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# Metrology systems for active alignment control of the Hobby-Eberly Telescope[*] Wide Field Corrector

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## ABSTRACT

The Hobby-Eberly Telescope (HET) Wide-Field Upgrade (WFU) will be equipped with new metrology systems to actively control the optical alignment of the new four-mirror Wide-Field Corrector (WFC) as it tracks sidereal motion with respect to the fixed primary mirror. These systems include a tip/tilt sensor (TTS), distance measuring interferometers (DMI), guide probes (GP), and wavefront sensors (WFS). While the TTS and DMIs are to monitor the mechanical alignment of the WFC, the WFSs and GPs will produce direct measurement of the optical alignment of the WFC with respect to the HET primary mirror. Together, these systems provide fully redundant alignment and pointing information for the telescope, thereby keeping the WFC in focus and suppressing alignment-driven field aberrations. We describe the current snapshot of these systems and discuss their roles, expected performance, and operation plans.

**Keywords**: Metrology, Active alignment, Hobby-Eberly Telescope, HETDEX

## 1. INTRODUCTION

In the next two years, the Hobby-Eberly Telescope (HET) will be upgraded with a 22-arcmin. diameter field of view wide field corrector (WFC), a new tracker and prime focus instrument package (PFIP), and new metrology systems to support the Hobby-Eberly Telescope Dark Energy experiment (HETDEX)[1-2]. The new corrector has improved image quality and a 10 m pupil diameter[3]. The periphery of the field (i.e. an annular field from 18′ to 22′ diameter, called the metrology service field) will be used for guiding and wavefront sensing to provide the necessary feedback to keep the telescope correctly aligned. The WFC will give 30 times larger observing area than the current HET corrector. It is a four-mirror design with two concave 1 meter diameter mirrors, one concave 0.9 meter diameter mirror, and one convex 0.23 m diameter mirror. The corrector is designed to feed optical fibers at f/3.65 to minimize focal ratio degradation, and so the chief ray from all field angles is normal to the focal surface. This is achieved with a concave spherical focal surface centered on the exit pupil. The imaging performance is 0.5 arcseconds or better over the entire 22 arcminutes field of view, and vignetting is minimal. As in the current HET, the WFC will track sidereal motion with respect to the optical axis of the fixed spherical primary mirror (M1). Therefore, the WFC needs to be continuously positioned and oriented to maintain its alignment in order to deliver the required image quality. This demands constant monitoring and updating of the position of its components. Table 1 shows the allowed ranges of misalignments of the WFC as a rigid body at any given track position.

**Table 1. The allowed ranges of misalignments of the WFC.**

| Alignment parameters | Decenter | Defocus | Tip/tilt | Rho |
|---|---|---|---|---|
| Requirement | ±10 μm | ±10 μm | ±4 arcsec. | ±20 arcsec. |

The feedback to keep these alignment specifications requires robust metrology and we plan to deploy the following metrology subsystems for this:

- Guide probes (GP): Monitoring the position on the sky, plus plate scale of the optical system, and monitor the image quality and atmospheric transparency.
- Wavefront sensors (WFS): Monitoring the plate-scale, focus, and tilt of the WFC.

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

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- Distance measuring interferometer (DMI): Monitoring the physical distance between the WFC and primary mirror.
- Tip-tilt sensor (TTS): Monitoring the physical tip/tilt of the WFC with respect to the optical axis of the primary mirror.

The wavefront sensor is a newly introduced metrology system to the HET in order to close the loop on all axes of the system together with the DMI and TTS adapted from the current tracker metrology system. Both operate at a near infrared wavelength[4]. These systems can provide sufficient redundancy for the highest possible reliability in monitoring the alignment of the WFC. DMI and TTS measurements are directly related to the alignment state of the mechanical structure of the WFC, while responses from the WFS and GP are analyzed to determine the "*optical*" alignment state of the WFC. The WFS analysis is based on the following alignment–aberration relations: Decenters of the WFC causes systematic wavefront tilts across the field. This is equivalent to the telescope pointing error and equivalent to the stellar position measurement from the GP. Tilt errors add field constant coma to the aberration field of the WFC, while the axial motion introduces defocus aberration that is also field constant. The defocus aberration, however, can also be produced when the global radius of curvature (GRoC) of M1 changes. As this variation can also produce plate scale variation, an appropriate monitoring system is necessary. Although the segment alignment maintenance system (SAMS) maintains the positions of the 91 mirror segments with respect to each other[5], it is less sensitive to the GRoC change. Thus, we plan to monitor the GRoC variation by the combination of focus position from the WFS with the physical measurement from the DMI and to verify this by the plate scale measured from the positions of guide stars on the GP and WFS. The feedback from the SAMS can be used as a redundant piece of information on the GRoC change. The primary mirror tip/tilt is currently controlled by the mirror alignment recovery system (MARS). MARS maintains the segment tip/tilt to an accuracy of 0.14 arcsec rms[6]. We plan to continue using this system for the WFU. We also plan to use three DMIs to correct the segment piston errors. For this, we will deploy DMIs instead of one in order to reach all mirror segments across the M1. The DMI, TTS, GP, and WFS systems can provide fully redundant alignment and pointing information for the telescope, thereby keeping the WFC in focus and suppressing alignment-driven field aberrations. We describe the current snapshot of these systems and discuss their roles, expected performance, and operation plans.

