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Invited Paper

Present and Future Instrumentation for the Hobby-Eberly Telescope[*]

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ABSTRACT

The Hobby-Eberly Telescope (HET) is an innovative large telescope of 9.2 meter aperture, located in West Texas at McDonald Observatory. The HET operates with a fixed segmented primary and has a tracker which moves the four-mirror corrector and prime focus instrument package to track the sidereal and non-sidereal motions of objects. The HET has been taking science data for nearly a decade. Recent work has improved performance significantly, replacing the mirror coatings and installing metrology equipment to provide feedback that aids tracking and alignment of the primary mirror segments. The first phase of HET instrumentation included three facility instruments: the Low Resolution Spectrograph (LRS), the Medium Resolution Spectrograph (MRS), and High Resolution Spectrograph (HRS). The current status of these instruments is briefly described.

A major upgrade of HET is in progress that will increase the field of view to 22 arcminutes diameter, replacing the corrector, tracker and prime focus instrument package. This wide field upgrade will feed a revolutionary new integral field spectrograph called VIRUS, in support of the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX[§]). VIRUS is a facility instrument that consists of 150 or more copies of a simple unit integral field spectrograph. In total VIRUS will observe 34,000 spatial elements simultaneously, and will open up wide-area surveys of the emission-line universe for the first time. We describe the HET wide field upgrade and the development of VIRUS, including results from testing the prototype of the VIRUS unit spectrograph.

Keywords: Telescopes: Hobby-Eberly Telescope, Astronomical instrumentation: Spectrographs, VIRUS

1. INTRODUCTION: OVERVIEW OF THE HET AND INSTRUMENTS

The HET[1,2,3] is an innovative telescope with an 11 m hexagonal-shaped spherical mirror made of 91 1 m hexagonal segments that sits at a fixed zenith angle of 35°. It can be moved in azimuth to access about 70% of the sky visible at McDonald Observatory. The pupil is 9.2 m in diameter, and sweeps over the primary mirror as the x-y tracker follows objects for between 40 minutes (in the south at $\delta = -10.3^{\circ}$) and 2.8 hours (in the north at $\delta = +71.6^{\circ}$). The maximum track time per night is 5 hours and occurs at +63°. Detailed descriptions of the HET and its commissioning can be found in refs 1-5. The HET facility instruments are the Marcario Low resolution Spectrograph (LRS)[6-8], which rides in the Prime Focus Instrument Package (PFIP) on the tracker, allowing it to image as well as take spectra, the High Resolution Spectrograph (HRS)[9,4], and the Medium Resolution Spectrograph (MRS)[10,11,4]. The HRS and MRS are fed by fibers from the fiber instrument feed (FIF) [10] that is part of the PFIP and are installed in the basement spectrograph room under the telescope, internal to the pier.

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The HET primary mirror has a radius of curvature of 26164 mm, and a 4-mirror double-Gregorian type corrector is designed to produce images with FWHM < 0.6 arcsec in the absence of seeing, over a 4 arcmin (50 mm) diameter science field of view. Another mirror folds the light-path towards the LRS, for a total of six reflections to reach the LRS slit. The FIF is fed directly without a further reflection.

2. HET CURRENT PERFORMANCE

The HET is a prototype for a new breed of cost-effective large telescopes, and is the basis for the newly constructed Southern African Large Telescope (SALT)[12]. In particular, the primary mirror[13], based on a steel truss, and the tracker[14] were key to realizing the project for the initial modest cost of $16M. Initial performance of the HET was not, however, to specification in the areas of image quality and primary mirror stability[1]. Subsequent completion of the telescope to improve image quality, has brought the total expenditure to about $20M, still a very modest price for a large telescope[1,2]. The price paid for this low cost is that HET and SALT are the most complex telescopes in existence, requiring constant realignment of the optics during a track in order to maintain image quality. Since last reported [3,5], we have continued to achieve site-seeing limited images at times on a regular basis, and have installed metrology equipment to ensure the best possible alignment of the optics at all times.

The image quality delivered by the HET depends on (a) the accuracy of the primary mirror alignment (stack), (b) the stability of the primary mirror to changes in temperature, (c) dome seeing, (d) accuracy of the motions of the tracker, and (e) the figure and internal alignment of the corrector. In early operations, typical images delivered by the telescope were 2.5-3.0 arcsec FWHM. Since then, we have undertaken a series of projects[5,2,3,15] designed to understand and correct the poor image quality of the HET with the result that typical images have been reduced to 1.5 arcseconds and images of 0.7 - 0.8 arcseconds have been obtained sporadically during science operations.

2.1 Primary Mirror

The segments of the primary mirror are aligned with a Shack-Hartmann system, located in the center of curvature tower to produce an image from each mirror aligned with a fiducial spot. This Mirror Alignment Recovery System (MARS[16]), has been operational since October 2001 and alignment now has a negligible effect on the delivered image quality. Once aligned, the segments are held relative to one another with an edge-sensor Segment Alignment Maintenance System (SAMS[17]). SAMS uses inductive sensors and has been in operation since January 2002. These systems combine to align and hold the mirror within specification all night, most nights. Maintaining the global radius of curvature (GROC) of the PM within +/-0.3 mm of 26,164 mm is an important requirement for HET performance. Installation of a distance measuring interferometer arm in the center of curvature tower now allows the position of the center of curvature of the mirror to be set accurately, so GROC is now set to 0.1 mm at each realignment of the mirror with MARS.

Images from the individual segments combine to form an image from the primary of 0.4 arcsec. FWHM (0.5 arcsec. EE(50%)), which meets the specifications. As a result, the PM is making a negligible contribution to even the best images delivered by the telescope.

2.2 Tracker Metrology System

Another aspect of image quality that is unique to the HET design, is the effect of the tracker position on the image. The HET is a complex opto-mechanical system with no natural axes: everything is time-dependent. The tracker[14] has six axes: x, y, focus (z), tip (θ), tilt (ϕ), rotation (ρ). In order to maintain image quality during a track, the tracker needs to accurately maintain the 4-mirror corrector in the PFIP perpendicular to the PM within 25 seconds of arc, and 10 μm in focus. SAC tip and tilt errors with respect to the primary lead to coma and distance errors lead to defocus. The tracker metrology system (TMS) is used to align the SAC during observations. The system consists of an auto-collimator called the tip-tilt camera (TTS) and a distance measuring interferometer (DMI) both working in the near-infrared at 1.5μm (Ref. 15). The DMI is a low-coherence distance measuring interferometer developed by Fogale-Nanotech and the TTS is a custom-designed assembly based on commercial components. The DMI has 1 μm repeatability and long-term accuracy of about 10 μm. The TTS has 0.2 arcsecond repeatability and 75 arcsecond capture range in tip and tilt. Ideally these errors would be measured directly via a wavefront sensor. The relatively small 4 arcmin. diameter field of the current HET SAC precludes this, but wavefront sensing is part of the HET Wide Field Upgrade, as described below.

