First Light of NIRPS, the Near-Infrared Adaptive-Optics assisted high resolution spectrograph for the ESO 3.6m

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ABSTRACT

NIRPS is an infrared precision Radial Velocity (pRV) spectrograph covering the range 950 nm-1800 nm. NIRPS uses a high-order Adaptive Optics (AO) system to couple the starlight into a fiber corresponding to 0.4" on the sky as efficiently or better than HARPS or ESPRESSO couple the light in a 1.0" fiber. This allows the spectrograph to be very compact, more thermally stable, and less costly. Using a custom tan(θ)=4 dispersion grating in combination with a start-of-the-art Hawaii4RG detector makes NIRPS very efficient with complete coverage of the YJH bands at just under 100 000 resolution.

On the ESO 3.6-m telescope, NIRPS and HARPS are working simultaneously on the same target, building a single powerful high-resolution, high-fidelity spectrograph covering the 0.37-1.8 μm domain. NIRPS will complement HARPS in validating Earth-like planets found around G and K-type stars whose signal is at the same order of magnitude than the stellar noise.

While the telescope-side AO system was installed on the ESO 3.6-m telescope in 2019, the infrared cryogenic spectrograph has been integrated at the telescope in early-2022 and has had first light in June 2022.

Results from the first light mission show that NIRPS performs very nicely, that the AO system works up to magnitude *I*=14.5, that the transmission matches requirements and that the RV stability of 1 m/s is within reach

While performance assessment is ongoing, NIRPS has demonstrated on-sky m/s-level stability over a night and <3 m/s level over two weeks. Limitations on the RV performances arise from modal noise that can be mitigated through better scrambling strategies. Better performances are also expected following a grating upgrade in July 2022; these will be tested in late-2022.

Keywords: Radial velocity spectrograph, adaptive optics fiber coupling, infrared spectrograph

1. NIRPS SCIENCE CASE

While the progress made in exoplanet study over the last two decades is commanding, we have only begun the study of potentially habitable Earth-like planets around nearby stars. While the Earth-likeness of a planet is a somewhat arbitrary concept, it is generally thought of as a terrestrial planet in the zone around its star where it could host liquid water at its

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surface. While finding an Earth analog around a Sun-like star is still beyond the capacity of current RV spectrographs, M dwarfs offer an appealing short cut to the study of these planets. M dwarfs are lighter than our Sun (7-50%), have smaller radii (0.1-0.5 R_{sol}) and are significantly cooler (2400 to 4000 K versus 5700 K), all of which conspire to increase the radial-velocity signal of a planet in their habitable zone. An Earth-mass planet with an Earth-like equilibrium temperature around a late-M will lead to an RV signature >10 times larger than that of the Earth, which makes its detection possible with existing technology. NIRPS is designed to detect M-dwarf planets by obtaining RV measurements over the peak of their spectral energy distribution in the near-infrared domain.

NIRPS will be a key instrument for following science cases:

- Detection of exoplanets around M dwarfs, active stars and young stars,
- Detection of planets around the closest M dwarf to image with ELT,
- Mass and density characterization of transiting exoplanets,
- Exoplanet atmosphere characterization though transmission spectroscopy at high resolution,
- Identification of nearby stellar component and blended binaries thanks to the AO guiding camera,
- Long term monitoring of the Sun observed as a star using HELIOS solar telescope.

2. INSTRUMENT ARCHITECTURE

To address the science case outlined above, the NIRPS design has been derived from a short set of top-level requirements:

- A spectrograph operating in the Y, J, H bands (980 nm – 1800 nm),
- High spectral resolution of about R > 100 000 to best exploit the spectral content,
- High-RV precision and high spectral fidelity at a level corresponding to the 1m/s over short and long-time scales (years), able to conduct coherent and long-lasting programs,
- Reach a photon noise of 1 m/s in <30 min for an M3 with *H*=9.

To satisfy the requirements, NIRPS has been conceived as a cryogenic infrared spectrograph fed through a fiber link by an adaptive optics system. The design of the NIRPS system has already be published in Wildi 2017[1]. The three sub-systems are described in detail in three daughter papers presented at this conference. The concepts and the performance of the AO system built at the telescope focus is described in Blind 2022[2], the modal noise performance of the fiber link in Frensch 2022 [3], and that of the infrared spectrograph is described in [4]

An overview of the different NIRPS sub-systems is presented in Fig. 1.

