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Discovery Channel Telescope active optics system early integration and test

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ABSTRACT

The Discovery Channel Telescope (DCT) is a 4.3-meter telescope with a thin meniscus primary mirror (M1) and a honeycomb secondary mirror (M2). The optical design is an f/6.1 Ritchey-Chrétien (RC) with an unvignetted 0.5° Field of View (FoV) at the Cassegrain focus. We describe the design, implementation and performance of the DCT active optics system (AOS). The DCT AOS maintains collimation and controls the figure of the mirror to provide seeing-limited images across the focal plane. To minimize observing overhead, rapid settling times are achieved using a combination of feed-forward and low-bandwidth feedback control using a wavefront sensing system.

In 2011, we mounted a Shack-Hartmann wavefront sensor at the prime focus of M1, the Prime Focus Test Assembly (PFTA), to test the AOS with the wavefront sensor, and the feedback loop. The incoming wavefront is decomposed using Zernike polynomials, and the mirror figure is corrected with a set of bending modes. Components of the system that we tested and tuned included the Zernike to Bending Mode transformations. We also started open-loop feed-forward coefficients determination.

In early 2012, the PFTA was replaced by M2, and the wavefront sensor moved to its normal location on the Cassegrain instrument assembly. We present early open loop wavefront test results with the full optical system and instrument cube, along with refinements to the overall control loop operating at RC Cassegrain focus.

Keywords: DCT, Discovery Channel Telescope, Lowell Observatory, Active Optics, early integration, opto-mechanics, wavefront control

1 INTRODUCTION

The DCT Active Optics System (AOS) maintains collimation and mirror figure to provide seeing-limited images. The AOS can operate open loop or closed loop. Open loop AOS operation maintains collimation and M1 mirror figure with operational parameters and calibration data (i.e., a Wavefront Open Loop Model – WOLM). Closed loop AOS operation maintains collimation and M1 mirror figure with corrections using combined WOLM and Shack-Hartmann wavefront error measurements.

Before installing the optics, we used M1 and M2 mass simulators to test the Active Optics System (AOS) in the telescope. This proved valuable in tuning the lateral supports (M1L), M1 axial position loop (M1P), M2 axial position loop (M2P), and verifying M2 Control System (M2S) tilt conversions. We resolved most of the major control issues during testing on the M1 and M2 mass simulators.

In the summer of 2011, we installed the M1 into the telescope. After M1 installation, we conducted tests to verify that the control systems were stable. Before looking on-sky, the AOS sent demands to bend M1 with force suites applied to the axial supports. The resultant force feedback produced by the bending mode demands was consistent with the desired bending mode shapes. Final verification required on-sky testing with a star and wavefront measurements. After AOS daytime checkout, night operations started. Initially, the M2 was still being figured so we installed the Prime Focus Test Assembly (PFTA) on the M2 cage to support early on-sky testing at prime focus. During testing with the PFTA, tests verified the transformation from Zernikes to bending modes, the initial empirical data to create the zenith angle dependent open loop model, and the corrections to wavefront seen by a Shack-Hartmann sensor in near real time.

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So far, the testing has shown AOS is working very well without closed loop corrections. DCT is capturing one arc-second FWHM or better images with the axial supports maintaining equal, uniform forces on the M1. We are currently developing the WOLM. With the current WOLM corrections, the image quality has improved by 0.1 arc-sec FWHM.

2 AOS OVERVIEW

The AOS design is described in greater detail in ref. 1.

In open loop operation, the AOS uses operational parameters including ambient temperature, M1 temperature, mount temperature, and zenith angle as inputs to the Wavefront Open Loop Model (WOLM). WOLM inputs are corrections in terms of focus and coma (Zernikes 4, 7, and 8 – Noll convention[2]) and 26 bending modes[3].

In closed loop operation, the AOS uses the WOLM as well as wavefront sensor feedback. The WOLM corrects the majority of the wavefront error with the Wavefront Sensor (WFS) providing fine adjustments. The AOS receives up to 47 Zernikes coefficients from the WFS. The AOS uses Zernike 4 (focus), 7, and 8 (coma) for collimation corrections. For M1 figure correction, the AOS converts Zernikes 5, 6, and 9 through 47 to 26 bending modes. The AOS receives a decomposed wavefront every 30 seconds. The closed loop bandwidth is approximately 0.01 Hz.

