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# Mechanical Systems Performance of the HET Wide-Field Upgrade

John M. Good*[a], Ron Leck [a], Jason Ramsey [a], Niv Drory [a], Gary Hill [a], James Fowler[b], Herman Kriel[b], Martin Landriau[c]

[a] The University of Texas at Austin, McDonald Observatory,
2515 Speedway, RLM 13.116, C1402, Austin, TX 78712-1486; [b] The University of Texas
McDonald Observatory, 82 Mt. Locke Rd., McDonald Observatory, TX USA 79734-3005,
[c]Lawrence Berkeley National Laboratory, 1 Cyclotron Road Mailstop 50R5008, Berkeley, CA USA
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## ABSTRACT

We have completed a major Wide Field Upgrade (WFU) of the Hobby-Eberly Telescope (HET) and reentered scheduled queue science operations in mid-2016. This paper assesses the performance of the various mechanical systems which were upgraded, or added to HET, including the Telescope Structure, the star Tracker (aka, WFU Tracker), Prime Focus Instrument Package (PFIP), and VIRUS Support Structure (VSS). The upgrades were required to increase the field of view of HET, from 4 arc-minutes, to 22 arc-minutes, increasing the observed area of sky by 30 times the original FoV. In the process, the total weight of the system increased from 100 tons, to 153 tons, requiring a complete overhaul of most of the mechanical, servo, and control systems. The new 13-axis Tracker and control system was tested extensively prior to shipping and installation, and followed up with laser tracker measurements, which brought the tracking system to within 1 arc-minute RMS pointing, and followed up with on-sky derived mount-models, which has improved the pointing and guiding to within 12 arc-seconds RMS, and 0.1 arc-seconds, respectively. A completely new structural support system was implemented to house and connect a total of 156 VIRUS spectrographs, plus 4 new Low-Resolution Spectrographs (LRS2). The VIRUS units are arrayed in two large enclosures mounted to either side of the telescope. Each enclosure is approximately 1.3m deep x 6.7m wide x 6.2m tall and weighs 38 tons fully loaded. This structure is attached to HET in a way that allows it to be positioned by, but stand independent of, the HET during observation. As commissioning has transitioned to phased-science/engineering operations, and subsequently, to science operation, the tracking software and mechanical performance of the Tracker and VSS have been improved to meet specification. Performance data and lessons learned are provided.

**Keywords:** Hobby Eberly Telescope, WFU Tracker, HETDEX, VIRUS, Wide Field Corrector, Mount Modeling, Control Systems

## 1. INTRODUCTION

The Wide Field Upgrade to the HET was initiated in order to support the science mission of the Dark Energy Experiment (DEX) and consisted of a complete redesign of the upper portion of HET which tracks and acquires star light[1,2,3,4]. The WFU consisted of a new Wide Field Corrector, a new Tracker and Prime Focus Instrument Package, as well as upgrades to the telescope structure, and a housing and support structure for 156 VIRUS spectrographs. The WFC was designed and built at the University of Arizona, College of Optical Sciences. The Tracker was designed and build by The University of Texas Center for Electromechanics, with the exception of the Hexapod, which was designed and built by ADS International (Valmadrera, Italy). The Prime Focus Instrument Package was designed and built in-house, by the McDonald Observatory Engineering staff. The VIRUS Support System was designed by CEM and McDonald Engineering, and constructed by Systems Integration, Inc. (Arlington, Texas, USA).

Following laboratory testing and characterization, and installation of the 13-axis WFU Tracker, a series of tests were performed in order to create a first-order system mount-model. At the time of the tracker installation the WFC had not been completed so the system was characterized using a Laser Tracker to perform measurements on a facsimile of the WFC. By mounting four Spherically Mounted Retro-reflector's (SMR's) to its bottom surface, which is located at the Primary Mirror focus, and hence, on the tracking sphere of the optical system, measurement of the entry pupil and well as the tip and tilt of the WFC was possible. Using this technique we were able to create a mount model establishing a pointing accuracy of 1 arcminute. After the Corrector and Prime Focus Instrument Package (PFIP) was installed, on-sky tests began and steady improvements have been made to both pointing and guiding sufficient to permit science

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operations of the tracker & and its instruments, which include the Habitable Planet Finder (HPF), Low-Resolution Spectrograph 2 (LRS2), and the High-Resolution Spectrograph (HRS), in addition to VIRUS. The other major mechanical change to the HET was the addition of a completely new support system, the purpose of which is to house VIRUS, called the VIRUS Support Structure (VSS). VIRUS consists of an array of 156 fiber-fed spectrometers which are divided into two arrays of 78 spectrometers positioned on either side of the primary mirror. The height and positioning of the arrays was optimized to minimize the fiber length, while permitting a VSS design that was compatible with the HET science goals. The result was an independently mounted structure and housing that sits on the telescope pier, and utilizes the azimuth drive of the telescope during azimuth positioning between observations. The concept for this design was initially developed by Comsat RSI, under a contract for a feasibility study. Refinements to the design were developed by the Center for Electro-Mechanics (CEM), as well as by the McDonald Observatory engineering staff. The housing for VIRUS spectrometers was designed by McDonald as well as Texas A&M engineers. The VSS supports all aspects of the VIRUS functions, including cryogenic cooling with liquid nitrogen, environmental thermal control, light-tight operation, a class 10,000 cleanroom environment, electrical power, and data & signal communications.

