Optical fibers for precise radial velocities: an update

Bruno Chazelas[a], Francesco Pepe[a], François Wildi[a]

[a]Observatory of Geneva University of Geneva.

ABSTRACT

Optical fibers are an essential component for some of the most Precise Radial Velocity (PRV) instruments. They provide image and pupil scrambling, making the illumination of the instrument stable and independant of the the atmospheric perturbations. Square and octagonal fibers have been investigated[1] as a potential improvement for the PRV spectrographs and have already shown a great potential. Here we present an updated characterization of these fibers and present their performances on the HARPS-N[2] instrument.

1. INTRODUCTION

For the PRV instrument using simultaneous calibration technique such as with sources like thorium lamps,[3] Fabry Perot Etalons[4] or laser comb, it is essential that the instrument stays stable between the wavelength calibration frame and the actual scientific measurement. These instruments are usually in pressure and temperature controlled environments for example under vacuum. However this is not sufficient to reach the instrumental stability required to get to precision level of the ms^{-1} and below required to build the next generation PRV instruments. Another requirement is an as constant as possible illumination of the spectrograph to stabilize the line profile of the instrument. To achieve this, it is necessary to use a device that will scramble the light coming from the star to mitigate the effects of the atmosphere. In addition this device should not increase significantly the beam etendue, which is already a technological challenge for large telescopes. The common solution to this problem is to use optical fibers. Historically the solution has been to use circular fibers[5–9] as they were the only one available. Recently for other purposes non-circular fibers have been developed and made available. They have been tested,[1,10] and present an important improvement in the scrambling over the circular fibers. We will present in this paper the properties of the octagonal fibers used for the HARPS-N[2] instrument and the achieved performance of its fiber train.

2. HARPS-N

HARPS-N is a copy of the HARPS south[11] instrument at La Silla. It is a fiber fed echelle spectrometer at high resolution. HARPS-N,[2] has recently been installed on the TNG at La Palma. For this telescope, the fiber train is 25 m long, and includes as in the HARPS south case a double scrambler.[7,12] The fiber train has been upgraded to have octagonal fibers.

This instrument will be dedicated mainly to exoplanet and in particular to the follow-up of the Kepler planet candidates.

3. FIBERS FOR HARPS-N

The instrument being a copy of the HARPS and the TNG being of the same diameter of the 3.6m at La Silla, the diameter of fiber is fixed. The fiber has been fabricated by the CERAMOPTEC Company: a 70 microns core octagonal fiber with a circular cladding of 125 microns and a polyimide protection (see figure 1). The material for this fiber is optran WF from CERAMOPTEC. It gives an overall good transmission over the full spectrum of the instrument. A piece of this fiber has been drawn at a slightly higher diameter and has been used successfully on the SOPHIE spectrograph.[1,10]

4. FIBER TRAIN PERFORMANCES

For an instrument like HARPS-N the fiber train should have the following characteristics:

Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II,
edited by Ramón Navarro, Colin R. Cunningham, Eric Prieto, Proc. of SPIE Vol. 8450, 845013
 · doi: 10.1117/12.926188

