NIRPS: a stepping stone for AO-fed high-resolution spectroscopy on ELTs

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ABSTRACT

NIRPS is a near-infrared, fiber-fed, high-resolution precision radial velocity (pRV) spectrograph currently under construction for deployment in early-2020 on the La Silla 4-m telescope. Through the use of a dichroic, NIRPS will be operated simultaneously with the optical HARPS pRV spectrograph and will be used to conduct ambitious planet-search and characterization surveys through a 720-night of guaranteed time allocation. In order to minimize the instrument's size, maximize spectral resolution and maintain a reasonable overall efficiency, NIRPS 0.4″ fiber is fed by an Adaptive Optics (AO) system and will be one of the first instrument to do so. The combination of AO and high-resolution spectroscopy is seen as one of the most promising methods for direct detection of exoplanets in reflected light with ELTs. NIRPS will provide a first opportunity to test, on sky, modal-noise mitigation, fiber coupling efficiency, and retrieval, through cross-correlation, of a handful of self-luminous imaged planets. NIRPS will pave the way for instruments such as TMT PFI and ELT HIRES that will attempt the direct characterization in reflected light of super-Earths, and even possibly Earth-sized planets.

Keywords: Radial velocity, infrared

1. INTRODUCTION

Precision radial velocity (pRV) measurements are key in the study of exoplanets, either for the discovery of hitherto unknown planets or to measure a dynamical mass of a planet uncovered through photometric measurements (i.e., transits). For the vast majority of systems, pRV is the only means to obtain dynamical masses; the main exception being very compact systems where transit-timing variations can be detected. As of late-2019, 1060

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planets have had their masses determined through pRV, and these measurements are key in establishing bulk properties when combined with radius measurements, thus providing the only constraint we currently have on these planets interiors. In recent years, instruments designed for pRV have also proved to be excellent tools to probe planetary atmospheres through transit spectroscopy[1,23] or through cross-correlation techniques when probing the unresolved light of the planet and its host star.[4,5]

While optical (0.4-1.0 μm) pRV is now a mature field with a number of instruments delivering ~ 1 m/s accuracy over timescales of years (e.g., HARPS,[6] ESPRESSO[7]), near-infrared pRV (chiefly Y, J, H and, for some instruments, K) is still in its infancy. A number of nIR pRV instruments have seen first light in the last few years (e.g., SPIRou,[8] IRD,[9] CARMENES-IR,[10] HPF,[11] GIANO[12]). There are a number of reason to move pRV efforts to the infrared; most notably, stellar activity is expected to have a lesser effect at nIR wavelengths, cool stars are brighter at these wavelengths than they are in the optical, and a number of chemical species (e.g., He, H_2O, CH_4, CO) have strong signatures in this domain. While reaching an accuracy similar to that of optical pRV remains challenging, an number of exciting transit spectroscopy and thermal emission results have demonstrated the interest of the near-infrared domain for the study of exoplanets.[13,14]

2. NIRPS & HARPS; A PRV DUO AT THE LA SILLA 3.6-M TELESCOPE

The NIRPS[15] instruments is a nIR pRV spectrograph currently under assembly and slated for first light at the La Silla 3.6-m telescope in the second half of 2020. NIRPS is a joint endeavour of teams from the Observatoire de Genève, Université de Montréal, Université Laval, Laboratoire d'Astrophysique de Grenoble, Universidade do Porto, Instituto de Astrofísica de Canarias, Universidad de Natal.

NIRPS is a fiber-fed spectrograph that covers the $0.98 - 1.80\,\mu$m domain and is scheduled for first light at the ESO 3.6-m telescope in late-2020. It will be used simultaneously with the High Accuracy Radial velocity Planet Searcher (HARPS[6]), providing a simultaneous optical (378 nm - 691 nm) and YJH coverage; a similar approach has also been pursued by combining GIANO with HARPS-N[12] at the TNG 4-m class telescope. This broad wavelength coverage will enable activity correction in precision radial velocity; planetary Doppler signal is achromatic while activity-induced jitter is stronger at shorter wavelengths. NIRPS is designed for very stable spectroscopy, with a goal of reaching < 1 m/s radial velocity accuracy over timescales of years. Calibration is performed through a set of uraniun-neon and Fabry-Pérot étalon lamps; a laser-comb option is currently being pursued.

