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Gary J. Hill, Phillip J. MacQueen, Carlos Tejada, Francisco J. Cobos, Povilas Palunas, Karl Gebhardt, Niv Drory, "VIRUS: a massively replicated IFU spectrograph for HET," Proc. SPIE 5492, Ground-based Instrumentation for Astronomy, (30 September 2004); doi: 10.1117/12.552474

Event: SPIE Astronomical Telescopes + Instrumentation, 2004, Glasgow, United Kingdom

VIRUS: a massively-replicated IFU spectrograph for HET

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ABSTRACT

We investigate the role of industrial replication in the construction of the next generation of spectrographs for large telescopes. In this paradigm, a simple base spectrograph unit is replicated to provide multiplex advantage, while the engineering costs are amortized over many copies. We argue that this is a cost-effective approach when compared to traditional spectrograph design, where each instrument is essentially a one-off prototype with heavy expenditure on engineering effort. As an example of massive replication, we present the design of, and the science drivers for, the **V**isible **I**FU **R**eplicable **U**ltra-cheap **S**pectrograph (**VIRUS**). This instrument is made up of 132 individually small and simple spectrographs, each fed by a fiber integral field unit. The total VIRUS-132 instrument covers ~29 sq. arcminutes per observation, providing integral field spectroscopy from 340 to 570 nm, simultaneously, of 32,604 spatial elements, each 1 sq. arcsecond on the sky. VIRUS-132 will be mounted on the 9.2 m Hobby-Eberly Telescope and fed by a new wide-field corrector with a science field in excess of 16.5 arcminutes diameter. VIRUS represents a new approach to spectrograph design, offering the science multiplex advantage of huge sky coverage for an integral field spectrograph, coupled with the engineering multiplex advantage of $>10^2$ spectrographs making up a whole.

Keywords: Astronomical instrumentation: Spectrographs, Integral Field, VIRUS, IFU

1. THE NEED FOR INDUSTRIAL REPLICATION

The traditional astronomical instrument has a monolithic design and is a one-off prototype, where a large fraction of the cost is expended on engineering effort. As telescope size increases, geometric considerations are forcing us to the point where the size and cost of spectrographs for the current generation of very large telescopes (VLTs) is approaching a limit. The physical size of VLT instruments (particularly those mounted at Nasmyth foci) is such that careful design and active correction of flexure is needed to maintain instrument alignment. This complexity is reflected in the \$10M-20M price tags for typical instruments, when engineering costs are fully accounted for.

Adaptive optics (AO) promises to alleviate this situation to some extent by enabling near-diffraction limited images, and is the only way that traditional spectrographs could be mated to the next generation of extremely large telescopes (ELTs), without pushing beyond feasible sizes and costs. In any case, instruments with refractive optics in the meter class are being proposed, which is at or beyond the current state of the art, and which will be very expensive[1]. AO is not, however, the silver bullet that will prevent the cost and complexity of instruments from escalating, because:

- AO is very effective in the near-IR, but practically ineffective at UV and blue wavelengths
- AO may keep the scale size of spectrographs observing single, or a few, objects within a controllable regime, but the number of spatial resolution elements within an interesting field of view is multiplied greatly. Access to the full information content potentially provided by a diffraction-limited ELT will require a new instrument paradigm.

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Ground-based Instrumentation for Astronomy, edited by
Alan F. M. Moorwood, Masanori Iye, Proceedings of SPIE Vol. 5492
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/\$15 · doi: 10.1117/12.552474

Instrumental pupil diameter growth can be mitigated by multiplexing. There are several ways to approach multiplexing, all of which would allow the size of individual spectrographs to be limited:

- Image slicing of a single image or small field of view into a single spectrograph
- Pupil slicing of a single image into single or multiple spectrographs
- Field slicing into multiple spectrographs

All slicing methods require more detector area, but allow instrument scale to be controlled. When compared to monolithic instruments, there are cost savings from creating several copies of a spectrograph to gain multiplex advantage, because the optics are less expensive and the engineering is simplified. The cost of optics increases rapidly when sizes exceed 100-150 mm diameter. Several current instruments use small-scale replication to achieve multiplex advantage. These include the 2dF[2] and SDSS[3] fiber-fed spectrographs, with two copies of each to gain field of view, and the DEIMOS[4] and VIMOS[5] imaging spectrographs with two and four copies of each, respectively, within a single structure. The proposed MUSE instrument[6] for ESO VLT makes the next step by field-slicing into 24 duplicated spectrographs.

