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Gary J. Hill, Phillip J. MacQueen, Povilas Palunas, Matthew D. Shetrone, John A. Booth, "Present and future instrumentation for the Hobby-Eberly Telescope," Proc. SPIE 6269, Ground-based and Airborne Instrumentation for Astronomy, 626907 (27 June 2006); doi: 10.1117/12.672642

Event: SPIE Astronomical Telescopes + Instrumentation, 2006, Orlando, Florida , United States

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 six years. Work over the past two years 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 includes 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 described.

A major upgrade of HET is planned 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).

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

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 $\delta = -10.3^{o}$) and 2.8 hours (in the north at $\delta = +71.6^{o}$). 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)[9,5], and the Medium Resolution Spectrograph (MRS)[10,11,5]. 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

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[8]. 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.

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

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Ground-based and Airborne Instrumentation for Astronomy, edited by Ian S. McLean, Masanori Iye,
Proc. of SPIE Vol. 6269, 626907, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.672642

2. HET UPGRADE PROJECT AND 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]. As such, it is has been a test-bed for engineering and operations concepts designed to minimize cost while maintaining performance. 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, will bring 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 are installing metrology equipment to ensure the best possible alignment of the optics at all times.

In conjunction with image quality improvements at HET, we now have a five-year baseline of site seeing measurements recorded by a Direct Image Motion Monitor. The median zenith seeing has been 1.0 arcsec FWHM with the best images being 0.7 arcsec or better 9% of the time. The summer seeing is better than in winter (0.9 versus 1.3 arcsec). At the 35 degree zenith distance of the HET, this translates to a median of 1.13 arcsec, and minimum of 0.8 arcsec FWHM. 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 aligns the mirror segments to 0.2 arcsec rms (projected on the sky), and alignment now has a negligible effect on the delivered image quality. Operational efficiency has also been improved with the MARS system, with typical restacks taking only about 10 minutes under normal conditions. Once aligned, the segments are held relative to one another with an edge-sensor Segment Alignment Maintenance System (SAMS[17]). SAMS has been in operation since January 2002. SAMS uses inductive sensors, which have sensitivity to temperature, and we found it necessary to calibrate each sensor in order to improve the temperature stability of the system. For temperature changes within +/-1.5 degrees of the temperature at which the PM was aligned, the degradation is now acceptable. For larger temperature excursions, we are forced to realign the PM with MARS. In practice, one to two alignments per night are required, so the overhead is low. 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. GROC was initially controlled by SAMS through a combination of temperature sensing and mirror-gap sensing. Installation of a distance measuring interferometer now allows the position of the center of curvature of the mirror to be set accurately, so GROC is now maintained at each realignment of the mirror with MARS. GROC now has a dispersion of 100 μm, reduced from 400 μm previously.

The mounts of the individual segments have been evaluated, and a new mirror handling fixture aids with their removal from the mirror truss. Extra-focal imaging at the center of curvature with the HET Extra-Focal Imager (HEFI[15]), shows that the more carefully set up mounts have eliminated instances of very poor figures on the segments noted in the last report[5,15]. 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 Corrector Alignment, Mount Model, and New Metrology Systems

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. A trajectory for the tracker is loaded into the tracker control computer from the telescope control computer. This trajectory controls the x-y position of the tracker, and the six hexapod legs and rotation axis that manipulate the payload. In order to track an object accurately, the tracker payload must be maintained on the focal sphere of the spherical primary mirror, and must be pointed accurately perpendicular to it. 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 "mount model" needs to accurately maintain the 4-mirror corrector in the PFIP perpendicular to the PM within 25 seconds of arc, and in focus to within 10 μm. Originally the tracker was actively guided in x, y only, and the other axes ran open-loop. During a track, the PFIP rotates (up to +/-19.4° in the north) to maintain a fixed PA on the sky. The mount model has proven inadequate for maintaining focus or tip/tilt of the corrector, resulting in significant image quality degradation. Tip/tilt of the corrector results in coma. Hartmann testing and the fact that excellent images have been recorded, indicates that the internal alignment of the corrector is acceptable.

