Conceptual design for the High Resolution Optical Spectrograph on the Thirty-Meter Telescope: a new concept for a ground-based high-resolution optical spectrograph

Cynthia Froning*[a], Steven Osterman[a], Matthew Beasley[a], James Green[a], Stephane Beland[a]
[a]Center for Astrophysics and Space Astronomy, University of Colorado at Boulder, 593 UCB, Boulder, CO, 80309, USA

ABSTRACT

We present a conceptual design for a High Resolution Optical Spectrograph (HROS) for the Thirty Meter Telescope, a 30-m primary aperture ground-based telescope currently under development (www.tmt.org). To decouple downstream optics sizes from the size of the seeing disk and/or AO performance, we use fiber fed IFUs to generate a 0.1" pseudo-slit. The use of multiple IFUs instead of a slit also allows for spatially resolved spectroscopy, multi-object spectroscopy, positionable sky sampling, and insertion of a simultaneous wavelength calibration signal into the beam. Instead of a cross-dispersed echelle design, our concept uses a dichroic tree to provide spectral separation. The dichroics feed 32 independent first-order spectrographs that cover the 310 to 1100 nm optical waveband at a nominal spectral resolution of R=100,000. This approach allows for the optimization of coatings and on-blaze grating performance in each channel, resulting in high efficiency, near-uniform dispersion, and reduced program risk and cost due to the high degree of component commonality. We also discuss the general applicability of this concept for achieving high resolution spectroscopy in the next generation of ground-based instrumentation.

Keywords: Optical, spectroscopy, high resolution, Thirty Meter Telescope, HROS, CU-HROS

1. INTRODUCTION

In tandem with efforts to develop the next generation of ground-based telescopes (often designated Extremely Large Telescopes, or ELTs) is the increasing study of instrumentation for ELTs. Already, it is clear that the large physical scales and ambitious performance requirements of ELTs necessitate a fundamentally new approach to instrument design: simple scalings of existing instrument designs to ELTs often result in concepts that are unwieldy, inefficient, and expensive. Here, we describe a novel concept for a high resolution optical spectrograph for the Thirty Meter Telescope (hereafter designated CU-HROS to distinguish it from the generic HROS instrument intended for TMT). In a departure from the cross-dispersed echelle designs used for such instruments in the past two decades, our concept achieves high spectral resolution and broad wavelength coverage by using a dichroic tree to spectrally divide the beam into 32 individual channels, which then feed simple first-order spectrographs. In this paper, we demonstrate how this design can achieve the desired performance for HROS while minimizing cost and risk. Our organization is as follows: In Section 2, we briefly examine the science case for HROS and outline the resulting design drivers for the instrument. Section 3 presents an overview of the CU-HROS concept and its principal components. Finally, in Section 4, we discuss the general, overall advantages of this concept for achieving high resolution spectroscopy on ELTs.

2. SCIENCE DRIVERS

As part of our feasibility study, we developed the science case for HROS on TMT, and, more generally, the case for providing high resolution optical spectrographs on the next generation of large ground-based telescopes. Comparable instruments on current telescopes are providing data that is driving scientific progress in a number of disciplines; most notably in the areas of observational cosmology (from the epoch of reionization to the modern universe), the discovery and burgeoning study of extrasolar planets and planetary systems, and analyses of the history of structure formation and metal production in the universe through observations of stars and gas in the Milky Way and its satellites.

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* Cynthia.Froning@colorado.edu; phone 1 303 492 0376; fax 1 303 492 5941; casa.colorado.edu

An instrument such as HROS on TMT will be equally important in the next phase of observational astrophysics. The coupling of the large collecting area of TMT with the high spectral resolution (R~100,000) and broad wavelength coverage (310 – 1100 nm) of HROS will enable high precision, high signal to noise (S/N) spectroscopy of targets to V~20, and discovery science of targets down to V~22. This extension of the limiting magnitudes of targets that can be obtained at high resolution and high S/N well beyond the current limits will enable key advances in numerous areas of astrophysical research, including studies of the intergalactic medium, dark matter distributions, and baryonic structure evolution at unprecedented spatial sampling; extension of extrasolar planet observations out into different components of the Milky Way and observations of planetary atmospheres in transit systems; and the study of the cycles of matter infall, enrichment, and outflow between the intergalactic and interstellar media and stars out into the Local Group and beyond.

