New Scramblers for precision radial velocity : Square and Octagonal fibers.

Bruno Chazelas[a] ,Francesco Pepe[a], Francois Wildi[a], Francois Bouchy[b,c],Sandrine Perruchot[c], Gerardo Avila[d]

[a]Observatory of Geneva, University of Geneva, 51 chemin des maillettes, 1290 Versoix, Switzerland;
[b]Institut d'Astrophysique de Paris, UMR7095 CNRS, Université Pierre & Marie Curie, 98bis Bd Arago, 75014 Paris, France;
[c]Observatoire de Haute-Provence, CNRS/OAMP, 04870 St Michel l'Observatoire, France;
[d]ESO, Garching

ABSTRACT

One of the remaining limitation of the precise radial velocity instruments is the imperfect scrambling produced by the circular fibers. We present here experimental studies on new optical fibers aiming at an improvement of the scrambling they provide. New fibers shapes were tested: square and octagonal. Measurements have been performed of the scrambling performances of these fibers in the near field as well FRD measurements. These fibers show extremely promising performances in the near field scrambling: an improvement of a factor 5 to 10 compared to the circular fiber. They however show some strange behavior in the far field that need to be understood.

1. INTRODUCTION

The radial velocity technique, is and will be a very important tool for the field of exoplanetology. It has already permitted the discovery or confirmation of most of the known extrasolar planets. Currently the best achieved precision is 30 $cm.s^{-1}$ (achieved on HARPS[1,2]) which is enough to detect Super Earth. In order to reach the earth size precision, it is necessary to reach the precision of the $cm.s^{-1}$. This require to address at the same time astrophysical issues and instrumental issues. One of the important issue is the scrambling by optical fibers, necessary to mitigate the effect of atmosphere on the instrumental profile of the spectrometers. More over improving the scrambling of optical fiber might enable smart and innovative instrument configuration (see the case of ESPRESSO[3]). In the frame current generation circular fiber show their limitations. Square and polygonal light pipe being a classical way to get more homogeneous[4]illumination, the idea of using square and polygonal optical fiber has been studied with simulation[5] and showed some very promising performances. This paper will report the experimental characterization of these fibers with regard to near field scrambling and Focal Ratio Degradation (FRD).

This work has been done in collaboration in the view of the next generation of precision radial velocity instruments. Observatory of Geneva, ESO, OHP, and IAC teamed up to procure and characterize these new fibers. This paper aims at showing the results obtained with the Observatory of Geneva test bench. See reference [6] in this conference for other results on these fibers.

2. TESTED FIBERS

Two fiber shapes were investigated, the square and octagonal fiber. The former would be useful for the combination of the light comming form multiple telescope, as in the case of ESPRESSO. The latter is useful for the single pupil scenario, because better matched to the circular shape.

The fiber we tested come from several sources :

- The CERAMOPTEC company in Germany: Their fibers are build by with standard fused silicate for core and cladding. They were available on the shelf because they have some use in laser application for mode scrambling. The structure of the fiber we have tested is not completely standard. It is build out of a core, a cladding, and successive buffers. Unfortunately one of the buffer is made out of nylon which has a lower refractive index than the

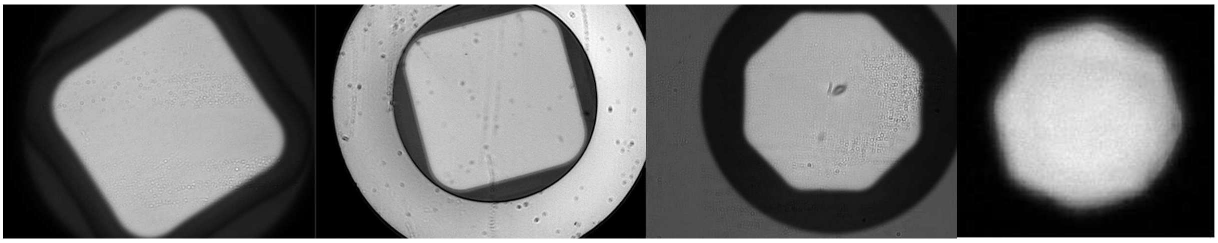


Figure 1. Photo of the near field of the tested fibers in order from the left. a square fiber from CERAMOPTEC of 70 micron core, a square fiber from CERAMOPTEC of 200 micron core, an octagonal fiber from CERAMOPTEC of 70 micron core and an octagonal fiber form Le Verre Fluoré of 100 micron core.

previous materials. Thus the fibers have spurious guiding structure that we had to deal with. It is to note that the fiber are really well done in term of geometrical shape (see figure1). Three fibers were tested, a square fiber of 200 microns core, a square fiber of 70 microns core and an octagonal fiber of 70 microns core.

