NIRPS Back-End – Design and Performance

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ABSTRACT

NIRPS is a near-infrared (YJH bands), fiber-fed, high-resolution precise radial velocity (PRV) spectrograph installed at the ESO 3.6-m telescope in La Silla, Chile. Using 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. NIRPS aims at detecting and characterizing Earth-like planets in the habitable zone of low-mass dwarfs and obtain high-accuracy transit spectroscopy of exoplanets. The spectrograph is compact for better thermal stability. Using a custom R4 grating in combination with a state-of-the-art Hawaii4RG detector, the instrument provides a high resolution and high stability over the range of 950-1800 nm. This paper focuses on the lens and optomechanical design, assembly, and test of NIRPS's spectrograph. Some performance tests conducted at Université Laval (Canada) during the integration and at La Silla during commissioning are presented.

Keywords: near-infrared, fiber-fed, radial velocity, spectrograph, cryogenic, Hawaii4RG, planet-search, planet survey, habitable zone, transit spectroscopy.

1. INTRODUCTION

NIRPS (Near InfraRed Planet Searcher) is a near infrared (YJH bands), fiber fed, high resolution precision radial velocity (PRV) spectrograph installed at the ESO 3.6m telescope in La Silla, Chile. NIRPS aims at detecting and characterizing Earth-like planets in the habitable zone of low mass dwarfs and obtain high accuracy transit spectroscopy of exoplanets. NIRPS science case will focus on finding and confirming earth-mass planets in the habitable zone of low-mass M stars, in particular those identified by future space missions like TESS and PLATO. Such small planets require a radial velocity follow-up at precision lower than 1m/s. The simultaneous observation with HARPS (La Silla – ESO), covering the 400-1800nm domain, will in addition help disentangle the stellar activity signal from planetary RV signal. This will be particularly important for early-to-mid-M dwarfs, where NIRPS and HARPS are expected to have a similar RV accuracy. NIRPS will also be used for the atmosphere characterization of known transiting exoplanets, through very high-resolution transit spectroscopy.

There are three sub-systems in NIRPS:

1. The Front-End which extract the 700-2400 nm band from the telescope beam, corrects for atmospheric dispersion and injects the YJH light into the fiber link. A dichroic sends the visible part of the signal straight into HARPS.
2. The fiber link which guides the light from the telescope to the spectrograph. The fiber link also scrambles the light to stabilize the illumination of the spectrometer.
3. The Back-End which is the spectrograph itself.

In this paper, we give an overview of NIRPS Back-End lens and optomechanical design, assembly, and test of NIRPS's spectrograph. The performance tests were conducted at Université Laval (Canada) during the integration and at La Silla during commissioning.