The tracker metrology system has been in operation for two years. It has contributed to an improvement in setup time and operational efficiency. The contribution of the telescope to the delivered image quality continues to be approximately 1 arcsec. Hartmann testing shows that part of this error appears to be due to degrading alignment and internal flexure of the SAC, which will be addressed this summer.

2.3 Queue Scheduling and Operation Efficiency

HET is a fully-queue scheduled telescope due to its design[18]. HET operates a responsive queue with a great deal of interaction between the Resident Astronomers and HET users. This model allows fine tuning of programs to ensure completion and rapid response to targets of opportunity. Programs are ranked into four bands of time by the time allocation committees of the partner institutions. Completion within the two highest priority bands is in excess of 95% and ranges between 75% and 90% for the next band, depending on weather patterns. Program completion is emphasized as this leads to the greatest science impact. Over the past two years, the HRS has been used 71%, the LRS 28%, and the MRS 1% of the observed time. The majority of the HRS observations are for extra-solar planet search programs that utilize the strength of the HET queue for synoptic observations, but which involve short exposures. As a result, overhead has remained at ~33% while shutter-open time has risen to 56%, due to reduction in primary mirror alignment time to 4% of nighttime hours, and reduction of time lost to problems to 7%. HET is a mature facility and is performing well in the areas that play to the strengths of the design.

2.4 Facility instruments

The designs and performance of the facility instruments have been reviewed before[4,5]. Details of the instruments can be found on the HET web site at http://het.as.utexas.edu/HET/hetweb/. We concentrate here on instrument development that has occurred in the last two years since the previous review[4].

The HET LRS[6-8] has been in operation for nine years. It is a high-throughput grism spectrograph with three modes of operation: imaging, longslit, and multi-object. The field of view of the HET is 4 arcmin in diameter, and the LRS has a 13-slitlet Multi Object Spectroscopy (MOS) unit covering this field. The MOS unit[19] is based on miniature components and is remotely configurable under computer control. A series of longslits (1.0, 1.5, 2.0, 3.0, and 10.0 arcsec wide) may be selected, each 4-arcmin long. A selection of 12 broad band and blocking filters are carried at any one time, along with two grisms. LRS operates with four grisms. Grism 1 is 300 l/mm covering 407 to 1170 nm at a resolving power R~600 with a 1 arcsec wide slit; grism 2 is 600 l/mm covering 426 – 730 nm at R~1300. Grism 3 based on a volume phase holographic grating (VPHG)[20], covers 630 to 900 nm at R~2000 in first order. The highest resolving power (R~2800) is achieved with an echelle grism designated E2 which is designed for galaxy dynamics work and has wavelength coverage 470 – 590 nm in 3rd order with a custom blocking filter for this region.

LRS obtains spectra to m~22.5 in normal operations. Its versatility is well-suited to target of opportunity observations of supernovae and gamma ray bursts (for example), and to large surveys to classify faint objects. A prime example is the recently completed Sloan Digital Sky Survey – II supernova survey[21]. HET provided spectra of the most distant third of the sample, ~200 objects, with a median redshift of z~0.3, extending to z=0.5. The typical brightness of the supernovae was r=21.5 and the faintest had r=22.5, all observed with two 1200 s exposures. The responsive queue of the HET allowed the majority to be observed within 24 hours of discovery. This project is ideally suited to the HET since the SDSS-II survey targets a long strip, at constant declination, and the queue-scheduling is well adapted to rapid follow up of new targets.

The HET MRS[10,11,4] is a versatile, fiber-fed echelle spectrograph. The MRS has two beams. The visible beam has wavelength coverage from 450 - 900 nm in a single exposure with resolving power between 5,000 and 20,000 depending on the fiber configuration selected. This beam also has capability in the ranges 380 - 950 nm by altering the angles of the cross-disperser gratings. A second beam will operate in the near-infrared and has coverage of 900 - 1300 nm in a single exposure with resolving power between 5,500 and 11,000. The MRS now has the visible beam with single object direct feed mode with 1.5 and 2 arcsec diameter fibers in regular use. The faintest objects so far observed with MRS have been 18th magnitude.

The HET HRS[9,4]. It is a fiber-fed, grating cross-dispersed echelle spectrometer operating over bandwidth 375 nm – 1.05 μm at resolving powers of 15,000, 30,000, 60,000, and 120,000. An insertable temperature-stabilized I_2 gas absorption cell provides a reference for greatest wavelength accuracy. The HRS CCD system is a mini-mosaic of two

E2V 2kx4k CCDs oriented in HRS with the columns parallel to the echelle orders. The red-side CCD was upgraded in May 2006 as it had many faint hot columns and very poor serial CTE. The hot columns were problematic in data reduction of high signal-to-noise spectra. The new CCD is a grade one E2V deep depletion device that is free of hot columns, has excellent CTE, and lower readout noise. The deep depletion properties give much improved red quantum efficiency and have increased the wavelength for the onset of fringing from approximately 680 nm to 780 nm.

A significant upgrade is being undertaken on HRS to increase its efficiency by replacing the entire feed from the telescope to the entrance slit. Currently, the light exiting the fibers from the telescope is relayed onto the spectrograph slit, with the slit width being changed to set the resolving power. With the standard 2 arcsec. fiber, there is no slit loss at R=17,000, a 28% loss at R=30,000, a 68% loss at R=60,000, and an 84% loss at R=120,000. The HRS Input Upgrade project (HRS-IU) will recover most of the lost light through the use of image slicers, greatly improving the competitiveness of HRS.

The HRS-IU consists of the following subsystems and components. New fibers will be used to better match the anticipated delivered image quality of the HET to the spectrograph. An improved fiber mounting technique will be used to improve the focal ratio degradation properties, and the fiber ends will be AR coated via a window and lenslet. Dual modified Bowen Walraven image slicers will be used for each HRS resolving power to slice an object fiber and a sky fiber. The image slicers are deployed at the internal f/40 focus of the fiber relay optics, with the entire system yielding high throughput and excellent image quality over the full HRS bandwidth. The dual fiber feed allows calibration light to be feed through one fiber while the object light is fed through the other. This will allow the expansion option of Th-Ar or laser comb light being integrated simultaneously during precision radial velocity observing. Unlike the current design, an aperture stop applies to all configurations for both telescope and calibration light for improved calibration stability. The relay optics provide collimated space for the iodine cell and the filters used to suppress the cross disperser second order. An exposure meter will measure both object-plus-sky and sky for both improved observing efficiency and improved barycentric velocity corrections in precision radial velocity programs. A high efficiency fiber double scrambler has been successfully designed and prototyped, and will be one option for feeding the spectrograph, once again in support of precision radial velocities. Finishing out the HRS-IU will be slit and pupil viewers to allow the fibers and preslit optical alignment to be monitored. This project is funded and will be commissioned in 2009.