The overall architecture of NIRPS is similar to that of other fiber-fed pRV spectrographs, as it includes a front-end module (see Figure 1) where light is injected into a fiber. This fiber travels to a back-end cryostat (see Figure 2) maintained in a environmentally-controlled pier lab where it is dispersed at very-high resolution by a cross-dispersed spectrograph. Simultaneous calibration is recovered simultaneously with science observations by interlacing science and calibration orders on the array.

3. AO-FED FIBER HIGH-RESOLUTION SPECTROSCOPY

In order to minimize the size of the spectrograph and its optical elements, we opted for a small fiber fed by an AO system. The $0.4''$ fiber (so-called High Accuracy Fiber, or HAF) is a factor of $\sim$3 smaller than what would be required for a seeing-limited instrument. All other things being equal, the grating of a HRS scales linearly with the size of the input fiber: therefore the spectrograph of NIRPS is particularly compact, with an optical train only 1.2 m in length (i.e. two times less than HARPS for instance). This ensures both a high resolution ($\lambda/\Delta\lambda \approx 100\,000$) while maintaining a compact form. Of particular interest, the R4 grating ruled area is only 80x320mm.

A larger, seeing-limited fiber (so-called High Efficiency Fiber, or HEF) covering $0.9''$ is also available for fainter targets for which the AO performances are sub-optimal. The far-field of this octagonal fiber is sliced in two halves in the double scrambler, and are re-imaged onto the near field of a rectangular fiber with 4:1 ratio. This allow to maintain a high spectral resolution (although lowered) of $\lambda/\Delta\lambda \approx 80\,000$ in seeing-limited conditions. Note that this second fiber option (in its sliced form) came for free thanks to the high number of pixels offered by the choice of an H4RG detector, and did not constrain the AO or spectrograph optical design.

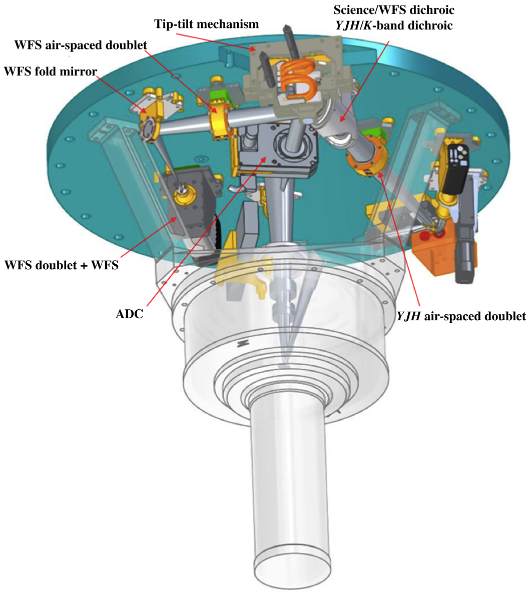

Figure 1. Schematic view of the NIRPS front-end. The optical beam continuing towards the HAPRS pRV continues straight toward its bonette, while the $> 0.7\,\mu$m flux is sent to the AO system for wavefront sensing and science $> 0.98\,\mu$m.

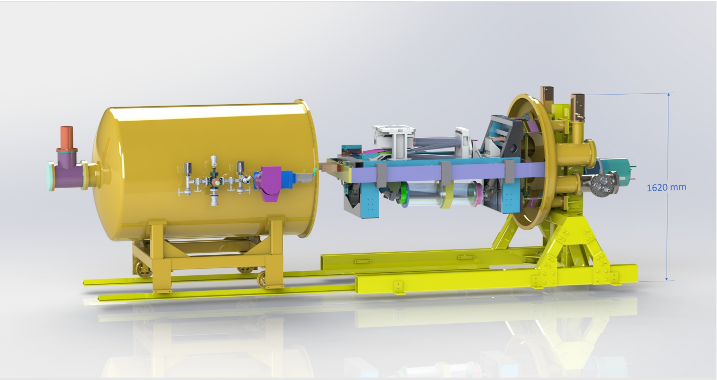

Figure 2. Exploded view of the NIRPS back-end spectrograph. The optical bench itself is only $\sim$1.2 m long.