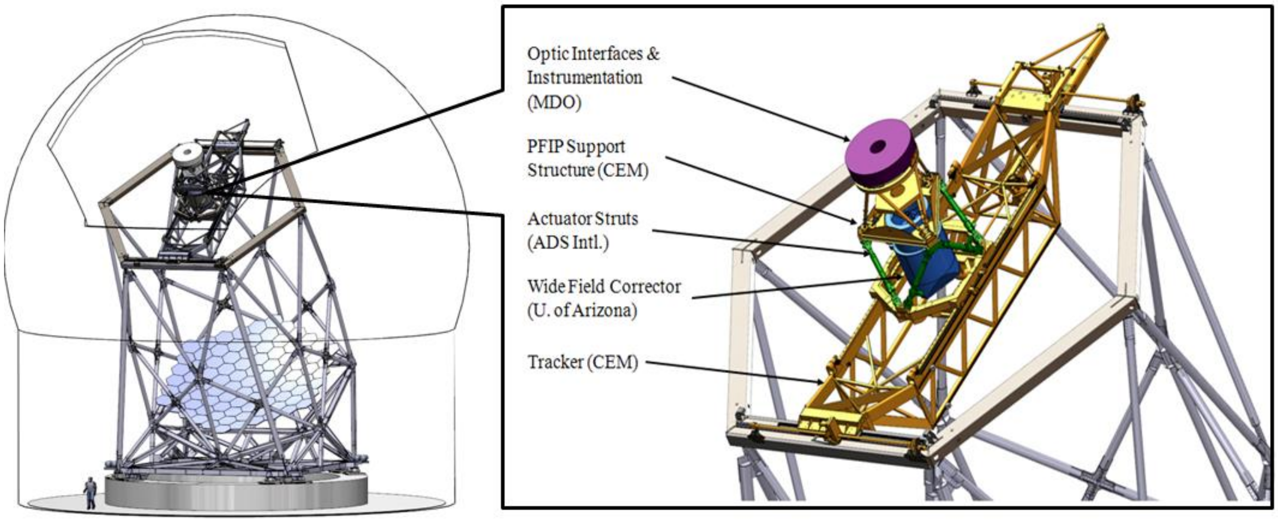
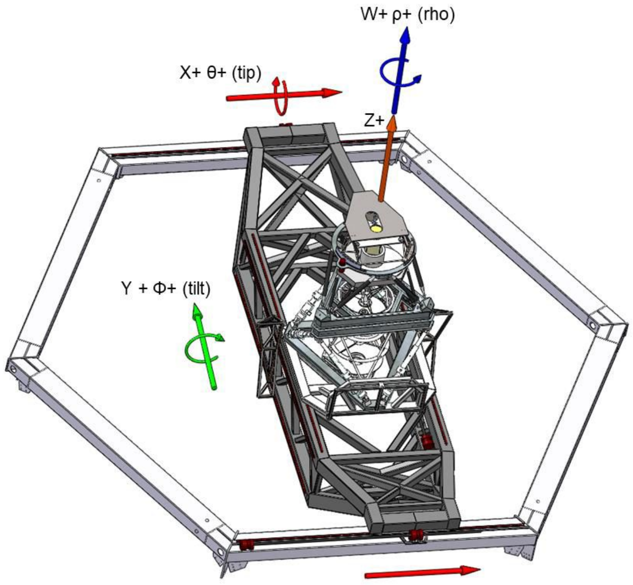


Figure 1. The 4-element Wide-Field spherical aberration Corrector (WFC) is mounted on the 13-axis tracker of the HET. The corrector provides a 22 arc-minute field of view for the HETDEX survey, the Habitable Planet Finder, as well as low-resolution and high-resolution spectrometers.

*good@astro.as.utexas.edu; phone 1 512 471-0394; http://mcdonaldobservatory.org/

## 2. SYSTEM PERFORMANCE SPECIFICATIONS

The system pointing and guiding specifications for the Wide Field Upgrade were established as detailed in table 1 below. Note that the image scale for the primary mirror at focus is 63μm/arcsec.



| Parameter | System Error Budget (Pointing) | System Error Budget (Guiding) | Notes |
|---|---|---|---|
| Tip/Tilt (β) | 40.0” | 10.0” | Angle between W & Z axes |
| Defocus (ΔW) | 200 µm | 15 µm | ΔW along W axis |
| Decenter (ΔR) | 1.5mm (25”) | 16 µm (0.25”) | ΔR measured in the X/Y plane |

Figure 2. The Wide Field Corrector system error budget for pointing and guiding. The primary mirror image scale is 63μm/arc-second.

# 3. MECHANICAL SYSTEMS

## 3.1 Structure[5]

The original structure had a fundamental mode of 6.5 Hz, and a total mass of 81647kg. The tracker exerted normal forces on upper and lower beam of 29,205N (combined). The lateral tracker-force was constrained entirely on the lower beam and had a value of 20,450N.

The upgraded structure has a fundamental mode of 5.3 Hz, and a total mass of 104,325kg. The WFU Tracker exerts normal forces on upper and lower beam of 151587N (combined). In order to keep the fundamental mode of the structure above 5 Hz, a requirement of the design, the tracker lateral forces were distributed 33% to the upper beam, and 66% lower beam by means of a force mechanism using springs. The travel range of the force mechanism is large enough to prevent binding between the upper and lower x-axis as it moves over its +/- 1800mm range of travel. Additionally, the lower beam was modified to increase stiffness by 118.8% normal, and 370% lateral. Thus the total lateral load is 106,140N, with 70,000N determined by the lower beam, and 35,000N spring-force loaded on the upper beam.

The second major change to the HET structure was to the azimuth air-bearings, manufactured by AeroGo, Inc. (Seattle, WA, USA). The increase in mass of the WFU Tracker from 88,790kg, to 104,240kg, shifted the center of mass forward from 0.215m to 1.236m, and upward from 4.808m to 6.349m above the structure base square. This translated to an increase in the required capacity for each of the 4 air-bearings from 106,757N (AeroGo Model #36NX), to 175,242N (AeroGo Model #36HDXAC1338). The original capacity of the air compressor system was determined to be adequate for the upgraded bearings, and that has been demonstrated following installation of all the new subsystems, including the VSS.

## 3.2 Tracker[6]

Original tracker mass was 3638kg (including 440 kg payload), and had a fundamental mode of 11.5 Hz. It utilized a 13-axis drive system in order to position a 4-element spherical aberration corrector in 6 degrees of freedom to follow a moving star image from a stationary primary mirror.

Due to the added mass and size of the WFU Corrector, PFIP, and the 36,000 fiber IFU system feeding VIRUS, the WFU tracker mass increased to 18,883kg (including 2339 kg payload) and has a fundamental mode of 9.4 Hz. It utilizes a similarly configured 13 axis positioning stage, plus an additional drive axis to offset the mass of the payload and mechanisms traveling in the Y-axis in order to prevent free-fall of the Y-axis components in the event of failure of the primary Y-drive system.

### 3.2.1 X & Y Axis Drive Systems[7,8]

The key component of the translational drive system is a system of preloaded high precision planetary roller screws to provide motion in the x and y axes. The drive screws, manufactured by SKF, are 60mm in diameter and have a 10mm per turn thread pitch. Fine positioning in tracking mode is accomplished by rotating the screw, and course positioning for pointing is provided by rotating the nut containing 6ea., 6-start planetary rollers, that engage the threads of the screw. A system of brakes is utilized to switch from tracking mode to slew (pointing) mode. The precision of each screw (SKF class G1) is within 6µm per 300mm, or better. The linear bearings are manufactured by THK (SHS series) and utilize caged-ball technology to increase load capacity.

### 3.2.2 Hexapod Drive System[9]

Tip-Tilt and Focus positioning are provided by a hexapod actuator system designed and manufactured by ADS International (Valmadrera, Italy). The load bearing capacity is 28 kN per actuator. The travel range for each actuator is 300mm. The precision of each actuator screw is 4µm per 400mm (Rollvis class G1). The positioning accuracy during tracking is 2µm, and 5µm during slew. The nominal (or home) position length of each actuator is 1440.5mm between the pins of the end-joints. Each actuator has a mass of 230kg. The assembled hexapod has a nominal height of 1450mm, and a diameter of 2500mm, and a tip-tilt range of +/-9°. The fundamental mode of the complete assembly is 13.4 Hz.