Currently HRS is a single, configurable arm spectrograph as funding forced the initial two-arm design to be reduced to the single-arm design. A high performance blue arm has been designed using a VPHG cross disperser, 5-element-4-group dioptric camera, and 2kx4k CCD. A high performance dichroic has been designed by a vendor that splits the light near the spectrograph intermediate focus in the narrow 490-500 nm wavelength band. The blue arm will be a fixed configuration covering 365-500 nm, and the current HRS arm will be used as a configurable red arm covering 490-1050 nm. The split wavelength is chosen with little compromise so that the entire 500-630 nm iodine cell bandwidth falls in one arm. This project is partially funded, and is expected to be started in late 2008.

2.5 Science Highlights

In addition to the successful campaign on SDSS-II supernovae candidate follow-up, HET has contributed a number of notable science achievements over the past few years. Highlights include:

- Rapid observation of the brightest gamma ray burst ever at z=0.94, detected by SWIFT: http://live.psu.edu/story/29615
- First ground-based detection of the atmosphere of a planet outside our own solar system[22]: http://mcdonaldobservatory.org/news/releases/2007/1205.html
- Discovery of the most powerful supernova ever seen [23]: http://mcdonaldobservatory.org/news/releases/2007/1010.html
- Discovery of one of the most distant objects known, a quasar at z=6.01 [24]: http://mcdonaldobservatory.org/news/releases/2007/0608a.html
- Detection of a multi-planet system around the low metallicity star HD 155358 [25]: http://mcdonaldobservatory.org/news/releases/2007/0523.html
- Detection of a Neptune-sized planet around another star. At the time it was the smallest extrasolar planet known[26]: http://mcdonaldobservatory.org/news/releases/2004/0831.html

3. HET WIDE FIELD UPGRADE

The HET was originally envisioned as a spectroscopic survey telescope, able to efficiently survey objects over wide areas of sky. While the telescope has been very successful at observing large samples of objects such as QSOs spread over the sky with surface densities of around one per 10 sq. degrees, the HET design coupled with the limited field of view of the corrector hampers programs where objects have higher sky densities. In seeking a strong niche for the HET going forward, we desire a wide field of view coupled with a highly multiplexed spectrograph in order to exploit the strengths of the telescope and of the site. In particular, the upgrade of HET is motivated by the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX[27]), an ambitious project to measure the expansion history of the universe since z~4, to gain insight into the evolution of dark energy.

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[28]. The new corrector has much improved image quality and a 10 m pupil diameter. The periphery of the 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 for feeding 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 primary mirror spherical aberration and the off-axis aberrations in the wide field are controllable due to the first two mirrors being near pupils, and the second two mirrors being well separated from pupils. The imaging performance is 0.5 arcseconds or better over the entire 22 arcminute field of view, and vignetting is minimal (zero within 18 arcminutes). The performance and manufacturability of the WFC has been analyzed by two potential vendors in detailed design contracts. They independently agreed that the design will meet our specifications when the mirrors are mounted with straightforward engineering. They provided detailed cost and manufacturing plans that indicate delivery in about two years. The WFC is the longest-lead item in the WFU, and is now in procurement.

A new tracker is needed to accommodate the size and four-fold weight increase of the new PFIP. It will be a third generation evolution of the trackers for HET and SALT, and is in essence a precision six-axis stage. The preliminary design of the tracker is being developed by the Center for Electro-Mechanics (CEM) at the University of Texas at Austin, and was reviewed in May. Construction is starting, with integration at the CEM facility scheduled for late 2009.

HET requires constant monitoring and updating of the position of its components in order to deliver good images. The WFC must be positioned to 10μm precision in focus, and tip/tilt with respect to the optical axis of the primary mirror. This axis changes constantly as the telescope tracks, following the sidereal motions of the stars. Tilts of the WFC cause comatic images. In addition, the global radius of curvature of the primary mirror can change with temperature (as it is essentially a glass veneer on a steel truss), and needs to be monitored. The segment alignment maintenance system (SAMS) maintains the positions of the 91 mirrors with respect to each other, but is less sensitive to the global radius of curvature of the surface. The feedback to maintain these alignments requires excellent metrology, which is provided by the following subsystems:

- Guide probes to monitor the position on the sky, and plate scale of the optical system, and monitor the image quality and atmospheric transparency
- Wavefront sensors (WFS) to monitor the focus and tilt of the WFC
- Distance measuring interferometer (DMI) to maintain the physical distance between the WFC and primary mirror
- Tip-tilt sensor (TTS) to monitor the tip/tilt of the WFC with respect to the optical axis of the primary mirror

The upgrade adds wavefront sensing to HET in order to close the loop on all axes of the system, in conjunction with the DMI and TTS adapted from the current tracker metrology system. There is redundancy built into the new metrology system in order to obtain the highest reliability. Two guide probes distributed around the periphery of the field of view provide feedback on position, rotation, and plate scale, as well as providing a record of image quality and transparency. The alignment of the corrector is monitored by the wavefront sensors as well as by the DMI and TTS. The radius of curvature of the primary mirror is monitored by the combination of focus position from the WFS with the physical measurement from the DMI and checked by the plate scale measured from the positions of guide stars on the guide probes. The SAMS edge-sensors provide a less sensitive but redundant feedback on radius of curvature as well.

Two guide probes will use small pick-off mirrors and coherent imaging fiber bundles to select guide stars from the outer annulus of the field of view. They will be located ahead of the focal surface, before the shutter. Each will range around the focal surface on precision encoded stages, accessing a 90 degree sector. They are being designed to have a small size to reduce shadowing of the focal surface, and will have a field of view of 20 arcseconds each. During setup on a new target, they will be driven to pre-defined positions, and the initial pointing will be made by centering the guide stars in the probes. Small offsets will be made by driving the probes in sympathy with telescope moves. This system is a significant upgrade from the current pellicle-based guiders.

Two wavefront sensors will also range in the outer field. Their function is to provide feedback on the low-order errors in the wavefront (focus, coma, spherical, and astigmatism). These errors are caused by misalignment of the corrector with the primary mirror focal surface and by global radius of curvature and astigmatism errors in the primary mirror shape. Their update rate will be 1-0.1 Hz. In addition to the WFS probes there will be an analysis wavefront sensor as part of the acquisition camera that will allow more detailed feedback analysis of the image quality, simultaneous with the operation of the WFS probes, independent of seeing.