- Le Verre Fluoré company in France: They provided an octagonal fiber of 100 microns core made of fluoride glass and having a more standard structure : core and cladding. The cladding is a polymer (this has been done for economical reason).

3. TEST BENCH AND MEASUREMENT PROTOCOL

To optimize a fiber fed spectrometer, the fibers have to have a good transmission over the whole bandwidth of the instruments, but this not the only required property. In the case of precise radial velocity measurements, the fiber should have also good scrambling properties in the near field and in the far field, in order to illuminate the instrument in the most constant way possible. This ensure that the instrument profile is as stable as possible. They should also provide the smallest possible FRD (an increasing of the speed of the beam at the output of the fiber).

As the octagonal and square fiber are mainly made of standard material for astronomy, the test bench was optimized to explore the geometric properties of these new fibers.

3.1 Test bench

For these fiber two main characteristics were measured :

- Near Field scrambling
- Focal Ratio Degradation

To make these measurement light has to be injected in the fiber simulating a star at the entrance of the fiber. For this we designed a test bench (see figure 2) that allow to illuminate the control fiber in a controlled way, in the near field and in the far field. The illumination system is composed of a circular optical fiber that is imaged thanks to two photographic objectives on the test fiber. Changing the diameter of the illumination fiber control the image size in the near field of the tested fiber. The second objective allow the choice of the beam aperture in the test fiber. The light source is a Light Emitting Diode at 470 nm. The test fiber is mounted on a five axis adjustment mount: three translations of which one is motorized, and two rotations. In addition in order to ensure that no light enter in the optical fiber in an undesired way there is a pinhole in front of the fiber that let nearly only the core of the fiber free to be illuminated.

At the output of the tested fiber two different imaging configuration are used:

- A combined near field and far field imagery system were a microscope objective is used for imaging the near field on a CCD, and a beam splitter picks the light after the objective to make the image of the far field, using an additional lens. This configuration is optimal for near field imagery, and enable to make health check on the far field. However the far field imagery is suboptimal an cannot be used for real measurement.
- To image properly the far field and also calibrate the angular content of the beam at the output of the test fiber another configuration is used. The tested fiber is placed directly in front of a CCD that can be translated precisely thanks to a micrometer allowing the measure of angle.

