NIRPS – The Near Infra-Red Planet Searcher: Design, integration and tests of the Atmospheric Dispersion Compensator

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ABSTRACT

NIRPS, the Near Infra-Red Planet Searcher, is part of a new generation of Adaptive Optics fibre-fed spectrographs. It will be installed in the ESO La Silla 3.6 m telescope and will be operated individually or jointly with HARPS.

NIRPS aims at spectroscopic observations of stellar objects in the NIR, from 970 nm to 1800 nm (with the option for later extension to 2400 nm). The instrument is assisted by an AO system, whose sensing bandwidth will be from 700 nm to 950 nm.

Even if telescope pointing and guiding is perfect at a given reference wavelength, atmospheric dispersion will shift the image centroid at different wavelengths, with impact on fibre injection. Moreover such effect will vary during acquisition with the observation zenith angle. Therefore an Atmospheric Dispersion Corrector (ADC) is mandatory to achieve the instrument requirements.

In this paper we will present the design, integration and test results for the NIRPS ADC.

Keywords: Atmospheric Dispersion Compensator, high resolution spectrograph

1. INTRODUCTION

NIRPS, the Near Infra-Red Planet Searcher[1], is a new powerful instrument installed on the ESO 3.6-metre telescope at the La Silla Observatory in Chile. NIRPS is a high accuracy radial velocity infrared spectrograph designed to detect Earth-like rocky planets around the coolest stars.

NIRPS will complement the HARPS (High Accuracy Radial velocity Planet Searcher)[2] instrument currently attached to

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the ESO 3.6-metre telescope at the La Silla Observatory in Chile. HARPS is the world's most productive planet-hunting instrument using the radial velocity method, and it has revolutionised our understanding of exoplanetary systems. NIRPS will become the "red arm" of HARPS, extending the telescope's capability into the infrared and allowing astronomers to characterise planetary systems. ESO will allocate 725 observing nights over a five-year period to the NIRPS team.

The main goal of NIRPS[1] is to use the radial velocity method to detect and characterise planets orbiting cool, red, low-mass M-type stars. In particular, NIRPS aims to find Earth-like rocky planets that could potentially be habitable. M-type stars are of particular interest because the radial velocity variations induced by an orbiting planet are larger for a less-massive star than a Sun-like star, and hence their planets - including those in the habitable zone - are more easily detected. NIRPS will operate in the infrared as this is the main range of wavelengths emitted by such small, cool stars. For red stars, which are the most common kind in the solar neighbourhood, NIRPS is expected to produce data that are at least as accurate as currently available with the HARPS instrument.

NIRPS is part of a new generation of Adaptive Optics (AO) fiber-fed spectrographs. Its originality resides in the use of a multi-mode fiber, much less affected by AO correction residuals than a single-mode fiber, allowing comparatively higher coupling efficiency in degraded seeing and on fainter targets, with relaxed AO specifications. This is the first time adaptive optics have been combined with optical fibres. Along with an elegant optical design, this has allowed NIRPS to be built as a more compact and simpler instrument. Being an infrared extension of HARPS, NIRPS will cover instantaneously the Y, J and H band (973.79 to 1808.53 nm). A K-Band extension is possible. NIRPS is a fibre-fed Echelle spectrograph with a spectral resolution of at least 80'000.

The front-end[3] comprises everything, which is mounted to the Cassegrain focus of the 3.6m telescope. Three design principles have been followed:

- HARPS related parts, especially HARPS POL (polarization mode) shall in no way be compromised
- the NIRPS spectrograph will be fed with fibres[4] employing adaptive optics to improve the coupling efficiency; there will be two fibres which can freely be selected: a circular one (NA 0.125), feeding NIRPS in high dispersion mode (R~100000) and an octagonal one (320µm), feeding NIRPS in the high efficiency mode (R~80000);
- there is an extra port to hook up an optional K-band spectrograph

Figure 1 - The NIRPS Front End.

The back-end[5] is a high efficiency and high stability spectrograph. The cryostat has a cylindrical form, 1120 mm outside diameter, 3370 mm long in operational mode (when closed). The cylindrical portion of the cryostat slides along its axis to allow easy access to the optical housing. The total mass of the cryostat estimated to be 1450 kg. This number excludes vacuum pumps and cryogenic pumps, electronics and other supporting hardware.

The optical housing (optical bench) is located in a horizontal position. It is supported at two points from a cold support frame by a hexapod type arrangement. Cold support frame combines active shield and structural support. It is maintained at the operating temperature of 80K utilizing active thermal controls.

