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FIES fiber injection upgrade

Julian Stürmer^a, Andreas Seifahrt^a, Christian Schwab^b, NOT staff^c, Davide Gandolfi^e, Pilar Montañés Rodríguez^d, Lars Buchhave^f

^aUniversity of Chicago, USA; ^bMacquarie Univ., Australia; ^cNordic Optical Telescope, Spain; ^dInstituto de Astrofísica de Canarias, Spain; ^eUniversità degli studi di Torino, Italy; ^fDTU Space, National Space Institute, Technical University of Denmark, Denmark

ABSTRACT

We report on the upgrade of the fiber link of FIES, the high-resolution echelle spectrograph at the Nordic Optical Telescope (NOT). In order to improve the radial velocity (RV) stability of FIES, we replaced the circular fibers by octagonal and rectangular ones to utilize their superior scrambling performance. Two additional fibers for a planned polarimetry mode were added during the upgrade. The injection optics and the telescope front-end were also replaced. The first on-sky RV measurements indicate that the influence of guiding errors is greatly suppressed, and the overall RV precision of FIES has significantly improved.

Keywords: optical fibers, radial velocity, FIES, echelle, spectrograph

1. INTRODUCTION

FIES is a cross-dispersed, high-resolution echelle spectrograph at the 2.56 m Nordic Optical Telescope. The instrument offers three resolution modes $R=67,000$ (high-res), $R=46,000$ (med-res) and $R=25,000$ (low-res). The wavelength range recorded by the CCD is 370 nm to 940 nm. However, for wavelengths longer than 800 nm, the order spacing in the high-res mode is becoming too small to cleanly extract spectra. In the med-res mode, the extended wavelength range is available. FIES is most commonly used to measure stellar abundances, to study stellar activity and seismology, and for exoplanetary research. In the past, FIES has reached a RV precision of about 8 m s^{-1} for RV standard stars over timescales of days to weeks.¹ On-sky tests have shown that its RV stability was mainly limited by insufficient spatial scrambling. Optical fibers with non-circular cross sections have been shown to improve spatial scrambling significantly²⁻⁴ and are now the standard choice for newly built RV spectrographs.⁵⁻⁷ They have also successfully been retrofitted to older instruments to improve their RV stability.^{8,9} Here, we report on the fiber injection upgrade for FIES.

2. TELESCOPE FRONT-END

In the process of replacing the circular fibers, the telescope front-end was also replaced for two reasons. The old injection system for calibration light only supported two different light sources. Since FIES will be upgraded with an etalon calibration source in the near future, an additional port became necessary. The second reason is that the old front-end projected the telescope pupil onto the near-field of the fibers. Although this allows minimizing the number of optical surfaces in the optical system that converts the telescope f-ratio to the faster f-ratio needed to feed the fiber efficiently, it is not optimal with respect to scrambling. Guiding errors affect the stellar image shape and position more than the telescope pupil. Non-circular fibers only effectively scramble the fiber near-field. As long as no double-scrambler (i.e. optics that exchange near- and far-field) is used, it is therefore beneficial to map the stellar image onto the fiber, rather than the telescope pupil. An additional motivation to change the front-end optics was that the old fiber bundle fed the light in a relatively slow beam ($f/6$) into the fibers. Since focal ratio degradation (FRD) is lower for faster beams, we decided to use smaller fibers and a f-ratio of $f/4.8$.

The fiber input head at the telescope end of the fibers consists of 4 fibers with individual telecentric optical systems that convert the $f/11$ telescope beam to $f/4.8$ (FN-systems). One FN-system consists of two custom

Further author information: (Send correspondence to JS)
E-mail: stuermer@uchicago.edu

