PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Scrambling and modal noise mitigation in the Habitable Zone Planet Finder fiber feed

Roy, Arpita, Halverson, Samuel, Mahadevan, Suvrath, Ramsey, Lawrence

Arpita Roy, Samuel Halverson, Suvrath Mahadevan, Lawrence W. Ramsey, "Scrambling and modal noise mitigation in the Habitable Zone Planet Finder fiber feed," Proc. SPIE 9147, Ground-based and Airborne Instrumentation for Astronomy V, 91476B (24 July 2014); doi: 10.1117/12.2055342

Event: SPIE Astronomical Telescopes + Instrumentation, 2014, Montréal, Quebec, Canada

Scrambling and modal noise mitigation in the Habitable Zone Planet Finder fiber feed

Arpita Roy[a,b], Samuel Halverson[a,b], Suvrath Mahadevan[a,b], and Lawrence W. Ramsey[a,b]

[a]Department of Astronomy & Astrophysics, The Pennsylvania State University, 525 Davey Laboratory, University Park, 16802, USA.

[b]Center for Exoplanets & Habitable Worlds, The Pennsylvania State University, University Park, PA 16802.

ABSTRACT

We present the baseline fiber feed design for the Habitable-zone Planet Finder (HPF), a precision radial velocity (RV) spectrograph designed to detect Earth analogs around M-dwarfs. HPF is a stabilized, fiber-fed, R∼50,000 spectrograph operating in the near-infrared (NIR) from 0.82 to 1.3 μm, and will be deployed on the Hobby-Eberly Telescope (HET) in Texas. While the essential function of the optical fibers is to deliver high throughput, this mode of light transport also provides the opportunity to introduce radial and azimuthal scrambling, which boosts instrument stability and thereby RV precision. Based on the unique requirements of HPF on the HET, we present initial tests showing very high scrambling gains via a compact scrambler in conjunction with octagonal fibers. Conversely, the propagation of light through the fibers injects modal noise, which can limit achievable RV precision. Laboratory tests of a custom-built mechanical agitator show significant gains over a static fiber feed. Overall, the fiber feed is designed to provide high relative throughput, excellent scrambling, and reliable modal noise suppression. We will also attempt to minimize focal ratio degradation (FRD) to the extent possible with the chosen configuration. HPF inculcates several other new technologies developed by the Penn State Optical-Infrared instrumentation group, including a rigorous calibration system, which are discussed separately in these proceedings.

Keywords: Exoplanets, spectroscopy, near-infrared spectrograph design, instrumentation, modal noise, fibers, scrambling

1. INTRODUCTION

The quest for habitable planets has propelled the field of precision radial velocity (RV) forward, into previously uncharted regimes of spectral variation measurements. And yet the confident detection of the first true Earth analog remains on the fringes of our technological capability. In an effort to bypass the stringent sub-m/s instrumental precision requirements for habitable planets around Sun-like stars, the focus is shifting towards M-dwarfs, whose lower luminosity and mass imply a stronger RV signature from potentially habitable planets.[1] However, the flux distribution of mid-late M-dwarf peaks sharply in the near-infrared,[2] precluding these promising targets from the current generation of optical spectrograph surveys, and establishing a need for high-precision infrared instruments.

The Habitable-Zone Planet Finder[3] is a stabilized near-infrared (NIR) fiber-fed high-resolution (R∼50,000) spectrograph being built at Penn State for deployment on the 10m Hobby-Eberly Telescope (HET) in Texas. It is optimized to search for Earth-like planets around M-dwarfs. The spectrograph design incorporates lessons learnt from high-precision optical spectrographs (e.g. HARPS), but also demands innovation in problem areas that are exacerbated in the NIR, or on the partially steerable HET. The instrument will be connected to the HET via optical fibers integrated into the Prime Focus Instrument Package (PFIP), situated at the focal plane of the telescope. The primary purpose of the fiber feed is to transport the highest possible fraction of light from the focal plane to the instrument, without introducing artifacts from the mode of conveyance. Additionally, optical fibers allow the possibility of minimizing memory of input illumination patterns (via scrambling), thereby homogenizing the input to the instrument, and bolstering RV precision. Here we present the baseline fiber feed design for HPF, with a special focus on modal noise mitigation and scrambling requirements.