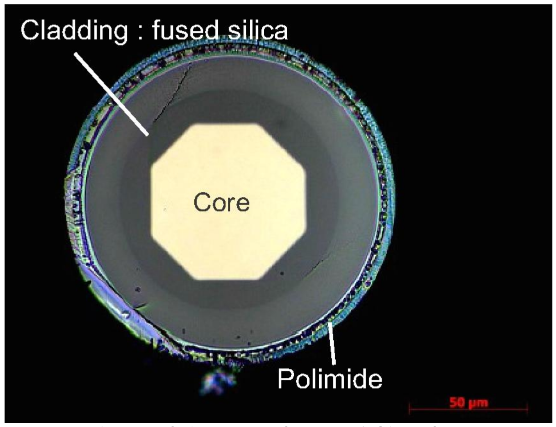


Figure 1: Photo of the manufactured fiber for HARPS-N

- A high transmission; there are several reasons for the loss in the system: the fiber material, the length of the fiber, the glass/air/vacuum interfaces and the Focal Ratio Degradation[13] (FRD). All but the last parameters can and have been optimized at the design level. The material of the fiber has been chosen to fit the spectral range of the instrument, the length of fiber has been minimised, the interfaces have all been treated with anti-reflection coatings (as a matter of fact all the fiber tips have lens glued on their exit face. These lens output faces have been anti-reflection coated). Focal ratio degradation however is both a result of the fiber fabrication process and of the following step of the integration of the fiber train. More over fiber manufacturer do not usually measure it. Thus it is one of the important things to monitor during the fabrication of the fiber train.
- A high degree of scrambling; the illumination at the output of the fiber should be as independent as possible of what happens at its entrance as well in the near field and the far field. The image of the near field of the output of the instrument fiber is directly the line profile. Thus as in a split spectrometer, fluctuation of the illumination barycentre at the tip of the fiber will be interpreted as a velocity shift. A modification of the far field illumination will produce chromatic line profile changes that will also be interpreted globally as a velocity shift.

Octagonal fibers have very good scrambling properties in the near field and only radial scrambling in the far field.[1] Thus a double scrambler[7,12] is used in order to benefit from the scrambling of the fiber both in near and the far field.

5. TEST BENCH FOR THE CHARACTERISATION OF THE FIBERS

Some of the tests of the fiber train have been done by the manufacturers: the measurement of the spectral transmission and of the overall transmission. The measurements of the scrambling of the fiber and its FRD have been done in Geneva with the test bench shown on figure 2. The description of its operation and measurement method has already been made in a previous paper.[1]

This test bench provide a controlled illumination of the tested optical fiber entrance, in the image and the pupil plane. It is possible to move with a motor the tip of the test fiber on the entrance side, thus simulating modification of the illumination of the fiber at its entrance in a way very similar to what happens in an actual telescope setup. At the output of the tested fiber there are CCDs on which one can image the near field or the far field.

With this setup it is possible to measure fiber scrambling properties in the near field, in the far field and measure the FRD. Near field scrambling can be measured up to scrambling ratio of 10000 (ratio between the actual movement of the star at the entrance of the fiber and the residual illumination barycentre movements).

FRD measurements are reproducible at a level of 3-4%. This is due to the fact that the injection into the fiber is done more or less blindly. Although retro-injection is used, the angular alignment of the acceptance cone of the fiber and the injected light cone are not perfects. Solution exists to solve the issue but they could not be implemented for the measurements presented in this paper.