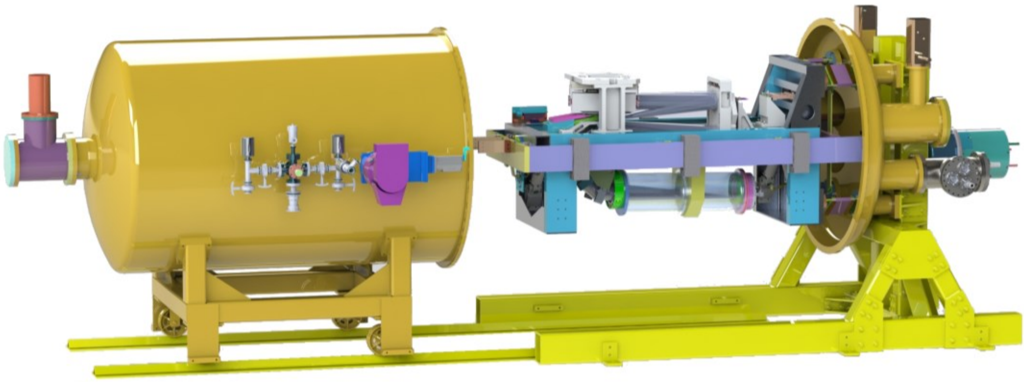


Figure 2 - The NIRPS Back End.

The beginning of 2022 saw the First Light of NIRPS[6].

2. THE NIRPS FRONT END

The NIRPS front end (NFE)[3] is directly attached at the back of the ESO 3.6m telescope rotator in La Silla. Its main goals are to collect the starlight, separate the visible and the near-infrared light and distribute the visible light to the HARPS Cassegrain Fiber Adapter (HCFA) or bonnette and the NIR light (YJH-band) to the NIRPS fibers. The existing HCFA is kept as is and its position with respect to the telescope remains the same.

The NFE support structure consists of:

- NIRPS Cassegrain adapter: This part is mounted on the 3.6 m telescope rotator interface. Moreover, it is the optical bench on which most of the NIRPS optical components are mounted.
- HARPS Front-end bracket: this part is holding the existing HCFA, the NIRPS/HARPS dichroic, the HARPS guiding camera and the associated optical components.
- Monopod: 3 monopods are holding the HARPS Front-end bracket. They are mounted onto the NIRPS Cassegrain adapter.

Figure 3 shows the structure of the NFE with some of the optical components. Besides the Atmospheric Dispersion Corrector (ADC), the main subject of this paper, the NFE also comprises (see Figure 4): HARPS/NIRPS dichroic mechanism, Science/WFS dichroic, Deformable mirror (DM) mounted on a tip-tilt mechanism, Wavefront sensor, NIR guiding camera, Visible guiding camera, Fiber heads mechanism, Fold mirrors, Lenses and Calibration sources heads.

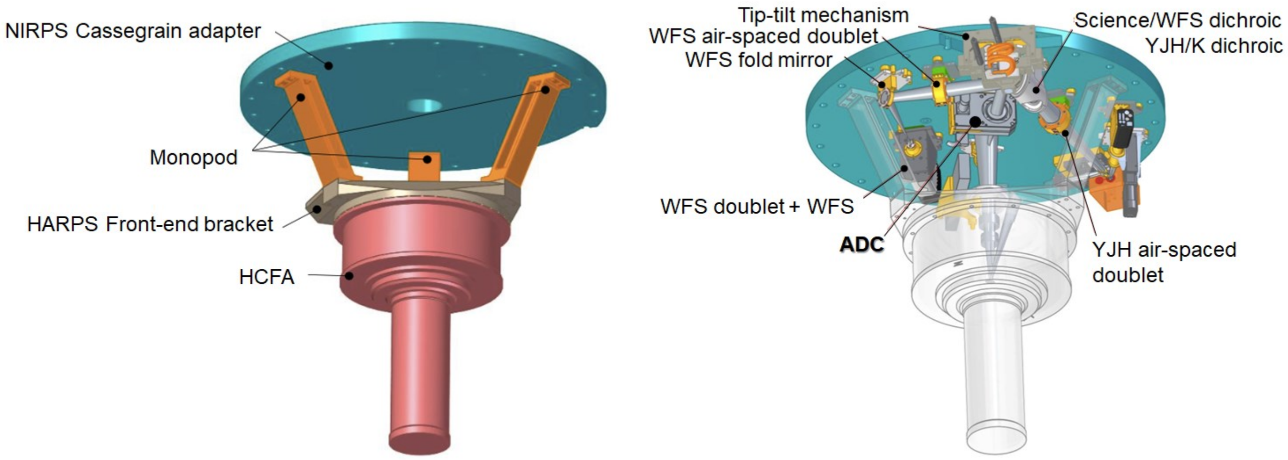


Figure 3 – NIRPS NFE Structure with the indication of some of the optical components.