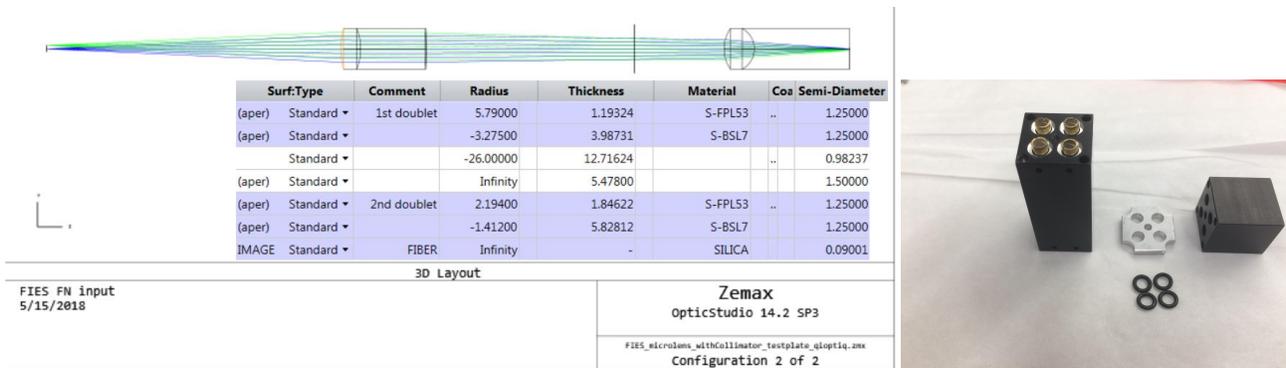


Figure 1: FIES FN-system design that convert the f/11 telescope beam to f/4.8 (left). All lenses have a diameter of 2.5 mm and are held in a thin brass tube. Due to optical constrains, all fibers had to sit closely (6 mm distance) together (right).

microlens doublets (manufactured by Qioptiq, Asslar, Germany) with 2.5 mm diameter, the same size as the fiber ferrule. The second microlens has a flat exit surface that is in physical contact with the fiber to minimize glass-air transitions. Lenses and fiber ferrule are both held in a single brass tube that is cut along its axis to provide radial clamping. The lens system provides diffraction limited performance over the entire wavelength range (370 nm to 900 nm) and the lenses are AR coated on all air-glass surfaces with an average of 99% transmission from 400 nm to 900 nm. The FN design and the partially assembled fiber head is shown in Figure 1.

Placed in front of each FN-system is a 12.7 μm thin metallic mirror with a precision machined central hole with either 210 μm (med- and high-res) or 350 μm (low-res) diameter, manufactured by National Aperture. The mirrors sit on a slanted surface and reflect the light of the PSF wings to a camera for guiding. Each mirror was individually aligned to optimize the registration of the hole with respect to the actual fiber position.

Each fiber can be illuminated by calibration light. The new front-end has four calibration fiber ports. Inside the front-end, one fiber from each port is merging into a single fiber connector. A subsequent FN-system and mirrors create a f/11 beam that can be moved in front of each fiber via a precision XY stage (see Fig. 2).

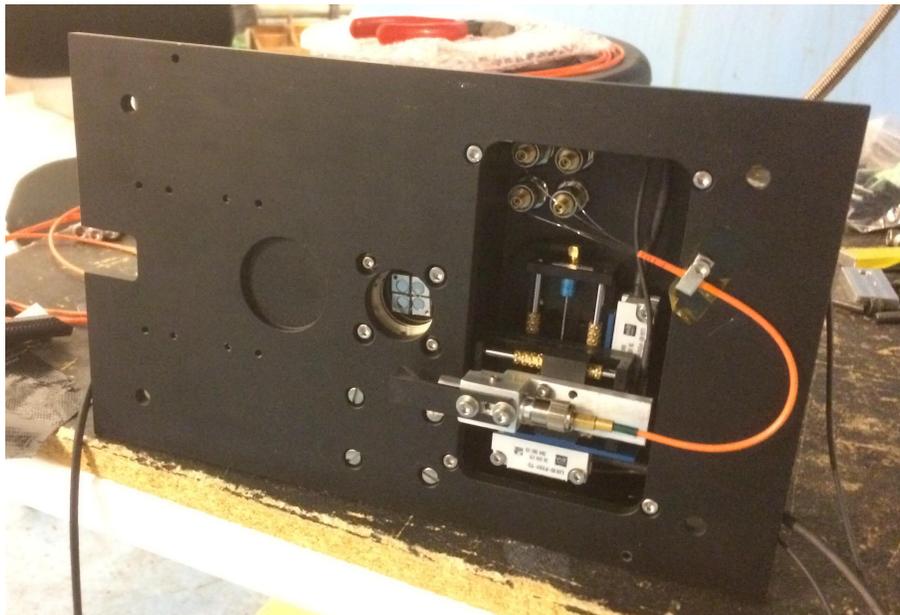


Figure 2: Part of the FIES telescope front-end. In the center, the four metallic guiding mirrors are visible. At the right sits the XY-stage that moves the calibration arm in front of the science fibers.

3. OPTICAL FIBERS

In order to support all three resolution modes of FIES, three different fibers were used: Two octagonal (CeramOptec WF Oct 179/250A and CeramOptec WF Oct 89/125A) for the low- and med-res modes, and a 4:1 rectangular fiber (CeramOptec WF RCT 45x180/52x207/360/450A) for the high-res mode. Both octagonal fibers were drawn from the same preform. The total length of each fiber is 42 m, intersected by FC-FC connectors after about 40 m.