A trade-off has been made between Shack-Hartmann (S-H) wavefront sensing and curvature sensing via extrafocal imaging. Michael Lloyd-Hart (Steward Observatory AO group) has provided a detailed analysis of the two approaches and has investigated the sensitivity of wavefront sensing to the low-order errors we will be controlling on HET. The effect of the changing pupil illumination as HET tracks has been evaluated. The conclusion is that curvature sensing is too sensitive to residual errors in knowledge of the pupil illumination as the HET tracks, whereas a S-H system would naturally accommodate this feature of the HET, and is preferred. A straw-man S-H system with 7x7 sub-apertures across the pupil can meet the requirements using 17th magnitude stars, many of which will be available in the outer arcminute annulus of the WFC field of view. We are building a wavefront sensor for the current HET with 19 sub-apertures across the pupil. The final design will be informed by direct experience with this sensor. The design of the wavefront sensors is straightforward, but their application to the HET, with the varying illumination of the telescope pupil during a track, will require development of a robust software system for analysis of the sensor data to produce reliable wavefront information.

4. VIRUS

Large targeted surveys of continuum-selected objects are now becoming the norm, and have greatly increased our understanding in many areas of astronomy. Surveys of the emission-line universe, however, are limited currently to wide field imaging with narrow band filters or to narrower fields with Fabry-Perot etalons. Integral field (IF) spectrographs offer a huge gain over these techniques, providing much greater sensitivity, or much greater wavelength coverage, respectively. The current generation of IF spectrographs are well-adapted to arcminute-scale fields of view, with several thousand spatial elements, and adequate spectral coverage for targeted observations of individual extended objects. They have the grasp to detect simultaneously of order 0.5 million (spectral x spatial) resolution elements.

HETDEX will map the spatial distribution of about a million Lyα emitting galaxies (LAEs) with redshifts $1.9 < z < 3.5$ over 420 sq. deg. area (9 Gpc^3). This dataset will constrain the expansion history of the Universe to 1% and provide significant constraints on the evolution of dark energy. The LAEs will be detected with the Visible Integral-field Replicable Unit Spectrograph (VIRUS[29-31]), a set of 150 to 192 IF spectrographs, arrayed in the 22 arcmin. field. The advantage of an IF spectrograph for this project is that the tracer galaxies are identified and have their redshifts determined in one observation. In order to achieve the order of magnitude increase in grasp needed for HETDEX and other wide field surveys, a scheme involving massive replication of a simple spectrograph has advantages over traditional monolithic astronomical instruments. Instruments such as MUSE[32] will use replication of up to 24 unit spectrographs, but significant additional cost savings can be realized by replicating in excess of 100 copies of a more basic spectrograph. We refer to this level of production as "industrial replication"[33]. VIRUS is the first instrument employing such large-scale replication, and represents a model for future ELTs, where the multiplex advantage of such an approach can be used to image slice and thus avoid growth in the scale of instruments on ELTs.

Each VIRUS unit is fed by 224 fibers that each cover 1.8 arcsec^2 on the sky. The fibers feeding a two-unit module are arrayed in a 50×50 square arcseconds IFU with a 1/3 fill-factor. A dither pattern of three exposures fills in the area. The spectral resolution is 5.7 A, with coverage of 350–550 nm. The optical design is simple, using three reflective and two refractive elements. With dielectric reflective coatings optimized for the wavelength range, high throughput is obtained. The full VIRUS array will simultaneously observe a minimum of 33,600 spectra with 12 million resolution elements. The IFUs are arrayed within the 22′ field of the upgraded HET with ~1/7 fill factor, sufficient to detect the required density of LAEs for HETDEX. Development is proceeding with the prototype (VIRUS-P [34]), deployed in October 2006, and pre-production prototype where value engineering is being used to reduce the cost for production.

4.1 VIRUS Prototype

The motivation for building VIRUS-P is to provide an end-to-end test of the concepts behind HETDEX, both instrumental and scientific. Construction and testing of VIRUS-P has verified the opto-mechanical design, the throughput, the sensitivity, and demonstrated the utility of such an instrument for surveys of emission-line objects. It has also served as a test-bed for the software development needed for analyzing the data from the full VIRUS array. The parallel nature of VIRUS means that the prototype can be used to develop the final software pipeline. VIRUS-P is also designed to be a facility instrument on the McDonald 2.7 m Smith Reflector. The basic layout is shown in Figure 1. The instrument consists of three basic sub-units: the IFU, the collimator/grating assembly, and the camera assembly. The beam size is 125 mm, allowing the collimator to accommodate an f/3.32 beam from the fibers, allowing a small amount of focal ratio degradation of the f/3.65 input from the telescope. In VIRUS-P, the collimator and grating pivot about a horizontal axis passing through the plane of the grating, to allow reconfiguration of the instrument for different wavelength ranges and resolving powers and to shift the blaze of the volume phase holographic grating. Gratings are interchangeable to provide flexibility for different scientific applications. The final VIRUS units will have fixed formats, but will have the capability to swap dispersers. The instrument mounts within a light-tight box that incorporates a lead-screw to adjust the tilt of the collimator with respect to the camera. The camera is a f/1.33 vacuum Schmidt design with a 2k x 2k @ 15 μm pixel CCD at its internal focus. Details of the design of VIRUS-P are provided elsewhere in these proceedings [34-38].

VIRUS-P has been designed to mount on the McDonald 2.7 m Smith telescope for testing and to conduct a pilot survey of Ly-α emitting galaxies in support of the HETDEX project. It mounts at the f/9 bent Cassegrain focus, is fed by a f/3.65 focal reducer (Figure 1). It is supported within a gimbal in order to mimic the mounting on the HET, where the instrument will be fixed with respect to gravity but will see the full range of operating temperatures. The design is optimized for stability against temperature changes. VIRUS-P has also been mounted on the HET to study observing strategy and verify sensitivity limits for the HETDEX survey.

