Towards 1st light of the 6.5m MMT adaptive optics system with deformable secondary mirror

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1.Abstract

In this communication, we present the progress of the 6.5m MMT adaptive optics system. During the last part of 2001 and the 1st part of 2002, the system has been validated in the laboratory statically and dynamically with sample frequencies of up to 550 Hz. In June 2002, an attempt has been made to make this system work on the telescope but has been hampered by mechanical failures. However, ease of installation of the system and open-loop operation of the mirror was demonstrated at this occasion and offers reasons to be optimistic on the future of the system.

The MMT-AO system is the first AO system 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. Today, the deformable mirror is characterized and accepted. It features a 1.8 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 for position sensing and actuator driving. The system has been characterized in the laboratory at sampling speeds up to 550 Hz and had been integrated on the telescope.

Keywords: Adaptive optics, adaptive secondary, thermal infrared

2.System introduction

The adaptive optics (AO) system of the 6.5m monolithic MMT has already been presented in a number of communications [see for example 3 and 6] and we will only emphasize here its principal characteristics: The deformable mirror (DM) of this system is the secondary mirror of the telescope. This lay-out makes it particularly suitable for thermal infrared astronomy when the number of warm surfaces needs to be minimized and makes it also very attractive for multi-conjugate AO since the secondary is roughly conjugated to the strong ground layer [1].

Technology for building large, fast deformable mirrors with comparatively low actuators density is not readily available and its development is one of the major undertakings of this project. The 640mm diameter f/15 deformable secondary mirror has been built and characterized in the past couple of years and has performed very satisfactorily in the laboratory [2,3,4,7]. And we show some of its performance below.

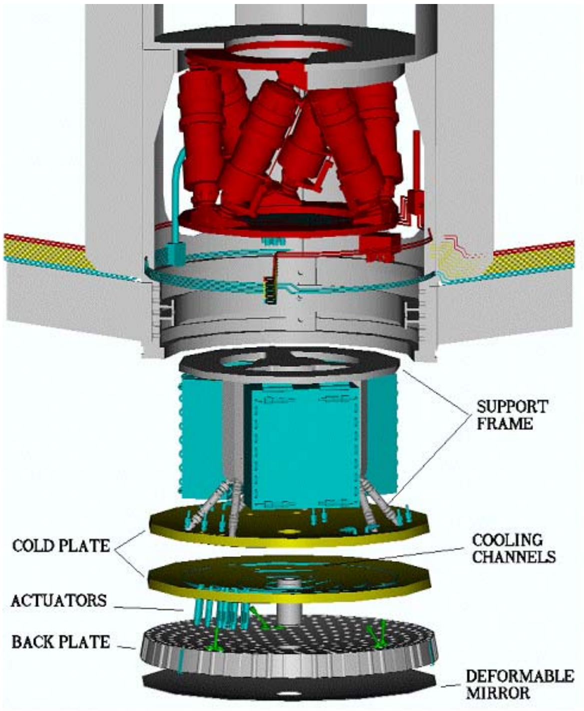
An AO system with a deformable secondary is intrinsically a distributed system. Unlike traditional AO system, it cannot be enclosed in a single box that acts as an optical "sharpener" between telescope and science instrument, with wavefront sensor and deformable mirror co-located. The DM is at the secondary while the wavefront sensor (WFS) package is located at the telescope focus, behind the dichroic separating the IR science beam from the visible WFS light. While this set-up is very promising from the performance point of view, it is quite challenging from the engineering point of view. On the MMT where the AO mode is only one of 3 possible telescope modes, the traditional solid secondary mirror has to be replaced with the deformable secondary at the beginning of each run, power and cooling connections to the DM have to be established and the DM and WFS co-aligned and registered.

In addition, as previously explained [3], testing of this distributed system in a laboratory environment is challenging in several ways:

1. Since the f-ratio of the beam has to be conserved, the test structure has to be of a size similar to the telescope itself (along the z-axis)
2. Illumination of the DM from the primary has to be replicated, which implies test optics larger than the secondary itself.

