Precise Stellar Radial Velocities
ASP Conference Series, Vol. 185, 1999
J. B. Hearnshaw and C. D. Scarfe, eds.

The fiber-fed spectrograph, a tool to detect planets

D. Queloz

JPL, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

M. Casse

ESO, Karl-Schwarzschild-Str. 2, D-85748 Garching b. München, Germany

M. Mayor

Observatoire de Genève, 51 ch. des Maillettes, CH-1290 Sauverny, Switzerland

Abstract. The use of fibers to feed spectrographs is a very efficient way to increase the precision of radial velocity measurements. It has already proved to be successful with the very first detection by the ELODIE fiber-fed spectrograph of the planet orbiting the star 51 Peg. The basic key properties of fibers in the very high radial velocity precision measurements context are described in this review. The ELODIE spectrograph is used to illustrate the thorium simultaneous calibration technique. The use and the effects of a double-scrambler to increase the stability of the slit illumination are also discussed.

1. Introduction

Planet detection by Doppler shift measurements from stellar spectra observations requires very high radial velocity precision data over many years of measurements. A precision better than $10\,\mathrm{m\,s^{-1}}$ in radial velocity measurements is required to detect a planet like our own Jupiter. A lot of serious instrumental problems have to be considered and must be solved to reach this level of accuracy, that is about 1000 times smaller than the resolution of typical high resolution spectrographs. (see in Queloz 1999 for more details and references).

One of the most critical issues in high precision radial velocity measurements is the entrance slit illumination of the spectrograph. Any tracking or centering offset at the slit entrance produces an instrumental velocity zero point change on the recorded spectrum. Any slight seeing modification during the night also affects the final spectral resolution.

The computed radial velocity from stellar spectral lines is very sensitive to any point spread function (PSF) change of the instrument itself. Mechanical and thermal effects must be kept to a minimum in order to get an instrument PSF as stable as possible.

The position of the stellar spectrum is not stable on the detector. From the Earth orbital motion effect, the spectral line position moves by many pixels over the months and the various pixel and intra-pixel responses of the detector affect the accuracy on line shift measurements. Moreover, if the instrument is not pressure and temperature controlled, the sole changes of the air index produce a large velocity shift compared to the gravity effect of a planetary companion that one strives to detect.

In the next two chapters we describe the use of a fiber as a way to solve many of these problems. The example of the ELODIE échelle spectrograph illustrates, in the next section, a successful use of fibers to get high precision radial velocity measurements.

2. Optical fibers, some basics

An optical fiber is a waveguide in which only specific modes (eigenvalue solutions to Maxwell's equations) can propagate. The number of different modes passing through a fiber depends on its core size. For fibers with core diameters less than about $10\,\mu$m, only one mode can propagate. These small section fibers are named: "*single mode fibers*". For larger cores (50–$500\,\mu$m), the fibers are multi-mode.

One of the most important properties of a fiber, when it is used to feed a spectrograph, is the image scrambling effect at the output of the fiber (see Heacox 1988 for details). A single-mode fiber is, by definition, a perfect scrambler. However, the core size is too small to link a large telescope with its instrument efficiently[1]. Multi-mode fibers are excellent beam scramblers in the azimuthal direction of the fiber section but not in the radial direction (se Fig. 1). However, a fiber is never perfectly circular and there are impurities in the fiber core. Both increase the quality of the beam scrambling.

The various fiber imperfections and microbendings (stemming mostly from core cladding interfaces) increase the output beam aperture (random walk phenomena). This *focal ratio degradation* (FRD) effect increases rapidly with the input focal ratio. However, if the input focal ration is small, this effect can be almost negligible (see Fig. 2). Interestingly a fiber with some FRD has a better scrambling efficiency than a perfect one.

Intrinsic losses in the fiber are negligible for typical lengths used in astronomy. If microbendings and stresses from fiber connectors are minimal, the fibers can almost get up to 80% transmission. Contrary to a somewhat common misconception, a well mounted fiber is not a photon well.

One last and obvious property which comes with the use of fibers is the ability to move the instrument away from the "noisy" telescope environment. This may simplify the design of the instrument, but also permits to isolate the instrument from any perturbation like pressure or temperature changes and mechanical bendings stemming from instrument position changes. Usually fiber-fed échelle spectrographs are located on a stable optical bench in an isolated room, far away from the telescope.