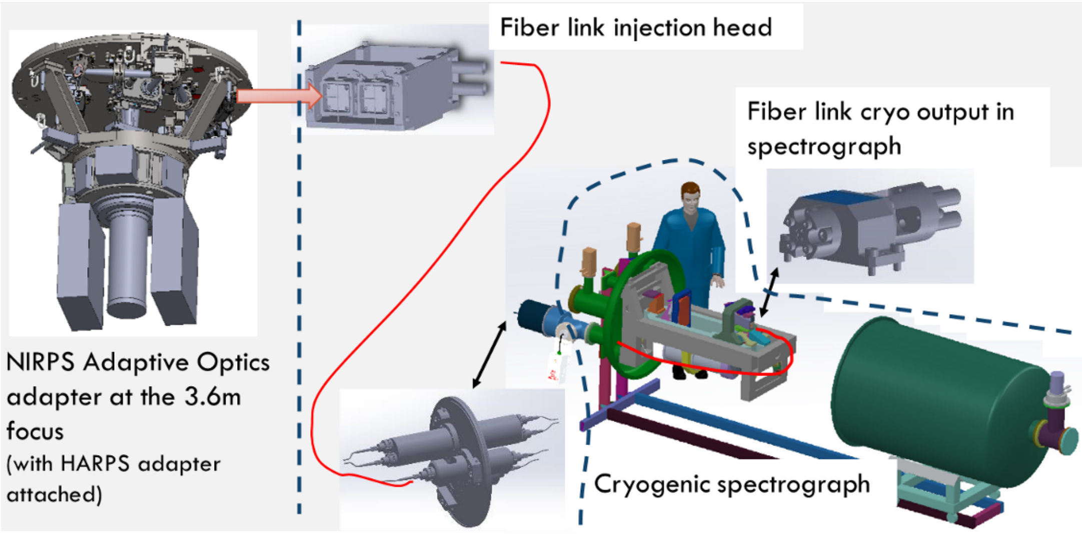

Figure 1. Overview of the NIRPS instrument.

NIRPS sub-systems also include a calibration unit very similar to the ESPRESSO one including two uranium-neon hollow cathode lamps for wavelength calibration, a tungsten lamp for spectral order geometry and spectral flat-field, a Fabry-Perot cavity for wavelength solution and instrumental drift monitoring and 2 fiber-coupled laser diodes for AO calibration.

3. FRONT-END PERFORMANCE

NIRPS has the specificity to be a Single Conjugate AO-assisted instrument, allowing the main fiber (so-called High Accuracy fibers (HAF)) to be only 0.4" in diameter on the sky, and the spectrograph and grating to be much more compact than seeing-limited instruments. A seeing-limited fiber (High Efficiency Fiber (HEF)) with a field of view of 0.9" is also available delivering only 20% lower spectral resolution thanks to a slicer by 2, see §4.

The NFE first splits the light between HARPS and NIRPS allowing simultaneous observations of the two instruments. A dichroic transmits light (380-690nm) to HARPS. In the reflected NIR part light is split between the Wave-Front Sensor (WFS) (700-950 nm) and the science fibers (980-1800 nm). We did not implement a cold stop in the front-end, thermal emission being negligible up to 1800 nm.

The adaptive optics is a classical on-axis system based on a 14×14 sub-apertures Shack-Hartmann WFS featuring a sub-electron read-out OCAM2 camera and an ALPAO DM241 deformable mirror. It runs at up to 1kHz and corrects efficiently on guide stars up to I=14.5.

A guide camera steers the beam to the input lens of the fiber link by introducing slope offsets in the AO feedback loop. This guide camera has a second, high-magnification lens that allows AO quality assessment and focal plane wavefront sensing to correct the non-common path aberrations. On new objects, this high magnification lens is also used to explore and vet the field before starting an RV measurement. Fields with binaries or other contaminants are discarded.

