# Lessons learned from the first adaptive secondary mirror

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## ABSTRACT

The adaptive optics system for the 6.5 m MMT, based on a deformable secondary mirror, has been on the sky now for three commissioning runs totalling approximately 30 nights. The mirror has begun to demonstrate uniquely clean point-spread functions, high photon efficiency, and very low background in the thermal infrared. In this paper we review the lessons learned from the first few months of operation. Broadly, the hardware works well, and we are learning how procedures related to operation, system error recovery, and safety should be implemented in software. Experience with the MMT system is now guiding the design of the second and third adaptive secondaries, being built for the Large Binocular Telescope. In this context, we discuss the general requirements for retrofitting an adaptive secondary to an existing large telescope. Finally, we describe how the new technology can support the design of adaptive optics for 30-m class telescopes, with particular attention to ground-layer adaptive optics (GLAO), where conjugation as close as possible to the turbulence is important.

**Keywords:** Adaptive optics, adaptive secondary mirrors, extremely large telescopes

## 1. INTRODUCTION

To date, almost all astronomical adaptive optics (AO) systems introduce wavefront compensation at a deformable mirror (DM) placed at an optical conjugate of the telescope's entrance pupil. This requires a train of optics, first to form an image of the pupil on the DM, and then to bring the light to the corrected focus. The one exception to this paradigm is the AO system recently put into operation at the 6.5 m MMT. In this system, wavefront aberrations are corrected at the secondary mirror of the telescope itself, eliminating the need for the succeeding optical train.

Implementing the adaptive secondary mirror (ASM) at the MMT (figure 1) has been technically difficult, but there is strong scientific incentive to undertake the challenge. Reducing the number of optical surfaces in the light path improves the telescope's optical throughput while reducing thermal background radiation,[1] an important consideration for imaging and spectroscopy at wavelengths longer than 2.4 $\mu$m. In addition, the actuators employed on the MMT secondary have large stroke and no hysteresis, while providing feedback on their position in real time to the control system. These features are crucial in delivering point-spread functions (PSFs) of great cleanliness and stability, removing the need for independent tip-tilt correction, and enabling chopping to improve thermal IR sensitivity.

After three commissioning runs in November 2002, and January and May 2003, the MMT's ASM has been shown to operate very successfully. Controlling just 52 modes of the aberration, H-band Strehl ratios of around 20% are achieved, limited entirely by vibrations in the telescope structure at $\sim 20$ and $\sim 40$ Hz which have yet to be fully diagnosed and eliminated.[2] The telescope's thermal emissivity has been measured at 7%, competitive with any IR optimized telescope even without AO. PSFs obtained at H, M, and N bands show only very small effects of systematic errors in the figure of the ASM (figure 2), which appear as small asymmetries in the illumination of the outer Airy rings.

During those runs, we have learned much about the ASM's performance, its operational requirements, and its robustness in the real environment of the telescope. We describe in this paper the major lessons to be drawn

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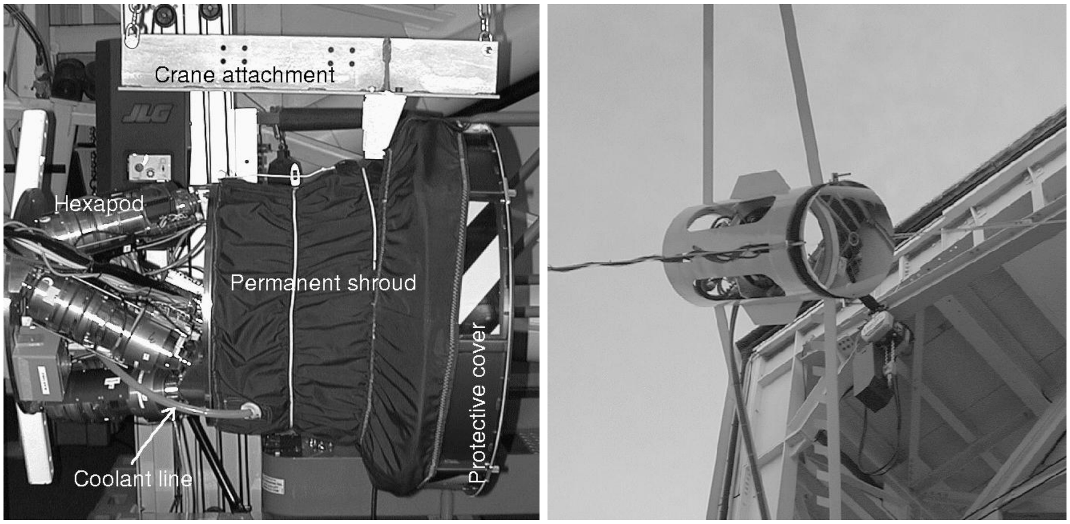


Fig. 1. The ASM ready to be lifted into the telescope's secondary hub (left) and mounted on the MMT (right).

from our experience, and how they can be applied to the implementation of ASMs on existing and future large telescopes. We also discuss the application of ASMs in the compensation of boundary layer aberration, for which they are uniquely well suited.

