Extreme Doppler precision with octagonal fiber scramblers

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ABSTRACT

The detection of Earth analogs with radial velocity requires long-term precision of 10 cm/s. One of the factors limiting precision is variation in instrumental profile from observation to observation due to changes in the illumination of the slit and spectrograph optics. Fiber optics are naturally efficient scramblers. Our research is focused on understanding the scrambling properties of fibers with different geometries. We have characterized circular and octagonal fibers in terms of focal ratio degradation, near-field and far-field distributions. We have characterized these fibers using a bench-mounted high-resolution spectrograph: the Yale Doppler Diagnostics Facility (YDDF).

Keywords: Radial velocity, Optical fibers, Astronomical optics, Exoplanet detection

1. INTRODUCTION

Since the discovery of the first exoplanet,1 more than 700 planets have been found using the radial velocity (RV) method. Currently, state-of-the-art spectrometers, such as HARPS2 on the 3.6-m telescope in La Silla and HIRES on Keck I,3 typically achieve precisions of 1-3 m s$^{-1}$.4,5 This only permits the detection of planets with RV amplitudes larger than the measurement errors, typically Super Earth or Neptune-mass planets in relatively short period orbits, or more massive Jupiter-like planets out to several AU. The Earth induces a reflex velocity of only 9 cm s$^{-1}$ on the Sun, so the search for true Earth analogs requires Doppler precisions of about 10 cm s$^{-1}$, corresponding to typical spectral line shifts across one ten-thousandth of a pixel. Further complicating the analysis, the periodicity of this shift occurs over time scales of months or years for the most interesting planets in the so-called habitable zone. This requirement for a measurement precision of 10 cm s$^{-1}$ leads to the demand for an instrument that exceeds the stability of current instruments.

In order to reach the desired precision, we must reduce errors in the model of the instrumental profile, which cross-talk with our measurement of the Doppler shift. In many spectrographs, the starlight is coupled from the telescope to the instrument using a narrow slit. However, the slit illumination varies rapidly because of changes in seeing, focus and guiding errors. Changes in slit illumination affect the spectrum in two ways. Since the spectral lines are direct images of the slit, changes in slit illumination produce changes in the shape of the spectral lines. Additionally, variations in slit illumination can result in changes in the illumination of the spectrograph optics. This will in turn introduce different aberrations, which will change the instrumental response. Mathematically, these two effects are modeled simultaneously by convolving the spectrum with the instrumental profile, in such a way that any variability impedes our ability to recover Doppler shifts with the desired precision. If the instrumental profile were unchanging, variations in the final extracted spectrum would be dramatically reduced. Thus, instrumental profile stability has become a focus of current instrumentation work.

Optical fibers provide an excellent way to reduce variability in the illumination of the spectrograph. Fibers have been used since the 1980’s to couple telescopes to high-precision spectrographs.6 The throughput of fibers was initially low, however, they offered unprecedented convenience in mechanical design. The attribute of fibers that is particularly important today for high-precision Doppler measurements is the natural ability of optical fibers to scramble light7–10 and produce a more uniform and constant output beam. Because light from the
telescope must be efficiently coupled into the fiber, the fiber diameters must match the size of the seeing disk (typically 100 or 200 microns at F/5), so multi-mode fibers are required.

As described by Hunter and Ramsey, two characteristics are of importance when it comes to the light distribution after the fiber: the far-field and the near-field intensity patterns. The far-field is the cross-sectional intensity distribution of the diverging beam. The far-field will be projected onto the collimator, the grating and the rest of the spectrograph optics. Variations in the far-field will therefore cause different parts of the grating and the optics to be illuminated. This will in turn introduce different aberrations, which will change the instrumental profile. The near-field pattern is the intensity distribution across the output face of the fiber. The spectral lines are direct images of the fiber output face, so variations in the near-field pattern are also important in the stability of the final spectrum. Commonly in astronomy, the term near-field is used to describe the image of the output face of the fiber by an optical system. We will adopt this definition throughout this paper.

Even though fibers improve greatly the stability of the instrumental profile, we also have shown evidence of imperfect scrambling. It has been suggested that fibers with different geometries (square, hexagonal, octagonal) were better scramblers and were therefore more suitable for high-precision radial velocities.