In order to overcome the shortcomings of the mount model, we are in the process of enabling closed-loop feedback on the tip/tilt and focus of the tracker with respect to the primary mirror using a distance measuring interferometer (DMI) and a tip-tilt camera (TTCAM). This system was also adopted by the SALT[12], and we have installed[15] a DMI system working at 1.5 μm wavelength manufactured by Fogal, and a custom tip-tilt camera also working at 1.5 μm. The tip-tilt camera is still being commissioned, but the DMI is in regular use and allows the focus to be maintained more accurately than before. It also has a separate arm to the center of curvature tower that enables the focus of MARS to be set automatically. On-sky testing that combined Hartmann mask imaging, direct imaging, and metrology with the DMI and TTCAM, has demonstrated that the alignment of the corrector can be set with sufficient accuracy using the metrology[15]. We expect this system to enter regular use in summer 2006.

Ultimately we wish to move to a wavefront sensor feedback for the alignment of the tracker since this deals directly with what we care about. We will prototype such a system with the current corrector, but its application will be severely limited for most science by the limited field of view. We are planning to upgrade the HET with a much wider field corrector, and this upgrade is driven significantly by the need for bright wavefront sensing stars within the field of view for all observations.

2.3 Dome Environment and Seeing

Dome seeing was a major component of the poor image quality delivered initially by HET[4,5]. The original ventilation concept used a down-draft fan system similar to that on the Keck telescopes to draw ambient air in through the dome aperture. The system proved inadequate to the task of flushing the dome under typical conditions encountered in West Texas. It became obvious that significant perforations of the HET enclosure would be required to prevent stagnant air conditions. The Dome Ventilation System consists of a series of 15 louver panels modeled after those on the Mayall 4 m at KPNO. The louvers were installed in 2002, and the image quality was seen to steadily improve during installation[2,4].

Significant remaining heat sources on the tracker have been eliminated by ducting the heat away, and the pupil of the telescope no longer shows any local sources of convection. However, inspection of Hartmann test images obtained at prime focus and occasionally at the center of curvature with HEFI shows periods with large coherent displacements of the images of segments, indicating significant dome seeing. Until the alignment of the telescope can be removed from the image quality equation by the metrology systems currently under commissioning, it will be difficult to disentangle the seeing component. A systematic evaluation of seeing will be undertaken once the metrology system is properly commissioned, and on-tracker wavefront sensing is available.

2.4 Throughput of the HET

The HET optical design includes five reflections to reach prime focus (six to reach the LRS). Denton Vacuum FSS-99™ enhanced silver was chosen, initially, which has high reflectivity at wavelengths above 400 nm, and is better than bare aluminum for $\lambda > 380$ nm. Accounting for central obstruction, the pellicle guider, and the atmosphere, the predicted on-axis efficiency was 54% at 600 nm for prime focus and 52% for the light delivered to the LRS. We encountered significant degradation of these coatings in practice, and Denton Vacuum re-coated the corrector mirrors in mid-2000. The mirrors continued to degrade, so the corrector mirrors were recoated in 2003 with a high durability broad-bandpass LLNL reflective coating[18]. By 2003, the primary mirror segment coatings had degraded to ~45% reflectivity at V. As a result, the on-sky throughput of the HET was about 25% at prime focus[5]. In addition, the coatings were scattering significantly, and the background measured during dark time was almost a magnitude brighter than recorded at the other telescopes at McDonald. This scattered light was in the pupil of the HET and could not be baffled. The combination of low reflectivity and high scattering was degrading the performance of the telescope by a magnitude in sensitivity for background-limited observations. Since the last report[5] we have recoated the majority (95%) of the segments with bare aluminum, and expect to complete the process in June 2006. The new coatings on the primary mirror and corrector result in a throughput 80% of the original design with pristine FSS-99 coatings. Below we discuss the effect this has had on throughput measured by the Low Resolution Spectrograph. In the longer term we are evaluating more durable commercial coatings for the primary, and expect to initiate a new round of recoating shortly. A key contributor to the degradation of the original mirror coatings was dust, and we now have the ability to clean the mirror in about 20 minutes with dry ice. We have installed a dry ice plant and now clean the primary mirror at least three times per week, and can respond immediately if there is a high dust event. With no mirror cover and a fixed elevation, it is crucial to keep the HET mirror very clean, and to react to incidents that contaminate the coatings.