# 2. WFC METROLOGY SYSTEMS

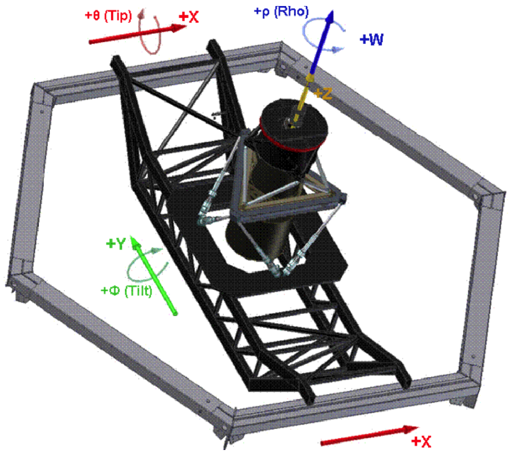

**Figure 1** The intrinsic motions given by the tracker mechanisms in the WFU.

On the HET, the optical alignment of the WFC with respect to the M1 must be held dynamically while the image moves as much as 3.8 m with respect to the main telescope structure along the M1 focal sphere. The mechanisms controlling the tracker synthesize the required tracker motions along the focal sphere by a combination of x, y, focus (z), tip (θ), tilt (φ), rotation (ρ) axes of stacked x and y stages, a hexapod system and a rotation stage. The range of motion for each axis is: 3.8 m in x and y, 130 mm in z, 17° in θ and φ, and 44° deg in ρ (Figure 1). In the very original design of the telescope the only feedback to control the motion with respect to the M1 was provided by a guider which constrained only the two pointing degrees of freedom. The remaining degrees of freedom were to be modeled. To overcome the deficiencies of the mount-models, additional metrology systems were added to provide feedback on focus, tip and tilt of the corrector with respect to the M1. Focus is measured with an absolute distance measuring interferometer (DMI) while tip and tilt are measured with an auto-collimator system called the tip/tilt sensor (TTS)[4]. Both the DMI and TTS operate at a wavelength of 1.5 μm that is outside the range of any current or planned instrument used on the HET. These two systems are to be directly adopted for the same metrology in the WFU. In order to close the alignment control loop on all axes for the WFU, we plan to add wavefront sensors to the suite of metrology systems. In conjunction with the guide probes, the WFS will provide direct information on the *optical alignment state* of the WFC. The individual metrology sub-systems are detailed below.

## 2.1 Distance Measuring Interferometer (DMI)

The DMI is a low-coherence distance measuring interferometer developed by Fogale-Nanotech[7]. The system operation is based on a pair of Michelson interferometers where all of the optical paths, except the measurement arm, are along optical fibers (Figure 2). The first interferometer encodes the phase difference to the primary mirror with respect to a

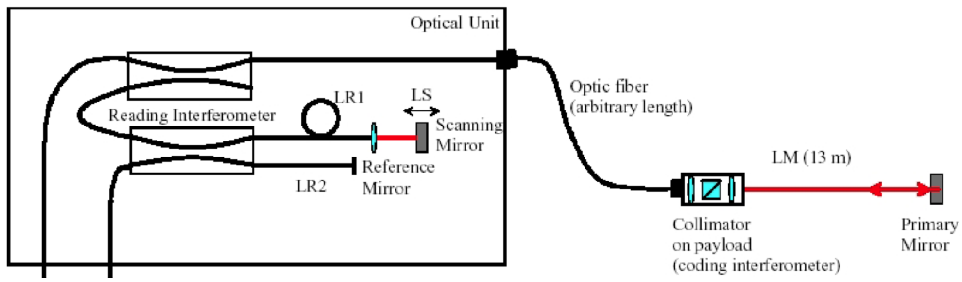

**Figure 2** The operation principle of the distance measuring interferometer[4].

reference at the collimator measurement head, a distance equal to 2LM. The two arms of the second interferometer induce phase delays of 2(LR1+LS) and LR2 respectively. Here, LS can be adjusted by an optically encoded scanning mirror. The second interferometer reads the phase difference from the coding interferometer by scanning through the exact phase matching condition where LR1+LS-LR2 = LM. The system light source is a poly-chromatic super-luminescent diode (SLED). An interference signal is detected only when the phase difference is less than the coherence length of the source and is modulated by a peaked function called the visibility curve. Figure 3 shows an example of an interference curve. The peak of the visibility curve occurs at the exact phase matching condition of LR1+LS-LR2 = LM. This configuration allows the compact measurement head (Figure 4) of the instrument to be mounted remotely. The length of the optical fiber feeding the measurement head can be arbitrary and the distance measurement is unaffected by thermally induced changes to the length of feed fiber. The reading interferometer is housed in a thermally controlled chamber to maintain stability. The absolute distance is obtained by finding the peak. The range of the scanning mirror is 40 mm. This allows a sufficiently wide range for locating and setup of the measurement head which can be scanned in 5 sec. The scanning range is in fact narrower than 40 mm to reduce the measurement time. The visibility curve is sampled in 10ms. The RMS repeatability of measurements is 1 µm over time scales several minutes. The long term accuracy is specified at 1ppm[7].