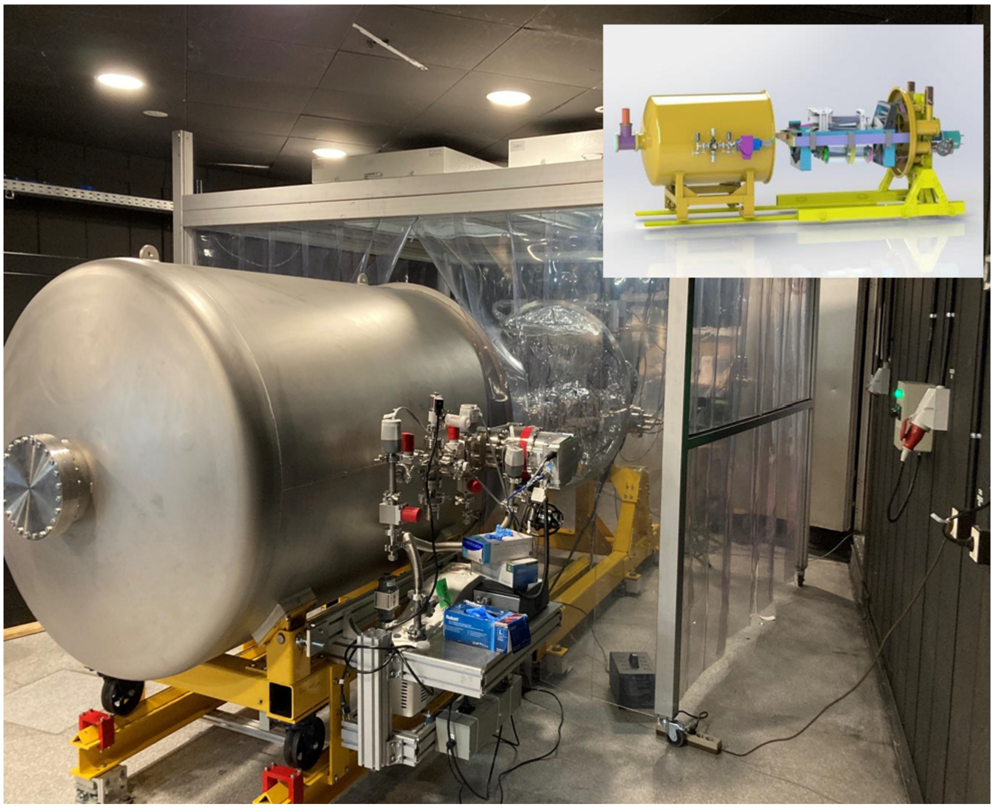


Figure 1. NIRPS spectrograph at La Silla

2. OPTICAL AND MECHANICAL DESIGN

NIRPS Back-End [1] includes one parabola working in triple pass, a R4 echelle grating (90 mm x 320 mm with a blaze angle of 76 degrees and ~ 13.3 gr/mm), a flat folding mirror, 5 cross disperser ZnSe prisms, a refractive camera, and a Hawaii4RG detector. Figure 1 shows the Back-End optical layout, and the optical path sequence is as following:

1. The fiber end tip is converted to the spectrograph input object (29 um core fiber @ F4.2 to 55um @ F8.0)
2. The parabola collimates the fiber beam (first pass on parabola).
3. The collimated beam is relayed to the grating.
4. The grating diffracts the collimated beam and is relayed back to the parabola.
5. The parabola focuses the diffracted collimated beam (second pass on parabola).
6. The flat mirror folds back the diffracted focused beam back to the parabola.
7. The parabola collimates the diffracted focused beam (third pass on parabola).
8. The diffracted collimated beam is rotated by a series of 5 refractive prisms which also separate the grating orders.
9. The refractive camera focuses the diffracted collimated beam onto the detector.