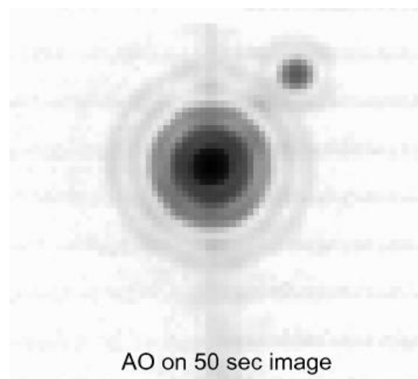


Fig. 2. Image of the binary star $\alpha$ Tauri recorded at 11 $\mu$m. Strehl ratio $\approx$ 98%. Six Airy rings are visible in this logarithmic stretch. The horizontal lines are residual detector artifacts.

## 2. QUESTIONS ANSWERED BY THE MMT ASM

A number of concerns regarding the ASM's ability to control wavefront aberrations accurately have been addressed in experiments in the laboratory and at the telescope. For a review of the ASM hardware itself, we refer the reader to the paper in these proceedings by Brusa et al.[3] Briefly, the ASM is a continuous glass membrane 642 mm in diameter and 2 mm in average thickness. The shape of the membrane is adjusted by 336 voice coil actuators with $> \pm 10$ $\mu$m stroke. Actuator positions are controlled by 168 digital signal processors (DSPs) located immediately behind the mirror. Control is on the basis of capacitive position sensors colocated with each actuator and read by the DSPs at 40 kHz. On each cycle of the optical loop, the average capacitive sensor readings are made available to the reconstructor computer.

### 2.1. Mirror Responsiveness

As for any DM, the ASM is required to change its shape rapidly in response to commands sent from the wavefront reconstructor computer, so that it does not limit the overall frequency response of the AO system. Overcoming the natural resonances of the thin glass membrane has therefore been a key goal in the design of the ASM. Several hundred bending modes of the glass have resonant frequencies below the 550 Hz update rate of the AO system servo loop, and without some way to damp these, the glass would oscillate uncontrollably as drive signals were sent to it. Passive air damping is implemented by placing the glass membrane just 40 $\mu$m from a 50 mm thick rigid ULE substrate (figure 3). With the resonances heavily damped, DSP control of the actuator positions can be applied with high gain, making the actuators effectively very stiff. In addition, to minimize the excitation of these modes, the actuator driving signals are low-pass filtered by the driver electronics before being applied. In other respects though, the control algorithm for the AO loop can safely ignore dynamical effects in the mirror.

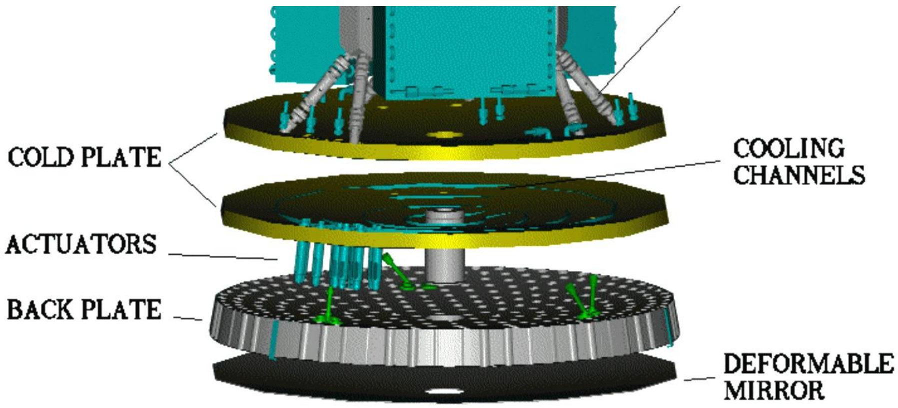


Fig. 3. Solid model of the lower components of the ASM in exploded view. In operation, the gap between the deformable mirror and backplate is normally maintained at an average of 40 $\mu$m.

Examples of step responses by the ASM to modal commands of low and high spatial frequency are shown in figure 4. Although the lowest frequency modes are slightly overdamped, the time to reach 90% of the commanded position is 1–2 ms in both cases, fast enough to implement control at the full speed allowed by the WFS camera. We note in particular that the response time is not a strong function of modal spatial frequency because of the very high stiffness of the voice coil actuators when operated in closed loop about the capacitive position sensors. The high stroke and fast response allow the ASM not only to control atmospheric tilt errors, but also to implement chopping, which can greatly increase the sensitivity of imaging in the thermal IR where atmospheric background fluctuates very rapidly.