Here we make the final step, and explore the design of an instrument that uses industrial-scale replication, which we (arbitrarily) define to be in excess of 100 units. The aim is to outfit the 9.2 m Hobby-Eberly Telescope (HET[7]) with a new wide-field survey capability. HET represents an extreme among current VLTs due to its large pupil size coupled with a site that delivers 1.0 arcsec FWHM median images, exacerbating the instrument pupil-size problem, and making it comparable to a 30 m telescope on a 0.3 arcsec site, from an instrument design point of view. We present the design of a simple, modular integral field spectrograph that is replicated 132 fold, to cover what is a very wide field of view for an integral field. The engineering effort is expended in developing a prototype and designing for minimum cost of manufacture, and we expect the engineering costs to be ~1/10 of the total, rather than >1/2 in the case of a conventional instrument. This savings in engineering effort, coupled with lower unit cost for the optics, allows a powerful instrument to be realized for a significantly lower investment. This concept breaks new ground and appears to be a cost-effective approach to outfitting the coming generation of ELTs, for certain instrument types.

2. THE VIRUS CONCEPT

This paper builds upon the concepts laid out in Hill & MacQueen (2002)[8], where a 64-fold replicated spectrograph was described, fed by deployable integral field units (IFUs) on a 2 m class telescope. They concluded that industrial replication offers significant cost-advantages (roughly a factor of two) when compared to a traditional monolithic spectrograph, particularly in the cost of the optics and engineering effort. Here we apply the concept to the 9.2 m Hobby-Eberly Telescope with the IFUs arrayed in a fixed pattern for wide area surveys.

The **V**isible **I**FU **R**eplicable **U**ltra-cheap **S**pectrograph (**VIRUS**) module consists of a fiber-coupled IFU feeding a single, simple spectrograph. The design and construction of each VIRUS module is well within the state of the art, and industrial replication is used to build many copies of the module to be integrated into a single instrument. The design of the basic VIRUS module has a number of limitations imposed upon it to maximize the cost-to-performance ratio in regard to the science drivers discussed in the next section. In particular:

- Beamsize ~75 mm in order to keep the size of most of the optical components to <100 mm diameter. This minimizes the cost and weight of the optics while providing a beamsize sufficient for the required resolution (R~1000).
- Use of VPH gratings for high efficiency, to maximize reconfiguration options, and to allow detailed customization of the design. Fringe frequencies less than about 1500/mm to maintain a broad bandpass.
- Coverage down to 340 nm in the blue, which dictates use of some more challenging materials such as calcium fluoride. These materials should be limited to smaller elements if possible
- Final f/ratio slower than f/1.3, which simplifies the design while providing suitable sampling of the resolution element, and accepting a sufficiently large number of fibers.
- Small CCD format (~30 mm), but sufficient to achieve the required IFU coverage with fewer than ~150 spectrographs. This choice is also driven by the beamsize limitation.

- Fiber IFU feeds because the Hobby-Eberly Telescope tracker has limited load capacity. The fibers allow the bulk of the mass to be off-loaded, but the length must be limited to 10 meters or less, in order to maintain UV performance.
- An IFU element size of 1 sq. arcsec. per fiber, well-matched to the HET median site seeing of 1 arcsec FWHM.
- High efficiency to minimize the time needed for the survey, and to maximize depth in the limited track times available with the HET for a given observation.
- A total area coverage of ~30 sq. arcminutes per observation with fewer than 150 VIRUS modules.

3. SCIENCE DRIVERS FOR VIRUS

There are numerous science projects that can be pursued with a wide-field integral field spectrograph on a large telescope. In the most general sense, such an instrument would open up the emission-line universe to systematic surveys for the first time, uncovering populations of objects selected by their line emission rather than by their continuum emission properties.

3.1 Attacking the problem of Dark Energy

The discovery that the expansion rate of the Universe in recent epochs is dominated by an unknown dark energy[9] is of profound importance[10]. Understanding the nature of Dark Energy (DE) is arguably the most important question facing Astrophysics today, and several experimental techniques are being developed to attack the problem. DE is only observable through its effect on the evolution of the geometry of the universe, so observations that measure luminosity distance or angular diameter distance can be used to constrain the expansion history of the Universe and hence the equation of state of the DE. Progress on the question of the nature of dark energy requires more information about its properties beyond its mere existence, and major observational projects are planned to trace its effect on the expansion history of the Universe. The SNAP satellite (launch ~2014)[11] is planned to locate ~2000 Type 1a supernovae to z~1.7, and in addition perform a weak lensing survey[12]. The Large Synoptic Survey Telescope[13] will perform a weak-lensing survey of a significant fraction of the sky, as will the Square Kilometer Array[14].

