PRIME FOCUS COMA CORRECTOR FOR THE MMT WITH "OFF THE SHELF" COMPONENTS

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ABSTRACT
A small prime focus corrector for the new 6.5 m MMT telescope has been built using small off-the-shelf optical components. Its purpose is to aid in initial tests of the primary mirror. At f/1.25 the paraboloidal primary is by far the fastest of any large telescope, and without correction the field and the plate scale are both inconveniently small. The corrector design is based on the Maksutov camera, with a concave spherical relay mirror and a refractive meniscus corrector to subtract the coma introduced by the primary mirror and balance out the spherical aberration from the relay mirror. The result is a 48 arcsec field at f/7 (220 μm/arcsec) with 80% encircled energy within 0.25 arcsec diameter (the uncorrected field is 6 arcsec). The instrument includes a CCD with 500x500 20 micron pixels (0.09" per pixel), a guide camera and provision for a fast wavefront sensor to measure mirror figure and atmospheric turbulence. The instrument was tested at the telescope before implementation of the active control of mirror support forces or the mirror air conditioning system. Nevertheless images with FWHM 0.53 arcsec were recorded.

Keywords: Prime focus, coma corrector, wavefront sensing, paraboloid primary tests

1. INTRODUCTION
The MMT has been rebuilt with a single 6.5 m diameter, f/1.25 primary mirror of borosilicate honeycomb glass structure. Several Cassegrain secondaries will provide a range of foci for wide field (1 degree at f/5) 1 and adaptive correction (an f/15 adaptive secondary 1.8 mm thick with 336 actuators) 2, 3. The primary itself, though rigid compared to existing 8 m meniscus mirrors, is provided with 100 actively controlled force supports. These are to be tuned according to mirror figure measured by a stellar wavefront sensor. In addition, a forced air ventilation system is to be used to bring the glass structure into thermal equilibrium, at ambient temperature, to eliminate mirror seeing.

Initial tests of the primary are being conducted directly at the prime focus. Because the primary is so fast, the raw field of view is very small, less than 6 arcsec for images less than 1/4 arcsec diameter. Also the plate scale is inconveniently small for critical sampling, 45 μm/arcsec. The amount of coma expressed in terms of wavefront coefficients versus field angle is shown on figure 2 (dashed line) 4. The full extent of the image is set by the coma and quarter arcsec resolution can only be obtained within 6 arcsec diameter field.

To aid in the initial set up of the telescope, we have built a small prime focus corrector to provide a wider field at a larger plate scale. Our goal is a resolution of 1/4 arcsec, to match good seeing conditions. The corrector we designed extends the field diameter by a factor 8, with 1/4" resolution inside 48 arcsec field of view. We took advantage of that field while testing the 6.5m primary recording the first light images. An image of the globular cluster M15 is shown in the last section of this article. The first section will describe the corrector concept design and fabrication while the following section will describe the camera, which was built around that corrector.

2. COMA CORRECTOR FOR THE MMT
2.1. Optical Design
There is little literature on extremely fast wide field correctors. The Subaru prime focus design which acts on a f/1.8 primary corrects a 30 arcmin field with 7 lenses 5. The f/1.14 prime foci of the LBT will be corrected over a similar field with fewer lenses where one is aspheric 6. This last design is based on the Wynne 7, 8 corrector which was inspired by the 3 lens Ross 9 corrector. These designs use rather large lenses in order to correct the large field. The design we present here use small lenses to correct a small field.

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The idea of the corrector is a Maksutov configuration with a concave spherical relay mirror followed by a meniscus lens with opposite curvature. The mirror reimages the focus to f/7, removing most of the coma while introducing spherical aberration at the same time. The meniscus lens then removes the introduced spherical. The optical layout is shown in figure 1, and the prescription is given in table 1. The performance is shown on figure 2. After the coma corrector the aberrations are limited to 3 waves P-V of spherical, 2 waves P-V of coma and 2 waves P-V of astigmatism at the edge of the 48 arcsec field diameter. For larger field the coma linearly increases with field angle but the astigmatism introduced mainly by the fast spherical mirror \((f/# = 0.8)\) but also by the meniscus lens increases as the square of the field angle and becomes predominant. This is also shown on figure 3 where the right figures shows the minimum resolution within a 2-D field region. The left diagram for the uncorrected case shows the resolution of 0.25" limited to inside a field angle less than 6" due to the coma effect. The right diagram shows that with the corrector and for the same resolution the field is extended by a factor 8. The astigmatism becomes clearly visible with the spot diagrams which were overlaid on that same figure.