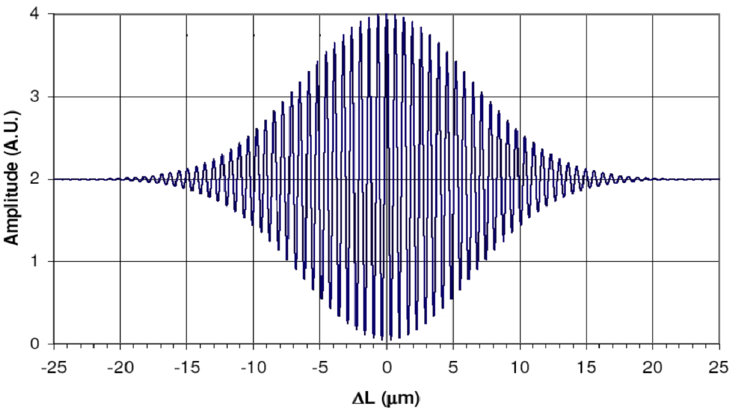

**Figure 3** An example of an interference curve. The peak of the visibility curve occurs at the exact phase matching condition of LR1+LS-LR2 = LM. The absolute distance is obtained by finding the peak[4].

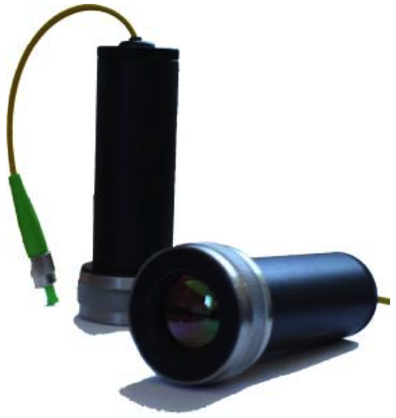

**Figure 4** The DMI measurement heads with a focusing lens at the output end of the head[7].

The system currently installed at the HET has two channels: one is to measure a nominal distance of approximately 12.6 m, located at the current corrector, and used for tracker metrology, and the other channel is set to measure a nominal distance of approximately 26.2m to measure distances at the center of curvature of the primary mirror. For the WFU, we plan to add one more two-channel DMI. In total, three DMI heads are to be distributed within the WFC in such a way that we can measure physical distances between the WFC and all mirror segments and the piston map of the entire M1 mirror segments can be obtained, which is otherwise difficult with only one DMI on the WFC. Each head will have its optical axis passing through the center of curvature (CoC) of the M1. This approach is expected to make a better correction to the M1 mirror segment piston errors.

### 2.2 Tip Tilt Sensor (TTS)

The TTS installed in the current corrector was developed in house due to the lack of a commercial product operating in the near infra-red which met our specifications for accuracy, stability and capture range[4]. The current TTS projects a beam at a normal to the primary mirror and the return beam is steered by a beam-splitter to a camera with a phosphor coated CCD yielding a spot size of 2 mm. The current TTS has a capture range of ±75 arcsec and rms repeatability of 0.2 arcsec. Due to the fact that the measurement head and the CCD are packaged in the same housing, relatively large volume is necessary to accommodate the entire TTS system near the optical axis of the corrector. In the WFU, this is likely to be an issue and therefore we will adopt most of the features of the existing TTS, but with some modifications. In the new TTS for the WFU, the return beam is routed through a beam-splitter to a coherent imaging fiber bundle from Schott. Consisting of several hundred thousand 10 μm-core coherent fibers packed in a 8 mm by 10 mm rectangular array format, the approximately 4.6 m-long fiber bundle transmits the TTS spot image on its input end to the output end of the bundle. A phosphor-coated screen butted to the bundle output surface produces visible photons that are imaged by a relay optic onto a CCD. There will be a long pass filter in front of the input fiber bundle surface to prevent the visible glow of the phosphor from escaping the TTS during observations. The advantage of using an imaging fiber bundle is that only the compact measurement head needs to be installed near the WFC optical axis while the bulky CCD and electronics can be remotely installed within a separate electronics box.