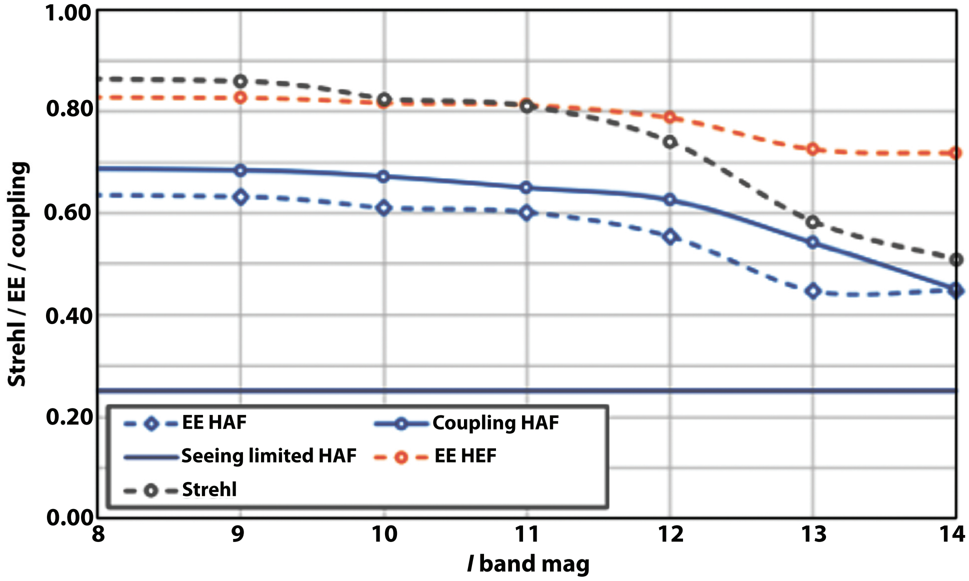

Figure 3. AO and coupling performance of NIRPS estimated during the integration and test phase for a seeing of $0.9''$. EE and Strehl are estimated from the AO telemetry output (dashed lines), while the coupling and seeing limited performance are measured directly through fiber injection (continuous line).

Another benefit of smaller étendue from NIRPS HA fiber is the reduction of the thermal and sky background. By having a $0.4''$ fiber, OH lines will be 9 times fainter than for a fiber such as that of SPIRou ($1.2''$). This scaling also applies to the thermal emission of the telescope, sky and fiber itself.

While it may appear as an over-specified AO system for coupling to a multi-mode fiber, a high density of actuators is actually necessary to correct high order aberrations and correct speckles far from the fiber core. At the end of the integration phase, we estimate NIRPS can achieve an average fiber coupling $\geq 50\%$ over the YJH-band up to $I = 12.5 - 13$ (Figure 3).

Although we could afford running the AO at frequencies of $250 - 500$ Hz, running faster is enabled by our hardware choices, increasing coupling by a few percent on brightest stars, helping against potential telescope vibrations, and making it more robust against low τ_0 situations. The complete trade-off and design study of the AO system can be found in.[16]

Comparison to the Single-Mode solution -

The consideration regarding spectrograph size and modal noise have led a number of teams to propose very compact and stable nIR pRV spectrographs behind AO systems. In the recently commissioned Palomar Radial Velocity Instrument (PARVI[*]), the P1640 adaptive optics system is used to inject a single-mode fiber for pRV over the JH domain.

Nevertheless, the compactness advantage of single-mode spectrographs cannot be maintained in the eventuality that a seeing-limited fiber is required for fainter objects. The increase in input étendue requires to increase equivalently the detector and/or grating size.

We can enumerate a few advantages offered by a multi-mode fiber over a single-mode one:

- Higher coupling efficiency, with a given AO system;
- Higher magnitude limit, thanks to relaxed AO requirements;

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[*] http://www.astro.caltech.edu/palomar/observer/newsletter/palomarobserver4.html#parvi

- Lower sensitivity to seeing variations and AO correction quality (i.e. seeing and guide star magnitude);
- Lower sensitivity to non-common path aberrations (NCPA), atmospheric dispersion correction (ADC) errors, vibrations: while 100 nm RMS NCPA would lead to $10-35\,\%$ losses in a single-mode fiber in YJH band, it is limited to $5\,\%$ in a few-mode fiber.

Overall, the gain of the multi-mode solution ranges from 1 to 2 magnitude over the single-mode one.