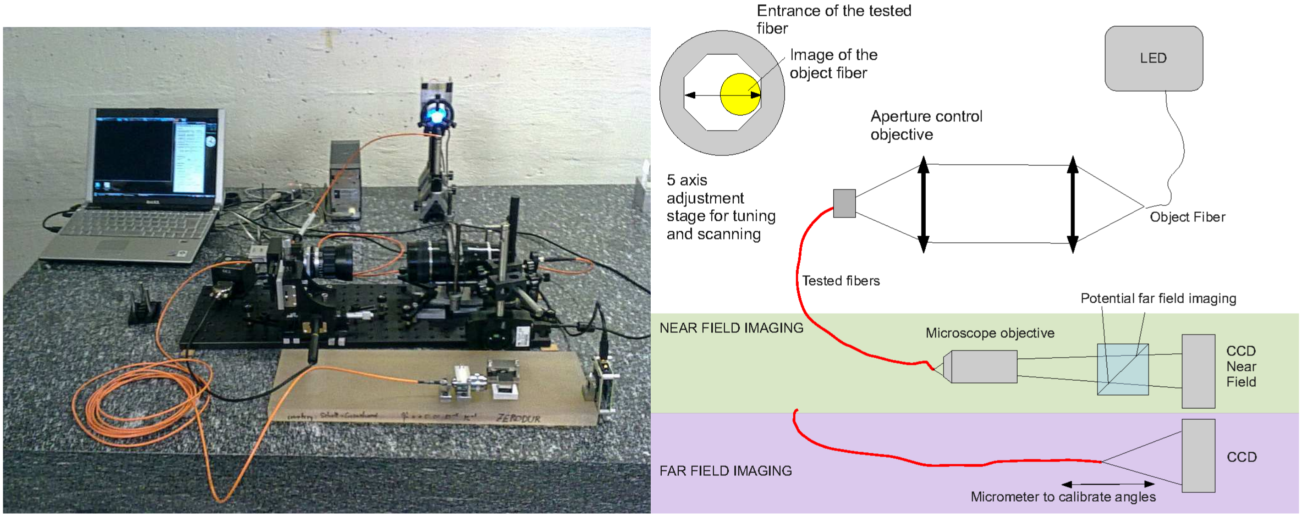


Figure 2. Geneva Observatory fiber test bench. This test bench allow to illuminate the tested fiber in a controlled way and make picture of near and far field in a stable way in order to measure scrambling and FRD.

3.2 Measurement of the near field

The near field scrambling is measured using an image of the output of the fiber through a microscope objective. The beam at the entrance at the fiber is scanned across the core of the tested fiber, simulating guiding errors in the telescope. The scrambling will be defined as the ratio between maximum residual movement of the barycenter of the near field illumination and the size of the core of the fiber.

The measure of the barycenter position is done the following way:

- An image of the near field is taken with a CCD,
- A "dark"/ ambient light correction is applied using the mean flux in one corner of the image,
- A mask is produced by a threshold method that permit ignore pixels under a certain threshold (75% of the maximum). This mask is used to avoid diffused light that is produced in the optics of the test bench (that are not extremely clean),
- The barycenter position is measured inside the mask.

The precision of the measurement is limited by the following factors:

- The movement of the fiber image on the detector. In the test bench this aspect has been reduced by going as fast as possible in doing the measurement. A scan of the fiber core lasts one to two minutes. More over the near field imaging bench is build on a low dilatation material, zerodur and invar. There however residual drifts see figure 3. The attained precision is 0.08 one-thousandth of the core diameter of a fiber for a 70 micron fiber. This is perfect to obtain good scrambling characterization.

- Spurious light: diffusion by the dusts in the optics, ambient light variation can limit the precision of the measurement. In order to reduce this to a maximum, when performing measurement the room in the dark, and the test bench is protected by an additional opaque baffle.
- Dust along the imagery system: The test bench has been assemble from stock optics, and is not stored in a clean environment. There is a lot of dust that can be seen on the CCD and along the imaging system. This will tend to increase the residual barycenter movements if the illumination pattern of the end of the fiber is changing (this is the case for the circular fiber).

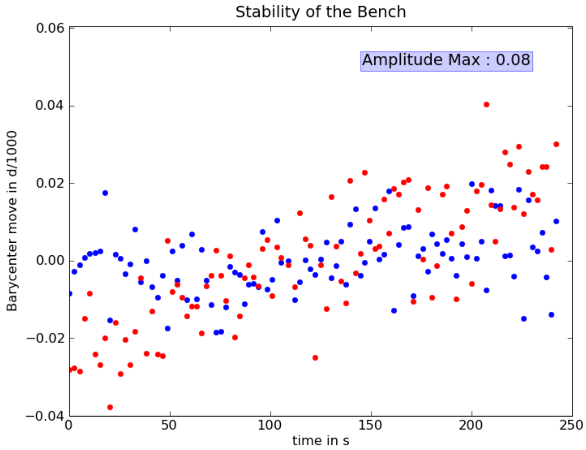


Figure 3. Stability of the test bench for near field imaging. This measurement was performed with an octagonal fiber of 70 micron core. A standard near field scrambling measurement lasts around 100 secs. Thus precision that one can reach is around 0.08 one-thousandth of the fiber core. In this setup this means measuring movements at the scale of 0.03 pixel.