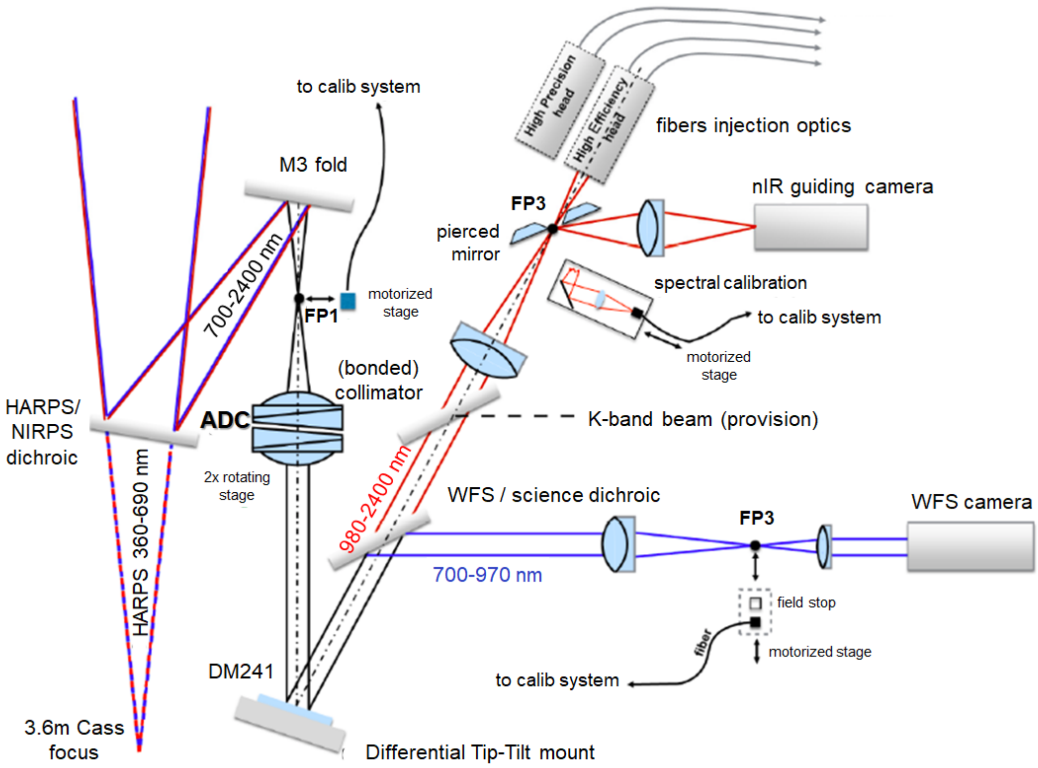


Figure 4 – NIRPS NFE NIRPS optical design layout.

3. THE NIRPS ADC

NIRPS aims at spectroscopic observations of stellar objects in the NIR, from 950 nm to 2400 nm. The instrument is assisted by an AO system, whose sensing bandwidth will be from 700 nm to 950 nm.

Even if telescope pointing and guiding is perfect at a given reference wavelength, atmospheric dispersion will shift the image centroid at different wavelengths. Moreover such effect will vary during acquisition with the observation zenith angle. In an Adaptive Optics instrument, an Atmospheric Dispersion Corrector (ADC) is fundamental, even in the infrared region (where dispersion is smaller.

In the NIRPS wavelength range (700 nm to 2400 nm), atmospheric dispersion reaches up to 0.75 arcsec peak-to-valley (PTV) in the sky, under standard conditions in La Silla (Altitude 2400 m, Temperature 11.5 °C, Relative humidity 44%) and for an azimuth angle of 60° (Figure 5). All the calculations presented in this document were obtained using Filipenko atmospheric model[7].

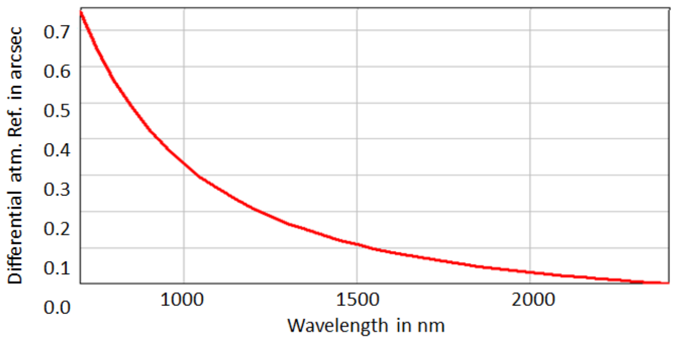


Figure 5 – Atmospheric dispersion relative to 2400 nm, in standard conditions in La Silla (Altitude=2400 m, T=11.5 °C, hr% = 44%) for an azimuthal angle of 60°.

The following table presents the main requirements considered for the design of the ADC.

Table 1. Requirements for the ADC preliminary design.

Parameter	**Requirements**
Wavelength coverage	700 – 2400 nm
Throughput	> 90% for λ = 700 – 2400 nm
Operating conditions in front-end	parallel to F/25 converging beam
Beam diameter at ADC (no FOV)	35 mm
Azimuthal angles	0° to 60°
Pupil shift	Pupil shift up to 10% of the pupil diameter is acceptable for 5% coupling loss
Residual elongation for maximum azimuthal angle	<160 marsec PTV over λ = 700 - 950 nm <140 marsec PTV over λ = 950 - 1800 nm <140 marsec PTV over λ = 1950 - 2400 nm
Field wobble during rotation/motion	0.8 arcsec PTV

The design of the ADC was done considering that it will be located in a convergent beam with optics (glued to the prisms) that allow the ADC prisms to be defined in a collimated beam (less critical in terms of aberrations and minimizes manufacturing complexity).

There are two basic requirements for an ADC:

1. variable dispersion to compensate that of the atmosphere at a given zenith angle;
2. zero-deviation at a reference wavelength, within the range of interest for all zenith angles.

