Investigating spectrograph design parameters with the Yale Doppler diagnostic facility

Christian Schwab*a, Thales Gutcke*b, Julien F.P. Spronck*a, Debra A. Fischer*a, Andrew Szymkowiak*a
(*Yale University, New Haven, USA, bZAH-Landessternwarte, Heidelberg, Germany)

ABSTRACT

The detection of earth-like exoplanets with the Doppler technique requires extreme precision spectrographs stable over timescales of years. The precision requirement of 10 cm/s is equivalent to a relative uncertainty of 3x10^{-10}, and, with the typical dispersion of the Echelle spectrographs used for this purpose, translates to a shift of a few nanometers of the spectrum on the detector. Consequently, the instrument must be well understood and optimized in every component and detail. We describe the Yale Doppler diagnostic facility (YDDF), a dedicated bench mounted Echelle spectrograph in our lab at Yale University, which will be used to systematically study the influence of different components at this precision level. The spectrograph bench allows for a flexible optical configuration, high resolution and sampling, and wide spectral coverage. Further, we incorporated a turbulence and guiding simulator to realistically reproduce the situation at the telescope, enabling end-to-end tests of important parameters.

Keywords: Spectroscopy, exoplanets, radial velocities, Doppler method, Echelle, spectrograph, iodine cell

1. INTRODUCTION

High resolution, high precision Echelle spectrographs have been the workhorse instruments for the exoplanet community over more than two decades. The rapid development of the field into the diverse topic it is now is largely due to the discovery and confirmation of more than 500 exoplanets with the Doppler technique since 1995, which spurred the conception of new planet formation theories as well as paving the way for the development of the excellent, dedicated instruments to find and study exoplanets with different techniques, that have been developed since. This in turn drives the need for higher precision with the Doppler technique, to keep in step with the discovery of ever smaller planets.

Considering the importance of spectrographs, it is somewhat surprising that comparatively few attempts have been made to systematically study the influence of spectrograph parameters and design choices on the performance of the instrument for radial velocity (RV) measurements. Recently, the focus of interest has been fibers with optimized scrambling properties to stabilize the spectrograph illumination and the line image. Investigation by several groups shows the superior scrambling properties of non-circular fibers and the optical properties of various geometries and material combinations have been characterized [1]. However important these measurements are, these are only secondary indicators for the impact of different fibers on the RV performance of the spectrograph. The complex and very precise wavelength calibration and spectral extraction has to be simulated based on the above measurements, and evaluated with radial velocity precision in mind. The same holds true not only for the choice of fibers, but also for parameters like the input coupling, external scrambling techniques, the effect of image or pupil slicers, the placement of the pupil in the spectrograph, aberrations in the spectrograph optics, different optical layouts, ghosts and straylight, temperature and pressure control. A great example for this kind of investigation is the work of Baudrand and Walker [2] on fiber agitation and pupil projection, more than a decade ago.

To be able to study the impact of various hardware choices, benchmark different components against each other and calibrate our models of RV precision as a function of spectrograph parameters, we set up a dedicated Echelle spectrograph in our lab at Yale University. The optical design of the current bench setup is derived from the CHIRON spectrograph, which is advantageous as this is our primary scientific instrument, and also allowed for a cost efficient implementation. However, the layout and mounting of the YDDF spectrograph is rather flexible, and various different layouts can be implemented. We are in the process of obtaining additional hardware (optics and mounts) to facilitate a wider range of basic design choices; for example different values for sampling and cross dispersion, but also a reconfiguration to a true Littrow or a white pupil design.

*christian.schwab@yale.edu
Fig. 1: The YDDF setup on the optical bench at Yale. The fiber entrance is on the far left, the grating mount in the back. In the center the cross disperser prism with the kinematic mount for the collimator visible below. On the right, the Takahashi refractor with FLI focuser and CCD camera mounted to the back.

Fig. 2: Schematic of the YDDF bench. Light from calibration lamps is fed via an optional turbulence simulator to a test fiber. Lenses L1 to L3 provide a slow focus and a small collimated beam. The Echelle grating is used with a gamma angle of 6 degrees, and followed by the cross disperser. A refractive camera images the spectrum onto the detector, which is mounted on the refractor.
Fig. 2 shows a schematic of the spectrograph. The instrument consists of the following basic components:

- **Fiber coupling bench**: we have a test bench for FRD measurements which allows us to couple light into a test fiber under controlled conditions. We have also set up a rotating turbulence phase screen, which introduces Kolmogorov-like turbulence to the wavefront, and enables us to test the fiber under realistic conditions (Fig. 3) [3].