In order to determine the WOLM coefficients, we collected empirical data and ran the data through a linear regression analysis since most physical terms are separable, which leads to linear corrections (e.g., We fit for the coefficients m_i where i = 0….3, Z4 coefficient = m_0 + (1-cos(z))*m_1 + sin(z)*m_2 + mountT*m_3). See 5.3 for further discussion.

3 AOS DAYTIME TEST RESULTS

With M1 and M2 mass simulators in the telescope, we ran tests to verify the time domain and frequency domain response of M1L, M1P, and M2P/M2S. The time domain tests verified the sidereal tracking, slew and mount 2 degree step performance of the AOS, which supports meeting the RC open loop delivered image quality of 0.47 arc-sec FWHM (excludes atmosphere). These tests demonstrated disturbance rejection while the mount was moving. In the case of M1P and M2P/M2S, since these are the only subsystems that move independently from the mount, step responses included subsystem (i.e., M1P or M2P/M2S) input demands. See Table 1 for time domain results. After M1 and M2 installation, we ran closed loop frequency domain tests on M1L, M1P, and M2P. Since the subsystems proved stable, we did not repeat the time domain tests. See Table 2 for closed loop frequency response results. For M2V, we ran only time domain tests (sidereal tracking, slew and mount 2 degree step performance) since M2V is a simple on-off controller.

	Sidereal Tracking Measurement (Requirement)	**Slew Performance Measurement** (Requirement)	**Two Degree Step Measurement** (Requirement)
M1L	**< 6 lbf** (< 10lbf)	**4 sec** (< 5 sec)	**4 sec** (< 5 sec)
M1P			
Piston	**< 0.1 um** (< 0.1 umRMS)	**17 sec** (< 5 sec)	**17 sec** (< 5 sec)
X-Tilt	**< 0.06 urad** (<0.1 uradRMS)	**17 sec** (< 5 sec)	**17 sec** (< 5 sec)
Y-Tilt	**< 0.06 urad** (<0.1 uradRMS)	**17 sec** (< 5 sec)	**17 sec** (< 5 sec)
M2S/M2P			
Piston	**< 0.05** (<0.25 umRMS)	**1 sec** (< 5 sec)	**0 sec** (< 5 sec)
X-Tilt	**< 0.05 urad** (<0.71 uradRMS)	**1 sec** (< 5 sec)	**1 sec** (< 5 sec)
Y-Tilt	**< 0.05 urad** (<0.71 uradRMS)	**1 sec** (< 5 sec)	**1 sec** (< 5 sec)
M2V	**< 3 lbf** (< 3lbf)	**2 sec** (< 5 sec)	**2 sec** (< 5 sec)

Table 1 AOS Daytime Time Domain Test Results Summary

	Closed Loop Frequency Response (- 3dB Down Point) **Measurement** (Requirement)
M1L	**1.1 Hz** (> 0.1 Hz)
M1P	**1.7 Hz** (> 0.1 Hz)
M2P	**1.6 Hz** (> 0.1 Hz)

Table 2 AOS Daytime Closed Loop Frequency Domain Test Results Summary

3.1 Sidereal Tracking Performance

The sidereal tracking test demonstrated that the AOS held the mirrors stable and within the error limits needed to deliver the desired image quality. We ran the tests with the mount tracking at sidereal rate in Right Ascension, which requires all three axes to move- azimuth, elevation, and Cassegrain rotator .

M1L, M1P, M2P/M2S, and M2V all passed the sidereal track performance test.

For M1L, the subsystem requirement was to maintain the force error in the Y direction (+Y is toward the sky when the mount is at horizon) to less than 10 lbf. The cumulative Y force stayed below 6 lbf during the track.

For M1P, the subsystem requirement was to maintain piston to less than 0.1 μm RMS and X-,Y-tilt to less than 0.1 μrad RMS. From the test data, the piston error was less than 0.1 μm and the tilt errors were less than 0.06 μrad.

For M2S, the subsystem requirement was to maintain piston to less than 0.25 μm RMS and X-, Y-tilt to less than 0.71 μrad RMS. M2S maintained piston error to less than 0.05 μm and X-/Y-tilt error to less than 0.05 μrad.

For M2V, the subsystem requirement was to maintain the absolute value of the cumulative force on the three axial posts to less than 3 lbf. During the sidereal tracking, M2V maintained the cumulative force on the mirror to less 3 lbf.

3.2 Slew Performance

The slew performance test demonstrated the steady state error during a slew as well as the settling time after the mount stopped. We determined that the worst case performance for all AOS subsystems resulted from slewing in elevation. This was done in both ascending and descending directions. There was very little difference between the two directions.

