Status of the NGS Adaptive Optic System at the MMT Telescope

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ABSTRACT

The Natural Guide Star (NGS) Adaptive Optics System at the MMT Telescope (MMTAO) on Mt. Hopkins in Southern Arizona is the first in the world the use the secondary mirror as the correcting deformable mirror. Its 2.0 mm thin shell mirror, whose shape is controlled by 336 voice coil actuators, allows for nearly maximum throughput of light into the science camera. With several more deformable secondary mirrors coming online in the next few years, the lessons learned building, characterizing and operating the MMT Adaptive Optic System has proven to be quite valuable. These lessons will be discussed as well as future plans for the MMTAO System.

Keywords: Adaptive optics, deformable mirrors, adaptive secondary mirrors

1. INTRODUCTION

The project to build the first Adaptive Optics (AO) system which uses an Adaptive Secondary mirror as the deformable mirror has been in development for over ten years. The initial idea was outlined by Salinari[1] with details of the development of our system found in Brusa.[2] The construction of the full Adaptive Optics system for the MMT Telescope was completed in the Spring of 2001 followed by a year long phase of laboratory testing. Using a test stand, we lovingly called the Shimulator (it simulated the shimmering of the sky), we characterized the adaptive secondary mirror, characterized the wavefront sensor camera and optics that reside in the topbox (the optical bench mounted at the Cassegrain focus) and exercised the real-time computer calculating the wavefront and controlling the shape of the AS (called the wavefront computer). Finally in June 2002 the AO system was installed on the MMT telescope but mechanical problems, described by Wildi,[3] prevented AO corrections from being applied. First light with the MMT AO system occurred in November 2002, described by Wildi,[4] with a multitude of runs approximately every four months since. Results, both scientific and engineering, of the many runs can be found in Kenworthy[5] and Brusa[6] and the reference therein.

In this paper we will describe our Adaptive Optics system in section 2, discuss the current performance of the system in section 3, touch on some problems encountered with our AO system and their solutions in section 4 and finally describe the future for the MMT AO system in section 5.

2. SYSTEM DESCRIPTION

The Adaptive Optics System at the MMT Telescope is the first in the world that uses the secondary mirror as the deformable mirror. The concept is very straight forward and sketched out in Fig 1. As can be seen, the three major parts that make up our AO system are the Adaptive Secondary (AS), the Wavefront Sensor Camera (WFSC) and the Wavefront Computer (WFC).

A diagram of the Adaptive Secondary can be seen in Fig 2. The individual parts, from top to bottom, are the support frame which houses the three electronic crates and supports the cold plate. Attached to the cold plate is the backplate, or reference body, which is used to determine the position and shape of the deformable mirror. The deformable secondary mirror is not connected to the reference body, but is held in positions by 336 voice coil actuators by a magnetic field. The 336 actuators are mounted in the cold plate, which removes most of the heat dissipated by the actuators, and extend through holes in the reference body to within a centimeter or so of the deformable mirror. 336 small permanent magnets have been glued to the back of the thin shell deformable