3.3 Measurement of the far field

The far field is also imaged using a CCD set directly at the output of the test fiber. There is no intermediary optics. In order to get an angular measurement the CCD detector is translated precisely using a micrometer. As the symmetry of the far field is circular, the final measure product is a radial profile of the far field.

To produce these radial profiles, images undergo a specific treatment in order to get the best precision possible:

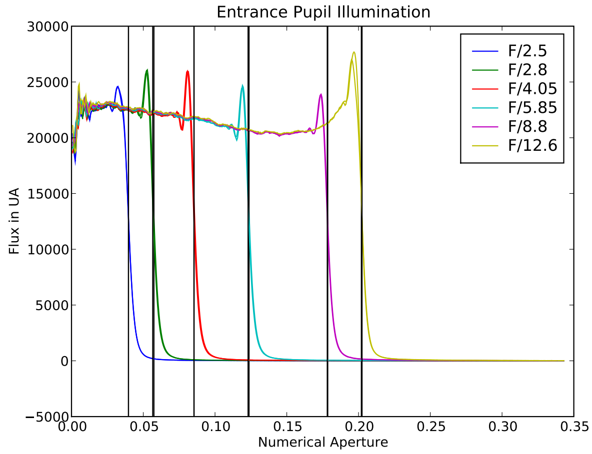
- First the background is subtracted in a similar way than for the near field,
- Then the barycenter of the image is calculated
- This barycenter is used as the center of a new coordinate system in which the image is projected.
- A radial projection is performed,
- Finally a cut of the far field is produced by averaging on all the angles in the projection.

In order to calibrate the images in angle the procedure is to take several radial profile of the same far field at different distances. Then the relative dilatation of the image is measured using a threshold and an interpolation.

This measurement method suffer from different issues :

- There is a strong hypothesis on the symmetry of the far field. It will be shown later in the text some of the issues
- Images are not done at the infinite, they are done at a distance near to the Rayleigh distance ($R = D^2/2\lambda$), thus Fresnel diffraction effects arise. The typical distance between the fiber and the CCD is 6 to 8 mm, while for a 70 micron fiber the $R \simeq 5$ mm.
- The angle between the beam and the CCD detector is not exactly 90 degree, and change from one measure to the other. As a consequence the image of the far field is not strictly circular. This will tend to smooth the radial profile that are obtained with the image processing described above. However the main effects are removed by calibrating the angles each time this relative orientation is modified. Thus the the angles are measured in unbiased way.
- To perform the measurements one needs a great deal of care, to center the entrance of the test fiber. This is an issue if as in the case of this test bench, in which one ca produce misalignment when changing diaphragm.

This method has also been used to calibrate the speed of the beam provided by the aperture controlling objective of the test bench, see figure 4.



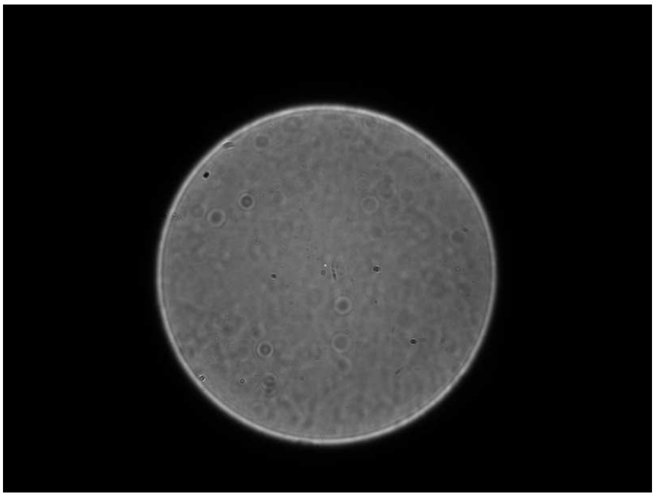


Figure 4. Profile of the entrance pupil versus the beam aperture measured with the same method as the Far field of the fibers. The hole at the center is artifact due to the presence of dust. The ripple on the border is Fresnel diffraction.

4. RESULTS

The fibers that have been tested on the Geneva Test bench, have been connectorized with SMA connectors, using a special glue that do not introduce constraints in the fiber, and thus reduce the FRD.