## 2.2. Operation as a Rigid Secondary Mirror

Given the inherently very floppy nature of the ASM's reflective surface, it was not initially clear how the mirror would behave when commanded not to move in the face of wind buffeting and changing gravity vector. Poor performance in this area would prevent conventional seeing-limited use of the telescope with the ASM mounted. We find in practice though that this is not a concern. The response to wind has been tested by commanding

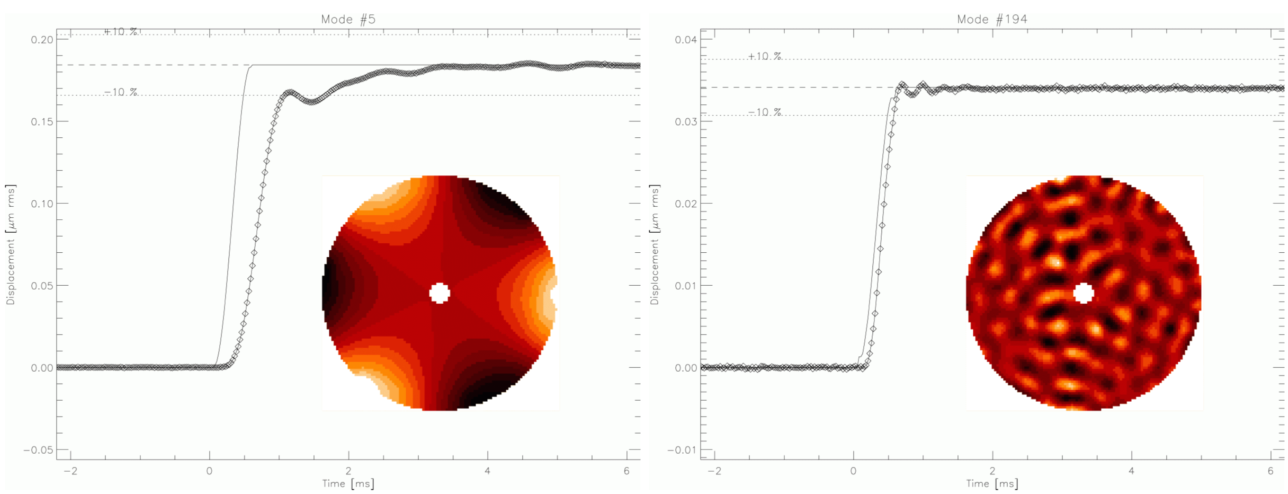


Fig. 4. Response of the ASM to commands imposing a mode of low (left) and high (right) spatial frequency.

the ASM to hold position with the MMT pointed into a wind of $\sim$ 7 m/s. Under these conditions, the RMS wavefront deviation caused by motion of the mirror surface is $<$ 20 nm, about 2 orders of magnitude below the uncorrected atmospheric aberration.[4] We note also that the AO system has successfully closed the loop with surface winds as high as 15 m/s.

In tests that explored the ASM motion with telescope elevation angle, no detectable motion was seen by the capacitive sensors down to 30° above the horizon. This indicates that the separation between the glass membrane and the 50 mm reference plate is not changing. Examination of closed-loop images in H band shows that approximately 50 nm of astigmatism is introduced as the telescope moves from zenith to 30°, which we believe is atributable to flexure of the reference plate itself. Since there is no active control of the shape of the reference plate, this error will need to be removed by introducing offsets in the WFS centroids, as is currently done to compensate for non-common path errors between the WFS and the science focal plane.

### 2.3. Robustness against a Harsh Environment

Unlike the DMs in typical astronomical AO systems, the ASM must operate in the open air environment of the telescope chamber. It is subject to much handling, airborne particulates, and to a wide range of temperature and humidity. The greatest concern before commissioning was that small dust particles would find their way into the 40 $\mu$m air gap that provides the essential damping of the glass shell's resonant modes. Indeed, during the installation in July 2002, when the ASM was inadequately shrouded against particulates, dust contamination was seen, preventing operation of the mirror.[5] The entry path for dust was identified as the holes in the reference plate that accommodate the actuators. Since then, the entire electronic assembly has been protected by a sealed shroud of material that has successfully prevented further contamination.

Since the capacitive position sensors are fully exposed to changes in temperature and humidity, care was taken in the design of the amplifier circuit to guard against concommitant changes in calibration. This has been successful, and we see no evidence of calibration changes between telescope runs in winter and summer.