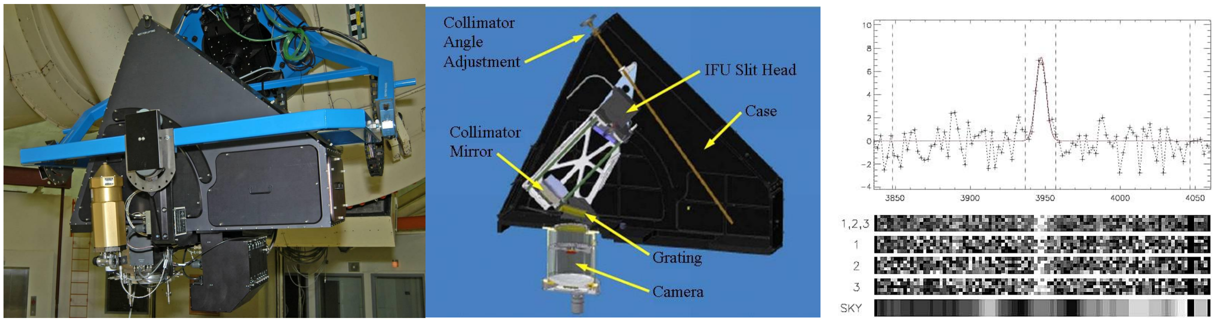

Figure 1. The photograph on the left shows VIRUS-P installed on the Harlan J. Smith telescope. The blue structure is a gimbal to maintain orientation with respect to gravity. The illustration in the middle shows the interior components which are fed by an IFU that contains 246 fibers with 200 μm diameter cores. For reference the size of the camera and collimator modules is about 0.6 m. The black case incorporates an adjuster to reconfigure the collimator angle for wavelength range adjustment. A spectrum of a candidate LAE, acquired with VIRUS-P during the pilot survey, is shown on the right. The object is detected in three separate fibers as the IFU position is dithered to fill in the area.

It is essential to couple VIRUS to the HET with fibers due to the weight and space constraints at the prime focus of the telescope. In addition, the variable effects of the changing pupil illumination of HET during a track are mostly removed by azimuthal scrambling along a fiber, producing much greater stability in the data calibration than is possible with an imaging spectrograph. HET has a fast focal ratio in order to couple efficiently to fibers, and VIRUS uses a densepak-type IFU. The VIRUS-P IFU uses 200 μm core-diameter Polymicro FBP fiber and has 247 fibers arrayed in a hexagonal pack with a 1/3 fill-factor. Anti-reflection coated cover plates mounted to the fiber ends with index-matched optical couplant ensure maximum throughput. This layout is most optimal for covering area, since a dither-pattern of three exposures exactly fills the field of the IFU, while maximizing the efficiency.

On the 2.7 m the fiber cores subtend 4.1 arcseconds, and the IFU covers 3.5 sq. arcminutes. While the fibers are large, projected on the sky, the IFU covers the largest area of any current IF spectrograph and this results in great sensitivity for wide area surveys and particularly for low surface brightness emission. VIRUS-P covers 350-580 nm in one setting at R~900 and can be set for wavelengths between 340 and 670 nm where the dielectric mirror coatings are optimized. The prototype incorporates adjustment of the collimator angle and the grating angle, as well as allowing different gratings to be employed. These features will not be incorporated into the final VIRUS modules, which are fixed in order to ensure simplicity and to save space and money. It does however test all the features of the instrument needed for the full VIRUS array.

4.2 Software Development

The software for VIRUS must process a highly parallel data stream, quickly, and detect single-line objects, reliably. Development of the final software pipeline for reduction of VIRUS data is being led by MPE. Since VIRUS is naturally a parallel instrument, all the requirements for and attributes of the software can be developed and tested on the prototype. This was a key motivation for the deployment of VIRUS-P on the telescope early in the project. Two pipelines have been developed, one in Texas called VACCINE and the other in Munich, called CURE. VACCINE has been used primarily to reduce and analyze data from the pilot survey on the McDonald 2.7 m, while the algorithms of CURE are tuned for use on the HET. The difference is driven primarily by the plate scale difference between the telescopes. On the 2.7 m the fibers are significantly larger than the image size, while on HET they are comparable. This leads to differences in the detection algorithm. Care is being taken to propagate errors and avoid interpolation through resampling of data which leads to position-dependent smoothing and can alter the noise characteristics. CURE uses a Bayesian detection algorithm that assigns a likelihood of a source to every (spatial and spectral) resolution element. Tests show robust rejection of cosmic rays and reliable detection of 5-σ line flux objects, as required for HETDEX. We have also demonstrated sky subtraction to the Poisson noise limit, with both pipelines, aided by the fact that most of the fibers of VIRUS are observing sky in any exposure. There is a huge advantage to having the ability to exercise software on real data this early in the project, and we expect to come on line with a fully operational and debugged pipeline when VIRUS is turned on.

The data volume from the full VIRUS array (of up to 192 spectrographs) is about 9 GB per exposure. Observation times per field are short for the HETDEX survey, and we expect to generate 100 TB of raw data over the course of the survey, including calibrations. These data volumes are quite modest in the context of the coming generation of large image imaging surveys. The data reduction pipeline will reduce each night's data in 8 hours, requiring around 128 processors at today's speeds.

4.3 VIRUS-P Performance

VIRUS-P has been in use since October 2006. It has been used primarily on the McDonald 2.7 m Smith Reflector for a pilot survey to study the properties of Lyman-α emitting (LAE) galaxies. Figure 1 shows an example LAE detected in this survey. In March 2008 we took the instrument to the HET for the first of a series of tests of its performance to verify predicted sensitivities. More tests will be needed to verify that LAEs are detected at the expected rate, but the first tests resulted in a successful deployment of the instrument and were able to detect faint LAEs and continuum objects. Detailed discussion of the performance of VIRUS-P is presented in Ref. 34, here we summarize the results:

- Throughput of VIRUS as a function of wavelength (ignoring aperture effects at the input to the fibers) peaks at 40% and is 30% at 350 nm with 15 m long fibers, in line with predictions based on the measured throughputs of individual components. On-sky, including the atmosphere, the throughput peaks at 18%. This performance exceeds that required for HETDEX.
- The 5-σ point source line flux sensitivity is ~5×10^{-17} erg/cm^2/s, in 2 hours observing, in line with predictions. Significant numbers of emission-line galaxies are being detected (an example is shown in Fig. 1).
- Image quality of the instrument meets requirements. Optical alignment was achieved with simple setup procedures.
- The instrument is extremely stable against temperature changes, with images moving 1/20 of a resolution element with a 12 Celsius temperature change, exceeding requirements. On HET, the VIRUS units will be mounted fixed, so stability against gravity vector changes is not a requirement.

