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Chang Jin Oh, Eric Frater, Andrew E. Lowman, Peng Su, Chunyu Zhao, Ping Zhou, James H. Burge, "Development of a wide field spherical aberration corrector for the Hobby Eberly Telescope: design, fabrication and alignment," Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 914509 (22 July 2014); doi: 10.1117/12.2056879

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2014, Montréal, Quebec, Canada

# Development of a wide field spherical aberration corrector for the Hobby Eberly Telescope: Design, Fabrication and Alignment

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## ABSTRACT

A 4-mirror prime focus corrector is under development to provide seeing-limited images for the 10-m aperture Hobby-Eberly Telescope (HET) over a 22 arcminute wide field of view. The images created by the spherical primary mirror are aberrated with 13 arcmin diameter point spread function. The University of Arizona is developing the 4-mirror wide field corrector to compensate the aberrations from the primary mirror and present seeing limited imaged to the pickoffs for the fiber-fed spectrographs. The requirements for this system pose several challenges, including optical fabrication of the aspheric mirrors, system alignment, and operational mechanical stability. This paper presents current status of the program which covers fabrication of mirrors and structures and pretest result from the alignment of the system.

**Keywords:** Wide Field Corrector, Hobby Eberly Telescope, Alignment, Computer Generated Hologram, Aberration

## 1. INTRODUCTION

The Hobby Eberly Telescope* is in the midst of a significant upgrade to enable an unprecedented spectroscopic survey. [i] As part of this, the University of Arizona is providing the 4-mirror Wide Field Corrector (WFC) which corrects the spherical and field aberrations from the primary mirror to provide sub-arcsecond images over a 22 arcmin diameter field. The top level requirements for the WFC are summarized in Table 1.

**Table 1.** Key requirements for the HET Wide Field Corrector

| **Parameter** | **Requirement** |
|---|---|
| Field of view | 22 arcminute diameter |
| Image quality | 80% EE 0.45 arcsec to 5 arcmin, 0.8 arcsec to 11 arcmin |
| Optical throughput | Relative to 10-m circular aperture, 0.80 on axis, > 0.64 at 11' |
| Effective focal length | 36.5 ± 0.05 m (177 µm/arcsec) |
| Image mapping stability | Image position must be stable to 70 µm across field over all conditions |
| Wavelength range | 350 – 1800 nm |
| Mass | < 2000 kg |
| Stiffness | Lowest resonance > 20 Hz |
| Interfaces | Three-point semi-kinematic attachment |
| Operational environment | 35° elevation, ±8.5° in el, az<br>10°C ± 20° |
| Enclosure | Air-tight, light-tight, with steady positive pressure purge |
| Alignment methodology | Must provide method and tooling to removed and realign mirrors |

* The Hobby – Eberly Telescope is operated by McDonald Observatory on behalf of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximillians-Universität München, and Georg-August-Universität, Göttingen.

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Ground-based and Airborne Telescopes V, edited by Larry M. Stepp, Roberto Gilmozzi,
Helen J. Hall, Proc. of SPIE Vol. 9145, 914509 • © 2014 SPIE
CCC code: 0277-786X/14/$18 • doi: 10.1117/12.2056879

The optical design of the system was based on a design from O'Donoghue[ii], and refined for HET by MacQueen and Hanshin Lee. The layout of the optical system is shown in Figure 1.