3. THE FACILITY INSTRUMENTS

The HET is making queue-scheduled observations with its full compliment of facility instruments: the Marcario Low Resolution Spectrograph (LRS), the High Resolution Spectrograph (HRS), and the Medium Resolution Spectrograph (MRS). 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[5].

3.1 The Marcario Low Resolution Spectrograph

The LRS[6-8] 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 now 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 1 covers more than one octave of wavelength, and is used with blocking filters GG385, OG515, or OG590 depending on which part of the wavelength range is needed. Grism 2 is also used with the GG385 blocking filter since the LRS has sensitivity down to 360 nm. For higher dispersion and efficiency in the red, we have added a new first-order grism (grism G3) based on a volume phase holographic grating (VPHG)[20]. The wavelength coverage is 630 to 900 nm at R~2000 in first order. This grating has 700 fringes per mm and is used at a Bragg angle of 11.5 degrees. This angle of incidence (and diffraction) is achieved by sandwiching the grating between two identical prisms of SF57 with AR coated outer faces. The throughput with this grism at 700 nm equals the peak with grism 1 at 550 nm.

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. The grism has a 316 l/mm 63.5 degree blaze Richardson Grating Lab (now Newport Spectra-Physics) grating replicated on the hypotenuse of a large BaK2 prism. The prism is cylindrical in cross-section with 160 mm diameter and 270 mm height. This grism is typically used with the 1 arcsecond wide slit to measure the dynamics at large radii in galaxies. LRS is very competitive for such observations, having a higher resolving power for a given slit width than other low resolution spectrographs, by virtue of its large 142 mm diameter pupil.

The LRS mounts in a restricted space, as part of the PFIP, which rides on the HET tracker. The principal consequence of the tight space and weight constraints is to limit the range of configurations (grisms) that may be carried by the LRS at any one time. The HET is queue-scheduled, so the limited configurations are factored into the queue-selection of projects executable on any given night. The addition of the two new high dispersion grisms to the compliment for LRS has led to some scheduling issues, however, as these have enabled several high priority programs, and there have been instances where completion of programs has been hampered by the grism mounting schedule. This situation is unfortunately unavoidable with the restrictions placed on the LRS design.

As the primary has been aluminized, the performance of LRS has improved markedly, particularly for background limited observations of faint objects, where the combination of poor reflectivity and high scattering of the degraded coatings was costing a magnitude of sensitivity. The main improvement in performance of LRS has come from the recoating of the HET primary mirror and corrector mirrors. The failed coatings on the primary mirror in particular had very low reflectivity and high scattering. As the primary mirror segments have been recoated with bare aluminum there has been a steady improvement in throughput and background as well. Figure 1 shows the throughput measured for the HET+LRS with G1 and GG385 blocking filter at 600 nm over the past 5 years. Throughput is defined relative to an area of 9.2 m diameter with a 3.713 m linear obstruction, above the Earth's atmosphere, and ignores slit losses by using a 10 arcsec. wide slit. The trends seen in this figure are dominated by the degradation of the primary mirror coatings between early 2000 and mid 2003 and the subsequent improvement in the primary mirror reflectivity due to the recoating of segments with bare Al. At the last point shown on this graph the primary was 65% recoated, and it is now 95% recoated. Comparison of features in the plot with events relating to the LRS (complete refurbishment of LRS and replacement of the CCD between August and October 2001, or replacement of the failed GG385 filter in March 2003, for example), reveal no significant changes in throughput at this wavelength. The failed GG385 filter did cause the shape of the throughput curve to change at bluer wavelengths, however. The most significant event was the replacement in August 2003 of the coatings on the four mirrors of the corrector and on the three mirrors associated with the LRS (two fold flats and the camera spherical mirror). There was not a significant change in throughput at this time. This is because the LLNL coating[18] has 96% reflectivity at 600 nm, resulting in little net change in throughput relative to the less degraded FSS-99 coatings on the corrector and the still pristine coatings inside the LRS. The new primary mirror and corrector coatings result in a throughput 80% of the value with pristine FSS-99 coatings in 1999. This correction factor accounts for most of the remaining difference in throughput (10% versus 12%) between 1999 and the present.