From the detailed science case for HROS, we developed a list of design drivers that shaped the instrument requirements. These include specifications for spectral resolution, spectral coverage per exposure, spatial sampling and resolution, sensitivity, and short and long-term stability. HROS should support spectral resolutions up to R=100,000 to best leverage the strengths of HROS on TMT over current instruments and to meet the science goals of the instrument. Similarly, the desire to maximize efficiency of precious observing time and cover spectral features of interest at visible wavelengths indicates that HROS should cover the full optical waveband in a single exposure. A number of scientific programs, most notably radial velocity detections of extrasolar planets, require output spectra that can be corrected to high precision: <3 m/s goal but preferably to <1 m/s. In additional to stability within an exposure, the instrument must support the acquisition of spectra over multiple years that can be compared at comparable precision, necessitating a stable, well-characterized instrument. Finally, HROS should have a flexible design that can accommodate future upgrades, such as support for multi-object spectroscopy, adaptive optics interfacing, or extension of the available wavelength range.

3. CONCEPT OVERVIEW

This manuscript provides a broad overview of the CU-HROS concept. Additional details on elements of the design, in particular the fiber-fed IFUs and dichroics, are presented in a companion paper in this volume (Osterman et al. 2006)[1]. HROS will be a multi-purpose high-resolution optical spectrograph for the TMT. In order to meet its operational and functional requirements, there are several issues to confront. First, the large size of the TMT primary aperture requires either that its instruments have very large optics, small spatial sampling, and/or diffraction-limited performance (although this last is not feasible over the full optical waveband at present). Second, the instrument has to provide a spectrum from 310 nm to 1100 nm, ideally in one exposure. Combined with a R=100,000 desired spectral resolution, this requirement results in large pixel counts for the detectors (≈50 Mpixels per spectrum). The spectrograph should maximize throughput over as much of the bandpass as possible, as spectral features of interest (rest and redshifted lines) span the entire optical waveband. Finally, the design should accomplish its requirements with a design that minimizes risk and overall cost.

Our solution is to use an array of multiplexed 1st order spectrograph fed by fiber optic integral field units (FIFUs). This concept results in high throughput, high stability, and high spectral resolution performance over the full optical waveband. Figure 1 shows a schematic illustration of CU-HROS. Light from the TMT is fed into the instrument enclosure. After passing through the foreoptics assembly, the beam is reconstructed by the FIFUs into multiple pseudo-slits that are 0.1" wide. After collimation, the spectrum is divided into 32 spectral bins of roughly equal spectral grasp via a 31-element dichroic mirror array. The dichroic tree then feeds 32 narrowband, first order spectrographs. The bulk of the instrument (excluding the foreoptics) is enclosed in a thermal and pressure-controlled environment, such as a vacuum chamber and/or clean room, to minimize drifts and vibrations in the hardware.