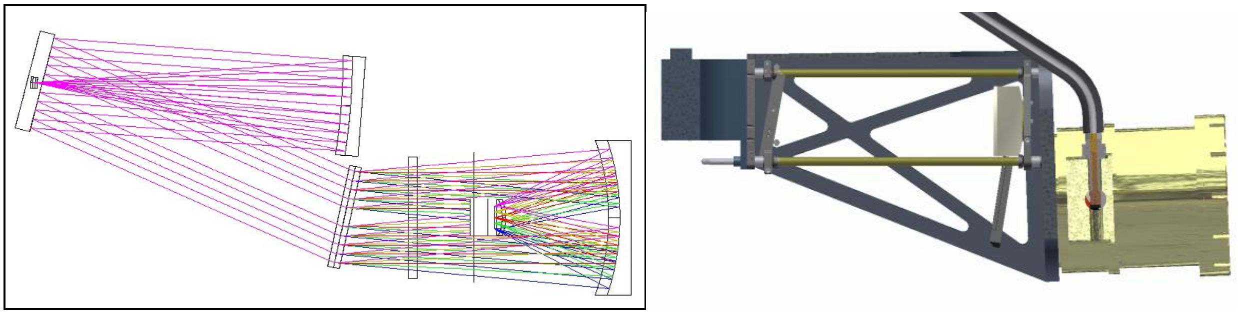

Figure 2: Left, optical layout of the production VIRUS with the grating and camera rotated 180 degrees about the optical axis to make the design more compact. The grating has 930 l/mm and the coverage is 350-550 nm. Right, early evolution of the VIRUS-P mechanical design towards production, shown in the same orientation, with the IFU slit box on the left, the collimator assembly with grating in the middle, and the camera cryostat on the right. The cryogenic cold-finger and bayonet protrudes in from the top.

VIRUS-P is being used for an extensive survey of the properties of LAE galaxies, in order to better understand their evolution and large-scale clustering in preparation for HETDEX. To date we have surveyed 134.4 arcmin^2 on the COSMOS, MUNICS-S2, and GOODS-N fields. Analysis of 40 arcmin^2 area on the COSMOS field detected 99 unique emission line sources, of which half are LAEs and half are low redshift emitters[27]. This survey is providing confirmation that we can discriminate LAEs from low redshift galaxies.

5. VIRUS PRODUCTION DESIGN

Evolution of the design of VIRUS from the prototype to the production model will be made in two steps. First a pre-production prototype (VIRUS-PP) will be developed that incorporates the production engineering to reduce costs. Production engineering is being done in collaboration with the Advanced Research Lab (ARL) at Penn State University. VIRUS-PP will be evaluated and used as a test bed for alignment fixturing to prove the production, assembly, and alignment model for the instrument. Its performance will be evaluated on sky and compared with that of VIRUS-P. Following incorporation of any design modifications gleaned from this experience we will enter production with an initial batch of 10 units, followed by full production. Assembly and testing of the VIRUS modules will take place at Texas A&M University, where a large lab complex has been allocated to the project.

5.1 Optomechanical Design

We have already made some significant changes to the design, based on experience with VIRUS-P and responding to the development for the HET WFU design. The most significant is to double the spectrographs so that a pair shares a single IFU, a common collimator housing, and a common cryostat. The motivation for this has come first from fiber cable handling: it is more efficient in terms of weight and cross-sectional area to double the number of fibers in a cable (note that the fiber itself is not the dominant weight in a bundle). There is not expected to be significant cost-savings on the IFU, but the cable handling becomes significantly easier with 75 instead of 150 cables to accommodate (the goal is 92 cables, and the IFU handling system is being designed for this number). The other advantage to the double unit is that two cameras share a vacuum, and have a single connection to the LN_2 cooling system. This saves cost on vacuum valves and other fixturing.

The optical layout has been modified to make the system more linear and allow the units to be packed more tightly in the housings (Fig. 2). Analysis of the fiber diameter for maximizing the number of Lyman-α emitting (LAE) galaxies detected by the HETDEX survey indicates that the ideal is 1.5 arcseconds for the expected range of image quality to be encountered in the survey (1.3 to 1.8 arcsec FWHM). Analysis of the expected number of LAEs with redshift also indicates that the majority of the objects are located at $z<3.5$ due to the change in distance modulus with redshift coupled with the steepness of the LAE luminosity function. As a result, the decision has been made to reduce the wavelength coverage so as to preserve spectral resolution, while accommodating the larger fibers (265 vs 200 μm core diameter). This is a small change and the increase in dispersion of the grating (930 versus 830 l/mm) should not effect diffraction efficiency. Wavelength coverage is 350 – 550 nm ($1.9 < z < 3.5$) and resolving power is R=800 at 450 nm. Fig. 3 shows views of the double camera cryostat conceptual design.

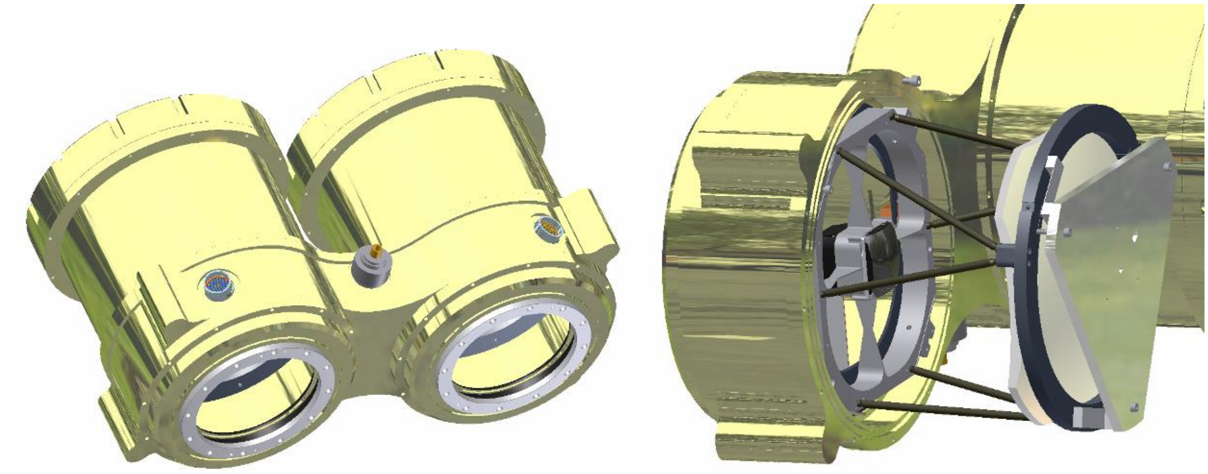

Figure 3: cryostat concept for double camera. The cryostat consists of three castings. Connectors for two CCD controllers and the cryogenic bayonet connection are shown on the kidney-shaped casting that supports the precision parts of the assembly. The two cylindrical covers are vacuum vessels and play no part in the optical alignment. On the right is a view with one cover removed, showing the detector head spider assembly and the mirror adjuster assembly. These components are tied together with an invar truss and the intent is to pre-align this assembly to reduce setup time.