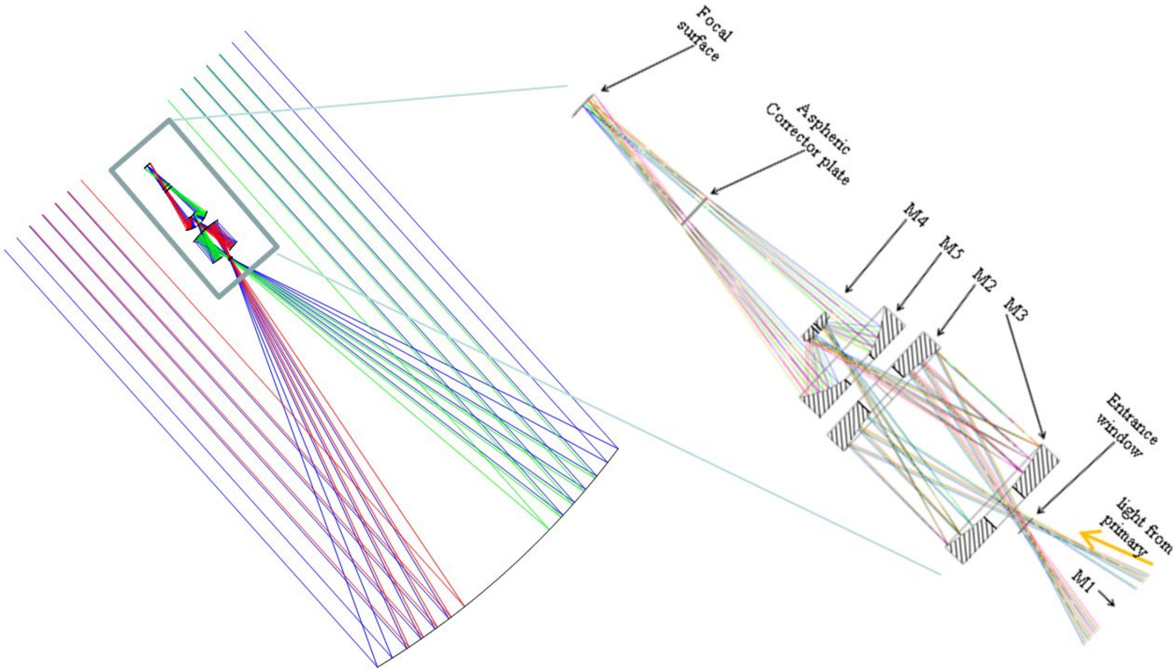


**Figure 1.** Layout of the design of the 4 mirror Wide Field Corrector for the Hobby Eberly Telescope

This paper provides a summary of the design, fabrication, and alignment of the 4-mirror system. Section 2 covers the systems engineering and tolerance analysis. The mirror and mechanical system fabrication and testing are provided in Section 3. The alignment plan and preliminary result from subsystem CGH test are in section 4.

## 2. SYSTEM ENGINEERING AND TOLERANCE ANALYSIS

The analysis of system performance includes everything that may affect the image quality, and we make our best assessment of our ability to control each item. We divide the analysis into two classes of errors, tolerances for parameters, which we can simulate, and mirror figure errors which are budgetary. The parameter tolerances are purely statistical – we estimate the distribution, but will never know the true value. The surface irregularity is different – we establish a specification, and we will work the optics until we meet it. The allocation of errors is provided in Figure 2.

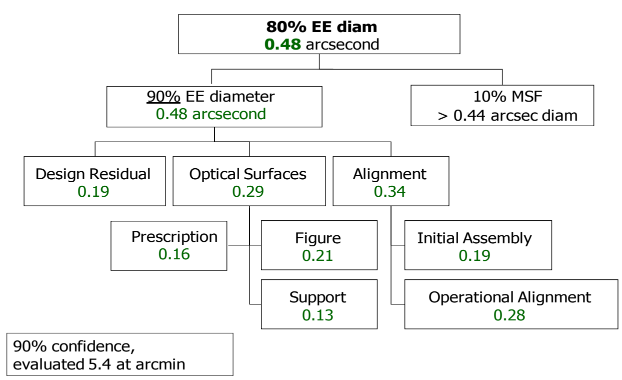


**Figure 2.** The error budget for image quality. The particular numbers shown here correspond to 90% confidence level, evaluated at 5.4 arcmin. We use a root-sum-squared analysis to combine the various contributions.

### 2.1 Mirror Fabrication and testing

Mirror fabrication tolerances in this section include the error in the knowledge of the radii and conic constants. All other errors (such as those in the higher order aspheric terms) are included in the polishing and figuring errors section. Table 2 lists the measurement tolerances used in the Monte Carlo simulation to estimate performance. The manufacturing tolerances are several times looser, since we can accommodate known offsets in these parameters by respacing.

**Table 2.** Manufacturing tolerances for M2, M3, M4 M5 and focal plane

| | **M2** | **M3** | **M4** | **M5** | **Focal Plane** |
|---|---|---|---|---|---|
| $\Delta R$ uncertainty (mm) | 0.075 | 0.075 | 0.045 | 0.04 | 3.44 |
| $\Delta k$ uncertainty | 0.0011 | 0.0008 | 0.0006 | 0.0001 | NA |

### 2.2 Alignment Tolerance and Operational Stability

Alignment tolerances include allowable uncertainty in relative position of the individual mirrors and groups of mirrors, as listed below in Table 3. The decenter and tilt tolerances are provided for each of the x and the y directions, so the net alignment tolerance is 1.4 x larger, at arbitrary angle. The tolerances for operational changes are assigned ¼ of the initial alignment tolerances. All of the tilts in Tables 3 are given in µm displacement across the diameter. The diameters assumed are provided in Figure 2.

**Table 3.** Alignment tolerances in microns

| | |
|---|---|
| M2 to M3 axial | 100 |
| M2 to M5 axial | 100 |
| M4 to M5 axial | 20 |
| M2 decenter (x or y) | 50 |
| M3 decenter (x or y) | 50 |
| M4 decenter (x or y) | 20 |
| M4 M5 decenter (x or y) | 50 |
| M2 tilt (x or y) | 50 |
| M3 tilt (x or y) | 50 |
| M4 tilt (x or y) | 20 |
| M4 M5 tilt (x or y) | 50 |
| Focal plane axial position | 1000 |
| Focal plane tilt (x or y) | 50 |
| M2-M5 together decenter (x or y) | 250 |
| M2-M5 together tilt (x or y) | 250 |

## 3. SYSTEM CONSTRUCTION

### 3.1 Mirror Fabrication and testing

3 large mirrors are fabricated by the robotic polishing system guided by Swingarm Optical CMM(SOC) then Null CGH test was performed to each mirror. M4 mirror was fabricated by outside vendor and it was tested by a Null CGH test provided by the University of Arizona. All 4 mirrors are very steep aspheric shape except M2. M2 is a quite mild aspheric mirror which has about microns of aspheric departure. M4 is a convex aspheric mirror and the measurement of the convex mirror M4 is made through the fused silica substrate. This requires a combination of two measurements to calibrate the effects of the back surface and the refractive index inhomogeneity. The test set up is in the Figure 3.