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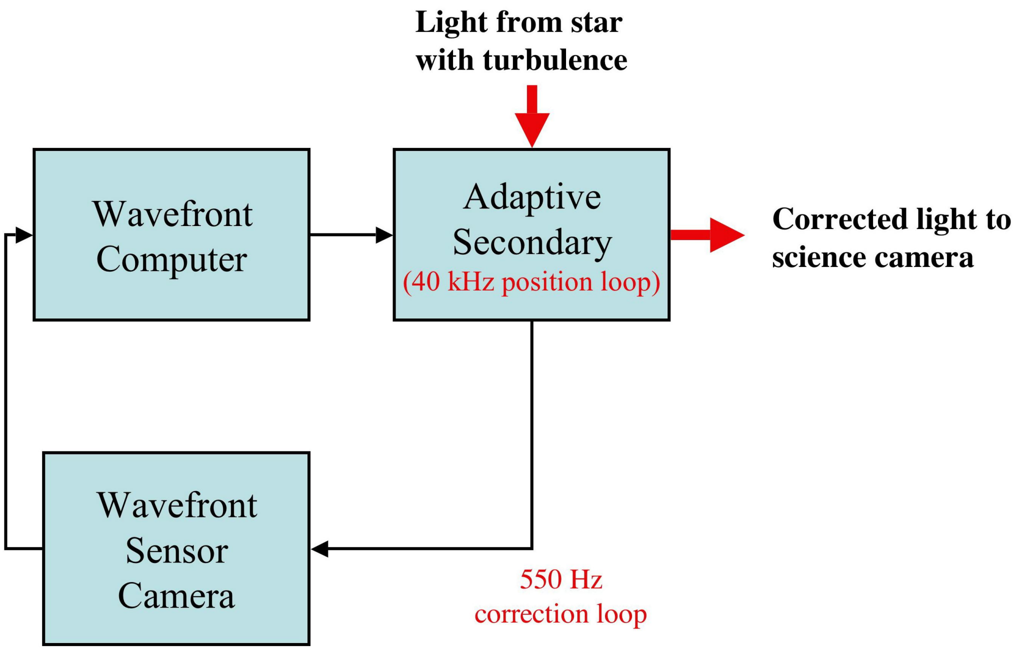

Figure 1. Schematic of the AO correction loop. The Adaptive Secondary shape is updated at a rate of 550 Hz. The loop internal to the AS of 40 kHz uses 336 capacitive sensors co-located with the 336 actuators to keep the thin shell at the requested position.

mirror which protrude up into the actuators holes in the reference body to within a millimeter of the voice coil actuators. By changing the current in the voice coil actuators the magnetic repulsion or attraction felt by the magnets on the back of the deformable mirror change and in this way the shape of the deformable secondary mirror is controlled. The three electronic crates mentioned above house 168 digital signal processors (DSP), each one controlling the current in two actuators. Software on these DSP's have a 40 kHz position control loop (see Fig 1) that measures the position of the deformable mirror at the location of the actuator it is controlling via a capacitive sensor co-located with the actuator and then changes the current to the actuator so that the capacitive sensor will have a requested reading. This position is set by an external computer, the wavefront computer.

The requested position of all 336 actuators are determined by the wavefront computer and relayed to the adaptive secondary control electronics via a fiber optic communication link. This requested position (the 336 individual actuator positions) are determined using information from the wavefront sensor camera. The visible light reflected from the adaptive secondary is separated from the infrared light, which travels into the science camera (see Fig 3 and the discussion in section 2.1), and re-imaged on the wavefront sensor camera. This camera is a Shack-Hartman wavefront sensor that has 12x12 quad-cell subaperatures. With the proper re-imaging, each subaperature measures the slope, both x and y directions, of the wavefront at the location of the adaptive secondary mirror. This 216 slopes (not 12x12x2=288 because the WFSC is square but the image of the secondary is round) are passed to the wavefront computer where the wavefront shape is reconstructed and the shape, specifically the position, of the AS is determined that will cancel the wavefront aberrations so the wavefront arriving at the WFSC will be flat. In reality, only about 30 to 50% of this correction is applied because of stability considerations in this correction loop.

The wavefront sensor camera is able to read out a frame in about 1.8 milliseconds, Thus, the correction loop to remove aberrations of the wavefront at the WFSC, and at the science camera, runs at 550 Hz (see Fig 1). The resulting correction loop, due to noise in our measurement of the wavefront by the WFSC and a delay of about 3.6 milliseconds from measurement to application of the correction on the AS, give us a correction bandwidth of