---

[1]This may not be true in the near future with the use of efficient AO systems

https://doi.org/10.1017/S0252921100048284 Published online by Cambridge University Press

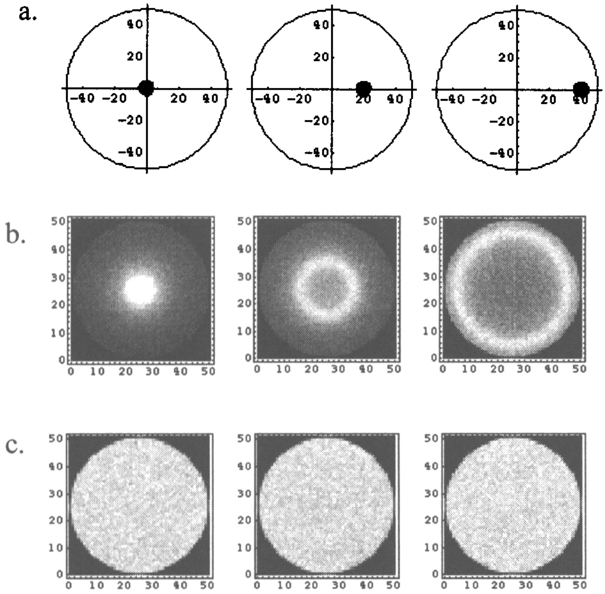

Figure 1. Display of the scrambling effect by a perfect fiber (ray tracing simulation). **a.** input beam locations (filled dots), **b.** output images of the fiber section (near-field images). **c** far-field images of the output (pupil).
The toroidal structure of the output near-field images is the result of the combination of a very good output beam azimuthal scrambling with a poor one in the radial direction. It is worth noting that the illumination of the far-field is mostly uniform and independent of the position of the input beam.

3. Increasing the output beam scrambling quality: the double-scrambler solution

The far-field output illumination of a fiber is very uniform and almost independent of details of the entrance illumination (see on Fig. 1). The idea of the double-scrambler is to use this very good *angular* scrambling and transform it into a spatial one to feed another fiber. The double-scrambler couples two fibers, where the angular information of the ouput rays from the first fiber is transformed by two lenses into off-axis distances on the input face of the second fiber (see Fig. 3). Since there is no angular information on the output of the first fiber – the far-field illumination of the output beam is very uniform – the input illumination of the second fiber is therefore also very uniform.

Some near-field information from the output of the first fiber is now in the far-field output of the second fiber which feeds the spectrograph. Since

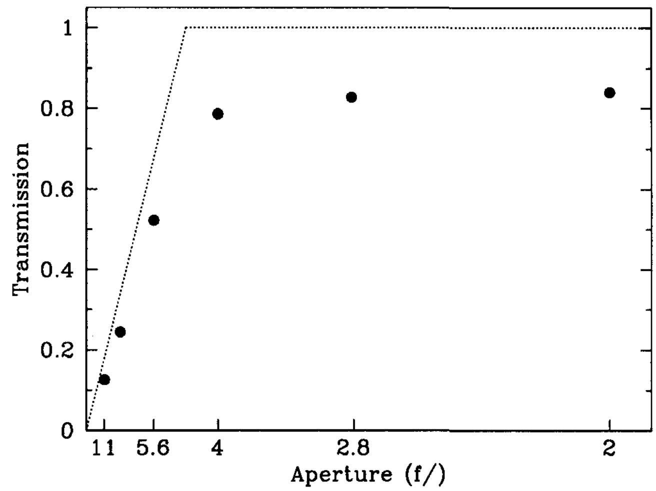

Figure 2. Illustration of the focal ratio degradation effect. One of the ELODIE fibers is illuminated with a 5000Å beam with an f/4.5 aperture (dotted line). At the output an 80% transmission is measured for apertures larger than f/4 [data from Baranne et al. (1996)]. The focal ratio degradation in this case is small since we have about 70% transmission at f/4.5 output aperture.

the pupil of the beam illuminates the grating, one may see some effects, from any illumination changes of the entrance of the first fiber, on the PSF of the instrument. So far nobody has even tried to see such second order effects, but at some level they should be visible.