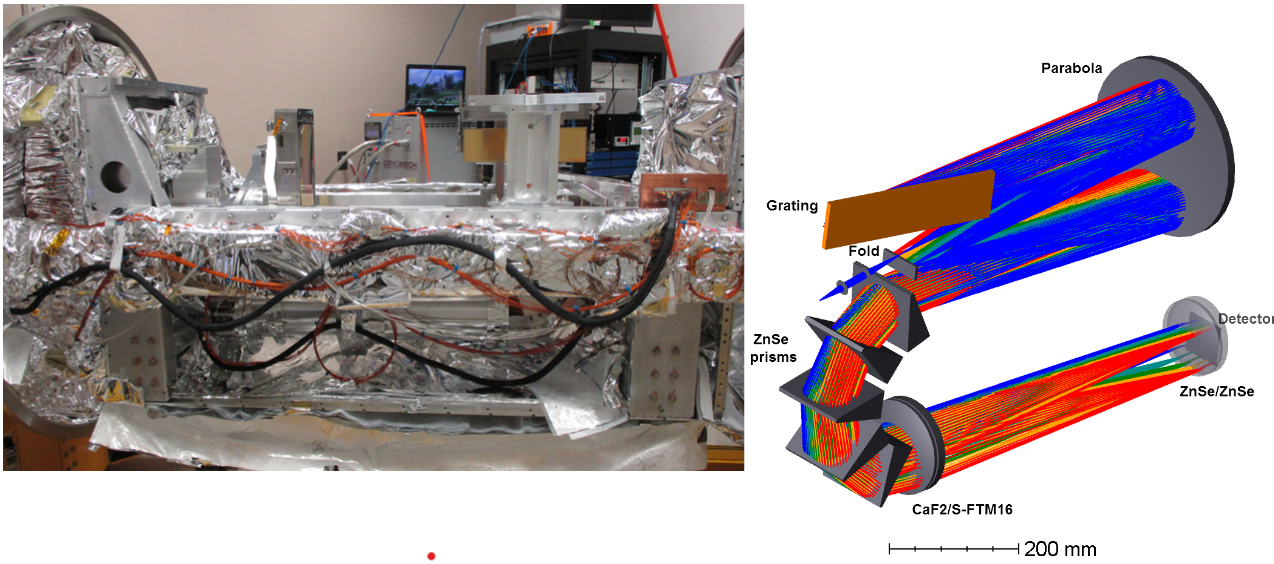


Figure 2. NIRPS spectrograph (Left: Instrument view, parabola at left, grating and injection at right, camera and detector underneath;, Right: optical layout.)

Given the spectral range of the instrument and the 80K operating temperature, the glasses use during the optical design phase were limited to a restricted range of materials for which a custom catalogue of refractive indices at 80K was created. This allows optimizing the design directly at 80K and later calculate the thicknesses and radiuses at room temperature by using the proper CTE from 80 to 270K for each individual component. The airspace (vacuum) between the elements is also calculated according to the mechanical material CTEs. We can thus build a prescription of the design at room temperature which we call the "warm" design (the nominal 80K design is called the "cold" design). Both the cold and warm version of the design are also updated using the inspection data of the optical elements obtained from the manufacturers. The designs are then transferred to the mechanical designer for him to double-check and prepare the final mechanical designs. The final warm design is the design used in the laboratory during the integration, test, and validation phase because a diverse set of optical and metrology measurements can easily be made without having to go through a cryogenic cool down of the instrument.

Figure 3-5 shows the optical layout, mechanical cross section and cell of the camera along with rays for the center and outermost orders arriving at the detector. Notice on figure 4, a series of baffles specially designed to control the stray light.

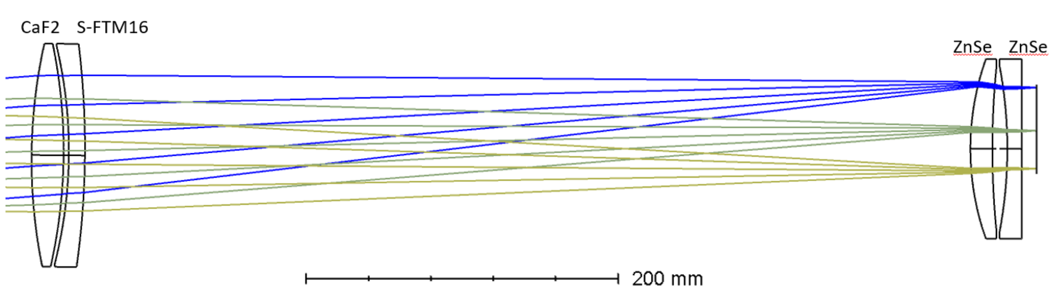


Figure 3. NIRPS spectrograph camera layout.(detector right)