For all subsystems, there was not a requirement for steady state error during the slew. The requirement was for each subsystem to settle within the limits mentioned in 3.1 within five seconds.

All subsystems passed the five second settling time requirement except M1P. This is expected since the axial supports are controlling piston and tilts simultaneously. We deemed the settling time of 17 seconds acceptable.

3.3 Two Degree Mount Step Performance

The two degree mount step test demonstrated that the AOS can settle within 17 seconds after the mount step. The telescope is required to move off target by two degrees and be ready to acquire an image (i.e., within limits stated in 3.1) within five seconds. The requirement pertains to all AOS subsystems. As with the slew test, this test was done only with a two degree step in elevation. M1P was the only subsystem to fail the test for the same reason it failed the slew test. The result was still acceptable.

3.4 Closed Loop Frequency Response Performance

As with any control system, the closed loop response demonstrates that each subsystem is stable and responds quickly enough (closed loop bandwidth) for the application. Only M1L, M1P, and M2P had a frequency response test performed. Only these subsystems required frequency domain testing since the other subsystems do not directly act on physical hardware.

The setup used to capture the frequency response was not with a traditional frequency analyzer. We used a National Instruments CompactRIO with analog input and output modules. The design minimized delays as much as possible but the phase plot still shows a phase shift indicating test instrument delay.

The required M1L closed loop bandwidth was greater than 0.1 Hz. The actual closed loop bandwidth was 1.1 Hz.

The required M1P closed loop bandwidth was greater than 0.1 Hz. The actual closed loop bandwidth was 1.7 Hz.

M2P controls the three, individual actuators, which axially position the M2 cell. The required M2P closed loop frequency response was > 0.1 Hz. The actual closed loop frequency response was 1.6 Hz. The acquisition method was the same as M1P.

4 PRIME FOCUS TEST ASSEMBLY

Since the M2 figuring continued at this time, we installed and used the PFTA to start early evaluation of M1 system performance. Using Wavefront Sensor (WFS) feedback, we manually entered the WFS feedback into the AOS. Part of the testing included verifying AOS coefficient signs and amplitudes compared to the Zernike coefficients produced by the WFS. Over four months of on-sky testing, we identified and resolved operational issues with the AOS software and WFS. By the end of PFTA testing, the software had been streamlined for operations both in control and user interface.

4.1 Overview

The PFTA used the same opto-mechanical and detector assembly used later for the WFS and GCS probes at RC focus. This included an e2v CCD67 frame transfer CCD, with 256x256 pixels, each 26 um square. The CCD plate scale was approximately 0.34 arc-sec/pixel, which results in a 87x87 arc-sec FoV. The PFTA also used the same focus motion stage used by the WFS and GCS. The probe includes a LED-illuminated pinhole source as the wavefront reference. The use of the same CCD and stage was intentional to prove out the design and software. In order to use a probe assembly designed for the f/6.1 RC focus at the f/1.9 prime focus, the PFTA used a corrector assembly to change the f/ratio while correcting the spherical aberration inherent in the hyperbolic M1 and maintaining the same pupil position as the RC configuration. Figure 1 shows the PFTA and its mounting to the top of the M2 cage. The PFTA had asymmetric vignetting of the beam by the cage structure, affecting the accuracy of the wavefront slope solutions. The test objectives were met with the reduced wavefront accuracy.