The use of the Ramsey et al. (1989) double-scrambler –from an original idea by Connes (1985)– on the AFOE (Brown et al. 1994) spectrograph led to a precision increase (on short term) from 5 to 1 m s^{-1} (Brown 1990) at the expense of a poor 20% efficiency compared to a plain fiber. Most probable losses come from micro-bendings arising form the coupling of the two fibers itself together with small lenses. (See also Casse & Vieira (1996) for similar results but with a slightly different design). An enlarged version with achromat lenses is used on ELODIE (Queloz et al. 1997). For this one particularly, the losses stemming from the double-scrambler are almost negligible compared to the other set of plain fibers (about 10% loss).

An interesting new concept under development is a compact "solid scrambler" proposed and studied by one of us (MC). This solution uses a gradient index lens to make an image of the far-field of the fiber and a tapered (conical) section of fiber acting as a focal reducer (see Fig. 4). All the components are optically glued together. This solution offers the advantages of high stability and compactness similar to the Ramsey et al. (1989) design but with a much better

https://doi.org/10.1017/S0252921100048284 Published online by Cambridge University Press

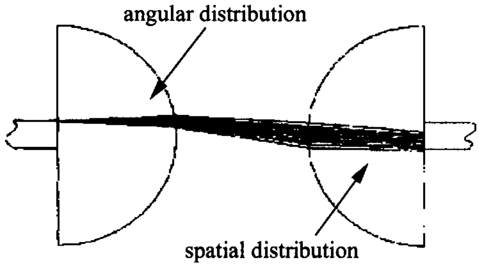

Figure 3. Illustration of the angular to spatial inversion carried out by a "double-scrambler". The far-field output beam from the first fiber (on the left) is transformed into a near-field to feed the second fiber (on the right) by two lenses. In other words, one makes an image of the output far-field of the first fiber on the entrance of the second fiber. An inversion of the far-field to the near-field (and the opposite) have been carried out.

transmission efficiency. From Fig. 3 one easily notices that the double-scrambler design is highly sensitive to misalignments. Any slight misalignments between the two lenses would change the spatial illumination on the second fiber and, therefore, would produce a change of the zero point of the spectrum. The use of a compact "solid scrambler" is a way to prevent any misalignments from ageing or from mishandlings.

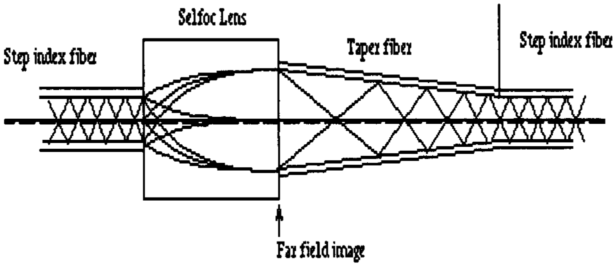

Figure 4. Schematic design of a "solid scrambler". The Selfoc gradient index lens makes an image of the far-field of the first fiber output (on the left). The taper fiber acts like a focal reducer to feed the second fiber (on the right) .

https://doi.org/10.1017/S0252921100048284 Published online by Cambridge University Press

4. The ELODIE solution

The use of fibers to feed spectrographs yields a uniform and stable illumination of the instrument. However the instrument itself needs to be stable to ensure a constant PSF.

The resolution of a typical échelle spectrograph is usually not good enough to "resolve" stellar spectral profiles of old cool stars like our Sun. Therefore, most of the line profiles, for these stars, are images of the PSF of the spectrograph. Since the accuracy aimed at is 1000 smaller than the line width, any tiny profile change stemming from PSF changes has a direct effect on the precision of radial velocity measurements.

The ELODIE spectrograph is located in a temperature controlled room and the cryostat is connected to an automatic N_2 feeding system. Nobody ever enters the instrument room during spectrograph operations. However, the instrument is not isolated in a vacuum tank and the filling of the cryostat (thermal shock) has some "negative" effects on the temperature stability of the spectrograph many hours after the filling. We need to monitor the velocity point drift of the instrument. The instrument is not stable enough so that we can have confidence in its overall stability but only in its PSF. The zero point is monitored with the simultaneous thorium technique.

