The upgraded WIYN Bench Spectrograph

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ABSTRACT

We present the as-built design overview and post-installation performance of the upgraded WIYN Bench Spectrograph. This Bench is currently fed by either of the general-use multi-fiber instruments at the WIYN 3.5m telescope on Kitt Peak, the Hydra multi-object positioner, and the SparsePak integral field unit (IFU). It is very versatile, and can be configured to accommodate low-order, echelle, and volume phase holographic gratings. The overarching goal of the upgrade was to increase the average spectrograph throughput by ~60% while minimizing resolution loss (< 20%). In order to accomplish these goals, the project has had three major thrusts: (1) a new CCD was provided with a nearly constant 30% increase is throughput over 320-1000 nm; (2) two Volume Phase Holographic (VPH) gratings were delivered; and (3) installed a new all-refractive collimator that properly matches the output fiber irradiance (EE90) and optimizes pupil placement. Initial analysis of commissioning data indicates that the total throughput of the system has increased 50-70% using the 600 l/mm surface ruled grating, indicating that the upgrade has achieved its goal. Furthermore, it has been demonstrated that overall image resolution meets the requirement of <20% loss.

Keywords: fiber-fed spectrograph, collimator, volume phase holographic grating, CCD, bench spectrograph

1. INTRODUCTION

The WIYN 3.5m telescope is the most modern optical/near-infrared telescope on Kitt Peak mountain, which is located outside of Tucson, Arizona. Commissioning of the telescope began in 1994, and one of the two instruments initially offered to the astronomical community was the Hydra multi-object positioner, which feeds a Bench Spectrograph. Hydra with the Bench was initially designed for and commissioned on the Kitt Peak National Observatory (KPNO) 4m Mayall telescope at the f/8 Cassegrain focus[1]. The Bench was modified to produce a 152 mm collimated beam from f/6.7 fiber output to accommodate its move to the WIYN 3.5m f/6.3 Nasmyth focus[2,3]. In 1997 the (now retired) Integral Field Unit (IFU) DensePak[4] was added to the capabilities available with the Bench Spectrograph, followed by the IFU SparsePak[5,6] in 2001. This suite of instruments, along with a variety of available gratings and two cameras has ensured that the Bench Spectrograph is used 60-65% of the time each observing semester. Until the addition of the WIYN High-Resolution Infrared Camera (WHIRC)[7], the Bench had been the primary bright-time instrument at WIYN.

1.1 Why upgrade the Bench?

The WIYN Consortium, which runs the 3.5m telescope, is a partnership between the University of Wisconsin – Madison, Indiana University, Yale University, and the National Optical Astronomy Observatory (NOAO). A significant fraction of the astronomical community it serves does primarily spectroscopy, and thus, the Bench Spectrograph and the instruments that feed it have been instrumental in enabling many scientific projects since the WIYN 3.5m was commissioned. As an example, the collaborators of the "WIYN Open Cluster Survey (WOCS)" use the Bench with Hydra, and have published 38 papers to date. Part of the mission of the Consortium is to support current and future scientific needs of its scientists, including enabling frontier astrophysical research.

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Previous to the current upgrade, it had been determined that the total system spectroscopic throughput (including telescope and atmosphere) ranges from 3-7% on axis[8]. The specific value depends on the selected grating, fiber, and spectrograph configuration and is a factor of two lower at the ends of the pseudo-slits and another factor of about two at each end of the wavelength range depending on the grating blaze function and camera-grating distance. This relatively low throughput compromises the scientific competitiveness of spectroscopy on WIYN. During its strategic planning efforts in 2004, the Consortium recognized that there was a strong desire from its community to improve the capabilities of the Bench Spectrograph in order for it to (1) regain competitiveness with spectrographs available on other 4m-class telescopes, and (2) ideally enable some unique "niche" science.

1.2 The proposed upgrade

The details of the modeling process that led to the overall plan for the upgrade of the Bench Spectrograph were previously reported elsewhere[8]. The most significant component of the proposed upgrade was the implementation of a new collimator. Based on the modeling results, it was determined that adopting a 160 mm collimated beam with a reduction of the collimator focal-length to 800 mm would increase system throughput by 40-70%, while minimally degrading spectral resolution with the smallest fibers for which instrumental resolution is limited by optical aberrations and pixel sampling. This effective f/5 collimator should enclose 90% of the light instead of the 60% enclosed within the 152 mm beam of the current system.

Sizing the collimator to allow for a 200 mm beam (f/4) would capture most of the 10% remaining signal. An additional gain of 10% could also be achieved by placing the pupil 450 mm beyond the grating location toward the camera. This choice was a compromise between different camera-grating distances between spectrograph configurations, necessitated to achieve the spectrograph's multi-purpose science mission. While this latter gain may seem modest, the throughput improvement for pseudo-slit ends is anticipated to be typically a factor of 2. To consolidate these conceptual optical design gains, the mechanism (called the "fiber foot") which takes the fiber bundle and physically positions the fibers into a pseudo-slit, and the mechanism that mounts to it (called the "toe") which houses the baffles and slots for order-blocking filters, needed to be modified and repositioned. This included shortening and opening the toe to un-obstruct the f/5 (and as much as possible, the f/4) beam, and removing the foot from the optical path via a refractive collimator.

Thus, the goals for the main component of the upgrade were to:

- Increase spectrograph throughput by 60% while minimizing resolution loss (< 20%).
- Capture the f/5 input beam (EE80 to EE90) into 160 mm collimated beam (collimator focal length of 800 mm).
- Minimize vignetting by optimizing pupil placement and opening toes and collimator optics to f/4 (EE95).
- Tune the image quality to Bench Spectrograph Camera (BSC), which is used for more than 95% of observing programs, and a wide range of commonly used configurations.

In addition to providing a collimator that was a much better match to the telescope/instrument system, a second major component of the upgrade was to replace the existing CCD (T2KA) with a new CCD with new electronics. The program specification was for a low-noise detector (≤ 3e- [rms]) and excellent quantum efficiency (>75%) from 400-850 nm, and good quantum efficiency shortward (>50% $350<\lambda<400$ nm) and longward (>40% $850<\lambda<950$ nm) of the peak region. The delivered system also needed to fit within mechanical constraints of Bench Spectrograph Camera, Simmons camera, associated camera rails, other optical bench hardware, and other bench-spectrograph room hardware (e.g., shoe rack) or require very limited modifications to existing hardware. The cabling had to allow for full range of camera-collimator angles and camera-grating distances without requiring cable disconnection or power-down of system.

A third major component of the upgrade was to provide the potential for possible "niche" science. To this end, the upgrade included a requirement to accommodate a new suite of VPH gratings. This included restructuring the spectrograph layout to handle angles of incidence at $10^{o} < a < 70^{o}$.

All of these upgrade components were bounded by the following constraints:

- Use the existing camera(s), cables, room, and optical bench: this was to be a modest-cost "Upgrade", not a new system.
- Maintain use of the 11^{o} off-Littrow echelle configuration and the existing low-order surface-ruled gratings.
- Maintain the use of order-blocking filters.