The first of these requirements suggests counter-rotating prisms with dispersion maximum (minimum) when the apex angles of the prisms are in the same (opposite) directions. Two prisms are sufficient to satisfy this requirement, but they cannot satisfy the zero-deviation condition unless each prism by itself is a zero-deviation unit, a pair of prisms with different dispersions and oppositely directed apex angles. Thus an ADC is a set of four prisms paired to satisfy the given requirements. Rotation ability on both prisms must be performed to match the telescope parallactic and zenith distance angles. When the two prisms are in opposite orientations they give null dispersion, while they give maximum dispersion when their orientation is the same (Figure 6).

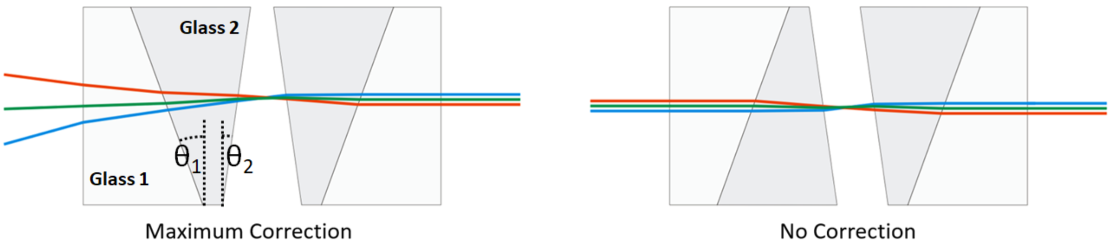


Figure 6 – ADC with counter rotation prisms, for a maximum correction at highest zenith (left) and no correction at 0° zenith (right).

The ADC glass selection was done using a tool[8] that considers all the possible combination of glass pairs in SCHOOT and OHARA catalogues, with the following step:

1. selection of glass by transmission efficiency;
2. calculation of residuals for all possible pair of glasses;
3. selection of possible candidates ordered by residuals, transmission and pupil shift;

The ADC design considered a 35 mm beam diameter (corresponding to an angular magnification of ~102).

The analysis showed that there are several pairs of glasses that can achieve good performances in terms of (dispersion) residuals and transmission. The graph in Figure 7 presents the performances of the 10 glass pairs selected from the analysis. As seen, pupil shift is largely bellow the requirements.

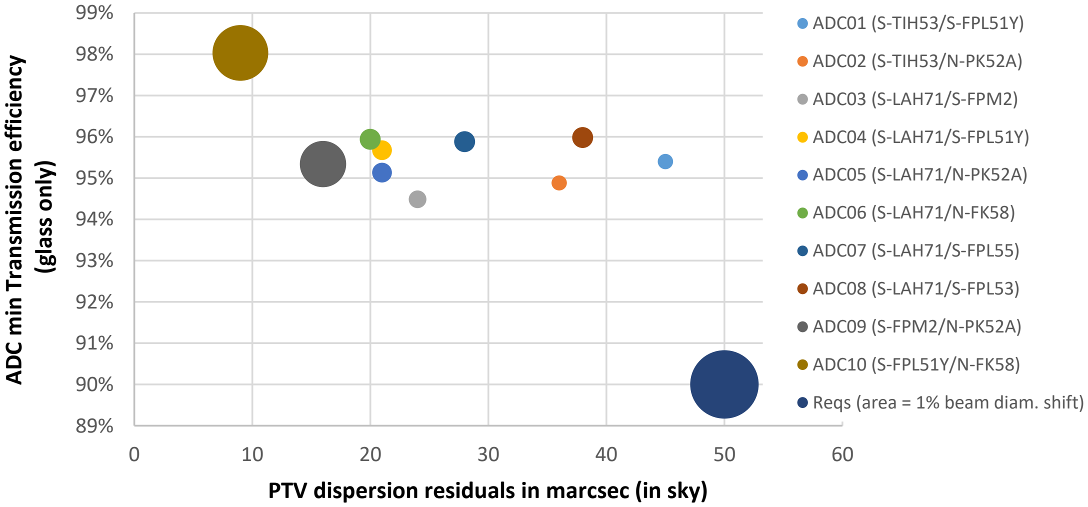


Figure 7 – Performances of the 10 glass pairs selected for the NIRPS ADC.

As seen from the previous analysis all the 10 options can fulfil the requirements and none of them is clearly better than the others for all performance parameters. The final choice considered also the behaviour of the selected glasses in the Front End overall optical performances (mainly in terms of chromatic correction). For all the possible glasses, the pair (ADC08) S-LAH71 + S-FPL53 was the one that demonstrated a better integration in the overall optical design.

Finally, we analysed the influence of the manufacturing tolerances on the ADC prism angles to fully evaluate the performances and verify the compliance with the requirements. For that, the ADC dispersion correction was analysed for a manufacturing tolerance on α and β (see Figure 8) of 0.5 arcmin. As seen in Figure XXX+1, the manufacturing tolerances do not degrade the amplitude of the residuals but can introduce a significant shift that must be corrected by the Front End guiding.

This analysis validated S-LAH71 + S-FPL53 from OHARA as the glassed for the NIRPS ADC.

