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John Good, John Booth, Mark E. Cornell, Gary J. Hill, Hanshin Lee, Richard Savage, Ronnie Leck, Hermanus Kriel, Martin Landriau, "Laboratory performance testing, installation, and commissioning of the wide field upgrade tracker for the Hobby-Eberly Telescope," Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 914546 (22 July 2014); doi: 10.1117/12.2057113

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

Laboratory Performance Testing, Installation, and Commissioning of the Wide Field Upgrade Tracker for the Hobby-Eberly Telescope

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ABSTRACT

A major upgrade of the HET is in process that increases the pupil size to 10 meters and the field of view to 22' by replacing the four-mirror corrector and prime focus instrument package to track the sidereal and non-sidereal motions of astronomical targets. To support the new payload a new Tracker, comprising 13 axes, and weighing 20 tons, was designed, built and tested at the University of Texas Center for Electromechanics, in Austin, Texas. It was then disassembled and installed on the HET. Structural modifications were performed on the upper hexagon of the telescope structure to support the net increase of 15% to the total mass of the system and maintain fundamental mode performance of 5Hz. Testing in the laboratory, as well as subsequent commissioning tests on the HET, confirm that the Tracker will position the payload to acquire and track within the specified +/-9.5um de-center, +/-15um de-focus, and +/-4.4 arc-sec tip/tilt requirement[*].

Keywords: Hobby-Eberly Telescope, HET, HETDEX, Wide Field Upgrade, VIRUS

1. INTRODUCTION

The Hobby-Eberly Telescope (HET) was originally envisioned as a spectroscopic survey telescope, able to efficiently survey objects over wide areas of the sky. While the telescope has been very successful observing large samples of objects such as quasi-stellar objects (QSOs) spread over the sky with surface densities of around one per 10 sq. degrees, the HET design, coupled with a small field of view corrector, hampers programs where objects have higher sky densities. In seeking a strong niche for the HET going forward, the field of view will be increased from 4′ to 22′ so that it can accommodate the Visible Integral-field Replicable Unit Spectrograph (VIRUS), an innovative, highly multiplexed spectrograph that will open up the emission-line universe to systematic surveys for the first time, uncovering populations of objects selected by their line emission rather than by their continuum emission properties.

In July of 2013, the Wide Field Upgrade (WFU) Project received permission from a review panel and the HET Board, to proceed with plans to remove the original Spherical Aberration Corrector (SAC) and tracker, and install the WFU tracker and Wide Field Corrector (WFC). This approval was based upon successful testing of the WFU tracker at the University of Texas Center for Electro-Mechanics (CEM), located at the Pickle Research Campus, in Austin, Texas. This upgrade project consists of three primary elements:

- HET WFU which includes designing, fabricating, and deploying a larger field of view corrector (WFC) that will replace the existing SAC. It also requires the design, fabrication, and deployment of a new prime focus instrument package (PFIP) and tracker, as well as modification to the HET's azimuth bearings, to accommodate the additional weight being added to the telescope.
- Design, fabrication and deployment of VIRUS on HET.
- Execution of the Dark Energy Experiment (DEX) survey with the VIRUS on HET.

Aside from the need to precisely align the tracker assembly, it was important to obtain measurements that verified that a mount model could be written, and then to independently test the control algorithms for the whole system of 13 axes in

[*] 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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Ground-based and Airborne Telescopes V, edited by Larry M. Stepp, Roberto Gilmozzi,
Helen J. Hall, Proc. of SPIE Vol. 9145, 914546 • © 2014 SPIE
CCC code: 0277-786X/14/$18 • doi: 10.1117/12.2057113

order to verify that the tracker is capable of tracking stars *prior* to installation on the HET. Since there was no cost effective way to perform an optical verification of this performance, a process combining the metrology capabilities of laser trackers, and data fitting software, was used to characterize the commanded v. resultant positioning of a test payload, referred to as the WFC Test Mass, as well as verify the motions equivalent to tracking a star.

The laboratory set up for assembly and testing of the WFU tracker is briefly reviewed, including relevant test results indicating readiness for installation. This is followed by details of the construction and installation as well as measurements of its performance on the HET for controls tuning and mount-modeling, and early measurements of its performance.