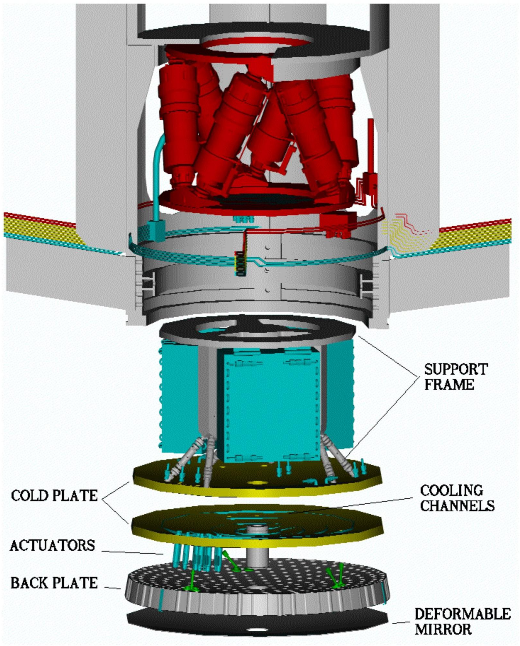

Figure 2. Exploded view of the Adaptive Secondary Mirror. When assembled the mirror unit is 0.642 m in diameter and 0.45 m long.

about 18 Hz. This means any changes in the wavefront aberrations less than 18 Hz will be corrected and changes faster than 18 Hz will not (see section 4 for a discussion of our 20 Hz vibrations).

This wavefront information, the 216 slopes, are converted to deformable mirror positions via the reconstructor. The reconstructor is a matrix that relates a change in the wavefront shape at the WFSC to a position of the AS which will correct the the wavefront to flat (see section 2.2

An Adaptive Optics system that uses the secondary mirror as the deformable mirror has several advantages and disadvantages compared to the traditional AO systems, where all the light from a star travels through most of the re imaging and wavefront sensing optics (see Fig 3). The advantages, maximum throughput and low infrared background, will be discussed below, as well as the disadvantages of our Adaptive Secondary AO system, mainly a full system test requires the telescope or a very complicated test stand.

2.1. Advantages

In Fig 3 a schematic is shown illustrating the path of star light through the telescope and AO system and into the science camera. It can be seen that the Adaptive Secondary system has the minimum number of surfaces in the path of the infrared science light; primary, secondary and dewar window. In our system, the dewar window is a dichroic beam splitter which allows wavelengths longer than 0.8 microns to pass through and shorter wavelengths are reflected. In this configuration, the maximum amount of the infrared light enters the science camera and the wavefront sensing system, which requires several re-imaging and image positioning optics, uses the visible light.

Minimizing the number of surfaces in the line of sight of the science camera has several effects. First, each reflective surface, on average, reflect only 93% of the incident light, less if the surface is not clean. Thus, the fewer reflective surfaces in the system the better. In the path of the infrared light to the science camera there are only three surfaces so we have the maximum possible amount of infrared light entering the telescope available delivered to to the science camera for a science images. In the path to the wavefront sensor camera re-imaging and positioning optics are required, but these surfaces are not in the path of the science light.