- Maintain or improve the ergonomics of configuration changes and operations of the spectrograph.
- Maintain or improve the source acquisition TV and fiber rear-illumination system (ATV).

In fact, it was a strongly desired goal of the upgrade to eliminate the scissor stage used to insert the acquisition TV and back fiber illuminator into the collimator beam. This was desirable because the stage was very slow (insertion/removal time >1 minute) and thus negatively impacted observing efficiency.

2. OVERVIEW OF COMPLETED UPGRADE

The whole upgrade was done in phases over the course of 18 months. The first phase was the delivery and commissioning of the 740 l/mm VPH grating. Subsequent phases included delivery and commissioning of the new CCD system, the 3300 l/mm VPH grating, and finally installation and commissioning of the new collimator. Other associated activities included replacing the grating turret, new fiber toes for all three fiber cables, relocating the ATV and back fiber illuminator, and updating/upgrading software interfaces. Aspects of the phased upgrade that were reported on previously[8] will not be duplicated here. Instead, we concentrate on the aspects that have been completed since the last proceedings. For the details of the completed upgrade, readers are encouraged to visit the Bench Spectrograph Upgrade status web page[9].

2.1 CCD

The upgraded Bench system uses a STA 2600x4000 12 μm pixel device (STA1). This CCD has been in regular use for two years, and most of the salient features of the CCD and its electronics were described in a previous proceedings[8]. As noted there, STA1 substantially outperforms the earlier CCD subsystem in all significant respects. Here we note a few items that have been determined since the last report.

It has become apparent that STA1, which is a back-side illuminated thin device, has significant fringing redward of 7000 Å (see figure 1). This can be removed during data processing, but observers working redward of 7000 Å need to take several flatfield images each time the configuration is changed.

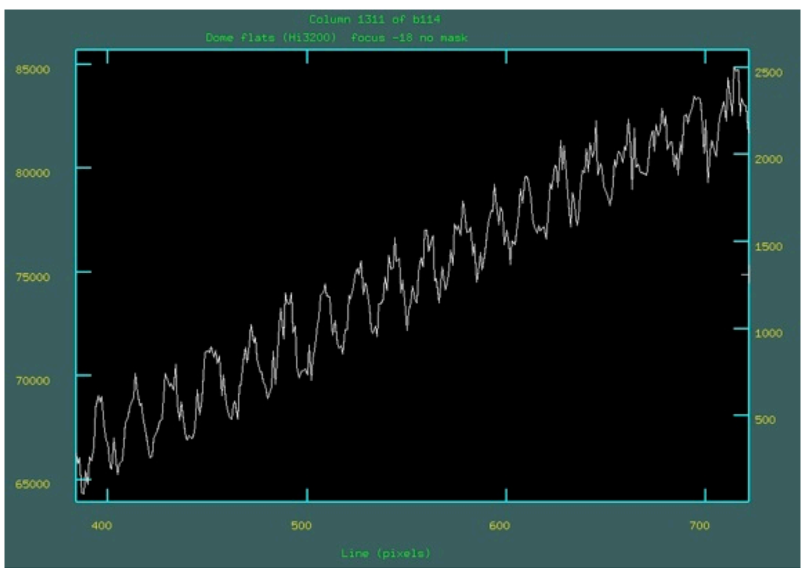

Figure 1. A sample of fringing for STA1 at around 7500 Å. Data are from a single column of a quartz lamp flatfield exposure and have been overscan subtracted.

It has been noted[8] that STA1 does have a measurable dark current, and that about 0.2% of the pixels (in unbinned mode) can be classified as "hot pixels" that have a very high dark count of 1200 e-/hr on average. Overall, the dark current has proved to be stable over time. In addition, the hot pixels were checked and seem to behave as linearly as other pixels over signal levels corresponding to the range 4700 e- to 74000 e-. This was determined by removing the overscan and then dividing a long exposure (t=16 seconds) by a t=2 seconds exposure for one test and by a t=4 seconds for another test. Using the IRAF[§] task imstat to measure the statistics in the region of [201:2400,201:3800] => 792000 pixels gave: (1) for 16/2: mean=8.015; for 16/4: mean=4.012. It is assumed that the means are not closer to 8 and 4 because of an uncertainty in the shutter timing.

Finally, it was recognized after the fact that because the STA1 CCD only has 2600 pixels of 12 μm each in the spatial direction, the blue-sensitive Simmons Camera loses 15 fibers corresponding to the top and bottom of the fiber foot because they are not imaged onto the CCD. Since there are also several broken fibers, there are only 66 usable fibers per configuration. In practice, this camera is used very rarely (typically less than once per year).

2.2 VPH Gratings

As a part of the upgrade, the project delivered two Littrow volume phase holographic gratings (VPH). The performance of the 740 l/mm grating was described previously[8], and so will not be repeated here. The details about the 3300 l/mm grating are presented later in this subsection.

In order to accommodate the two new VPH gratings, and allow for additional VPH gratings in the future, a number of steps were necessary. First, we had to restructure the spectrograph layout to handle angles of incidence with $10^o < \alpha < 70^o$. It was recognized that we would have to modify the turret that holds the gratings to accommodate the 3300 l/mm grating and potentially other large VPH gratings, and the flat for the 740 l/mm grating (the 740 l/mm grating itself is mounted on a second turret). In the end it was determined that purchasing an entirely new turret with supportable firmware would be preferred. Thus, a new turret was installed and commissioned. Storage cases and a new storage cart were designed and fabricated as well. The cart was designed to facilitate the installation and removal of the heavy VPH gratings by including a secure, repeatable mount on its top level, where the grating could be positioned to easily be picked up by a crane mounted on the Bench table.

In addition to the elements necessary to support a future suite of VPH gratings, the new 3300 l/mm VPH required the design of a special cell and mount. The mount allows for the precise, repeatable positioning of this grating, which is critical given its very steep blaze function. This mount could be used with other large VPH gratings. The cell was designed to (1) allow for the removal and replacement of the grating, so we can coat it in the future, and (2) allow for precision tuning of the grating in the cell to optimize its location relative to the optical path of the Bench.

The 3300 l/mm grating delivers spectral resolution in 1^{st} order similar to the 316@34° echelle in 11th order near 5100 Å and operates near peak efficiency between angles of 50° and 65° degrees (corresponding to central λ between 4643 and 5493 Å). The spectral coverage is roughly 235 Å across the detector and the spectral resolution ($\lambda/\Delta\lambda$) increases with angle from 11,000-19,800 for Hydra red cable, 7340-13,200 for the Hydra blue cable, and 4400-7925 for SparsePak. The grating is currently uncoated. When combined with the new STA1 CCD and the all-refractive collimator, it is now possible to do photon-limited science at or below the dark sky-level at high dispersion. Figure 2 shows the efficiency versus wavelength for a representative set up grating angles for the 3300 l/mm grating. There is a steep blaze function for this grating, even when well tuned to Littrow, as can be seen in the figure.