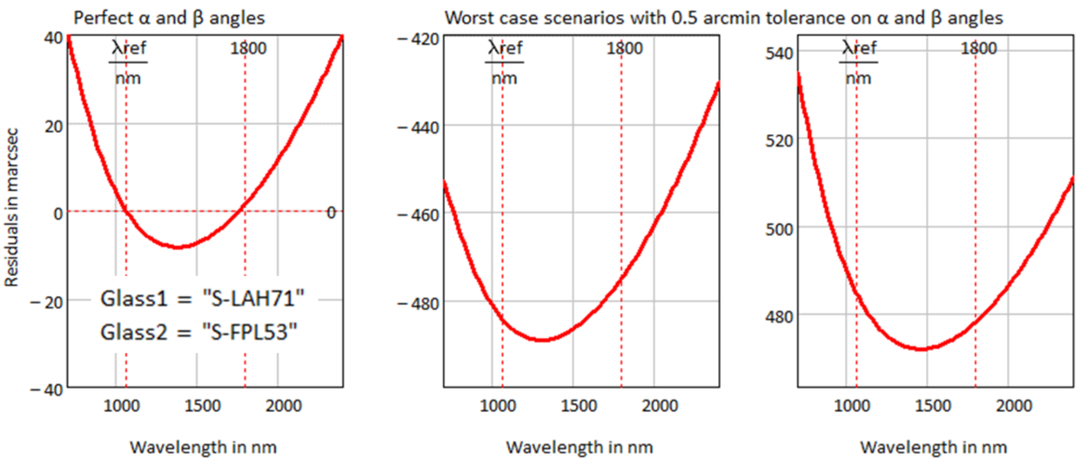


Figure 8 – Residuals for perfect angles and for a manufacturing tolerance of 0.5 arcmin (worst cases) for the selected ADC.

As the pupil is not located in the middle of the ADC the full diameter was increased to 60 mm. Figure 9 show the optical design of the ADC prismatic part composed of two equal prisms, the second mirrored relative to the first.

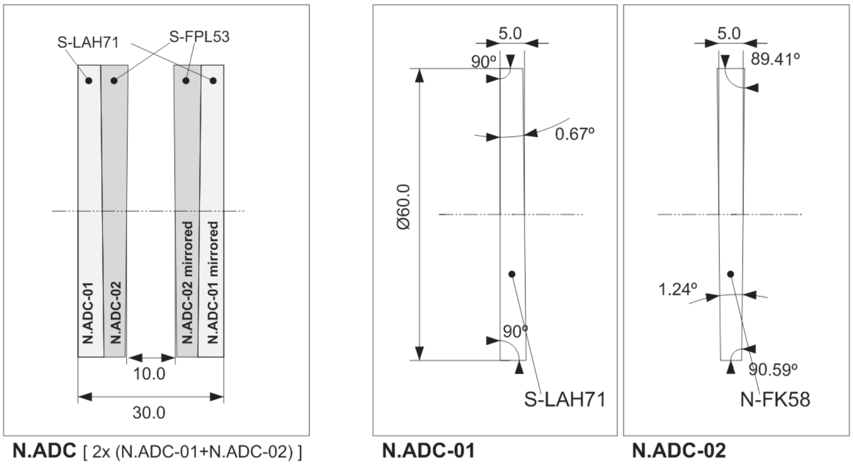


Figure 9 – NIRPS ADC composed of two equal prisms (the second mirrored relative to the first). Dimensions in mm.

3.1 NIRPS ADC Characterisation tests

After the manufacturing, several characterisation tests were performed with the ADC in order to validate the requirements and the performance in the NIRSP Front End.

Figure 10 shows the setup used to measure Wavefront Error (WFE) and Back Focal Length (BFL) of the ADC and Figure 11 the prism exit/entrance angles and ADC induced wobbling (with stage rotation). These tests showed that all the requirements were fulfilled except for the pupil wobbling that was higher than expected due to a manufacturing error (clock angle between prisms). The pupil wobbling error is corrected by M3 mirror in the NFE that has a tip/tilt stage.