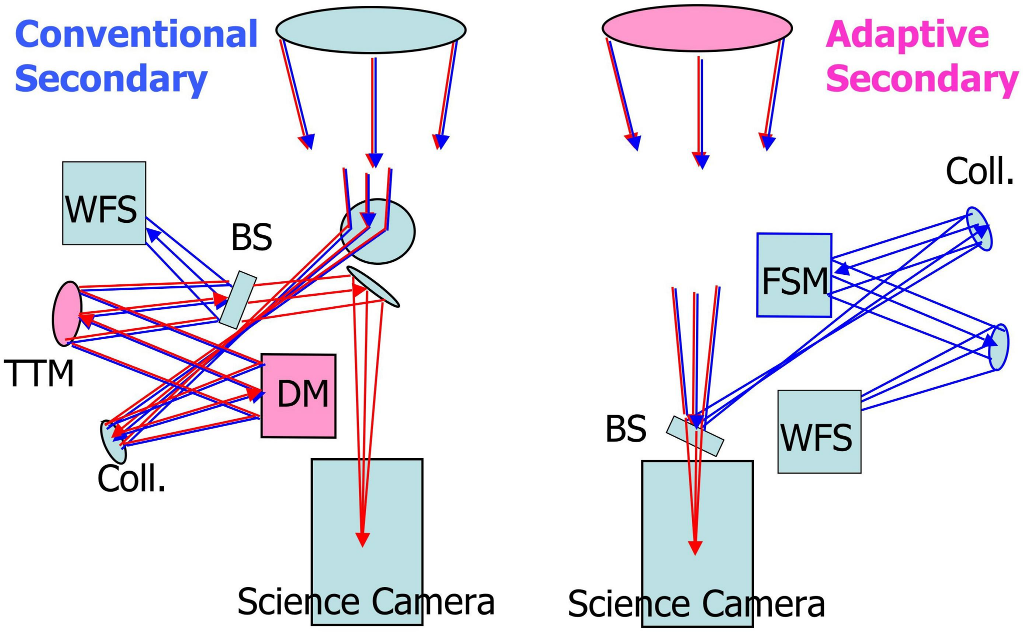

Figure 3. Comparison of Adaptive Optics systems using a conventional secondary and an adaptive secondary. It can be seen that the adaptive secondary system has the minimum number or surfaces in the path of the infrared science light; primary, secondary and dewar window. Note, the dewar window is a dichroic beam splitter which allows wavelengths longer than 0.8 micron to pass through and shorter wavelengths are reflected. In this configuration, the maximum amount of the infrared light enters the science camera and the wavefront sensing system, which requires several re-imaging and image positioning optics, uses the visible light.

Second, each warm (the ambient temperature the telescope) surface emits infrared radiation. So again, the fewer surfaces in the line of sight of the science camera the lower the background level in the science image. In addition, the adaptive secondary mirror is the pupil stop for the telescope so the science camera is not seeing the edge of the primary mirror or the primary mirror support structure. The MMT telescope was designed to minimize its contribution to the infrared background by using very narrow spider arms to hold the secondary mirror and insuring there would be no warm telescope surfaces seen by the science camera.

2.2. Disadvantages

The biggest disadvantage of our AO system with its adaptive secondary mirror is that any full system test requires the system to be mounted on the telescope, the telescope dome open and starlight traveling through the system. With telescope time being a precious commodity and tens of hours of work for several people to install the AO system on the telescope, testing our system is not straight forward. Alternative to telescope testing, a very complicated test stand would be required to reproduce the light path through our AO system. Conversely, traditional adaptive optics systems at other telescopes are generally separate instruments and thus it is fairly straight forward to produce a beam of light to inject into the system for testing.

During the development of our Adaptive Secondary mirror AO system for the MMT telescope we build a test stand to be able to test the our full AO system. This test stand was required to be able to “flatten” the secondary mirror and to measure the reconstructor. The term “flatten” refers to the proper settings for 336 voice coil actuators so that the front reflective surface of the deformable mirror has a near perfect parabolic shape needed to focus light from a star at infinity to a single point. To determine this setting, we used an interferometer to measure the front surface of the AS and determine what areas maybe be high or low relative to the surface position we want. To change this surface, we change the current in the appropriate voice coil actuators so that the desired areas of the mirror moved up or down. We then iterate many times in order to get the front surface smooth and the shape we want. To be able to reproduce this shape without having to measure the front surface with an interferometer, which would be impossible at the telescope, we use 336 capacitive sensors co-located with the voice coil actuators to measure the distance between the reference body and the back of the deformable mirror. We measure the "flat" of the AS once, record the 336 capacitive sensor reading for this flat position and then we can reproduce this flat position by commanding the mirror and mirror electronics to hold the mirror so that these capacitive sensor readings are replicated. "Flattening" the adaptive secondary will be discussed again in section 5.