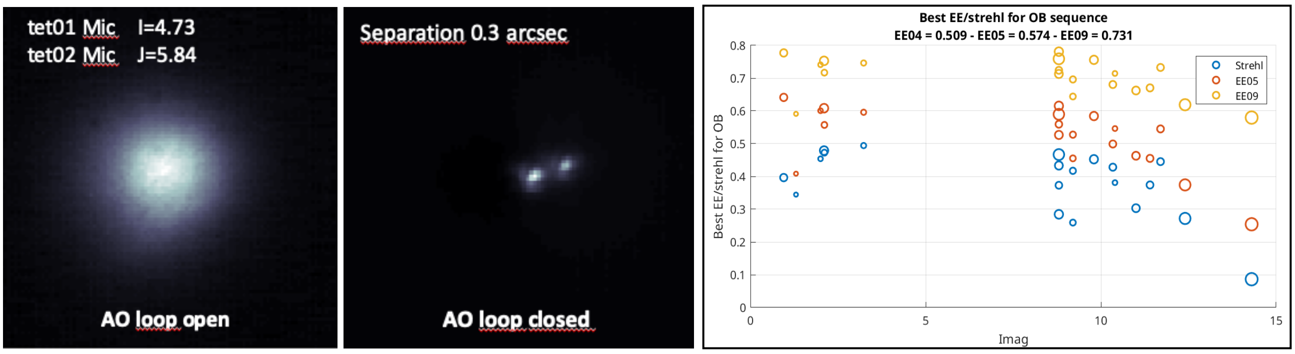

Figure 2. Illustration of the performances of the NIRPS AO system on Sky. (Left) Spatial resolution of the θMic components. (Right) Strehl ratio and encircled energy in the HA and HE fibers as function of the star magnitude in the I band. More details can be found in [2].

4. FIBER LINK PERFORMANCE

NIRPS Fiber Link (NFL) subsystem allows carrying the light coming from the telescope through the FE to the spectrograph.

From a functional point of view the NFL subsystem have the following tasks:

- Converts the F/10.9 telescope beam, from the FE, in a F/4.2 beam and injected it into an optical fiber that is used to transport light to the spectrograph.
- Feeds the spectrograph located inside of a cryostat.
- Mixes the modes propagating in the fiber in a fiber stretcher.
- Scrambles the image and pupil to improve the stability of the spectrograph illumination.

In addition, the NFL must support 2 observing modes required by NIRPS. Each mode requires a specific pair of fibers, and each pair of fiber is mounted in a specific head:

- The High Accuracy (HA) mode with a fiber that has a conjugate size of 0.4" on the sky.
- The High Efficiency (HE) mode. This mode uses target fiber which conjugate size is 0.9" on the sky. In the NFL the image of the fiber will be sliced in two halves, feeding a rectangular fiber. This enables to keep a high resolution.

In the NFL, four units can be differentiated:

1. Input End: It is the injection device that couples the beam from the telescope through the FE to a fiber and feeds the light from there to the Coudé room where light enters the mode mixer
2. Fiber Stretcher: This unit literally stretches the HA science fiber. This modulates the optical path seen by the propagating modes and partially mixes them to uniformize the spectrograph PSF. This is a purely mechanical device that contains no optics. It is built to handle a single fiber.
3. Double Scrambling: This module serves as a feed through from the ambient into the vacuum vessel of the spectrograph. This subsystem is also used as optical scrambler to stabilize the spectrograph illumination. In addition, for the HE mode, the scrambling module slices the pupil.
4. Output End: The interface with the optical bench of the spectrograph; this unit adapts the fiber F/# (4.2) to the spectrograph F/# (8.0) using an air-spaced triplet because of the cryogenic conditions

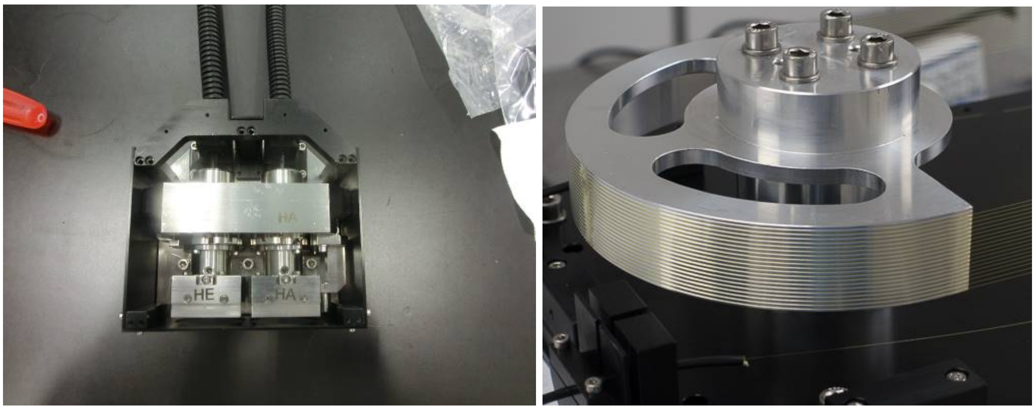

Figure 3. (Left): Fiber Link Input End on the Front End. (Right): The 20 loops of fiber coiled the stretcher half pulley.