5.2 Detector System

Engineering work is focusing currently on the detector head where careful design of the chip carrier and mounting of the field flattener is required to reduce complexity over the prototype design. The main detector system requirements are low read noise (3 electrons) at a fixed readout rate of 100-200 kpxl/sec, coupled with low unit cost. The CCD format of 2k x 2k with 15 μm pixels is available from several manufacturers, and we expect to develop the final packaging as part of non-recurring engineering with the selected vendor. The baseline plan for the controller is to simplify and adapt the McDonald Version 2 controller to run the pair of detectors within each cryostat, in collaboration with ARL. The preliminary design is being developed with emphasis on simplification and reduction of component count to minimize the number of boards. The architecture will have two modules, each with a preamplifier/analog board, mounted to the cryostat, and a third module with the digital signal processing, clock driver and power for both channels. We are also exploring purchasing an integrated detector and controller system and are in discussions with vendors on this possibility.

5.3 Fiber Integral Field Unit Development

IFU development at AIP and UT has focused on establishing a design that minimizes FRD, maximizes throughput, and is manufacturable in quantity. Detailed testing[37,38] shows that for the fast f/3.65 focal ratio of the HET WFC, FRD is minimal. The optics of VIRUS can accommodate an f/ratio of f/3.35, allowing a degree of focal ratio degradation. Testing of fibers from Polymicro (FB200220240), FiberTech (AS200220UVPI), and CeramOptec (UV200/220P) shows that this f-ratio accepts over 95% of the light input at f/3.65. Additionally, the effectiveness of immersing the fiber ends against cover plates in healing residual polishing roughness has been clearly demonstrated in our tests. The uniformity of the throughput from fiber to fiber is at the 5% level, and the efficiency closely matches the prediction based on fiber internal transmission and AR coatings applied to the cover plates, at 92% in the green[37]. This exceeds the throughput requirement for the IFUs, allowing there to be some variation within batches for manufacture. As expected, there is not a great difference between fibers from different manufacturers.

As part of this development, we have identified a number of manufacturers with the capability to manufacture the fiber cables for VIRUS in quantity. These include Frank Optic Products, FiberTech, and CeramOptec. Bundles have been delivered by Frank Optic Products and FiberTech, and another is being manufactured currently by CeramOptec. Figure 6 shows examples of the input and output ends of the IFU and shows how the IFUs will be arrayed at the focus of the upgraded HET.

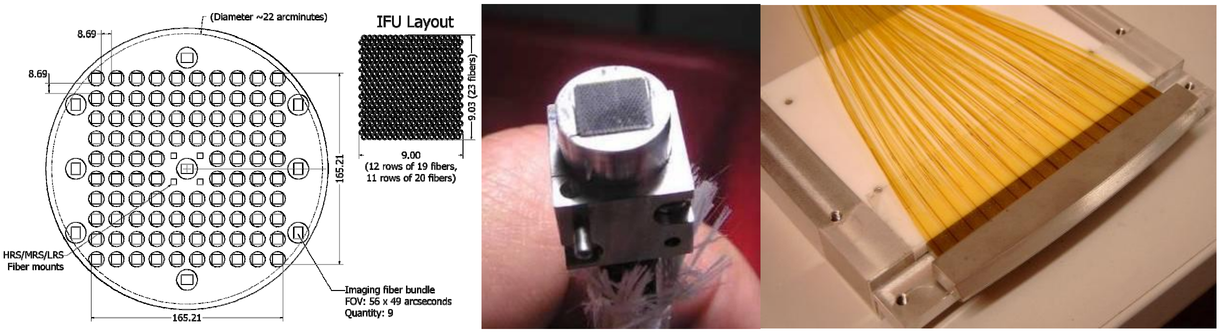

Figure 4. The illustration on the left shows the IFU arrangement at the WFC focal surface for 92 double size IFUs. The layout achieves a ¼ fill factor over a 16x16 sq. arcminute field. The center photograph is a closeup of a VIRUS-P input head which contains 246 fibers. The block of fibers is 5 mm on a side. The photograph on the right illustrates how the fibers are "fanned out" into a linear array at a VIRUS-P output head.

5.4 Grating Development

We have undertaken development of volume phase holographic (VPH) gratings including the construction of an automatic test facility to characterize samples and full size gratings[39]. Samples and full size gratings have been procured from Wasatch Photonics and Kaiser Optical Systems International (KOSI). Performance approaching the theoretical rigorous coupled-wave analysis prediction for the holographic layer has been demonstrated, and cost estimates provided for volume production. Gratings are a long-lead time item, and procurement will commence soon.

5.5 Cryogenic System

The distributed layout of the VIRUS array presents a significant challenge for the cryogenic design[40]. Allowing 5 W heat load for each detector, with all losses accounted for and a 50% margin, the cooling source is required to deliver 3,600W of cooling power. We have engaged Applied Cryogenics Technology to evaluate the options and provide an initial design. Following a trade off between cryocoolers, small pulse-tubes and liquid nitrogen based systems, it is clear that from a reliability and cost point of view liquid nitrogen is the best choice[40]. The problem of distributing the coolant to the distributed suite of spectrographs is overcome with a gravity siphon system fed by a large external dewar. A trade off between in-situ generation of the LN_2 in an on-site liquefaction plant, and delivery by tanker has been made, with the result that the delivery option is both cheaper and more reliable. The 11,000 gallon holding dewar would have in excess of 4 weeks operation capacity, and would be refilled every 2 weeks.

An interesting aspect of the cryogenic design is the requirement to be able remove a camera cryostat from the system for service, without impacting the other units. This is particularly difficult in a liquid distribution system. A system has been developed that combines a standard flexible stainless steel vacuum jacketed line (SuperFlex) to a standard cryogenic bayonet incorporating custom copper thermal connector contacts into each side of the bayonet. When the bayonet halves are brought together they close the thermal contact. The resulting system is completely closed, i.e., it is externally dry with no liquid nitrogen exposure. The camera end of the connector is connected by a copper cold finger to the detector. Sizing of the flexible tube is set to prevent film boiling (where connection between the liquid and the cooled surface is broken due to boiling to gas in a sheet), and remain in the nucleate boiling regime. The heat load to surface area required for nucleate boiling are well understood and for our 10W load for the camera pair ~15cm^2 of contact surface is required to ensure that the system is not permanently in the film boiling regime. Assessing the power limits to maintain and reach nucleate boiling will be the subject of early prototyping. This design has another desirable feature. In normal operation the SuperFlex tube slopes downwards and the bayonet is oriented vertically. Liquid evaporation will flow monotonically up in order to avoid a vapor lock. If the bayonet is unscrewed and raised upwards, a vapor lock will occur and the bayonet will be cut off from the cooling capacity of the liquid nitrogen. This effectively acts as a "gravity switch", which passively turns off cooling to that camera position. Development of this design will proceed from prototyping of the bayonet connection to a full test setup for ten VIRUS units.