The second task which required the test stand was to measure the reconstructor. This reconstructor in reality is a matrix 216x336 that contains the information that relates the shape of the wavefront seen on the wavefront sensor camera (216 slopes of the wavefront are measured) to the position of the deformable mirror (336 actuator positions) needed to exactly correct this wavefront to be flat. The procedure to measure this relationship had four steps. First, the test stand was set to produce a test beam that was completely flat, or had no aberrations. Second, after the beam has been reflected by the deformable secondary the light is sent into the wavefront sensor camera where the wavefront is measured by measuring slope pairs (x and y directions) of the wavefront at 106 positions across the pupil image, which is the location of the secondary. This is the reference wavefront. Third, the deformable mirror is commanded to take a known shape (336 actuator positions) such that a known aberration is applied to the wavefront. Finally, the shape of the wavefront seen at the wavefront sensor camera is measured, the reference wavefront is subtracted and we now have the change of the wavefront due to a change in the shape of the AS. This four step process is repeated for many different orthogonal shapes, or modes, applied to the AS. In this fashion we are able to build a reconstructor matrix that allows us to correct most aberrations that we see on the wavefront sensor camera.

We measured this reconstructor matrix in the lab using our test stand three years ago and have used this same matrix during all of our subsequent telescope runs. There was concern that as the properties of the adaptive secondary and associated electronics changed with time and use, or the actuators or capacitive sensors changed, or the measurement of the wavefront by the wavefront sensor changed this reconstructor matrix would no longer be valid. We would then be required to go back into the lab and use our test stand to re-measure the reconstructor. However, we have found that our system is very stable and the performance of our AO system has been quite good with this original reconstructor measured three years ago.

Currently we are working on a method to measure the reconstructor matrix using the MMT telescope and a star. A description of this method, called reconstructor on the sky, is described by Brusa.[6]

2.3. Science Cameras

The purpose of our Adaptive Optics system is to remove the aberrations in starlight due to the atmosphere. So far we have described this light as being used by a science camera to record an image. Currently there are two science cameras which we can mount at the Cassegrain focus to collect light: BLINC/MIRAC and ARIES. MIRAC3 is a mid-infrared camera able to take images in 4 to 25 microns range. With the addition of BLINC, the combination becomes a nulling interferometer. ARIES is a near-infrared imager, with the addition of a spectrograph in the spring of 2005. See[5] for descriptions of the instruments and some results of using the Adaptive Optics system at the MMT Telescope.

3. PERFORMANCE

The performance of an Adaptive Optics system is usually measured in strehl. Thus, Fig 4 shows the a 1.2 micron image (left panel) of a standard star and the normalized intensity as a function of distance from the center of the image (right panel). The black line with diamonds is the measured intensity and the red line with no symbols is the diffraction limited flux distribution calculated by looking at the residuals seen on the Shack-Hartman wavefront sensor camera. As can be seen, the measured peak value, or the strehl, is only 40% of the peak of the diffraction limited peak. Specifically, the calculated curve is telling us how good of correct we should be able to achieve if we were using all the information available from the wavefront sensor camera. Thus, the right panel in Fig 4 show us that our AO correction loop is not optimized.