E-mail: arpita@psu.edu, Telephone: 1 814 863 5565

Ground-based and Airborne Instrumentation for Astronomy V, edited by
Suzanne K. Ramsay, Ian S. McLean, Hideki Takami, Proc. of SPIE Vol. 9147,
91476B · © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2055342

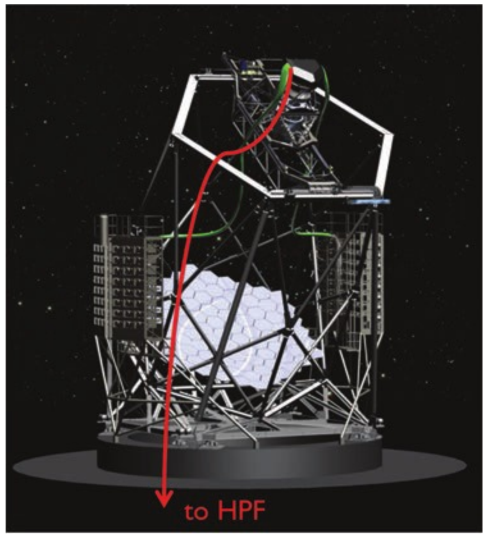

Figure 1. The Hobby-Eberly Telescope with Wide Field Upgrade (WFU) and VIRUS spectrographs as part of HETDEX.[4] A notional HPF fiber is shown in red, descending from the center plate that straddles the prime focus.

2. BASELINE FIBER FEED

The Wide Field Upgrade (WFU) to the Hobby-Eberly telescope,[4] implemented under the Hobby Eberly Telescope Dark Energy Experiment (HETDEX), will define the specifications of the telescope feed available for the HPF instrument. The HPF fiber system interfaces with the telescope at the PFIP; Figure 1 is an illustration of the upgraded telescope with a notional HPF fiber that mounts to the center plate. We estimate that a fiber run on the order of 40m will drop down from the prime focus and route through the telescope bearing to the basement spectrograph room.

Figure 2 shows the overall configuration of the fiber feed. A combination of 300μm circular and octagonal fibers transport light from the telescope prime focus to the HET basement, which will house HPF. We maintain the possibility of inculcating a lens relay that will pipe calibration light directly into the science fiber, as an alternative to having it travel up to the PFIP first, to minimize light loss. It is important to be able to feed calibration light into both science and calibration fibers simultaneously to periodically track instrument stability. The consequent fiber path includes a double scrambler and mechanical agitator before interfacing with the instrument vacuum chamber.

2.1 Selection of Fiber Diameter

Measurements of the atmospheric turbulence at McDonald Observatory indicate that the median seeing is $\sim$1.0", which is the value adopted for the WFU image quality error budget. Taking into account the 20-30% WFU telescope error budget on seeing, and to ensure that most of the light is collected from the focal plane, even on nights when the seeing is poor, we adopt a conservative value of 1.5" median seeing for our calculations. The range of the full-width at half-maximum (FWHM, very close to EE50 for a perfect Gaussian PSF) of the seeing disk is assumed to be 1.2"- 2". To minimize flux loss at the PFIP input, it is important to match the fiber diameter to expected seeing conditions. The plate scale at the PFIP is 177μm/arcsec, implying that a Gaussian seeing disk with FWHM 1.5" translates to a physical extent of 265.5μm. Assuming that the target is centered in the optical fiber, a 200μm fiber diameter will lead to 67% light loss, while a 300μm diameter will cause 41% loss (purely geometric, not including Fresnel losses). This potential light loss at the fiber entrance is large enough to warrant the choice of a relatively large aperture 300μm input fiber, regardless of other factors along the light path that might benefit from smaller fibers (e.g. slit loss).