- **Fore optics**: relay optics provide a slow focus to insert image slicers as well as a collimated small beam for gas cells.

- **Main bench**: A collimator, an Echelle grating and a cross disperser disperse the light; the camera images the Echelle spectrum onto the detector

- **Detector system**: A thermoelectrically cooled CCD camera with automated focuser

Fig 3: The phase mask to produce a Kolmogorov like wavefront turbulence. It is mounted on a small DC motor with variable speed. The mask is a glass substrate with hairspray applied to produce the phase variation.

### 2. OPTICAL LAYOUT

The optical layout is a pseudo-Littrow design as implemented in CHIRON, and described in [4]. For YDDF, we adopted a slightly smaller grating and matched optics. The grating is a Richardson/Newport R2 grating with 31.6 g/mm on a 30 mm thick Zerodur substrate and a ruled area of 102 x 204 mm. The collimator is a 108 mm f/4 parabola. This allows us to use fibers directly in the focus of the collimator. To be able to insert image slicers, slit masks or an Iodine cell, we use a similar fore optics train as in CHIRON. The fiber aperture is reimaged by an achromatic doublet L1 with a magnification of M = 13.6. In the slow intermediate focus we can insert image slicers or slits. The separation between the lenses provides ample space, and the slow beam enables us to use Bowen-Walraven type slicers without significant image blur in the final spectrum due to defocus between the slices. A second achromat, L2, recollimates the light with a beam diameter of about 2.5 mm. Iodine cells, filters, as well as etalons for PSF calibration, are inserted here. A third achromat L3 refocuses the beam with a focal ratio matched to the collimator. The small 90 degree mirror in front of L3 folds the beam to use the collimator like a Newtonian telescope. The collimated beam size is about 90 mm in diameter.
The optics are mounted on kinematic or x/y/z mounts, respectively. While the alignment of the dispersive elements is critical, and we consequently use very simple mounts for the Echelle and the prism, we found it very helpful to have very precise and orthogonal mounts for the elements from the fiber to the collimator. The fiber is mounted in a true Gimbal mount which can tilt the fiber about a pivot point on the fiber surface to account for different fiber end angles between fibers. The highly powered lenses L1 and L3 are mounted in precisely centered threaded barrels for focusing without crosstalk to the lateral alignment.

We use a commercially available high-end amateur telescope as the camera lens. The Takahashi FSQ 106 ED is a modified Petzval type lens with 4 lenses in 4 groups. The optical design is proprietary; however, some data on color correction, spot size and field curvature is available, see Fig. 5 [5, 6]. The refractor is intended for large field of view astrophotography, and provides very good correction on a large image circle. Focal reducers and Barlow lenses are available to change the focal length to accommodate either a higher dispersion grating or yield better sampling.

As we do not use a white pupil design, the front lens of the Takahashi is the limiting aperture, despite its size of 106mm, which is larger than the grating width. The beam size of 90mm is a compromise between throughput and resolution. Fig. 6 shows the total vignetting on the front element as function of beam size. With a 90 mm beam diameter and a camera focal length of 530 mm, the total magnification of the spectrograph becomes $M_{tot} = 1.23$. 

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**Fig. 4:** Interferogram of the Echelle grating in Littrow condition as provided by Newport; on the right side, power has been removed. The peak to valley wavefront error is 0.26 waves, after removing power about 0.16 waves.

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**Fig. 5:** Chromatic focal shift, vignetting, and spot diagrams for the Takahashi FSQ 106 ED as shown in the manufacturer’s manual. The box size for the spot diagrams is 100 micron.
We use a large prism made from Schott F2 glass as the cross disperser. The prism is assembled from two 22.5 degree prisms cut from a cube and optically cemented to form a single 45 degree prism. The surfaces are dielectrically anti-reflection coated. The transmitted wavefront over a circular 100 mm aperture is lambda/4 peak to valley (Fig. 7).