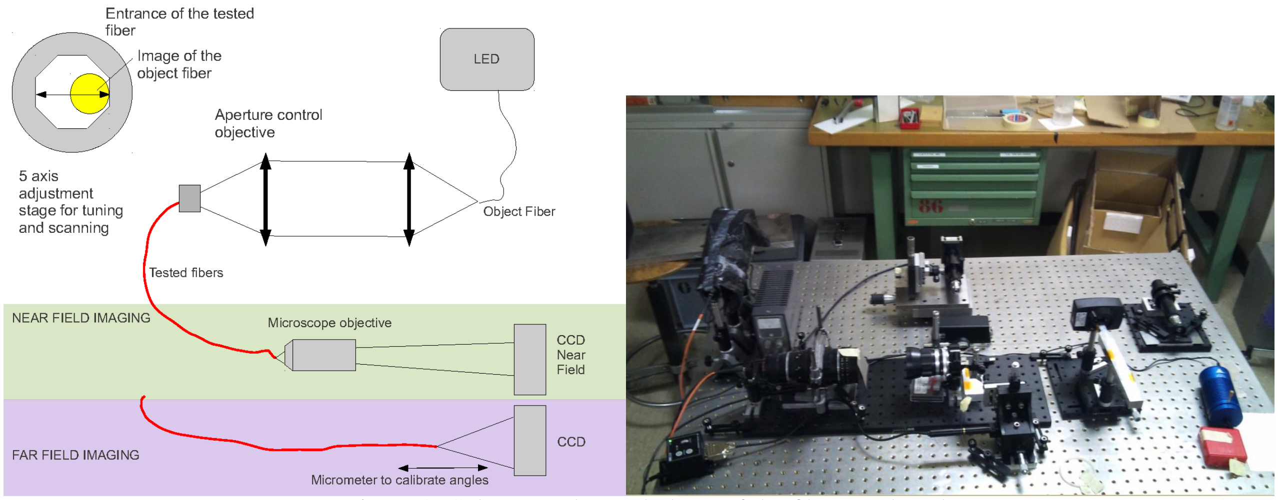


Figure 2: Scheme and actual photo of the fiber test bench.

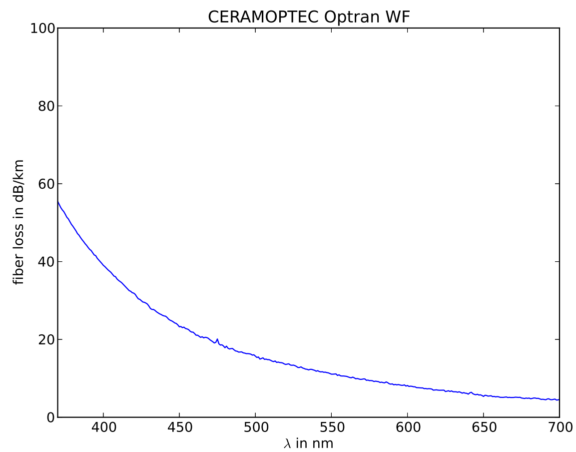


Figure 3: View of the fiber transmission across the wavelength range of HARPS-N. For a 25 m fiber the maximum loss is ~ 25 % at the extreme blue part of the spectrum.

6. CHARACTERISATION OF THE NAKED FIBER

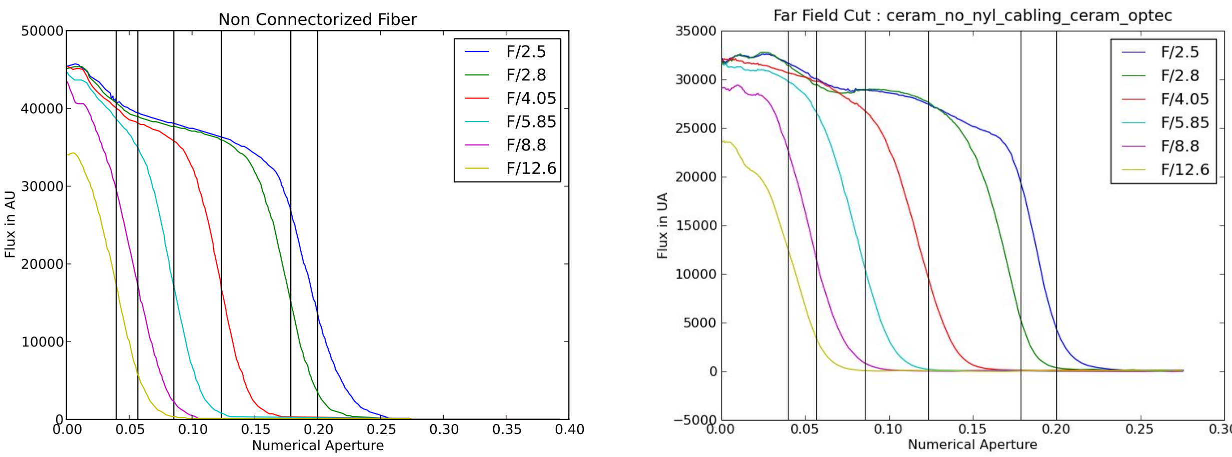
Once the fibers have been manufactured, the provider made a transmission measurement check, shown on figure 3. With such performances, for a fiber of 25 m the expected transmission is ~ 75% at 380 nm and 97% at 690 nm.