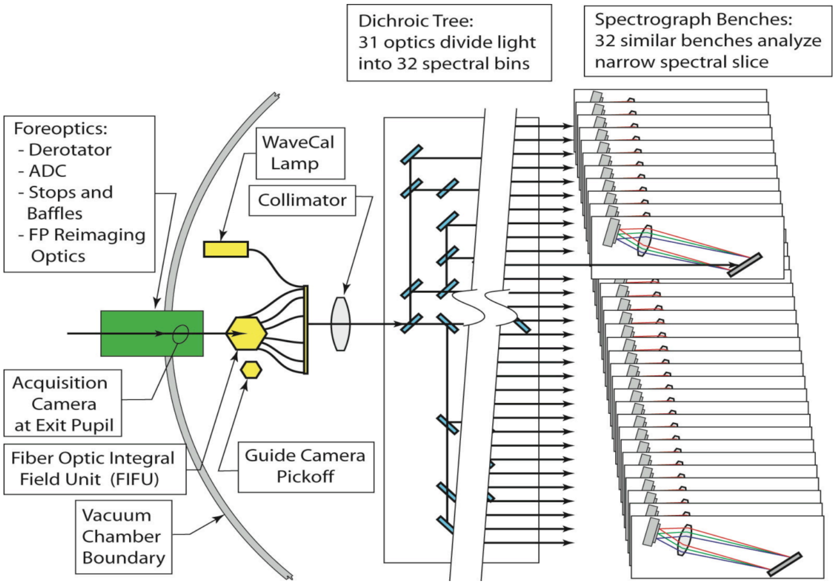

Figure 1: Schematic diagram of the CU-HROS concept. Light enters the instrument from the left, passing through the foreoptics assembly, which includes a derotator (the instrument will be mounted on a Nasmyth platform), an atmospheric dispersion corrector, and reimaging optics (if needed). The remainder of the instrument is enclosed in a temperature and pressure-controlled environment, such as a vacuum chamber. The focal plane assembly consists of pickoffs for acquisition and guiding, calibration subsystems, and five fiber optic integral field units (FIFUs), each covering 1"x1" on the sky at a spatial sampling of 0.1". After collimation, the beam passes through the dichroic tree, an array of 31 dichroics that dissect the beam spectrally into 32 narrow wavebands. The dichroic tree feeds 32 first-order spectrographs, consisting of gratings, camera optics, and detectors. CU-HROS will deliver R=100,000 spectra from 310 – 1100 nm in a single exposure.

Figure 2 illustrates the light path from the telescope to the detector for one channel. Although only one FIFU is shown, the baseline design has 5 FIFU bundles, each covering 1"x1" with approximately 100 fibers matched to 0.1" per fiber. In the baseline design, the FIFUs will be in a fixed pattern — likely with one oversize grouping in the center of the FOV covering 3"x3" and two FIFUs away from the central group to provide sky coverage — with the option of upgrading the instrument to positionable FIFUs for multi-object spectroscopy at a later date. After dissecting the beam in the FIFUs and collimating the light, the beam will pass through the dichroic tree. Each photon will encounter five dichroics in a combination of reflections and transmissions. The dichroic tree feeds the 32 spectrographs. The gratings will be operated in first order and on blaze in each channel. In addition, to maximize performance, the gratings, cameras, and detectors will be optimized for maximal performance over the narrow waveband covered by each channel.

The nominal design for CU-HROS therefore operates in a single mode, delivering five spectra at R=100,000, spatially sampled at 0.1", and covering 310 – 1100 nm in a single integration. As discussed further below, lower spectral resolution observations at higher sensitivity are accommodated by the use of on-chip binning in the spectral direction. As a result, CU-HROS has no mechanisms in the bulk of the instrument, allowing for maximum stability in mount design for the optical components without compromising instrument performance. In the following subsections, we discuss the principal characteristics of the major instrument subsystems.

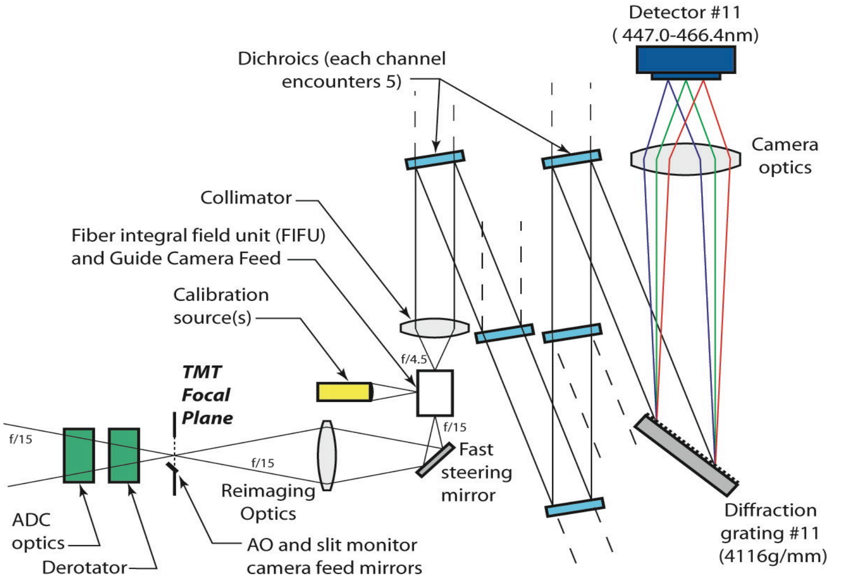

Figure 2: Block diagram showing the major components of CU-HROS and the light path for a single channel. Each photon passes through five dichroics in a combination of reflections and transmissions. The gratings are holographic gratings operated in first order and on blaze for maximum throughput over the full optical spectrum. Each spectrograph is further optimized for its waveband coverage in the choice of optics coatings and detector parameters. All of the channels operate at near-uniform dispersion, with the spectral resolution in the default mode varying from R=100,000 to R=104,000 over the full, 310 – 1100 nm, optical waveband.