2. LABORATORY PERFORMANCE TESTING

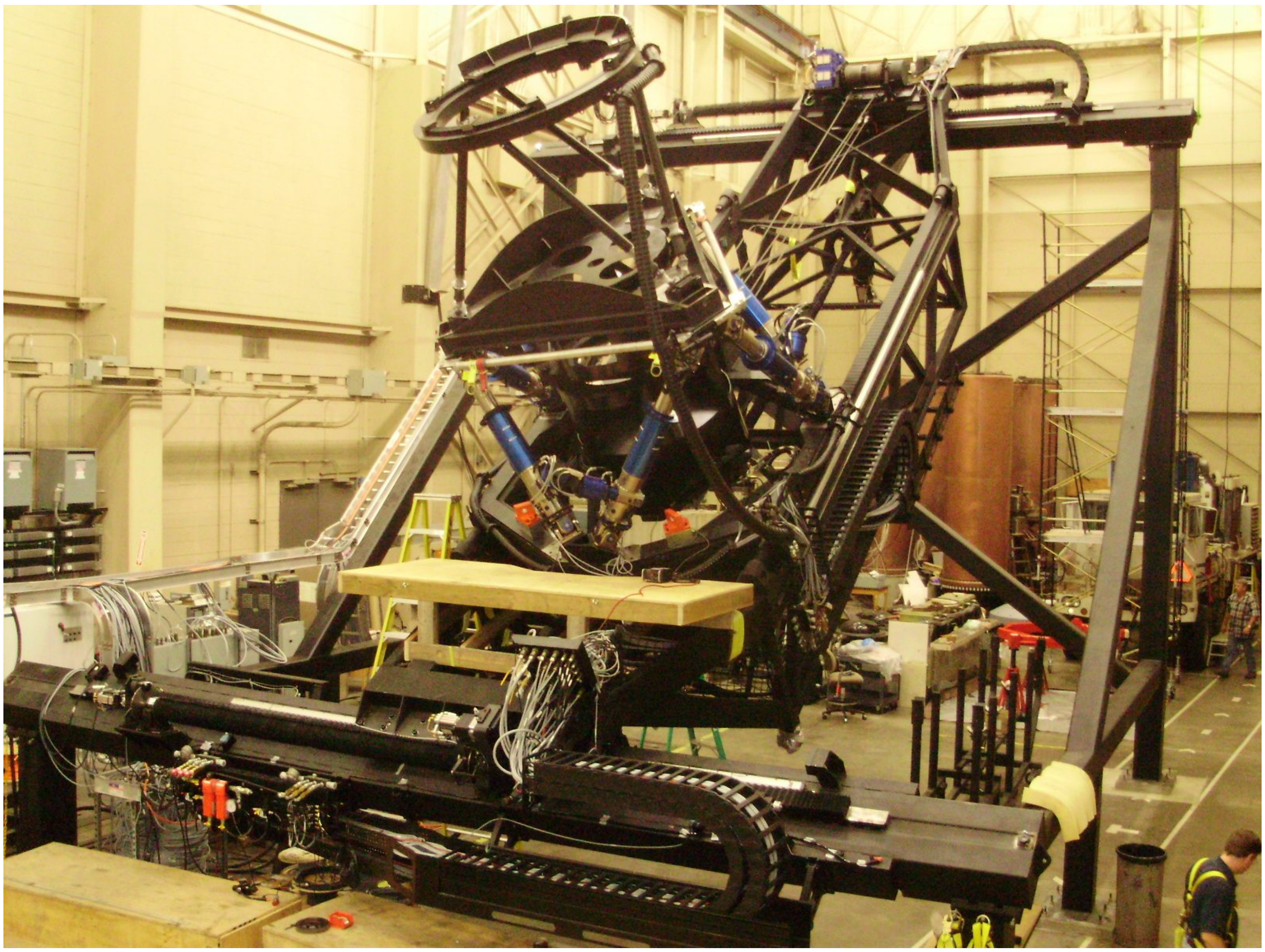


Figure 1. The test stand, used until July 2013, to troubleshoot and pre-commission the WFU Tracker at CEM prior to installation on the HET. A payload test mass is mounted in place of the Wide Field Corrector.

A test stand configured as shown in Figure 1, was constructed in the CEM High-Bay, which was equivalent to the mounting interface on the HET. The upper and lower beams of the tracker test stand were a welded assembly of standard structural Hollow Structural Section (HSS) shapes that duplicated those on the telescope structure, and held the tracker at an angle of 35 degrees from zenith.

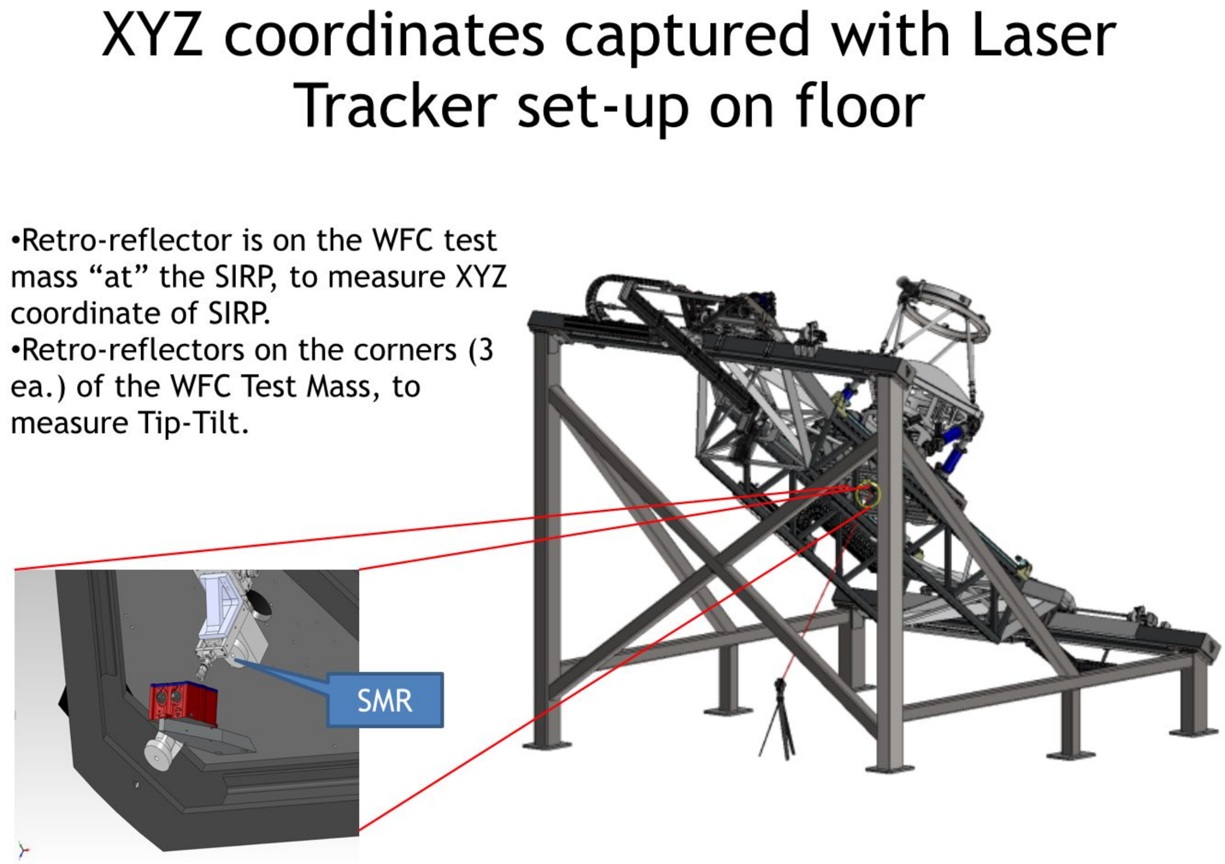


Figure 2. A laser tracker was situated under the WFU Tracker in order to independently measure the commanded position of the Stationary Image Rotation Point (SIRP) of the Wide Field Corrector (WFC).

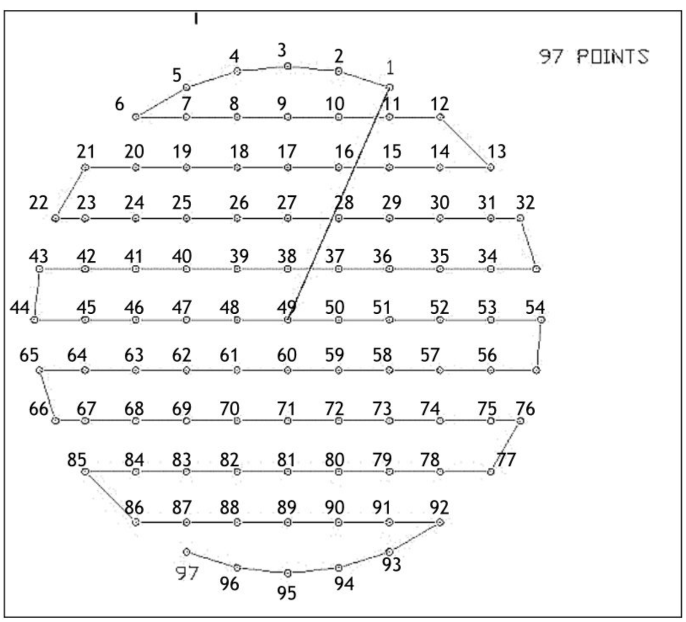


Figure 3. A grid of 97 points was established over the 2 meter radius operating range of the tracker. The points were commanded and measured in sequence.