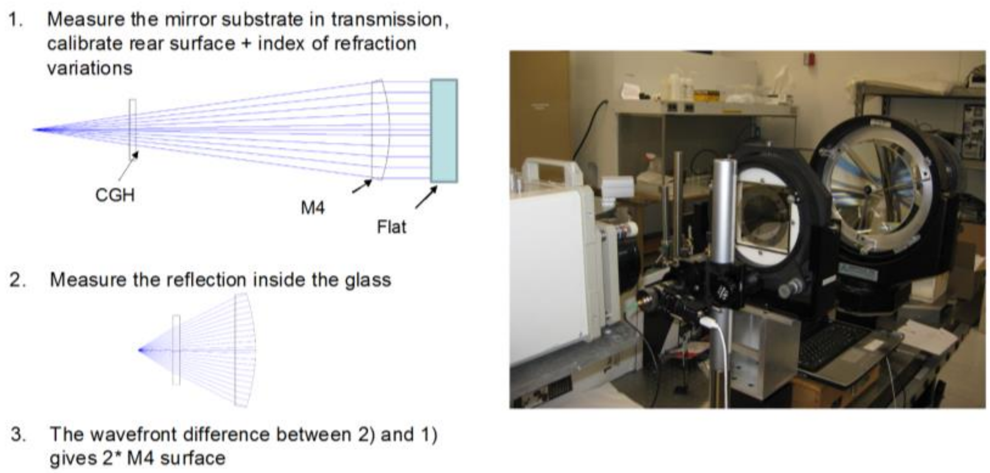


**Figure 3.** M4 Null CGH test set up

M3 is about 1m in diameter and it has 1.24mm aspheric departure. Due to the extremely big aspheric departure in M3 the mirror cannot be tested with a single CGH. The test was designed to measure inner anulus and outter anulus independantly with overlap region for the final stitching. M3 is measured by Swingarm Optical CMM (SOC) as well and the result has been chosen for the final mirror parameter.

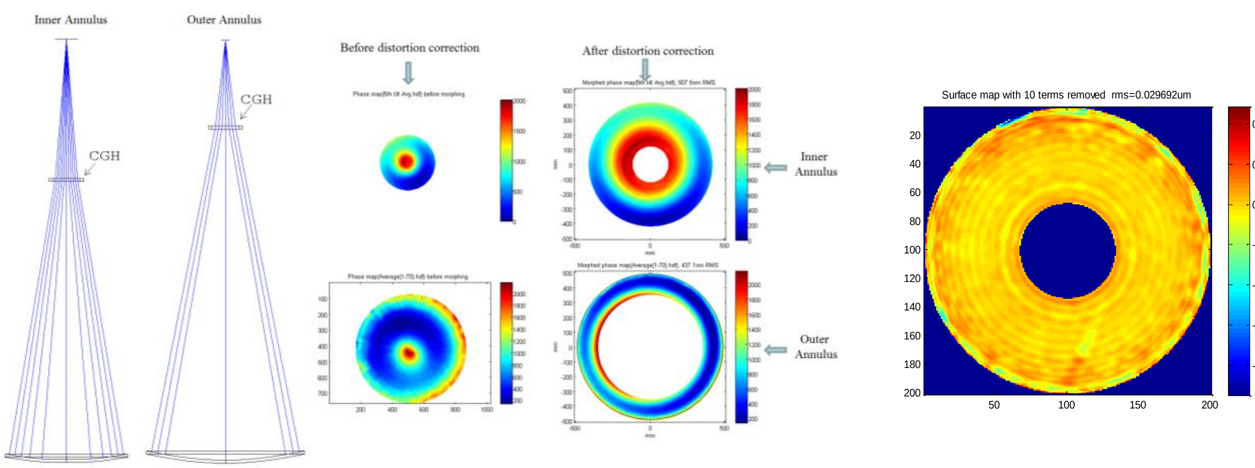


**Figure 4.** M3 CGH test with distorsion correction and surface map by SOC

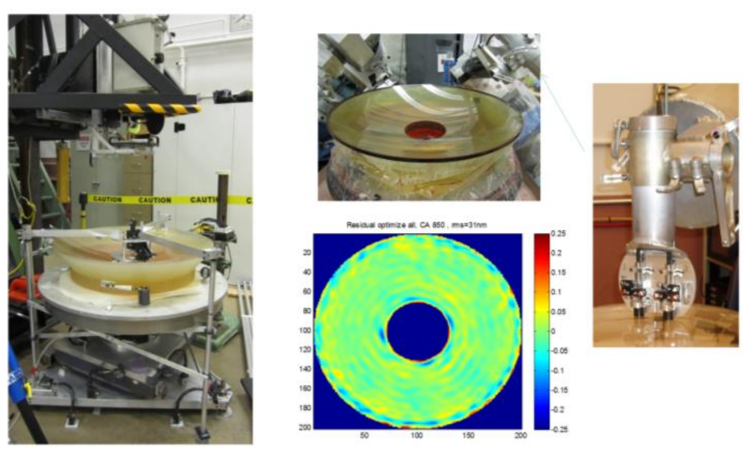

**Figure 5.** M5 Null CGH test set up and SOC test

The M5 is about 900mm in diameter and a very steep aspheric mirror. M5 mirror has been tested by null CGH test and Swingarm Optical CMM (SOC). This mirror is a steep aspheric mirror and also has very short radius of curvature of 742.3 mm. The short radius curvature and bigh asphericity induced technical challenges in the mirror testing such as wavefront correction using a single CGH, alignment of CGH test and unwanted Swingarm defelection in SOC. The test set up is in the Figure 5.