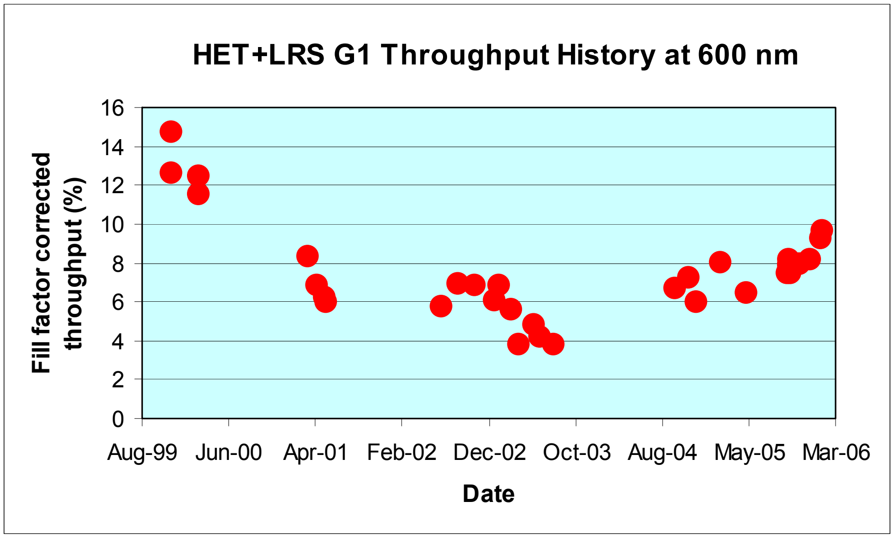

Figure 1: Throughput measured for the HET plus the LRS with grism G1 at 600 nm as a function of time. Variations are mainly attributable to degradation of the primary mirror and corrector mirror coatings, followed by an improvement since mid 2003 as these coatings have been replaced. The difference between the 10% recorded recently and the 12% recorded in 1999 is accounted for by the change in coatings (see text).

Concurrent with the improvement in throughput since 2003, the measured background in the V band has decreased markedly, again because of the replacement of the failed primary mirror coatings. Measurements of sky in globular cluster standard star fields shows a decrease in V sky brightness from 20.6 to 21.5 mag per sq. arcsec. The best images recorded during setup observations with the LRS have had 1.0 arcsec FWHM (without intensive adjustment of the corrector orientation for best image quality). The median images are ~1.5 arcsec FWHM, however, so control of the tracking as discussed above should result in significant further improvement in the sensitivity of LRS.

These improvements have led to success in observing difficult targets. An example is the observation of the central cD galaxy NGC 6166 of the Abell 2199 cluster[21], where the extremely low surface brightness outer envelope of the galaxy has been traced to 2 arcminute radius, sufficient to detect the increase of the stellar velocity dispersion to match that of the galaxies in the cluster, for the first time. This observation reaches significantly further out in the envelope of this galaxy than data taken previously with Keck LRIS, with similar exposure times.