Also of concern prior to commissioning was the power dissipation from the actuators, their driver amplifiers, and the DSP electronics. In total, this is on the order of 1 kW, depending on prevailing seeing. Liquid cooling removes waste heat with a 50/50 mixture of methanol and distilled water at 13 liters/minute flow rate. Care must be taken with the coolant because it will sustain a flame, but in the event of spillage onto any optical surface it will evaporate with no residue. The cooling system holds the optical surface to within $\sim$ 1° C of ambient temperature, but the external surfaces of the electronics crates rise to $\sim$ 10° C above ambient because of inadequate thermal coupling between the circuit boards and the internal coolant pipes. This will be addressed in a future refurbishment, yet for the present we see no evidence from recorded WFS images of any thermal plume rising from the ASM.

The ASM is by design very tolerant of actuator failures. To date, the mirror has not been controlled in closed loop with more than 80 modes, far fewer than the 336 actuators. Although we anticipate using more modes with a future higher order WFS, at present many actuators could fail, provided their distribution across the mirror were sufficiently random, before fitting error worsened noticeably. Since there is no mechanical coupling between the actuators and the glass membrane, a failed actuator behaves as though it were simply not there, and the glass floats over the top as neighboring actuators move. Furthermore, the modes used to control the wavefront are not the usual Zernike polynomials, but instead the natural bending modes of the glass as driven by the functional actuators. In the event of an actuator failure, these modes are recomputed, thereby minimizing the residual fitting error.

So far, the ASM has suffered a loss of 13 actuators. Of these, 9 were lost when a leak developed in the cooling system in July 2002. Since then, the cooling system has been reworked and no new leaks have occurred. Nine of the 13 actuators revived of their own accord, and the ASM now has 4 dead actuators, with no losses sustained during the last 3 telescope runs.

### 2.4. Operational Procedures and Needed Improvements

The important advances in our understanding of the ASM have been made in the context of a very cautious approach to commissioning the MMT AO system. At present, two people are required to operate the system. In addition to the usual AO operator, responsible for system setup and closed loop operation, a dedicated ASM operator is responsible for mirror operation and safety. Furthermore, a number of operational limits, described below, have been set conservatively. Our goal over the next year is to eliminate the need for the ASM operator by encoding many procedures now done by hand into software, and relaxing some limits to allow more robust closed-loop operation.

System parameters that are currently monitored and limited in hardware or software include:

*Power dissipation.* Total power dissipation in the actuators is limited by a current limiting circuit in the drivers' power supply. In addition, a hardware current sensor on the power supply lines will shut down the ASM in the event that a preset current limit is exceeded. The limit corresponds to an acceleration of 0.25g away from the reference plate (downward in the normal zenith-pointing position). This is designed to prevent excessive force being applied to the glass membrane as it rests on four very small restraining clips. So far, the current limit has never been exceeded with the ASM in operation.

*Peak force applied by any one actuator.* At the output of the real-time reconstructor, software checks ensure that actuator forces exceeding a preset value are never sent as commands to the ASM. Presently, if such a condition is detected, the AO loop is opened, and the ASM put in a "safe" mode in which all actuators pull the membrane against the reference plate. We find in operation that this criterion is generally too conservative, and in future a more sophisticated algorithm, now being designed, will be used to limit excessive force. Peak force will be clipped, but forces at this limit will be allowed for a small number of actuators and a limited number of successive cycles of the AO loop.

*Temperature inside the DSP crates.* Temperatures are continuously monitored inside the three electronics crates containing the analog and digital logic circuits. If the temperature rises above 40°C, the ASM either will not start, or will shut itself down. This guards against damage in the event of a failure in the fluid cooling circuit.

*Power supply voltages.* Voltage supplied to the digital electronics is monitored by a sense line that automatically adjusts the level to account for variability in dissipation in the transmission lines. These are approximately 20 m long, so ambient temperature changes can significantly affect their resistance.

In addition, procedures are in place to guard against mishaps dangerous either to the ASM itself or to its functionality, and to recover in the event of a failure in some part of the telescope or AO system:

*Installation on the telescope.* Unlike the DM in a typical AO system, the ASM must be mounted and unmounted from the telescope for each AO run. When not on the telescope, the ASM is bolted to a wheeled cart. For installation, the cart is maneuvered below a crane at the front of the horizon-pointing telescope. The ASM is attached to the crane, the secondary mirror alignment hexapod attached, and the assembly lifted for insertion into the secondary hub. Throughout the operation, the ASM is never subjected to any shock $> 1.5$g. The safe limit for the glass membrane is calculated to be 2g.

*Preserving the air gap.* Preventing contamination of the 40 $\mu$m air gap by dust is essential. A shroud is permanently wrapped around the electronics assembly, and when not in operation, a sealed aluminum and plexiglass hood is placed over the mirror (see figure 1). When the telescope is slewed to horizon, which must be done to replace or remove the hood each night, the mirror is held in safe mode, closing the gap against the intrusion of dust. At present, this is done by hand; in future, the AO system will be commanded by the telescope control system software prior to a move below 30° elevation.