The as-built mirror parameters with uncertainties are listed in the Table 4. Currently all mirrors are coated and assembled to the wide filed corrector structure for the alignment.

**Table 4. Summary of as-built mirror parameters**

| Parameter | M2 | Uncertainty (2 s) | M3 | Uncertainty (2 s) | M4 | Uncertainty (2 s) | M5 | Uncertainty (2 s) |
|---|---|---|---|---|---|---|---|---|
| Radius of Curvature (mm) | 376.606 | 0.02 | 2032.675 | 0.06 | 376.606 | 0.02 | 742.343 | 0.05 |
| Conic Constant | -2.09843 | 0.00068 | -7.7137 | 0.0019 | -2.09843 | 0.00068 | -0.2672 | 0.00038 |
| A6 | | | -8.25E-17 | | | | 1.59E-19 | |
| A8 | | | 8.43E-23 | | | | 6.44E-26 | |
| A10 | | | -3.87E-29 | | | | | |

### 3.2 Mechanical System Fabrication

The mechanical systems were designed to maintain the figure and position of the mirrors, as well as to provide the structural stability to withstand changes in orientation, temperature, and dynamics. The system design utilizes two strongbacks that support the large mirrors, provide interfaces for system mounting, and provide interfaces to truss tubes that connect the strongbacks and the M4 headring.

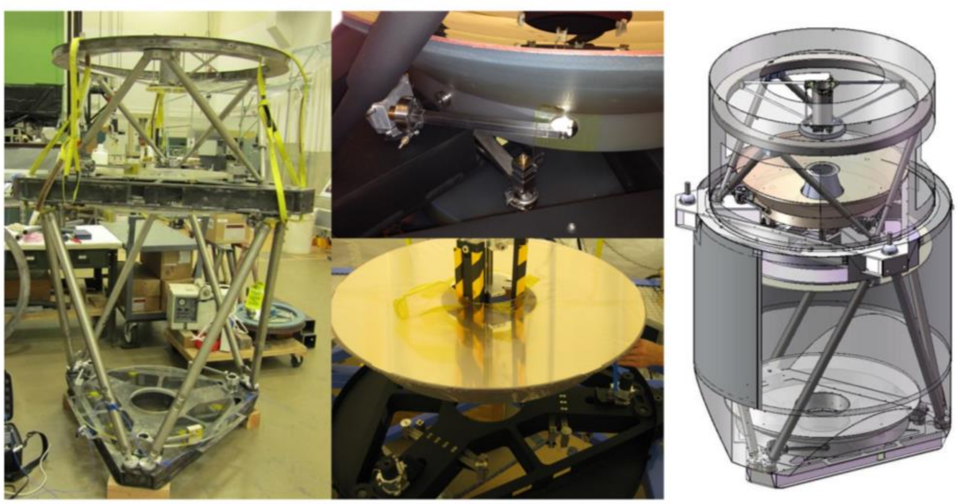

**Figure 6.** Photo of the actual structure with insets showing detail of embedded mirror support rockers and mounting interface. The strongbacks are steel and the truss tubes combine invar and steel for athermalization.

The complete system weighs 1800 lbs, including 950 lbs for mirrors, 550 lbs steel and invar, 120 lbs aluminum baffles and covers, and 182 lbs for HET instrumentation mounted to the M3 strongback. The lowest resonant frequency for the structure is 25 Hz frequency. The tightest tolerance is for M4 with respect to M5. The mechanical design is optimized to maintain this spacing by using invar to athermalize the structure, and using am adjustable flexure that will provide axial compliance in the headring so that M4 will shift the same as M5 when the system is tilted.

Each of the large mirrors is lightweighted by contouring from the back, and is supported using a 6-point axial constraint with 3 rockers, and 3 tangent links for lateral support. The support for M5 is shown in Figure 8, but the same design has been adopted for M2 and M3. The smaller convex mirror, M4, is mounted differently, as shown in Figure 7

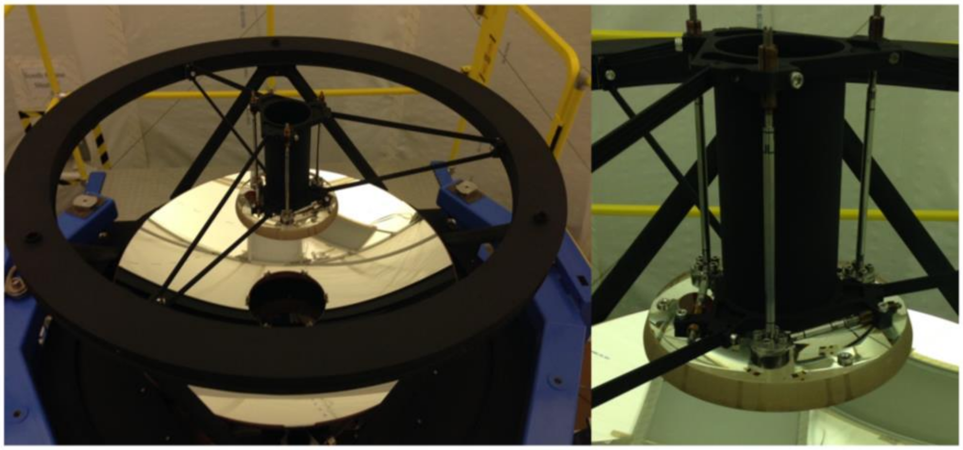

**Figure 7.** The small convex mirror, M4 is supported at three points. Connections via 6 flexures are made from these points to the M4 support structure, which is held by six tensioned vanes to a headring. The headring is supported by 6 truss tubes