5.6 Location of VIRUS

The science drivers for VIRUS require high throughput at λ > 350 nm. This argues for minimizing the length of fiber in the integral field units. Initially, locations around the top hexagon of the HET structure were explored, resulting in a minimum fiber length of 15 m. The location for this length is shown in the right hand panel of figure 5. A fiber handling concept was refined by CEM resulting in the "cricket legs" shown in the figure[41]. Models linking instrument performance to sensitivity and predicted number of LAEs detected in the HETDEX survey allows a trade-off between fiber length, cost, and survey requirements. Analysis of the structure required to support the VIRUS instruments (total weight 30,000 kg) indicates that there is significant expense associated with the high location, and we have undertaken a trade-off between performance and location of VIRUS, with the result that we have chosen a lower location for the VIRUS enclosures with a 20 m average length of IFU fiber, shown in the left panel of Fig. 5. The impact on throughput at the blue limit of VIRUS is about a factor of 0.94, and the total number of LAEs detected by the HETDEX survey falls from 0.8 to 0.75 million. This small shortfall can be made up with ten more spectrographs or about ten more nights observing. This trade is close to being finalized and it is likely that the lower location will be chosen, since installation and maintenance of the VIRUS units will also be simplified.

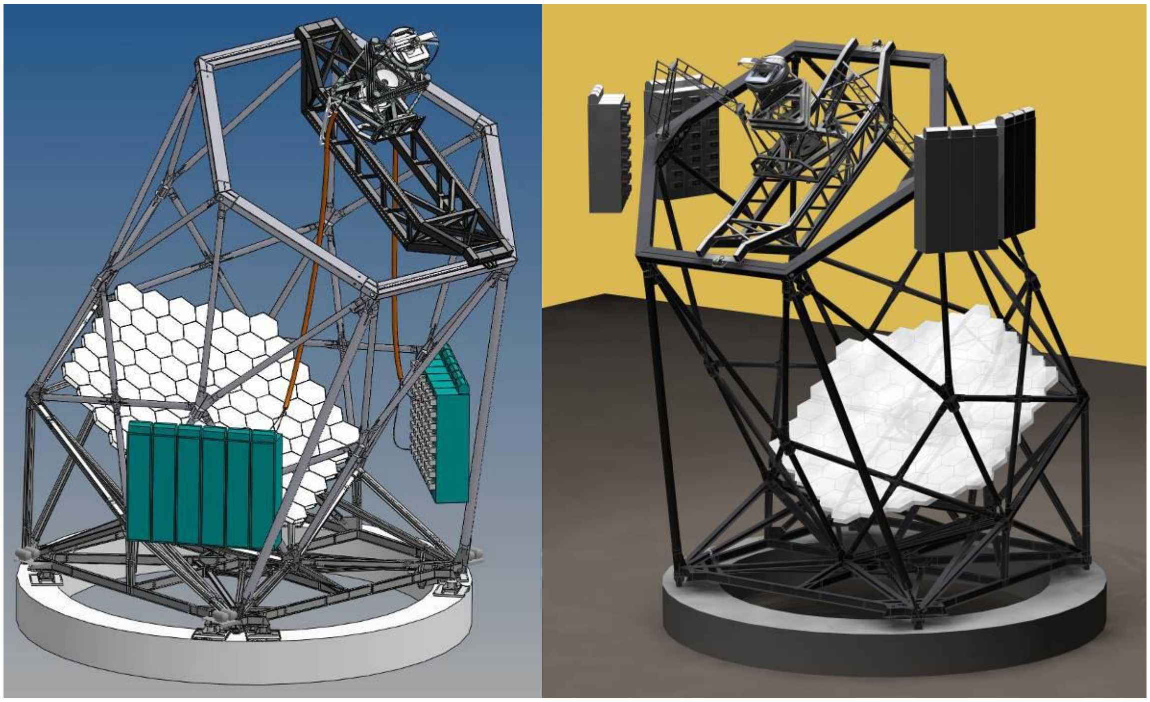

Figure 5: Two views of the VIRUS spectrographs mounted in 12 environmentally sealed enclosures and located at alternative positions on the telescope structure. The left hand configuration has 20 m long fibers and keeps the weight of VIRUS low on the structure. The right hand configuration minimizes the fiber length to 15 m, supporting the IFUs via articulated legs which move with the PFIP as it tracks across the sky. Support structure for the VIRUS units is not shown, but is quite significant for the right hand configuration. In each figure, the tracker is shown at one of the extreme ends of its travel limits.

6. SUMMARY AND STATUS

The HET is in routine operations achieving high observing efficiency with its three facility instruments. We continue to work on improving the efficiency and image quality of the telescope. The HET Wide Field Upgrade will reinvent the telescope as a premier wide field survey facility and, with the VIRUS integral field spectrograph, will enable the HETDEX project. Metrology systems in the WFU will provide closed-loop control of all degrees of freedom to ensure the best possible image quality and a new control system will offer improved operational efficiency.

The combination of the HET WFU and VIRUS will create an unparalleled facility for blind spectroscopic surveys. Objects that would not normally be targeted such as those dominated by emission lines will be selected directly by spectroscopy. VIRUS probes the interesting $2 < z < 4$ epoch when star formation and nuclear activity in galaxies peaked, and will provide the ability to probe the large-scale structure of the universe at that epoch. The HETDEX survey will contain significant numbers of interesting objects such as metal-poor stars, and will be an important resource in astronomy. In comparison with existing facilities, VIRUS on HET will be able to survey an order of magnitude faster, and it is an excellent complement to next generation instruments such as MUSE, which will provide detailed spatially-resolved spectroscopy of small regions of sky to great depth.

The existing HET facility instruments will be adapted to the new wide field corrector and prime focus instrument package. This is a relatively simple upgrade for the HRS and MRS, involving adaptation of the input optics of the spectrographs to the faster focal ratio of the WFC. Indeed the HRS-IU project will specifically adapt the HRS to the upgraded HET. The LRS cannot be maintained as an imaging spectrograph with the upgrade due to the optimization of the corrector for feeding fibers and due to the large rotation angle range demanded of the PFIP in order to set the position angle of the slit on sky. This range cannot be accommodated with the fiber feed for VIRUS. As a baseline the current LRS will be adapted to be fiber fed, but we ultimately intend to replace LRS with a more capable, fiber-optimized instrument fed by integral field units and optimized for the red. The science imaging capability of LRS is rarely used, but will be maintained with an acquisition camera.

HETDEX, consisting of the WFU, VIRUS, and the survey of 420 sq. degrees is about 2/3 funded and procurement of major components for the WFU such as the corrector is underway. We are planning for deployment of the upgrade and VIRUS in about two and a half years from the time of writing.

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