3.Deformable mirror breakdown

As a remainder, we review here the main elements of the deformable mirror. In this article, we define the DM as the functional ensemble implementing the function of a reflective surface controlled in position by 336 actuators.
It is made of a *support frame*, *3 boxes of electronics* hosting the 168 digital signal processors that implement to position control, a *cold plate* in which the 336 actuators are clamped, a glass *reference body* and a deformable glass membrane called "*shell*" in short.
The cold plate holds the actuators and removes their heat. A water circuit running through the cold plate and the boxes of electronics removes the heat generated by the coil actuators and their drive circuit.
The reference body provides a stiff reference surface against which the 336 sensors associated with the 336 actuators measure the local position of the shell



4.Performance in the laboratory

4.1. Laboratory set-up

Between April 2001 and May 2002, the DM has been tested and characterized optically in the laboratory using the test set-up described in [11,10,5]. This set-up is shortly described below for consistency:

1. A dual-laser artificial star (580nm 1550nm) is shone onto the DM through a computer-generated hologram (CGH) and a pair of doublets. The purpose of the CGH is to pre-correct for the 4000 waves of spherical aberration generated by the doublets.
2. Optionally, 2 acrylic plates with Kolmogorov turbulence machined into their surface can be inserted into the beam just before the CGH to simulate atmospheric turbulence [5].
3. The DM reflects the beam back through the 2 doublets after which it hits a dichroic filter implemented on the upper surface of the science dewar window.
4. About 8 meter from the DM, the IR light (1550nm) goes through the dichroic into the science camera while the visible light (590nm) goes through some relaying optics into the Shack-Hartmann WFS.

5. Before the dichroic, some of the visible light is fed into a phase shifting interferometer for static performance characterization.

This set-up has been used with a solid f/15 secondary for initial alignment, then with the DM fitted with a spherical shell [3] and finally with the telescope-grade hyperbolic shell. Experience has shown that the alignment of the AO optics and the test bench is quite complex and this is essentially to trace to the bench itself, with its numerous pieces of optics, some of them requiring tolerances smaller than the mid-term stability of the large test structure.

4.2. Static tests

The most important part of the static tests is the determination of the best achievable optical figure with the shell mirror and the determination of the best trade-off between the optical figure and the amount of force required from the actuators to obtain it. This operation is called "flattening", a reference to the fact that we are trying to generate a flat wavefront in the pupil plane just ahead of the WFS lenslets.

The procedure used to flatten the shell is the following: First bring the wavefront within the capture range of the interferometer by manually applying corrective modes based on visual analysis of the PSF at the f/15 focus, then use an iterative modal decomposition of the residual error measured by the interferometer and correct until the residual error is satisfactory, without the flattening forces being to big. The modes used during this phase are the bending modes of the shell as determined during the measurements of the feed-forward matrix [4].

The figure below is the best wavefront obtained with the aspheric shell: The rms wavefront error is 88nm and is goes down to 60nm if the 3 manufacturing artifacts at the edge are removed. The average force to hold the weight of the shell is 0.072N/actuator rms. The rms force to produce the flat (and hold the weight) is 0.080 N/actuator using 150 modes