### 3.2.3 Rho Drive System

Rotation on the sky during tracking is handled by the Rho stage. This system is positioned above the hexapod and provides the mounting platform for the Prime-Focus Instrument Package. It has a positioning accuracy of 0.047 arcsec during tracking, and 3 arcsec for positioning in slew. It has a payload capacity of 1000kg, and an operational rotation range of +/-21 degrees. The drive mechanism utilizes a capstan and 8 redundant cables to provide 1569 N-m of torque.

## 3.3 Prime-focus Instrument Package[10]

The Prime Focus Instrument Package contains acquisition, guiding, and wave-front sensing instrumentation, as well as fiber feeds for VIRUS, LRS2, HPF, and HRS. It also has a shutter mechanism for the entire focal surface, and a dithering mechanism to allow the focal surface to be shifted during trajectories. The original PFIP mass was 350kg. The upgraded PFIP mass is 1126kg, including the portion of the VIRUS IFU's that are attached to the fiber feed mounting plate and the first of three strain-reliefs that support the 21 meter long, 36,000 fiber IFU system. The reader is encouraged to see reference [10] for a detailed treatment of the PFIP design and its capabilities.

Relevant to the mechanical systems performance of the Tracker, are the Acquisition Camera (ACAM), and the Guide Cameras (GC1 & GC2), the Distance Measuring Interferometer (DMI), the Tip-Tilt Camera (TTCAM), and the Wave-Front Sensor. The ACAM has a 3 arcmin FoV, from a deployable pick-off mirror in the center the HET field. Additionally, there are two guide cameras, GC1 & GC2, on radial positioning stages on the outer 3 min periphery of the 22 arcmin FoV. The FoV of each guide camera is 22.6 arcsec. The two cameras are independently mounted on radial tracks and can rove about the outer ring of the telescope FoV to access guide stars. The DMI provides a real time measurement of the WFC distance from the Primary Mirror. The TTCAM senses tip and tilt relative to the PM, and the WFS provides real time focus sensing of guide stars.

## 3.4 VIRUS Support Structure[11,12]

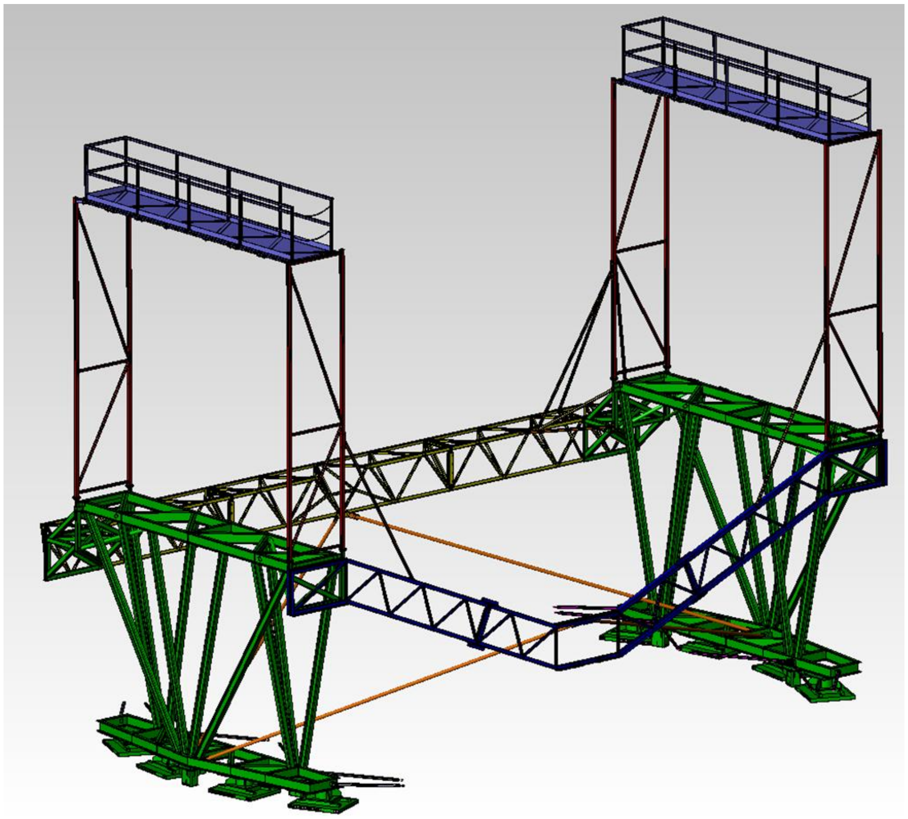


Figure 3. The VIRUS Support Structure is coupled to the HET (not shown) for azimuth rotation, but isolated during observations. The structure is suspended on air-bearings, identical to HET, during azimuth moves, but rests on the HET pier during observations. The symmetric arrangement houses 80 IFU-fed spectrometers per side (160 total).

A new support structure was added to the HET, the purpose of which is to optimally position and house 156 Fiber-fed VIRUS Spectrographs + 4 Fiber-fed Low-resolution Spectrographs. The VIRUS Support Structure (VSS) has a mass of 26,308kg, and has a first harmonic mode of 3.15 Hz. The VSS divides VIRUS into two arrays of 78 spectrometers positioned on either side of the primary mirror. The height and positioning of the arrays was optimized to allow IFU lengths to be in the 20 meter length range, while permitting a VSS design that was accessible, dynamically stable, and independent of the HET structure.

To prevent adding mass and lowering the fundamental mode of the HET structure, VSS was designed as an independently mounted structure and housing that sits on the telescope pier, but has rotational linkage to HET so that it can utilize the azimuth drive of the telescope, as a tractor, during azimuth positioning. The concept for this design was initially developed by Comsat RSI, under a contract for a feasibility study. Refinements to the design where subsequently developed by the Center for Electro-Mechanics (CEM), as well as by the McDonald Observatory engineering staff. The VSS supports all aspects of the VIRUS functions, including cryogenic cooling with liquid nitrogen, environmental thermal control, light-tight operation, a class 10,000 cleanroom environment, electrical power, and data & signal communications.

The linkages between VSS and HET contain travel limited slides and rubber bushings to couple yet isolate the two structures in order to eliminate vibration cross-talk due to wind-shake. No wind-induced vibration problems have been reported to-date, since HET operations resumed in 2016.