### 3.3 Mechanical System Testing

To ensure the corrector assembly work as designed the mechanical system has been tested with a dummy mirror set which is provided by HET. Each dummy mirror has been configured to have equivalent mass distribution and same location of the center of gravity to the actual mirrors. Also each dummy mirror holds three sphere mounted retro-reflectors (SMR) and the mirror position has been monitored while the corrector system with dummy mirrors is set at two extreme operation angles using a laser tracker. The actual test set up is in Figure 8 and the result is in Table 5. As listed in the table the spacing change between M4 and M5 at each extreme angle remains within 10 μm and it meets the system alignment requirement with margin. Also the lateral movements and vertex positions of M2, M3 and M5 mirrors meet the requirement.


**Figure 8.** Mechanical system test with dummy mirrors.

**Table 5.** Relative displacement of dummy mirrors

| | Displacement at 43.5 deg | | | Displacement at 26.5 deg | | |
|---|---|---|---|---|---|---|
| | UX(um) | UY(um) | UZ(um) | UX(um) | UY(um) | UZ(um) |
| M2 | 5.5 | -20.2 | -3.5 | -4.9 | 14.5 | 3.6 |
| M3 | 20.7 | -65.9 | -15 | -26.6 | 21.7 | 10.8 |
| M4 | 15.9 | -6.5 | 2.1 | 6.2 | 14.7 | 0.1 |
| M5 | 6.8 | -10.4 | -8.1 | -8.3 | 12.6 | 8.2 |

# 4. SYSTEM ALIGNMENT

## 4.1 Mirror registration

Due to the high asphericity in each mirror the conventional optical alignment tools do not work for the wide field corrector and we developed an optical alignment tool called the center reference fixture for the corrector. The center reference fixture is a removable optical mechanical artifact which has been registered to the optical axis and the vertex of each individual mirror while the finished mirror is under optical test. The mirror is rotated about its optical axis under the interferometric test. Then the optical reference is placed to align its centration and tilt to the rotation axis, thus the optical axis. The targets themselves consist of axisymmetric diffraction grating (zone plates) on flat substrates. The centration of one pattern relative to another is measured by comparing the positions of the images created by the zone plates. When the mirrors are installed in the system, these references are picked up with an alignment telescope to define the centration and tilt for each surface. Figure 9 shows the actual set up of the center reference fixture registration and the registration result from each mirror has been listed in the Table 6. As listed in the result the registration was done very accurately, however, after about one year later we observed long term instability in the tilt registration. As mitigation, an independent tilt reference fixture for M4 was made and the alignment procedure has been modified to use subsystem CGH test.

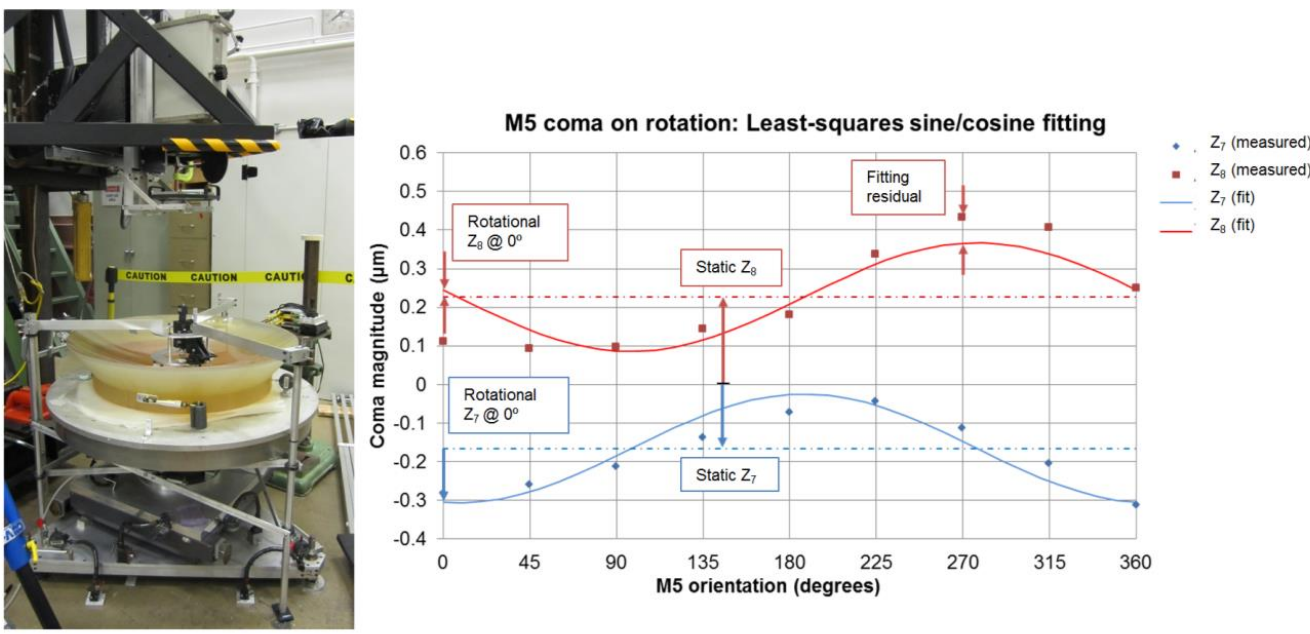


**Figure 9.** Photo of the center reference fixture registration under optical test and centeration calulation by coma measurement of M5