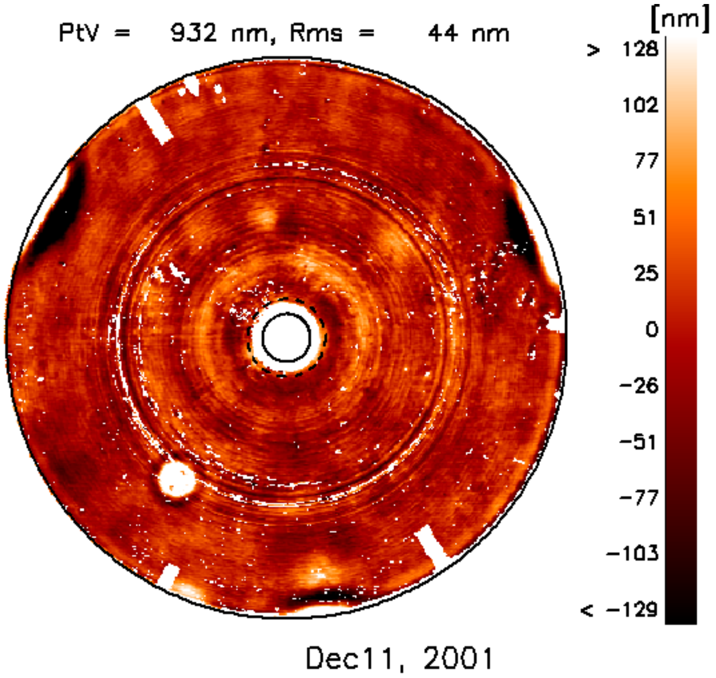


Figure 1. Best flat using 150 modes for the correction. The 88nm rms wavefront error goes down to 60nm if the 3 manufacturing defect at the edge are discounted. The 3 square indentations at the edge are fiducials while the round void at the lower left is a defect in the bench optics. Flattening forces are 0.035 N/actuator rms while gravity forces are 0.072N/actuator rms.

4.3. *Dynamic tests*

These tests address both the dynamics of the DM itself and that of the AO loop.

The step response time of the DM using the spherical shell has been shown to be 1-2 ms depending on the mode applied, with the sloppy modes being the slowest [4]. The step response using the aspheric shell is the essentially the same since the only difference between the 2 configurations is the shell itself. And while the 60μm of spherical departure represent a lot of spherical departure from the optical point of view, they are only a small fraction of the 1.8mm of shell thickness. However, the magnets glued on the back of the aspheric shell tuned out to be some 10% weaker that the ones glued on the spherical and some adjustments of the DM control parameters were required to obtain the same speed.

As far as the AO loop dynamics is concerned, it is dominated by sampling time of the WFS camera controller and the optical loop controller, which is a simple integrator. As shown in the figure below the response time is in the order of 10ms at 550 WFS frames/s. The maximal rate of the WFS is 650 Hz which can speed up the response by 10-15%. It is worth noting that our reconstructor permits the implementation of a FIR with up to 5 taps and we will use it to experiment with various types of predictors.

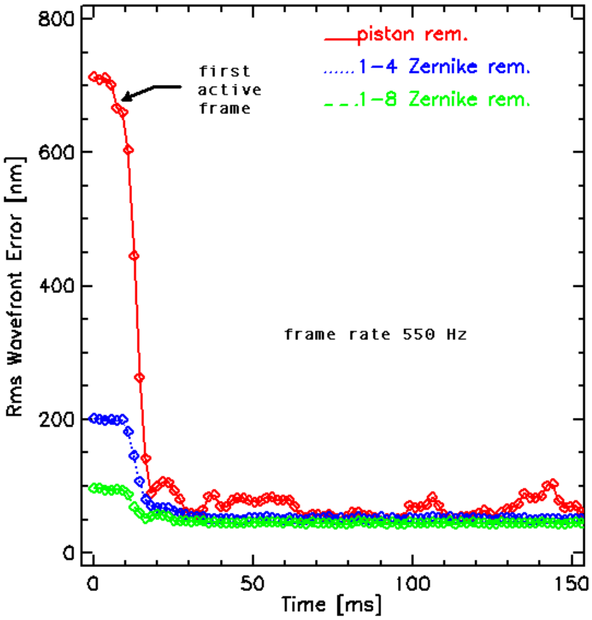


Figure 2 Typical residual error curve at the time the AO loop is turned ON. The system 10%-90% rise time is ≅ 10ms.

5.Integration and tests at the telescope

As pointed out in chapter 2, integrating an adaptive secondary AO system on a telescope is a major undertaking because major elements of the telescope have to be interchanged, in particular the secondary mirror. In the situation of the MMT, this is rendered even more challenging by the fact that an AO mission is considered like a mission with an ordinary instrument and the telescope has to be converted back to the traditional (i.e. solid) f/9 secondary configuration at the end of the run.