At redshifts larger than z~1.5 tracers such as supernovae and weak lensing become ineffective due to detection issues and crowding. At these redshifts the only suitable tracer of the expansion history is the imprint of the baryonic acoustical oscillations, seen in the CMB[15], on the large-scale distribution of galaxies. The gravitational evolution of large-scale structure (LSS) wipes out the relic of the baryonic acoustical oscillations on progressively larger scales as time passes, to the point where even the first peak is going non-linear at the current epoch. At z~1 the first two peaks are still in the linear regime, and at z>2 all the detectable peaks would be observable. Very large surveys are required to achieve statistics sufficient to provide constraints on DE by this method, but the power of this approach lies in its insensitivity to systematics, and in its simple geometric application. Comparison of the angular scale size of the peaks of the oscillations with the scale size in the redshift dimension provides direct measurement of the angular diameter distance to, and the Hubble constant at, that redshift[16]. The angular diameter distance to the redshift in question integrates over the geometry of the universe back to that redshift, including the effects of any time variability of the equation of state of the DE.

As a driver for the VIRUS spectrograph we consider the large-volume survey of LSS required to detect the relic of the baryonic acoustical peaks at $2 < z < 4$ and constrain the equation of state of the dark energy to better than 10%. In combination with the surveys targeting lower redshifts, this survey will allow us to trace the expansion history of the Universe from the present epoch back to z~4.

3.2 Instrument Requirements

In order to realize a survey of LSS at high redshift covering sufficient volume to measure the relic of the baryonic acoustical peaks in the galaxy power spectrum, a highly multiplexed spectrograph is required. The basic requirement for sufficient statistics is to survey a volume of at least 1 Gpc^3 containing at least 0.5 M galaxies[16]. This translates to an area ~100 sq. degrees with $\Delta z \sim 1$ (~1 Gpc depth at z~2). The volume does not need to be sampled on scale sizes much smaller than the non-linear scale size at the redshift in question. A surface density of only 2000-3000 objects per sq. degree provides sufficient statistics. It is more important to cover volume than to have more tracers, because cosmic variance dominates the statistics on the largest scales[16].

The optimum design of the instrument depends on the tracer. Lyman-break galaxies (LBGs) have been suggested as tracers of LSS at z~3 (refs 16). They are easily found in deep imaging surveys and could be targeted by a multi-fiber spectrograph with very wide field of view (2 sq. degrees or larger) on an 8 m class telescope. The proposed KAOS spectrograph[17] on a new prime focus for one of the Gemini telescopes would meet these requirements, and one of its primary science drivers is to constrain DE in this way. The relatively low surface density of LBGs, ~1 per sq. arcminute, is well suited to a multi-fiber system where crowding is an issue.

Lyman-α emitting galaxies (LAEs) are an alternative tracer of LSS. They have much higher surface density, and have the advantage that obtaining redshifts from emission lines requires significantly less integration time. An integral field spectrograph with the properties outlined in Section 2 would be capable of performing a survey of sufficient volume in a tractable amount of telescope time, and these requirements were applied in outlining the properties of the instrument:

- Wavelength coverage of 340 – 570 nm covers $1.8 < z < 3.7$ in a single exposure, equivalent to a depth of about 2 Gpc. The UV coverage allows the survey to reach a sufficiently low redshift to tie in with future supernova surveys such as SNAP, providing an independent test of systematics in those surveys.
- Lyman-α emitters have a surface density ~20,000 per sq. degree at a line flux limit of ~3e-17 erg/cm^2/s, a level reached in a short (200 s) exposure with an integral field spectrograph with resolving power R~1000 on an 8 m class telescope.
- The optimal number of tracers is ~2000-3000 per square degree, implying a required sampling (fill-factor) of ~1/9. If the spatial scale of this sampling is significantly smaller than the projected non-linear scale size, the incomplete fill-factor will have no effect on the power-spectrum. At z~2, this scale size is ~10 arcminutes.
- The sky area sampled must be ~1 sq. degrees per night in order to realize the survey in 100 nights

The integral field spectrograph capable of completing this survey is a very ambitious instrument, but it can be realized with the VIRUS module and industrial replication. With these requirements in mind we turn to the detailed design of the instrument.

Table 1: Comparison of lenslet-coupled and bare fiber Integral Field Units

	Lenslet-coupled IFU	**Bare fiber IFU**
Pros	contiguous coverage of field	higher throughput because losses at a given f/ratio are lower
	speeds up slow f ratios to minimize FRD	lower precision bundle needed, as not matching pitch of lenslet array
	ideal for retrofitting existing spectrographs	Much lower cost per unit
	for HET it is ideal to image the varying pupil onto the fiber to benefit from azimuthal scrambling	
Cons	diffraction losses and poor figure at the edges of lenslets lead to significant losses	requires fast input f ratio or fast re-imaging optics to avoid FRD. This is OK for the HET
	good coupling requires the micropupil image to be undersized with respect to fiber core, so must choose loss of resolution or of light	requires rastering of images to achieve filled coverage of PSF
	requires more expensive high precision bundle to avoid pitch-error build-up	Non-contiguous coverage less suited to observing resolved objects

