror collimation and active optics.

10. OTHER OPTIONS FOR PUPIL ANALYSIS

Tokovinin and Heathcote (2006) provide a useful summary of various techniques that can be used to sense wavefront aberrations with a single extrafocal pupil image. We experimented briefly with Tokovinin’s DONUT code and achieved useful results. We did not immediately adopt the DONUT code as it required manual selection of the pupil image to be analyzed, and because it was somewhat slow (on an average workstation) when analyzing the 60-pixel diameter pupils from the 8.4-meter aperture. It seems clear that both of those obstacles could be...
overcome with a bit more work in IDL. We are grateful to A. Tokovinin for providing a copy of the DONUT code to assist us in our testing.

11. SUMMARY

We have developed and implemented an active optics system for prime focus imaging at LBT based on a geometrical method of analyzing a single extrafocal pupil image. Low-order Zernike coefficients measured by the LBCFPIA program from the science array are fed to the primary mirror to optimize the image quality at prime focus. This system has been used for collecting science data for nearly two years. We continue to improve the system to make it robust and stable in a wide variety of atmospheric conditions. We are also implementing on-the-fly focus corrections using technical CCDs to avoid interrupting the science observations to make active optics measurements.

REFERENCES