This situation was not only evaluated from the aspect of extra manpower but also from the risk point of view. Since, the MMT AO system is optimized for the thermal infrared, the secondary is the stop of the optical set-up. Therefore, there is no mechanical structure around the secondary and the edge of the glass shell is totally unprotected mechanically. Handling the DM ensemble is very risky indeed. This is why a protective cover was designed for all manipulation phases and it is only removed when the complete system is ready for optical alignment or AO work. This cover is guided on 4 rods so that even the possibility of hurting the shell with the cover is minimized.

In addition, a temporary rail system in installed on the hub when the DM is installed. A holding bracket is used to haul the DM to the hub and when at the proper location and this bracket attaches to sliders on the rails. The DM is then slid into the hub where it is bolted and connected to the power, data and coolant lines.

In practice, the installation of the DM into the hub turned to be straightforward even if somewhat strenuous. For various reasons (see below) the DM was installed and removed from the hub a total of four time within 10 days during the 1st light mission without damaging it nor anything else.

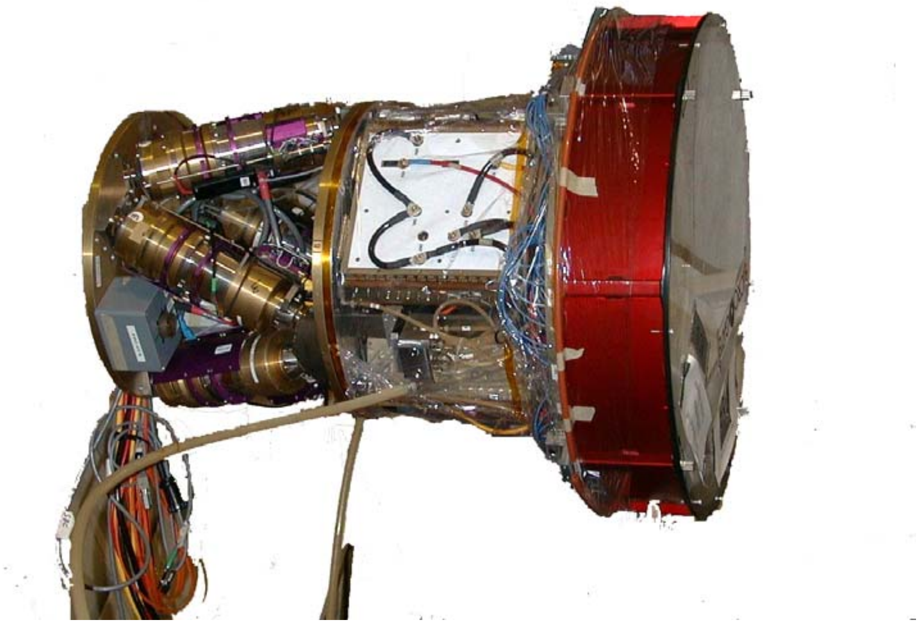


Figure 3 Deformable secondary (right part) attached to the hexapod that allows its positioning with respect to the primary. The mirror itself is protected by a cover (vertical cylinder at right) and the rather extensive cable wrap can be seen hanging below. This complete ensemble is installed into the telescope hub.

Unfortunately, throughout the run, we were hampered by coolant leaks at the DM cooling plate level. This was a real surprise because not a single leak had been observed during over a year of intensive lab. operation. The DM started leaking already during the pre-integration at the telescope site. At first, a selective shut-off of certain cooling channels was attempted. This solution seemed to work but we discovered later as the DM was already on the telescope, that other channels had started leaking. The only solution that we could implement during the timeframe of the mission was to disconnect the cold plate from the cooling circuit, leaving only the electronic crates actively cooled.

More problems appeared as we were trying to repair the coolant leaks: While the first functional test after installation in the secondary hub showed that the DM was working properly, it rapidly appeared that the gap between the reference body and the shell was contaminated by dust as the nominal 40 µm gap could not be obtained. This turned out to be a recurrent problem during the first half of the run and had a sever impact on the schedule for the following reason: The tools and procedures developed to handle the delicate and very expensive shell where meant to operate when the DM was in vertical position, looking down. However, on the telescope, the only possible access to the DM was when the telescope was pointing horizontally, and therefore the DM pointing horizontally also. This meant that the removal of the entire DM from the telescope hub was required before the shell could be removed to clean the gap and that cost us a lot of time and energy.