*ASM initialization and recovery.* Before the mirror can be operated in closed loop, the actuators must be set to their nominal positions. Presently, this procedure, which takes several minutes, is initiated by hand and must be performed each time the ASM puts itself in safe mode for any reason. In future, a revised and quicker procedure will be used and automated.

## 3. IMPLEMENTATION ON CURRENT LARGE TELESCOPES

We anticipate that ASMs are likely to be adopted by several current-generation large telescopes. The first will be the Large Binocular Telescope (LBT), comprising two 8.4 m primary mirrors on a common mount, which will be dedicated to AO. Its only secondary mirrors will be ASMs that are now being built in Arizona and Italy.[6] It will also be feasible to retrofit existing telescopes with an ASM.

### 3.1. Improvements to LBT Secondary Design

Each of the LBT's two ASMs will be 910 mm in diameter and employ 672 voice coil actuators. As a result of experience with the MMT ASM, significant improvements have been made to the mirror design.

- The telescopes will be Gregorian, allowing easier calibration and testing.
- Actuators are inserted from the front (mirror) side of the ASM, rather than the back as with the MMT. Removing the glass membrane to do this has proven to be much easier than anticipated, and in fact involves less risk than moving the electronics crates, the alternative used with the MMT ASM.
- At 1.6 mm average thickness, the glass membranes will be thinner than the MMT's at 2.0 mm. This will halve the stiffness, allowing control of $\sim 4\times$ as many modes for given power dissipation.
- To reduce further the risk of dust contamination in the air gap, individual gaskets will be placed around each actuator. These will seal the main paths by which contamination has occurred in the MMT's ASM. In addition, a UPS permanently connected to all the actuators will ensure that the ASMs will be lifted to the safe position even when powered down.
- The purely passive air damping in the MMT mirror will be augmented by electronic damping. This will be done by adding a derivative term to the actuator/capacitive sensor control loops, which in the case of the MMT are purely proportional. The LBT's ASMs will then be operable with a gap of 100 $\mu$m, allowing chop angles of $\sim$ 10 arcsec. Experiments with a 45 actuator prototype demonstrate that even with the reduced air damping, the mirror response will be a factor of two faster than for the MMT mirror.

### 3.2. Impact of Implementation at Existing Telescopes

While most large telescopes now in operation use a Cassegrain configuration for compactness, there are arguments, summarized in table 1, for adopting the Gregorian configuration instead for an ASM. In the case of the MMT, with its Cassegrain ASM, only minimal modifications to the telescope were required, but the convex curvature makes testing and calibration difficult. There is no natural place to insert a point source illuminator, and closed-loop testing prior to system integration at the telescope required construction of a separate optical assembly.[7] Perhaps of greatest importance though is that the Gregorian configuration places the ASM at an optical conjugate close to the strong boundary layer of turbulence, which may be responsible for half or more of the total wavefront aberration. We explore the benefit in some detail in Section 4.

Table 1. Trade-offs between Cassegrain and Gregorian ASM designs

| **Cassegrain** | **Gregorian** |
|---|---|
| Shorter, stiffer telescope | ASM easier to test and calibrate in situ |
| Cheaper modifications to telescope/building | Better conjugation to the ground widens GLAO compensated field |
| Smaller mirror for given focal ratio | |

We anticipate that ASMs will generally be applied to observations in the near and mid IR. Other seeing-limited applications, for instance wide field imaging or multi-object spectroscopy in shorter wavelengths, will need secondary mirrors with different prescriptions. An ASM is therefore not likely to be mounted permanently on the telescope, but will need to be swapped occasionally for one or more rigid secondaries. Nevertheless, our experience with rigid operation of the MMT's ASM suggests that there is no need to provide a separate rigid secondary for seeing-limited IR observations.

In addition to the mirror itself, integration of an ASM at an existing telescope requires a number of new support facilities to be provided. A standard requirement for all AO systems is an artificial star that can be used for testing and calibration. In the Gregorian configuration, this can be attached to the telescope itself at the prime focus, as will be done for the LBT. For convex mirrors, a separate fixture is much easier to implement; the MMT employs a single full-aperture lens to illuminate the ASM from a point source in the same way as does the primary mirror. Since the illuminator is a laser, achromatizing the optics is not necessary.

Other needed services include cooling fluid plumbed to the secondary mirror hub, suitable handling fixtures, and a small clean room on site where the mirror can be partially disassembled for occasional maintenance without risk of contamination. At the MMT, a portable clean room about 2 m on a side has proved quite adequate.