4. DESIGN OF VIRUS

4.1 Integral Field Units

The HET tracker carries the spherical aberration corrector, positioning it with a hexapod system. This hexapod would be unable to support the weight of a large prime-focus spectrograph utilizing coherent image slicers, so fiber-coupled IFUs are required. Fiber IFUs can utilize microlens arrays, providing close to 100% fill-factor[18], or be of the simpler "densepak" type[19]. The pros and cons of each type are summarized in table 1. For VIRUS we have elected to use the densepak type of bare fiber bundle to maximize throughput and minimize cost. The primary advantage of lenslets is in coupling the slower f/ratios of typical foci to the fast ratio required to minimize focal ratio degradation[20], and such IFUs are ideal for retro-fitting existing spectrographs. Lenslets do not provide perfect images, however, so if there is flexibility to choose the input f/ratio to the fibers and if the fill-factor can be tolerated, trading it against total area, the bare bundle provides the best efficiency. We choose a fill factor of 1/3 and elect to dither the IFU arrays as shown in Figure 1. Note that if the f/ratio of the microlens case is the same as the f/ratio from the telescope in the bare-fiber case, and the lenslets subtend the same area on the sky as the bare fibers, then the fill-factor of the densepak type array is exactly offset by the larger area that the bundle covers per exposure. So in the case where maximum areal coverage is required, the bare bundle is the preferred solution[21].

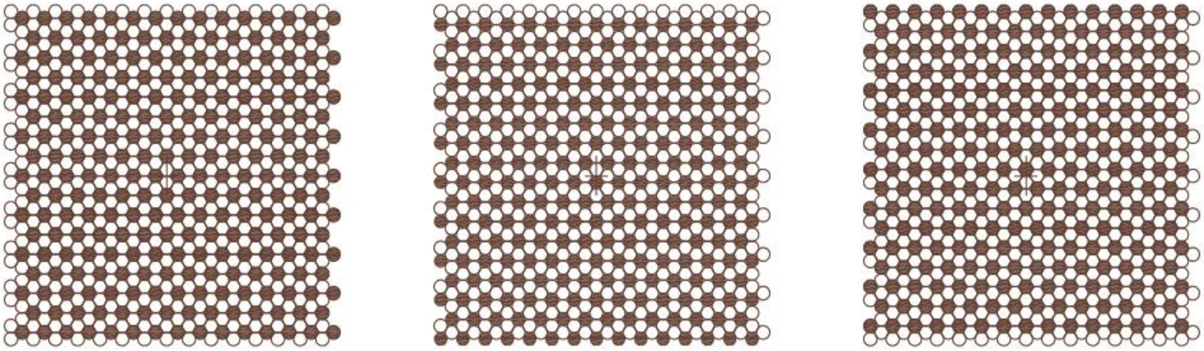

Figure 1: The basic VIRUS IFU consisting of 247 fibers with a 1/3 fill-factor. Each fiber (shown shaded) covers 1.0 sq. arcsec., and the bundle has dimension 29 x 29 sq. arcsec. The three panels illustrate the three-position raster pattern required to fill in the field. A typical observation would repeat the raster pattern a second time, offset by half a fiber diameter in order to provide better sampling of the telescope point-spread function.

The HET site has a median seeing of 1.0 arcsec. FWHM, and we adopt 1 sq. arcsec. per fiber as an optimal compromise between sensitivity and area coverage. The base IFU has 247 fibers in a hexagonal packing pattern with a 1/3 fill factor, as illustrated in Fig. 1. The current HET corrector is f/4.65, but the future wide-field corrector is likely to be faster, with ~f/4. At this f ratio a 200 μm core fiber has the desired 1 sq. arcsec. area. The 1/3 fill factor would require a spacing of 333 μm, but typical hard polyimide buffer diameters would have ~240 μm diameter. The desired spacing can be achieved by using a matrix of metal or glass tubing to establish the grid. One option would be to use capillary tubing with tightly controlled ID and OD bonded into a hexagonal packing pattern, with the optical fiber inserted into the tubes and then glued with a low expansion epoxy[†]. The fiber bundle will be immersed to an AR coated faceplate to minimize coupling losses. The optimal packing factor is still under investigation with simulations, and we intend to manufacture test bundles with various packing methods to investigate this aspect of the design.

Figure 2 illustrates the layout of 132 of these bundles in the future HET focal plane. The basic unit is arrayed with a 1/9 fill-factor, since the DE science driver requires coverage of maximum area rather than maximum fill-factor. Most surveys are not compromised by such a sparse sampling, and the engineering of such an array is simplified by having

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[†] This solution suggested by Gary Nelson at Polymicro Technologies Inc.

adequate space around each IFU for access. The central block of IFUs would be in the form of a monolithic bundle, feeding 16 spectrographs, covering 3.5 sq. arcminutes. We added this block to allow the most efficient observation of resolved objects, such as galaxies, in order to enable flexibility in the science application of the instrument.