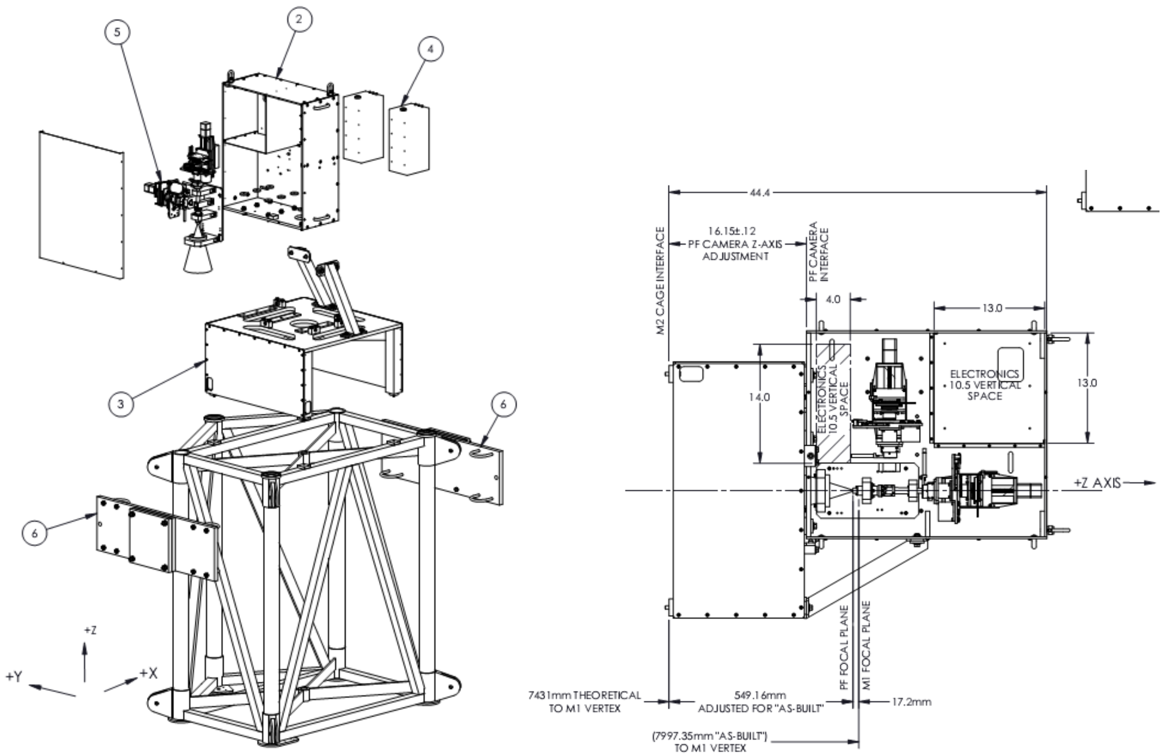

Figure 1 Prime Focus Test Assembly (PFTA) Mounted on M2 Cage

4.2 Converting WFS Zernikes to AOS Bending Modes

To maintain a common interface for wavefront sensors, the WFS to AOS interface uses 47 Zernikes. Internally, the AOS uses Zernikes 4 (focus), 7(y-coma), and 8 (x-coma) as well as 26 bending modes[3]. We deemed it possible to use a Zernike to bending mode transformation matrix without amplifying any existing errors[3]. For PFTA tests, Zernikes 4, 7, and 8 were converted directly to M1 piston, Y-tilt, and X-tilt, respectively.

Initially, the transformation matrix excluded the stiffer bending modes 13, 16, and 17 while using bending modes 2, 5 and 6. This proved problematic. The coefficients used for converting bending modes 2, 5, and 6 were very large. In particular, Zernike 11 is functionally similar to bending mode 13 but not bending mode 2 (See Figure 2). This resulted in axial supports forces outside their acceptable range. By excluding bending modes 2, 5, and 6 and using bending modes 13, 16, and 17 in the transformation matrix, we reduced the resulting axial support forces to acceptable levels.

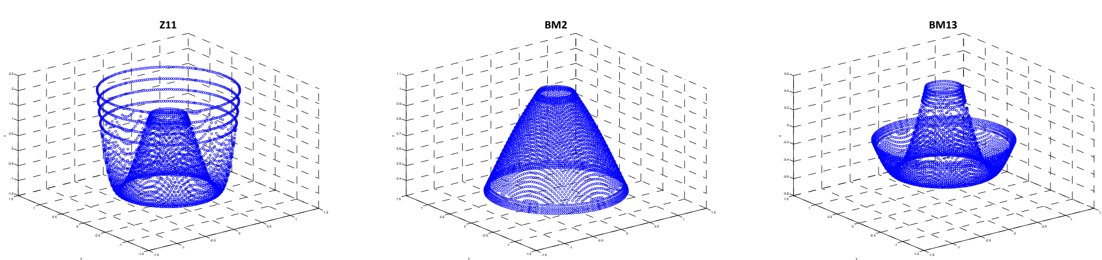

Figure 2 Zernike 11, Bending Mode 2, and Bending Mode 13

4.3 Converting AOS Zernikes to M1 Piston, X-Tilt, and Y-Tilt

Like the bending modes, we verified the signs and amplitudes of rigid body modes conversions. The WFS sensed the correct value of each term for the M1 piston, X-tilt, or Y-tilt introduced. The AOS also passes a pointing offset to the Telescope Control System (TCS) to negate the pointing change caused by a X-tilt or Y-tilt change. The AOS passed the pointing offset with the correct sign and amplitude.