[§] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

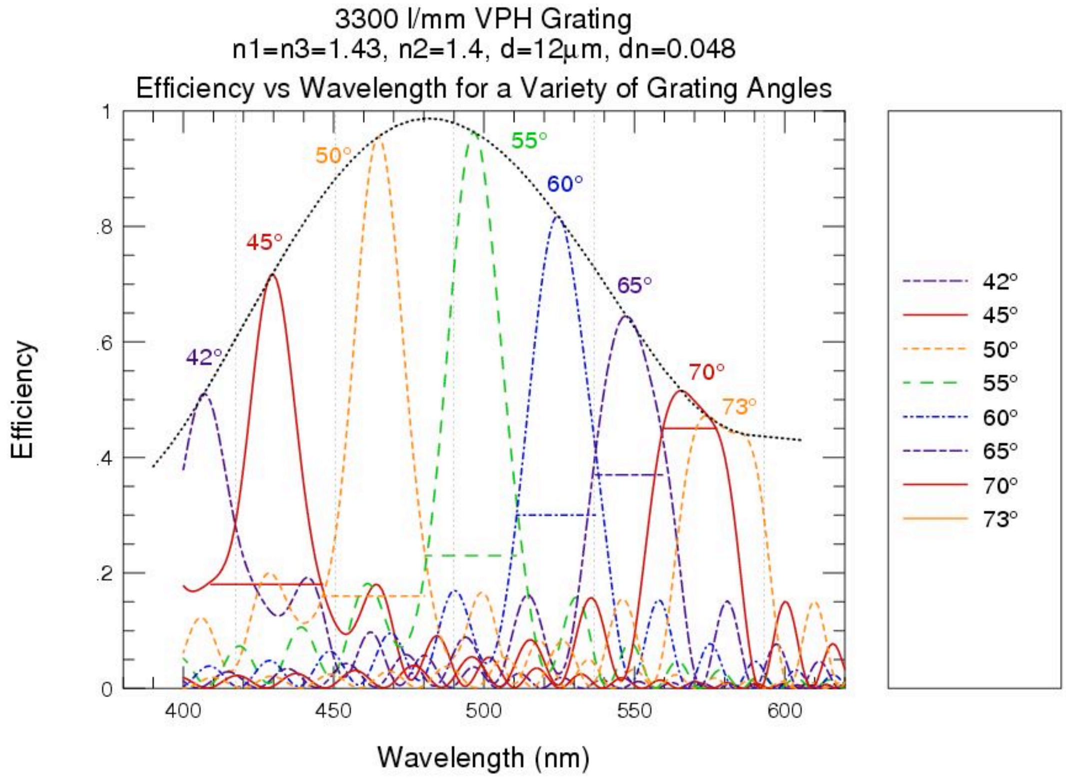

Figure 2. Predicted relative efficiencies for the 3300 VPH for several grating angles.

A comparison was done of the relative throughput of the 3300 l/mm and the 316@63º echelle grating, both centered at 5130 Å (α=57.8 degrees) using comparison lamp spectra with 300 second exposure times in unbinned mode. The Hydra red fiber bundle, which has 1.9" fibers, was used. The echelle was setup in order 11 with the X14 blocking filter. No blocking filter was used for the 3300 l/mm setup. The integrated flux ratios and full width half maxima (FWHM) were measured along the direction of dispersion for ~20 lines in each setup. These are shown in figures 3 and 4. It can clearly be seen that even uncoated, the 3300 l/mm grating is 2 times more efficient than the echelle in this setup. However, the VPH does not have the benefit of the anamorphic demagnification that improves spectral resolution. Thus, the FWHM of the lines in the VPH setup are about 30% larger than those in the echelle setup. The measured $\Delta\lambda/\lambda$ for the VPH from this configuration was 16,700. Depending on the requirements of the scientific program, an observer can choose whichever setup better suits his or her needs.

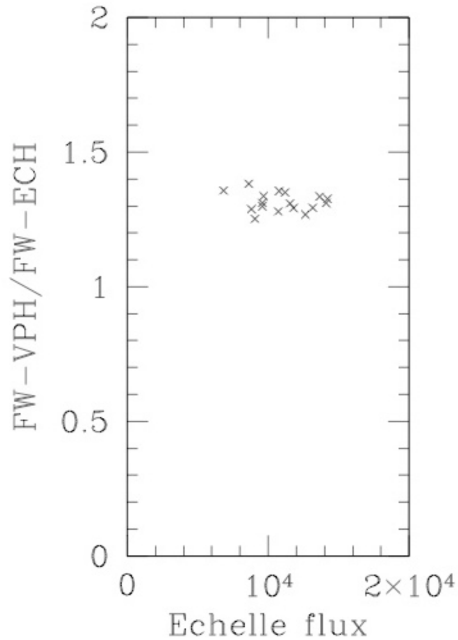

Figure 3. The measured ratios of line widths in the direction of dispersion for the 3300 l/mm VPH grating and the 316@63º echelle at 5130 Å (α=57.8 degrees). The anamorphic demagnification of the echelle narrows the lines about 30% compared to the VPH.

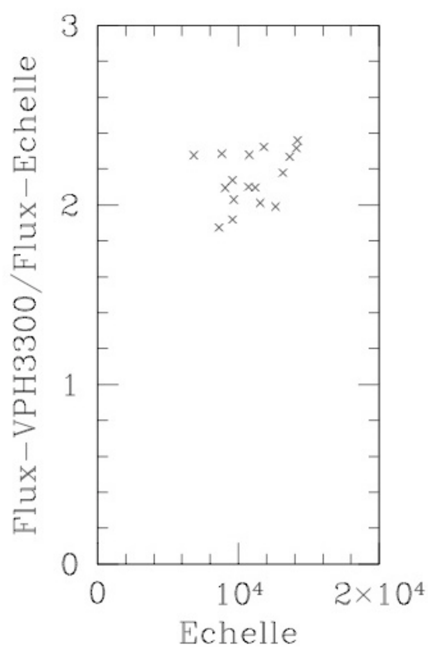

Figure 4. The measured flux ratios for ~20 lines for the 3300 l/mm VPH grating and the 316@63º echelle at 5130 Å (α=57.8 degrees). The 3300 l/mm grating is about twice as efficient as the echelle in this setup.

2.3 Collimator

The design process and selection of the final collimator optical design were detailed in the earlier proceedings[8]. Briefly, the collimator is an all-refractive design of 4 elements, nominally producing a 160 mm beam (per fiber) for f/5. The design has all fused-silica (FS) lenses, with the exception of one doublet-lens, which is flint glass (LF5) for chromatic balance (Lens 3). LF5 has above 90% transmission above 350 nm for the designed central thickness. The optics were optimized for f/5, but sized for f/4, except for a D-shaped cut in the objective (doublet) to allow the 11-deg camera-collimator angle for echelle configurations. To cover the spatial field, the largest element (doublet) has a clear aperture of 320 mm diameter. In addition to the collimator design, the rear element for the primary Bench camera, the BSC, was redesigned to serve as a field-flattener for the new, flat STA1 CCD.