The main drawback of the choice made for NIRPS resides in the LSF stability: with only 10 to 35 modes propagating into the fiber, modal noise can potentially limit RV precision to several 10 m/s. Work on new scrambling strategies[17] have demonstrated that we can reach an RV precision better than 1 m/s thanks to:

- The AO system can act as an efficient mode scrambler via continuous tip-tilt scanning of the fiber near-field;
- A fiber stretcher, acting as a phase scrambler, can get rid of long term (minutes to months) thermal and mechanical variability of the fiber link.

4. PAVING THE WAY FOR ELTS

4.1 Technical Demonstration

While the injection with an AO system was initially seen as a mean of having a smaller instrument, it also enables a number of technological tests that are relevant for fiber-fed spectroscopy on 30-m class telescopes.

HIRES is a proposed second generation ELT instrument with ambitious primary goals of detecting life signatures through transit spectroscopy and testing the stability of fundamental constants over the lifetime of the Universe. This will be done through two spectrographs covering overall the 0.4-1.8 μm domain at spectral resolution of 100 000. TMT also has a proposed instrument, HISPEC (High-resolution Infrared Spectrograph for Exoplanet Caracterisation) with a pathfinder, Multi-fiber High-resolution NIR spectometer (MODHIS), to be deployed at the Keck 10-m telescope.[18]

NIRPS will be paving the way for ELTs fiber-based HRS spectroscopy through a number of technical advances. Firstly, its line-spread-function will be much more stable line-spread function than slit spectrographs (e.g., CRIRES+). The NIRPS AO system allows for decentering $0.4''$ fiber to a planet within a $2''$ radius of host star. There are a few directly imaged planets that are within that range of separation from their host star (e.g., HR8799 bcde, β Pic b). NIRPS could measure their rotation profiles through cross-correlation techniques and refine their orbital parameters. While, for these objects, the contrast gains will be very modest (a factor of a few tens from PSF wings; NIRPS does not include a coronagraph), it will demonstrate the multiplicative gain of cross-correlation techniques and PSF removal. This multiplicative gain in contrast is seen as a mean of directly imaging Earth-mass planets on ELTs.[19]

4.2 Guaranteed Time Observations

The NIRPS science team has been awarded a 720 nights over the first 5 years of operations at La Silla. This amounts to $40\,\%$ of all nights, and it will be entirely dedicated to exoplanet science enabled by the near-infrared coverage of NIRPS; M dwarf planet searches and transit spectroscopy. The NIRPS GTO time will be split about evenly between three large programs; a pRV search of planets around very nearby stars, a transit follow-up survey and a transit-spectroscopy survey.[15]

NIRPS will be used to conduct a pRV survey of nearby ($< 7\,$pc) M dwarfs, continuing the work done with HARPS,[20] and pushing it to cooler M dwarfs. This sample is particularly important as these planets will be prime targets for direct imaging with ELTs. The instruments planed for these observatories will be largely used to characterize known planets rather than identify new ones, which takes a lot of time if observations are not guided by previous indirect detection.

The pRV follow-up of planets uncovered through large-scale transit surveys (mainly TESS,[21] but also ExTrA[22] and NGTS[23]) and determine their kinematic masses. Combined with constraints on the planet diameter from transit data, these will constrain the bulk density of these planets. This measurement is key in assessing the atmospheric scale height of the planet and prioritizing transit spectroscopy follow ups, either at high-resolution (e.g., NIRPS and ELTs in the future) or low-to-intermediate resolution (mainly JWST).

Lastly, we will obtain a large number of transit and eclipse spectroscopy measurements with NIRPS. High-resolution ($R > 100\,000$) transit spectroscopy data provides complementary information on planetary atmospheres compared to low-to-intermediate ($R < 5000$) resolution obtained with HST or JWST in the near-future. Among other things, high-resolution spectroscopy informs on wind profiles in planetary and allows to probe narrow features (e.g., helium at $1.083\,\mu$m) that would be lost in a number of neighbouring spectral features. The very large GTO allocation will allow for numerous visits of individual systems. Gathering numerous visits of a transiting or eclipsing system is challenging due to scheduling constraints, and the NIRPS GTO extension over 5 years will allow us to obtain dataset that would be challenging to obtain elsewhere.

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