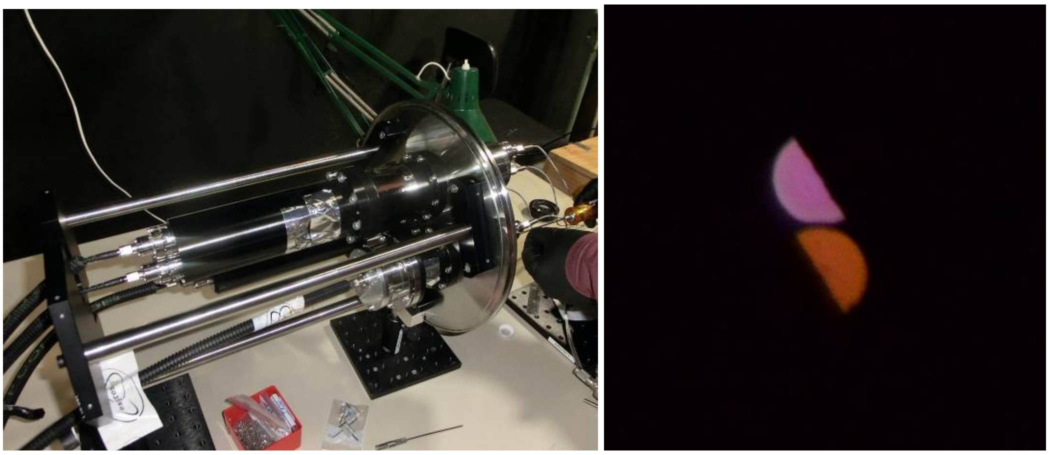

Figure 4. (Left) NIRPS Fiber Link Scrambler and (Right) an image of the pupil sliced

Table 1. Total efficiency of the subsystem including Fresnel losses, fiber internal transmission, fiber alignment at the scrambler and F/# conversion. Requirement and measured values are reported.

Fiber	**980 nm**		**1100 nm**		**1500 nm**	
	Req.	**Test**	**Req.**	**Test**	**Req.**	**Test**
HA STAR	70 %	73.6 %	75 %	73.1 %	73 %	70.0 %
HA SKY	70 %	77.3 %	75 %	76.1 %	73 %	71.6 %
HE STAR	67 %	72.5 %	72 %	72.2 %	70 %	72.8 %
HE SKY	67 %	72.8 %	72 %	73.2 %	70 %	72.3

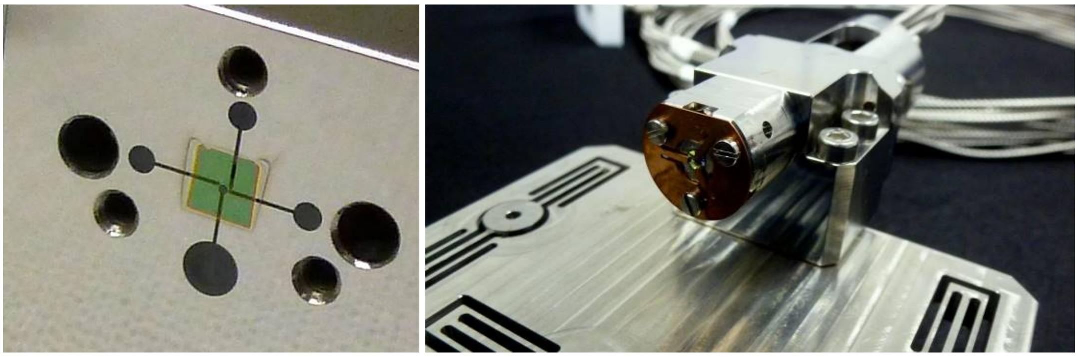

Figure 5. NIRPS Fiber Link Output End. (Left) The four fibers are closely packed together in a ferrule, at the end of the EDM generated slots. They are AR-coated (green square). (Right) The ferrule fitted with the adapting optics, mounted on the spectrograph interface plate.

5. SPECTROGRAPH PERFORMANCE IN THE LAB

5.1 Thermal stability

The cold bus of the spectrograph is controlled through several temperature sensors and heaters. As shown in Figure 7, the spectrograph shows excellent temperature stability at the sub-milli Kelvin level over a period of three days. Some slight drift (~1 mK over three days) have been measured for optical elements that have no active control. Those drift are under investigation but are likely due to a slight coupling of the cold bus with the ambient temperature. We are working on implementing a close-loop heating system to regulate the warm shell of the vacuum vessel a few degree above room temperature.