The mechanical design-concept for the collimator incorporated a separate sub-bench that attaches on a semi-kinematic mount to the existing optical bench. The sub-bench was designed so that it could be fully assembled, internally aligned, and tested in the lab, and then delivered as a unit to the spectrograph for direct integration and alignment with the rest of the system. The sub-bench design is structurally rigid enough to allow for cantilevering 700 mm off the table to optimize layout (see previous proceedings for layout requirements[8]), and integrates the existing fiber-feed module and mount. The two singlets (Lens 1 and 2) are contained in one barrel, with the doublet (Lens 3) in a second barrel that contains a manual slide to stop the system down to f/5. Figure 5 shows a rendering of the new sub-bench positioned on the optical bench, with all the major components labeled.

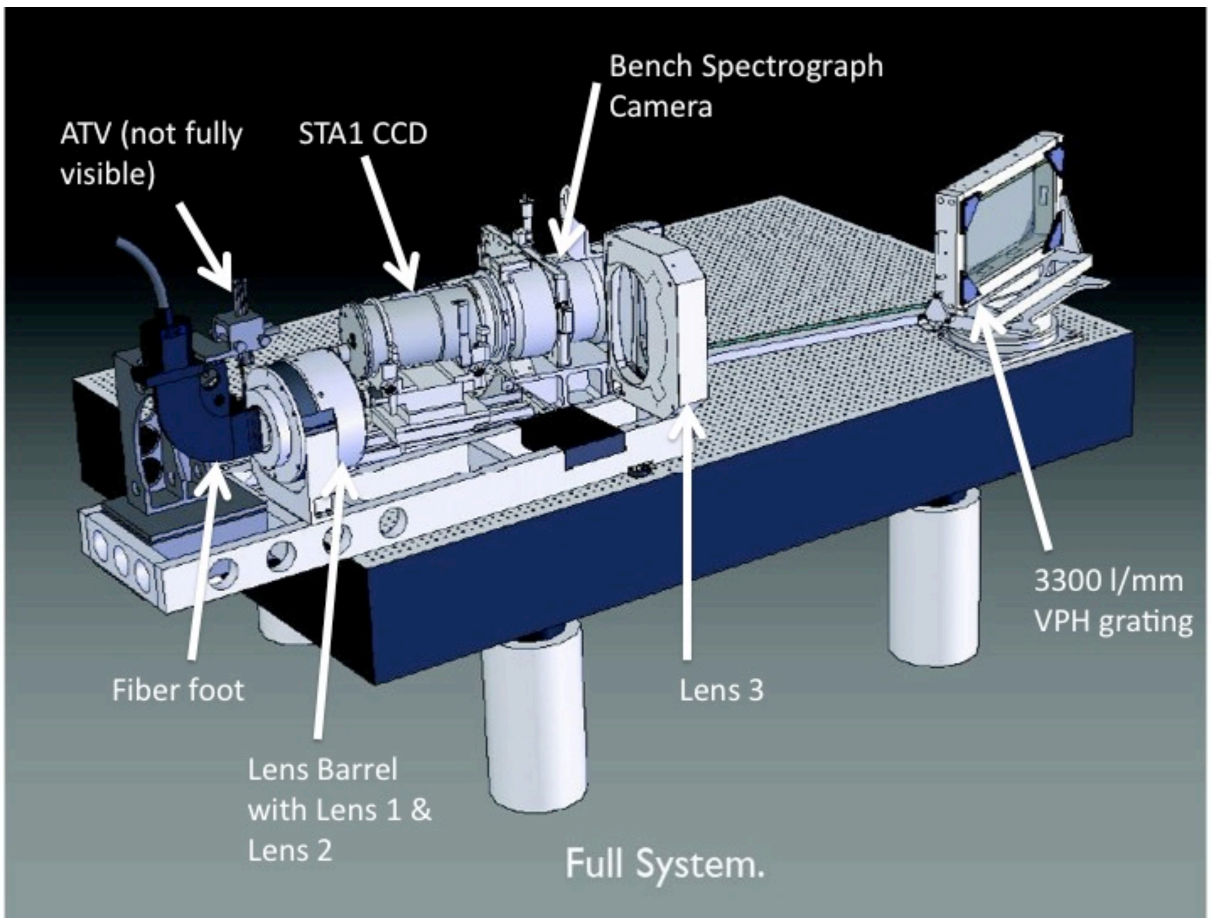

Figure 5. Rendering of the upgraded Bench Spectrograph. Not shown is the electronics box that mounts to the STA1 CCD or the BSC rear element.

The collimator was assembled and tested in the NOAO optical laboratory during October 2008. Once that testing was complete, the sub-bench and the lenses were shipped to the WIYN 3.5m for installation and commissioning, along with the new rear element for the BSC camera. Figure 6 shows the new collimator after installation while it was being aligned on 3 November 2008. After the initial alignment the 600@10° grating was installed and centered on λ= 7500 Å using the red Hydra cable. An order-blocking filter was used. Once reasonable camera and fiber foot foci were determined, it immediately became apparent that there was significant astigmatism in the system, which had not been present with the previous collimator. Extensive testing and troubleshooting was done over the next month in order to identify the source of the astigmatism. It was eventually traced to Lens 1 being improperly seated within its cell. The lens barrel containing Lens 1 and Lens 2 was sent back to the optical laboratory in Tucson, where it was disassembled, Lens 1 was re-seated, the barrel was reassembled, and shipped back to the telescope.

In addition to the astigmatism seen due to the poorly seated lens, it was discovered that the new rear lens element for the BSC was not located at the correct distance optically, introducing additional astigmatism. This problem was resolved by sending the BSC down to the optical laboratory. It was partially disassembled, and the retainer ring for the rear lens element was machined so that the element would be properly located. The camera was the reassembled, shipped back up to the telescope, and re-integrated with rest of the Bench system, and the alignment procedure for the collimator was repeated. This second alignment was successful, and the Bench was then re-commissioned. The performance of the system as a whole is reported in Section 3. The effective focal length of the collimator has been measured to be 776 mm.