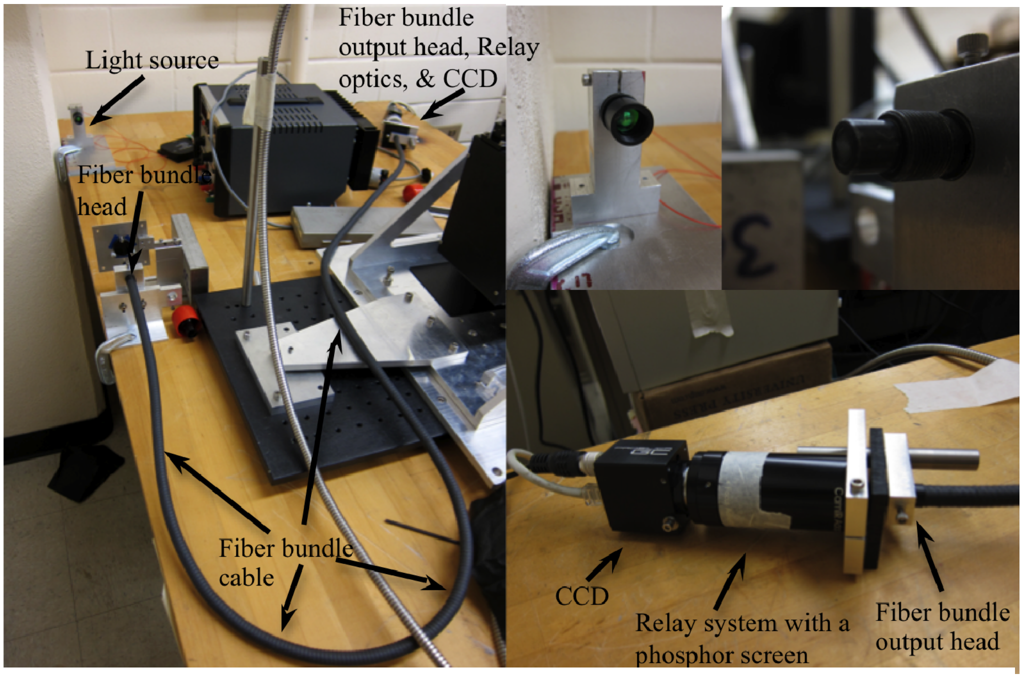

**Figure 5** (Left) The lab test of the Tip/Tilt Sensor for the WFU. (Top middle) the low-coherence fiber coupled light source, (Top right) the input end of an imaging fiber bundle, (Bottom right) The output end of the fiber bundle butted to a relay system with a phosphor screen and the prosilica CCD at the end.

We have conducted a lab test of the new TTS configuration (Figure 5). The light source is a fiber-coupled amplified spontaneous emission (ASE) source from Lightwaves2020. The source has the central wavelength at 1.55 μm with a spectral width of approximately 50 nm, which eliminates problems with fringing due to a laser source and forms a smooth Gaussian-like PSF (Figure 6). In the current setup, the collimated beam of the light source is fed through a long-pass filter to a 4 mm x 4 mm imaging fiber bundle from Schott. In this configuration, the size of the fiber bundle input surface determines the dynamic range of the tip/tilt sensing. For the production version of the TTS, we plan to use a fiber bundle with a larger input surface area of 8 mm x 10 mm, which gives the tip/tilt dynamic range of ±75 arcsec in the longer dimension and ±60 arcsec in the shorter dimension. The output head of the fiber bundle is mounted to an IR imaging relay system from Edmund Optics. The relay system consists of a phosphor-coated screen and an imaging lens. The phosphor screen is butted to the fiber bundle output surface and produces visible photons that are captured by the imaging lens. We use a prosilica GC655 CCD (659 x 493 pixel format with 9.9 µm pixel size). The CCD is attached to the end of the IR imaging system and records the visible spot image. The imaging lens has a linear magnification of approximately 0.33. The measured image centroid stability in the current test setup is less than a tenth of a pixel. The source power of 0.8 mW produces sufficiently high signal-to-noise ratio (SNR ~ 3800). In the actual TTS system, the beam goes through a beam splitter twice. Thus, SNR would be a factor of 2 lower, but it is always possible to increase the source power if necessary.