## 4. IMPACT ON ELT DESIGN

A new generation of extremely large telescopes (ELTs) in the 30 m class is now being designed.[8–10] AO will be required on these telescopes to maximize the scientific return and justify their high cost. Indeed, multi-conjugate AO systems are envisioned to provide the largest field of view at the very high resolution allowed by diffraction. We explore here two key areas where telescope design is likely to be influenced by the development of ASM technology.

### 4.1. Use of ASM Technology for ELT MCAO Systems

Multi-conjugate AO systems now being designed[11] are still planning to use conventional DMs. These mirrors, with small size, flat figure, and substantial hysteresis, present additional challenges not only to the optical designer who must relay images of the required altitude conjugates to the correct DMs, but also the servo engineer, who must understand in detail how to decouple the actuation effects of each mirror from all the others. Ellerbroek[12] finds in numerical simulations conducted to date that these effects are so strong as to prevent stable closed-loop operation.

A solution identified in that paper is to drive the DMs in a pseudo-open-loop mode. Independent real-time knowledge of the shape of the mirror can be used to supplement the information from the WFSs to derive the open-loop shapes of the incoming wavefronts. This is already an integral part of the ASM control: position information from the capacitive sensors at each actuator is used firstly to close local servo loops, turning the voice coils from force actuators into position actuators, and secondly to sense directly the presence of mirror modes that are either not seen by the WFS or are filtered out by the reconstructor and are therefore not controlled by the optical servo loop. We believe then that an MCAO system whose DMs provide this kind of position feedback can be made stable in closed loop.

Furthermore, the curved nature of ASMs addresses the needs of the optical designer. Milton et al.[13] have described a tri-conjugate AO system for the Giant Magellan Telescope using three large curved DMs placed at distinct conjugates in the atmosphere, in which each DM not only introduces wavefront compensation, but reimages the next conjugate onto the following DM. Asking each mirror to perform both tasks makes the MCAO system much more optically efficient.

### 4.2. Ground Layer Compensation

Partial image correction over a wide field of view, perhaps 10 or 20 arcminutes, can be achieved by correction of aberration caused by boundary layer turbulence. Such correction is likely to be of most value for multi-object fiber-fed spectroscopy in the near IR. Improved energy concentration can allow higher resolution than a typical seeing-limited instrument while maintaining high throughput.

To do GLAO, wavefronts from several beacons across the field must be sensed, and essentially averaged to yield an estimate of the boundary layer contribution. Compensation must then be applied to a DM optically conjugated near the turbulence. While a conventional DM could be appropriately placed in the optical path (indeed this is already approximately the case with currently operating AO systems), the small size of such mirrors presents a major problem. To take a specific example, if a 15 cm DM were used to correct ground-layer aberration at a 30 m telescope over a 20 arcmin diameter field of view, the Lagrange invariant implies that rays would be incident from a solid angle of well over a steradian. Not only does this make the manufacture and tolerancing of the reimaging optics very difficult, but the projection effect would cause a 15% change in the correcting OPD from the center to the edge of the field.

A more tractable solution is the use of an ASM, whose large size overcomes these problems. It is also feasible to place the ASM optically very close to the turbulence by adopting a Gregorian configuration with a fast primary mirror. The GMT design, as an example,[13] with a primary mirror focal ratio of f/0.7 places the image of its secondary 150 m above the telescope, ideally located for GLAO.

A Gregorian secondary however lengthens the telescope compared to the usual Cassegrain arrangement, raising the cost and lowering the structural stiffness. Use of a very fast primary mirror presents its own challenges of optical tolerancing. How pressing in fact is the need to adopt such a design, which minimizes the misregistration between the height of the boundary layer turbulence and the DM conjugate, if GLAO is a goal? A simple numerical simulation has been written to explore the effect of varying the height difference.

The model assumes perfect knowledge of the true ground-layer aberration in the direction of the telescope's axis, and then subtracts this from stars at each point in the field. The degree of correction to be expected from a real GLAO system is in fact underestimated near the axis in this scheme, since the angular coherence of low-order modes that results in partial correction of upper-altitude layers is ignored. Nevertheless, for present purposes we will be concerned with high-order modes, and the effect is unimportant.

We have modeled a 10 m telescope, though results are almost independent of telescope diameter. A layered atmosphere had a mean height, weighted by $C_n^2$, of 3500 m, $r_0$ of 0.9 m at 2.2 $\mu$m wavelength, and two-thirds of the power in the aberration in the boundary layer. PSFs were computed as a function of field angle at K band for two cases in which the vertical separation between the boundary layer and the DM conjugate was either 200 m or 400 m. These values are intended as rough approximations to typical Gregorian and Cassegrain arrangements respectively.