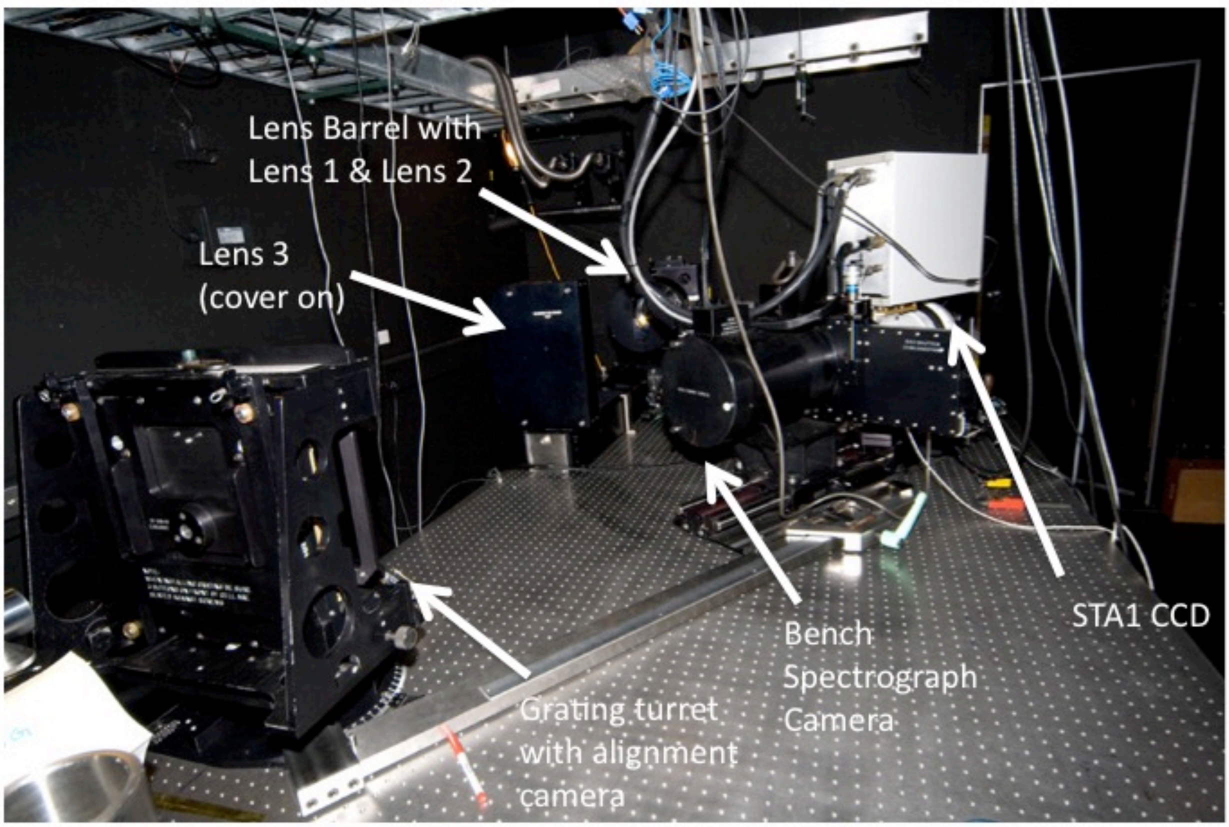

Figure 6. New collimator and most other major components on optical bench during the alignment procedure. Not shown are the fiber foot, the ATV, or the BSC rear lens element.

2.4 Focal surface module (ATV) and the fiber feed

The focal surface module consists of a rear-slit viewing camera and an LED fiber back-illuminator, referred together as the ATV. The purposes of this unit are to verify target acquisition (camera) and to verify positioning at the telescope focal plane (LED rear-illumination). In the original design this system sat on a motorized scissor stage in front of the foot between the foot and the reflective parabolic collimating mirror, remotely controlled via a GUI on the data acquisition computer. In the new all refractive design there was insufficient room between the end of the fiber foot and the first collimator element. A new scheme was devised for feeding the ATV from the side by modifying the ends of the fiber feet, known as the “toes,” and using one filter slot to insert a 45° fold-mirror to feed the ATV, which was relocated to a fixed position on the side of the foot. (See figure 5.) This design was described in the previous proceedings[8].

2.5 Operational and software interface

The upgrade included several Graphical User Interfaces (GUIs) for use in observing, as well for use in setting up the Bench Spectrograph and for calibrations and target acquisition. The decision was made to replace the command line based interface used by previous CCD’s electronics with a simple GUI for observers to use. The new observing interface is called the Modified Observing Platform (MOP) and was designed to communicate with the MONSOON electronics that operate the new CCD, STA1, which was provided as a part of the upgrade. This GUI replicates all the options provided by the previous system, including the selection of exposure time, number of exposures, and exposure type. It allows the observer to select the directory where the data will be written, set the image number, and add a title and comments that will be captured in the header information of the image. It automatically communicates with the Telescope Control System (TCS) to populate the image headers with required information such as target coordinates, airmass, etc. In addition, it allows the user to selected the gain and binning that are best suited to their scientific program. A snapshot of the observing interface is provided in figure 7.

Figure 7. The new user interface for observing with the upgraded Bench Spectrograph.

Two existing GUIs needed to be modified to ensure that they worked with new turret and collimator. Although not originally part of the Bench Upgrade, a decision was made to port the GUI software for these two GUIs from SunOS to Linux in order to improve their long-term supportability prior to modifying them for the upgrade. The first GUI that was modified is the Bench Setup GUI. This GUI is normally used by observatory support personnel while they are installing the requested grating for an observing run. This includes such things as setting the required grating position angle, setting the camera and fiber foot foci, and inserting an order-blocking filter, if required. In addition to being modified to correctly communicate with the new grating turret, the needed information for setting up the two new VPH gratings was added, a color-coded status system was implemented, the information about the filter slots was updated to reflect the removal of one slot and the incorporation of a second slot for use with the ATV, and two status buttons that track the communications with the grating turret were added. See figure 8 for a snapshot of this GUI. Normally an observer would not need to use this GUI except to monitor the status of the grating and turret.

The second GUI is the primary Bench GUI. This GUI provides information about the current configuration of the Bench Spectrograph, including grating, wavelength coverage, and dispersion. This information is often of interest to the observer, and can be used as a first-order check that the system is configured the way he or she desired. (The final check should always be to establish the wavelength coverage using comparison lamps.) Observers use this GUI to install or remove the acquisition TV and/or back fiber illuminator. The former is often used with SparsePak while acquiring objects and positioning them in the correct fiber. The latter is used with Hydra, mostly to monitor the progress of field configurations. This GUI was modified to properly report the configuration information if one of the new VPH gratings is used, or to reflect the dispersion depending on the binning chosen. In addition, a new slide bar was implemented to control the illumination of the ATV or back-fiber illuminator. A snapshot of this GUI can be seen in figure 9.

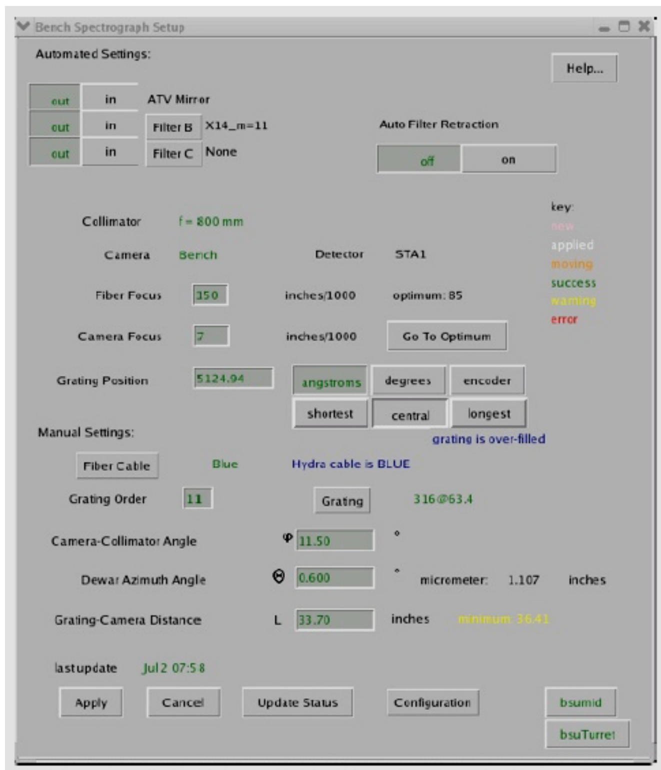

Figure 8. The new setup GUI for the Bench Spectrograph. In addition to duplicating the capability of the former GUI, a color-coded status reporting system was installed (color key is visible on the right about a quarter of the way down), and two status buttons were added for the two processes that run the Bench (see bottom right corner.)