In this paper, we compare three circular and three octagonal fibers of the same lengths and same diameters and quantify the improvement in instrumental profile stability due to the fiber core geometry. In Section 2, we describe our experimental set-up as well as the fibers that we studied. In Section 3, we measure the transmission of all fibers. In Section 4, we measure their focal ratio degradation (FRD). In Section 5, we compare the fibers in terms of near-field and far-field intensity patterns. Finally, in Section 6, we used a high-resolution bench-mounted echelle spectrograph, called the Yale Doppler Diagnostics Facility (YDDF), to quantify the instrumental profile stability for all fibers. We show a factor five or better improvement when using octagonal fibers instead of standard circular fibers.

2. EXPERIMENTAL SET-UP

A schematic drawing of the experimental set-up is depicted in Fig. 1. As light sources, we used a green He-Ne laser (543 nm) or a white LED (Thorlabs MCWHL2). The light was sent into a 100-µm multi-mode fiber (object fiber). The end of the fiber was re-imaged onto the test fiber using two achromatic lenses (L2 and L3) of focal lengths 100 mm and 75 mm respectively. The image of the object fiber is therefore 75-µm in diameter, while the test fibers all had a core diameter of 200 µm. To accurately position the spot onto the test fiber, the fiber was mounted on a precise (to less than 1 µm) translation stage with differential screws. The translation stage allows us to move the fiber with respect to the incoming beam and therefore simulate guiding errors. We imaged the spot and the front surface of the test fiber onto a camera (CCD1) using a pellicle beam splitter and a 300-mm lens (L4) in order to check the spot position onto the test fiber.

Light from the test fiber was then collimated (by lens L5) and re-focused (by lens L7) onto a CCD (CCD2). Lens L6 moves in and out of the light path to enable measurements of the near-field (out) and the far-field (in) patterns.

Additionally, two iris diaphragms were used. The first one (D1) after the lens L2 to control the input focal ratio into the test fiber and the second one (D2) after lens L7 to allow focal ratio degradation (FRD) measurements. To measure the transmission and the focal ratio degradation of the fibers, we used two power meters: P1 flips in instead of the test fiber to measure incoming power and P2 flips in after the diaphragm D2 to measure the power after the test fiber.

In this paper, we studied six optical fibers. All fibers had a core diameter of 200 µm and were 20 m long. Three fibers had a circular core and cladding and the other three had an octagonal core but a round cladding. The circular fibers are Polymicro FBP200240280 fibers. They have a 200-µm core, 240-µm cladding and 275-µm polymide buffer. They have SMA connectors on both ends. The three octagonal fibers are CeramOptec OCT200/672N/BPGS fiber. The silica core is 200-µm from flat side to flat side. The cladding is round and is 672-µm in diameter. A 780-µm buffer, a 1100-µm nylon jacket and a PVC coated mono-coil jacket surround the fibers. The octagonal fiber were terminated with FC connectors on both sides and polished to 0.3 µm.
We first measured the transmission of all fibers. We used the white LED as light source as it was more stable than the He-Ne laser. Both photodiodes $P_1$ and $P_2$ were connected to the same power meter. With these two photodiodes, we could measure the power before and after the test fibers and therefore their transmissions. Fig. 2 shows the transmission of the six test fibers as a function of input focal ratio. The blue dotted lines correspond to the three circular fibers, while the red solid lines are the transmissions of the octagonal fibers. Different symbols depict different fibers. The symbols and color codes are conserved throughout the paper. We see that all circular and octagonal fibers have similar transmissions of $\approx 84\%$ for all input focal ratios from $F/5$ to $F/10$. Since the photodiode $P_2$ is positioned after the lens $L_5$, we should add 2% to these numbers to take into account the transmission of the lens. These measurements are consistent with the transmission of 20-m uncoated fibers.
4. FOCAL RATIO DEGRADATION

An important characteristic of optical fibers for high-resolution spectrographs is focal ratio degradation. Multi-mode fibers tend to transform the incident beam into a faster beam (smaller focal ratio). This behavior is called focal ratio degradation. A high FRD translates into light loss or decrease in resolution for existing spectrographs and further complicates the design of future spectrographs.