Due to time and cost constrains the parts which enter in the fabrication of the corrector were purchased from catalogues. These parts needed some modifications in order to accommodate the design. The mirror M1 was bought as a lens and sent to be coated with silver, that produced a satisfying spherical mirror for our purpose but we noticed high order zonal distortions which are due to the lens polishing process. The meniscus lens L1 was fabricated by using two BK7 commercial lenses, one plano concave one plano convex. These lenses were glued to a 6mm window UBK7. The corrector was aligned in the lab by simulating the MMT prime focus with a microlens ball (R=1.5mm) used as a reflector near the telescope focus position on which 1mm collimated beam was sent. The laser source was located behind the mirror M1 which was drilled at its center to let a 1mm HeNe laser beam passes through and fall on the ball. Moving the ball is

<table>
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<th>Radius</th>
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<th>diam.</th>
<th>c</th>
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</tr>
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<td>13.6</td>
<td>BK7</td>
</tr>
<tr>
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<td>108.42</td>
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Table 1. Corrector Prescription in mm. where \(c\) is the conic constant and \(diam.\) is the clear diameter.

| M1 | MG LFF244 silver coated |
| L1 | MG LPK007 + Flat + SH 312314 |
| beamsplitter | SH 335520 |
| L2 | MG LA0019 |
| L3 | N KPX088 |
| L4 | SH 322286 |

Table 2. List of the Off the shelf corrector components part numbers
Figure 3. The right figure shows the minimum resolution within a 2-D field region. The left diagram for the uncorrected case shows the resolution of 0.25" limited to inside a field angle less than 6" due to the coma effect. The right diagram shows that with the corrector and for the same resolution the field is extended by a factor 8. For larger fields (> 48") the resolution start to decrease rapidly from 0.6" to 1" due the astigmatism as seen on the spots diagrams.

Figure 4. System drawing
equivalent to moving off-axis without introducing coma. In consequence the corrector when perfectly aligned with the ball off center generates opposite coma than the MMT primary. The alignment consists in minimizing the spherical aberration by adjusting spacing between the mirror and the lens and aligning the axis of the corrector with the center of the imaging camera.

2.2. Peripheral implementations

The output of the corrector is viewed with a 512x512 20 micron pixels detector covering a field of 52"x52". In addition to this imager we added a guiding leg to facilitate the object search specially in the case of faint ones. The faintest object the instrument might detect is 23-24 magnitude in a 1 minute maximum exposure time limited by the rotation of the image. The guiding leg is composed of 2 lenses, a 32 mm eyepiece and an 8mm camera lens that reimage the output image at f/1.8 which correspond to a 1.5 x 1.1 arcmin on a Electrim camera. The guiding leg is seen on the right of the figure 5. The optics can be exchanged for a relay optics which feed a Shack-Hartman wavefront sensor as shown in figures 4 and 6. These optics form a pupil image 1.73 mm on the 13 x 13 lenslet array inside the wavefront sensor dewar. The field of view is stopped down to 3 arcsec at the intermediate focus. The plate scale on the wavefront sensor detector is 0.372" per pixel. That translates into one pixel motion corresponding to 1.67 waves of tilt across each of the 50 cm subapertures. This relay was used to test the Shack-Hartman wavefront sensor at the MMT in order to record both static low order aberrations and atmospheric high order aberrations as described in McGuire 10. The components which enter in the fabrication of the corrector, WFS leg and guiding camera were also all purchased from catalogues. A list of these components is shown on table 2.

3. OBSERVATIONS

The first observing run with this instrument was performed on the 21 October 1999. During this time the primary mirror did not have thermal control and active support. In the absence of thermal control the support actuator electronics dissipates enough heat to raise the back plate temperature by 1/2 degree Celsius. The good data we have were obtained at the very beginning of the night when the mirror was close from equilibrium with the cooling air in the dome as given by Woolf 11. As the air cools down and the support dissipates heat the best image quality can only be achieved during roughly soon after dark. As a consequence best possible resolution could not been achieved during these tests. Nevertheless we obtained during that night 0.53" FWHM in part of the field we looked at, the bottom right corner of the figure 7.
Figure 7. M15 globular cluster 52"x52"

which presents a 52"x52" 5 sec exposure of the globular cluster M15. The image is the raw data we obtained with no color filter so the wavelength range is limited by the detector response (0.35 to 0.9 microns). This image was calibrated against HST images of the same sky region in order to determine the orientation of the image and the plate scale of our detector. The plate scale was found to be 0.1024 arcsec per pixel. The FWHM of the star on that picture range from 0.7 arc sec at the upper right and lower left corners to 0.53 arc sec at the lower right corner. The dominant residual error we see on this image is astigmatism which comes from the primary mirror not being tuned. Figure 8 shows a close up view of the double star which lies at the bottom right of figure 7. We clearly resolve the two stars which are separated by 0.635 arcsec on the HST plates.

3.1. Conclusion

The corrector that we designed and built within a few months greatly enlarges the MMT prime focus field of view, and allowed us to conduct useful test of the primary in its support cell on the mountain. Although the primary mirror was not thermalised and the support forces not tuned the achieved resolution was 0.53". Phase maps were obtained with the Shack-Hartmann during that same period and with the same instrument. We have found that the same type of corrector that uses an aspheric mirror with a meniscus spherical lens can be designed to correct very fast primaries over a wider field of view up to 5 arcminutes diameter where the elements would be less than 20 cm in diameter.

ACKNOWLEDGMENTS

We thank Bruce Fitz-Patrick, Steve West, JT Williams, Craig Foltz and the MMT team for making this work possible. This work was supported by grant F49620-96-1-0366 from the Air Force Office of Scientific Research to the Center for Astronomical Adaptive Optics at Steward Observatory.

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