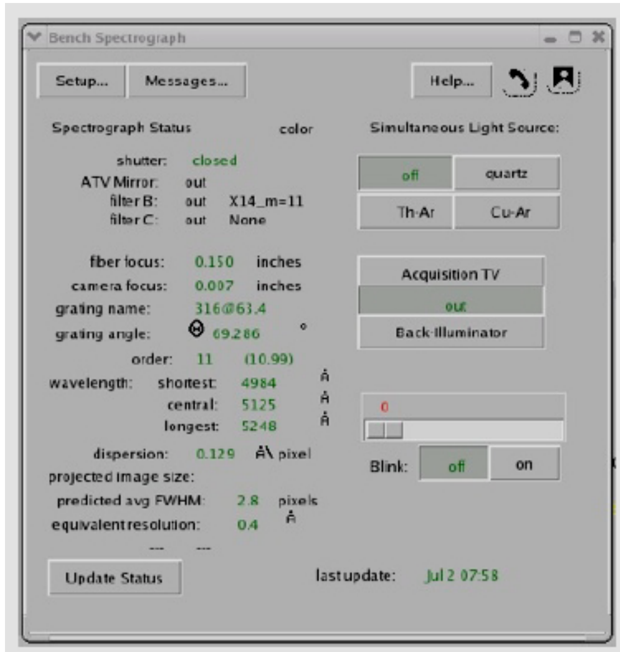

Figure 9. The new Bench calibration and object acquisition GUI. This allows the observer to control the various calibration lamps (see right, about one quarter way down), as well as insert either the acquisition TV or back illuminator and control the illumination of either to aide in target acquisition (see middle and lower quarter right). The left side reports the details of the current grating configuration.

3. SYSTEM PERFORMANCE OF THE UPGRADED BENCH

3.1 Delivered image quality

One of the main goals of the upgrade project was to minimize instrumental resolution loss (< 20%) due to the new collimator. Predictions shown in the earlier proceedings[8] indicated that there should be on average no loss with the smallest (200 µm) red Hydra fibers, 0-15% losses for the 300 µm blue Hydra fibers, and 10-20% losses with the 500 µm SparsePak fibers. The actual relative loss will depend on the configuration.

To test the delivered image quality we looked at data obtained with the 600@10º grating centered at 5600 Å with no blocking filter. The Hydra red cable, which has the smallest fibers, was used. This results in a large (>2700 Å) coverage. The data were binned 2x2 so that each pixel is 24 µm, allowing a direct comparison with the T2KA CCD, which had 24 µm. This particular configuration was predicted to have essentially no change in the delivered image quality after the upgrade. A full width half maximum (FWHM) of ~2.2 pixels was measured on average. This is consistent with typical FWHMs measured in this configuration prior to the upgrade. Even more impressively, the variation from the blue end to red end of the spectrum is only ~0.1 pixels. This indicates that we have achieved our goal of minimizing the instrumental resolution loss.

3.2 Relative throughput improvement

The combination of the new collimator and the new fiber toes was expected to significantly decrease the vignetting both is the spatial and spectral directions. An example of this improvement is show below for the Hydra red cable using the low dispersion 600@10º grating centered at 5200 Å with no blocking filter. The data were taken before the upgrade began, and then after all the major components of the upgrade were installed and the spectrograph had been re-commissioned. The data were overscan and bias subtracted.

Figures 10 and 11 show a cross-cut of the fibers in the spatial direction before and after the upgrade. Two things can be seen in these images. First, the vignetting in the spatial direction has been significantly reduced. This is apparent by the relatively uniform response of the fibers across the field (as opposed to the inverted "u" shape in the response of the fibers due to the vignetting). The remaining variations from fiber to fiber are most likely due to the quality of the prism attached to the input end of the fiber and inherent stresses in each fiber. Gaps represent broken fibers. Second, looking along the bottom of the plot, it can be seen that the fibers are now very cleanly separated spatially, i.e. there is no flux overlap as can be seen in the graph before the upgrade, especially at the edges.

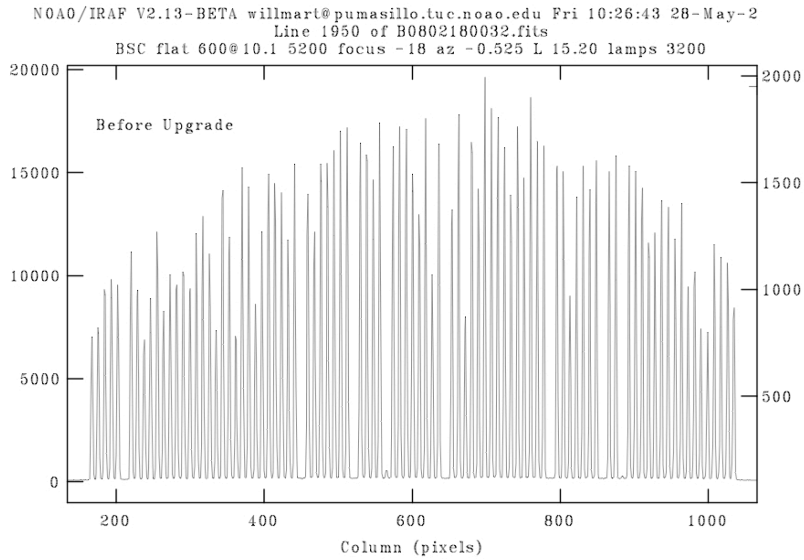

Figure 10. A cross-cut of the fibers in the spatial direction before the upgrade. The vignetting in the spatial direction produced the inverted "u" shape in the overall response of the fibers. Other variations from fiber to fiber are due to the quality of the prism attached to the input end of the fiber and inherent stresses in each fiber. Gaps represent broken fibers.

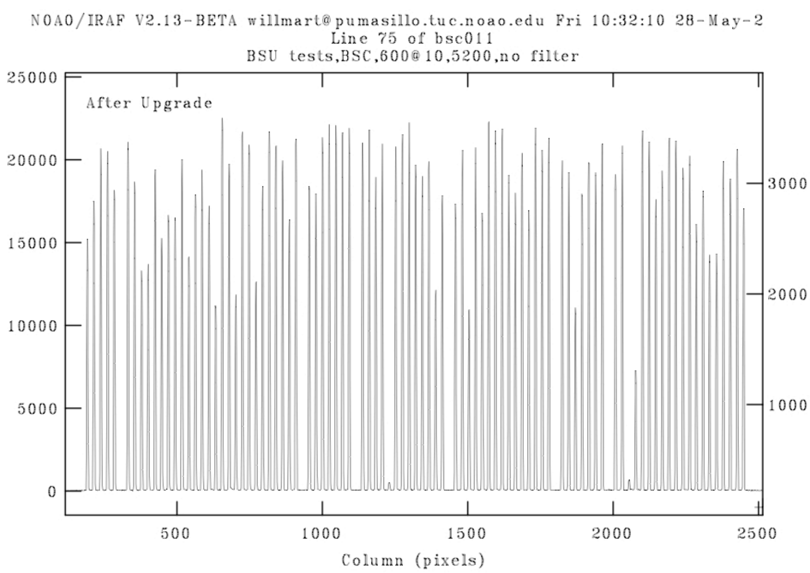

Figure 11. A cross-cut of the fibers in the spatial direction after the upgrade. The inverted "u" shape is gone. Remaining variations from fiber to fiber are due to the quality of the prism attached to the input end of the fiber and inherent stresses in each fiber. Gaps represent broken fibers.