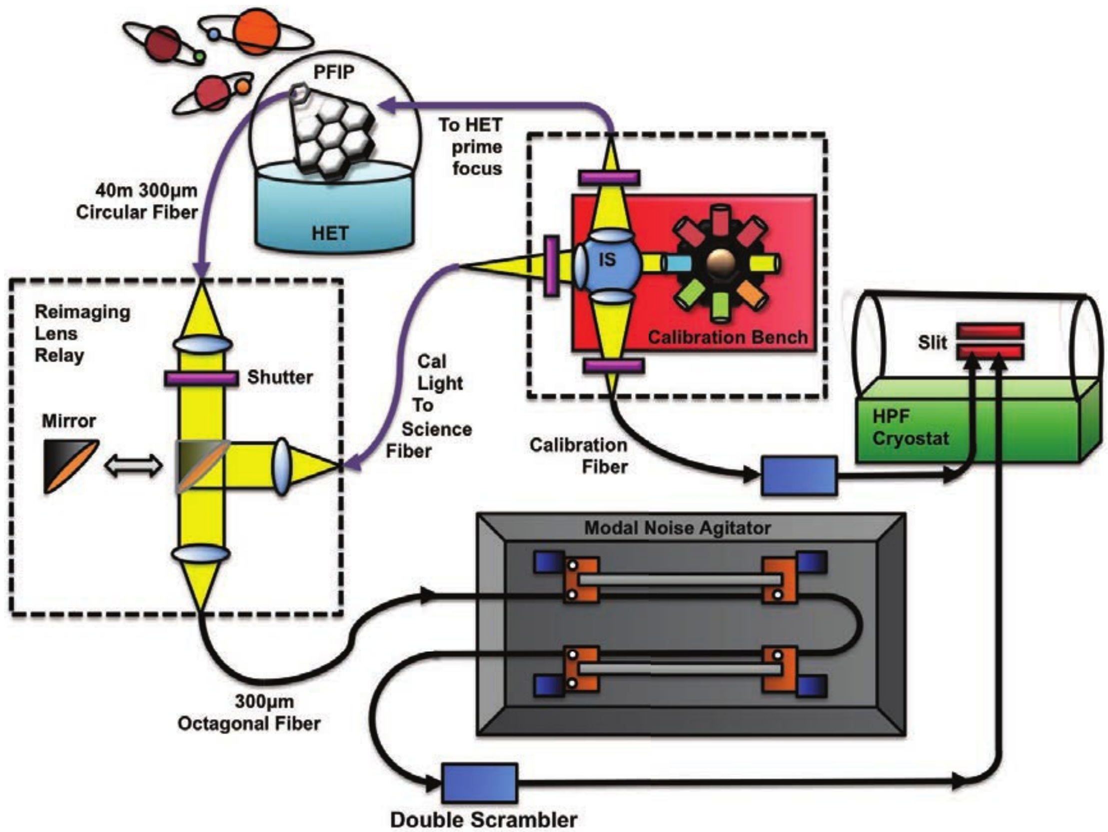

Figure 2. The baseline fiber feed for the Habitable Zone Planet Finder spectrograph, including the custom-built modal noise agitator and prototype double scrambler.

2.2 Guiding Induced RV Errors

Apart from seeing-induced losses, decentering, telecentricity, and the non-uniformity of the HET track are other factors that might further exacerbate the loss of light as it enters the first fiber. However, the WFU puts forth stringent requirements and the PFIP positioning performance is expected to deliver $\pm 0.1^\circ$ in tip/tilt, ± 0.03 mm in decenter, and ± 0.1mm in defocus. Further, with a much poorer median site seeing of 3" and a guiding accuracy of 0.3", the SOPHIE+ team reports that guiding and centering errors do not cause systematics larger than 1-2m/s for their instrument, which uses both double scrambler and an octagonal fiber.[5]

Guiding in the new WFU is accomplished not directly on the target star, but using guide stars located at the edge of 22' FOV. Differential atmospheric refraction at the entrance of the fiber can also lead to loss of starlight, and RV errors due to decentering. Figure 3 shows the differential refraction as a function of the airmass range at the HET where the central sec(z)=1.22. For simplicity, a flat stellar profile across wavelength is assumed. Note that HET only works in a narrow range of airmasses ($z \sim 29$-41°), making this problem less severe than on a fully steerable telescope. Errors incurred by guiding in the V (0.551μm) or R (0.658μm) bands are too high, indicating that we should be guiding in the I (0.808μm) or Z (0.900μm) bands in order to ensure that the differential atmospheric refraction errors do not exceed the ± 0.1" tracker specification included in the error budget.