Another notable science result is the observation and typing of 70 supernovae from the Sloan Digital Sky Survey – II survey. These were observed during the Fall 2005 trimester, and benefited greatly from the improved image quality, throughput, and background of the telescope. The median 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. Figure 2 shows the redshift distribution of the supernovae for the entire SDSS-II Fall 2005

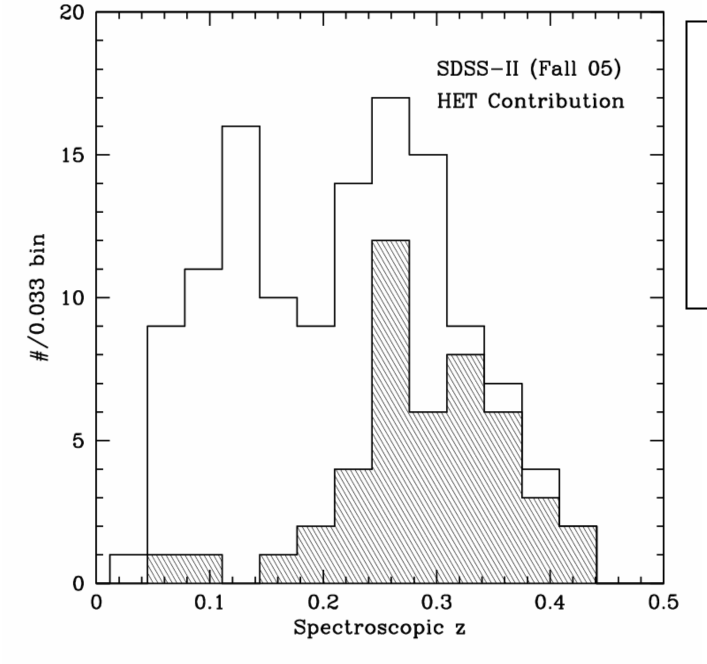

Figure 2: Redshift distribution of supernovae discovered by the SDSS-II survey during the Fall 2005 campaign, with the 70 confirmed by HET highlighted. The median magnitude of the supernovae was r= 21.5 with the faintest being r=22.5. All were observed with 2x1200 s exposures, the majority within 24 hours of discovery.

campaign and the contribution of the majority of the high redshift objects by the HET. This project is ideally suited to the HET since the SDSS-II survey targets a long strip, at constant declination.

3.2 The Medium Resolution Spectrograph

The HET Medium Resolution Spectrograph (MRS)[10,11,5] is a versatile, fiber-fed echelle spectrograph. This instrument is designed for a wide range of scientific investigations and includes single-fiber inputs for the study of point-like sources, synthetic slits of fibers for long slit spectroscopy, six independently positionable probes for single or multi-object spectroscopy, and the potential for a fiber integral field unit (IFU). The MRS consists of 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 started commissioning in summer 2002, and now has the visible beam with single object mode in regular use. Of the many potential modes of MRS, only the direct feed (DF) with 1.5 and 2 arcsec diameter fibers is commissioned, currently. The image quality of the optical system meets specifications over the entire wavelength range, and the stability of the instrument is good. The instrument was described in more detail in the last review[5].

The throughput of MRS has been measured under varying conditions of seeing against bright stars and also estimated from planetary nebula emission lines with known line fluxes. These measures indicate that with 1.5 arcsec. FWHM image quality, the MRS with 1.5 arcsec diameter fibers gives a peak throughput of ~5%, including the fiber insertion losses. The faintest objects so far observed with MRS have been 18th magnitude.