Then the FRD of the naked fiber (without connectors) has been measured. This measure was done to assess the fundamental FRD properties the fiber. These properties are coming from the micro-roughness and micro-bending in the fiber and are the result of the manufacturing process. Once the fiber is drawn there is no way to improve on these performances. As shown on figure 4 the general FRD of the fiber is quite low and has been accepted for the use in HARPS-N. It is to be noted that the same manufacturer produce an octagonal fiber with even lower FRD (see figure 6), having a very large buffer.

The scrambling properties of the fiber where in line with the expectations[1] see figure 5. The scrambling ratio higher is 5-10 times better than with a circular fiber. In the far field these fiber have a comparable behaviour than the circular fibers.

7. TEST OF THE FIBERS ALONG THE ASSEMBLY PROCESS

It is necessary to follow closely the FRD during the fabrication of an optical fiber train. The use of connector at the end tips of the fiber is a major source of FRD. A soft glue has to be used to avoid strains in the fiber. The process of



(a) (b)

Figure 4: Profile of the far field of the octagonal fiber as a function of the entrance beam aperture. From these measurements one can calculate the FRD. (a) The naked fiber (b) The connectorized fiber.

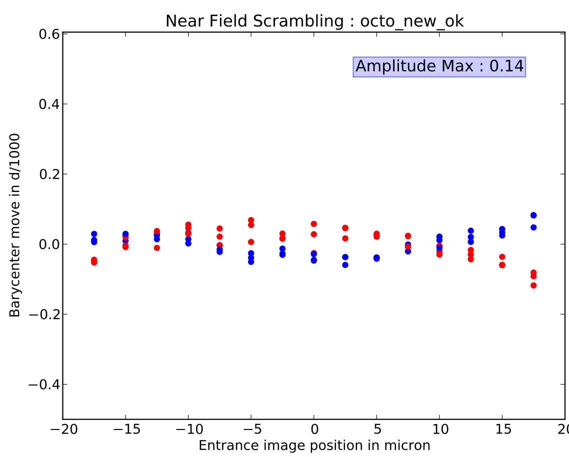


Figure 5: Residual output near field illumination barycentre movements measured at the output of one of the HARPS-N octagonal fiber when the source at the entrance of the fiber is moving by the amount shown on the x axis. This movement is expressed in one-thousandths of the core diameter. It corresponds to a scrambling ratio of 7100. A standard circular fiber has a typical scrambling ratio of ~ 900. Red points are for the x axis on the CCD, blue points are for the y axis on the CCD. The orientation of these axes is arbitrary.

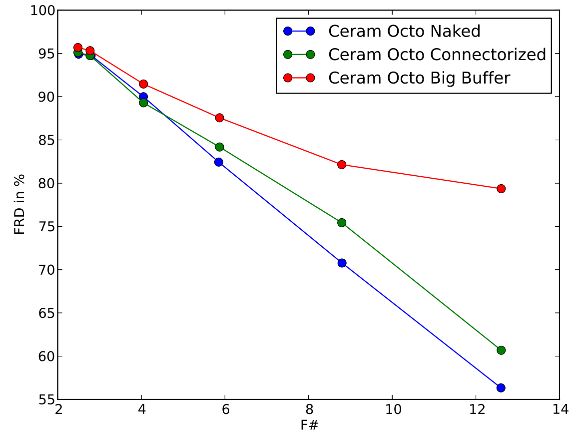


Figure 6: Compared FRD for 3 fibers: The octagonal fiber for HARPS-N, naked and connectorized and another octagonal fiber from the same company with a much larger cladding and buffer. The later has the best FRD we have ever measured. The fact that the naked fiber seems to have a worse FRD than the connectorized one is to be attributed to systematic errors in the measurements. One has to see they have a similar behaviour.

connectorizing should be monitored at the level of the workshop. A simple experiment show immediately the effects of a bad connectorization: Injecting a laser into to the fiber at one end and measure the aperture of the beam at the other end. Bad connectorization gave us typical aperture around f/4.