Several observations were made during the testing of the fiber, and during the development of the test bench:

- For the tested fiber it is very important to avoid injecting light out of the core, because of the external guiding layer. Otherwise as well for square and octagonal fiber strange phenomenon appears, such as, additional patterns in the near field, destroying the scrambling performance, and strange radial structure in the far field. The solution to this issue is to have good optical alignment and also a pinhole at the entrance of the tested fiber that eliminate the light that could enter the cladding.
- The size of the image at the entrance of the fiber has important consequences on the "performance" of the fiber. A too small image at the entrance will degrade the scrambling performance of the fiber as well in the near field and in the far field. As a standardization it was decided that the entrance image size should be half of the core of the fiber (this is a more or less pessimistic case).
- For both the square and octagonal fiber, there seem to be a strong dependence of the far field at the output with the position of the image in the near field of the entrance of the tested fiber. This phenomenon is not yet well understood, and could be real or the consequences of some difficulty in the alignment (such as focus). To make measurement in the far field, a great care has been taken to produce measurements always in the same conditions : the entrance image is centered, and the focus is set as precisely as possible.

4.1 Square fibers

The square fiber shows very good near field scrambling performance. If one compare to a circular fiber the gain is of a factor 6 to 10 see figure7.

In the Far field (see figure 6,5) the result depend on the size of the fiber :

- The 70 microns fiber showed a big FRD that might be the result of stresses in the connectors.
- The 200 microns fiber showed very strange radial pattern, which origin is not clear. They can be partially canceled if one introduces stresses on the fibers. The central part of the far field is not stable. Very small movements of the fiber produce large effects (like if they were the results of interferences). This central part show also some linear structure.

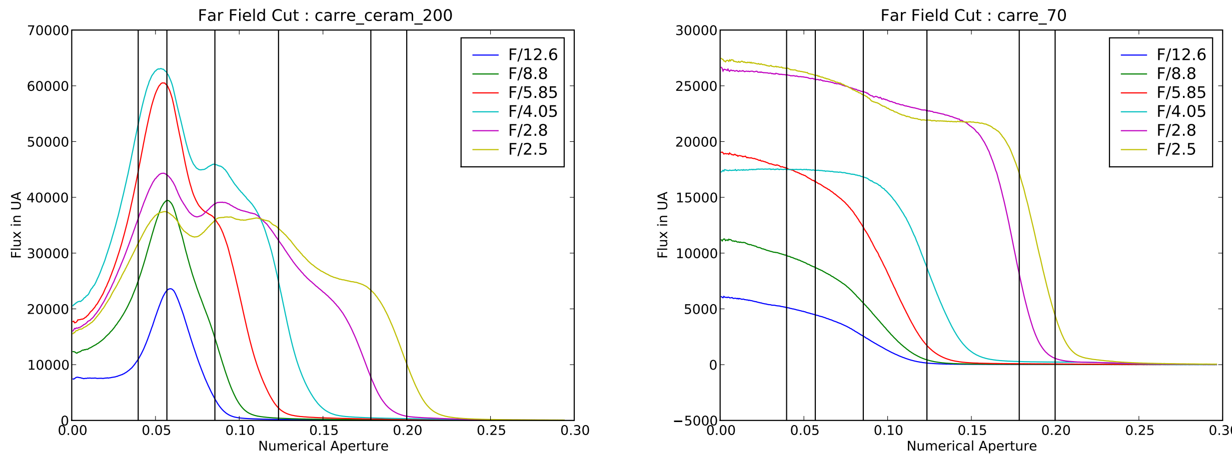


Figure 5. Far field of the square fiber, profile for FRD measurement. On the left the square fiber of 200 microns, on the right the one of 70 microns. Note that the angular calibration for the 200 micron fiber was not well measured, and has been extrapolated.