3.1 Foreoptics

Principal foreoptics components include (possible) reimaging optics, stops, and baffles, an atmospheric dispersion compensator (ADC), an image derotator, and an iodine absorption cell. The baseline concept does not use reimaging optics, simply feeding an f/15 beam to the FIFUs, but these can be included if desired based on the final beam speed delivered by the telescope. The iodine absorption cell can be inserted into the beam for precise wavelength calibration observations (although we also include fibers dedicated to simultaneous wavelength calibration observations in each FIFU; see Section 3.2). For the CU-HROS design, we specified a 70" field of view (FOV). The FOV was chosen to be large enough to ensure that all virtually every pointing would include a field star (in addition to the target) bright enough ($V \leq 19$) to support fast tip-tilt guiding. The FOV is also large enough to include one laser guide star image to support future adaptive optics (AO) upgrade paths for the instrument.

3.2 Focal plane

The focal plane consists of the FIFUs, guiding and acquisition subsystems, and calibration subsystems. The CU-HROS design relies on reformatting the entrance aperture to a 0.1" equivalent plate scale to keep optics sizes relatively small. Instead of adopting slits coupled with image slicers, we perform image slicing using fiber bundles. The baseline design consists of 5 FIFU units with each FIFU made up of approximately 100 fibers coupled with microlens arrays. The fibers will be scrambled to minimize modal noise and seeing effects, but will retain some concentration of the central fibers to the center of the resulting pseudo-slit to minimize the spread of the image on the detectors.

There are several advantages of the FIFUs over traditional slits. First, the sizes of the downstream optics and the spectral resolution performance of the instrument are decoupled from the size of the seeing disk. As the seeing disk decreases, due to improved observing conditions and/or the use of AO, the light is directed onto fewer pixels on the detectors, which results in improved S/N per pixel, but the *spectral* performance of the instrument is independent of the characteristics of the input beam. As a result, CU-HROS is flexible and responsive to changing conditions with a minimum of observing modes. The use of FIFUs also allows for multiple objects to be observed simultaneously (although the number of targets available of scientific interest will be limited by the FOV). We have chosen to specify 5 FIFUs for CU-HROS, but this number could be increased (up to 8 given the size in the spectral direction of our CCDs; see Section 3.4). The configuration of the FIFUs is also flexible. One or more of the FIFUs can be used for simultaneous sky observations, and the FIFUs can be grouped for spatially-resolved spectroscopy. In each FIFU, at least two fibers will be dedicated to observations of wavelength calibration sources during science acquisition. This method of wavelength calibration has proven successful in obtaining the extremely precise velocity calibrations required for extrasolar planet searches (Rupprecht et al. 2004)[3].

In the baseline concept, guiding is performed using tip-tilt correction with a fast steering mirror internal to the instrument. As the deformable secondary mirror is installed in TMT, guiding corrections can be sent directly to it. CU-HROS also supports an upgrade path to the use of single laser ground layer adaptive optics (SL-GLAO) to further reduce the size of the seeing disk. Calibration subsystems include internal flat field and wavelength calibration lamps. As mentioned above, two fibers in each FIFU will be dedicated to continuous observation of the wavelength calibration lamps, but the lamps can also be observed through the full FIFU to allow cross-calibration of the individual fibers. Standard gas emission line lamps can be used for wavelength calibration, but laser frequency combs also offer a promising technology to achieve ultra-precise, uniform calibration spectra that could become available for astronomical applications within a few years (Uden et al. 2002)[2].

3.3 **Dichroic tree**

Perhaps the key component that makes the CU-HROS concept feasible is the dramatic improvement in dichroic performance that has been achieved in recent years. Dichroic mirrors provide the primary wavelength selection for the CU-HROS instrument, and the performance of the instrument is dependent on these mirrors operating at high efficiency. Dichroic mirror technology has undergone substantial advances in the last several years, yielding mirrors with sharp transitions (>5nm from 90% rejection to 90% acceptance) and high efficiencies (typically >95% transmission/reflectance). (See Osterman et al. 2006 for a more detailed discussion of the expected dichroic performances for CU-HROS). As a result, we are able to use multiple, stacked dichroics to perform spectral dissection of the input beam without substantial throughput loss (with the dichroics effectively acting as the cross-dispersers for the system).