The prism provides a linear dispersion of 138 Å/mm at 500 nm with the 530 mm focal length of the Takahashi lens. This separates the center of two adjacent orders by 320 µm, or 36 pixels. Assuming an inter-order gap of about 10 pixels, this dispersion is enough to use entrance apertures (fibers or slicers) with up to 200 micron µm in the cross dispersion direction. At 860 nm, this value is reduced to about 160 µm. The prism is also suitable to be used in double pass, to set the spectrograph up in real Littrow configuration, using the Takahashi lens in double pass as collimator as well as camera.
3. DETECTOR

The detector is the Kodak KAF16803 CCD in a commercial FLI ProLine camera. The CCD has 4k by 4k, 9 µm square pixels, on a 36 by 36 mm substrate. The spectral response of the CCD extends from below 400 to over 900 nm, with a peak quantum efficiency (QE) of about 60% in the iodine region (see Fig. 8).

The large detector provides ample space for recording either a large wavelength range or multiply sliced spectra with a correspondingly higher cross dispersion to separate the orders. With our R2, 31.6 g/mm grating, 500 nm (the beginning of the iodine region) is recorded in order number 113; the free spectral range (FSR) is 4.4 nm. The 4096 pixels of the chip can provide a maximum of 2048 resolution elements, corresponding to a theoretical, maximal resolution of 230000 if the full FSR is spread onto the width of the chip. In practice, this number is somewhat lower due to the anamorphic magnification of the grating which leads to an inhomogeneous sampling across one order. The native 530 mm focal length of the Takahashi lens theoretically provides a two pixel resolution of 129,000, and a linear dispersion of 2.25 Å/mm. With a dedicated 1.6x teleextender lens available for the Takahashi, the two pixel resolution becomes 206,000, and the FSR spans nearly the full width of the chip.

The Proline camera with the Kodak chip is convenient because it employs thermoelectric cooling via a Peltier element. We run the CCD at a temperature of -20°C. The dark current becomes negligible for our typical exposure times. Further, the camera has an iris shutter mounted in front of the CCD, which relaxes the requirements on background illumination when running tests, as the CCD is only illuminated through the actual exposure. However, one has to make sure to use exposure times significantly longer than the time it takes for the shutter to open, to avoid uneven illumination. The readout noise per pixel of our particular camera is reported as <9 e-/pixel by FLI. We use the camera with a dedicated focuser, the Atlas model from FLI. Focusing is achieved by moving only the camera, which again is facilitated by the small weight and the absence of a LN2 dewar. The back of the camera is air cooled with fans, which introduce vibrations. We yet have to measure to which extent this affects the setup, but optionally a water cooled back plate is available. The choice of camera for such a setup is an engineering compromise; the aforementioned points add to the flexibility and convenience of this camera, however, caution has to be taken concerning the pixel structure of the CCD, which is different from the standard scientific back illuminated device. The Kodak KAF CCD is a front illuminated device, using Kodak’s transparent indium-tin-oxide gate structure technology. The pixels are equipped with cylindrical microlenses which focus the incoming light onto the transparent part of the electrodes [8]. Consequently, the intra-pixel spatial response is most probably rather non-uniform. Oversampling the spectrum will reduce the impact of this.

Fig 8: The quantum efficiency curve of the Kodak KAF-16803 CCD [7].
4. TEMPERATURE AND PRESSURE CONTROL

Temperature and pressure influence the behavior of an optomechanical system. Changes in pressure induce a change in the refractive index of the surrounding medium, which obviously leads to a change in the optical prescription of the system. In case of an Echelle spectrograph, this has the most impact on the dispersive elements with the large optical path differences involved. For an R2 grating, the optical path difference between the top and the bottom of the beam after diffraction on the grating is roughly four times the beam diameter; with a beam size of 130 mm, this amounts to roughly one million waves in the center of the iodine region. Even a very small change in pressure leads to a shift of the spectrum that exceeds the desired RV precision by several orders of magnitude. For a peak to valley variation in atmospheric pressure of about 10% we calculate a spectral shift on the order of 1 km/s. However, this effect should be calibrated out with the Iodine cell technique (as with all simultaneous calibration techniques), as the reference spectrum imprinted on the stellar light experiences the same spectral shift. In reality it is not clear how well the calibration can trace these spectral shifts and if spurious effects add to the noise in the RV measurement. For YDDF, we obtained a highly precise barometer to record the pressure inside the lab, to correlate our data with the ambient pressure. Further, we designed a vacuum chamber for the Echelle grating, to isolate the grating from ambient pressure changes. This chamber also allows us to cycle the pressure around the grating on short time scales while keeping the rest of the spectrograph stable, to demonstrate the effect of pressure changes on the grating alone, and the potential benefit of a vacuum chamber for only the grating.