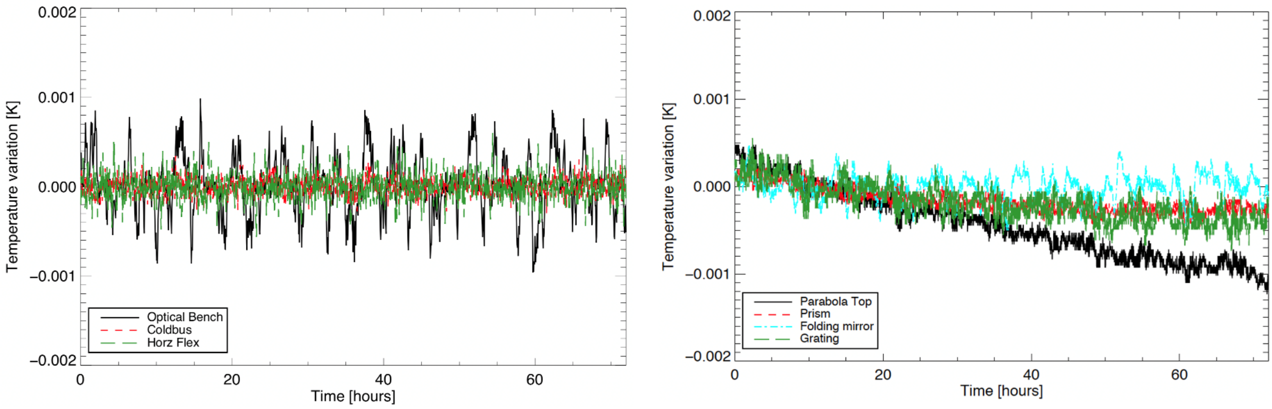

Figure 6. Temperature stability of the spectrograph cold bus. (Left) temperature measurements of various locations on the bench with active temperature regulation. (Right) temperature monitoring for some optical elements with no active temperature regulation. Overall, the temperature stability is at the sub-mK level over a period of three days.

5.2 Stability of the wavelength reference

For the wavelength reference, NIRPS uses a combination of a wide band 12 GHz FSR Fabry-Perot (FP) interferometer for stability measurements and UrNe hollow cathode lamps for the absolute calibration. About 500 Uranium-Neon lines are used to calibrate the FP cavity and more than 10 000 FP lines are used to derive the wavelength solution. The global uncertainty of the wavelength solution is estimated to be 0.75 m/s with the current calibration scheme but is expected to improve significantly with the upgraded grating (installed in July 2022) and laser frequency comb (to be installed in late-2022).

The stability of the instrument was tested in lab using the Fabry-Perot source. The instrument exquisitely good stability at the level of 30 cm/s (see Figure below)

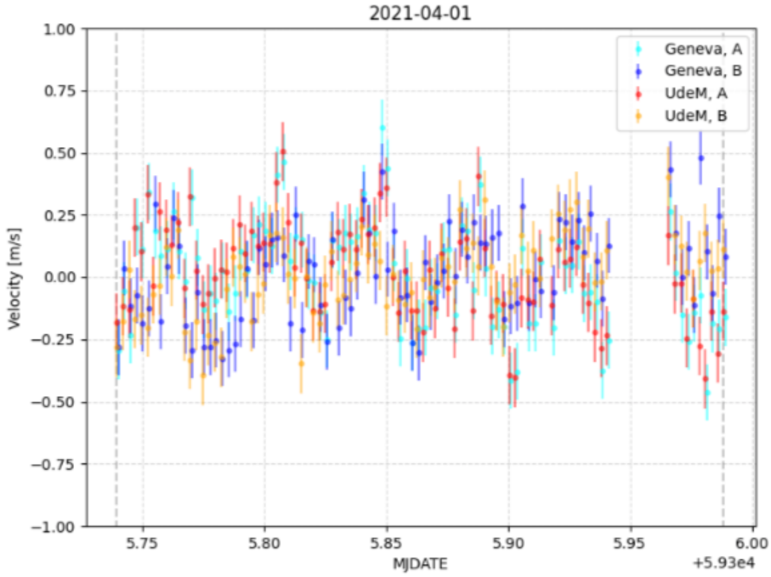

Figure 7. Intrinsic radial velocity stability of NIRPS measured in Lab on the HA mode showing a dispersion below 30 cm/s. The periodic modulations are correlated with room temperature.