The CU-HROS concept uses a tree of 31 dichroics to separate the 310 –1100 nm optical waveband into 32 channels, each spanning 13 to 46 nm. Each photon encounters 4 dichroics in a combination of transmissions and reflections. The waveband of each dichroic is oversized to allow for coverage of overlap wavelength regions between channels. Figure 3 illustrates how the optical waveband would be covered by CU-HROS for a sample QSO spectrum. The throughput through the dichroic tree is relatively flat at about 77% (see Table 2) over the full wavelength range, with the exception of the overlap regions between channels, where the throughput drops to about 50%. The overlap regions will be fixed in wavelength space and can therefore be calibrated in flat-fielding. If the observer has a feature of interest in an overlap region, he or she will know this in advance of the observation and can request the exposure time needed to obtain the desired S/N.

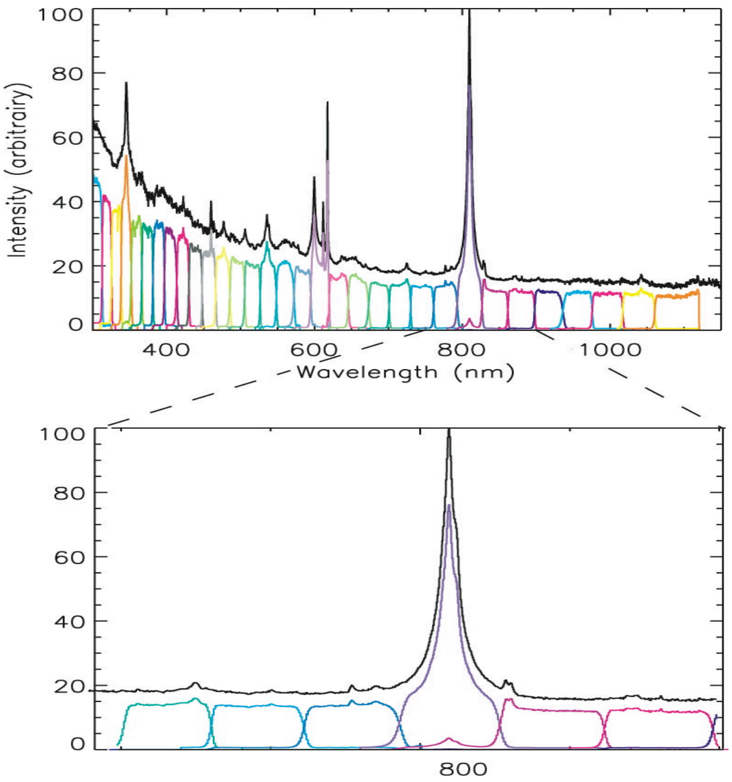

Figure 3: Simulation of a typical AGN spectrum before and after passing through the dichroic tree. The upper panel shows a spectrum of a QSO in black. The colored spectra show an illustration of how the 32 channels will cover the full optical waveband. The lower panel shows an expanded image of a portion of the spectrum. The instrument throughput will be largely constant over the optical waveband. The throughput drops at the edge of each channel, but because the channels are fixed, with no moving parts such as tiltable gratings, it will be straightforward to flat-field the overall spectral response, and to coadd the channels to recover the signal divided between two channels in the overlap regions.

3.4 Spectrographs and detectors

The CU-HROS spectrographs are designed to be simple, modular components that operate at maximum efficiency for each narrow waveband covered. The spectrographs will be structurally identical and currently contain no moving parts. All the gratings will be operated on blaze, and optics coatings are chosen to maximize throughput over the narrow (3%) bandpass covered by each channel. Holographic gratings are the preferred option for CU-HROS. Holographic gratings have very low scatter and, given the narrow bandpass in each channel, can be constructed with groove profiles designed to maximize efficiencies (≥65%). Each channel will be operated at comparable dispersion and at similar resolutions (R = 100,000 to 104,000 over the 310 – 1100 nm range). Preliminary groove densities for the gratings range from 6000 grooves/mm in the blue to 1700 grooves/mm in the red.

The cameras required for CU-HROS are fast (f/1.8) cameras with wide fields (14°) and excellent aberration control (with the spot FWHM equal to 15 μm). We have considered both refractive and reflective designs. The current baseline uses a three-mirror anastigmat design. The full width of the collimated field is 240 mm. Significant anamorphism in the beam from the grating to the camera compresses the beam to f/5 in the spectral direction.