The diaphragm $D_2$ was used to select the focal ratio of the beam entering the fiber. We measured the FRD of all six fibers by measuring the fraction of the energy encircled within an output focal ratio equal to the input focal ratio. Fig. 3 depicts this fraction of encircled energy as a function of input focal ratio. If there was no FRD, the beam would come out of the fiber with the same focal ratio as the input and the fraction of encircled energy would be 100% independently of the input focal ratio. We see that the three octagonal fibers (red solid lines) have less FRD than the three circular fibers (blue dotted lines). At F/5, 86% of the energy is encircled in an F/5 beam for the best octagonal fiber. However, FRD is often induced by stress when connectorizing the fibers. These circular and octagonal fibers have different connectors and were manufactured by different companies. This can account for the differences in FRD. The larger cladding of the octagonal fibers can also explain a lower FRD.

5. NEAR-FIELD AND FAR-FIELD INTENSITY DISTRIBUTION

For high-precision radial velocities, the most important property of optical fibers is their ability to scramble the light and therefore decouple the spectrograph from coupling errors, such as guiding, focusing and tracking. As mentioned in the introduction, variability in both near-field and far-field intensity distributions will introduce changes in the spectral line spread function (SLSF, also known as the instrumental profile). Spectral lines are direct images of the fiber output face, so stability of the near-field pattern is essential to the stability of the final spectrum. Variations in the far-field will cause different parts of the spectrograph optics to be illuminated, which will change the SLSF by introducing different aberrations.

In order to simulate guiding errors, we scanned the incoming beam across the entrance face of the fiber and we recorded near-field (without lens $L_6$) and far-field (with lens $L_6$) intensity distributions for each spot position for all three circular and three octagonal fibers (see Figs. 4 and 5). In these figures, the bottom row is an image of the input face of the fiber (back illuminated) and of the incoming spot. The three top rows in Fig. 4 are the near-field distributions for the three circular fibers (see Fig. 4 (a)) and the three octagonal fibers (see Fig. 4 (b)). Similarly, the top rows in Fig. 5 are the far-field intensity patterns for circular (see Fig. 5 (a)) and octagonal fibers (see Fig. 5 (b)). For all these measurements, the green He-Ne laser was used as a light source and the fibers were agitated to get rid of the speckle patterns. The input focal ratio was F/5.
We see in Fig. 4 (a) that the near-field intensity distributions clearly vary with the spot position for all three circular fibers. We also see that not all fibers have rotationally symmetric intensity patterns (e.g. Fiber 2). In order to check that this non-symmetric pattern was caused by the fiber and not the alignment of the experimental set-up, we have checked that the pattern was rotating when rotating the fiber. Note that no tip-tilt adjustments were used neither on the input nor on the output of the test fibers. The near-field pattern of Fiber 3 changes from a central maximum when the spot is centered to (asymmetric) ring-like patterns when the spot moves away from the center. Since the spot is 75 microns in diameter, some light will reach the cladding when in the two outer positions. In practice, this should be avoided if possible to prevent the propagation of cladding modes.\textsuperscript{12}

The near-field distribution for all three octagonal fibers is remarkably independent of spot position (see Fig. 4 (b)), which indicates that these fibers are very suitable for high-precision radial velocities. Indeed, their near-field shows no memory of the input face illumination. They can therefore decouple the spectrograph from any variability in guiding, seeing, tracking or focusing. We see that for the outer positions some non-negligible wings in the near-field energy distributions, which are cladding modes.

The far-field patterns for circular fibers (see Fig. 5 (a)) are irregular and show a lack of azimuthal symmetry but do not seem to strongly depend on the spot position. On the other hand, the far-field patterns of the octagonal fibers show variations depending on the spot position. We also see clear variations in the wings of the intensity distribution. Different sizes corresponding to different fibers are consistent with the FRD measurements of Section 4.

It is obvious from the near-field intensity patterns that the octagonal fibers are promising candidates for a highly stable SLSF. However, the far-field patterns still show significant variations. It should be noted that these results are not necessarily representative of all octagonal fibers. For example, we have a few 100-micron octagonal fibers that show exquisite near-field and far-field scrambling.