The spherical primary mirror of the HET produces an aberrated image of stars on a spherical surface at 1/2 the radius of the PM. In order to track a star the Tracker positions the spherical aberration corrector, also know as the Wide Field Corrector (WFC) along this spherical surface so that the light rays enter the 4-mirror WFC about a Stationary Image Rotation Point (SIRP). One of the tests used to independently confirm the performance of the Tracker, was to compare the commanded position of the SIRP on the tracking sphere, to an independent measurement of that position. To achieve an independent measurement, a Sphere Mounted Retro Reflector (SMR) was positioned at the SIRP of WFC Test Mass, and its position was measured using a laser tracker. The test was designed using a grid of 97 points which covered the operational range of the WFU Tracker. The overall test setup is shown in Figure 2, and a representation of the 97-point grid is shown in Figure 3. Figure 4 shows the resulting data from the laser tracker, which is compared to a best-fit sphere. The departure from an ideal sphere, to 1st order, follows a

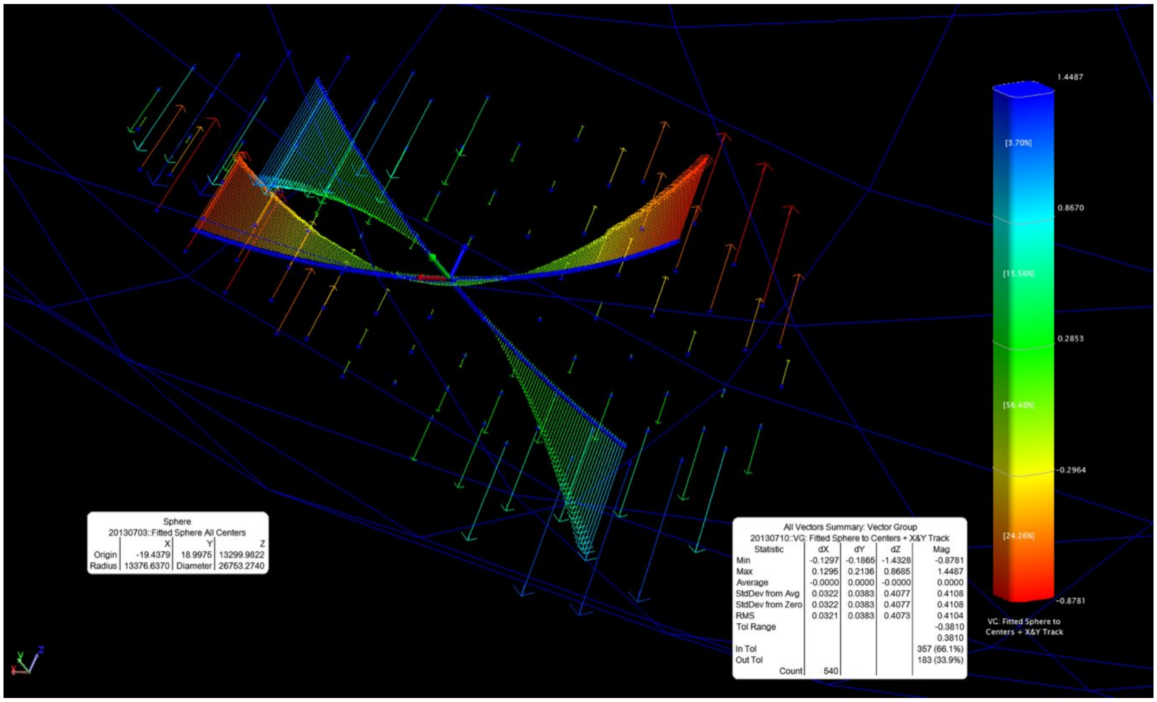


Figure 4. Vectors at each data point taken by laser tracker measurements show the departure from a best fit sphere. Structural deflections generated a saddle-shaped departure from the ideal sphere. This was illustrated in a separate data