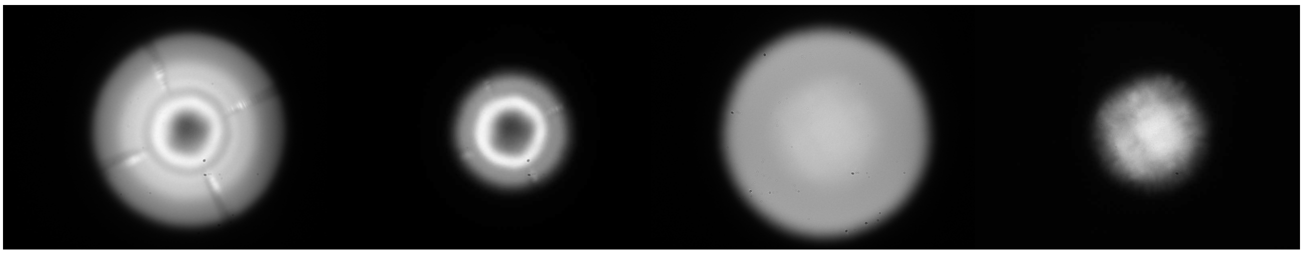


Figure 6. Far field images for the square fibers from CERAMOTPEC. The 2 images on the left are for the 200 microns fiber (F/2.5 and F/4.05). The 2 on the right show the 70 micron fiber(F/2.5 and F/12.6). On the small core Fiber there seem to be a lot of FRD, probably due to a bad connectorization. This might hide the radial structure that can be seen in the 200 micron fiber.

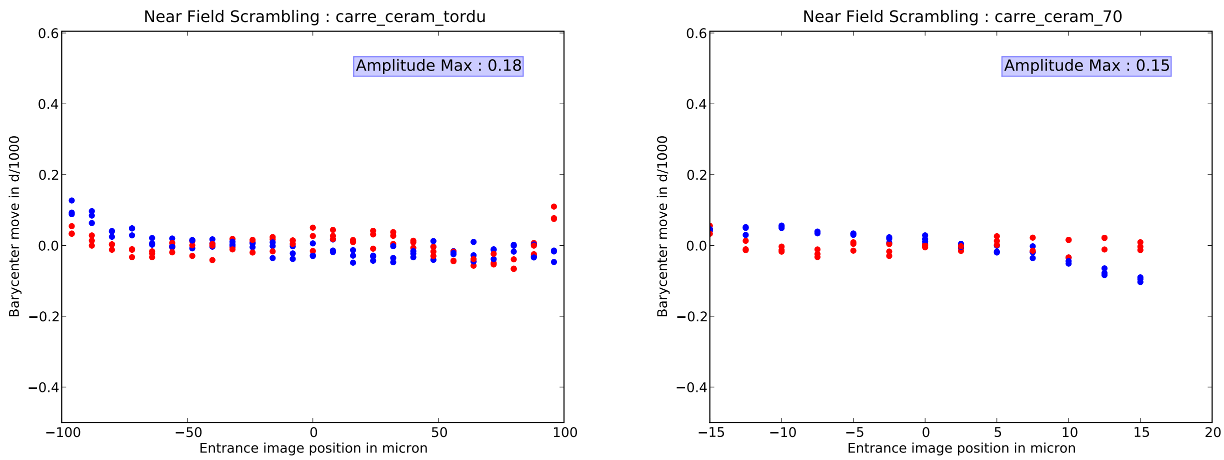


Figure 7. Near Field Scrambling for the 2 tested square fibers. On the left the 200 micron fiber from CERAMOPTEC, on the right the 70 micron CERAMOTPEC (under a squeezing stress). The curves represent the residual movements of the barycenter of the output near field during a scan of the entrance “star” on the core of the fiber. Red and Blue Curve are for the X and Y axis.