**Table 6.** Decenter and Tilt Registration

| | Mirror decenter magnitude (µm) | Mirror tilt magnitude (µrad) |
|---|---|---|
| M2, CGH1 | 18.5 ± 17.2 | 5.7 ± 5.6 |
| M2, CGH2 | 13.6 ± 15.3 | 2.6 ± 7.2 |
| M3, CGH1 | 3.7 ± 6.0 | 1.4 ± 2.1 |
| M3, CGH2 | 3.5 ± 6.1 | 1.2 ± 2.2 |
| M4, CGH1 | 2.4 ± 3.2 | 6.2 ± 12.7 |
| M4, CGH2 | 2.5 ± 2.6 | 7.2 ± 9.7 |
| M5, CGH1 | 4.1 ± 2.8 | 4.9 ± 3.0 |
| M5, CGH2 | 4.2 ± 2.8 | 5.1 ± 2.9 |

To set the spacing between each mirror in the corrector the location of vertex of each mirror should be identified. To do this we added three SMR nests to the body of center reference fixture for M2, M3 and M5. Then the offset between the plane formed by the center of three SMRs and the traced vertex of each mirror has been measured while the center reference fixture is engaged to the mirror. Similarly M4 vertex has been registered. Since M4 does not allow any large fixture which is able to hold 3 SMRs with wide enough separation, we used one SMR along the optical axis. Then we measured the offset between the center of the SMR and the vertex of M4 referenced to the back surface of M4 which is polished to an optical flat. The vertex registration has been done within ±8 µm in 2σ. With the vertex registration feature in the center reference fixture the axial mirror spacing is measured directly using a laser tracker.

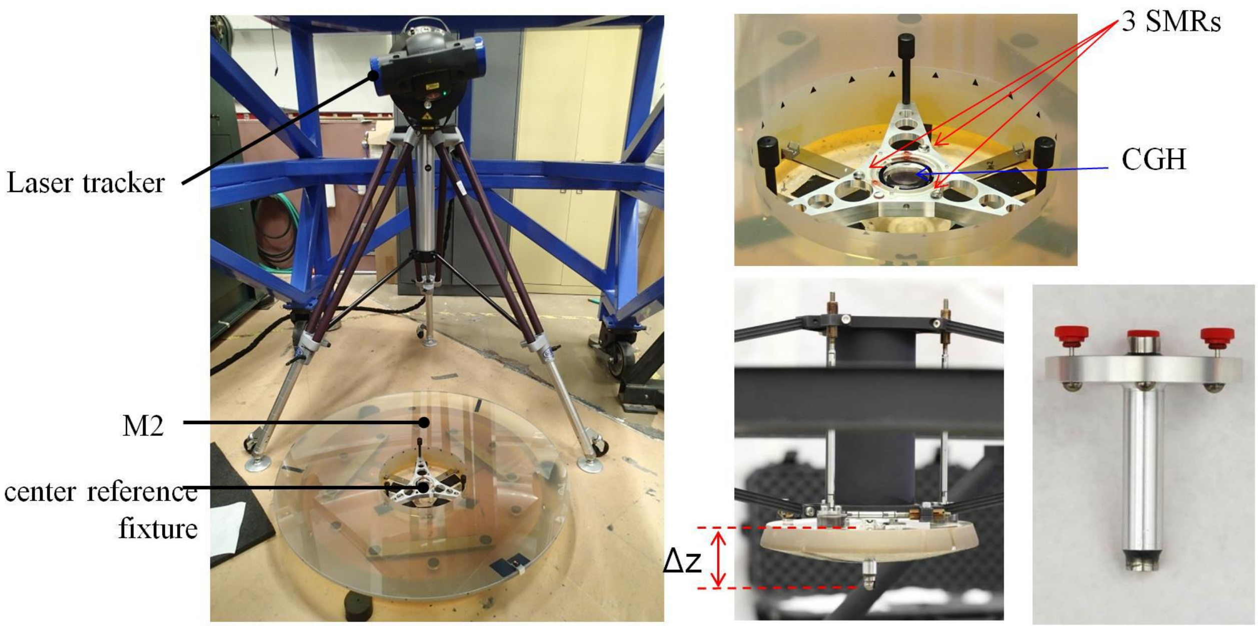


**Figure 10.** Photo of the vertex registration of M2 and M4

### 4.2 Susbsystem CGH test

The final system alignment will be tested using interferometry with computer generated holograms (CGHs). These holograms consist of flat mirrors with a zone plate written onto the surface to reflect the wavefront back through the system. This geometry, shown in Figure 11 is virtually the same as that used for calibrating null correctors. The complete wavefront for the system will be measured directly for the single on-axis field point. For the system alignment we define the M4 as the reference in decenter, tilt and spacing. Then M5 will be aligned to M4 by M4/M5 subystem CGH test and M2 and M3 will be aligned to M4 by M2/M3 subsystem CGH test.