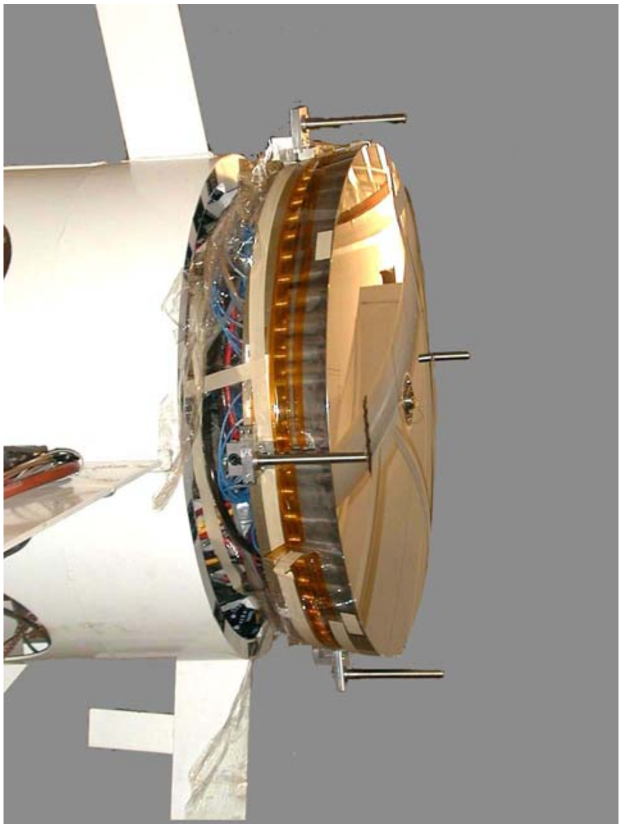


Figure 4: The adaptive secondary mounted in the 6.5m MMT telescope hub. Apart from the four cover support rods and the 4 spider vanes, nothing is obstructing the pupil. The four rods are nominally removed when doing scientific observations on the sky.

The loss of actuators cooling of course, severely degraded the possible performance of the DM but it did not preclude using it at all. Indeed, the energy dissipated by the actuators is highly dependant on the numbers of modes corrected on the mirror and on the optical figure of the relaxed shell. It turns out that the energy dissipated to figure the DM statically is just above 20W, which increases the temperature of the "cold plate" by of 10 °C given the good thermal insulation of this element with respect to the rest of the DM structure. Of course such an increase would have dear consequences on the dome seeing but would still make basic optical measurements possible.

The last and fatal blow to the mission was the discovery of an incorrect spacing between the telescope primary mirror and the DM. Calculations based on the estimation of the actual Cassegrain focus location showed that the DM was too close to the primary by 12.5mm and this was larger than the throw of the secondary hexapod. This problem was not discovered in the laboratory because the hexapod there had a much longer throw and its extension was never measured. No possible way of increasing the primary-secondary distance during the duration of the run could be identified and the crew was left with a couple of nights to use to characterize whatever part of the system was operable and in particular the DM in open optical loop.

For several hours, the DM was optically figured and the telescope was pointed at various azimuth and elevations. The position error of the actuators as well as the force put in by the 336 position controllers was recorded. In addition to the fact that this demonstrated the capability of the DM to operate in the telescope environment with wind and dust, it showed that the DM figure was only deformed by ±30 nm peak-to-valley by windshakes (10-20 nm rms wavefront).

5.1. Lessons learned

Despite the different problems that we encountered during the first telescope mission, the confidence in the system is actually larger than before. The problems faced are well understood and are being addressed by design changes and procedures modification. In particular, the telescope hexapod and the DM are being shortened to allow proper focusing and a cooling circuit external to the “cold plate” is being implemented. A new cold plate with a better leak-proof design will replace the existing one as soon as there is sufficient time for a major refurbishment.