In the simultaneous thorium technique, a second fiber is used to feed the spectrograph with a reference spectrum (thorium lamp, for instance). In the spectrograph there are two beams very close together (see Fig. 5). During a science exposure the second beam is illuminated by the thorium lamp. Each beam has its own wavelength calibration but their wavelength variations are correlated. We measure the zero point variation with the thorium spectrum and we apply this correction to the stellar spectrum taken at the same time. Intensive tests carried out with ELODIE showed that the velocity drift of each optical path matched each other with a precision of about $2\,\mathrm{ms}^{-1}$ (Baranne et al. 1996). If the stellar flux is stable during the exposure, the drift measured on the thorium will be the same as the mean drift on the science spectrum. However, if the stellar flux has a drastic drop during the exposure and if the instrument has a continuous drift, the mean drift computed from the thorium spectrum won't match the drift on the science spectrum since the instrument variations, when the flux dropped, have not been "recorded" by the stellar spectrum. In order to limit the effects of this *"flux mismatch"*, the exposure times must be limited to about 10-20 minutes.

In 1996, during the installation of the double-scrambler many improvements were made to increase the thermal and the mechanical stability of ELODIE. We also, at that time, decided to limit the exposure times to a 15 minute maximum in order to resrict the effects of the flux mismatch problem between the calibration lamp and the science target. All these improvements have increased the long term accuracy of the instrument which is now close to $10\,\mathrm{ms}^{-1}$ (see Fig. 6).

The current $10\,\mathrm{ms}^{-1}$ limitation is probably due to some PSF changes arising from slight temperature variations in the instrument. The instrument is not as stable as expected. Hysteresis in the temperature control of the ELODIE room changes the temperature setup between the summer and the winter (different temperature regulation regimes). This produces some systematics in radial velocities. The cryostat bending and thermal shock remnants from the cryostat

https://doi.org/10.1017/S0252921100048284 Published online by Cambridge University Press

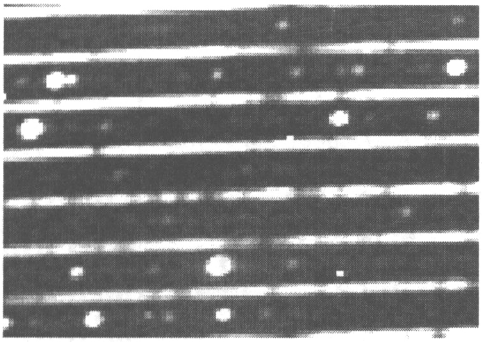

Figure 5. Small portion of a CCD frame obtained with ELODIE for a thorium simultaneous exposure. Two fibers feed the spectrograph. They lie on top of each other at the spectrograph entrance. The science spectrum (absorption) and the thorium spectrum (emission lines) are easily recognizable on the CCD frame.

filling also produce some small changes in the PSF of the instrument between the begining and the end of the night. Paradoxically, this short term effect is mainly seen as a long term precision loss because the observation time in the night, for a given star, changes during the year.

5. Conclusions

The use of fibers to feed échelle spectrographs is an easy and efficient way to improve their performance in terms of accuracy of radial velocity measurements. With the output beam scrambling property of a fiber and possibly the help of a double-scrambler, a fiber-fed spectrograph can have a very stable slit illumination. If the micro-bendings and stresses stemming from the mounting of fibers are kept to a minimum and the input focal ratio is small, the fibers are bright optical components with about 80% transmission. For échelle spectrographs particularly, the use of fibers does not restrict the large wavelength domain available. Modern fibers do not have strong wavelength limitations in the extended visible range (4000 Å to 1 μm).

By itself, the use of fibers does not yield accurate radial velocity measurements. The measurements have to be tied somehow to a stable radial velocity zero reference. In any case, a zero point monitoring is required. The simultaneous thorium technique provides us with an easy and efficient way to measure any zero point shifts occurring during the exposure. Usually, the observed spectral line profile is given by the instrument but not by the intrinsic stellar profile. Therefore the PSF of the instrument must be stable enough not to introduce systematics in the computation of the position of spectral lines. In order to have a stable PSF we must have a very stable instrument located in an isolated and controlled environment.

https://doi.org/10.1017/S0252921100048284 Published online by Cambridge University Press