6. RESULTS WITH THE YALE DOPPLER DIAGNOSTICS FACILITY
Near-field and far-field intensity patterns are important. However, in order to test the fibers in realistic conditions, we need to use them in a high-resolution spectrograph. We used a bench-mounted laboratory high-resolution spectrometer, called the Yale Doppler Diagnostics Facility (YDDF),\textsuperscript{17} in order to quantify the impact of fiber core geometry on SLSF stability. For this experiment, the combination of camera and fiber size gave a rather low resolution ($R \approx 15,000$) and oversampled spectral lines ($\approx 40$ pixels per line).

For this test, we injected light from a Th-Ar lamp into the 100-micron object fiber (see Fig. 1). As previously, the object fiber was re-imaged onto the 200-micron test fiber to create a 75-micron spot. The end of the test fiber was plugged into the YDDF. We then scanned the position of the entrance face of the fiber with respect to the spot, therefore simulating guiding errors. For each spot position, we recorded a Th-Ar spectrum with the YDDF.

We used three metrics to assess the SLSF stability as a function of guiding (spot position): the width (measured by the FWHM), the asymmetry (measured by the bisector at 50%) and the centroid of the Th-Ar lines. We considered the same $\approx 130$ well-behaved Th-Ar lines for all fibers. We have split the CCD into nine tiles and in each tile, we have measured these three metrics as a function of spot position. The results are depicted in Fig. 6 (a), (b) and (c). The blue dotted lines correspond to the three circular fibers and the red solid lines correspond to the octagonal fibers. We clearly see that the SLSF is far more stable (independent of guiding) with the octagonal fibers. For each fiber and each metric, we averaged the curves of Fig. 6 and calculated the standard deviation of the average (see Table 1). We then averaged these standard deviations to obtain one number per metric for the circular fibers and one number per metric for the octagonal fibers. We see that the FWHM is on average 4.9 times more stable for the octagonal fibers, the asymmetry 8 times and the centroid shift 4.5 times more stable, therefore demonstrating a clear improvement in SLSF stability when using octagonal fibers.

Note that with such a low resolution and oversampling, we most likely favor the near-field stability over the far-field stability. When used at a higher resolution, the far-field might become more important.
Figure 4. Near-field of circular (a) and octagonal (b) fibers as a function of input spot position.
Figure 5. Far-field of circular (a) and octagonal (b) fibers as a function of input spot position.
Figure 6. Comparison of (a) FWHM, (b) asymmetry and (c) centroid of the SLSF across the CCD for the three circular (blue dotted lines) and octagonal (red solid lines) fibers.
### Table 1. Standard deviations of the results depicted in Fig. 6 averaged over the chip for the three metrics: width, asymmetry and centroid shift.

<table>
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<th>Shape</th>
<th>FWHM</th>
<th>Asym.</th>
<th>Centroid</th>
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</thead>
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<tr>
<td>Circular 1</td>
<td>0.023</td>
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<td>0.31</td>
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<tr>
<td>Circular 2</td>
<td>0.077</td>
<td>2.0e-4</td>
<td>1.29</td>
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<tr>
<td>Circular 3</td>
<td>0.072</td>
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<tr>
<td>Circular Average</td>
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<tr>
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<td>Octagonal Average</td>
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**Improvement in scrambling** | 4.9 | 8 | 4.5

7. CONCLUSIONS

We studied three circular and three octagonal fibers with identical core sizes (200 µm) and lengths (20 m) in order to see the impact of fiber core geometry on instrumental profile, or SLSF, stability.

We measured the transmission of all fibers and found that all measurements are consistent with the transmission of 20 m uncoated fibers.

We then measured the FRD of all fibers and have found that the octagonal fibers have systematically lower FRD than the circular fibers. However, this is most likely due to different cladding sizes and to the stress induced when connectorizing the fibers (different connectors and different companies).

We then studied the near-field and far-field patterns of all fibers as a function of guiding (spot position). We have found that the near-field intensity pattern of octagonal fibers is far more stable than the near-field of circular fibers. However, the far-field of the octagonal fibers shows clear variations depending on spot position. We note that it is fiber dependent and that we have measured octagonal fibers that have stable near-field and far-field.

Finally, we used a high-resolution spectrograph, the YDDF, to quantify the improvement in SLSF stability when using octagonal fibers. We found that the SLSF of octagonal fibers was at least 4.5 times more stable than the SLSF obtained with circular fibers.

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REFERENCES