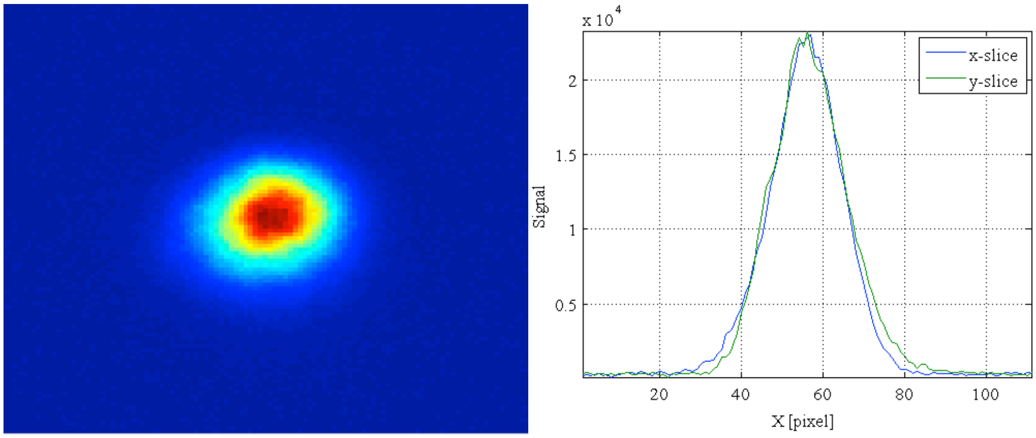

**Figure 6** The spot image on the lab-test TTS CCD (left) and x & y slices of the spot (right).

### 2.3 Guide Probe (GP) and Wavefront Sensor (WFS)

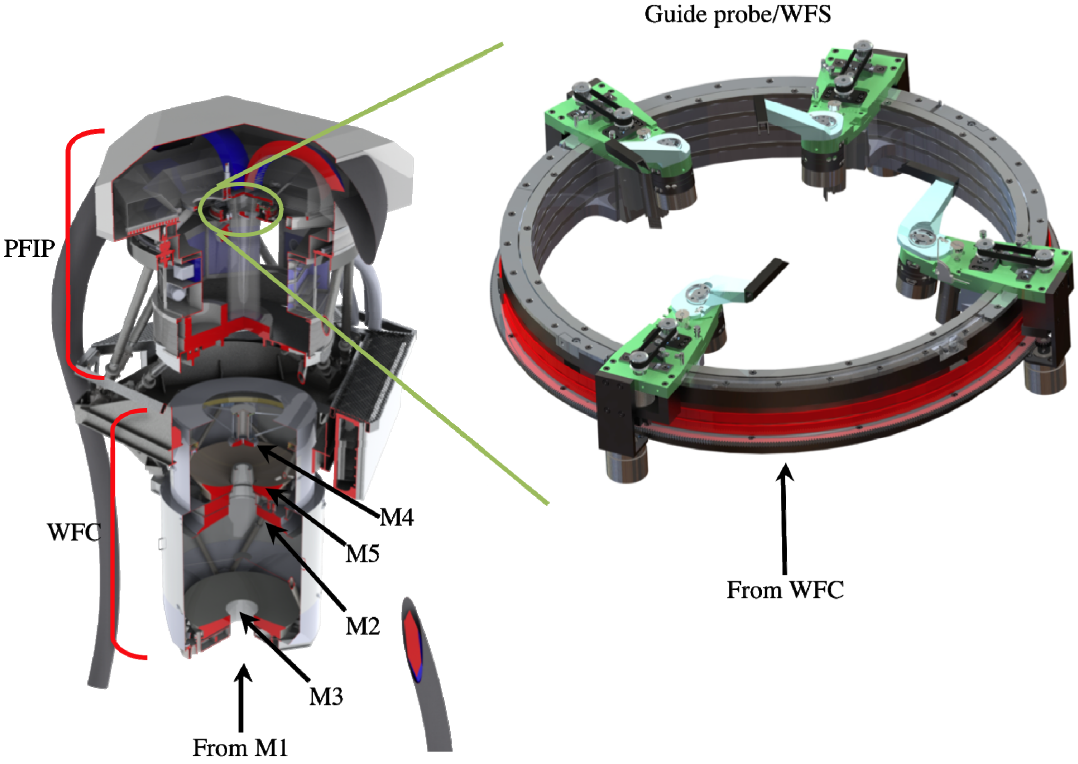

**Figure 7** (Left) A section view of the WFC and Prime-Focus Instrumentation Package (PFIP) where the guide probe and wavefront sensor assembly reside near the focal surface (marked by green circle near the top of PFIP). (Right) A close-up of the guide probe and wavefront sensor mechanical assembly where two guide probes and two wavefront sensor probes are mounted on a circular bearing; each probe has a probing arm; a folding prism is at the tip of each arm,

steering the beam from the WFC to an imaging fiber bundle (guide probe) or to a collimation lens that feeds a collimated beam to a lenslet array butted to an imaging fiber bundle (wavefront sensor) (optical components are not shown).

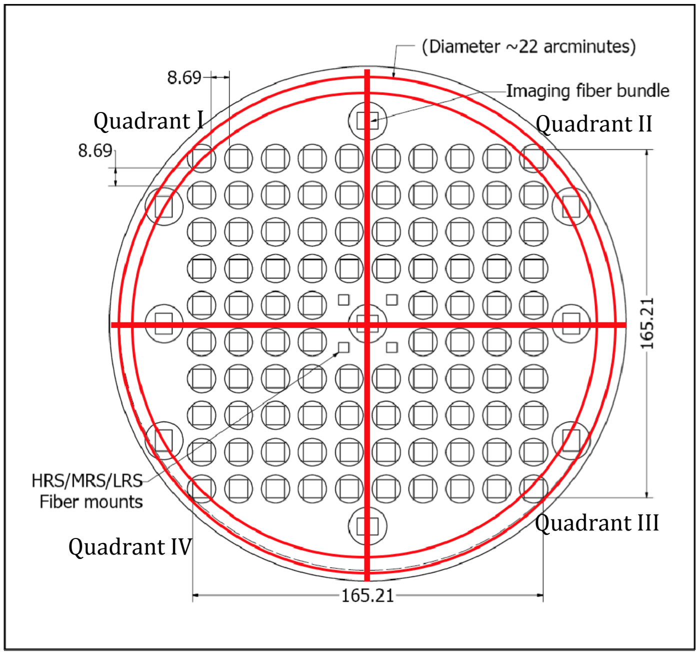

**Figure 8** The focal plane of the WFC. The metrology service field is indicated by two red solid circles. The annular field is divided into four quadrants by the crosshair.