6. SPECTROGRAPH PERFORMANCE ON THE SKY

6.1 Spectral range and spectral resolution

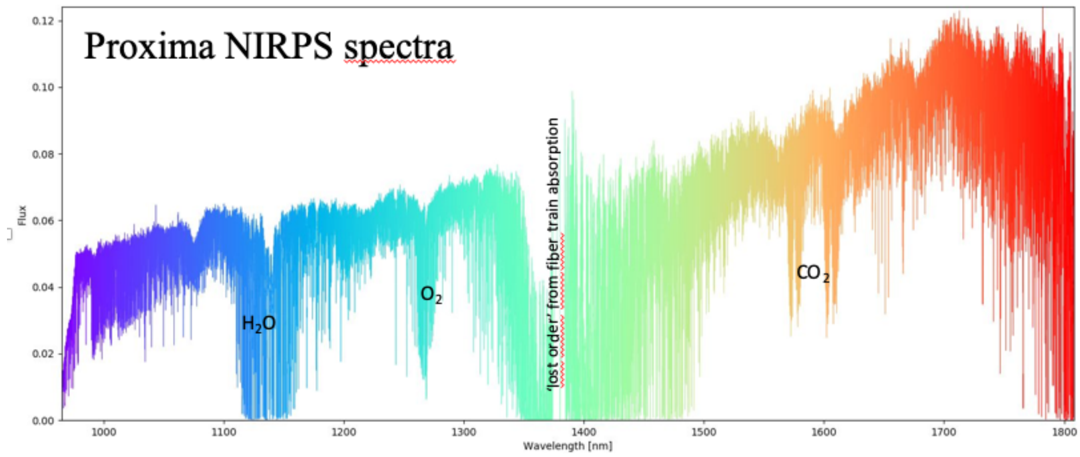

Figure 8. NIRPS spectra covers from 971 to 1854 nm over 70 spectral orders. One spectral order close to 1400 nm is lost due to the strong fiber OH absorption. The spectral resolution measured with the present grating is 82 000 in HA and 75 000 in HE. This data was obtained with a sub-optimal grating that has been replaced in July 2022 (see Section 7) and resolution should improve to >100 00 and >80 000 in HA and HE respectively.

6.2 Modal Noise in the fiber link

The optimal geometrical scrambling and the minimization of the modal noise, requested to reach 1 m/s precision in radial velocity, is obtained by combining octagonal fibers, a fiber stretcher, a double-scrambler, and a tip-tilt scanning of the 29-µm fiber core. We tested the performance of the fiber-link design on sky and evaluated the modal noise mitigation via near and far-field images taken at the fiber-link output. Without the inclusion of the stretcher and tip-tilt scanning, an injection position at the edge of the HA fiber induces a change in radial velocity of ∼15 m/s with respect to an injection at the center. The fiber stretcher significantly reduces the change in RV back to almost 0 m/s (see fig 9)

In June 2022, the first commissioning with the entire NIRPS took place. We investigated the modal noise properties by observing fast-rotating hot stars. Clear structures at the 0.5-2% level appear in the continuum of stellar spectra after spectral flat-field correction, especially in the *H* band. Here again, the fiber stretcher clearly shows a significant improvement reducing the modal noise by a factor ∼5. The tip-tilt scanning of the fiber entrance with the AO system also allows to significantly reduce modal noise by filling-up homogeneously as many modes as possible. If the AO injects a corrected image (close to diffraction limit) in the center of the fiber core (no AO scrambling), the modal noise reaches about 1.6% for the HA fiber. As expected, scanning the fiber entrance with tip-tilt reduces modal noise, and we observe that an annular scanning between 0.1" and 0.3" (avoiding central modes) significantly reduced the modal noise from 1.6% to 0.7%. Furthermore, we identified that fact that residual structures of the modal noise are stable over few hours, and independent of telescope pointing and environmental elements.