A comparison of "before and after the upgrade" quartz lamp flatfield data for seven evenly spaced fibers was done to check the relative throughput improvement in the spectral direction. The configuration was once again the Hydra red cable using the low dispersion 600@10º grating centered at 5200 Å with no blocking filter. The data were overscan and bias subtracted. The fibers were then extracted and dispersion corrected to a scale of one Angstrom per pixel, then corrected for the different gains of each detector (T2KA before and STA1 after). Finally, a small correction (~6%) was applied to correct for the drift in the flatfield lamp brightness as determined by the MiniMo data.

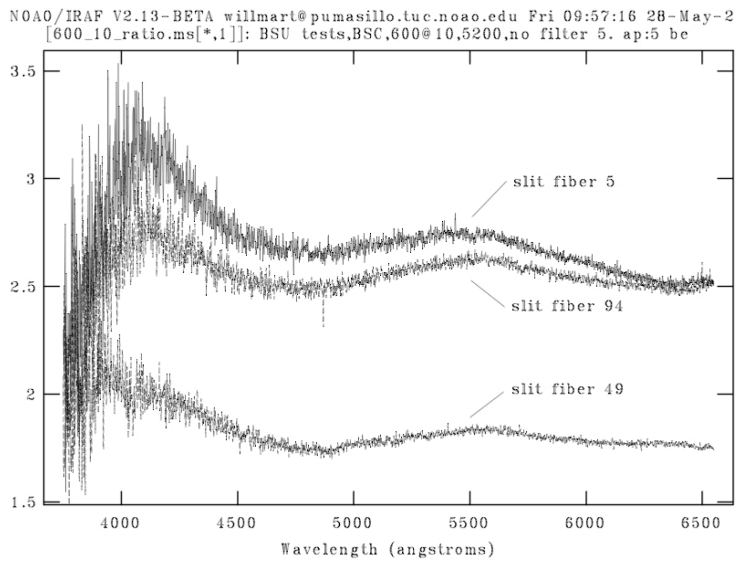

Figure 12. A comparison of the relative throughput improvement before and after the Bench Spectrograph upgrade as a function of wavelength for three red Hydra fibers. Fiber 49 is near the center of the fiber pseudo-slit, while fibers 5 and 94 are near the ends.

Figure 12 shows the results from three fibers. Fibers 5 and 94 are near the ends of the fiber pseudo-slit, where vignetting was most severe, while fiber 49 is near the center. It can be seen that the gain in the center is about a factor of ~1.8-2 while for the edge fibers in this configuration the improvement is ~2.7-2.8. The flatfield lamp flux is very low at the blue end of the spectrum, resulting in a noisy and less accurate measurement below 4900 Å. Potential sources of uncertainty in the measurement include scattered light effects and the accuracy of the CCD gains used, but these are expected to be small effects (of order a few percent).

3.3 On-sky performance

The on-sky performance has been tested in a several different configurations. Reported here are results using SparsePak. Data have also been taken with Hydra, and the analysis of that data is currently underway.

The most complete comparison, which was done using SparsePak and the 3300 l/mm grating at 58° (central $\lambda \sim 5170$ Å) with the spectrophotometric standard star Feige 34, is shown in figure 13. The “before” data were taken in April 2006, prior to the implementation of any of the phases of the upgrade. The “after” data were taken in 2009, at a time when all phases of the upgrade were complete. In the data reduction process, the different binning and pixel size were accounted for so that “per pixel” in the spectral dimension is the same thing for both data sets. Likewise the data were scaled to account for the different CCD gains. Since these data were taken using the large (4.7”) SparsePak fibers, and the full spectrum is extracted in the spatial direction, it is possible to calculate the total flux. The star was placed in the central fiber (fiber 52) of the IFU.

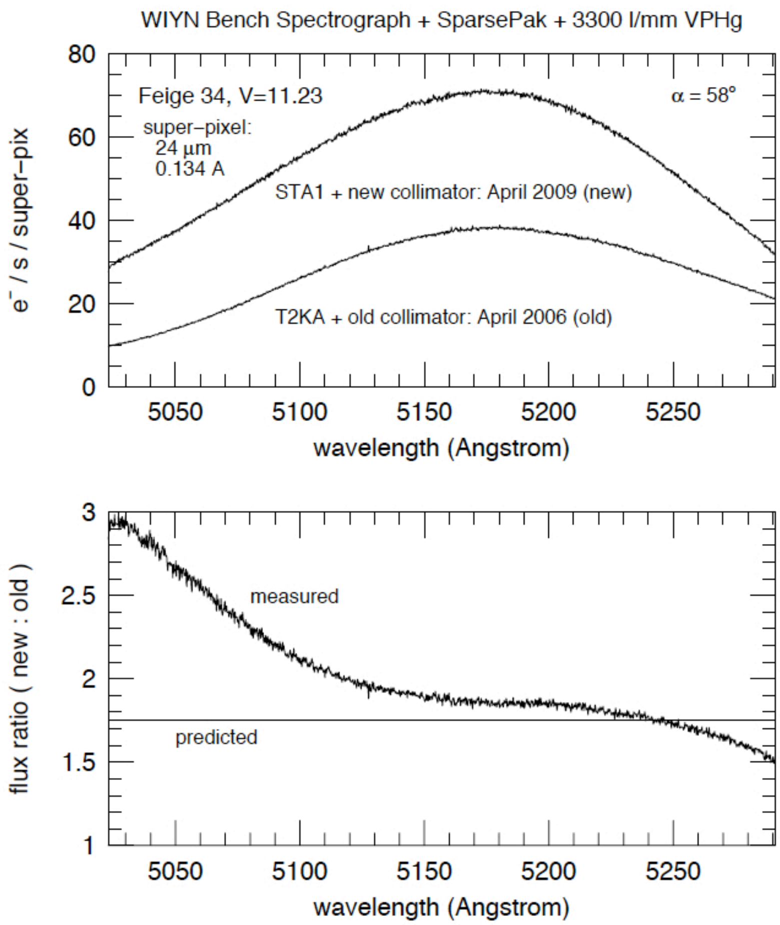

Figure 13. A comparison of the system throughput before and after the Bench Spectrograph upgrade. The top panel shows the flux as a function of wavelength, while the bottom panel shows the flux ratio, also as a function of wavelength.