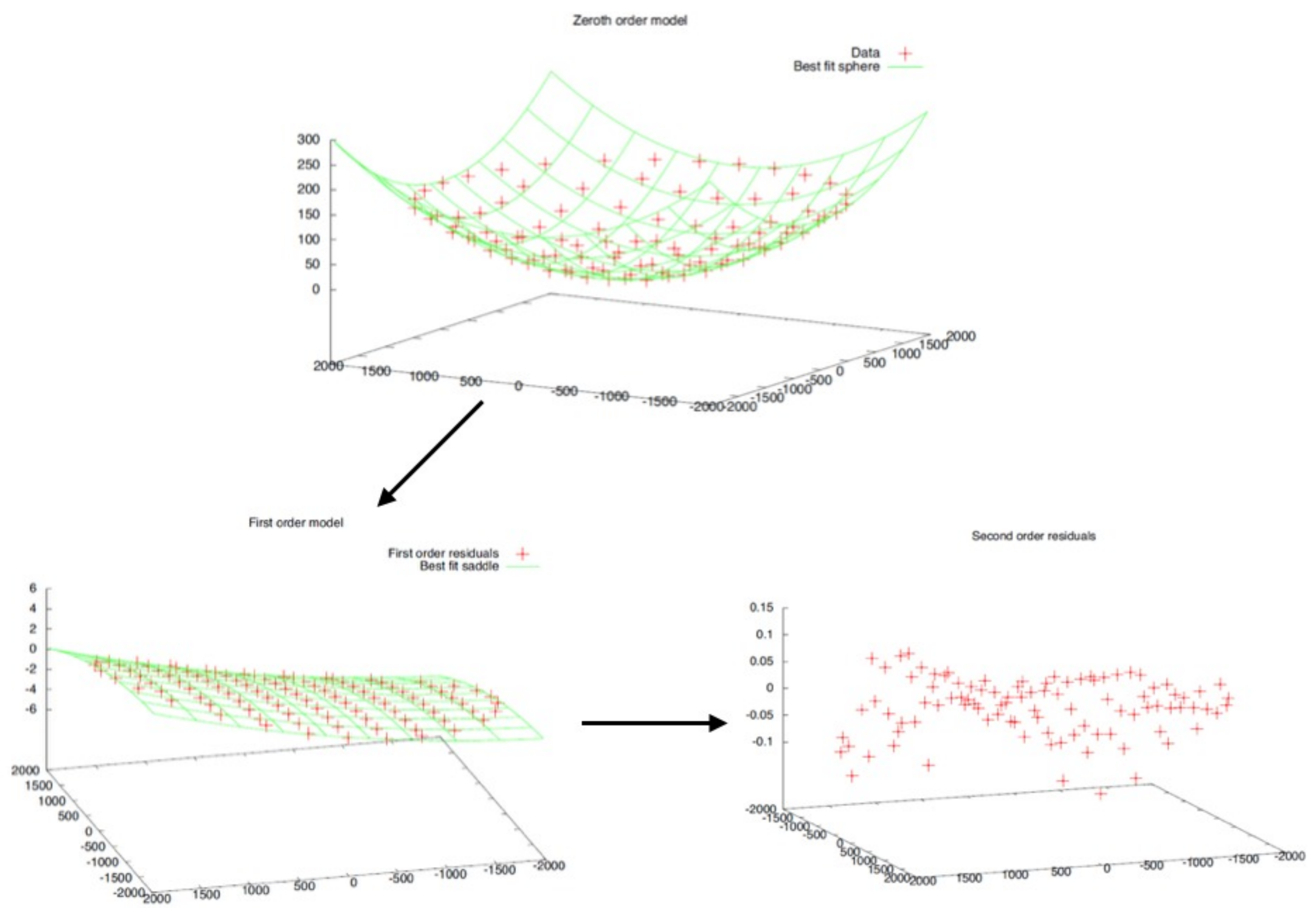


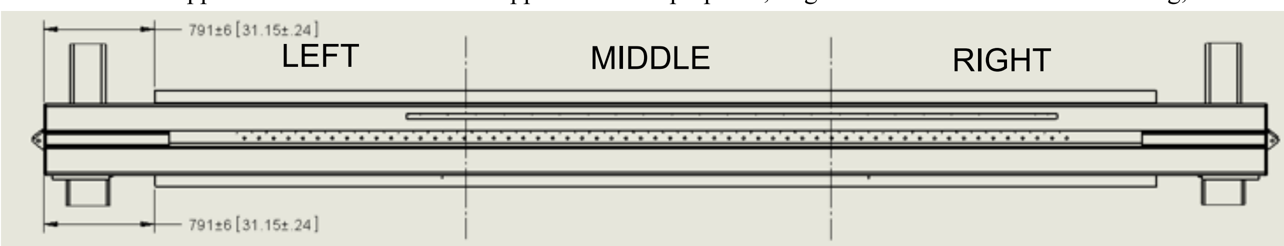
Figure 5. Laser tracker measurements of commanded positions on the 97-point grid are best-fit to a sphere, then the residuals are plotted revealing a saddle-shaped departure due to structural deflections. Second-order residuals appear randomly distributed but appear to increase with distance from the center of the 97-point grid.

saddle which is due to deflections in the support structure of the Tracker and test stand, and can thus be incorporated into a mount-model for the positioning (tracking) commands. If this operation is performed and backed out of the results, then 2nd order residuals are revealed, which are small enough to be captured and corrected by the real-time metrology and guide corrections. Several iterations of this test, as well as tests of tracking jitter, demonstrated to the Readiness Review Board, that the WFU Tracker was ready to install on the HET.

3. INSTALLATION

The original Tracker, drive mechanisms, and bearings were removed from the upper hexagon of the HET, leaving only the mechanical interfaces built-into the structure. Due to the 5x increase in mass of the new tracker, the lower beam had to be reinforced, necessitating extensive welds on the HET structure. A technique for welding had been tested on the laboratory test stand, in order to minimize distortions by the welding process, and this procedure demonstrated success in minimizing distortions to the beam. The sequence is detailed in Figure 6. Since it is impossible to prevent all distortion of the ideal shape desired, the bearing system of the tracker has been designed to accommodate reasonable departures from the ideal geometry. Subsequent measurements of the beam profile showed a departure of +/- 1.37 mm in the Y-axis, and +/- 0.23mm in the Z(focus)-axis, prior to loading by the new Tracker (Figure 7).

In order to facilitate shipping the new tracker to the Observatory, as well as to provide a guide for the construction and assembly, the Upper and Lower X-beams were cut from the test stand, and moved intact, to the enclosure floor of the HET. Once the upper and lower beams of the upper-hex were prepared, large sub-assemblies of the X-bearing, encoders,



axial position	A	B	C	D
1	1		38	
2		23		16
3	9		2	
4		31		24
5	17		10	
6		3		32
7	25		18	
8		11		4
9	33		26	
10		19		12
11	39		34	
12		27		20
13	5		40	
14		35		28
15	13		6	
16		41		36
17	21		14	
18		7		42
19	29		22	
20		15		8
21	37		30	

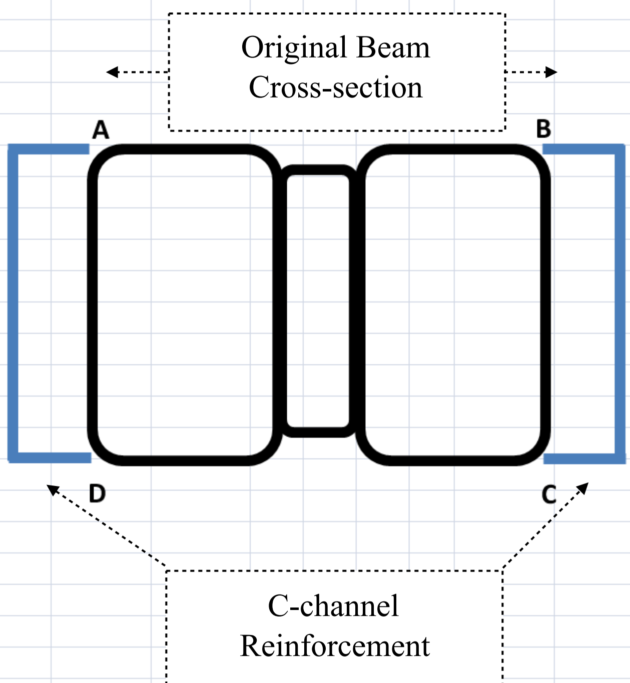


Figure 6. The welding sequence for C-channel (MC12x31) reinforcements to the lower-X beam of the HET structure. Weld length = gap length = 150mm. After initially stitch-welding the C-channels, the 42 weld pattern was repeated 3 times (for the middle, left, and right sections).