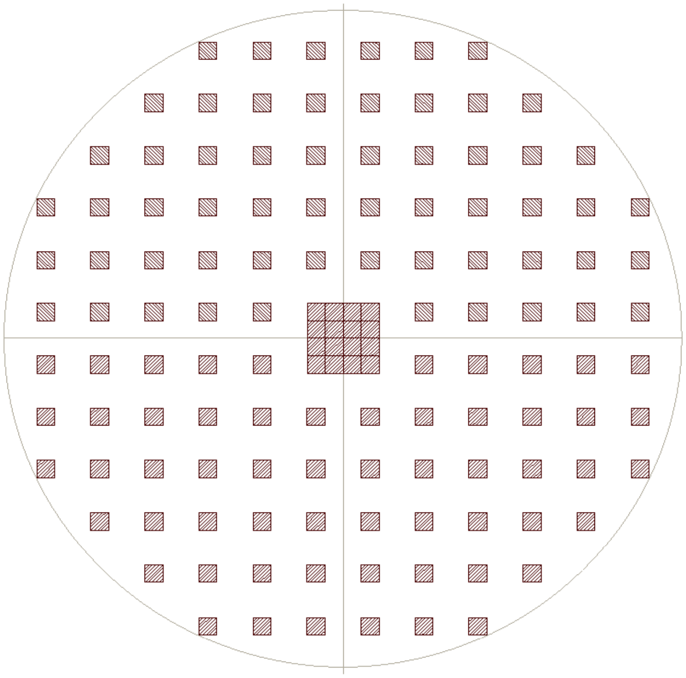

Figure 2: The layout of IFUs for VIRUS-132. Each IFU has size 29x29 arcsec.^{2}. The fill-factor of the basic layout is 1/9 within a field diameter of 16.5 arcminutes. An observation of three exposures as illustrated in Fig. 1 would cover a total area of 29 sq. arcminutes within the field of view of 214 sq. arcmin. The central block is a single densepack covering 3.5 sq. arcminutes

4.2 Spectrograph Module

The spectrograph has a beam size of 75 mm and the layout is shown in Fig. 3. A guiding rule in the development of this design was to avoid large elements (>120 mm diameter) which would drive up the total cost, significantly. The collimator is a catadioptric system with a spherical mirror and an aspheric corrector plate. It accepts an f/4 beam, which is likely to be the f ratio of the new HET corrector. It will be sized following investigation of FRD in test fiber bundles. Systems with all spherical optics are also being investigated that have a refractive corrector doublet. Such systems provide better control of the pupil position. The fibers are arranged into a pseudo-slit at the input to the spectrograph and bonded to the planar face of a lens. This element is primarily to improve coupling, but has power, which helps in placement of the pupil.

The refractive camera has an f ratio of f/1.35. The preliminary design uses two calcium fluoride elements, but their size is not large enough to drive the cost up significantly. Further refinement of the design will aim at optimizing performance at the bluest wavelengths, and designing for ease of manufacture.

The dispersing element is a volume phase holographic (VPH) grating[22] with 1200 l/mm. Optimization[23] suggests a peak efficiency of 85% and broad bandpass are achievable with efficiency >70% over the full 340-570 nm wavelength range covered in a single exposure. The use of a VPH grating allows higher dispersion and hence higher resolving power for a given beam size, and allows the grating to be customized to the application. There is the added advantage of tunability of wavelength range by changing the angle of incidence. In VIRUS this will be achieved by varying the collimator angle. Reconfiguration of the spectrographs will be manual, since VIRUS is intended to be a survey instrument, but the use of VPH gratings allows the instrument to attack a range of astrophysical problems. The maximum resolving power achievable with the configuration described here is R~3000.

4.3 Detector System

Larger format detectors would accommodate more fibers per spectrograph, but require significantly larger optics to illuminate them. Smaller CCD detectors have higher yields, but this advantage is offset by the increased packaging costs, and the cost per pixel is not significantly lower for smaller-format CCDs. As a result, the cost advantage of small optics dominates the trade-off in instrument design. The desire to keep optical elements smaller than ~120 mm diameter led to the beamsize of 75 mm and a maximum detector size of ~30 mm square. In this size, CCDs with 2048x2048 format and 15 μm or 13.5 μm pixels (E2V and others) are available. With the final f/1.35 f/ratio, the effective plate scale is 16.6 "/mm for the HET pupil size of 9.2 m, or 0.22 arcsec. per 13.5 μm pixel, ignoring any FRD, which is expected to be small. The 1.1 arcsec diameter fiber projects to 5.0 13.5 μm pixels, in a perfect system. The low read-noise achievable with the E2V CCDs is significant in the UV given the short integrations likely to be used (Section 5).