2.3 Achieving High-Level Scrambling

Scrambling tends to decouple the distribution of flux in the output beam from the illumination pattern at the telescope focal plane. This is integral to precision spectroscopy, since changes in the barycenter of the light transmitted at the fiber output causes spurious radial velocity (RV) shifts as the shape of the instrument profile

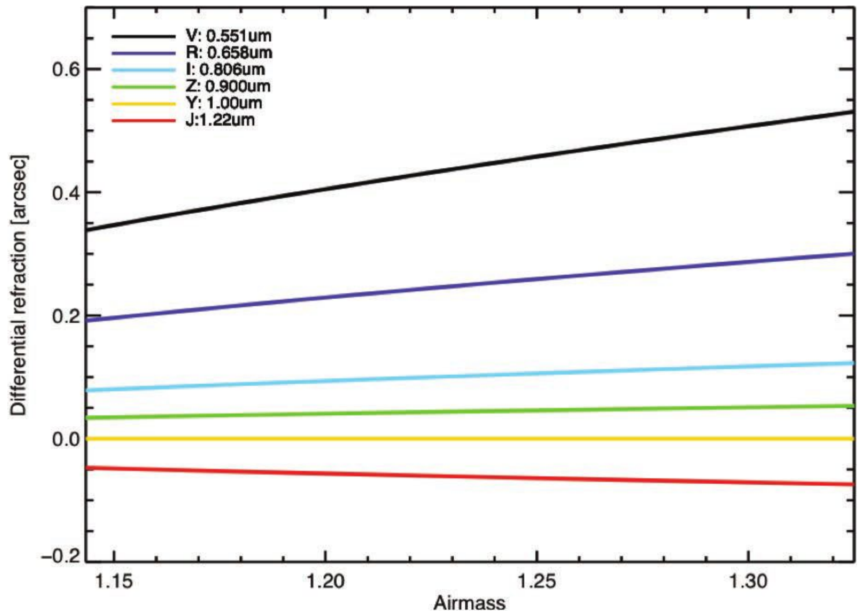

Figure 3. Differential atmospheric refraction at the HET. Calculations follow procedure from Filippenko (1982).[6]

varies. In fact, the stability of the PSF on the detector may be the limiting factor in the accuracy of radial velocity measurements on an otherwise highly stabilized spectrograph.[7]

While scrambling is very important for precision radial velocity work, it is critical on the HET, as the fixed-elevation design implies a highly variable telescope pupil based on tracker position. Optical fibers naturally provide a degree of azimuthal scrambling, but incomplete radial scrambling.[8] A measure of the degree of homogenization is provided by the scrambling gain[9] (SG):

$$\mathrm{SG} = \frac{d/D}{f/F} \tag{1}$$

where D is the fiber diameter, d is the shift of the star on the fiber input, F is the FWHM of the PSF, and f is the shift in the peak of the PSF. We quantify the minimum SG requirement, based on the overall error budget for HPF – with an input fiber diameter of 300μm, a resolution element (FWHM of PSF) of 6 km/s, guiding centroid stability of 0.17", and a desired radial velocity precision of 30cm/s – the fiber feed must guarantee SG $\geq$ 2,000. Higher values of SG reduce the contributed RV error or produce the same RV precision with worse guiding; in practice, SG>9,000 is desirable since that would significantly reduce the risk of guiding dominating the error budget.