3.3 The High Resolution Spectrograph

The HET High Resolution Spectrograph (HRS) has been described by Tull[9], and in a previous review[5]. It is a fiber-fed, grating cross-dispersed echelle spectrometer that uses Barranne's white-pupil concept as adapted for ESO's VLT UVES by Delabre and Dekker. A refractive camera avoids a central obstruction but limits the bandwidth to 410 nm – 1.05 μm. Light is fed from the HET with either 2 or 3 arcsecond fibers, and the choice of 0, 1, or 2 sky fibers. Resolving powers of 15,000, 30,000, 60,000, and 120,000 are available via a choice of 4 different widths, and the number of sky fibers passed by a given slit is determined by its length. Two cross dispersers are available, each being kinematically mountable at any one of 10 different angles of incidence. The 316 groove mm^{-1} grating gives 400 nm of coverage, with the central wavelength changing in 100 nm steps. The 600 groove mm^{-1} grating gives 200 nm of coverage, with the central wavelength changing in 50 nm steps. An insertable temperature-stabilized I_2 gas absorption cell provides a reference for greatest wavelength accuracy.

The CCD system is a mosaic of two Marconi Applied Technologies (now E2V Technologies) 2048 x 4102, 15 μm pixel CCDs. The CCDs are oriented such that the columns are parallel to the echelle dispersion dimension, so that the 72-pixel gap between the two CCDs takes out approximately one order rather than the center of all the orders. At R=15,000 and R=30,000, the recommended binning corresponds to about 3 pixels per resolution element, at R=60,000 it corresponds to either 2 or 4 pixels per resolution element, and at R=120,000 the only choice is 2 pixels per resolution element. Until now, the one significant issue was the cosmetic quality of the CCD that covered the red part of the spectrum. It has now been replaced with a deep depletion CCD from E2V in an upgrade that was achieved in May during one dark time so as to minimize the impact on the science queue. The detector performs very well, with 2.9 electrons read noise at 100 kpxl/second, and has resulted in a very significant increase in throughput in the red. The CCD has good cosmetics and does not show fringing for wavelengths < 790 nm.

The other upgrade has been replacement of the CryoTiger cryocooler refrigeration system for both the HRS and the LRS. Details of the systems can be found in previous papers[4,5,6]. Oil contamination of the lines due to wear of the compressors caused a reduction in cooling capacity and necessitated refurbishment of the compressors and replacement of the lines and cooling heads. These cryocoolers have been in continual use for 5-6 years, the longest of any systems in astronomy. This experience suggests the need for preventative maintenance and refurbishment of these systems every few years to prevent down-time.

The combination of the responsive queue scheduling of the HET with the stability of the HRS is very effective in the systematic discovery and characterization of extrasolar planets. Examples include the detection of a Neptune mass planet in the ρ 1 Cancri system[22], and a study of the statistics of planets around M dwarfs[23]. The ρ 1 Cancri observations relied on dense queue scheduling that targeted key points in the orbital phase to disentangle the very low mass planet in a system with four known planets. 100 observations were obtained in 180 nights, to reveal what at the time was the lowest mass planet known outside our own Solar System.

4. HET WIDE FIELD UPGRADE AND VIRUS

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 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.

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[24].

HETDEX[25] will map the spatial distribution of about a million Lyα emitting galaxies (LAEs) with redshifts $1.8 < z < 3.7$ over 250 sq. deg. area (5 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[26,27]), a set of 145 IF spectrographs, covering a 22 arcmin. field. The advantage of an IF spectrograph for this project is that the tracer galaxies can be identified and have their redshifts determined in one observation. VIRUS is optimized to survey 340-570 nm over 250 sq. deg., detecting ~1 million LAEs in about 110 nights. 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[23] 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 reproduction as "industrial replication"[29,26,27]. As monolithic instruments on VLTs reach limits of cost and weight, we need to explore industrial replication for the next generation of instruments on VLTs and ELTs[26,29].