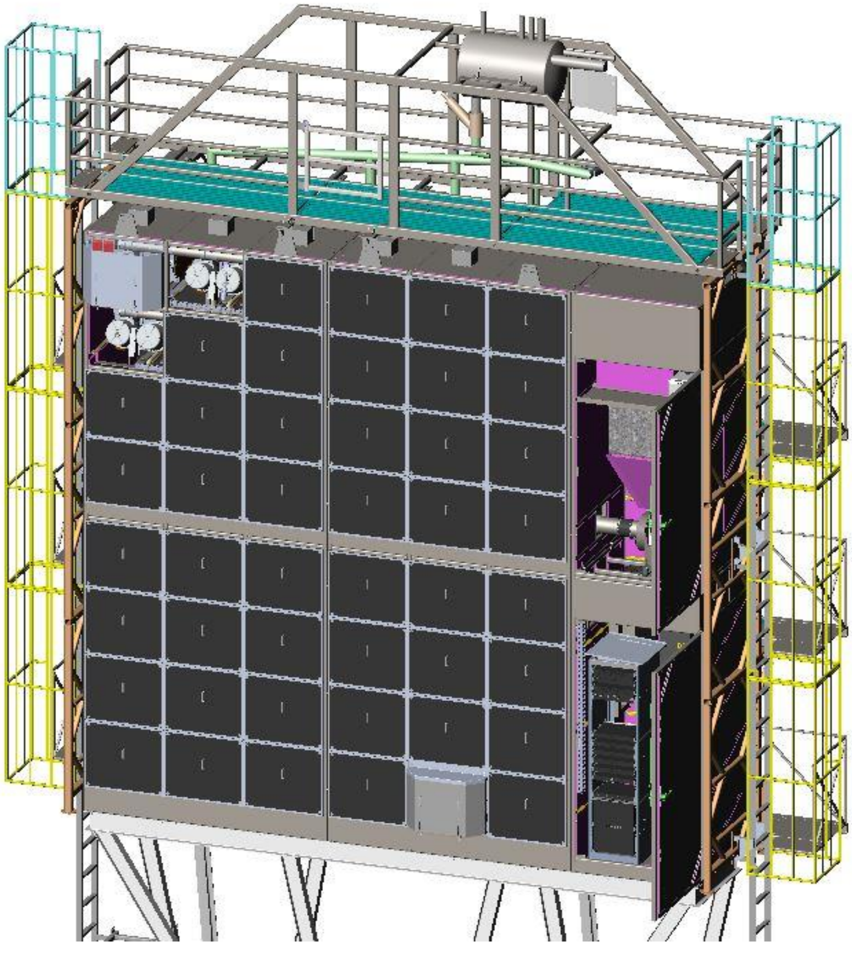


Figure 4. Each VIRUS Enclosure houses 40 spectrograph pairs for a total of 80 spectrometers per side. The column of enclosures next to the thermal control unit and detector readout multiplexers (on the right) is for access only. The LN2 tank at the top of the enclosure is fed automatically from a supply tank outside the facility and utilizes vacuum jacketed plumbing to cool each detector.

# 4. CONTROL SYSTEM[13,14]

The control system for the 13-axes of the WFU Tracker consists of a central control system made by dSpace Inc., and a second, customized control system running in parallel, called the Hardware Fault Controller (HFC), which provides independent monitoring and fault control, through a dedicated microcontroller, to force safe and controlled shutdown of the tracker if a fault is detected.

The dSpace controller runs two distinct software blocks comprised of a supervisory block; the Tracker Motion Control System – Supervisor (TMCS-S), and an algorithm block; the Tracker Motion Control System – Algorithms (TMCS-A). TMCS-S, receives input from a higher level control system called the Telescope Control System (TCS), which controls the entire telescope, including telling the dSpace system what it needs the tracker to do in terms of pointing and subsequent trajectories for guiding. Based upon the inputs from TCS, TMCS-S will enable servo-amplifiers and brakes as required to perform specific slew and track moves and pass commands for trajectories to TMCS-A. TMCS-A controls precision tracker motion by commanding the 13 axis system during guiding based upon input from the position sensors for each axis.

The system trajectory code and mount model is contained in TCS and is composed of a core algorithm which tells the telescope how to behave based upon the HET geographical location, elevation and azimuth position, and the ideal physical model of HET. These command inputs, based upon the theoretical model, are refined by physical layers of mount models derived from laser tracker measurements of the structure and tracker deflections as the Tracker was moved throughout its range of motion. This data characterized the tracking sphere relative to the tracker, and the telescope structure relative to the ground, as well as deviations in the flatness and levelness of the telescope pier. Finally, models were derived on-sky using heuristic methods by pointing at stars during commissioning, and subsequent engineering runs.

# 5. MOUNT MODEL

The WFU Tracker mount model is based upon data taken from three sources; Individual control axis characterization, telescope system characterization, and on-sky characterization.

## 5.1 Control Axis Characterization[15,16]

The initial tracker system testing followed a laddered approach where root-level tuning and error compensation algorithms and look-up tables were implemented; first through individual actuator or independent axis testing, followed by progressive grouping of subsystems. This approach created layered error compensation algorithms that were executed serially during motion control. Two test paths were implemented; one to characterize the X/Y system, and another which characterized the hexapod.

A number of improvements to the mechanical system where required to meet following error requirements for tracker guiding. Testing of the X drive system resulted in a change from direct-drive, to a 10:1 planetary gearhead, for tracking mode. Tests of the Y-axis, which includes a parallel Constant Force Drive (CFD) mechanism as a safety feature to prevent payload runaway, revealed the need to keep the load shared by the CFD limited to 10% of the total load, in order to keep Y-axis following errors in the 10µm RMS range. A change in the recommended lubricant (from SKF LGMT3 for the drive screws, and THK AFB-LF for the linear bearings) to Kluber Isoflex Topas NB52, was required as a result of performance measurements during cold tests.

The error compensation algorithm for the assembled hexapod system resulted in sub-3µm RMS in positioning error, and sub-10µm positioning for the X/Y system.

Figure 5. The WFU Tracker is illustrated on its test stand in the laboratory. A laser tracker is also represented as it was set up for individual axis tests as well as system tests of the tracker.