4.4 Generation of WOLM Data

Initially, we took wavefront data during elevation scans. We moved the telescope to targets in the zenith angles ranges of 5 to 85 degrees in 15 degree increments and back. The point was to determine if there was any zenith dependence or hysteresis in the wavefront going down versus going up. During the elevations scans, the AOS had no corrections (i.e., M1 and M2 at nominal positions and WFS not sending Zernikes). This provided a common configuration of wavefront data taken on different nights that combined into a single solution. Zenith angle changes should mainly affect collimation (Zernikes 4, 7, and 8). The linear regression provided the coefficients based on zenith angle. We did not test the coefficients since the RC Cassegrain instrument assembly was ready for installation. The AOS simultaneously collected mount temperature data during the elevation scans. Since number of points in the temperature data sample was deemed statistically insignificant, we did not attempt to determine the WOLM dependencies on temperature.

4.5 Pseudo-Closed Loop WFS Operation

The WFS software was not ready to send automatic measured wavefront to the AOS during PFTA testing. However, we ran tests manually entering the measured wavefront in the WFS user interface and sending the measured wavefront data to the AOS. The AOS corrected the wavefront error well during these tests. The AOS and support structure was stable enough that the image quality progressively improved as wavefront error terms were entered in sequence over a period as long as 10 to 20 minutes.

5 RC CONFIGURATION WITH CASSEGRAIN INSTRUMENT ASSEMBLY

In January 2012, we removed the PFTA and installed the M2 and its cell in the telescope. We performed some initial tests to verify M2V performance. At the same time, we finished the Cassegrain instrument cube assembly. We installed the Cassegrain instrument cube assembly at the end of February 2012.

5.1 Cassegrain Instrument Assembly Overview

The instrument cube assembly mounts to the Cassegrain rotator. The instrument assembly contains two identical probes, which either can be used for wavefront sensing (WFS) or guiding (GCS). The CCDs, e2v CCD67, used in the WFS and GCS probes were also used on the PFTA. As expected, the RC plate scale is 0.36 arc-sec/pixel, which is very close to the PFTA plate scale. The resultant FoV is 92x92 arc-sec. The RC configuration is f/6.1. GCS and WFS probes use the same focus motion stage as the PFTA. In addition, the instrument cube assembly uses two stacked stage pairs to move the two probes around the focal plane. To prevent probe collisions, only one probe can move to the center of the focal plane. The Cassegrain instrument assembly uses all the AOS and the WFS software used with the PFTA and additional modules to control stage motion. The Cassegrain instrument cube assembly is described in greater detail in ref. 4.

5.2 Initial RC Testing

In the RC configuration, the AOS controls both M1 and M2. Bending modes maintain M1 figure, while rigid body modes maintain M2 collimation (i.e., Zernikes 4, 7, and 8). We checked the AOS for correct signs and amplitudes used to convert Zernikes 4, 7, and 8 to M2 piston, Y-tilt, and X-tilt, respectively. The first on-sky images showed very good results. The image quality ranged from 0.9 to 1.1 arc-seconds FWHM without any wavefront correction (Figure 3) other than focus. With wavefront correction (Figure 4) from Z4 (focus) to Z11 (spherical aberration), the seeing-dominated image quality ranged from 0.8 to 1.0 arc-seconds FWHM. As sensed by the WFS, we can reduce the contribution of the optical figure and alignment to the image quality to 0.3 arc-sec FWHM (closed loop).