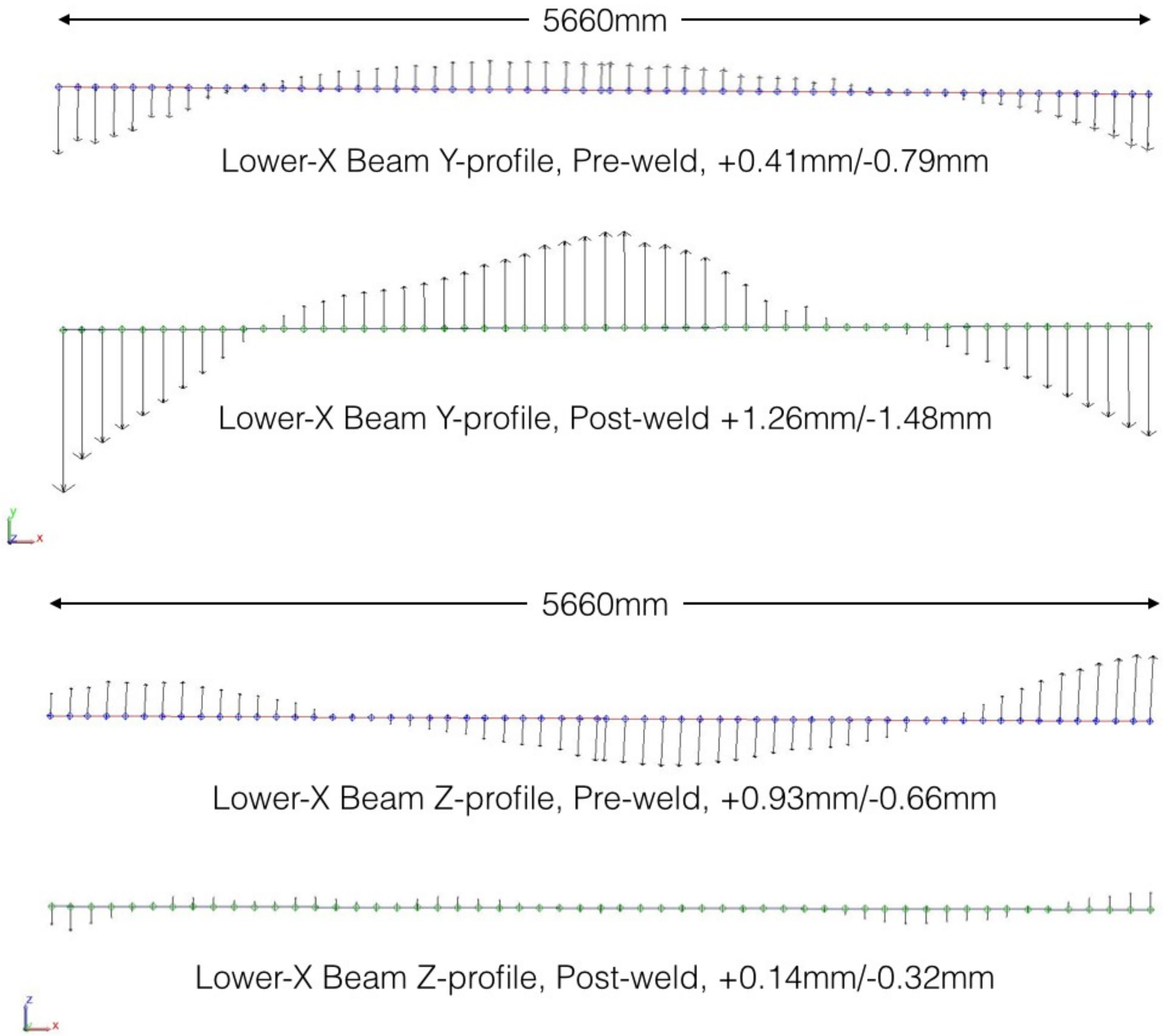


Figure 7. The beam profile was measured, pre and post-weld. Over the usable span of the beam (5.66 meters) the profile deteriorated by a factor of 3.3 in the Y-axis, and improved by a factor of 3.5 in the Z(focus)-axis. The effect on star tracking will be mitigated by mount-modeling. In addition, since the tracking motion will be corrected in real time for any trajectory 9mm or less (every 10 sec.), the X-beam profile will meet, or exceed, the specified requirements.

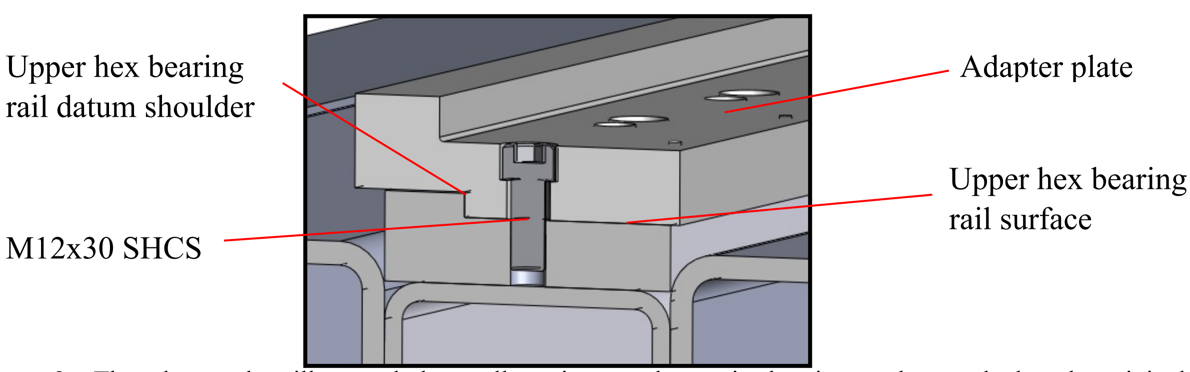


Figure 8. The adapter plate illustrated above allows increased capacity bearings to be attached to the original HET structural interfaces. The X-axis linear bearings were increased in size and load bearing capacity to accommodate the 5x weight increase of the WFU Tracker, over that of the original tracker.

and drive systems were transferred from the test stand beams, to the telescope structure. Before installation of the tracker bridge, the lower-X and upper-X axes were tested, first individually, then together, in order to verify safe and skew-free control of the bridge after installation. Following installation of the Y-axis drive system, a 6,400 kg test mass was mounted on the tracker, and the X and Y axes were tested, prior to mounting the hexapod. In particular, the constant-force drive, on the y-axis, was tested, in order to verify that its independent closed-loop control system was operational and reliable.

During the testing phase in Austin, clearance-testing for the WFC Test mass enabled a calculation to optimize hard-stops for the hexapod. Prior to installation of the hexapod on the HET, each actuator was partially disassembled and re-lubricated, and the hard-stops in each of the 6 actuators where replaced. Following this step, the remainder of the control axes, 6 each for the hexapod, and one for the Rho-stage, where installed and tested for functionality and travel.

4. ON-TELESCOPE PERFORMANCE TESTING & COMMISSIONING

System Mount Model

A series of on-telescope tests complementary to those performed on the test stand are being carried out as part of the performance testing and commissioning phase of the WFU. As an example, the 97-point test is being carried out in order to create a 1st order mount model for the system. In addition to compensating for structural deflections, as demonstrated on the test stand, the mount model must be able to account for ridged-body tips and tilts of the entire structure as the center of mass of the system changes during tracking, due to the shifting mass of the Tracker. By referencing each of the 97-point grid points to the primary mirror and pier during the test, we are able to derive a mount model which accounts for deflections and ridged-body motions during tracking.

Figures 9 & 10, illustrate the setup of the laser tracker lines of sight, and points to be measured. There are 8 measurement points on the upper half of the structure; 4 each on the WFC Test Mass, and 4 at reference points on the