Figure 7 illustrates the layout of the WFC and Prime-Focus Instrumentation Package (PFIP). The guide-probe and wavefront sensor assembly resides near the focal surface assembly marked by a green circle near the top of the PFIP. A close-up view of the guide probe and wavefront sensor assembly is shown on the right. There are four probes; two are guider and two are wavefront sensors. Each probe has its own arm and a folding prism is placed at the tip of the arm to route the beam within the metrology service field (i.e. an annular field from 18′ to 22′ diameter, see Figure 8) to an imaging fiber bundle (for GP) or a collimation lens feeding a collimated beam to a lenslet array coupled with an imaging fiber bundle (for WFS). The fiber bundles transmit stellar images (for GP) or a Shack-Hartmann (SH) wavefront sensor image (for WFS) to CCD cameras at the output end of the bundles. The CCD cameras are remotely located in a separate electronics box. We plan to use FLI microline CCDs (ML0261E) for the GP and WFS.

The recorded stellar images or SH images (Figure 9) are then analyzed to determine the centroids of guider images and the telescope aberrations, from which appropriate WFC alignment corrections are produced. The feedback from the guide probes is the telescope pointing on the sky, telescope plate scale, image quality (e.g. FWHM), and atmospheric transparency. The feedback from the wavefront sensor also tells us about the telescope pointing and plate scale change, but more importantly any misalignment of the WFC with respect to the M1 and the telescope aberration characteristics. The expected guiding accuracy from the guide probes is 0.25 c with 0.1arcsec as a goal in rms. The two WFS will have a low sub-aperture density (7 x 7 lenslet array). Up to 14 Zernike aberration coefficients can be measured by this WFS, among which the first 7 terms are explicitly related to the WFC alignment state. These WFS can reach SNR ~ 110 in a 60sec exposure for $m_v$=18 stars. This can lead to 0.05arcsec SH spot centroid accuracy in rms at a worst case. The expected intrinsic WFC alignment estimation accuracy from the WFS is ±1.26 μm in decenter, ±2.0 μm in focus, ±0.5 arcsec in tip/tilt, and ±0.85 arcsec in rho at 99% level[8]. Ideally, we wish to have stars for two guide probes and two wavefront sensors, each operating in one quadrant of the metrology service field, but the current baseline is to have at least two guide stars and one wavefront sensor star. We also plan to have another WFS with higher sub-aperture density (16x16). This WFS can operate at the center of the field of the telescope as a witness WFS and can also provide feedback for the WFC alignment control as well as higher-order aberration coefficients for monitoring any variations in the telescope optical components. We intend to use this witness WFS during WFU commissioning.

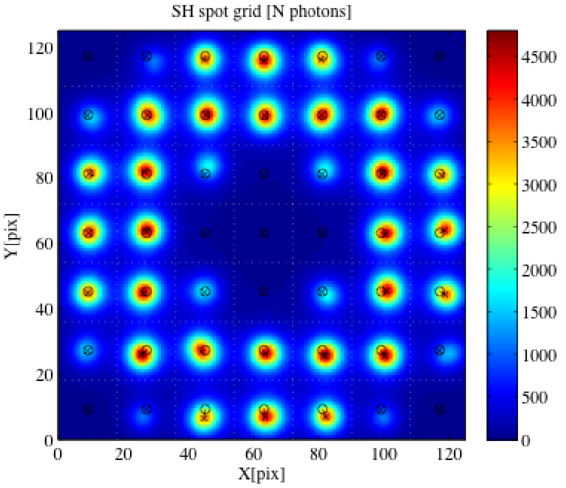

**Figure 9** A simulated example SH image seen by a 7x7 WFS at the center field of the HET WFC.

# 4. METROLOGY FEEDBACK & CONTROL

From the metrology systems, we will have sufficiently redundant information on the WFC alignment state with respect to the primary mirror. However, there is a fundamental difference between these metrology feedbacks. TTS and DMI will provide the mechanical alignment state of the WFC, while the GP and WFS will produce the WFC alignment control feedbacks based on optical measurements (thus yielding the optical alignment state of the WFC). Although both TTS and DMI are to be calibrated against the optical measurement by the WFS and GP so that the relation between the optical axes of TTS and DMI and those of the WFC will be known, there is a possibility that this relationship changes during the operation of the telescope due to, for example, misalignment of the internal components of the WFC (i.e. the WFC mirrors and focal plane assembly). The WFC internal components are to be rigidly mounted to their mounting structure, but the Finite-Element Analysis of the WFC suggests that the internal mirrors and focal plane will be shifted and rotated due to variations in gravity vector and temperature during telescope operations. The internal alignment variations are expected to be repeatable so that they could be explicitly modeled or measured and then subtracted. In a situation where this is not the case due to the existence of unknown (or less accurate) telescope mount models, the WFS feedback will be used to set the fiducials of the DMI and TTS. Each metrology system will have different update rates. The TTS and DMI will have an update rate of 10 sec. The GP update rate can be made as fast as 1 ~ 5 sec. The current baseline WFS update rate is 60 sec for an $m_V$=18 star. For brighter stars, the WFS update can be more frequent, but the exposure should not be shorter than 30 sec as it requires approximately 30 sec to sufficiently average out atmospheric aberrations which we do not wish to sense with the WFS. Given these differences between the metrology systems, it is necessary to coordinate the feedbacks from different metrology systems in order to optimally control the WFC alignment. The following chart illustrates the current snapshot of the metrology flow (Figure 10).