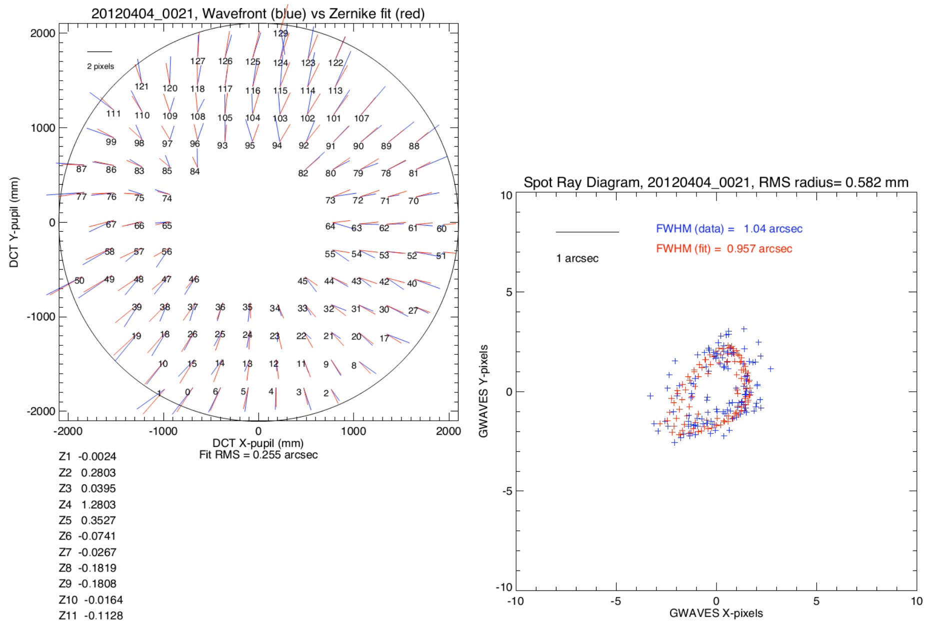

Figure 3 WFS Uncorrected Solution

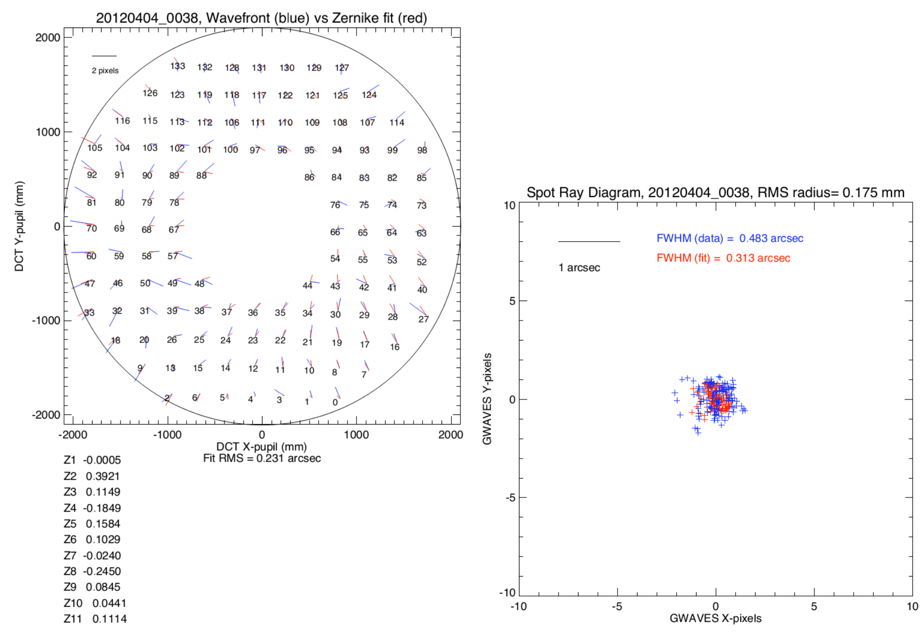

Figure 4 WFS Corrected Solution

5.3 Generation of WOLM Data

The effort to gather empirical data to create open loop coefficients continued during instrument cube testing. We performed several elevation scans over the course of a month. The data also gave an indication of temperature dependencies. Preliminary results show predictable and linear correlation between zenith angle and the rigid body modes. See Figure 5 to Figure 7 for preliminary results. Zenith angle mainly influences Z4 (focus) and Z7 (y-coma), which is expected. We started mount temperature data collection, which has led to preliminary temperature coefficients.

