Progress of the MMT Adaptive optics program

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ABSTRACT

The adaptive optics (AO) system for the 6.5 m MMT conversion telescope is the first to compensate the aberrated wavefront at the telescope's secondary mirror. This approach has unique advantages in terms of optical simplicity, high throughput and low emissivity. Its realization presents many technical challenges, which have now been overcome. The deformable mirror is now characterized and accepted. It features a 1.9 mm thick 640mm diameter convex aspheric mirror (manufactured at the Steward Observatory Mirror Lab), mounted on a 50 mm thick ULE reference body with 336 actuators, as well as a cluster of 168 DSP's and associated analog circuitry. A wavefront sensor with integrated CCD and lenslet array has also been completed. The complete system is now starting to produce laboratory results, which we present below. Closed loop operation is tested under an auto-collimation illumination system that reflects aberrated artificial starlight from the convex secondary.

Keywords: Adaptive optics, deformable mirror, reconstructor, closed-loop

1. INTRODUCTION

Work has been on-going for quite some time, to build an Adaptive Optics system for the upgraded 6.5m MMT (formerly Multi-Mirror Telescope). Recently, the project has gained momentum and exciting results have been achieved. Steward Observatory has taken delivery of its revolutionary deformable mirror (DM) which has been re-assembled, tested and mounted on the AO-system bench. The laboratory "first AO light" was achieved in July 2001 and the AO system is scheduled for its first engineering run on the MMT late this fall.

2. ADAPTIVE SECONDARY

The main characteristics of the DM used have already been presented (see for example 1 and 7). Following are the most exciting features of this element.

- The DM *is* the secondary mirror of the telescope, and its pupil, making the system highly optimized for thermal infrared observation (see 2) because of the radically diminished number of warm optical surfaces ahead of the science instrument.
- The DM actuators are of the voice-coil type. Each actuator is made of a coil attached to the reference body of the mirror and a magnet glued to the 1.9mm thick shell. The shell is suspended 50 micron from the reference body. This configuration provides for a mirror without the non-linearity and hysterisis associated with the existing DM's of piezo-stack type. This feature actually allows the mirror to be used as a static secondary, with the AO loop open.
- The DM has enough stoke to perform the tip/tilt correction, further simplifying the design.

The drawback of this design compared to existing technology is the complexity of the control system. Each actuator has a capacitive sensor and its associated conditioning electronics, and needs significant amount of computational power for closed-loop control. Thus, our DM is fitted with a cluster of 168 DSP to control its 336 actuators. To evacuate the heat generated both in the electronics housings and the coils themselves, a low pressure liquid coolantis used (water/ethanol mix). The figure below shows the components of the 6.5m MMT adaptive secondary and the telescope hub.