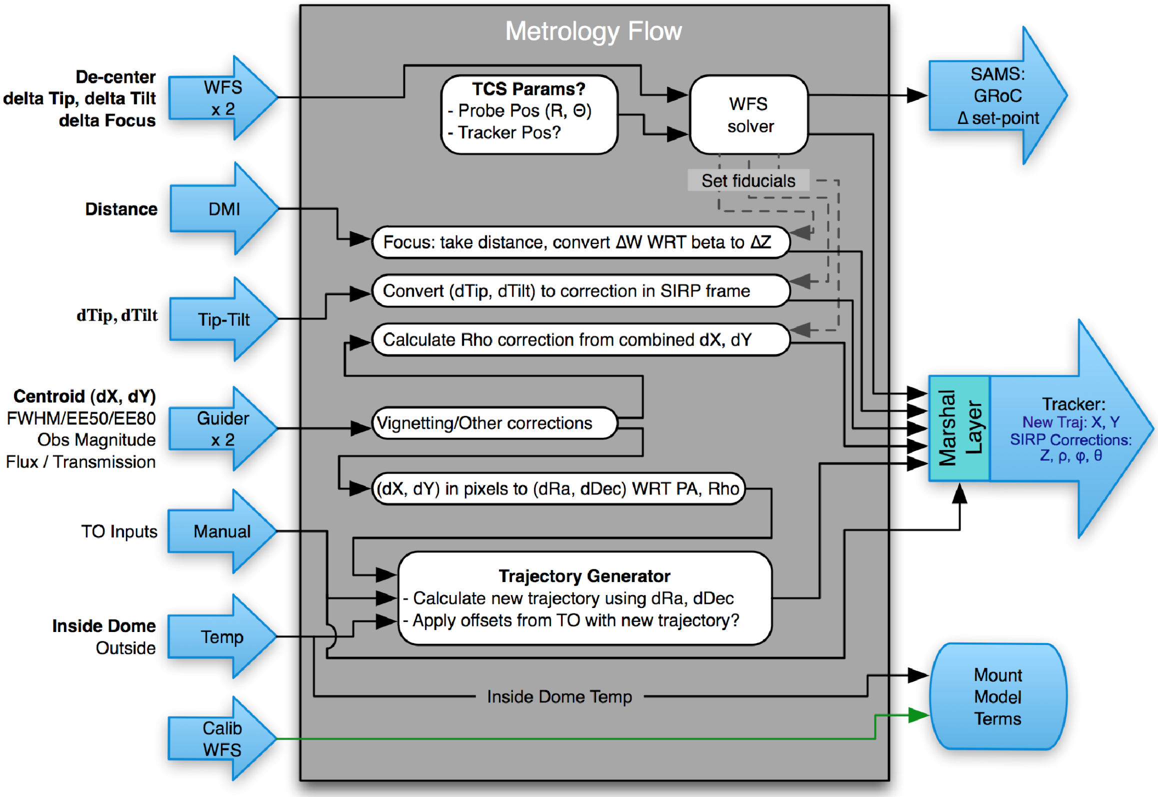

**Figure 10** Metrology control flow.

The witness WFS (Calibration WFS in the figure) is to be used for calibrating the two low-order WFS, DMI, and TTS. It will be also used to measure various telescope mount model terms during on-sky installation and commissioning. During observations, the GP, DMI, and TTS will provide necessary feedback for the WFC with fast update rate. The two low-order WFS will sense gross drift in the WFC alignment, the global radius of curvature (GRoC) of the primary mirror, plate scale variation (GP can also provide this), and any internal change in aberrations of the telescope. These are to be used as offset values for the DMI and TTS. Special attention needs to be given to GRoC control. The GRoC has essentially the same effect as the WFC defocus: blurring stellar images and adding defocus aberration to WFS signals. As a result, it is difficult to distinguish these two parameters just by analyzing the WFS aberration data and/or GP image quality data. Our plan for updating the GRoC is as follows. The DMI maintains the physical separation between the WFC and the M1 as the GRoC drifts. This will accumulate defocus aberration to the WFS signal, thereby increasing the required amount of the WFC focus correction given by the WFS. Once the amount of the *accumulated* WFS-based focus correction reaches a certain upper limit (which must be set by the required seeing-convolved image quality specification), the accumulated value is applied as change in the GRoC. At the same time, the DMI zero point also needs to be offset by this value. Although the GRoC variation leads to a change in the telescope plate scale (which can be monitored by the guider centroids and WFS tip/tilt aberrations), this variation is much less significant than the impact of GRoC on the image quality and thus may not be easily detected. However, we expect that monitoring the plate scale drift can also provide another constraint on a long-term GRoC variation.