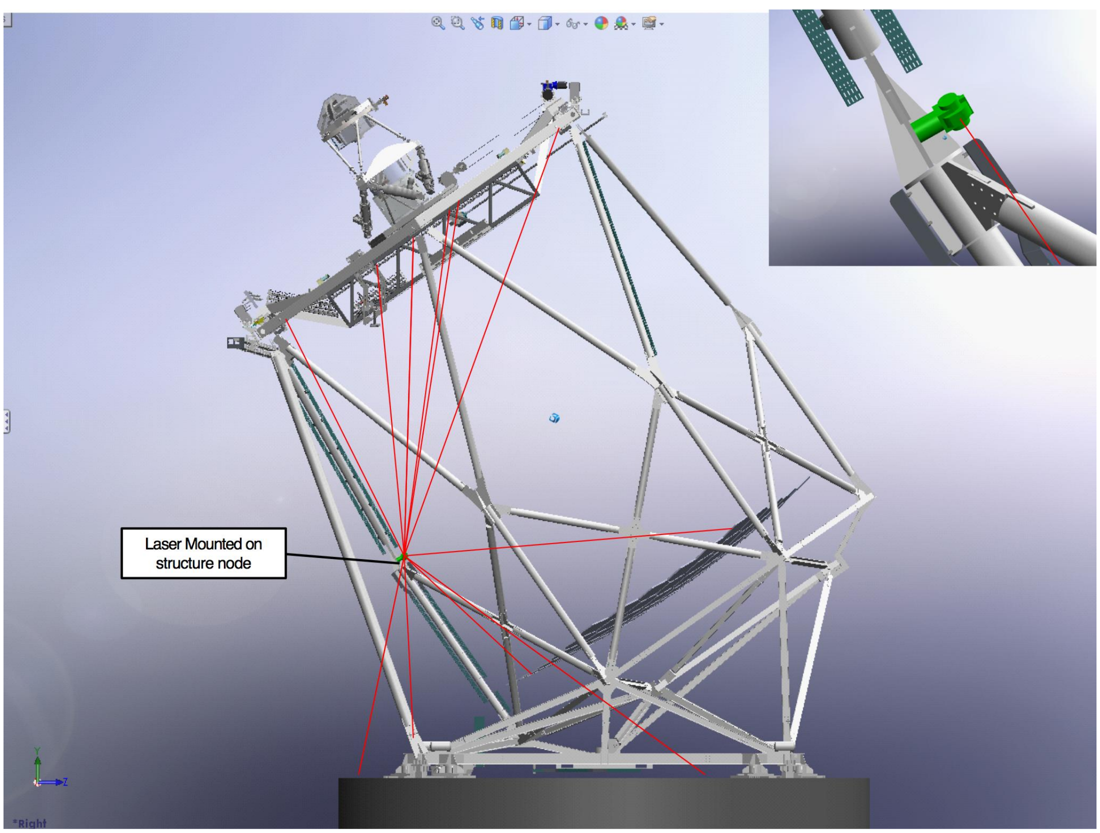


Figure 9. Setup and lines of sight for Laser Tracker measurements of the WFU Tracker, Primary Mirror, and Pier.

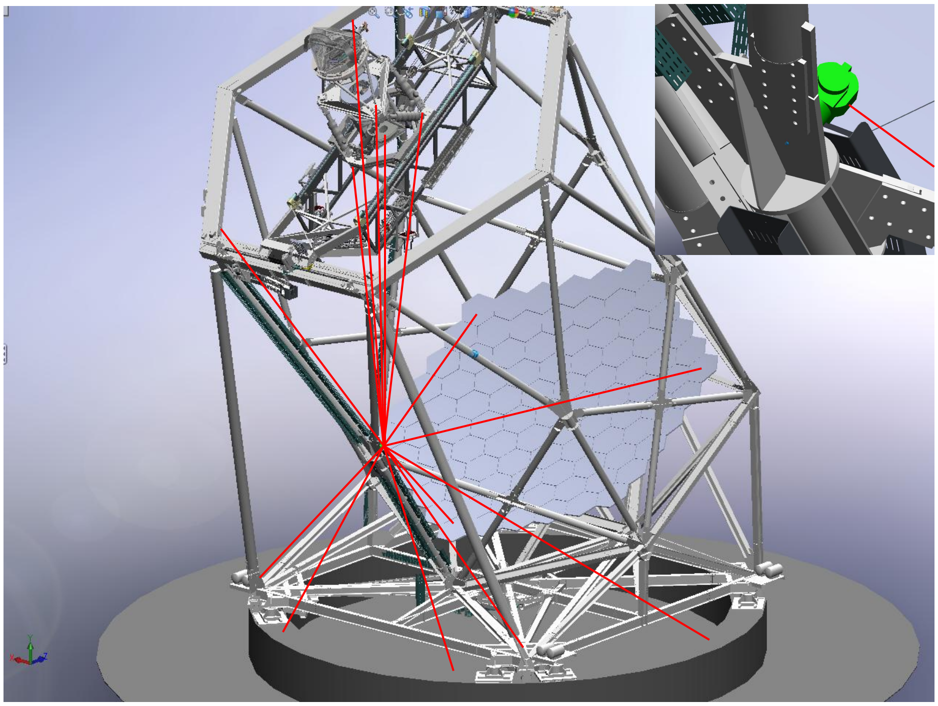


Figure 10. Setup and lines of sight for Laser Tracker measurements of the WFU Tracker, Primary Mirror, and Pier.

upper hexagon. Of the 4 SMR's on the WFC Test Mass, three are used to characterize tip and tilt of the payload, and one is located at the SIRP, in order to determine the X, Y, and Z location of the payload. On the bottom half of the structure 8 measurement points are required. Two are reference points for tying-in the overall structure, 3 are distributed on the periphery of the primary mirror, and 3 are on the telescope pier. Only the 3 SMR's on the pier are assumed to be motionless throughout the test. For cost reduction (current cost of an SMR >/= $1,150USD) the 97-point grid is run twice; once with the laser measuring the upper set of SMR's, and once looking down at the lower SMR's. Measurements are taken by means of an API T3-40M laser tracker. Since the largest distance to be measured is of order 11 meters, the absolute accuracy error of any 3D coordinate will be +/-55um, or smaller. Once a data set is reduced and applied to the mount model, the 97-point test will be iterated until corrections fall within the measurement errors. Further improvements to the mount model, if needed, will be determined by the on-board metrology on the bottom of the WFC. Since there is a schedule gap between this phase of the project, and the arrival of the WFC, tracking and pointing performance will be demonstrated and tuned by use of a Video Alignment Telescope mounted on the WFC Test Mass.

SUMMARY

The transition of the WFU Tracker is proceeding smoothly from its manufacturing and test facility, at the Center for Electromechanics, in Austin, to the HET structure. Installation has gone according to plan, the mechanical and control systems are working and the WFU tracker is currently being tested. Tests have been implemented, as well as currently in process which verify performance, and characterize behavior for commissioning.

The measurement methods proposed will be sufficient for determining and testing corrections to systematic errors in the individual tracker axes of motion and creating an initial mount model for the new Wide Field Corrector. Since these are only tests of the mechanical performance and not the optical performance of the system, modification to the tracking model will be required once it is installed on the telescope. However, the techniques proposed should provide a high degree of confidence in the performance of the mechanical system and its controls prior to retro-fit on the HET and reduce time for commissioning on the telescope.