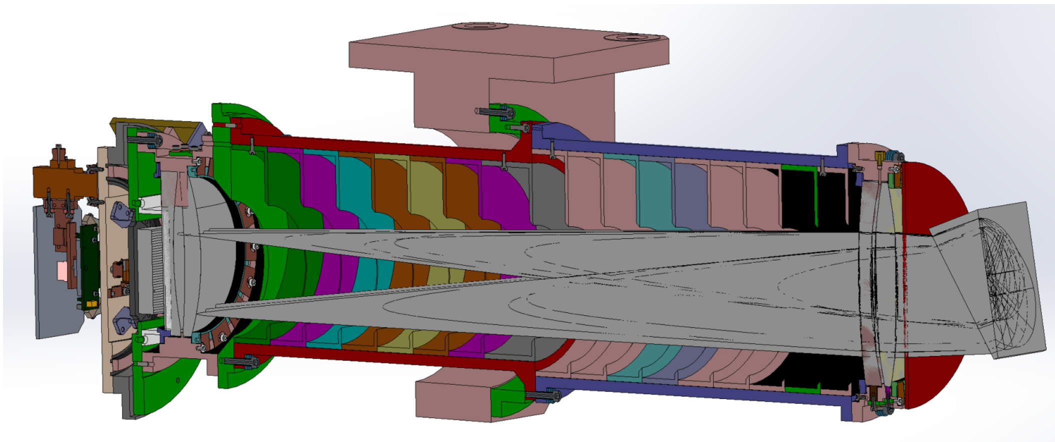


Figure 4. Camera mechanical cross section (detector left).

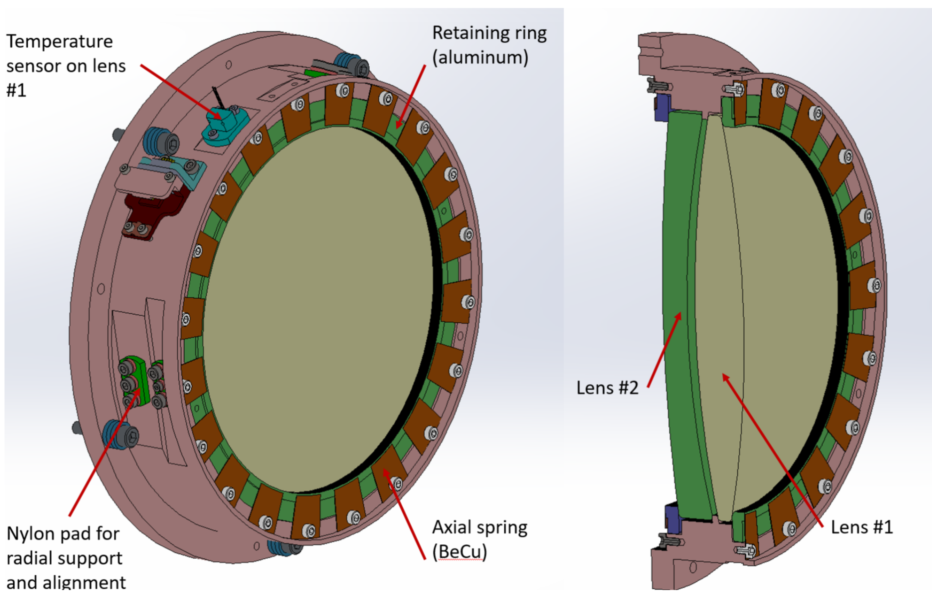


Figure 5 Camera lens cell assembly

3. ALIGNMENT, INTEGRATION, TEST AND VALIDATION

The performance tests conducted at Université Laval (Canada) during the integration and at La Silla during commissioning are presented.
The alignment, integration, test, and validation (AITV) phases rely on a combination of mechanical inspections and optical tests.

3.1 Room Temperature (U. Laval)

More precisely, the strategy included the key elements presented in figure 6 for each optical subassembly.