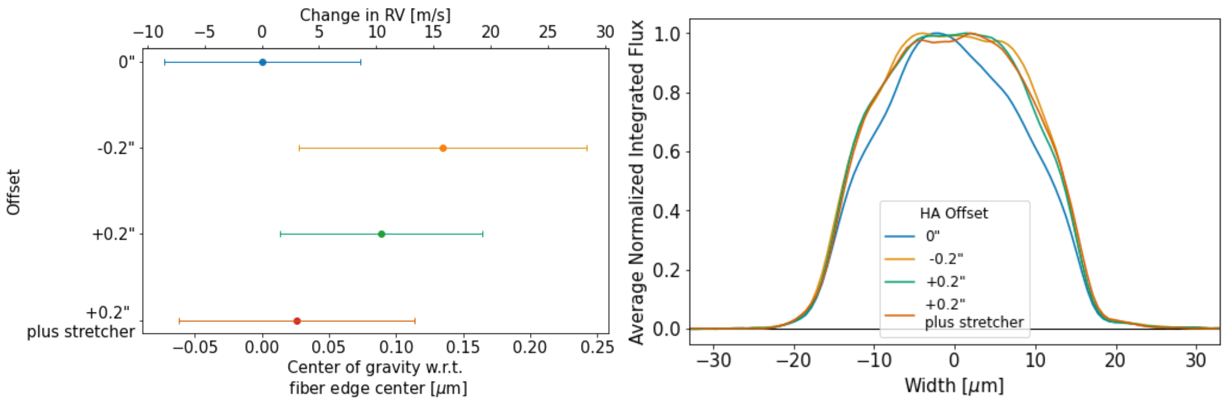

Figure 9. (Left) Relative variations of the measured RV as a function of PSF position on the tip of the fiber. Once activated, the stretcher resets the position-induced variation to almost 0. (Right) Normalized flux across the fiber tip. The smoothing effect of the stretcher is clearly visibly

More details on the modal noise of the NIRPS fiber link can be found in [3]

6.3 Overall performance

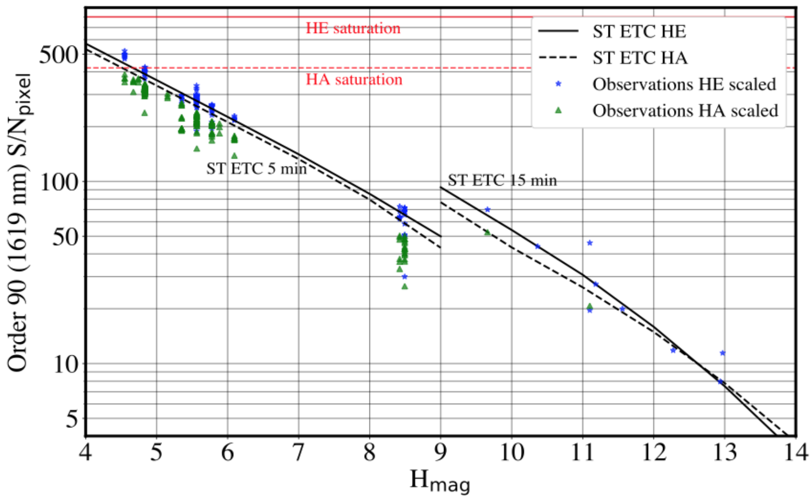

Figure 10. SNR computed at 1.619 µm for all targets observed during commissioning with 5- and 15-min exposure time are in very good agreement with the expectation from the Science Team Exposure Time Calculator. Even slightly better than expected for HE mode. The limit magnitude of the AO system and guiding camera is $I = 14.5$.

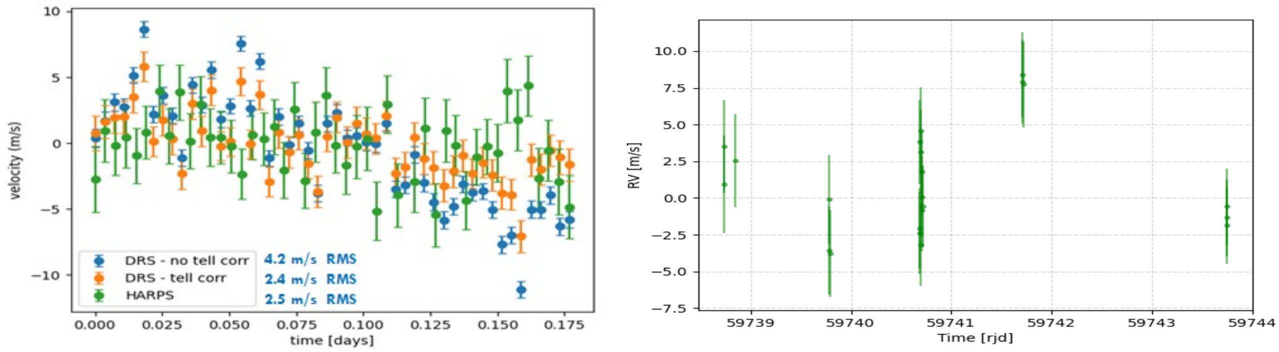

Figure 11. Preliminary raw results obtained during commissioning at the telescope using preliminary telluric correction and preliminary CCF masks. (Left) Proxima (M5V) over 4.2 hours showing RV precision < 3 m/s, slightly better than HARPS. (Right) Barnards star (M4V) over 6 nights showing RV precision of 3.3 m/s.