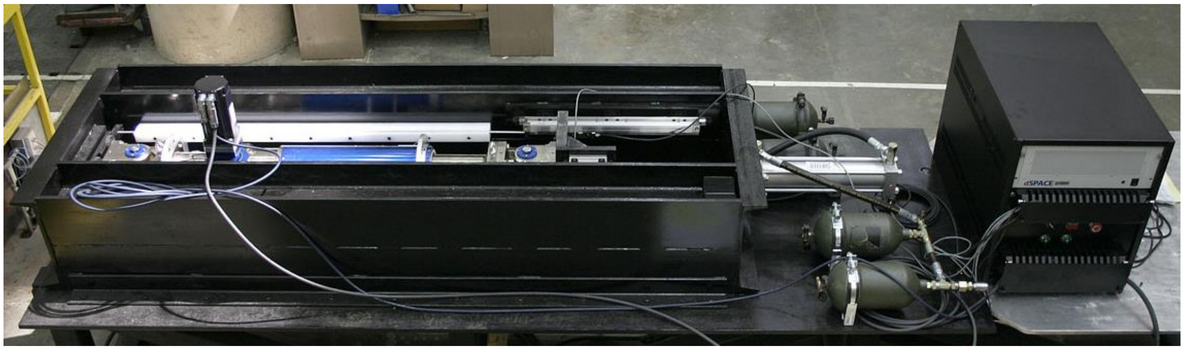


Figure 6. One of the hexapod actuators shown being characterized in a special purpose test stand. Testing of the command v. measured position allowed controller gain tuning resulting in 0.75µm RMS following error at 1mm/s velocity, which is typical for guiding. Full load testing of the actuator over the 300mm range of motion resulted in reduction of positioning error from 40µm to less than 5µm.

### 5.2 Total System Characterization

Following the installation on the HET, of WFU Tracker, and testing of the control system; a series of tests were performed in order to create a system mount-model based upon the behavior of the whole telescope as the tracker moved. Since the Wide Field Corrector (WFC) was still being tested at the manufacturer, there was no way to characterize the system on-sky, however, we were able to create a mount model of the system using a Laser Tracker to perform measurements on a test mass of the WFC which simulated its geometry and mass. Four Spherically Mounted Retro-reflector's (SMR's) where mounted to the bottom surface of the WFC test mass, one of which was located at the focus entry point, and the other three at outer radial positions. This configuration enabled measurement of the entry pupil and well as the tip and tilt of the WFC during pointing simulations.

In order to build the mount-model, a grid of 97-points was setup on the tracking sphere surface, which covered most of the operational range of the tracker. The mount model needed to correct for the physical motion of; 1) the 13-axes tracker with respect to the upper hexagon that it is mounted on, 2) the upper hexagon with respect to the telescope structure it is connected to, and 3) the telescope structure with respect to the pier the structure sits on. The laser tracker was set up in a variety of reference frames which allowed these measurements to be taken as the 97-point grid was implemented. Measurements were taken at night, and in favorable weather conditions, in order to minimize dimensional changes due to thermal effects on the 13m structure. By measuring the deviations between the commanded position v. measured position we were able to derive corrections which compensated for errors introduced by the new mechanical system.

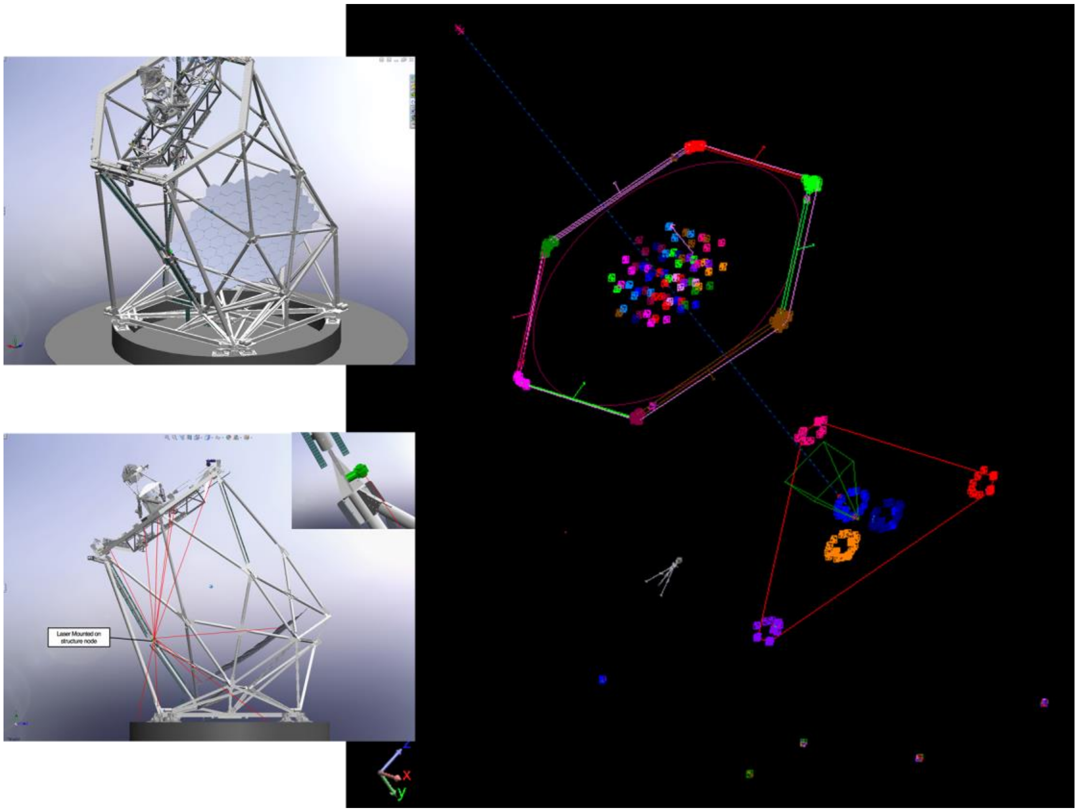


Figure 7. A graphical representation of various laser tracker data sets measuring the tracking sphere, primary mirror, and telescope pier. Data sets were taken at night to maximize dimensional stability of the steel HET structure. 97-point data set was divided into overlapping quadrants and stitched together in order to minimize thermal effects on the measurements. The average time to take data per quadrant was 2h:44m, with an average ΔT=0.5C, introducing errors of +/- 90µm, primarily in focus (Z). The measurement error for the laser tracker at these distances (average = 9.2m) was +/- 61µm.

Deviations from the commanded position were modeled by a cubic surface with derived coefficients in the table below:

$$f(x, y) = a_{00} + a_{10}x_c + a_{01}y_c + a_{20}x_c^2 + a_{11}x_cy_c + a_{02}y_c^2 + a_{30}x_c^3 + a_{21}x_c^2y_c + a_{12}x_cy_c^2 + a_{03}y_c^3$$

| | x | y | z | ϕ | θ |
|---|---|---|---|---|---|
| $a_{00}$ | 11.89 | -4.79 | - | 0.05 | -0.02 |
| $a_{10}$ | -0.007 | -0.0005 | 0.001 | -0.00003 | -0.000002 |
| $a_{01}$ | 0.0007 | -0.007 | -0.0003 | 0.000003 | -0.00003 |

Figure 8. For the individual commanded v. measured positions on the tracking sphere the linear terms provided useful corrections, while the quadratic & cubic terms were significantly in the measurement noise due to thermal fluctuations during the data set, and are thus not shown. The measurement sensitivity in focus (Z) could not be determined above the noise in the measurements.