Results showing three measures of image width are shown in figure 5. The first plot looks at the full width at half maximum (FWHM). This figure of merit is commonly used to quantify image improvement in high-order AO systems aiming to come close to the diffraction limit with high Strehl ratio. In this case, the improvement from GLAO is modest, as expected for partial wavefront compensation, but effective over a field of view of many arcminutes. The effect of the additional 200 m of height misregistration is apparent but not dramatic.

By contrast, two other figures of merit show quite different behavior. Plotted in the lower half of figure 5, $\theta_{50}$ and $\theta_{80}$ show the diameter of a circle enclosing 50% and 80% respectively of the total energy in the PSF. For spectroscopists, these numbers are of greater value as measures of image quality than FWHM or Strehl ratio since they describe the size of a spectrograph's entrance slit (and hence spectral resolution) that can be used for given loss of light. In this simulation, both quantities degrade more rapidly with field angle than the FWHM, and both show distinctly worse behavior as the height mismatch is increased. Indeed, for separation of 400 m, $\theta_{80}$ is only improved out to 3 arcminute radius; beyond that, the effect of GLAO is to make the image worse.

The difference in sensitivity to field angle of these three quantities is explained by their relative dependence on high- and low-spatial frequency aberrations in the pupil. Figure 6 illustrates how a height misregistration $\Delta$h causes errors in the compensation of ground layer turbulence by a shear effect. Aberration on spatial scales much longer than the shear length $s = (\theta_1 - \theta_2)\Delta\text{h}$ will be well corrected, but the correction will degrade at shorter spatial scales, until at $s/6$, the aberration starts to be made worse. The highest frequency wavefront components are therefore the first to become decorrelated with the applied compensation as the field angle increases, and these are exactly the components responsible for distributing energy into the outer halo of the PSF.

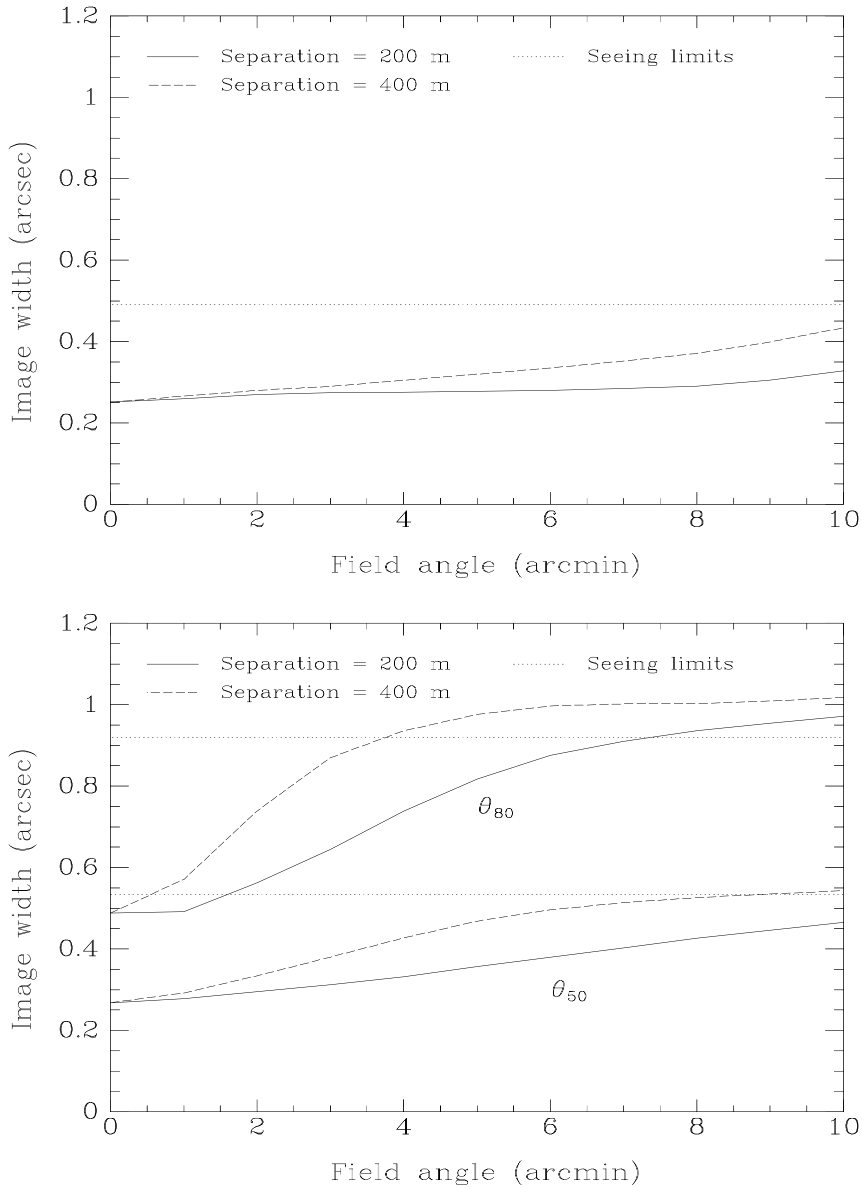


Fig. 5. (*Top*) FWHM and (*bottom*) diameters of 50% and 80% encircled energy contours for simulated K-band images with ground layer correction.