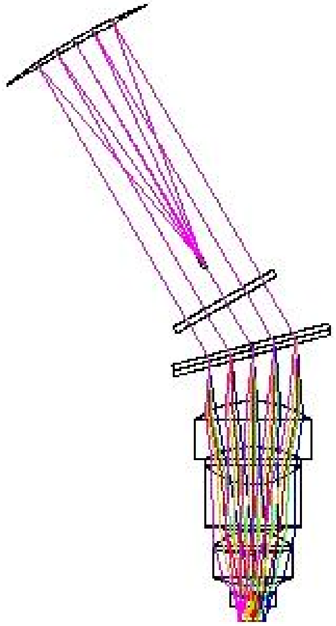

Figure 3: Optical design of the VIRUS spectrograph module. The standard setup is shown on the left, covering 340 – 570 nm at R=800. The linear fiber input is arrayed out of the page.

The fiber resolution element is reimaged to 5 pixels. At 8 pixel spacing between fibers, the 247 fibers of the IFU can be accommodated on the detector. The E2V detector can record 410 spectral resolution elements for each fiber, so each spectrograph surveys 247x410=101,270 spectral*spatial resolution elements per exposure. The full VIRUS-132 records 13.4 million resolution elements simultaneously. This is larger than any spectrograph in current use.

A system with 132 CCDs requires a highly parallelized readout in order to avoid unacceptable overheads. The VIRUS configuration lends itself to a modularized controller design. We intend to reconfigure the McDonald Observatory Version 2 CCD controller, simplifying it to a single mode, and laying out boards to simplify assembly, including machine assembly of many components. At 100 kpxl/sec readout rate, this controller should provide a read-noise of 2.7 electrons or less with the E2V detector, and a read-time of ~10 seconds per channel, binned 2x2.

4.4 VIRUS-132 on the Hobby-Eberly Telescope

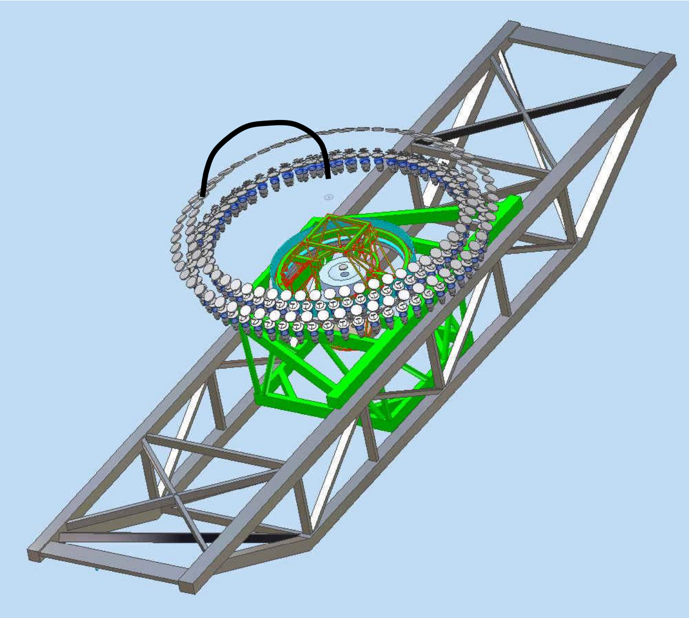

Figure 4: Conception of VIRUS-132 on the HET tracker beam. The spectrographs are arrayed within a diameter of 3.2m, which lies within the central obstruction of the corrector. The mass of the instrument would be borne by the tracker carriage (shown in green) rather than on the fully actuated central corrector payload, and would co-rotate with the corrector payload. This position would minimize the fiber length at about 3 meters. The alternative location would be at either end of the tracker beam, with a fiber length of about 10 meters. That location would allow the maximum mass to be carried, and may be the most practical choice.

The HET is a revolutionary 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 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°. A 4-mirror Gregorian-type corrector delivers a 4-arcminute diameter science field of view. It is positioned by a tracker with X-Y axes and a rotation stage and hexapod system to keep the corrector positioned normal to the primary and in focus. HET has been realized for ~$18M. Detailed descriptions of the HET and its commissioning can be found in references contained in ref 7. The scientific strengths of the HET design lie in large surveys and in synoptic observations, since the design demands queue scheduling to be effective.