A popular optical method of increasing the scrambling gain of a system is to split the fiber and exchange the near and far fields by means of a lens relay, called a double scrambler.[8] The alternative method of applying mechanical stress is disadvantageous as it increases FRD and affects the longevity of the fibers. More recently, it has been confirmed that fibers with polygonal cross-sections improve scrambling without greatly amplifying FRD.[10] Octagonal fibers, especially, have shown promising results both in laboratory experiments and on sky.[5,7,9,11,12] Figure 4 is a sample image from our scrambling tests, and illustrates the dramatic improvement introduced by the use of octagonal fibers. Splicing an octagonal section fiber into the fiber link before the double scrambler (only near-field scrambling) has been shown to provide SG∼3,500 in the laboratory, and ∼1,500 on sky.[5] We find that a combination of octagonal fibers and a custom-designed double scrambler allow us to meet the stringent scrambling requirements for HPF, with measured scrambling gains in excess of 9,000. A detailed description of the construction and performance of our scrambling system is forthcoming (Roy et al. *in prep*).

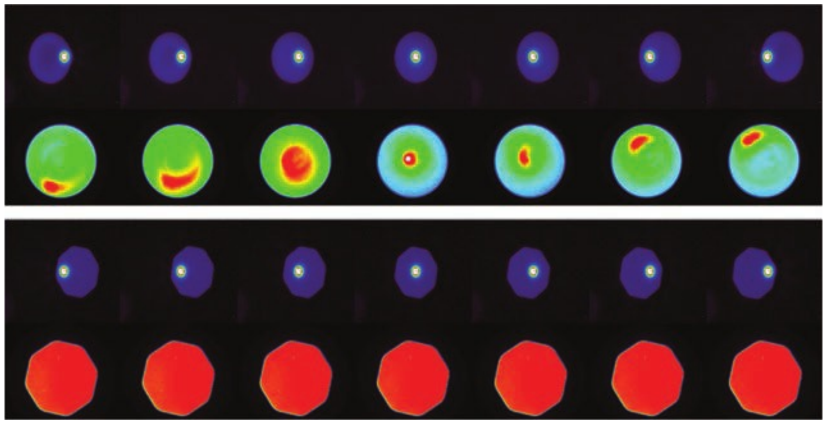

Figure 4. Near field as a function of input spot position, to show improved scrambling. Top row of each configuration shows input, bottom row is output. The image above is with a single circular fiber, while the image below is using an octagonal fiber. Notice the dramatic increase in output homogeneity with the introduction of non-circular fibers.

2.4 Mitigating Modal Noise

Fibers used in astronomy have relatively large apertures to couple light efficiently from the telescope to the spectrograph, which support several thousand waveguide modes and cause highly unstable, irregular light distribution across the fiber output. The changing pattern created by these modes, highly sensitive to small changes in fiber position, temperature, light injection geometry, and wavelength, is called modal noise.[13] It creates high-frequency structures in the spectrum that cannot be removed by flat fielding, because the injection geometry for the flat-field lamp cannot mimic that of the star. Additionally, modal noise can degrade the signal-to-noise ratio (SNR) in high-resolution fiber-fed spectrographs[13] and cause systematic errors in the precise measurement of Doppler velocities.

The number of modes populating a fiber decays rapidly with wavelength and thus presents a risk to the new generation of NIR spectrographs like HPF. Low-amplitude agitation of the fiber largely eliminates the effects of modal noise in the optical.[13] McCoy et al (2012)[14] presented experimental results of our early efforts at suppressing modal noise in the NIR using mechanical scramblers. The current mechanical agitator layout (Figure 5) creates large-amplitude motion and consists of two rails, upon which carriages will be able to translate via computer controlled stepper motors. The fiber cables are attached to these carriages with a clamp mechanism on their sides and passing through a loop at one end of the mechanism in order to create the "mixing zone". Actuation of the stepper motors will allow the operator to control scrambling of the fibers up to an amplitude of 170mm and at a max frequency of ∼1-2 Hz; faster frequencies can be handled, but at a smaller amplitude. The system also provides for a more modular design, as the rails can be widened further or moved to other locations on the optical breadboard in addition to changing the amplitude of motion. Since the constant mechanical motion of the agitator renders it a possible point of fiber breakage, this segment is placed to allow easy replacement of the fibers.