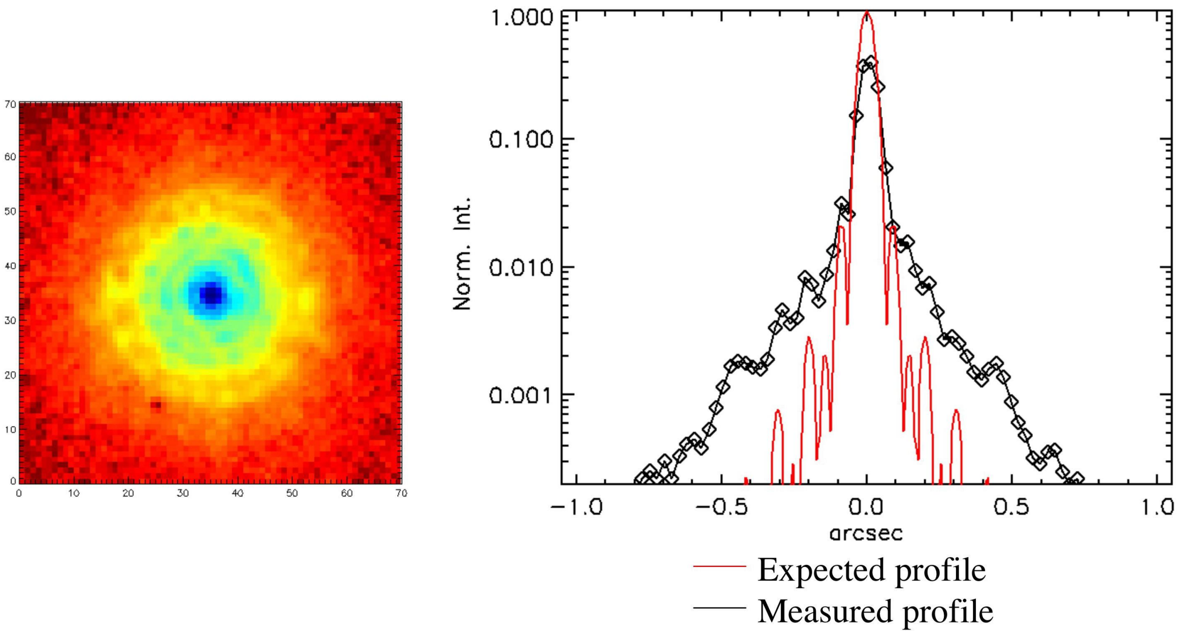

Figure 4. The left 2"x2" image is of a standard star acquired with AO correction. The plot on the right is the measure normalized flux as a function of distance from the center of the image (black line with diamonds) and the diffraction limited flux as a function of distance if our AO system were producing the optimal correction calculated by looking at the residuals seen on the Shack-Hartman wavefront sensor camera.

Most likely our biggest error, or reduction in strehl, is do to the speed of our AO correction loop. Currently our loop speed is limited by the readout time of the WFSC. By the time we have the slope information available to the wavefront computer, the information is already 2.7 milliseconds old.[*] The wavefront computer must then determine the new mirror position from these slope values and send the request to the adaptive secondary, which has a short but not negligible setting time. Considering all these delays, it is almost two frame times, or 3.6 milliseconds, between measured aberration and the applied correction.

To speed up our AO correction loop will require two drastic changes in our Adaptive Optics system. First, we must speed up our Wavefront Sensor Camera. This will require new WFSC controller electronics. Second, we must speed up the calculation of the reconstructor, eg speed up the wavefront computer. This will require a new Wavefront Computer. Both these requirements are discussed in section 5.

Another significant reduction in strehl is most likely due to errors in the measurement of the reconstructor. This matrix was measured in the lab and has proved to work well. But small changes in optics, or the wavefront sensor camera or a small error in the clocking of the WFSC due to the instrument rotator and associated derotation of the the WFSC, or misalignment or positioning of the pupil image on the WFSC could have a significant effect on the performance of our Adaptive Optics system.

The solution to this problem is to measure a new reconstructor at the telescope. Initial tests have be performed during the last three MMT runs and our method of measuring a reconstructor on the sky described by Brusa[6] looks very promising.

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[*] With an integration time of 1.8 milliseconds, the information in the current Shack-Hartman frame is an average so can be considered half an integration old, 0.9 milliseconds. Then it takes 1.8 milliseconds to read out the frame. Thus, the information is 2.7 milliseconds old

4. PROBLEMS AND SOLUTIONS

We have encountered several problems, with the two most significant being contamination of the 40 micron air gap between the reference body and the back of the thin shell adaptive secondary and the 20 Hz vibration in the structure of the telescope.