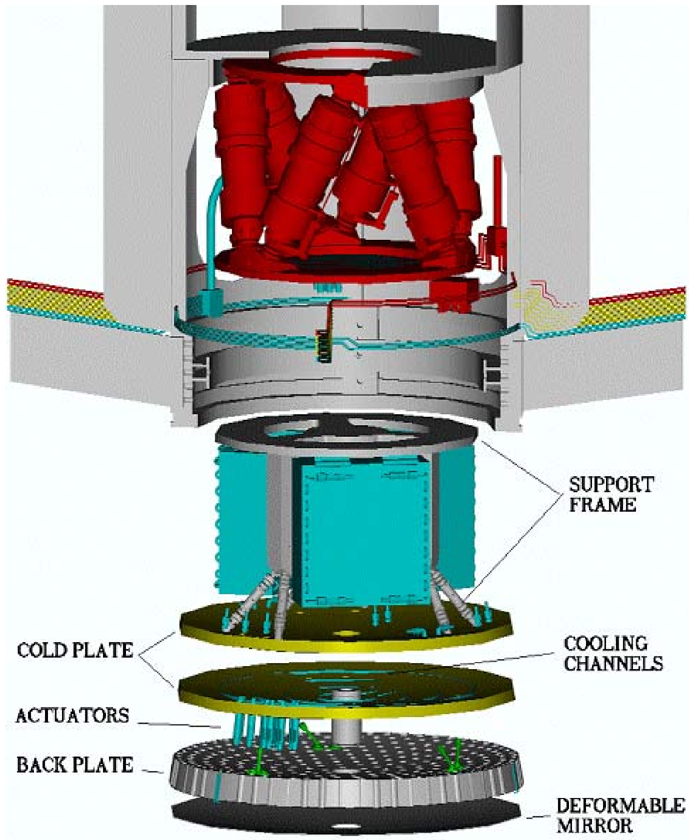

Figure 1. Diagram of the components of the 6.5m MMT adaptive secondary and the telescope hub. Note the power supply lines and the cooling lines running along the vanes holding the hub.

A position loop is implemented around each of the 336 actuators. A multi-variable feed-forward command allows both fast and stable response of the mirror, as can be seen in Figure 2. The feed-forward part of the control will provide the forces required to position the mirror, counter-acting the stiffness of the deformable shell, which vary linearly with increasing spatial frequency modulation (see Figure 3). This has two consequences: First the mirror is somewhat faster to respond to high order modes because the stiffness is known with better precision for these modes and the model error correction performed by the feed-back loop is less significant. The response time for low and high order modes vary by about a factor of two. The second consequence is that the power dissipated by the DM position control system is a sensitive function of the number of modes.
Reference 1 describes in details the dynamic behavior of the DM.

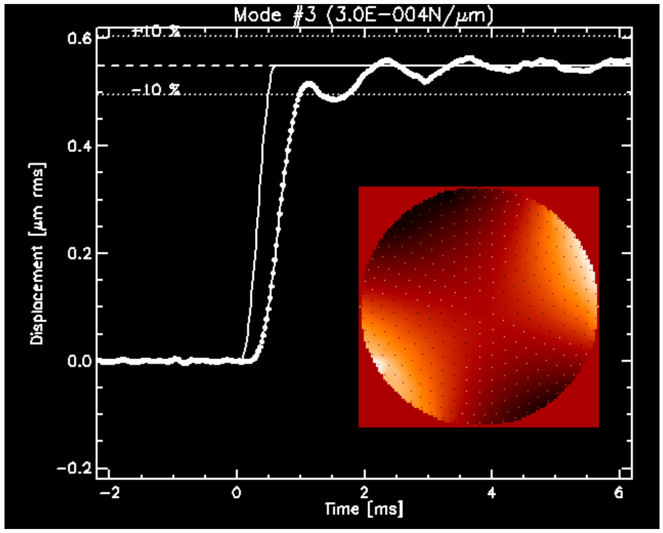

Figure 2. Adaptive secondary electro-mechanical step response. 10% to 90% response time is less than 0.5 ms

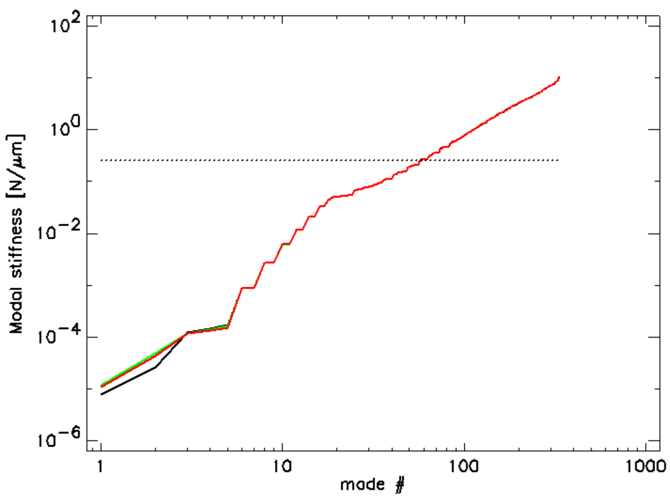

Figure 3. Adaptive secondary modal stiffness. Modes are numbered by decreasing eigenvalues. The position control system compensates for the mirror stiffness. Power dissipated in the actuators varies as the square of the forces.