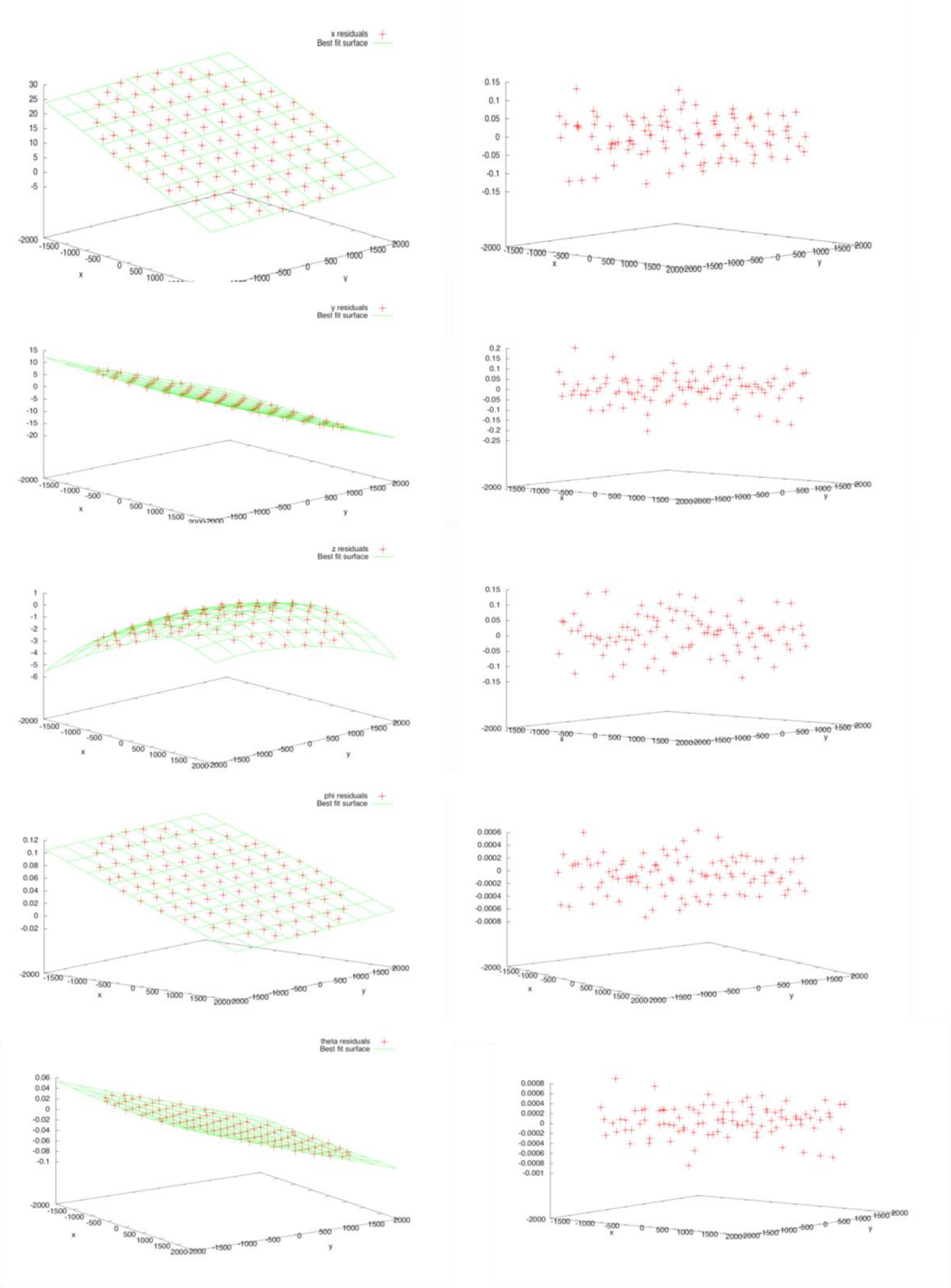


Figure 9. Deviations from commanded position with best fit cubic surface (left); residuals from best fit (right). The planar axes are in mm, the vertical axes are in mm (x,y,z), degrees (phi, theta). Except for Z, the relations appear mostly linear and the quadratic and cubic terms are small corrections.

In addition to characterization of the telescope system deflections, the data provided a nominal best-fit location and radius of the primary mirror and tracking sphere which established the nominal X, Y, and Z(focus) for the WFU Tracker. The result was: R = 13,378.84mm (compared to the nominal value of, R = 13,376.94, a difference of 1.9mm),with best-fit center WRT the center of the plane of the upper HET hexagon, aka the Ideal Tracker Frame (ITF) :

$$ITF(x0, y0, z0) = (4.44, 9.82, -235.26)\text{mm} \pm (0.76, 0.76, 0.06)\text{mm}$$

### 5.3 On-Sky Characterization

The laser tracker derived mount model resulted in a pointing accuracy of ~1 arcmin RMS, thereby allowing on-sky testing once the WFC and PFIP was installed, and the 3 minute FoV of the ACAM could be taken advantage of. Since that time, a great deal of progress has been made, thereby allowing the science mission of HETDEX to be initiated, albeit with engineering periods focused on significant improvement of pointing and guiding.

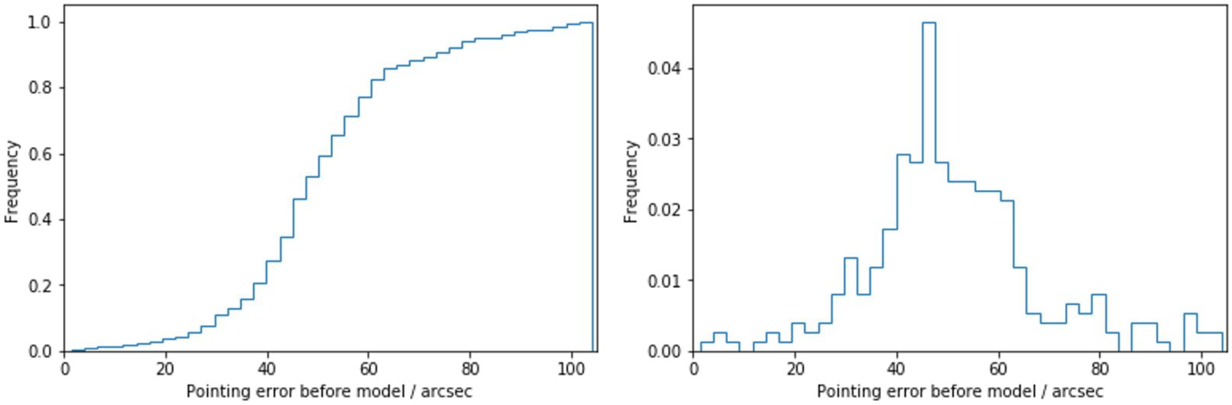


Figure 10. Prior to applying the on-sky derived mount model the pointing error is ~60 arcsec for about 80% of attempts.