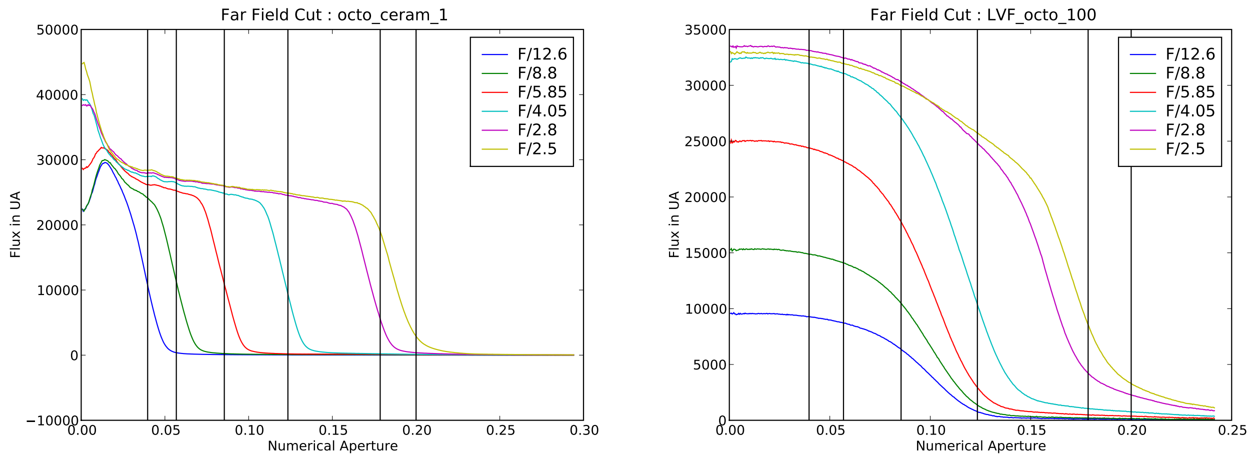


Figure 8. Far field of octagonal fiber, profile for FRD measurement. On the left the CERAMOPTEC octagonal fiber, on the right the one from Le Verre Fluoré.

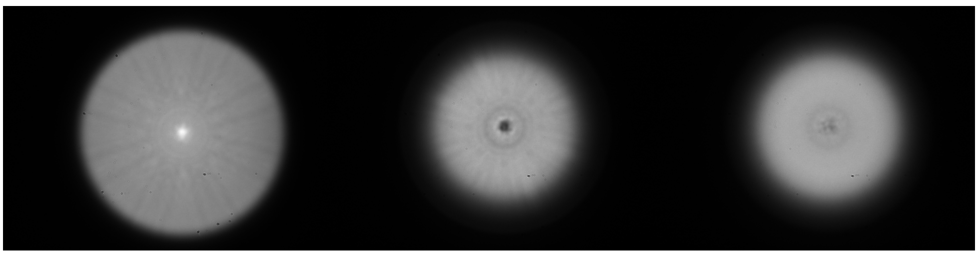


Figure 9. Far field images for the octagonal fiber from Ceramotpec. Ther is a strange radial structure and a central zone that have some strange properties. These structure are very sensitive to the movements of the fiber and to the near field injection. On can scramble these structure partially by applying constraints to the fiber but same strange speckle like structure remains at the center.

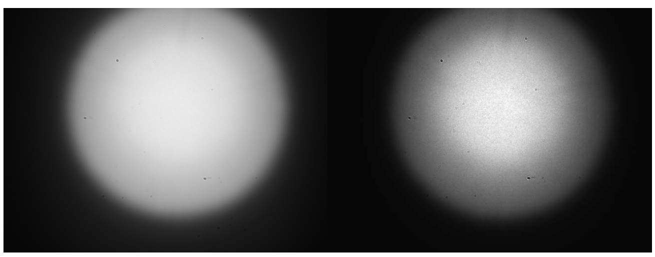


Figure 10. Far field of the the octagonal fiber from Le Verre Fluoré, though there is a high level of FRD hiding it, there are also some radial structures, that have been enhanced in the image on the left.