Laboratory tests of this design yield better results than any previous mechanical incarnations (including a paint mixer), and approach the limit of deliberate and highly effective hand motions (Figure 5). Modal noise issues are intensified for the calibration fiber (coherent, narrow-band illumination) in contrast to the star fiber (non-coherent, broad-band source). Mahadevan et al. (2014)[15] present a solution to mitigating model noise with calibration sources using a movable holographic diffuser and integrating sphere. Halverson et al. (2014, these proceedings) improve on this design and present our extremely successful solution to the modal noise issues for the calibration fiber. Although modal noise is not a fully solved problem for the science fiber, we are converging on an optimum design for the mechanical agitator.

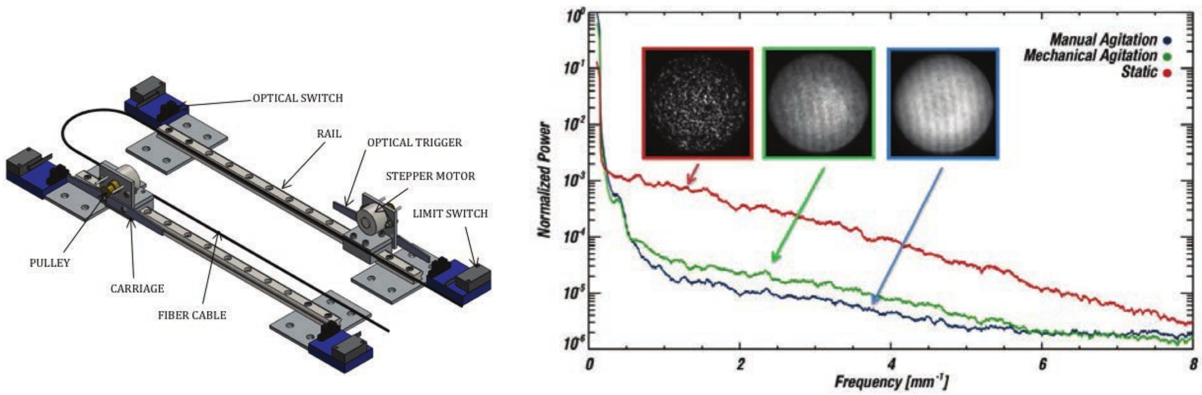

Figure 5. *(Left:)* Design for the mechanical agitator, built to mitigate modal noise. *(Right:)* Power spectrum of modal noise through static and agitated fibers. Bulk agitation by hand still produces the best results, but the mechanical scrambler approaches this limit.

3. SUMMARY

The fiber feed design for the HPF spectrograph is presented, along with a discussion of certain design trades that are necessary to enable our primary science goal of detecting habitable zone planets around M-dwarfs with 1-3m/s precision. We are currently finishing up the R&D phase of several fiber projects, including scrambling gain enhancement and modal noise suppression. Our scrambling system is able to achieve unprecedented levels of scrambling gain, with measurements of SG $>$ 9,000. Other sub-systems of the spectrograph are currently being assembled at Penn State in anticipation of instrument commissioning at the HET in late 2015 or early 2016.

ACKNOWLEDGMENTS

This work was partially supported by funding from the Center for Exoplanets and Habitable Worlds. The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, and the Eberly College of Science. We acknowledge support from NSF grants AST 1006676, AST 1126413, AST 1310885, and the NASA Astrobiology Institute (NNA09DA76A) in our pursuit of precision radial velocities in the NIR. AR acknowledges support from the Penn State Brumbach fellowship program and the Sigma Xi Grant-in-Aid program.

REFERENCES

[1] Endl, M., Cochran, W. D., Tull, R. G., and MacQueen, P. J., "A Dedicated M Dwarf Planet Search Using The Hobby-Eberly Telescope," *AJ* **126**, 3099–3107 (Dec. 2003).