We installed a similar vacuum chamber in CHIRON; for YDDF, as space was not critical, we adopted a simpler mechanical design based on a 200mm aluminum tube, with flanges welded on (see Fig. 9). The vacuum window is a 200 mm diameter optical flat, 50.8 mm thick, made from Fused Silica. The flat is nominally one sided, however, testing it against another test flat revealed that the back surface figure is good enough for our purpose. The window has no wedge, and insofar ghosts are a concern. We will apply a SolGel coating in house to reduce the reflectivity to less than 0.7% per side, suppressing the double bounce ghost to a level of less than 5x10⁻⁶ [9]. The flange for the window is tilted to place the direct reflections on the surfaces outside the field of view.

![Fig 9: 3D drawing of the main body for the vacuum enclosure of the Echelle grating. It is welded from Aluminum tube and plate material. The window is mounted on the circular flange; we use Viton O-rings for seals.](image-url)
The effect of temperature is somewhat more complicated as it affects the setup through expansion of the optics, which changes the radii of powered surfaces, and the groove density of the grating, but also through the dn/dT of the lens materials, and the expansion of the mechanical structure. In the current setup, we only measure the temperature of the bench, without any means to actively regulate the temperature. The lab itself has a rather stable temperature to within a couple of degrees Celsius. No particular effort has been made to select and match the CTE of the materials for the mechanics. A future option is an insulated cover for the setup with heating strips and a closed loop controller.

5. LIGHT SOURCES

We use a variety of light sources for calibration and illumination of the spectrograph. Flat fielding is achieved with quartz lamps. For wavelength calibration and to measure line widths, we use a Thorium Argon hollow cathode lamp. Both lamps are mounted inside a common housing, which couples to a fiber, and can be switched remotely between lamps. To flatten the blackbody spectrum of the quartz lamp, we can insert color filters. A B+W model KB15 photographic filter provides attenuation of the red part of the spectrum [10]. This filter is a so called color correction filter intended to correct the illumination of incandescent lamps to resemble natural sunlight for use with a daylight photographic emulsion. The filter exhibits some non-uniform behavior, but overall achieves a good illumination of the CCD frame. We align the spectrograph and study ghosts with green (543 nm) and red (633 nm) Helium-Neon lasers. We plan on capturing sunlight by using a long fiber link to a small camera lens and equatorial mount which can be set up outside the building.

6. SPECTRA

In Fig. 10 we show part of a quartz spectrum recorded with YDDF. The light was fed to the spectrograph with a single mode fiber (SMF), and in the collimated space between L2 and L3 we inserted a solid Etalon. The Etalon was obtained from Lightmachinery as a stock item, and has a Finesse > 6 with a free spectral range of 0.15Å at 550 nm wavelength, corresponding to a resolution of 37,000. The CCD was mounted perpendicular to the optical axis of the camera lens, resulting in a slight change of focus with wavelength due to longitudinal chromatic aberrations of the system. We designed an adapter to be able to tilt the CCD tangential to the focal plane in the region of interest, to minimize this effect.

Fig 10: Part of a spectrum of a quartz lamp + solid Etalon, recorded with YDDF.
We used the Thorium-Argon lamp coupled to a multimode fiber to measure the form of the focal surface by scanning through the focus range and measuring the optimal focus as function of position on the CCD. The result is shown in Fig. 11. The peak to valley focus variation is below 0.3 mm over the full field, and about 0.1 mm in the iodine region, dominated by field curvature along the orders.

![Graphs showing focus variation](image)

Fig 11: Through-focus scans for 3 x 3 segments of the CCD chip. Cross dispersion is along the rows, the blue end of the spectral format is on the left. The dotted line marks the position of best focus for this part of the chip.

7. SUMMARY

We have implemented a dedicated lab, known as the Yale Doppler Diagnostic Facility, for end to end testing of spectrograph hardware. Using the YDDF, we plan to examine the critical spectrograph design choices concerning the fiber feed and front end, with RV precision as the relevant metric. For testing the fiber feed, the possibility to inject a wavefront with Kolmogorov-like turbulence is particularly interesting. The lab will enable us to validate simulated data on spectrograph parameters, and systematically study the impact of different designs on key performance aspects, like spectral and PSF stability, sensitivity to alignment or pressure changes. The spectrograph will also be an important tool to evaluate alternative wavelength calibrators, like stabilized etalons.

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