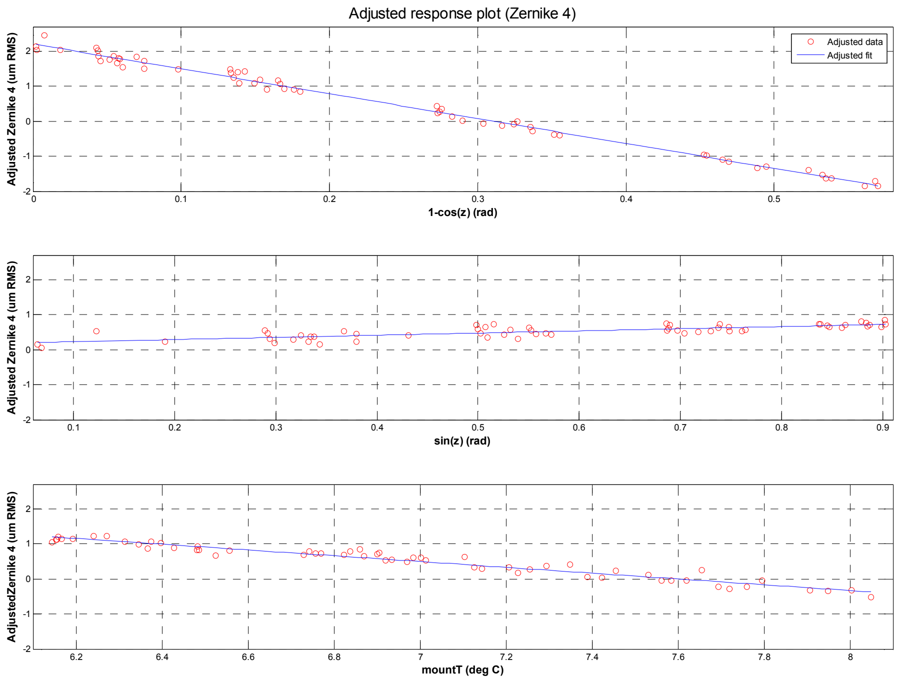

Figure 5 WOLM: Elevation & Mount Temperature Dependence of Z4 (focus)

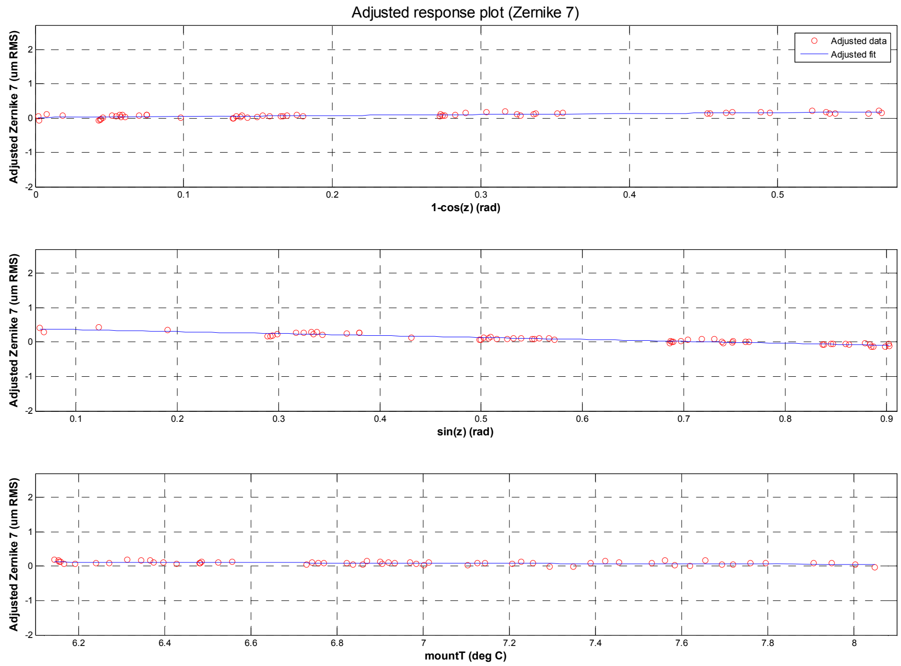

Figure 6 WOLM: Elevation and Mount Temperature Dependence of Z7 (coma in elevation direction)