The HET site delivers 1.0 arcsec FWHM median seeing, and we have demonstrated science performance with site-seeing limited images. The relatively small field of view of the current corrector is uncompetitive going forward, however, particularly for the survey niche, and we plan to outfit the telescope with a new wide field (20 arcmin. diameter) corrector and instrument payload on a timeframe of 3-5 years. The HET mirror coatings are being renewed to provide durability and coverage into the UV. The primary is being recoated with aluminum, and the corrector now has a high durability coating from LLNL[24]. UV coverage is crucial for the VIRUS science drivers.

The VIRUS spectrograph is well-suited to HET. The fiber IFU feed allows the weight of the instrument to be off-loaded from the hexapod system, which has limited capacity, and the fibers azimuthally scramble the far-field image of the varying pupil illumination, allowing higher precision by removing the majority of the time-variability. The limited track-times available with HET make rapid acquisition and setup essential, since setup time directly reduces integration time, and VIRUS requires no setup beyond pointing.

The weight of VIRUS-132 is estimated to be about 1.7 tonnes. This exceeds the current capacity of the hexapod positioning system for the corrector and instrument payload. There are two possible locations for mounting VIRUS on HET: either on the carriage that moves on the tracker beam, or on the ends of the tracker beam itself. The former is illustrated in Figure 4. In this case, the VIRUS units are arrayed in two tiers around the corrector within the central obstruction, and would be mounted on a rotation stage on the carriage. The rotation of the instrument would be slaved to

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[‡] HET is a collaboration of the University of Texas at Austin, Pennsylvania State University, Stanford University, Georg-August-Universität, Göttingen, and Ludwig-Maximillians-Universität, Munich.

that of the corrector to maintain orientation on the sky while allowing a minimal fiber length of about 2 m. This location is still subject to strict weight limits, but offers the best UV performance by minimizing fiber losses. The alternative location would array the units at the top and/or bottom of the tracker beam. The fiber length in this case can be kept within 10 m if we restrict the total rotation allowed for the top end. At this length, the throughput at 340 nm drops by 2% in absolute terms, which is acceptable (see Section 5), given the probable cost savings allowed by relaxing the weight limit.

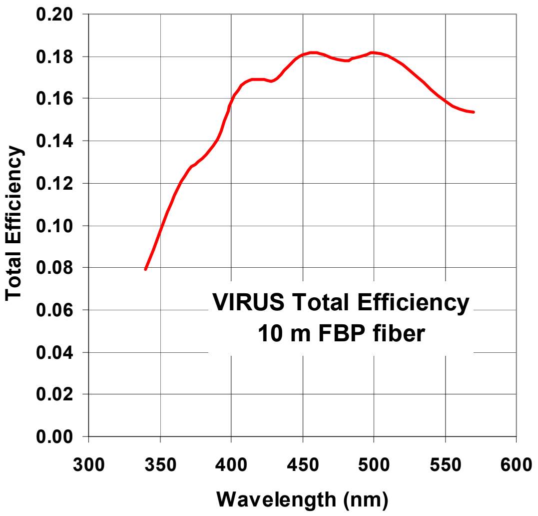

Figure 5: Total efficiency of VIRUS on the HET with a 10 m long fiber bundle of Polymicro type FBP fiber. The telescope model includes the atmosphere at the 35 degree zenith distance of HET and assumes a primary mirror coated with Aluminum and the 4-mirror corrector coated with the LLNL wide-band coating

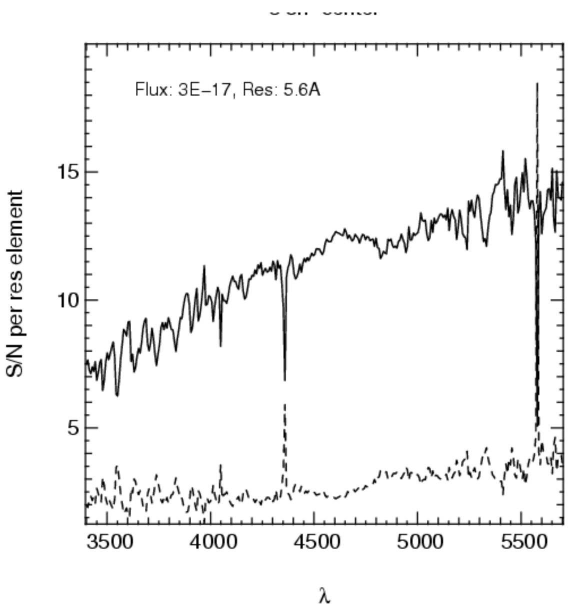

Figure 6: Predicted S/N ratio for an observation of a line flux of 3e-17 erg/cm^2/s as a function of wavelength. An observation consists of a dither of three 200 second exposures to fill in the area of the IFU as illustrated in Fig. 1. 1.2 arcsec FWHM seeing was assumed. The lower curve shows the ratio of the sky photon noise to CCD read-noise.