The source of gap contamination was found to be particles falling from above the cold plate through the actuator holes in both the cold plate and reference body and into the gap. The solution was two fold. First, we now spend much more time with a small vacuum cleaner removing as many dust particles as is possible from above the cold plate and inside the actuator holes. Second, we have installed a cloth shroud around the top part of the Adaptive Secondary, above the cold plate where the electronics crates reside. This has reduced the frequency of contamination from several per two week telescope run to one in the last three runs. Thus, we are confident with continued diligence we will not have serious problems with gap contamination.

The second major problem is a 20 Hz vibration in the upper end of the telescope structure. We see this vibration in the diagnostics performed on the AO correction loop as well as seeing the 20 Hz vibration using two, three-axis high resolution accelerometers. In Fig 5 the motions measure by the accelerometers are shown. We see a 20 Hz vibration in the z-direction (the optical axis of the telescope) and only z-direction. However, we see not only the 20 Hz z-axis vibration but also a small x and y direction vibration which is seen as a 20 milli-arcsec jitter in the science camera image. The implication is that either the hexapod and/or the adaptive secondary structure is not stiff enough and this 20 Hz z-axis vibration is being couple with the x and y-axis.

The solution is three fold. First, decrease the amplitude of the 20 Hz vibration. Currently the MMT Telescope staff is working to improve the elevation drive servo system, which has been proven to induce vibrations at several frequencies. Second, stiffening the current hexapod or replacing it will hopefully decrease the coupling between the z-axis vibration the x and y directions. Finally accelerometers are being mounted permanently on the back of the cold plate so vibration information can be passed to the wavefront computer and a feed-forward correction for the 20 Hz vibration can be applied to each of the calculated aberration corrections. This implementation will take place when we upgrade the wavefront computer to a faster architecture.

5. FUTURE

We, in fact, have a long laundry list of modifications, upgrades and replacements to our Adaptive Optics System. They are:

- **Electronics Refurbishment** This fall, 2004, we are refurbishing and upgrading the adaptive secondary electronics to include the Thin Shell Suction (TSS) system. This system will apply a current to all 336 actuators if and when power or communication is turned off or lost to the AS. This current will suck the thin shell deformable mirror safely against the reference body and greatly reduce the risk of gap contamination or damage to the AS.

- **WFSC Controller** We are in the process of purchasing new WFSC control electronics. This will allow us to run our AO correction loop at a faster rate. In fact, the new system will also lower the read noise of the WFSC and allow for better corrections on dimmer guide stars. This new controller will be ready for testing during our next telescope run in January 2005.

- **Wavefront Computer** We are currently performing initial tests in order to develop a PC based reconstructor computer. We will hopefully change control of the correction loop from our current VME based wavefront computer to a PC based WFC in the summer of 2005.

- **Feed-forward Vibration Information** Accelerometer will be permanently mounted on the cold plate during the electronic refurbishment the fall. The implementation of the feed-forward correction from these accelerometers will be included in the development of the new PC based wavefront computer and hopefully also ready for us in the summer of 2005