Table 2.

Table 2. Expected radial velocity photon-noise for H=9 M-dwarfs and comparison with HARPS

Spectral Type	**Teff**	**V mag**	**H mag**	**HARPS σ_{RV}**	**NIRPS σ_{RV}**
M1V	3700	12.9	9.0	**5.3 m/s**	**3.0 m/s**
M4V	3200	14.0	9.0	**4.8 m/s**	**2.2 m/s**
M6V	2800	15.9	9.0	**8.6 m/s**	**1.8 m/s**

7. BEYOND FIRST LIGHT

Several upgrades of NIRPS are already planned in the next few months both on the hardware side and on the software side:

1. A new diffraction grating is being integrated to the existing one. The present grating is a traditional grating ruled in a thick layer of aluminum deposited on a thick slab of Zerodur. Its performance is less than satisfactory, with an efficiency in the 45% range and numerous "features" all around the individual spectral lines. The new grating is made of etched crystalline silicon and has been tested to resolution of NIRPS is expected to be back to 100 000 from the present 85 000 after the upgrade. This will reduce the exposure time and improve the wavelength solution from 0.75 m/s to 0.50 m/s. More details on the etched silicon diffraction grating can be found in [5]
2. A turn-key electro-optically modulated laser frequency comb with a guaranteed stability of 3.3×10^{-10} (<10 cm/s) and an absolute calibration better than 100 kHz will be commissioned in late-2022 to simplify the operation as well as make them more reliable and stable
3. To make NIRPS more robust against the rapid thermal changes that can happen in the room where the spectrograph is located a thick thermal blanket will be fitted above the vacuum vessel and thermal control of the vessel skin will be implemented (2022-2023)
4. An optimization of the scanning of the AO PSF over the fiber tip and a calibration of the fixed part of the modal structure will be performed to decrease the spectral modulation. The level of improvement achievable is hard to access.
5. Data reduction fine-tuning will include better telluric line calibration, CCF mask optimization and line-by-line Radial Velocity measurement.

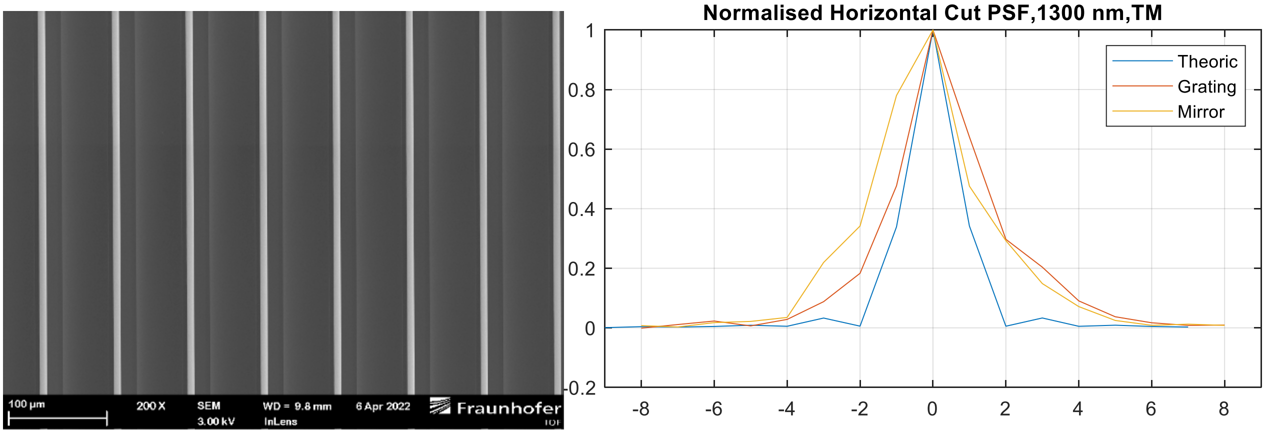

Figure 112. (Left) Micrograph of the etched silicon grating showing the exquisite quality of the groves. (Right) PSF obtained on the grating test bench. There is no significant difference between the PSF obtained with the grating and the PSF obtained when replacing it with a plano mirror

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