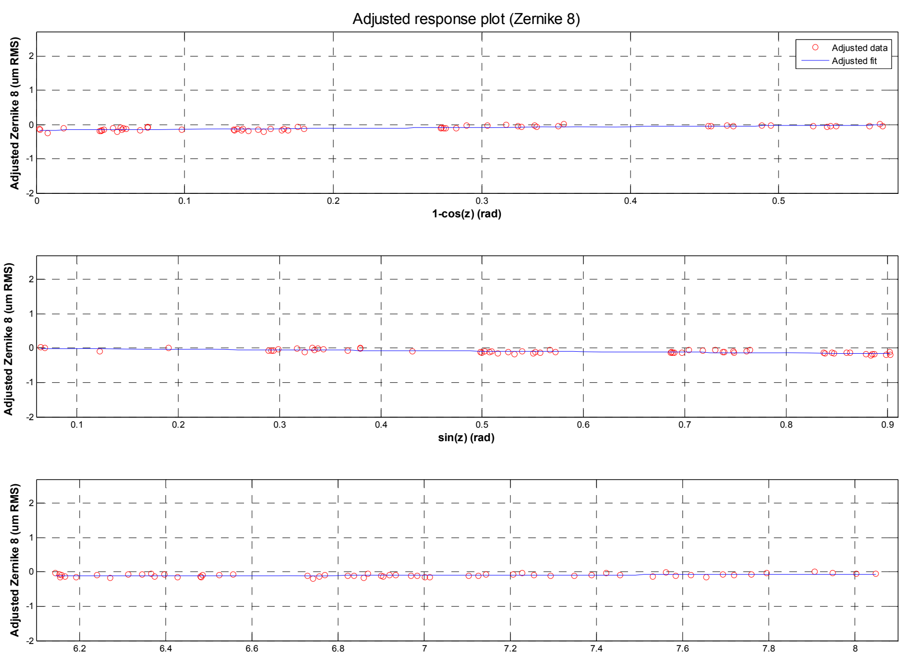

Figure 7 WOLM: Elevation and Temperature Dependence of Z8 (coma in azimuth direction)

5.4 M1 Tangent Definer Issue

In April 2012, the on-sky images started looking very comatic (Figure 8). The forces on M1 tangent definers did not look abnormal other than T1 was slightly lower than typical. AOS did show that M1P was not working very well at the time (i.e., M1P could not home every time it was requested and the position measurements were different than they should have been at nominal mirror position.). After physical inspection, we determined the T1 tangent definer pin that attaches the flexure to the M1 puck failed, so that the tangent definer was no longer connected to M1. Subsequent data analysis isolated the time and load at which the pin failed, and a solution to reduce the forces on the pins has been implemented. The event highlighted the diagnostic capability of the AOS, Figure 8, in detecting hardware failures and performance anomalies.

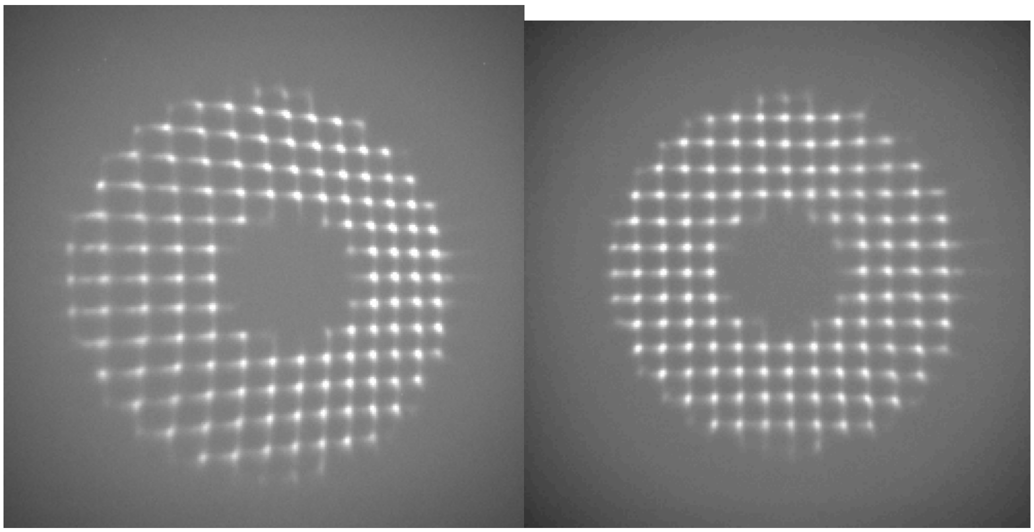

Figure 8 Shack-Hartmann Spot Pattern – T1 Pin Broken (left) and after T1 reattached to M1 (right)

6 CONCLUSION

We have made great progress in characterizing the AOS. The AOS performs well, shows no sign of hysteresis in elevation scans, and its stability suggests that open-loop corrections will be highly effective in achieving the 0.47 arc-sec FWHM open loop image quality (excluding atmosphere). The 1st-quartile average seeing was measured at 0.62 arc-sec FWHM during site testing[5] or a total delivered image quality of 0.78 arc-sec FWHM. However, there are more tests to complete before DCT is ready for 100% science operation. We need to operate AOS closed loop to meet the 0.31 arc-sec FWHM image quality (excluding atmosphere) or 0.69 arc-sec FHWM with the expected 1st-quartile atmospheric contribution. Listed below are the major tasks for completion in 2012.

1) Install RC corrector.

2) Measure M1 decenter relative to M2 using WFS data obtained around the field edge.

3) Measure the optical axis center relative to the Cassegrain rotator center.

4) Generate, test, and refine the WOLM using empirically determined coefficients.

5) AOS closed loop operation with WFS including closed loop performance tuning.

6) M1 Cold Plate Subsystem (CPS) performance testing.

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