When a fiber is suffering connector FRD, there is a minimum aperture of the beam at the output of the fiber with respect to the entrance aperture. The far field shows at this minimal aperture a structure that is independent from the input and looks very inhomogeneous.

Before assembling the complete fiber train, a test of connectorization has been performed in order to see if the manufacturer was able to keep the FRD low enough for our purpose. The results are shown on figure 4 and 6 and are very good. The fact that the measurements of the connectorized fiber seem better than the naked fiber is to be attributed to a systematic error in the measurement. Both FRD are comparable.

8. MEASUREMENT OF THE FRD OF THE CONNECTORIZED FIBERS OF THE HARPS-N TRAIN

Systematic measurements of the FRD of the all the fibers needed for the instrument including the spares have been made. The train installed on the instrument is the one with the best performances. Figure 4show the statistics for all the fibers. The Obtained FRD is globally very good, and is always better than 85% for the fibers that have been installed into the instrument. On figure 8 one can see an example of measurement at F/4 which is the working aperture of the beam inside the fiber.

The output FRD losses of the optical train is near to 10%. The overall transmission of the optical train has been calculated[2] taking into account length losses, Connection losses, the double scrambler and the FRD. It give en efficiency of 55% at 380 nm and of 65% in the red. This is excellent and an improvement over the HARPS south fiber link.

9. SCRAMBLING MEASUREMENT OF THE COMPLETE TRAIN

The test bench has been used to measure the scrambling performances of the complete train of HARPS-N, including the double scrambler. Measurements have been done with success in the near field, and also in the far field as there is a double scrambler.

The measurement in the near field is shown on figure 9. The measurement has been extended to have the image at the entrance of the fiber to move outside the core, to see the effects. The obtained scrambling ratio is around 10000 which is the limit of measurement accuracy of the test bench.