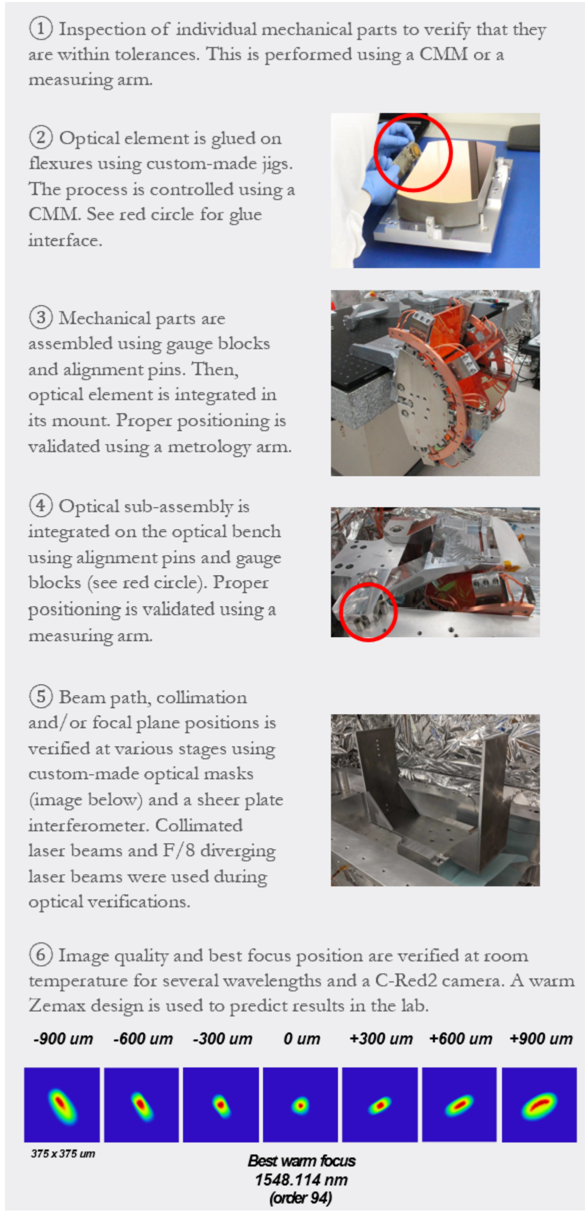


Figure 6 Room temperature integration and test flow

Optical tests were performed on some subassembly when possible. As an example, it was the case for the prisms. The figure 7 shows the prisms carousel secured in normal position (right image) on a solid and breadboard. The setup includes a C-RED2 located on a lab jack under the breadboard; the input fiber is fixed on a post holder on the readboard. A collimator is mounted on the fiber. The fiber is connected to the tunable laser (test wavelength: 1528.383 nm and 1565.087 nm). The light from the laser is directed on path A (both wavelength), if the dispersion is as expected, the distance at the output (C-red2) should be as designed. We repeat the experiment for a position B. The figure 8 gives the results which were under tolerance. We then concluded that based on metrology and optical test, the prism carousel performed as expected.

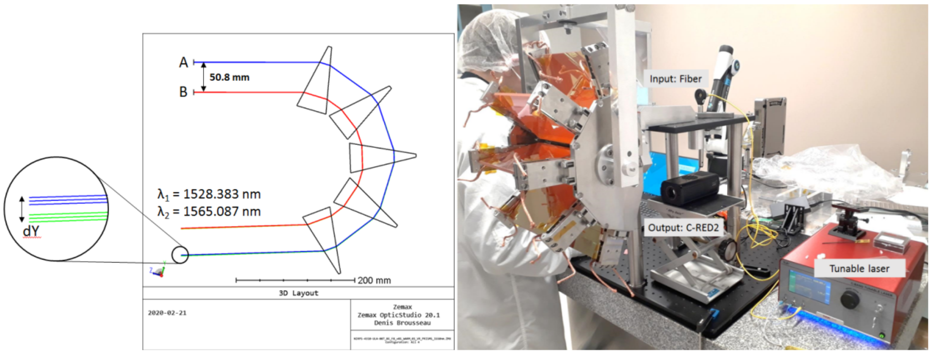
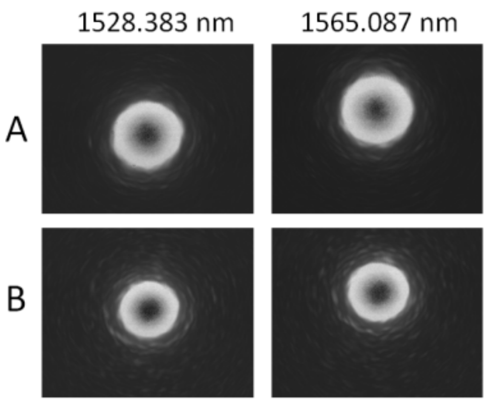