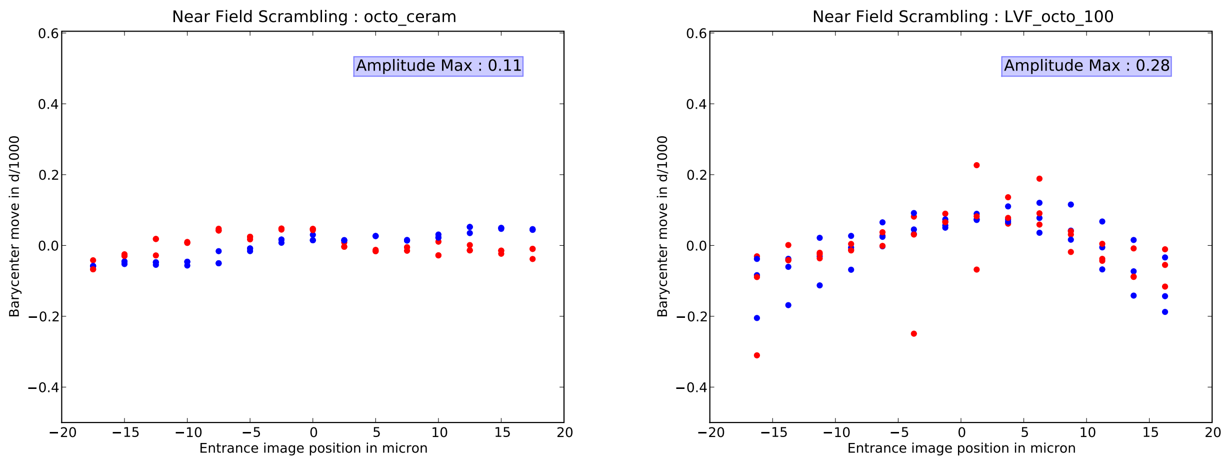


Figure 11. Near Field Scrambling for the 2 tested octogonal fibers. On the left the one of CERAMOTPEC, on the right the one of Le Verre Fluoré. The curves represent the residual movements of the barycenter of the output near field during a scan of the entrance "star" on the core of the fiber. Red and Blue Curve are for the X and Y axis.

4.2 Octagonal fiber

The octagonal fiber shows very good near field scrambling performances. If one compare to a circular fiber the gain is of a factor roughly 10.

- In the far field the 70 microns fiber shows some nice geometrical properties (see figure 8), however there are some radial structure (see figure 9) in the far field, and a central spot that is very sensitive to the movements of the fiber.
- The Fluoride Glass fiber, have poorer performance in the near field (see figure 11). In the far field they show a large FRD and also very faint radial structures (see figure 10) that seem to be attenuated by the large FRD. This FRD seems consistent with a too high stress in the connectors.

4.3 Summary

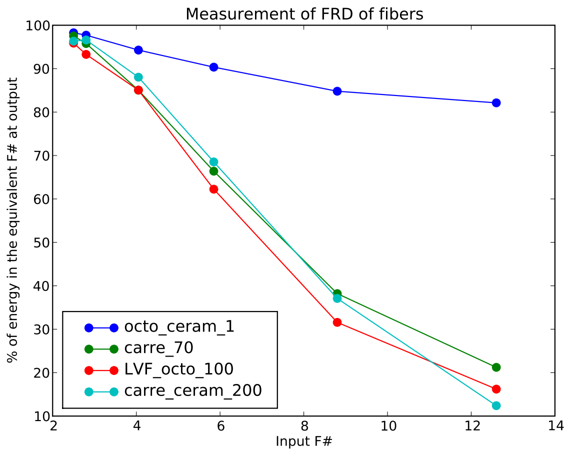


Figure 12. Geometrical FRD: Amount of light inside the beam aperture injected in the fiber (see figure 4). This does not take into account the potential losses. Summary for the measured Fibers

Fiber	Near Field Scrambling (in 1/1000th of the core diameter)	FRD (see figure 12)
Square 70 microns (CERAMOPTEC)	0.15	BAD (connector ?)
Square 200 microns (CERAMOPTEC)	0.18	Very Strange radial structures
Octagonal 70 microns (CERAMOPTEC)	0.11	Very Strange radial structures
Octagonal 100 microns (Le Verre Fluoré)	0.78	BAD (connector ?) Radial structures
Circular Fiber (Thorlabs) for comparison	1.1	BAD (connector ?)

5. CONCLUSION

Square and Octagonal fibers are very promising candidate for being the next generation optical scrambler for Precise Radial Velocity instruments. They have however still some very strange properties in the Far field, that are not yet understood. This might be the consequences of the unusual structure of the fiber we tested (external layer of nylon). Further tests are needed in order to understand better this phenomenon as it might jeopardize the use of these fibers. One of the next step will be to tests these fibers without the nylon layer.

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