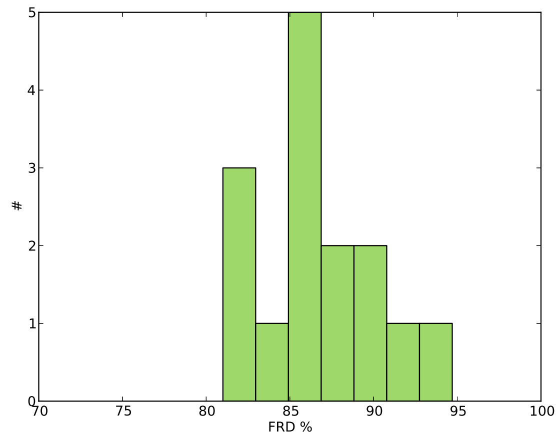
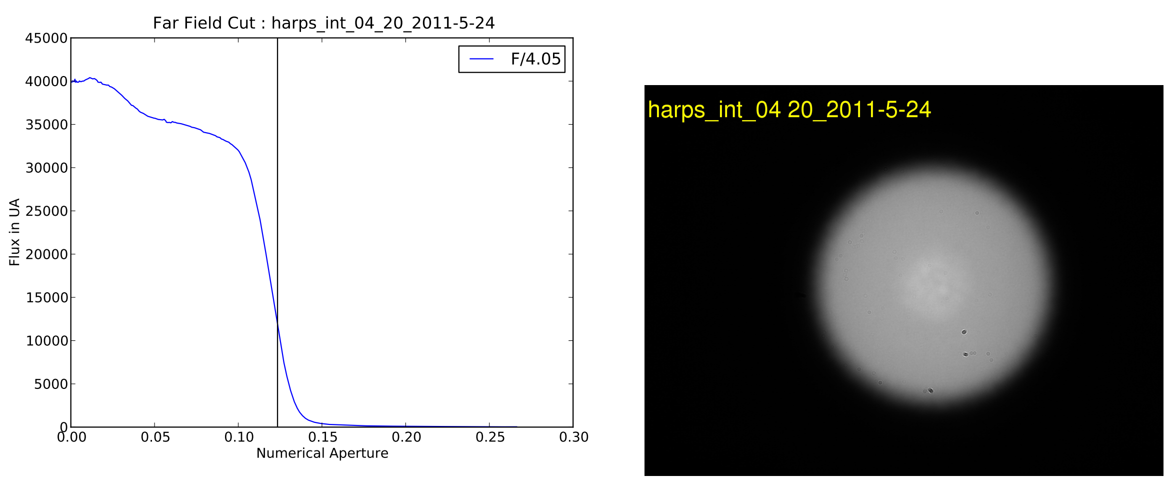
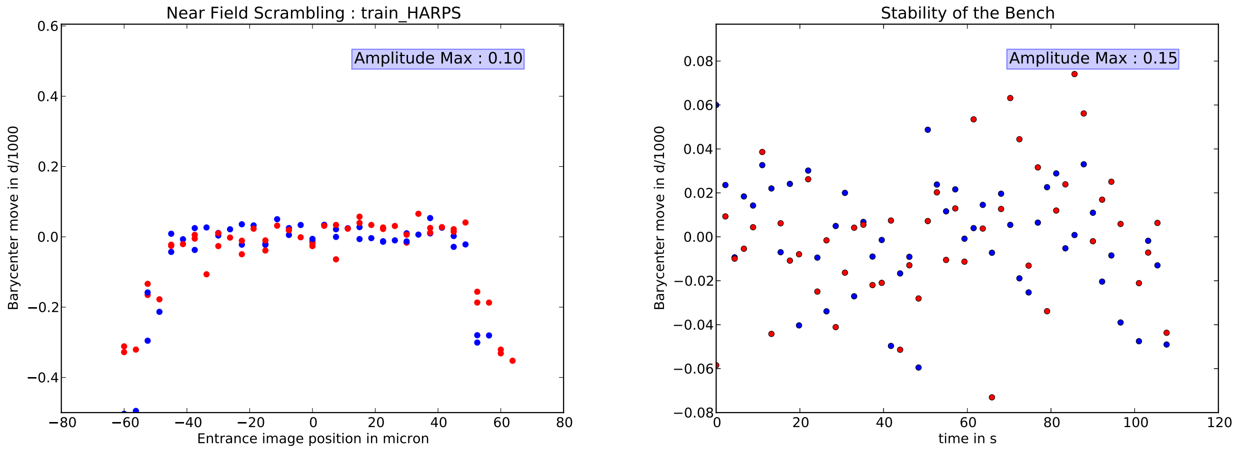


Figure 7: Histogram of all the measurement of the FRD measured at F/4 on all the ends of the fibre. All the fibers are better have an FRD better than 80%. The one used in the instrument have an FRD better than 85%.



(a) (b)

Figure 8: Example of an FRD measurement, on the left a radial profile of the far field calibrated in angle, on the right one of the image that was used to produce the curve.



(a) (b)

Figure 9: Illustration of the near field scrambling of the HARPS-N fiber train, in the laboratory. (a) the movements of the measurement in the near field of the scrambling performance of the whole fiber train. The scrambling Ratio is in the 10000 range. (b) limits of the measurement capability of the test bench. Red points are for the x axis on the CCD, blue points are for the y axis on the CCD. The orientation of these axes is arbitrary.