Table 1: basic properties of VIRUS

IFU	246 fibers, each 200 μm dia. or 1.0 sq. arcsec. area. Square format 29 x 29 arcsec^2, 1/3 fill-factor, hexagonal pack fed at f/3.65 at prime focus of HET
Collimator	accepts f/3.35, folded reverse-Schmidt reflective design, without corrector
Camera	f/1.33 Schmidt with 2k x 2k 15 μm pxl CCD at internal focus. Aspheric corrector plate and field flattener
Disperser	831 l/mm VPH grating gives 340-570 nm simultaneous coverage at R~850

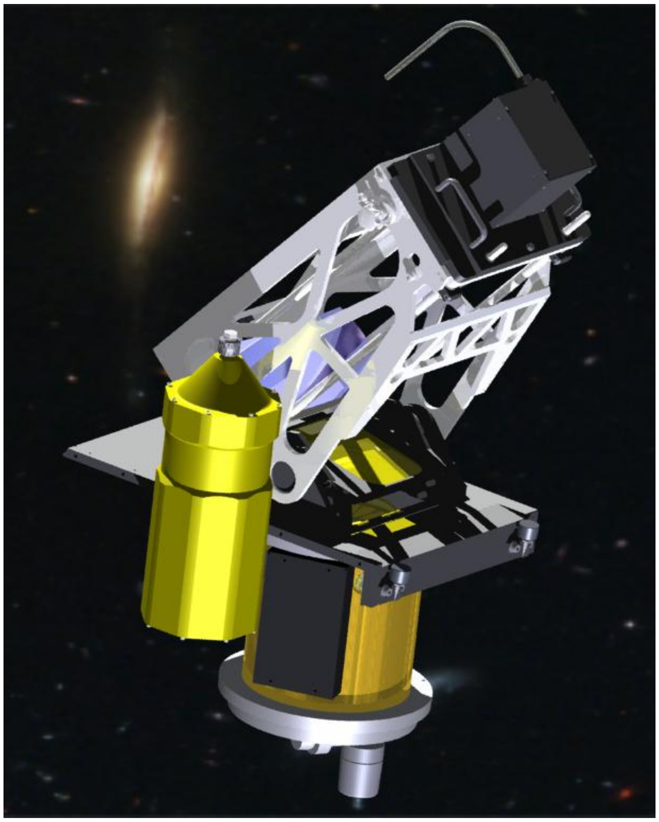

Figure 3: Rendering of the VIRUS prototype unit spectrograph. This design will be simplified further for production of 145 units, but allows testing of all possible modes and prototyping of all components

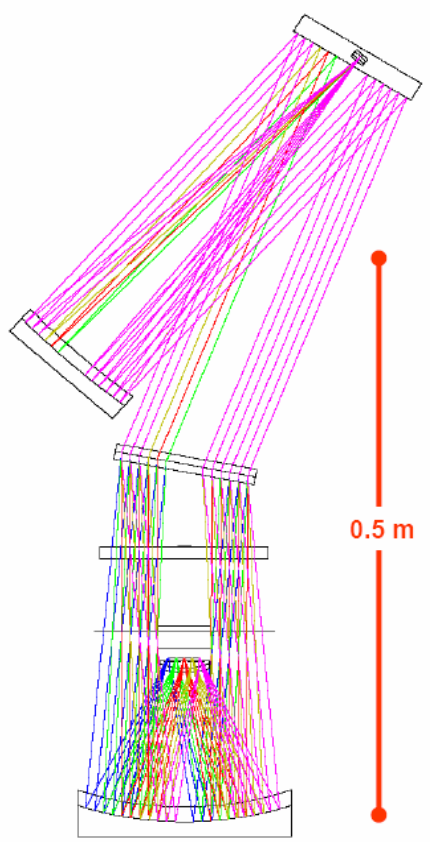

Figure 4: Optical design of VIRUS with three reflective elements, two refractive elements, and a volume phase holographic grating

The VIRUS opto-mechanical design[27] is summarized in Table 1. 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 will use a densepak-type IFU. The layout of the fibers is in a hexagonal pack with a 1/3 fill-factor[24]. This is most optimal for covering area, since a dither-pattern of three exposures exactly fills the field of the IFU, while maximizing the area covered per IFU.