5. PREDICTED PERFORMANCE

The design of the individual VIRUS spectrograph modules lies well within the state of the art, and estimation of performance is relatively straight-forward. The largest uncertainty lies in the throughout of the fiber IFU, mainly in accounting for insertion losses and focal ratio degradation (FRD). Detailed testing of fibers[20] indicates that for the fast f/ratio considered here the FRD is minimal so long as care is taken in the assembly of the bundles so as to avoid stresses in the fibers. Standard techniques for bundle assembly appear to meet these criteria[25]. We consider the (worst) case of mounting the VIRUS spectrographs at the ends of the HET tracker beam with 10 m long bundles, and factor in a 10% loss for coupling and FRD[20]. Under these assumptions the fiber bundle delivers between 68% and 88% of the light to the spectrograph, at 340 nm and 570 nm wavelength, respectively. With optimized coatings, the optics, VPHG disperser, and CCD can detect 25% to 40% of the photons over the bandpass, while the atmosphere and telescope have 30-50% throughput. These estimates combine to give the efficiency curve illustrated in Figure 5. Use of 3 m fibers would improve the throughput to 10% at 340 nm, but would have little affect longward of 400 nm. The resulting sensitivity for the target line flux is given in Figure 6. The lower curve in this figure shows the ratio of photon (sky) noise to CCD read-noise which is in excess of a factor of two even at the bluest wavelengths. It is evident that VIRUS has adequate sensitivity to reach the goals of the dark energy survey described in section 3.1, with S/N ratio well in excess of 5 for each set of three 200s exposures dithered to fill in the field of view of the IFU bundles.

With this sensitivity, and with efficient target setup, it should be possible to observe a total of 0.3 sq. degrees per night distributed within a total area of 2.1 sq. degrees. For the DE experiment, sparse sampling of the volume is acceptable (section 3.1), so 200 sq. degrees can be surveyed with $\Delta z\sim 2$ in ~100 nights. This corresponds to a volume of 6 Gpc^3, in a survey that would occupy the University of Texas fraction of HET for the dark time of two spring trimesters.

It is possible to design performance metrics that highlight the strengths of any given instrument, and in order to compare VIRUS with other survey instruments we consider the concept of Total Grasp which is the product of the collecting area of the telescope and the area of sky observed simultaneously[23]. Large area IFUs such as Sparsepak[23] PPAK[21], and the VIMOS IFU[26] have Total Grasp of 0.03M to 0.05M $\mathrm{m}^2\mathrm{arcsec}^2$, while the value for VIRUS-132 is 40-50 times larger at 1.6 M $\mathrm{m}^2\mathrm{arcsec}^2$. Even taking into account that objects lie on only 1-2% of the elements in any given survey exposure, VIRUS-132 beats the survey efficiency of the proposed KAOS spectrograph on GEMINI by a factor of two. Industrial replication can clearly produce an extremely competitive instrument without straining the state of the art in engineering.

6. COST

The premise that industrial replication leads to significant cost-savings for an instrument such as VIRUS will only be borne out by a detailed design and costing exercise to be undertaken in the next year. In the meantime, a conservative cost breakdown has been performed that suggests the instrument can be realized for about $10M, plus $1.5M of engineering effort for the prototype. About half the $75k unit cost is expended on the CCD system, which is perhaps the most complex part of the instrument. The estimated cost does represent a significant savings when one considers the fact that VIRUS-132 covers twice as many resolution elements per exposure as DEIMOS[4], and is directly competitive with the proposed KAOS instrument on GEMINI.

7. SUMMARY

We have explored the design of a highly replicated spectrograph that would be capable of attacking a central question in cosmology. The instrument would have many applications and would open up the emission line universe to systematic surveys for the first time. VIRUS is the ideal instrument for an upgraded wide-field Hobby-Eberly Telescope due to its strong niche as a survey instrument, and this combination would provide one of the most powerful survey facilities available.

The amortization of engineering costs over many replica spectrographs will certainly provide cost savings when compared to monolithic instruments. This type of design may be the only practical way to build certain types of instruments for the next generation ELTs, and it is essential that the designs for those telescopes allow sufficient space and payload capacity to carry instruments exploiting massive replication.

ACKNOWLEDGEMENTS

We thank Matt Bershady, Martin Roth, Andreas Kelz, Jeremy Allington-Smith, Marc Verheijen, Deqing Ren, Gary Nelson and the Polymicro team, Peter Schueker, Ralf Bender, Ulrich Hopp, Claus Goessel, Steve Rawlings, Carlos Allende-Prieto, John Booth, Gordon Wesley, and Ted von Hippel, for interesting and fruitful discussions about the science applications and technical aspects of VIRUS.

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