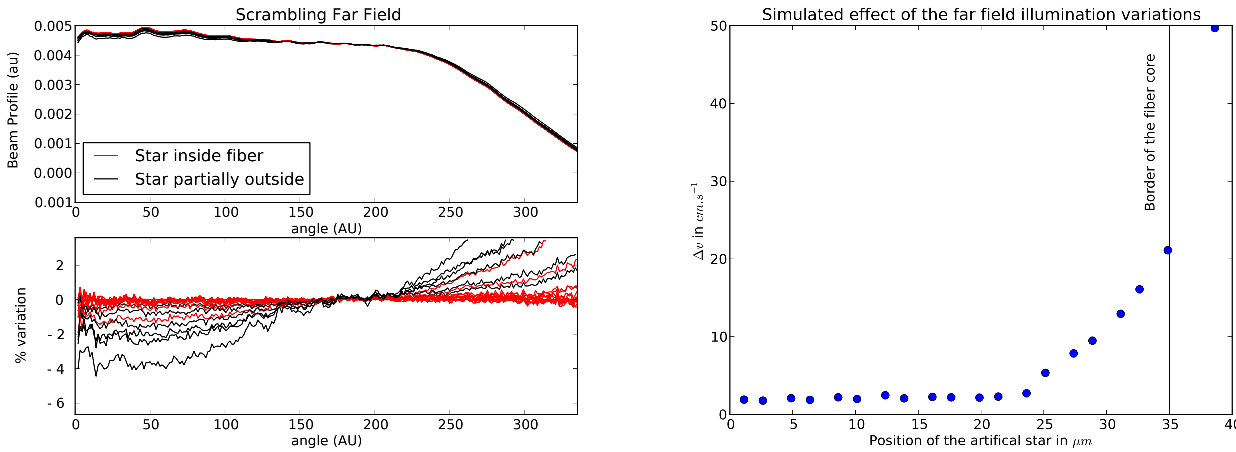
In the far field a similar test than in the near field is performed: An artificial star of a diameter of 12.5 microns for a core of 70 microns is scanned across the core diameter. The far field illumination is recorded and analysed. The results are shown on figure 10. The analysed factor here is the illumination variation on a radial basis. These variations through the aberration of the spectrometer optics will produce line profile variations that are interpreted as velocity shifts. One can use the measured flux variations to make simulations of the expected level of the effects on the instrument. In this case HARPS-N the observed variations could lead to velocity shifts of a maximum of $25\,cm\,s^{-1}$ when the star is on the border of the fiber. More over figure 10 (b) shows the detailed results of the simulation resulting from the far field illumination measurements: in normal guiding condition there should be no measurable modification of the line profile. It is an improvement on the HARPS south fiber link.

10. PRELIMINARY TESTS ON SKY

The first light of HARPS-N has been achieved on March 25th 2012. After this some technical observation time gave the possibility to have a first assessment of the scrambling performance of the fiber train on sky. The tests consisted in making exposure of the same star repeatedly with different guiding set points. Half of the exposures are made in the standard mode where the star is centred on the entrance fiber of the instrument; the other half was made in a way to have the star on the border of the fiber. These measurements (see figure 11) give only an upper limit of 0.55 $m\,s^{-1}$to scrambling performances. The exposure time was not long enough to average the p-mode oscillation of the stars, and furthermore the drift of the instrument is not corrected (it is however extremely low). This number is already an improvement of a factor 4 on the scrambling performances of HARPS South.

11. CONCLUSION

In this paper we have shown the performances of a fiber link made of octagonal optical fibers for the HARPS-N spectrograph. This new type of fiber is a huge improvement over circular fiber in terms of scrambling, and maintain an excellent overall efficiency for the fiber link. These fibers remove one of the instrumental obstacle to the detection of very small mass planets and paves the way for futur instruments like ESPRESSO or CODEX.



(a) (b)

Figure 10: Far field illumination scrambling: The far field is characterized by its radial profile. Its stability versus the illumination perturbation at the entrance fiber is measured. One can use this measurement to simulate the expected effect on the radial velocity. In this case the extreme effect is of the order of $25\,cm\,s^{-1}$. However in normal conditions, where the guiding is working properly the effect should be much smaller. (a) radial profile of the far field measured for different position of the artificial star at the entrance of the fiber field. (b) Simulated radial velocity shift for HARPS-N.