[2] Pavlenko, Y. V., Jones, H. R. A., Lyubchik, Y., Tennyson, J., and Pinfield, D. J., "Spectral energy distribution for GJ406," *A&A* **447**, 709–717 (Feb. 2006).

[3] Mahadevan, S., Ramsey, L., Bender, C., Terrien, R., Wright, J. T., Halverson, S., Hearty, F., Nelson, M., Burton, A., Redman, S., Osterman, S., Diddams, S., Kasting, J., Endl, M., and Deshpande, R., "The habitable-zone planet finder: a stabilized fiber-fed NIR spectrograph for the Hobby-Eberly Telescope," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446** (Sept. 2012).

[4] Hill, G. J., Booth, J. A., Cornell, M. E., Good, J. M., Gebhardt, K., Kriel, H. J., Lee, H., Leck, R., Moreira, W., MacQueen, P. J., Perry, D. M., Rafal, M. D., Rafferty, T. H., Ramiller, C., Savage, R. D., Taylor, C. A., Vattiat, B. L., Ramsey, L. W., Beno, J. H., Beets, T. A., Esguerra, J. D., Häuser, M., Hayes, R. J., Heisler, J. T., Soukup, I. M., Zierer, J. J., Worthington, M. S., Mollison, N. T., Wardell, D. R., and Wedeking, G. A., "Current status of the Hobby-Eberly Telescope wide field upgrade," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8444** (Sept. 2012).

[5] Bouchy, F., Díaz, R. F., Hébrard, G., Arnold, L., Boisse, I., Delfosse, X., Perruchot, S., and Santerne, A., "SOPHIE+: First results of an octagonal-section fiber for high-precision radial velocity measurements," *A&A* **549**, A49 (Jan. 2013).

[6] Filippenko, A. V., "The importance of atmospheric differential refraction in spectrophotometry," *PASP* **94**, 715–721 (Aug. 1982).

[7] Avila, G. and Singh, P., "Optical fiber scrambling and light pipes for high accuracy radial velocities measurements," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7018** (July 2008).

[8] Hunter, T. R. and Ramsey, L. W., "Scrambling properties of optical fibers and the performance of a double scrambler," *PASP* **104**, 1244–1251 (Dec. 1992).

[9] Avila, G., "FRD and scrambling properties of recent non-circular fibres," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446** (Sept. 2012).

[10] Allington-Smith, J., Murray, G., and Lemke, U., "Modelling complex phenomena in optical fibres," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446** (Sept. 2012).

[11] Spronck, J. F. P., Fischer, D. A., Kaplan, Z. A., Schwab, C., and Szymkowiak, A., "Fiber Scrambling for High-Resolution Spectrographs. I. Lick Observatory," *PASP* **125**, 511–521 (May 2013).

[12] Plavchan, P. P., Bottom, M., Gao, P., Wallace, J. K., Mennesson, B., Ciardi, D., Crawford, S., Lin, S., Beichman, C., Brinkworth, C., Johnson, J., Davison, C., White, R., Anglada-Escude, G., von Braun, K., Vasisht, G., Prato, L., Kane, S., Tanner, A., Walp, B., and Mills, S., "Precision near-infrared radial velocity instrumentation II: noncircular core fiber scrambler," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8864** (Sept. 2013).

[13] Baudrand, J. and Walker, G. A. H., "Modal Noise in High-Resolution, Fiber-fed Spectra: A Study and Simple Cure," *PASP* **113**, 851–858 (July 2001).

[14] McCoy, K. S., Ramsey, L., Mahadevan, S., Halverson, S., and Redman, S. L., "Optical fiber modal noise in the 0.8 to 1.5 micron region and implications for near infrared precision radial velocity measurements," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446** (Sept. 2012).

[15] Mahadevan, S., Halverson, S., Ramsey, L., and Venditti, N., "Suppression of Fiber Modal Noise Induced Radial Velocity Errors for Bright Emission-line Calibration Sources," *ApJ* **786**, 18 (May 2014).