The 2 m fiber bundle at the spectrograph side ends with a fused silica slit plate (manufactured by FemtoPrint) with precision machined holes where the fibers are glued in (see Figure 3). In the old fiber bundle, the smaller slit width for the high-resolution mode was realized by masking part of the circular fiber. Now, the high-resolution mode consists of an octagonal fiber at the telescope end and a subsequent rectangular fiber, connected only by physical contact. Both methods lead to a slit loss of about 40%. A planned image slicer should minimize this light loss and can easily be integrated as an upgrade at the fiber intersection (see section 5).

The smallest structural feedthrough of 10×40 mm between the telescope and the spectrograph posed a tight mechanical constraint for the fiber routing and limited the size of the connectors and mechanics connected to the fibers. We therefore decided to divide the fibers into a long 40 m section and a short 2 m section, connected via FC-FC fiber connectors. The additional light loss due to the junction was measured in the lab to be 2% to 3%. All fibers are protected by individual furcation tubes (Thorlabs FT020) inserted into a common stainless steel braided tube.

After installing the fiber bundle, simple tests using calibration light showed that the fibers suffered from focal ratio degradation, which led to an additional loss of about 25%. Since previous tests in the lab did not show any issues, we suspect that fiber installation led to mechanical stress inside the bundle and therefore the increase in FRD. We hope to improve on the protection tube design and fiber routing when delivering the spare fiber bundle, which currently is still in the laboratory.

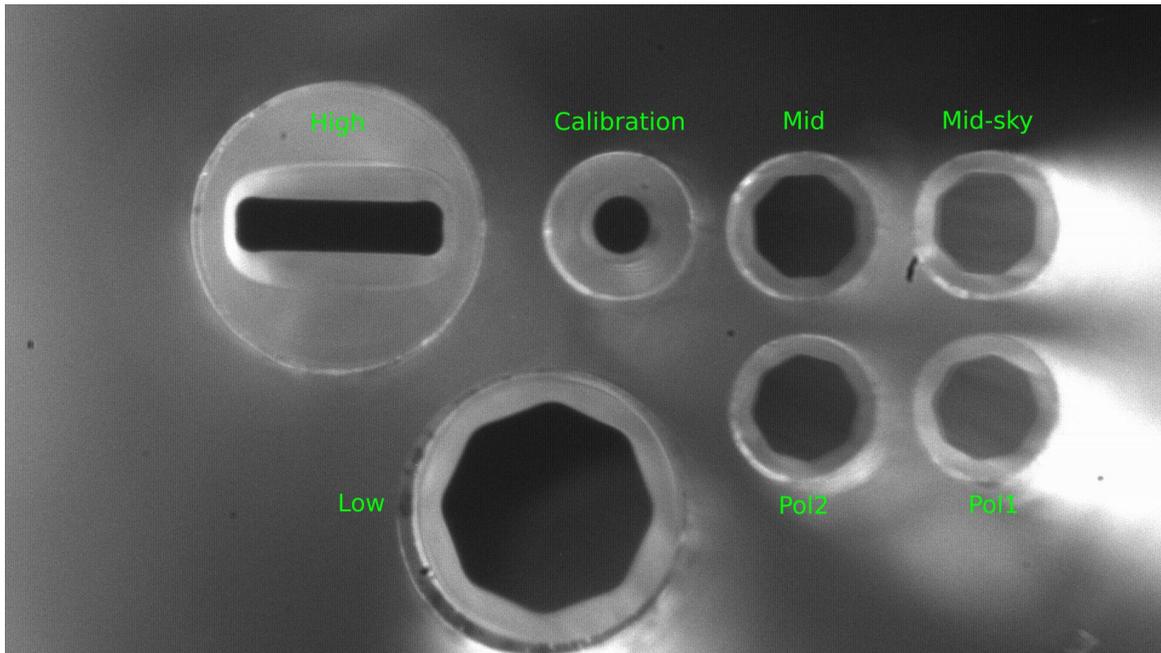


Figure 3: New FIES fiber exit slit plate illuminated from the side. The fibers are glued into a fused silica plate with precisely etched holes, and then polished. Clearly visible is the double cladding structure of the rectangular fiber (upper left). The dispersion direction is the y-direction.

4. ON SKY RESULTS

In order to test the improvements on the scrambling gain from the octagonal fibers, we observed a RV standard star (HD 185144) and tested its RV stability against guiding offsets during commissioning. We took a series of 11 stellar spectra and intermediate ThAr calibration frames in the high resolution mode while offsetting the star in $0.25''$ steps for the last 4 spectra. The resulting RVs were unaffected by the spatial offset of the star, contrary to the results of previous tests with the old bundle, where offsetting the star led to an RV shift of over hundreds of meters per second (see Fig. 4). The RMS scatter (corrected for mostly pressure-induced shifts of the spectrograph via the ThAr frames) was measured to be 1.8 m s^{-1} , a previously unattainable short-term stability.