Figure 7 Setup to test the prism carousel (left: zemax layout, right: setup)



- A, B: fiber heights with A – B = 50.8 mm (≡ 3" post holder – 1" post holder)
- 3 sets of measure #1, #2, #3
- #1(A) = dY = centroid Y(λ_1) – centroid Y(λ_2)
- Centroid X remains constant (verified during the test)

Important value to look for is A-B which is only dependent on the position difference between A and B.

	dY (mm)				
	#1	#2	#3	Mean	Zemax
A	1.125	1.216	1.122	1.154	1.092
B	0.804	0.867	0.777	0.816	0.793
A-B	0.321	0.349	0.345	0.338	0.299

Tilts or decenters have only a very small impact on the A-B value. Two possible explanations for the departure:

- A difference of 0.00015 from nominal in the ZnSe index between both wavelengths could explain the departure.
- Centroid calculation errors of +/- 1 pixel but would need to always impact the same way (no A-B values below the zemax expected value even if centroids are computed using different methods)

Figure 8 Results at room temperature of prism carousel optical dispersion test.

At the final hot integration, we use a narrow band source to measure the hot best focus position. This position is compared to the design value. Any difference is then reported on the back focal length (adjustment on the detector spacer). Then we can use a wide-band source (UrNe, tungsten...) to check the hot blaze angle, order position and cross dispersion.


Figure 8 Flat on C-Red2 (room temperature)

3.2 Cold Temperature (U.Laval)

The goal of the laboratory cryogenic and vacuum test was to:

- Confirm that cryovacuum subsystem is working as nominal (including software and safety),
- Confirm that H4RG detector performances are nominal compared to those obtained with the detector at UdeM.
- Determine the focus and detector tilt by using PSF geometry.
- Determine blaze centering, dispersion scale and pixel scale.
- Obtain calibration sequences as benchmarks for the DRS.
- Be used as a reference point for subsequent cycles to establish the impact of a thermal cycles on order positions.
- Determine the stability on the timescale of day

As we cannot report all results, the following picture (fig 9) shows an example of data recorded during these tests. We can see the data extracted from the order 21 using the FP in the calibration unit. From these kinds of results, we can compute the blaze function and the FHWM of each individual peaks.

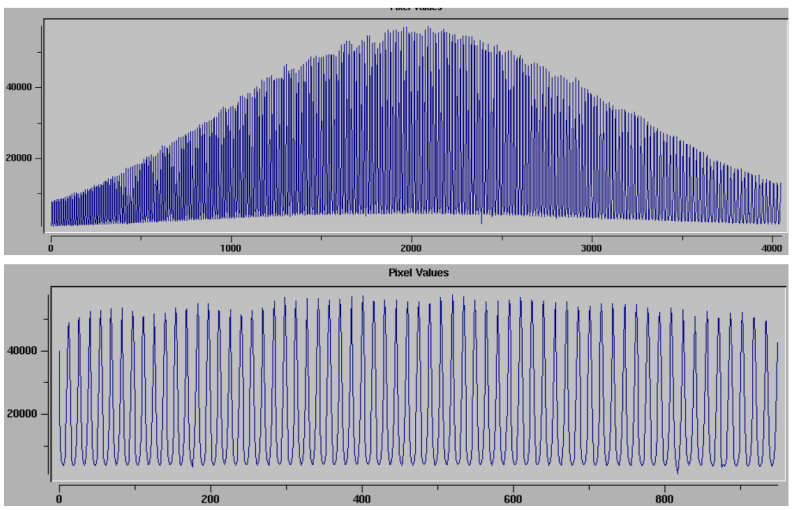


Fig 9: Extracted order #21 of Fabry-Perot

3.3 Validation (La Silla)

The back-end integration and verification mission to install NIRPS spectrograph at the 3.6m ESO telescope had several objectives to ensure performances at cryogenic temperature. After the installation of the back-end in place and interface with the fiber link, we verify that optical elements did not move in transportation using a measuring arm, we verify image quality and best focus position at room temperature for several wavelengths as a final verification before closing. Through focus is shown at figure 10. The data were compared to the measurement did just before shipping.