As pointing has been improved it has become necessary to divide the mount model into two major branches; one for East tracks (azimuth = $0 \leq Az < 180$), and the other for West tracks (azimuth = $180 < Az < 360$). In general the system is much better behaved for East tracks compared to West tracks, which emphasizes the utility of separate models for the E and W. This is a consequence of a 5x increase in the mass of the WFU Tracker over the original tracker which contributes to deflections which were not captured in the system laser tracker data. This is due to the fact that the laser tracker data was only taken at one azimuth position, and also due to limitations on the accuracy of the technique due to thermal and measurement noise.

The data make it clear that there is a strong dependence on Az as well as on tracker Ideal Tracker Frame (ITF) x and y, which is to say; both the WFU Tracker position in X, and the Tracker payload in the Y-axis, in the plane of the upper-hexagon of the HET structure. The current model is a polynomial in Az plus a 2D polynomial in ITF x and y, limited to second order terms:

$$ITF(x,y,Az) =$$

$$p0 + p1 \times az + p2 \times az^2 + p3 \times xx + p4 \times yy + p5 \times xx \times yy + p6 \times xx^2 + p7 \times yy^2 + p8 \times xx^2 \times yy + p9 \times xx \times yy^2$$

Where: az = raw Azimuth coordinate (degrees)

xx = raw ITF x coordinate (meters)

yy = raw ITF y coordinate (meters)

| ITF<br>(x,y,Az) | East | | West | |
|---|---|---|---|---|
| | dx(arcsec) | dy(arcsec) | dx(arcsec) | dy(arcsec) |
| p0 | +11.9564430510346345 | +25.3329284770476626 | +57.6951308838714070 | +27.7996322984731918 |
| p1 | +0.6537627796356856 | -0.1421149275536415 | -0.6533175944594011 | +0.4608951756783807 |
| p2 | -0.0033915510591776 | +0.0008594275332077 | +0.0027836021457454 | -0.0027948792130420 |
| p3 | -17.8731143653312152 | +16.1986009151236523 | -22.8904562968759855 | +16.0689774658954292 |
| p4 | -3.9114450993075085 | -9.3544007612137019 | -23.8764859667746450 | -6.7795630721411761 |
| p5 | -4.7411081130286385 | +4.4989007440263515 | -4.3958331614624715 | -2.6624641921437502 |
| p6 | +0.0544493028253461 | +7.4560382439920589 | -0.4830278164418262 | +2.3749013929916645 |
| p7 | -1.8964712362404892 | -1.5424401911418830 | +2.4267260451141035 | -1.2716790423573063 |
| p8 | +0.5968210732453225 | -6.4118439168933472 | -3.2533063959014554 | +8.7057597337255945 |
| p9 | +1.7525249419361957 | -7.1669279180159915 | -7.6882514175901200 | +0.1982922700462574 |

Figure 11. The models are functions of Az(degrees) in the East, and Az-180(degrees) in the West. ITF coordinates are in meters. The results are corrections to the pointing in arc-seconds in Az, and El..

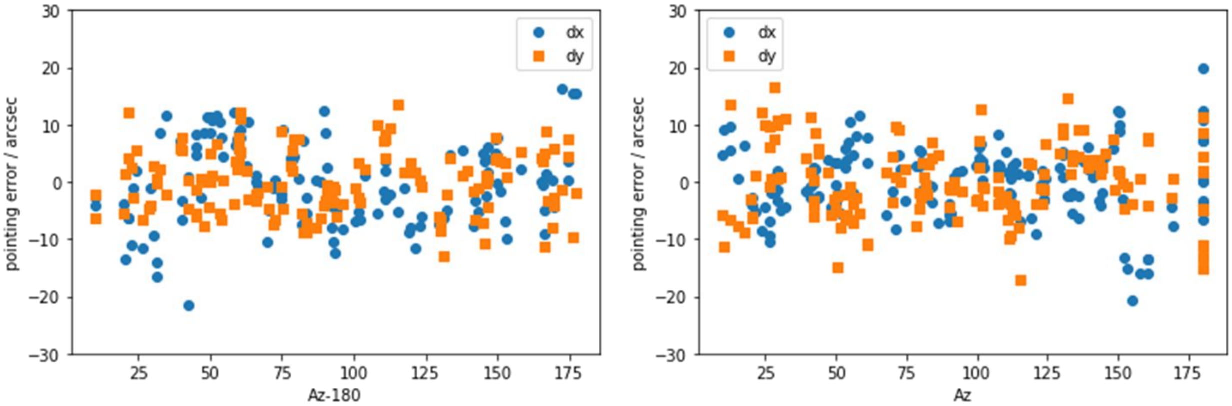


Figure 12. Residuals from the fit for East and West (respectively) pointing at the beginning of tracks.

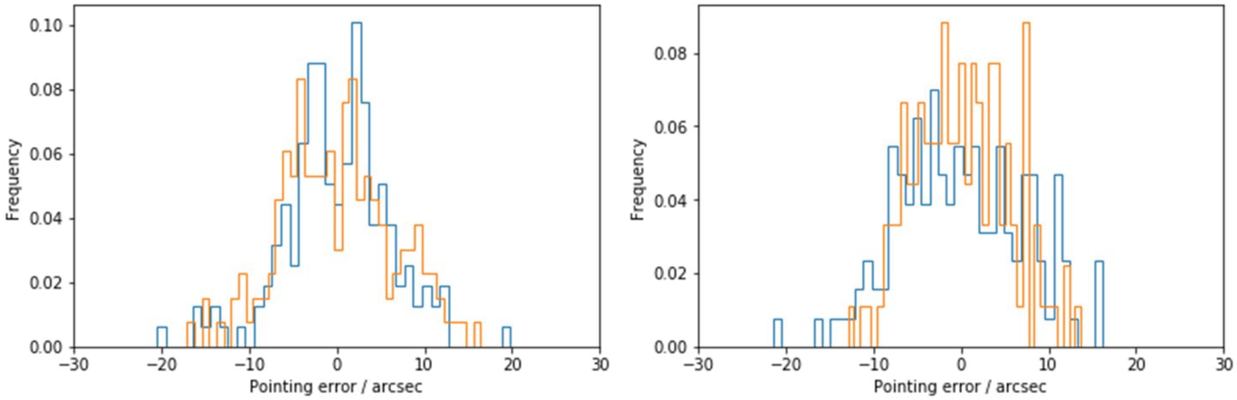


Figure 13. Point errors for East and West tracks respectively. Note that presently the East tracks are significantly better. The cause of this is being investigated.