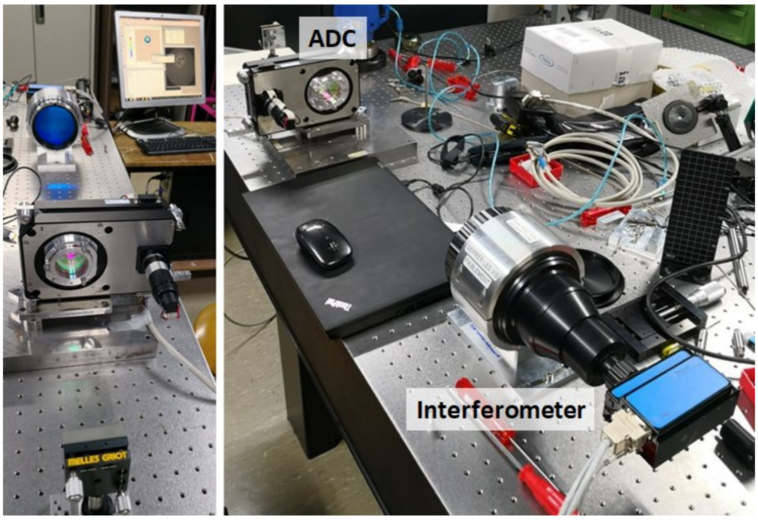
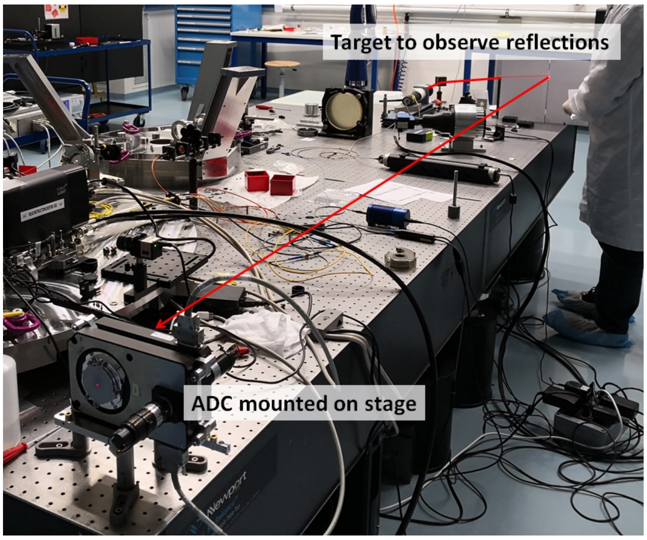


Figure 10 – Photos of the NIRSP ADC test setup for WFE and BFL measurements.

The ADC was then integrated in the NFE system and the behaviour was fully characterized (Figure 12 and Figure 13). This test allowed us to identify and fully characterize a fixed instrumental dispersion (~28 mas) that is considered in the dispersion correction model (the ADC corrects now both sky and instrumental dispersions).



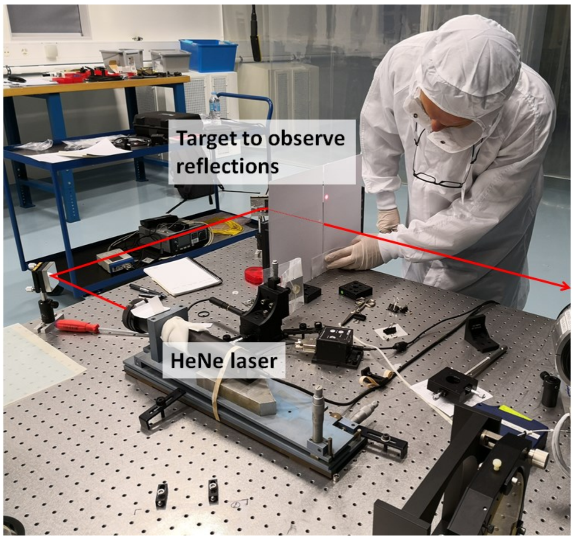


Figure 11 – Setup to measure NIRPS ADC prism exit/entrance angles and ADC induced wobbling (with stage rotation).

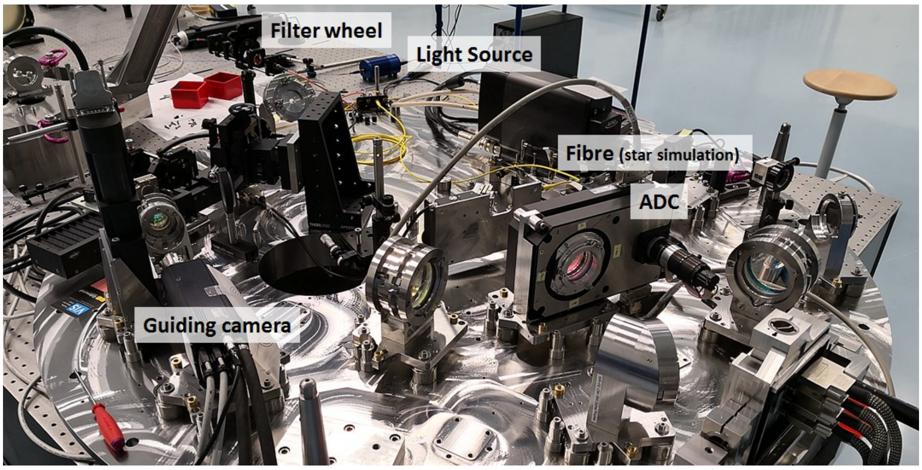


Figure 12 – NIRPS ADC integrated in the NFE bench for dispersion tests.

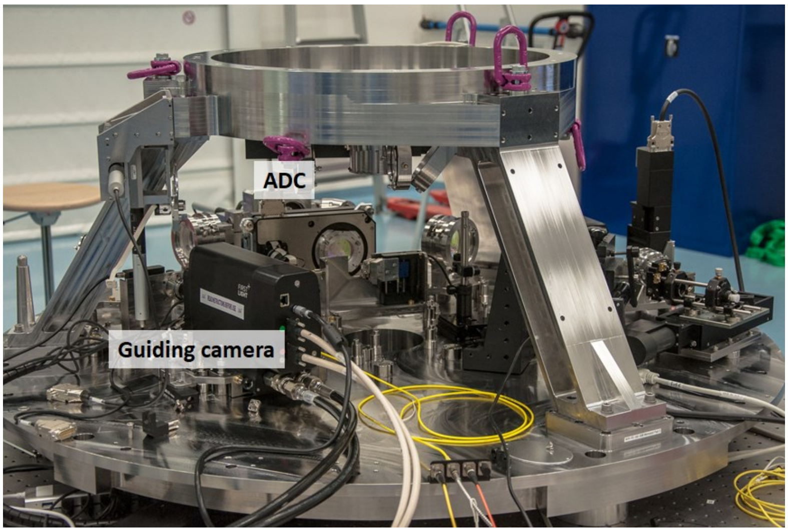


Figure 13 – NIRPS ADC integrated in the FE (with monopode) for characterization tests.