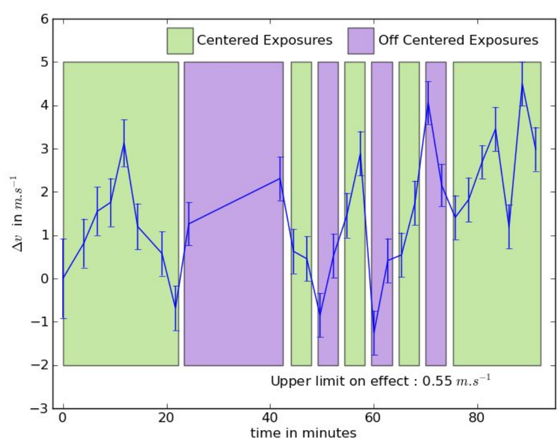


Figure 11: On sky test with HARPS-N: the star is observed, some exposure are made with the star centred (the purple zones) and other are off-centred (the star is on the border of the fiber). There is no obvious effect to be noted. An upper limit 0.55 $ms^{-1}$for the effect of decentring can be set. However this measure has not been done in an optimal way and the p-modes of the star are dominating all the effects.

ACKNOWLEDGMENTS

Thanks to Loic Reymond for his participation to the characterisation of octagonal optical fibers during his internship in the summer 2011

REFERENCES

[1] Chazelas, B., Pepe, F., Wildi, F., Bouchy, F., Perruchot, S., and Avila, G., "New scramblers for precision radial velocity: square and octagonal fibers," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7739** (July 2010).

[2] Cosentino Rosario et al, "Harps-n: the new planet hunter at tng," in [*Ground-based and Airborne Instrumentation for Astronomy IV*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446** (2012).

[3] Baranne, A., Queloz, D., Mayor, M., Adrianzyk, G., Knispel, G., Kohler, D., Lacroix, D., Meunier, J.-P., Rimbaud, G., and Vin, A., "ELODIE: A spectrograph for accurate radial velocity measurements.," *A&AS* **119**, 373–390 (Oct. 1996).

[4] Wildi, F., Chazelas, B., and Pepe, F., "A passive cost-effective solution for the high accuracy wavelength calibration of radial velocity spectrographs," in [*Ground-based and Airborne Instrumentation for Astronomy IV*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8446** (2012).

[5] Heacox, W. D., "On the application of optical-fiber image scramblers to astronomical spectroscopy," *AJ* **92**, 219–229 (July 1986).

[6] Heacox, W. D., "Radial image transfer by cylindrical, step-index optical waveguides," *Journal of the Optical Society of America A* **4**, 488–493 (Mar. 1987).

[7] 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).

[8] Avila, G., Kohler, D., Araya, E., Gilliotte, A., and Eckert, W., "Performances of HARPS and FEROS fibers in La Silla ESO Observatory," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], Moorwood, A. F. M. and Iye, M., eds., *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **5492**, 669–676 (Sept. 2004).

[9] 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*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **7018** (July 2008).

[10] Perruchot, S., Bouchy, F., Chazelas, B., Díaz, R. F., Hébrard, G., Arnaud, K., Arnold, L., Avila, G., Delfosse, X., Boisse, I., Moreaux, G., Pepe, F., Richaud, Y., Santerne, A., Sottile, R., and Tézier, D., "Higher-precision radial velocity measurements with the SOPHIE spectrograph using octagonal-section fibers," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8151** (Sept. 2011).

[11] F. Pepe et al., "HARPS: ESO's coming planet searcher. Chasing exoplanets with the La Silla 3.6-m telescope," *The Messenger* **110**, 9–14 (Dec. 2002).

[12] Casse, M. and Vieira, F., "Comparison of the scrambling properties of bare optical fibers with microlens coupled fibers," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], Ardeberg, A. L., ed., *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **2871**, 1187–1196 (Mar. 1997).

[13] Clayton, C. A., "The implications of image scrambling and focal ratio degradation in fibre optics on the design of astronomical instrumentation," *A&A* **213**, 502–515 (Apr. 1989).