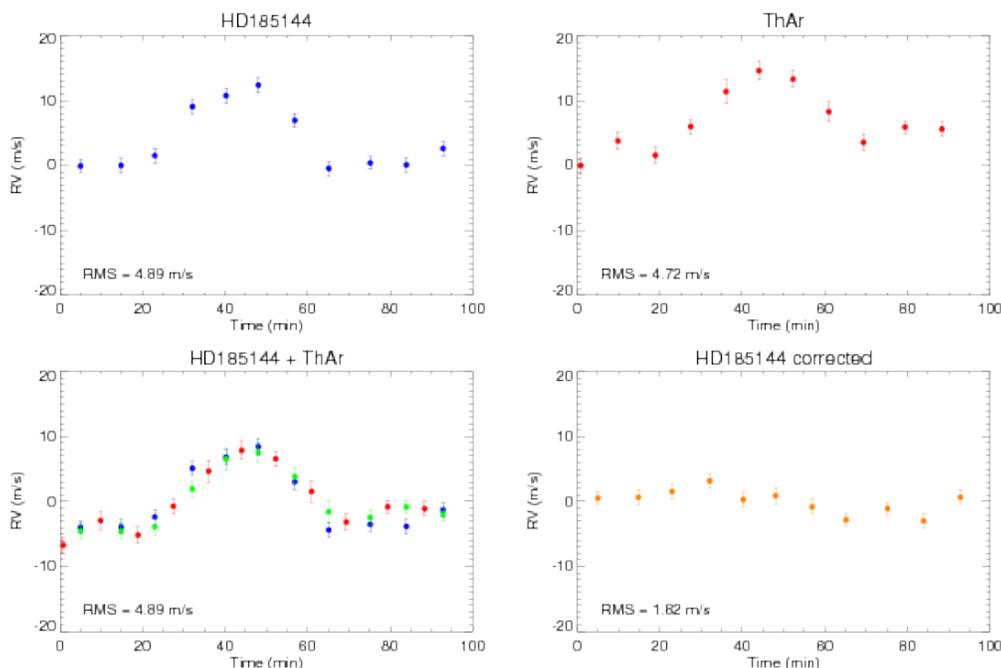


Figure 4: RV measurement of the RV standard HD185144 during commissioning of the new fiber bundle. For the last four spectra in this sequence, we deliberately offset the star on the guiding aperture in $0.25''$ steps to test the RV sensitivity to guiding errors. No significant change in RV was measured, demonstrating the greatly improved scrambling properties of the octagonal/rectangular fiber feed.

Another series of observations of an RV standard star using the medium resolution mode also showed excellent short term stability with an RMS scatter of 1.2 m s^{-1} (see Fig 5). On longer timescales, the achievable RV precision is currently under investigation, but we have strong indications that it also improved significantly.

5. CONCLUSION AND OUTLOOK

We reported on the successful upgrade of the fiber injection system of the FIES spectrograph at the NOT. By replacing the regular circular fibers with non-circular ones, we were able to improve the short term RV stability of FIES significantly to about 1 m s^{-1} to 2 m s^{-1} . The increased RV precision allows targeting of a significantly larger set of exoplanet candidate systems, with smaller planetary companions. The upgrade of FIES is not fully completed, yet. While the spectrograph is mounted in a temperature controlled room, it is not in vacuum and consequently suffers from large RV drifts caused by the variations in ambient pressure. A precise wavelength solution and an exact determination of the spectrograph RV drift are thus crucial to obtain precision RV measurements. To address this, a stabilized and actively scanned Fabry-Perot etalon will be deployed in the coming year as an additional calibration source.^{10,11} Additionally, we are working on an image slicer that will improve the coupling efficiency between the octagonal fiber coming from the telescope and the 4:1 rectangular high-res fiber fed into the spectrograph.

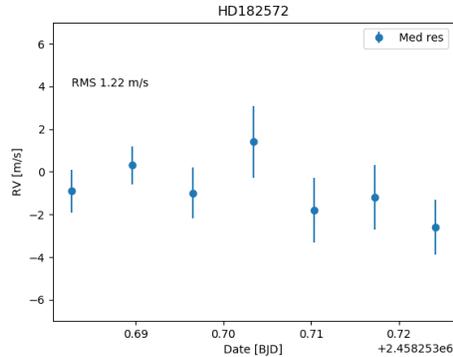


Figure 5: Another series of observations for a RV standard star, this time using the medium resolution mode, also shows excellent short term RV stability.

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