3.2 NIRPS ADC On-Sky Commissioning tests

When commissioning an ADC, two aspects play an important role:

1. The error in the alignment between ADC dispersion and the atmospheric dispersion direction
2. The error in the matching between ADC dispersion and atmospheric dispersion amount.

To verify these two aspects, we followed the method described in *Cabral, et al. 2021*[8]. It is well known that atmospheric dispersion can cause oblongness in an object image. The procedure is based on ellipse fitting of several intensity level cuts from the guiding camera images to determine a parameter that quantity that oblongness, identifying the angles where we reach a minimum level when the correction is properly applied and a maximum level when correction is not applied (Figure 14 shows an example of acquired images and the corresponding contour plots).

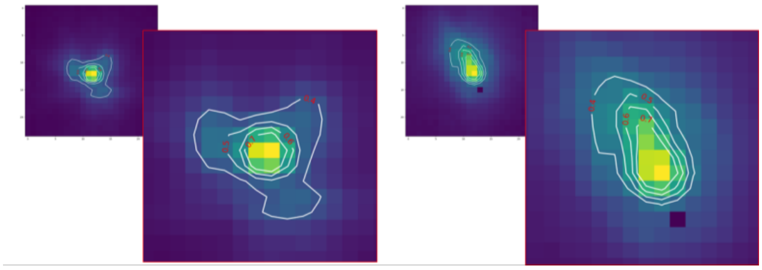


Figure 14 – Example of acquired images with low and high dispersion and contour plots to which the ellipse is fitted.

As mentioned before, an ADC is a set of two counter-rotating prisms that are used to correct for the atmospheric dispersion. To do so, we must think of the ADC and the sky as dispersion vectors, having a magnitude (corresponding to the amount of dispersion from blue to red wavelengths) and a direction. To cancel the atmospheric dispersion, the ADC should produce an equal amount and oriented in an opposite direction to that of the sky. The ability to counter-rotate the prisms allows the control of the amount of ADC dispersion (angle β). The ability to rotate both prisms simultaneously allows the control of the dispersion direction (angle α).

In the method, to optimize α, we rotate the two ADC prisms, and hence its dispersion direction, within a range around the nominal position with a certain step. Each point will result with a different dispersion residuals and hence different oblongness. The angle at which the minimum is found should coincide with the perfect α alignment.

Figure 15 and Figure 16 show two examples of the ratio *b/a* (major axis divided by minor axis) following the sequence of α scans (with the offset angle from 0° to 90°, 90° to -90° and back to 0°). The offset angle (at polynomial fit minimum) from these two runs are, respectively, +1.0° and -0.7° that, giving the dispersion of the results, is a good indication that the dispersion direction is set correctly. Note that to create a dispersion correction error larger than 10 marcsec we would need the error on α to be bigger than 3°.

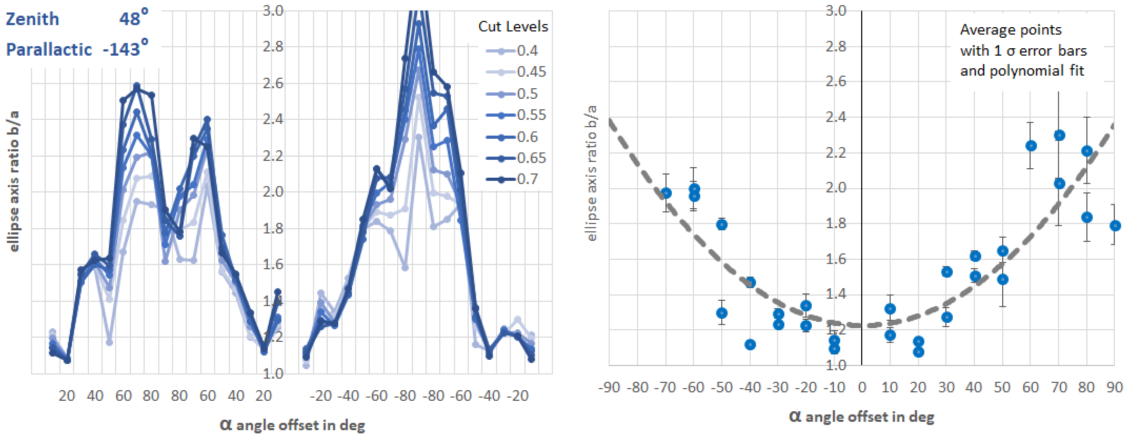


Figure 15 – Example of the ratio *b/a* (major axis divided by minor axis) for an α scans. The minimum of the polynomial fit on the right graph is at +1.0°. This data was obtained for a star with a zenithal angle of 48° and a parallactic angle of -143°.