The detectors for CU-HROS represent conventional technology in a large format application. In order to avoid gaps in spectral coverage, we have specified a single detector for each channel, resulting in a specification for 9K by 3K CCDs with 12.5 μm pixel pitch. This requires the procurement of custom CCDs, but although the first CCD in this format will be relatively expensive, the following 31 will be highly cost-effective. Note that CU-HROS does not require substantially more pixels than a conventional cross-dispersed echelle design that meets the same performance specifications: assuming a best-case f/1 final beam speed, the spatial scale of a 30-m telescope is about 150 µm per arcsecond, which for 15 µm pixels translates to >10 pixels per resolution element independent of instrument design. Larger pixels can be considered to reduce readnoise effects, but the trade between pixel size and reduced exposure times avoid loss of data from cosmic ray hits must be carefully considered.

Table 1 shows the number of pixels illuminated per resolution element for CU-HROS compared to a conventional cross-dispersed echelle design. The conventional echelle has R=50,000 matched to a 1" slit. R=100,000 is achieved for the echelle by the use of an image slicer under poor seeing conditions or by using a narrower slit when the seeing is 0.5" or better. The final column shows the number of pixels subtended for the echelle design if a tapered profile sampling of the spatial image is used. CU-HROS is optimized for R=100,000 spectroscopy. At these resolutions, a spectral resolution element on CU-HROS subtends fewer pixels per resolution element than an echelle design. Because of the concentration of the central fibers in each FIFU to the center of the pseudo-slit, the advantage of CU-HROS becomes more dramatic as the seeing disk decreases in size. As part of our goal to design a simple, stable instrument with a minimal number of moving parts, CU-HROS has one observing mode: lower spectral resolutions are achieved by binning up the spectrum. As a result, at lower resolutions, a conventional echelle typically illuminates fewer pixels than CU-HROS. However, CU-HROS has the advantage that its first-order spectra in each channel can be designed with minimal curvature and can be aligned along CCD rows or columns. As a result, the increased read noise at the lower spectral resolutions can be mitigated by adopting on-chip binning, both in the spatial and spectral directions. The CU-HROS design enables observers to make their own decisions about the trade between spectral resolution, signal, and read noise by selecting the on-chip binning amount before each observation and the size of the extraction aperture during data reduction.

Observing Condition	**CU-HROS**	**Conventional Echelle**	**With Profile**
1 arcsec, R = 100,000	156	200	160
0.5 arcsec, R =100,000	38	100	80
1 arcsec, R = 50,000	312	100	80
0.5 arcsec, R = 50,000	76	100	80
1 arcsec, R = 20,000	780	250	200
0.5 arcsec, R = 20,000	190	250	200

Table 1: Pixel illumination for CU-HROS and a conventional echelle on TMT.

3.5 Performance estimates

Table 2 presents an estimate of top-level efficiencies for CU-HROS. Component breakdowns and wavelength dependencies are discussed in Osterman et al. CU-HROS achieves an overall throughput of about 20% that is uniform over the full optical waveband. Such performance is in line with the peak throughputs achieved by current high resolution optical spectrographs, although CU-HROS does not have the rapid decline in efficiency seen in echelle designs away from the blaze.

System	**Efficiency**
Fore optics	0.72
FIFU	0.65
Collimator and vignetting	0.89
Dichroic tree	0.77
Spectrograph Bench including detector	0.55
Net CU-HROS Performance:	**0.18**

Table 2: Top-level efficiencies by subsystem and overall for CU-HROS

Table 3 shows the estimated limiting magnitudes (in 6 hours) for CU-HROS on TMT as a function of desired spectral resolution, size of the seeing image, and desired S/N per resolution element. These numbers assume a reduction in read noise through the use of on-chip binning by 5 pixels in the spatial direction at full (R=100,000) resolution and additional spectral binning for the lower resolution modes. The number of pixels binned on chip is set by the limitation that no more than 1% of the full detector readout can be lost in each 30 min exposure from cosmic ray hits. Under good observing conditions, CU-HROS can obtain R=100,000, S/N=100 spectroscopy of sources as faint as m_{AB} = 19 – 20 in 6 hours. At lower spectral resolutions, CU-HROS can observe down to limiting magnitudes of 22 or fainter.