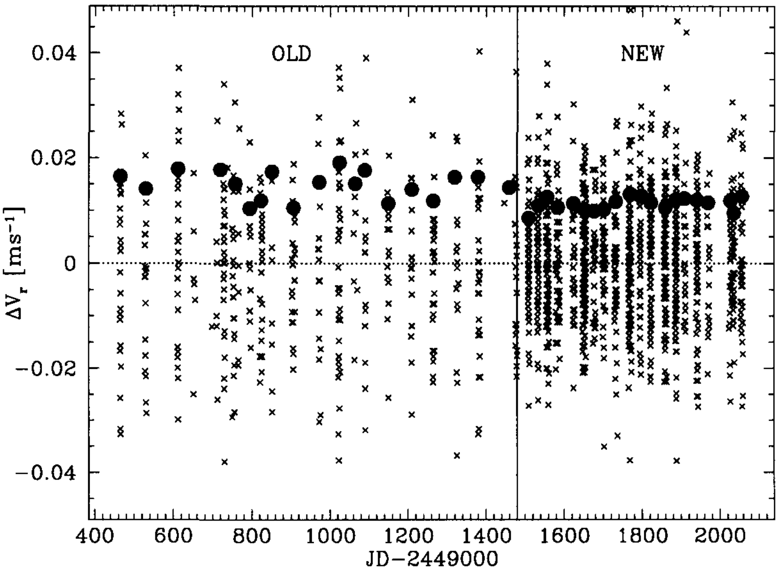

Figure 6. Summary of the performance of the ELODIE planetary search program in terms of precision. The individual radial velocity measurements over the whole duration of the survey (crosses) of all stars that didn't exhibit obvious velocity variations are displayed. The "NEW" period of time refers to the "new survey" after the addition of the scrambler and the improvement of the stability of the instrument. Filled dots indicate the oberevd r.m.s. $\sigma(V_r)$ per observing run. The precision gain from $15\,\mathrm{ms}^{-1}$ to $10\,\mathrm{ms}^{-1}$ after the improvements made on the instrument is clearly visible on the figure.

ELODIE and AFOE are the first fiber-fed instruments to reach radial velocity precisions close to $10\,\mathrm{ms}^{-1}$. Their current limitations probably come from imperfect controls of thermal regulation. In next generation of fiber-fed échelle spectrographs like CORALIE (an improved version of the ELODIE spectrograph), great care has been taken to increase overall stability. Early results suggest that a precision of about $5\,\mathrm{ms}^{-1}$ can be reached. We may hope that a third generation of dedicated instruments like for example HARPS, which ESO is considering for its 3.6-m telescope at La Silla, should be able to reach a precision of $1\,\mathrm{ms}^{-1}$ or even better.

Discussion

Marcy: Can you please describe the light losses at the air-to-glass interfaces for the fiber ends and transfer optics between fibers?

https://doi.org/10.1017/S0252921100048284 Published online by Cambridge University Press

Queloz: If the fiber mounting is done properly, then the losses are 19 %.

References

Baranne, A., Queloz, D., Mayor M., et al., 1996, A&AS, 119, 373.

Brown, T., Noyes, R. W., Nisenson, P, et al., 1994, PASP, 106, 1285.

Brown, T., 1990, in "CCDs in Astronomy", ed. G. Jacoby ASP Conf Ser. 8, 335.

Connes, P., 1985, ApSS, 110, 211.

Casse, M., Vieira, F., 1996, in "Optical telescopes of today and tomorrow", SPIE proceedings, 2871, 1187.

Heacox, W. D., 1988, in "Fiber Optics in Astronomy", ASP Conf. Ser. 3, S. C. Barden (ed.), 204.

Mayor M., Queloz D., 1995, Nature, 378, 355.

Queloz et al. 1997, in "Brown Dwarfs and Extrasolar Planets", ASP Conf. Ser., vol. 134 , Eds. R. Rebolo, E.L. Martin, M.R. Zapatero Osorio, 324

Queloz D., 1999, in "Planets Outside The Solar System", NATO ASI School, J.-M. Mariotti & D. Alloin (eds.), in press.

Ramsey et al. 1989, in "Frontiers of the stellar evolution", ASP conf. ser. 20, D. Lambert (ed.), 614. 368, 599.