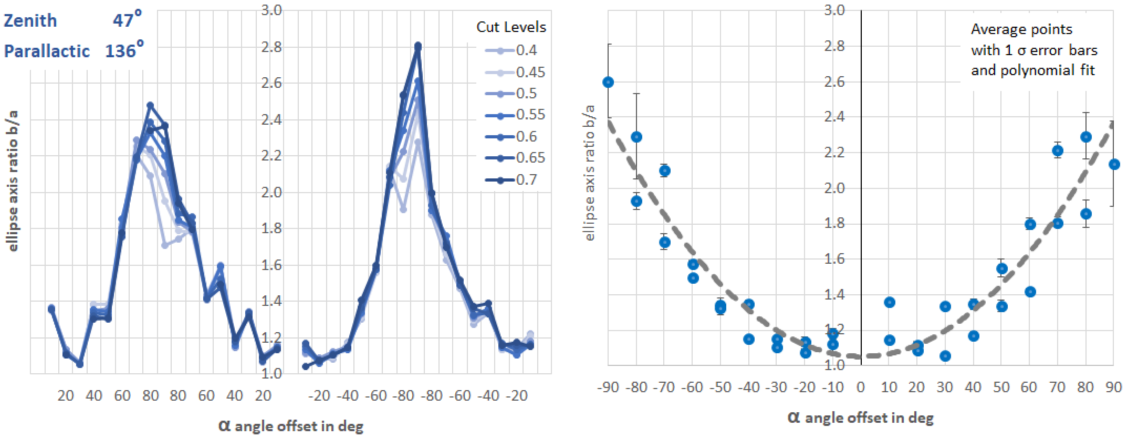


Figure 16 – Example of the ratio *b/a* (major axis divided by minor axis) for an α scans. The minimum of the polynomial fit on the right graph is at -0.7°. This data was obtained for a star with a zenithal angle of 47° and a parallactic angle of 136°.

Once α is verified to be correct, we counter-rotate the two ADC prisms to validate the β angle that correspond to the amount of dispersion determined by the model. In a similar manner of α optimization, we repeat the same procedure by varying the angle between the two prisms. The angle at which the minimum oblongness is found indicates how correct the correction is. Due to a technical problem we were only able to do one run of a β scan on the positive offset side. Figure 17 shows the results. As it can be seen, the fit would cross the ratio 1.0 at -1.5°, although the dispersion of the results can only indicate that it seems the correction is done properly. Note that if the error on β is equal to -1.5° that will result in the worst case (maximum dispersion) on a dispersion correction error of 10 marcsec, well below the required values.

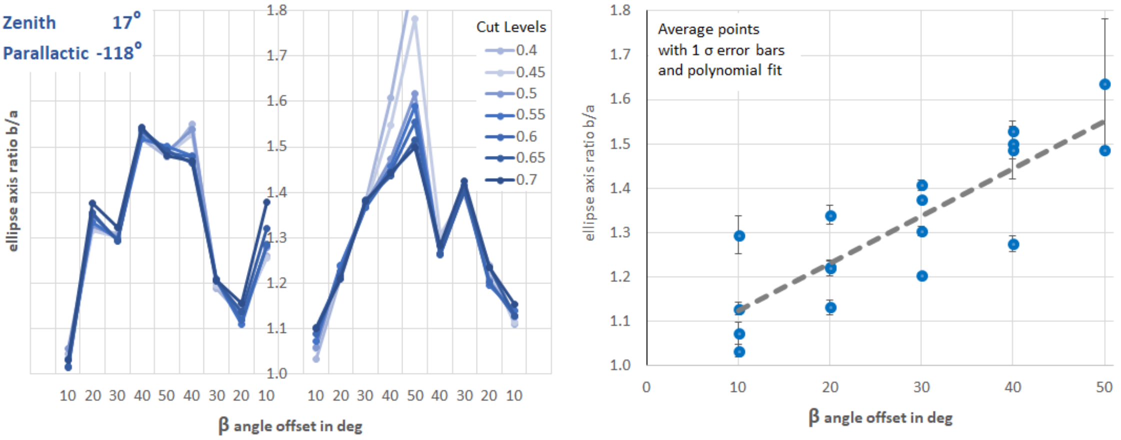


Figure 16 – Example of the ratio *b/a* (major axis divided by minor axis) for a β scans. The minimum of the polynomial fit on the right graph is at -1.5°. This data was obtained for a star with a zenithal angle of 17° and a parallactic angle of -118°.

4. CONCLUSIONS

We presented the design, integration and tests of the NIRPS Atmospheric Dispersion Corrector, showing the compliance with the requirements defined during the design phase and validated during the on-sky commissioning.

The characterisation tests showed the presence of a non-negligible instrumental dispersion. That amount was included in the overall correction model, improving the performance of the overall front end.

The on-sky commissioning tests allowed to show the power of a new test method that validated the ADC towards the first light obtained in the beginning of 2022[6].

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