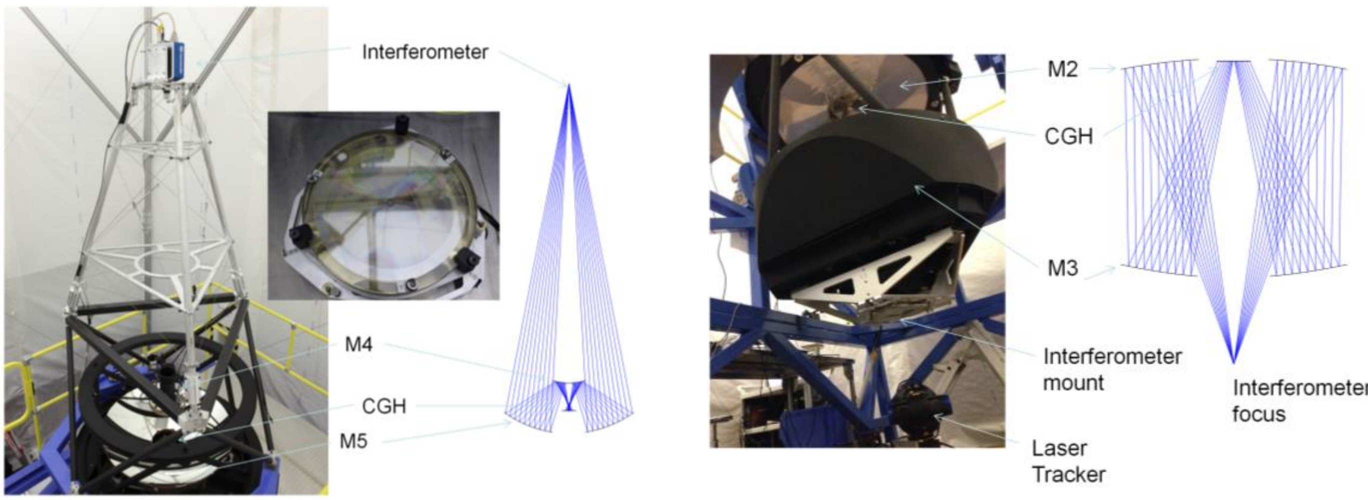


**Figure 11.** Subsystem CGH test configuration

Before the final test we performed pretest of M4/M5 and M2/M3 subsystem CGH test to verify alignment plan and also mirror parameters in the system. From the test the alignment of M5 was calculated using Annular Standard Zernike coefficient sensitivities generated with a model for the M4/M5 subsystem CGH test. The measured aberration coefficients for tilt, primary coma, secondary coma and tertiary coma are added to calculated contributions from M4 decenter, M4 tilt, focus decenter, test CGH decenter and test CGH tilt. The sum of the measured coefficients and contributions from other component misalignments yields a set of coefficients that would be measured if all test optics were aligned in all DOF with the exception of M5 tilt and decenter. This calculated set of coefficients is used to perform a least-squares calculation of the M5 tilt and decenter based on the sensitivities.
The subsystem wavefront response from the as-aligned status of M4/M5 subsystem CGH test is listed in the Table 7 and the alignment status of M4/M5 subsystem CGH test is in the Table 8. The calculated alignment status of M5 in decenter and tilt is in the Table 9 and as in the result the decenter and tilt meets the system alignment tolerance in the Table 3.

**Table 7.** Wavefron measurement from the M4/M5 subsystem CGH test (Unit is in waves)

| Zemax annular term # | Value (waves) | Aberration |
|---|---|---|
| Z2 | -7.918739942 | Tilt X |
| Z3 | 4.115788677 | Tilt Y |
| Z8 | -0.237668718 | Coma X |
| Z7 | 0.100006664 | Coma Y |
| Z16 | 0.018346737 | 2nd Coma X |
| Z17 | 0.129969281 | 2nd Coma Y |
| Z30 | 0.02206747 | 3rd Coma X |
| Z29 | -0.013460783 | 3rd Coma Y |

**Table 8.** As-measured alignment status of the interferometer, M4 and M4/M5 subsystem test CGH

| Optic | Interferometer | M4 | CGH |
|---|---|---|---|
| DecX (mm) | -0.053 | 0.000 | -0.014 |
| DecY (mm) | -0.019 | 0.000 | 0.021 |
| ToY (deg) | - | 0.00E+00 | 0.00E+00 |
| ToX (deg) | - | 0.00E+00 | 0.00E+00 |

**Table 9.** As-aligned status of M5 from M4/M5 subsystem CGH test

| | VALUE, calc (deg, mm) | VALUE, calc (urad, um) | Reference coordinate adjusted |
|---|---|---|---|
| M5 ToY | -0.002638 | -46 | -26 |
| M5 ToX | 0.001730 | 30 | 10.5 |
| M5 DecX | -0.027046 | -27 | -13 |
| M5 DecY | -0.014885 | -15 | -36 |

The tilt of M2 and M3 mirror was calculated using Annular Standard Zernike coefficient sensitivities generated with a model for the M2-M3 null test. The measured aberration coefficients for tilt, primary coma, secondary coma and tertiary coma are added to calculated contributions from M2 decenter, M3 decenter, focus decenter, test CGH decenter and test CGH tilt. The sum of the measured coefficients and contributions from other component misalignments yields a set of coefficients that would be measured if all test optics were aligned in all DOF with the exception of the M2 and M3 mirror tilts. This calculated set of coefficients is used to perform a least-squares calculation of the M2 and M3 tilts based on the sensitivities.