Resolution	**Seeing (90% encircled)**	**S/N**	**Limiting mAB in 6 hrs**
100,000	1.0	100	17.5
100,000	0.5	100	18.9
100,000	0.2	100	20.4
100,000	0.5	50	19.4
50,000	0.5	100	19.7
50,000	0.5	50	20.5
20,000	0.5	50	21.2
20,000	0.5	20	22.3

Table 3: Limiting magnitudes for 6 hour total exposure times, with 30 min individual exposures and on-chip binning.

3.6 Upgrade options

One advantage of the modular design of CU-HROS is the ease of incorporating a wide range of instrument upgrades. This also allows CU-HROS to be constructed at minimal cost with a straightforward upgrade path as additional funds become available. Examples of such upgrades include: implementation of positionable FIFUs for multiplexing, addition of wavefront sensors for AO capability, or the addition of a J-band arm for non-thermal infrared spectroscopy.

In the baseline design, the FIFUs are placed in a fixed pattern, such as an oversized FIFU (subtending 3"x3", for exaxmple) in the center of the FOV and additional units spread over the FOV for sky sampling. At a later date, CU-HROS could be upgraded to allow the FIFUs to be independently positioned so that multiple, selectable targets could be observed in a single exposure. Given the relatively small FOV envisioned for CU-HROS (70"), there would likely be only 5 to 8 FIFUs, which could be positioned with a simple, extending arm design.

The baseline design of CU-HROS has fast tip-tilt correction but does not include a full AO capability. AO is desirable for minimizing the size of the seeing disk, but its implementation at optical wavelengths is challenging. As AO capabilities on TMT become streamlined, its extension to shorter wavelengths will likely become more feasible. At this point, CU-HROS can be upgraded to include wavefront detection and control hardware for AO capability.

Finally, CU-HROS could be readily extended to cover the non-thermal near-infrared J band from 1100 to 1300 nm by the addition of three more channels on the red end of the instrument. Because each channel operates as an independent spectrograph, the J-band channels can use optical components, such as infrared focal plane array detectors, that are optimized for use outside the visible waveband.

4. ADVANTAGE OF CONCEPT FOR ELT HIGH RESOLUTION SPECTROSCOPY

For the past two decades, cross-dispersed echelle designs have been the preferred way to achieve high spectral resolution and broadband wavelength coverage on ground-based telescopes. Echelle-based designs have many advantages, especially in their efficient use of the 2D format of CCDs, which was of particular importance when CCDs were the most expensive component of the instrument. However, as telescopes become large (such as 30 meters) and their instruments remain seeing- or near seeing-limited (as in the optical) the sizes of such instruments grow dramatically. For example, the 450 m focal length of TMT results in a 1" slit height of 2 mm. Further on, a slit-limited spectral resolution of R=50,000 matched to a 1" slit on a 30m telescope results in a beam size at the echelle of 0.9 m. As a result, cross-dispersed echelle designs on ELTs require very large, high risk, one-off optical components that are challenging to fabricate, mount, and maintain, resulting in an expensive instrument.

In contrast, the size and cost of the CU-HROS concept is largely independent of telescope diameter. Our design confronts the issue of large optics by slicing the beam in 0.1" spatial elements, allowing for the use of smaller optics and decoupling of the spectral resolution performance of the instrument from observing conditions. We then spectrally divide the beam into narrow wavelength bins, which allows for the use of smaller, optimized optical components in each channel. We believe that the resulting design is the best way to achieve stable, high spectral resolution, broadband optical spectroscopy on TMT. Moreover, although CU-HROS was designed with TMT in mind, the concept itself is general, and one that is attractive for any ELT, where the same problems of size and risk will appear. We conclude by summarizing the generic advantages of CU-HROS for optical spectroscopy on ELTs:

- The use of FIFUs for image slicing allows for narrow spatial elements without loss of signal, acquisition of spatially-resolved spectroscopy and multiplexing, and the simultaneous observation of a wavelength calibration source;
- The use of a dichroic tree to spectrally divide the beam allows for the use of multiple, individually optimized 1st order spectrographs with fixed dispersion and small optics sizes rather than large, multi-order echelles and cross-dispersers;
- The individual channels can be optimized for their narrow (3%) bandpasses by the use of high throughput coatings on optical components and detectors and by operating the spectrographs on blaze;
- The use of a single observing mode that performs at specification over a broad range of observing conditions and desired spectral resolutions results in a design with a stable configuration and a minimum of moving parts;
- The use of small optics and replication of major components results in a low cost, low risk design that benefits from economies of scale in the design and fabrication stages of construction.

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