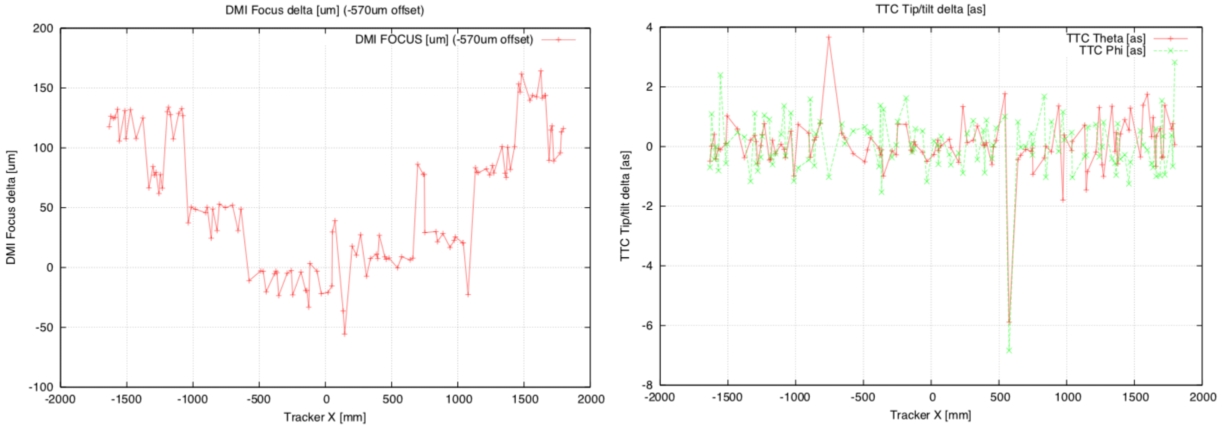

**Figure 11** DMI and TTS measurements made during an hour-long track at the current HET.

The DMI and TTS can also monitor the M1 segment piston/tip/tilt errors. Figure 11 shows the distance (left) and tip/tilt measurements (right) during an hour-long track from the current DMI and TTS in the HET. The DMI plot clearly shows a step-wise variation (amounting 50 to 70 μm) in the curve. When comparing this curve with the trajectory from the tracker, the step-wise variation appears to occur around the edges of two adjacent mirror segments. In between step-wise variations, the curve shows almost flat curve (with ±10 μm fluctuations). The points in these regions fall within a single segment. These step-like variations probably result from a combination of segment piston, tip/tilt, and figure errors. However, the TTS measurement on the right panel shows that the WFC tip/tilt relative to the primary mirror was consistently maintained within ±2 arcsec along the hour-long track. A 1 arcsec segment tip/tilt leads to roughly 3 μm piston at the edge of the segment. A recent investigation suggests that the surface figure error of the mirror segments is less than 1 wave at 632.8 nm in peak-to-peak across the M1[9], which is less than a micron in terms of surface sag value. Thus, the step-wise variation in the top plot is mostly from the segment piston error. Inversely, the plot suggests that the DMI measurement can be utilized to find appropriate segment piston corrections. In the WFU, we plan to use three DMIs for this purpose and expect that the M1 piston error can be reduced down at least to the level of the DMI accuracy observed in the left plot. Also, the TTS measurement can reveal step-wise change between segments if there is any large segment-to-segment tip/tilt error.

## 5. SUMMARY

In this paper, we described the key metrology systems for active alignment of the WFC. These systems are: the DMI, TTS, GP, and WFS. We plan to adopt the DMI and TTS used in the current HET. In addition to the current DMI system, we will add another two-channel DMI (3 DMIs in total). These DMIs will allow us to reach all mirror segments so that the segment piston errors across the M1 can be measured and corrected. During science operation, one DMI is to be used to maintain the mechanical separation between the WFC and the M1. The distance capture range of the DMI is 40 mm with intrinsic repeatability of 1 μm rms. A small modification is to be made to the TTS. The TTS signal is to be captured and transferred through a coherent imaging fiber bundle to a CCD located remotely, which will make the TTS measurement head compact. A lab test of this modified TTS measurement head has shown that this new concept should work. The TTS will be used to maintain the mechanical tip/tilt of the WFC with respect to the M1. The intrinsic measurement repeatability of the TTS is 0.2 arcsec. In conjunction with these two systems, we will have two guide probes and two (low-order Shack-Hartmann) wavefront sensors operating within the annular metrology service field at the edge of the telescope focal plane assembly. The guide probes will provide feedback on the telescope pointing, plate scale, image quality, and atmospheric transparency, while the wavefront sensors will optically monitor the WFC alignment and the variations in the telescope aberration characteristics. The expected GP guiding accuracy is 0.25arcsec or better in rms. The expected intrinsic WFC alignment estimation accuracy of the WFS is ±1.25 μm in decenter, ±2.0 μm in focus, ±0.5 arcsec in tip/tilt, and ±0.85 arcsec in rho at the 99% level. In the control loop, the DMI and TTS will frequently (~ every 10 sec) update the focus and tip/tilt feedback for the WFC alignment control, while the WFS updates the fiducial values for the DMI and TTS every 60 sec. The combination of the WFS and DMI feedback will be used to monitor and control the global radius of curvature of the M1 during operation. There will also be a higher-order Shack-Hartmann wavefront sensor. This will be the truth sensor against which the DMI, TTS, and two low-order WFS are to be calibrated. This sensor will also be used to establish and verify various telescope mount model terms during WFU installation and commissioning. Together, these systems can provide fully redundant alignment and pointing information for the telescope, keeping the WFC in focus and suppressing alignment-driven field aberrations.

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