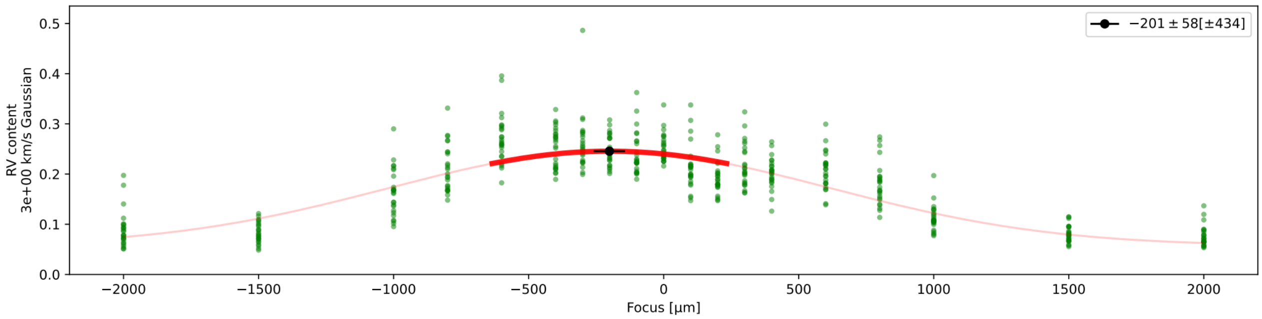


Figure 10: Through focus measurements before detector integration (Room temperature, April 2022, La Silla)

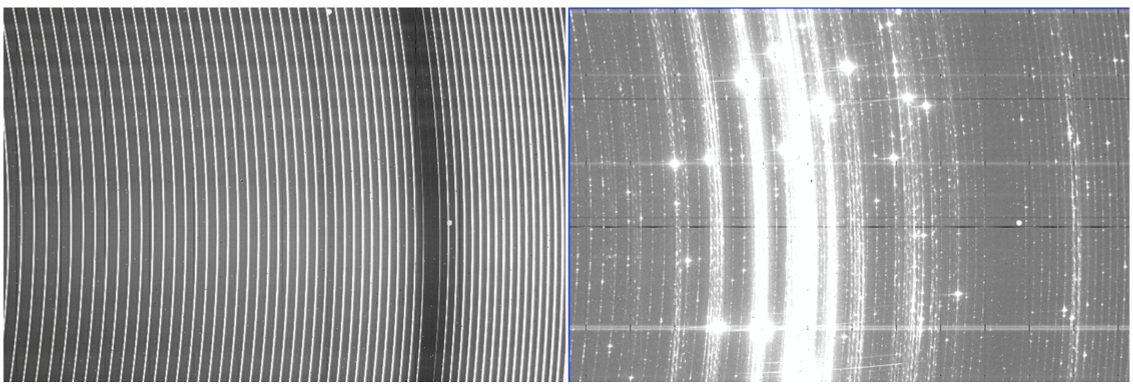


Figure 11: Tungstene, UrNe lamp

4. CONCLUSION

NIRPS kick.off was in Jan 2016, almost 6 years and one pandemic after, we got the first light in June 2022. It was a long road with the pandemic for the alignment, integration, and test. The work was successfully performed by a dedicated team from various countries. It was decided after tolerancing (PDR phase) that the alignment will be based on the mechanics. Careful integration with rigorous CMM measurements throughout the integration of subassemblies leads to success [1-4]. Many optical verification was done along the procedure at room temperature. In case of doubt (discrepancy between mechanical and optical measurements), we trusted the mechanical measurements. By doing so, we were able to successfully deploy NIRPS at La Silla.

The combination of HARPS in the visible and NIRPS in the 950-1800nm band with 100’000 resolution holds great promises in the detection of small planets in the HZ of M stars with both the sensitivity at the 1ms-1 mark and the ability to discriminate activity form RV by chromatic alalysis.

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