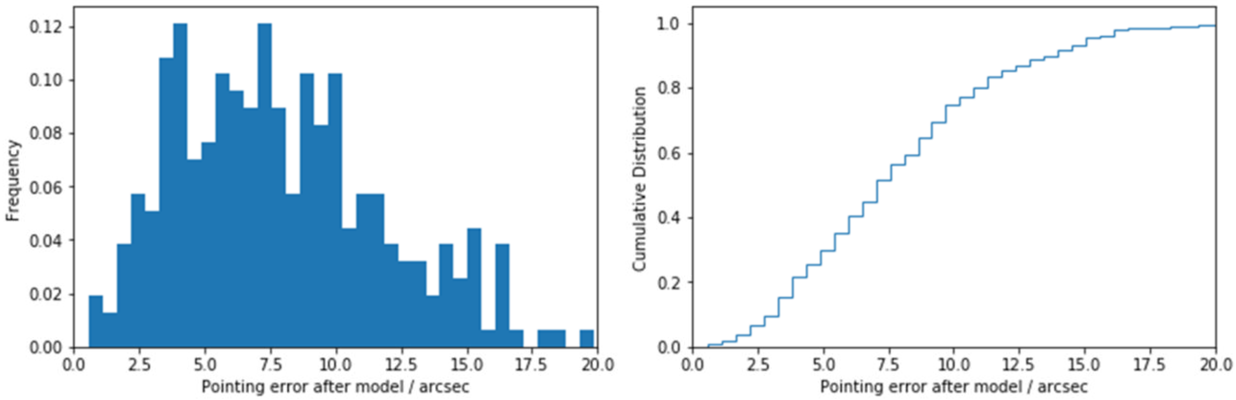


Figure 14. Total system pointing performance is better that 12 arcsec for 90% of pointing attempts, which is sufficient for acquiring stars with the Guide Cameras which have a FoV of 22 arcsec. This significantly improves the overhead when starting a new track v. using the ACAM to hand the star over to the Guide cameras.

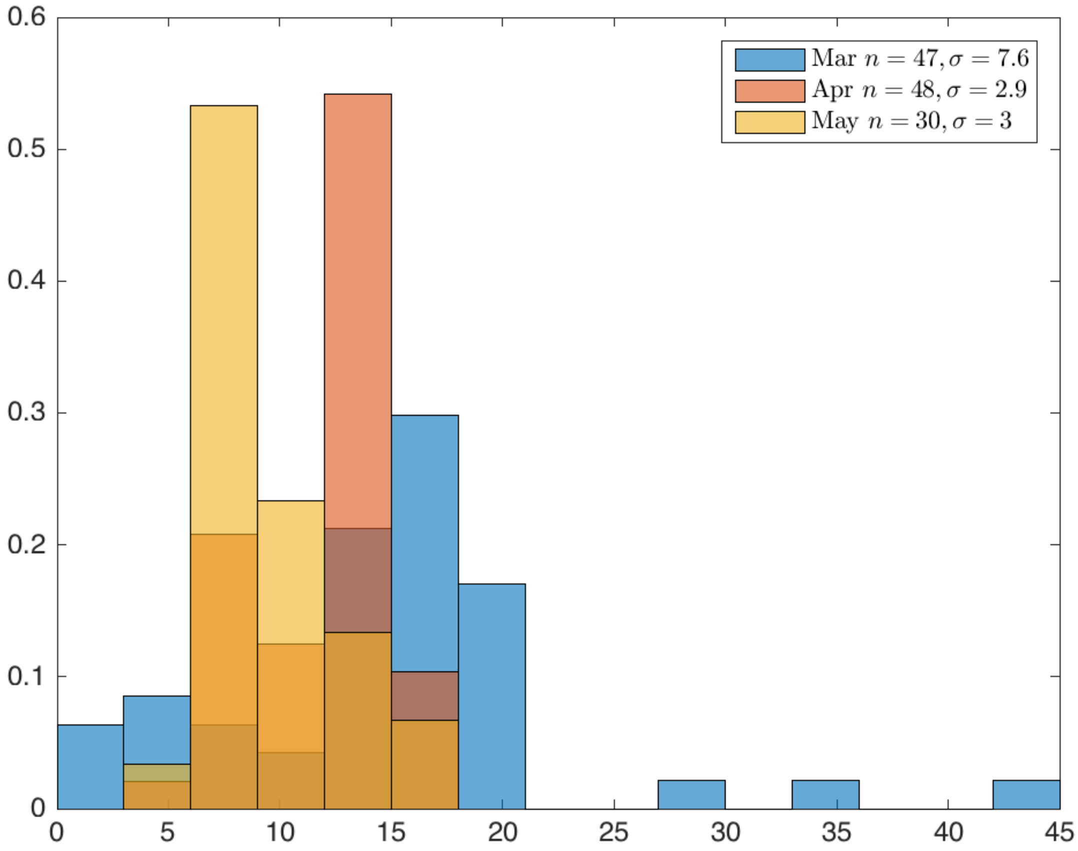


Figure 15. Pointing improvement during science runs for the last three months improved from 16 arcsec, to 12 arcsec, thereby greatly streamlining acquisition times since hand-off from the ACAM to the Guide Cameras is eliminated.

## 6. CONCLUSION

After a retrofit of practically every mechanical, electrical, and control subsystem on the telescope (with the exception of the Primary Mirror and the azimuth rotator), the HET is back online and doing science with a whole new suite of instruments, including VIRUS, HPF, LRS2, and in the future HRS. The WFU Tracker is functioning near the specified values, is improving with each engineering period, and is expected to meet the specified requirements. The Prime Focus Instrument Package, and VIRUS Support Structure, are functioning as specified. Laboratory testing and tuning of individual axes and subsystems provided the necessary foundation for optimizing the total system on HET. Following installation on the telescope, laser tracker measurements allowed the HET to point to within 1 arc-minute RMS of commanded targets, before the WFC was completed and installed. Following the installation of the WFC and basic elements of PFIP (in particular the Tip-Tilt Camera, Distance Measuring Interferometer, and Wave-Front Sensor), on-sky pointing has allowed creation and refinement of the final layer of the mount model, which currently is providing pointing accuracy of 12 arc-seconds about 90% of the time, and is improving with each engineering period. When stars are acquired, guiding is robust, with trajectory corrections at the 0.1 arc-second level, utilizing TTCAM, DMI, and WFS to close the loop. All of this indicates that the new HET mechanical systems are performing to-date, as needed for science, and are on track to meet all specifications in the coming months.

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