REFERENCES

1. Hill, G.J., Tuttle, S.E., Drory, N., Lee, H., Vattiat, B.L., DePoy, D.L., Marshall, J.L., Kelz, A., Haynes, D., Fabricius, M., Gebhardt, K., Allen, R.D., Blanc, G., Chonis, T.S., Cornell, M.E., Dalton, G., Good, J., Jahn, T., Kriel, H., Landriau, M., MacQueen, P.J., Murphy, J.D., Prochaska, T., Nicklas, H., Ramsey, J., Roth, M.M., Savage, R., Snigula, J., "VIRUS: production and deployment of a massively replicated fiber integral field spectrograph for the upgraded Hobby-Eberly Telescope", Proc. SPIE, 9147-25 (2014)
2. Hill, G.J., Drory, N., Good, J., Lee, H., Vattiat, B.L., Kriel, H., Bryant, R., Elliot, L., Landiau, M., Leck, R., Perry, D., Ramsey, J., Savage, R., Damm, G., Fowler, J., Gebhardt, K., MacQueen, P.J., Martin, J., Ramsey, L.W., Shetrone, M., Schroeder, E., Cornell, M.E., Booth, J.A., Walter Moriera, W., "Deployment of the Hobby-Eberly Telescope Wide Field Upgrade", Proc. SPIE, 9145-5 (2014)
3. Chonis, T. S., Hill, G. J., Lee, H., Tuttle, S. E., and Vattiat, B. L., "LRS2: the new facility low resolution integral field spectrograph for the Hobby-Eberly Telescope," Proc. SPIE 9147-9 (2014)
4. Chonis, T. S., Frantz, A., Hill, G. J., Clemens, J. C., Lee, H., Adams, J. J., Marshall, J. L., DePoy, D. L., and Prochaska, T., "Mass production of volume phase holographic gratings for the VIRUS spectrograph array," Proc. SPIE 9151-53 (2014)
5. Lee, H., Hill, G.J., Tuttle, S.E., Noyola, E., Peterson, T., Vattiat, B.L., "Field application of moment-based wavefront sensing to in-situ alignment and image quality assessment of astronomical spectrographs: Results and analysis of aligning 100 VIRUS unit spectrograph," Proc. SPIE, 9151-138 (2014).
6. Lee, H., Hill, G.J., "Hybrid Phase Retrieval Using Moment-based Wavefront Sensing and Gerchberg-Saxton Iterative Transform Method," Proc. SPIE, 9151-139 (2014).
7. Marshall, J. L., DePoy, D. L., Prochaska, T., Allen, R. D., Williams, P., Rheault, J. P., Li, T., Nagasawa, D. Q., Akers, C., Baker, D., Boster, E., Campbell, C., Cook, E., Elder, A., Gary, A., Glover, J., James, M., Martin, E., Meador, W., Mondrik, N., Rodriguez-Patino, M., Villanueva, Jr., S., Hill, G. J., Tuttle, S., Vattiat, B., Lee, H., Chonis, T. S., Dalton, G. B., Tacon, M., "VIRUS instrument collimator assembly," Proc. SPIE 9147-143 (2014)
8. Prochaska, T., Allen, R., Rheault, J. P., Cook, E., Baker, D., DePoy, D. L., Marshall, J. L., Hill, G., Perry, D., "VIRUS instrument enclosures," Proc. SPIE 9147-257 (2014)
9. Vattiat, B.L., Hill, G.J., Lee, H., Moreira, W., Drory, N., Ramsey, J., Elliot, L., Landriau, M., Perry, D.M., Savage, R., Kriel, H., Haeuser, M., Mangold, F., "Design, alignment, and deployment of the Hobby Eberly Telescope prime focus instrument package", Proc. SPIE, 9147-172 (2014)
10. Tuttle, S.E., Gary J. G.J., Lee, H., Vattiat, B.L., Noyola, E., Drory, N., Cornell, M.E., Peterson, T., Chonis, T.S., Allen, R.D., Dalton, G.B., DePoy, D.L., Edmonston, R.D., Fabricius, M.H., Kelz, A., Haynes, D.M., Landriau, M., Lesser, M.P., Leach, R.W., Marshall, J.L., Murphy, J.D., Perry, D., Prochaska, T., Ramsey, J., Savage, R., "The construction, alignment, and installation of the VIRUS spectrograph", Proc. SPIE 9147-26 (2014)
11. Kelz, A., Jahn, T., Haynes, D.M., Hill, G.J., Murphy, J.D., Rutowska, M., Streicher, O., Neumann, J., Nicklas, N., Sandin, C., Fabricius, M., "HETDEX / VIRUS: testing and performance of 33,000 optical fibres", Proc. SPIE, 9147-269 (2014)
12. Good, J.M., Lee, H., Hill, G.J., Vattiat, B., Perry, D., "Design and implementation of coating hardware for the Hobby-Eberly telescope wide-field corrector", Proc. SPIE 9145-160 (2014)
13. Good, J.M., Zierer, J., Worthington, M., Wesley, G., Hill, G.J., "Design of the HETDEX VIRUS support structure for the Hobby-Eberly telescope", Proc. SPIE, 9145-204 (2014)
14. G.J. Hill, P.J. MacQueen, P. Palunas, A. Kelz, M.M. Roth, K. Gebhardt, & F. Grupp, "VIRUS: a hugely replicated integral field spectrograph for HETDEX", New Astronomy Reviews, 50, 378 (2006); G.J. Hill, P.J. MacQueen, J.R. Tufts, A. Kelz, M.M. Roth, W. Altmann, P. Segura, M. Smith, K. Gebhardt, & P. Palunas, "VIRUS: a massively-replicated IFU spectrograph for HET," Proc. SPIE, 6269-93 (2006)
15. G.J. Hill, P.J. MacQueen, M.P. Smith, J.R. Tufts, M.M. Roth, A. Kelz, J. J. Adams, N. Drory, S.I. Barnes, G.A. Blanc, J.D. Murphy, K. Gebhardt, W. Altmann, G.L. Wesley, P.R. Segura, J.M. Good, J.A. Booth, S.-M. Bauer, J.A. Goertz, R.D. Edmonston, C.P. Wilkinson, "Design, construction, and performance of VIRUS-P: the prototype of a highly replicated integral-field spectrograph for HET", Proc. SPIE, 7014-257 (2008)
16. G.J. Hill, et al., "VIRUS: a massively replicated 33k fiber integral field spectrograph for the upgraded Hobby-Eberly Telescope," Proc. SPIE, 7735-21 (2010)
17. R.D. Savage, J.A. Booth, K. Gebhardt, J.M. Good, G.J. Hill, P.J. MacQueen, M.D. Rafal, M.P. Smith, B.L. Vattiat, "Current Status of the Hobby-Eberly Telescope Wide Field Upgrade and VIRUS", Proc. SPIE, 7012-10 (2008)
18. R. Savage, et al., "Current Status of the Hobby-Eberly Telescope wide field upgrade," Proc. SPIE, 7733-149 (2010)
19. G.J. Hill, et al., "Current status of the Hobby-Eberly Telescope wide field upgrade," Proc. SPIE, 8444-19 (2012)
20. Hill, G.J., Gebhardt, K., Komatsu, E., Drory, N., MacQueen, P.J., Adams, J.A., Blanc, G.A., Koehler, R., Rafal, Roth, M.M., Kelz, A., Grupp, F., Murphy, J., Palunas, P., Gronwall, C., Ciardullo, R., Bender, R., Hopp, U., and