Of the three measures of image width, $\theta_{80}$ is most sensitive to the energy distribution, and so degrades fastest as the shear effect decorrelates high frequency compensation, while the FWHM, measuring the central core of the PSF, remains almost unchanged. As a consequence, imaging applications taking advantage of GLAO may not be greatly affected by the choice of telescope configuration, but spectroscopic applications will strongly prefer Gregorian, and may find Cassegrain GLAO unusable outside a quite modest field.

## 5. CONCLUSIONS

Experience is showing that robust closed-loop operation of the MMT's ASM can be achieved routinely. After three telescope runs, the mirror has been successfully operated over the full range of environmental conditions

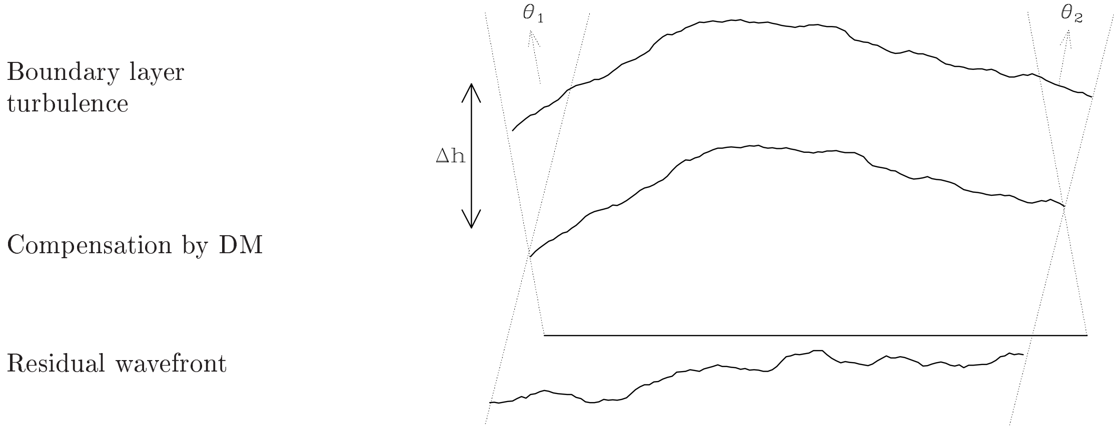


Fig. 6. Effect of correction of ground layer aberration with the turbulence and DM separated in height by $\Delta$h. If the compensation is perfect for a star at field angle $\theta_1$, then a wavefront from a second star at $\theta_2$ will be sheared. Aberrations with high spatial frequencies will be the worst affected.

including temperature, humidity, and wind that can be expected during the ASM's lifetime. The hysteresis-free actuators and explicit control of unsensed modes from the actuator position feedback yield a compensated PSF of great stability, with minimal diffraction spikes caused by static wavefront errors of high spatial frequency. If desired, the mirror can be used as a rigid secondary even in high winds.

Procedures have been established for safe handling and operation of the ASM. Being initially cautious in our approach, a number of the software procedures require human interaction. In an upgrade to the software package now being developed, however, initialization and system error recovery operations will be fully automated, and present limits on forces applied to the actuators will be judiciously relaxed.

The first telescope to take advantage of lessons learned from the MMT experience will be the LBT, for which two ASMs are now being built. With upgraded electronic hardware, improved performance over the MMT mirror has already been demonstrated in a prototype ASM, while simultaneously incorporating new features to improve robustness. For other existing telescopes, only a modest expansion to observatory infrastructure would be required to accommodate an ASM, with the largest impact likely to be to the telescope structure if the decision is taken to implement a Gregorian focus.

Future extremely large telescopes can also benefit from the use of ASMs. In addition to the advantages that accrue through use of an adaptive secondary, mirrors of very similar design can be incorporated into an MCAO system of great efficiency. The explicit real-time knowledge of the actuator positions can be helpful in ensuring stability of the closed loop.

Gregorian telescope configurations are likely to be prefered to the Cassegrain for GLAO because of improved PSF uniformity across the wide corrected field. This is particularly true for ELTs where the difference in conjugation between the two configurations may be many hundreds of meters. The scientific benefit will be most clear for multi-object spectroscopy since the reduction of power in the image halo means that the optical coupling into the spectrgraph's entrance slits will not be such a strong function of field angle.

## ACKNOWLEDGEMENTS

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