The acceptance test of the DM included dynamic tests. A sequence of actuator commands corresponding to the correction of a frozen turbulence wavefront with Kolmogorov statistics was sent to the mirror. The wavefront parameters where r0=0.16m in V with V_s=6m/s. Refresh speed of the DM position was 1 kHz and the sequence was 8 seconds long. Turbulence strength was reduced from 2.3 μm to 0.140 μm. Figure 4 below shows a typical frame.

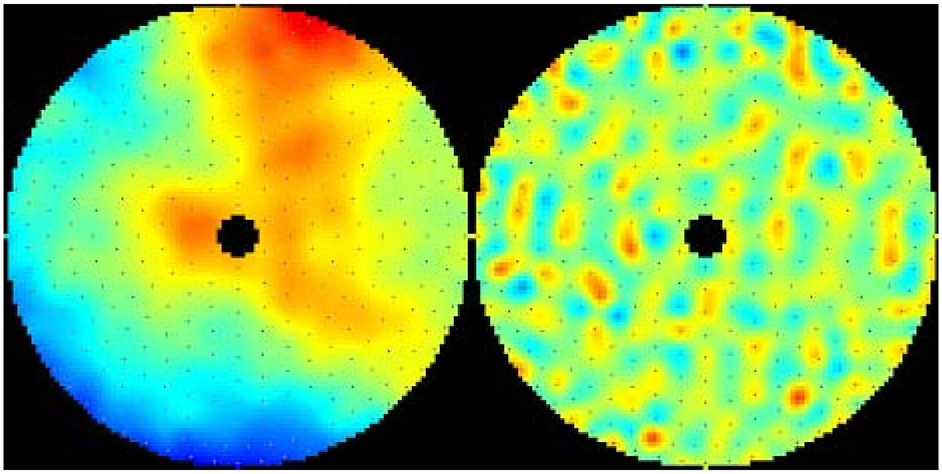

Figure 4. Image of a Kolmogorov turbulence spectrum imposed dynamically on the mirror and the total error (fitting and tracking) as measured by the capacitive sensors local to the actuators. The scale is 11 micron on the left and 1.1 micron on the side. rms values are 2.3 micron and 0.14 micron respectively.

3. WAVEFRONT SENSING OPTICS

Because of the particular configuration of the 6.5mMMT adaptive optics system, the wavefront sensing is separate from the wavefront corrector (aka the deformable mirror). A dedicated wavefront sensing assembly bolts to the 6.5m MMT field rotator as would any traditional instrument. Just ahead of the Cassegrain focus of the telescope, the visible part of the starlight is reflected into the wavefront sensing optics while the IR goes directly into the science camera. The beam-splitter IS the dewar window of the science camera, once again to diminish the number of warm surfaces.
The optical set-up is classic apart from the fact that the tip-tilt mirror visible just to the left of the wavefront sensor camera in Figure 5 is solely used to offset the guide star from the science object, the fast atmosphere-induced tip-tilt is taken care of by the adaptive secondary directly.
Worth mentioning is that the WFS camera is mounted on a motorized bearing. It can be counter-rotated when the field rotator is activated, in order to keep the registration between the actuators and the Shack-Hartmann 12x12 sub-apertures constant.
A description of the WFS unit can be found in reference 10. Its originality is to have a lenslet array that matches the detector pitch and which is glued directly onto the EEV CCD39 package. This makes for a compact, robust and alignment-free camera.
A point source at the main focus of the telescope is used to align the system. After alignment the residual wavefront error seen on the WFS is 30 nm rms, predominately in the high order modes. This includes the 26 nm induced by the misalignment of the lenslets array with respect to the CCD. This error can be calibrated out in the wavefront computer.
A San-Diego Sate University "Leach" controller using a fast read-out mode that can produce frames at 625 Hz reads the detector. This sets the maximal sampling frequency of the system.