The ratio in the bottom panel is very close to the factor of ~1.6-1.8 improvement that was predicted (see figure 7, left panel, in the previous proceedings[8]) for the low-order gratings before and after the upgrade. Even though this measurement is with a VPH, this is the correct comparison, since the measurement presented here is a comparison of the 3300 l/mm grating against itself. The 3300 l/mm point presented in the previous proceedings' figure 7 (left panel) is the ratio of the flux expected with the 3300 l/mm VPH grating with the new collimator and CCD plot to the flux from the *surface-ruled gratings* and the old collimator and CCD.

The change in the flux ratio with wavelength in the bottom panel of figure 13 is due to the spectrograph not being set up at Littrow in April 2006, so it was slightly off the super-blaze. The April 2009 spectrum is dead-on the super-blaze. This results in the slight shift toward the central wavelength (top panel) in the peak response. That shift is what causes the modulation in the ratio with wavelength in the bottom panel.

Using the data from the April 2009 run, we calculate that the peak total system efficiency at the blaze of the 3300 l/mm VPH at 58ºis 19%. This includes atmosphere, telescope, fiber losses (aperture and attenuation), plus all of the losses in the spectrograph and detector. This is slightly higher than our prediction (right panel of figure 7 of the previous proceedings[8]), but not unreasonable, especially if the mirrors were better than predicted.

Additional measurements of the standard stars Feige 34 and G191B2B were analyzed. The "before" data were taken on 19 February 2008 using SparsePak with the 600@10º grating centered at 5200 Å with no order-blocking filter and no binning (24 μm pixels). The "after" data were taken on 24 January 2009 using SparsePak with the 600@10º grating centered at 5600 Å with an order-blocking filter and binning 4x3 (12 μm pixels unbinned). The standard star was placed in the central fiber (fiber 52) of the IFU for both observations. The analysis indicates a ~70% increase in throughput for

Feige 34, and a ~50% increase for G191B2B. This is broadly consistent with the predicted increase of a factor of ~1.6-1.8 for this wavelength region. (See the left panel of figure 7 in the previous proceedings[8].) In particular, for these observations, the configuration setup was slightly different (different central wavelength, filter usage, and effective pixel size), some corrections had to be made. Also, the "after" data were not obtained by the Bench commissioning team, so there are some uncertainties that may affect the quality of the data. For instance, the accuracy of the placement of stars in fiber 52 and the sky conditions (clouds, seeing) at the time of the observations.

Finally, a comparison of an extended source, the galaxy J1152-02 was done. The "before" data were taken on 1 March 2005 with SparsePak and the 316@63.4° echelle centered at 6700 Å with an order-blocking filter. The "after" data were taken on 16 April 2009 with the same setup. The echelle configuration was strongly affected by vignetting prior to the upgrade, and so a significant improvement was expected for fibers far from the center of the slit. Two fibers were examined, fiber 31, which is adjacent to the central fiber (fiber 52) as projected on the sky, and fiber 82, which is offset 20" from the central fiber as projected on the sky. In this case, a sky spectrum was subtracted from each extracted fiber spectrum, and then three emission lines (Hα and the two [N II] lines and the continuum flux densities were measured for each fiber. On average, the flux ratio for the more central fiber, fiber 31, was 1.5, while the average flux ratio for the fiber 82 was 5.2. This clearly indicates that we have achieved the anticipated gain in throughput for fibers that were vignetted prior to the upgrade.

4. SUMMARY AND FUTURE PLANS

The upgraded Bench Spectrograph on the WIYN 3.5m telescope has been successfully commissioned. We have demonstrated that the upgraded Bench has met the project goals of increasing the average spectrograph throughput by ~60% while minimizing instrumental resolution loss (< 20%) over a wavelength range of 330-950 nm. For example, with the 600@10° l/mm surface-ruled grating there is no evidence of instrumental resolution loss, while the on-sky throughput in the central SparsePak fiber has increased by at least 50-70%. With the newly commissioned 3300 l/mm VPH grating and SparsePak, the peak total system efficiency at the blaze angle of 58º is 19%. This throughput is comparable to what is being achieved with much more recently deployed spectrographs, and ensures that the WIYN 3.5m will continue to be a competitive optical spectroscopic telescope for its aperture.

We continue to update our knowledge of the entire Bench system as different configurations are used. While this upgrade is complete, the upgraded system could enable several significant future developments. These include:

- CCD-subsystem: implementation of dual-amp read-out and associated data formatting and reduction software for increased read-out speed.
- VPH grating sub-system: (1) development of a full suite of gratings and (2) implementation of a larger optical bench to do away with second turret and fold-mirror.
- Fiber feeds: (1) New IFUs to replace and augment DensePak.[4] (2) Multi-object IFUs and filtered multi-slit modes for Hydra.[8] (3) Replacement of current single-fiber MOS system with new Polymicro FBP-series product, revisiting core diameter to re-optimize resolution-throughput product in context of current telescope delivered image quality and fiber-positioning accuracy.

REFERENCES

[1] Barden, S. C., Armandroff, T., Massey, P., Groves, L., Rudeen, A. C., Vaughnn, D., Muller, M., "Hydra – Kitt Peak multi-object spectroscopic system," ASPCS, 37, 185-202 (1993).

[2] Barden, S. C., Armandroff, T., Muller, G., Rudeen, A. C., Lewis, J., Groves, L. "Modifying Hydra for the WIYN telescope – an optimum telescopes, fiber MOS combination," Proc. SPIE 2198, 87-97 (1994).

[3] Barden, S. C., Armandroff, T., "The performance of the WIYN fiber-fed MOS system – Hydra," Proc. SPIE 2476, 56-67 (1995).

[4] Barden, S. C., Sawyer, D. G., Honeycutt, R. K., "Integral field spectroscopy on the WIYN telescopes using a fiber array," Proc. SPIE 3355, 892-899 (1998).

[5] Bershady, M. A., Andersen, D. R., Harker, J., Ramsey, L. W., Verheijen, M. A. W., "SparsePak: a formatted fiber field unit for the WIYN telescope Bench Spectrograph. I. Design, construction, and calibration," PASP 116(820), 565-590 (2004).

[6] Bershady, M. A., Andersen, D. R., Verheijen, M. A. W., Westfall, K. B., Crawford, S. M., Swaters, R. A., "SparsePak: a formatted fiber field unit for the WIYN telescope Bench Spectrograph. II. On-sky performance," ApJS 156(2), 311-344 (2005).

[7] Meixner, M., Smee, S. Doering, R. L., Barkhouser, R. H., Miller, T., Orndorff, J., Knezek, P., Churchwell, E., Scharfstein, G., Percival, J. W., Mills, D., Corson, C., Joyce, R. R., "Design Overview and Performance of the WIYN High Resolution Infrared Camera (WHIRC)," PASP 122(890), 451-469 (2010).

[8] Bershady, M., Barden, S., Blanche, P.-A., Blanco, D., Corson, C., Crawford, S., Glaspey, J., Habraken, S., Jacoby, G., Keyes, J., Knezek, P., Lemaire, P., Liang, M., McDougall, E., Poczulp, G., Sawyer, D., Westfall, K., Willmarth, D., "WIYN bench upgrade: a revitalized spectrograph," Proc. SPIE 7014, 15-25 (2008).

[9] www.wiyn.org/instrument/BSU/bench_upgrade.html