Below is a list of the major lessons that can be drawn from the first mission to telescope

- It is possible to a mount, operate and dismount the Adaptive secondary without breaking it! This sounds trivial but is actually not so. The DM is a instrument of formidable complexity from the optical, electronical and metrology point of view. Devising safe and effective procedures for installation and operation was a significant challenge. Four installations on the telescope have proven that the DM is robust enough and that the procedure is safe.
- We have not found evidence that the all-important gap between reference body and shell becomes contaminated by airborne particles from the side of the shell. The DM seems to be able to operate for extended periods of time without the wind pushing particles into the gap. Due to the location of the dust grains, we suspect that improper cleaning and handling during the installation resulted in dust accumulating in the DM structure and subsequently falling into the gap along the actuators. To prevent gap contamination in future missions, a hood is being designed around the DM and handling procedures are modified to improve the cleanliness in the integration and installation phases.
- With some bad luck, the DM can need a lot of handling. Efficient tools and procedures are needed. Special tools for the removal of the shell on the telescope (i.e. with DM pointing horizontally) have been produced and tested already. In addition, connection of the DM power and coolant lines which proved to be time consuming and prone to errors have been simplified and rendered safer by use of keyed connectors
- The DM is operable even with a significant number of failed actuators. Unlike traditional piezo-stack deformable mirrors, the technology used in the deformable secondary allows failed actuators. In the 1st type, if an actuator fails, it creates a local hard point at its location that will create a sharp bend in the mirror and can lead to breakage. In the 2nd case, a failed actuator creates a local soft point that will average the position of the surrounding actuators. Excellent closed optical loop results were obtained in the lab with 6 actuators off, during the MMT mission, we lost another two with minimal impact on the figure and no impact on the response.
- The failure of the cooling circuit in the cold plate forced us to realize that the required cooling of the actuators is modest with the number of modes used by the reconstructor today. On the other hand, replacing the cold plate with one of a better design requires a complete tear-down of the DM including all actuators. Therefore, a simplified cooling system is installed already to cover the need of the next few runs. A cold plate with buried copper cooling pipes is manufactured and will be installed in the DM at the next opportunity.
- It is good to be at able to test such a challenging system at a telescope like the MMT. The convenient location allows to rely on the services and goods one finds in a large city like Tucson, and the policy of the MMTO is to offer close support to experimenters. We were able to make use of the various facilities there including the machine shop.

6.Future plans

The team already is busy preparing the AO system for a 2nd mission. Two goals are pursued: The correction of the problems observed during the 1st mission and the extension of the capabilities.

6.1. Correction

In this area, we are drawing from the lessons learned:

1. Shortening the deformable mirror and the secondary hexapod to correct the focus problem

2. Implement a heat sink for the cold plate. A cooling line will run around the cold plate. It will carry small copper tabs that will be pressed against the cold plate edge, essentially removing the cooling function from the cold plate and leaving it with only the structural function
3. Fabrication of a dust-protective envelope that will always accompany the DM whenever it leaves its clean room.
4. Install power connectors to speed-up installation
5. Install a larger power supply to compensate for the larger losses in the longer cables installed on the telescope.
6. WFS optics are being recoated. Due to schedule constraints this was not done for the 1st mission and is now overdue

6.2. Extension

Extension of the capabilities is taking place essentially in the software area. The depth of the real-time telemetry is being augmented so that many minutes of WFS and mirror data can be stored in real-time. This should be enough for typical science exposure and offers the possibility of using the WFS data for the deconvolution of images. In addition, a procedure to permit the measurement of the interaction matrix on the sky is being developed and will be implemented. This technique is potentially useful to compensate for the fact that unlike in traditional AO system, an artificial star cannot be shone into an adaptive secondary system to calibrate the interaction matrix.

Work is also going on in the area of science instrument integration with the goal of controlling the AO and the telescope directly from the instrument user interface.

7.Conclusion

Although the first telescope mission of our system was not quit a success, it has actually increased the team's confidence in the system. Installation and pre-alignment of the DM were accomplished several times with success and the duration of these operation was in line or shorter than what we had anticipated. Installation and alignment of the top box was also easy and fast. Most the software including the real-time reconstructor (run with a gain of zero) was successfully run at the telescope.

8.Acknowledgments

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