Included in the WFS assembly a wide field visible camera is mounted on the optical table. This will give a 50' square field of view to help steer to telescope and acquire guide stars.

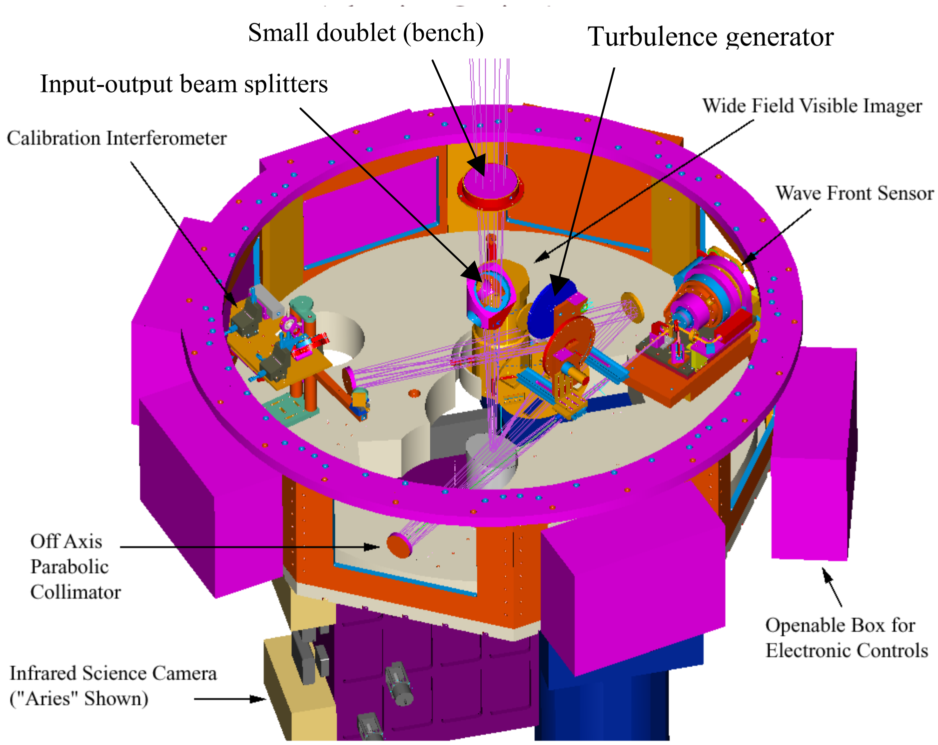

Figure 5. 3-D modeling of the wavefront sensing part of the 6.5m MMT AO system. This whole assembly bolts underneath the rotator ring at the Cassegrain focus of the 6.5m MMT. Also visible is the turbulence generator assembly, which light is folded into the beam by the beam splitter and sent to the adaptive secondary through the small doublet.

4. INTEGRATION AND TEST

Integration of our AO system is complicated by the fact that are two main optical units mounted at different locations on the telescope. To accommodate the deformable secondary and the wavefront sensing optics a large test bench was custom built. This bench features the same optical path between DM and WFS as the telescope and has optical elements allowing illuminating the system with an artificial star. This system has been presented in 9, 11 and 12.
Artificial turbulence can be added to the beam by two spinning machined Plexiglas plates and the wavefront can be analyzed at low speed by a visible phase shifting interferometer (PSI). This PSI is needed to perform the initial flattening of the mirror because the 12x12 sub-apertures of the WFS do not have the required spatial resolution. However, as pointed out in section 2, because of the stability of the capacitive sensors of the DM, this calibration only has to take place once.
The test bench optics are designed to work both with 0.594 μm and 1.55 μm laser light allowing wavefront sensing in the visible part of the spectrum and IR imaging at the direct Cassegrain focus.

For a successful integration, alignment of the test bench and flattening of the mirror has to be performed on one hand, while alignment of the WFS optics has to be performed on the other. After the two steps are completed, “mating” of the two optical systems is accomplished by using 2 fold mirrors to inject the f/15 focus at the correct location and direction from the test bench into the WFS optics.