The subsystem wavefront response from the as-aligned status of M2/M3 subsystem CGH test is listed in the Table 10 and the alignment status of M2/M3 subsystem CGH test is in the Table 11. The calculated alignment status of M2 and M3 in decenter and tilt are in the Table 12 and as in the result the decenter and tilt meets the system alignment tolerance in the Table 3.

**Table 10.** Wavefron measurement from the M4/M5 subsystem CGH test (Unit is waves)

| Zemax annular term # | Value (waves) | Aberration |
|---|---|---|
| Z2 | -0.7298 | Tilt X |
| Z3 | -0.038465 | Tilt Y |
| Z8 | 0.010774 | Coma X |
| Z7 | 0.05146 | Coma Y |
| Z16 | -0.02536 | 2nd Coma X |
| Z17 | -0.04421 | 2nd Coma Y |
| Z30 | 0.018405 | 3rd Coma X |
| Z29 | -0.013028 | 3rd Coma Y |

**Table 11.** As-measured alignment status of the interferometer, M2, M3 and M2/M3 subsystem test CGH

| | Focus | M2 | M3 | CGH |
|---|---|---|---|---|
| DecX (mm) | 0.098 | -0.003 | 0.073 | 0.005 |
| DecY (mm) | -0.113 | -0.009 | -0.074 | 0.005 |
| ToY (deg) | - | - | - | 3.75E-03 |
| ToX (deg) | - | - | - | 6.99E-03 |

**Table 12.** As-aligned status of M2 and M3 from M2/M3 subsystem CGH test

| | VALUE, calc (deg) | VALUE, calc (urad) | Reference coordinate adjusted, (urad) |
|---|---|---|---|
| M2 ToY | 0.00478 | 83 | 2.6 |
| M2 ToX | -0.00603 | -89 | -14.8 |
| M3 ToY | 0.00453 | 79 | 6.6 |
| M3 ToX | -0.00607 | -90 | -15.8 |

### 4.3 Full system CGH test

Full system CGH test provides an independent check of the system alignment status. In this test the mirrors will remain as aligned from M4/M5 and M2/M3 subsystem CGH test but the CGH and the interferometer will be compensator to get the best null fringe. The system configuration is as shown in the Figure 12. This test is expected to be performed in two extreme operation angle to simulate the actual operation condition.

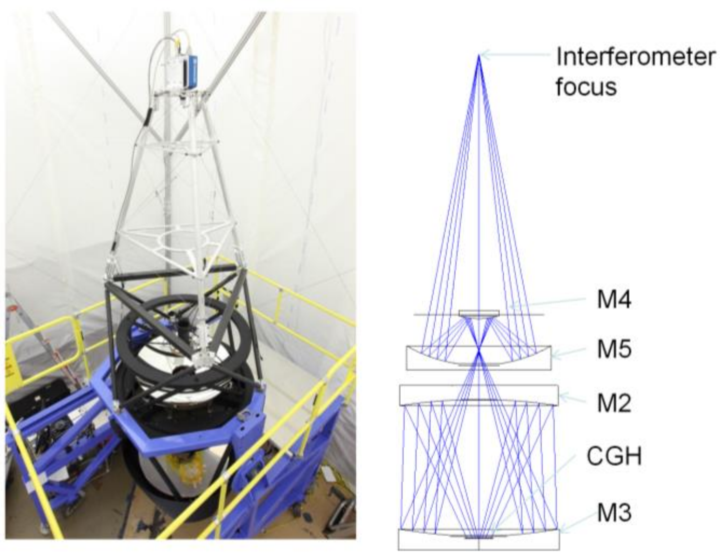


**Figure 12.** Full system CGH test

## 5. CONCLUSION

The 4-mirror wide field corrector for the Hobby Eberly Telescope is in the final stages of development. The designs, analysis and fabrication are complete. Currently the system is in final alignment process. A comprehensive plan for alignment and verification from pretest has been developed. This system is expected to be aligned and also the performance is to be verified in this year.


## ACKNOWLEDGEMENTS

HETDEX is run by the University of Texas at Austin McDonald Observatory and Department of Astronomywith participation from the Ludwig-Maximilians-Universitt Munchen, Max-Planck-Institut fr Extraterrestriche-Physik (MPE), Leibniz-Institut fur Astrophysik Potsdam (AIP), Texas A&M University, Pennsylvania State University, Institut fur Astrophysik Gottingen, University of Oxford and Max-Planck-Institut fur Astrophysik (MPA). In addition to Institutional support, HETDEX is funded by the National Science Foundation (grant AST-0926815), the State of Texas, the US Air Force (AFRL FA9451 -04-2-0355), and generous support from private individuals and foundations.
Also the authors would like to acknowledge Dr. Gary Hill and Dr. Hanshin Lee's insight and technical contribution to this program.


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