Schneider, D.P., 2008, "The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX): Description and Early Pilot Survey Results", in Panoramic Views of the Universe, ASP Conf. Series, vol 399, p 115
21. J. H. Burge, S. D. Benjamin, M. B. Dubin, S. M. Manuel, M. J. Novak, Chang Jin Oh, M. J. Valente, C. Zhao, J. A. Booth, J. M. Good, G. J. Hill, H. Lee, P. J. MacQueen, M. D. Rafal, R. D. Savage, M. P. Smith, B. L. Vattiat, "Development of a wide-field spherical aberration corrector for the Hobby Eberly Telescope", Proc. SPIE, 7733-51 (2010)
22. J. Good, et al., "Design of performance verification testing for HET wide-field upgrade tracker in the laboratory," Proc. SPIE, 7739-152 (2010)
23. M.S. Worthington, et al., "Design and analysis of the Hobby-Eberly Telescope Wide Field Upgrade bridge," Proc. SPIE, 7733-147 (2010)
24. N.T. Mollison, et al., "Design and development of a long-travel positioning actuator and tandem constant force actuator safety system for the Hobby-Eberly Telescope wide field upgrade," Proc. SPIE, 7733-150 (2010)
25. G.A. Wedeking, et al., "Kinematic optimization of upgrade to the Hobby-Eberly Telescope through novel use of commercially available three-dimensional CAD package," Proc. SPIE, 7733-148 (2010)
26. J.J. Zierer, Jr., G.A. Wedeking, J.H. Beno, J.M. Good, "Design, testing, and installation of a high-precision hexapod for the Hobby-Eberly Telescope dark energy experiment (HETDEX)," Proc. SPIE, 8444-176 (2012)
27. J.R. Mock, et al., "Tracker controls development and control architecture for the Hobby-Eberly Telescope Wide Field Upgrade," Proc. SPIE, 7733-152 (2010)
28. R.J. Hayes, et al., "Use of failure modes and effects analysis in design of the tracker system for the HET wide-field upgrade," Proc. SPIE, 8449-56 (2012)
29. M.S. Worthington, et al., "Design and development of a high-precision, high-payload telescope dual-drive system," Proc. SPIE, 7733-201 (2010)
30. N.T. Mollison, et al., "Collaborative engineering and design management for the Hobby-Eberly Telescope wide field upgrade," Proc. SPIE, 7738-84 (2010)
31. J.H. Beno, et al., "HETDEX tracker control system design and implementation," Proc. SPIE, 8444-211 (2012)
32. H. Lee, et al., "Analysis of active alignment control of the Hobby-Eberly Telescope wide field corrector using Shack-Hartmann wavefront sensors," Proc. SPIE, 7738-18 (2010)
33. H. Lee, et al., "Metrology systems for the active alignment control of the Hobby-Eberly Telescope wide-field upgrade," Proc. SPIE, 7739-28 (2010)
34. H. Lee, et al., "Orthonormal aberration polynominals over arbitrarily obscured pupil geometries for wavefront sensing in the Hobby-Eberly Telescope," Proc. SPIE, 7738-59 (2010)
35. H. Lee, et al., "Metrology systems of Hobby-Eberly Telescope wide field upgrade," Proc. SPIE, 8444-181 (2012)
36. H. Lee, et al., "Surface figure measurement of the Hobby-Eberly Telescope primary mirror segments via phase retrieval and its implications for the wavefront sensing in the new wide-field upgrade," Proc. SPIE, 7738-58 (2010)
37. J.J. Adams, et al., "The HETDEX Pilot Survey I. Survey Design, Performance, and Catalog of Emission-Line Galaxies," ApJS, 192, 5 (2011)
38. G.A. Blanc, et al., "The HETDEX Pilot Survey II: The Evolution of the Ly-α Escape Fraction from the UV Slope and Luminosity Function of $1.9<z<3.8$ LAEs," ApJ, 736, 31 (2011)
39. H. Lee, et al., "VIRUS optical tolerance and production," Proc. SPIE, 7735-140 (2010)
40. B. Vattiat, et al., "Mechanical design evolution of the VIRUS instrument for volume production and deployment," Proc. SPIE, 7735-264 (2010)
41. T. Prochaska, et al., "VIRUS spectrograph assembly and alignment procedures," Proc. SPIE, 8446-193 (2012)
42. S.E. Tuttle, et al., "Initial results from VIRUS production spectrographs," Proc. SPIE, 8446-221 (2012)
43. H. Lee, G.J. Hill, "Image moment-based wavefront sensing for in-situ full-field image quality assessment," Proc. SPIE, 8450-191 (2012)
44. H. Lee, G.J. Hill, S.E. Tuttle, B.L. Vattiat, "Fine optical alignment correction of astronomical spectrographs via in-situ full-field moment-based wavefront sensing," Proc. SPIE, 8450-192 (2012)
45. J.J. Adams, G.J. Hill, and P.J. MacQueen, "Volume Phase Holographic Grating Performance on the VIRUS-P Instrument", Proc. SPIE, 7014-258 (2008)
46. T.S. Chonis, G.J. Hill, J.C. Clemens, B. Dunlap, H. Lee, "Methods for evaluating the performance of volume phase holographic gratings for the VIRUS spectrograph array," Proc. SPIE, 8446-209 (2012)
47. T.S. Chonis, et al., "Development of a cryogenic system for the VIRUS array of 150 spectrographs for the Hobby-Eberly Telescope," Proc. SPIE, 7735-265 (2010)
48. J. M. Snigula, et al., "Cure-WISE: HETDEX data reduction with Astro-WISE," Proc. SPIE, 8451-78 (2012)
49. B.L. Vattiat, et al., "Design, testing, and performance of the Hobby Eberly Telescope prime focus instrument package," Proc. SPIE, 8446-269 (2012)

50. A. Kelz, S.M. Bauer, F. Grupp, G.J. Hill, E. Popow, P. Palunas, M.M. Roth, P.J. MacQueen, U. Tripphahn, "Prototype development of the integral-field unit for VIRUS", Proc. SPIE, 6273, 121 (2006)
51. J.D. Murphy, P. Palunas, F. Grupp, P.J. McQueen, G.J. Hill, A. Kelz, M.M. Roth, "Focal ratio degradation and transmission in VIRUS-P optical fibers", Proc. SPIE, 7018-104 (2008)
52. J.D. Murphy, et al., "The Effects of Motion and Stress on Optical Fibers", Proc. SPIE, 8446-207 (2012)
53. I. Soukup, et al., "Design of the fiber optic support system and fiber bundle accelerated life test for VIRUS," Proc. SPIE, 7735-180 (2010)
54. M.P. Smith, G.T. Mulholland, J.A. Booth, J.M. Good, G.J. Hill, P.J. MacQueen, M.D. Rafal, R.D. Savage, B.L. Vattiat, "The cryogenic system for the VIRUS array of spectrographs on the Hobby Eberly Telescope", Proc. SPIE, 7018-117 (2008)
55. J.T. Heisler, et al., "Integration of VIRUS spectrographs for the HET dark energy experiment," Proc. SPIE, 7733-153 (2010)
56. H. Lee, et al., "LRS2: a new low-resolution spectrograph for the Hobby-Eberly Telescope and its application to scalable spectrographs for the future of extremely large telescopes," Proc. SPIE, 7735-276 (2010)
57. T.S. Chonis, H. Lee, G.J. Hill, M.E. Cornell, S.E. Tuttle, B.L. Vattiat, "Design and construction progress of LRS2-B: a new low resolution integral-field spectrograph for the Hobby-Eberly Telescope," Proc. SPIE, 8446-103 (2012)
58. M.H. Fabricius, S. Barnes, R. Bender, N. Drory, F. Grupp, G.J Hill, U. Hopp, P.J. MacQueen, "VIRUS-W: an integral field unit spectrograph dedicated to the study of spiral galaxy bulges", Proc. SPIE, 7014, 234 (2008)