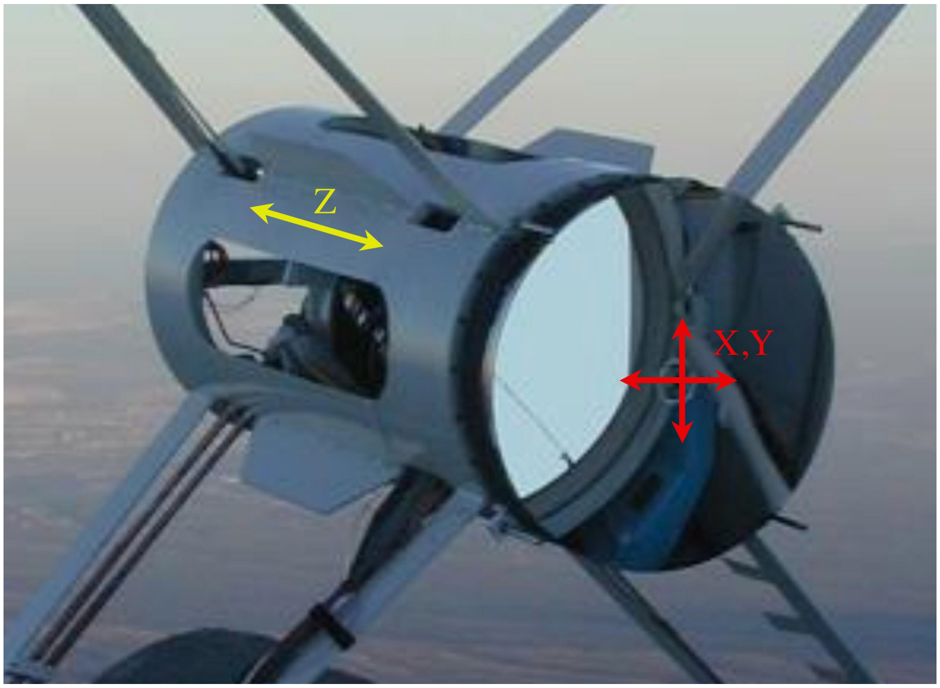

Figure 5. Vibrations at the hub of the MMT Telescope are seen as a 20 milli-arcsec motion at the science camera focus. Accelerometer measurements have shown a 20 Hz vibration in the z-axis and NO motion in the x or y directions for the telescope hub. However, we measure a 20 Hz motion in x, y and z-axis of the adaptive secondary cooling plate.

- **Reconstructor on the Sky** Initial test show our method to measure the reconstructor using the telescope and star light to be very promising. We are planning to acquire the needed data during our January 2005 run and use this new reconstructor in the spring of 2005

- **New Test Stand** A new simple test stand to enable us to "flatten" (see section 2.2) our adaptive secondary mirror much easier than the original Shimulator test stand is being build. The needed optics have been ordered and are being polished and an initial design is completed for the mechanical part of the test stand.

  The test stand will use a modified Hindle test to measure the front surface of our deformable secondary. The optical layout of the test stand is shown in Fig 6. The Adaptive secondary is on the right side of the diagram, the hindle sphere is next, a lens to shorten the light path from 10 m to 2.5 m is the next optic and on the left of the diagram is the interferometer used to measure the surface. The beauty of the modified Hindle test is that all the optics needed to measure the aspheric adaptive secondary surface are spherical, which are much easier to polish than aspherical surfaces.

  This test stand will be compact enough to live in a laboratory in the MMT dome and will act not only as a test stand but will serve as a clean room for routine maintenance and a storage unit for the Adaptive Secondary between runs.

We in the MMT Natural Guide Star Adaptive Optics group are excited about the future of our system and look forward to the many challenging task ahead of us.

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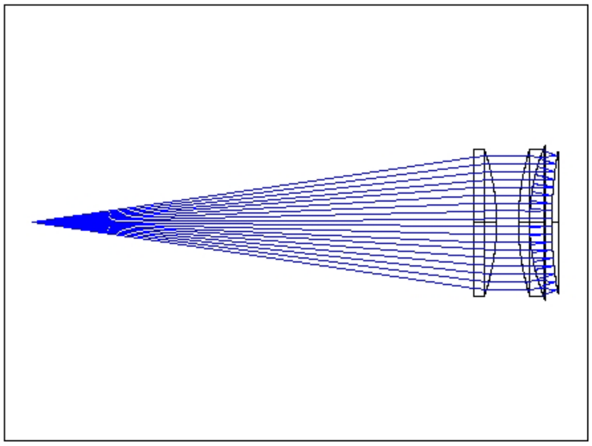

Figure 6. The ray trace of the test stand being built to measure the shape of the front surface of the thin shell. A modified Hindle test is used so that the test optics are spherical surfaces and easier to polish. The lens is used to shorted the focal length from 10 m to 2.5 m.

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