A prototype of the VIRUS unit spectrograph is currently being constructed and will be commissioned this summer. The layout of the instrument is shown in Figure 3, and the optical design in Figure 4. The instrument is described in detail elsewhere in these proceedings[27]. The VIRUS prototype will be used for a pilot survey of Ly-α emitting galaxies in support of the HETDEX project using the McDonald 2.7 m telescope. It will also be mounted on the HET to verify sensitivity limits for the survey.

As part of HETDEX, the HET will be upgraded with a 22-arcmin. diameter field of view corrector, a new tracker, and new metrology systems[3]. The new 4-mirror corrector has much improved image quality, a 10 m pupil diameter, and a 18 arcmin. diameter unvignetted field. The periphery of the field will be used for guiding and wavefront sensing to provide the necessary feedback to keep the telescope correctly aligned. HETDEX demands the largest area coverage, but does not require a high fill-factor for the IFUs within the field[25]. The field of the new HET corrector will be covered by 145 IFUs with ~1/9 fill-factor. This is 35,670 fibers, and >14 million resolution elements per exposure. Each observation of 3 dithered exposures will observe 32 sq. arcmin. area within the 250 sq. arcmin. HET field. Estimates show a line flux limit of 1-2 x 10^{-17} erg/cm^2/s in two 180s exposures per dither position. This observing sequence can be achieved in 20 minutes per field including setup time. It is expected that each exposure will detect 3000 LAEs, many more than are currently known.

5. SUMMARY AND FUTURE WORK

The HET has not yet achieved its specified performance in terms of image quality and throughput, but we have demonstrated that the telescope will meet specifications by delivering 0.8 arcsec. FWHM images for extended periods. Re-coating of the primary mirror with aluminum is almost complete and has resulted in a doubling of throughput and has cut the large scattered light background that was limiting faint observations. Addition of metrology systems is improving delivered image quality. In the longer term, it is evident that for HET to have a strong survey niche, it needs a wider field of view and we have designed a new corrector with a 22 arcmin. diameter field. This will provide a powerful multiplex advantage, and will allow us to use wavefront sensing to keep alignment of the corrector during a track, by providing access to a sufficient number of bright stars. We are also developing the design of a highly multiplexed integral field spectrograph for use with the new corrector, that will be capable of observing 30 sq. arcminutes at a time with 1 sq. arcsec resolution on the sky and coverage from 340-570 nm simultaneously. This instrument is called VIRUS and is described elsewhere in these proceedings[27].

ACKNOWLEDGEMENTS

We thank Roger Romani, John Kormendy, Mark Cornell, Bill Cochran, and Mike Endl for providing details of science results obtained with the HET. We thank Larry Ramsey, Don Schneider, and the HET staff for their contributions to the results presented here. We thank W. Altmann, S. Barnes, S.M. Bauer, C. Goessl, J. Good, F. Grupp, U. Hopp, E. Popow, P. Segura, M. Smith, J.R. Tufts, and G. Wesley for their contributions to the design of VIRUS and the HET wide field upgrade.

The Marcario Low Resolution Spectrograph is a joint project of the Hobby - Eberly Telescope partnership and the Instituto de Astronomía de la Universidad Nacional Autónoma de México (IAUNAM). Construction of the HET HRS was funded by NSF Grant AST-9531674, by supplemental funds under NASA Grant NAGW-1477, and by a legislative appropriation from the State of Texas, further supplemented by McDonald Observatory funds. Construction of HET MRS has also been supported by the NSF.

HETDEX is led by the University of Texas at Austin with participation from the Universitäts-Sternwarte of the Ludwig-Maximilians-Universität München, the Max-Planck-Institut für Extraterrestriche-Physik (MPE), Pennsylvania State University, and the HET consortium. The Astrophysikalisches Institut Potsdam (AIP) has also made important contributions to the VIRUS prototype. HETDEX is funded in part by a gift from Harold C. Simmons, a gift from the George and Cynthia Mitchell Foundation, by AFRL under agreement number FA9451-04-2-0355, and by the Texas Advanced Research Program under grant 003658-0005-2006. Thanks to Representative Henry Bonilla for his support.

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