5. FIRST LABORATORY CLOSED-LOOP RESULTS

For this fist time in this project's history, AO sharpened images where produced in the test bench in July 2001. The system was illuminated with a variable wavefront having r0≅0.20m in V and the optical loop was closed at 10 Hz using the calibration computer (not the real-time machine). A modal reconstructor using 100 modes was implemented and the "science" image was recorded on a commercial IR camera

The system proved to lock in every case and to stay closed as long as we would run the system. The performance obtained is outlined in Figure 6 below. The top part of the figure represents the uncorrected and corrected on a linear scale. The Strehl ratio is just above 20%, reflecting the fact that a lens installed to magnify the PSF in the IR camera introduces 0.2 wave of spherical aberration that is not corrected by the AO because it is located in the non-common path. I.e after the dichroic beam splitter. The Strehl expected with 0.2 wave of aberration is so close to the 20% we measure that it effectively hides any components that add in quadrature! After this measurement, the system was equipped with a better, diffraction limited lens but results are not available at this time.

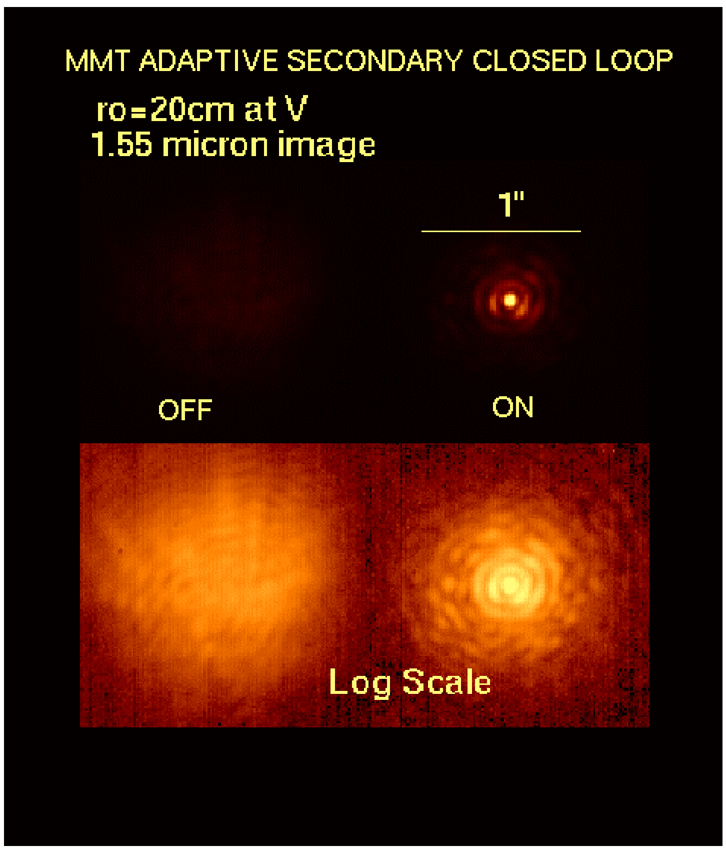

Figure 6. Laboratory first light image of the 6.5m MMT adaptive optics. As much as 3 Airy rings can be clearly observed on the logarithmic corrected PSF, demonstrating how well the wavefront is controlled.

6. FUTURE ACTIVITES

For safety reasons, the laboratory first light was made using a spherical deformable shell as the secondary mirror. Integration will proceed with the installation of the fully functional asphere shell that is now manufactured and coated. With an engineering run scheduled at the end of the year on the MMT, the AO team is now totally committed to the integration of the asphere shell, the integration the fast wavefront reconstructor, the implementation of the interface to the telescope and the preparation of the commissioning phases. ARIES, the new IR imager and spectrograph has been selected to be the instrument used during this fist run (see 13)

7. AKNOWLEDGEMENTS

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