A polarimetric unit for HARPS-North at the Telescopio Nazionale Galileo : HANPO

Francesco Leone*[a,c], Massimo Cecconi[b], Rosario Cosentino[b], Adriano Ghedina[b], Marina Giarrusso[a,c], Manuel Gonzalez[b], Vania Lorenzi[b], Matteo Munari[c], Hector Perez Ventura[b], Luis Riverol[b], Jose San Juan[b], Salvatore Scuderi[c]

[a]Università di Catania, Dipartimento di Fisica e Astronomia, Sezione Astrofisica, Via S. Sofia 78, 95123, Catania, Italy
[b]INAF Fund. Galileo Galilei, Rambla José Ana Fernández Perez 7, 38712 Breña Baja (La Palma), Canary Islands, Spain
[c]INAF Osservatorio Astrofisico di Catania, Via S. Sofia n. 78, Catania, Italy

ABSTRACT

Usually observational astronomy is based on direction and intensity of radiation considered as a function of wavelength and time. Despite the polarisation degree of radiation provides information about asymmetry, anisotropy and magnetic fields within the radiative source or in the medium along the line of sight, it is commonly ignored. Because of the importance of high resolution spectropolarimetry to study a large series of phenomena related to the interaction of radiation with matter, as in stellar atmospheres or more generally stellar envelopes, we designed and built a dual beam polarimeter for HARPS-N that is in operation at the Telescopio Nazionale Galileo. Since the polarisation degree is measured from the combination of a series of measurements and accuracy is limited by the instrumental stability, just the great stability (0.6 m/s) and spectral resolution (R=115000) of the HARPS-N spectrograph should result in an accuracy in the measurements of Stokes parameters as small as 0.01%. Here we report on the design, realization, assembling, aligning and testing of the polarimetric unit whose first light is planned in August 2014.

Keywords: Polarimetry, Spectroscopy

1. INTRODUCTION

Physical mechanisms responsible for polarisation in Astrophysics are: reflection from solid surface and small grains, Thomson scattering Rayleigh scattering, Halle effect, Zeeman effect, gyro-resonance and gyro-synchrotron emission.
So that, polarimetry has a role in almost all fields of Astrophysics as it can measure:

1. size, shape, orientation, and composition of dust particles (often critical for the determination of extinction values, the uncertainty of which dominates many error analyses),
2. weak reflected-light signatures (e.g., extra-solar planets, hidden nuclei of AGNs, deeply embedded protostars, massive stars with optically thick ejected envelopes),
3. scattering properties of light-reflecting screens (e.g., planetary atmospheres, dust shells, surfaces of rocky bodies, albedos for density measurements),
4. 3-dimensional shapes of point sources independently of distance and separately for physically distinct regions (e.g. physics of supernova explosions and aspect-angle dependency of their apparent luminosities),
5. formation of structure at very early epochs (e.g., AGNs, GRBs, dust grains),
6. stellar magnetic fields and their geometry (e.g., star formation, rotational braking, mass loss, convective processes, genealogy of advanced stages of stellar evolution, nature of soft gamma-ray repeaters).

The importance of polarimetry in Astrophysics and the current perspective of characterising the atmosphere of exo-planets justifies the technological effort to update the present instrumentation in order to include a polarimetric capability. As well, new instrumentations are designed including polarimetric modules.

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2. IMPORTANCE OF INSTRUMENTAL STABILITY IN SPECTROPOLARIMETRY

Important Astrophysical problems, as the detection and measuring of magnetic fields, can be faced only on the basis of high resolution spectropolarimetry. For such a reason during the last two decades several R > 100 000 spectrographs have been updated with a polarimetric module, UCLES at AAT (Semel et al.[1]), SARG at TNG (Leone et al.[2]) and finally HARPS-South at ESO (Snik et al.[3]).

Recently, Bagnulo et al.[4] explained how the discovery of longitudinal magnetic fields in FORS2 data (see Leone et al.[5,6]) can be due to non-photon noise, more specifically due to small offsets in the parallel and perpendicular beams, or non-predictable instrument instabilities or flexures, evidenced by changes in the individual spectra. As in Leone et al.[2], we have simultated the measurements of a magnetic field from the wavelength distance of σ components in left and right circular polarised light. Fig. 1 shows the accuracy dependence on signal-to-noise ratio, spectral resolution and instrumental stability as given in velocity stability. HARPS-North is expected to measure magnetic fields with an accuracy of tenths of gauss in a single line.

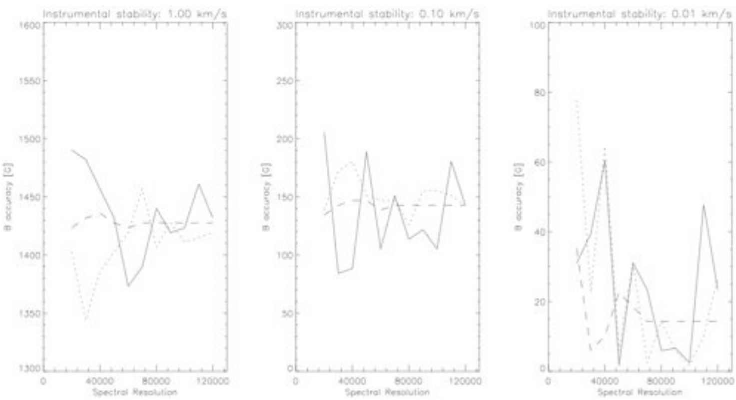

Figure 1. Expected accuracy in measuring the effective magnetic field (see Leone et al.[7]) on the basis of Stokes V parameters by combining to consecutive spectra is reported as a function of S/N = 50 (continuous lines), 100 (dotted lines) and 500 (dashed lines) for three values of the instrumental stability given in km s^{-1}. Magnetic fields as measured from a single spectral line are expected to be accurated as low as 20 G.

3. THE POLARIMETER

Two methods are commonly used to perform spectropolarimetry. One is based on a λ/2 and a λ/4 retarder (waveplate) that can be alternatively inserted along the optical path and rotated with reference to a beam displacer to measure the linear and the circular polarisation respectively (Leone et al.[2]). The other one, often called *dual-waveplate* method, is based on a λ/2 and a λ/4 retarders both inserted along the optical beam. The optical axes of these two retarders are opportunely rotated with respect to a beam displacer to measure the linear and the circular polarisation, as for the William-Wehlau spectropolarimeter (Eversberg et al.[8]). It has to be noted that both methods need the same number of exposures to measure the linear and the circular polarisation. The advantage of the *dual-waveplate* method is the absence of mechanisms necessary to exchange the retarders, but it **adds** all the defects of the two retarders. We decided to use the first method.
As it is usual for a spectrograph of an Alt-Azimuth telescope, the polarisation analyser has to be located after the tertiary mirror and a further folding prism (M4) bending the telescope beam towards HARPS-North (Fig. 2). During the project phase of the polarimeter, we had to overcome five main constrains:

a) a limited available space within the Derotator,
b) the large (370-690 nm) spectral range covered and high spectral resolution of HARPS-North,
c) matching of the two fibers, one along the telescope axis and the other 16 mm far,
d) the alt-azimuth mount that let the sky be apparently rotating when the polarimetric reference system is the equatorial one,
e) the instrumental polarisation, changing with the telescope position, mainly due to the tertiary mirror (M3) and folding prism (M4) that drive light from telescope to the spectrograph.

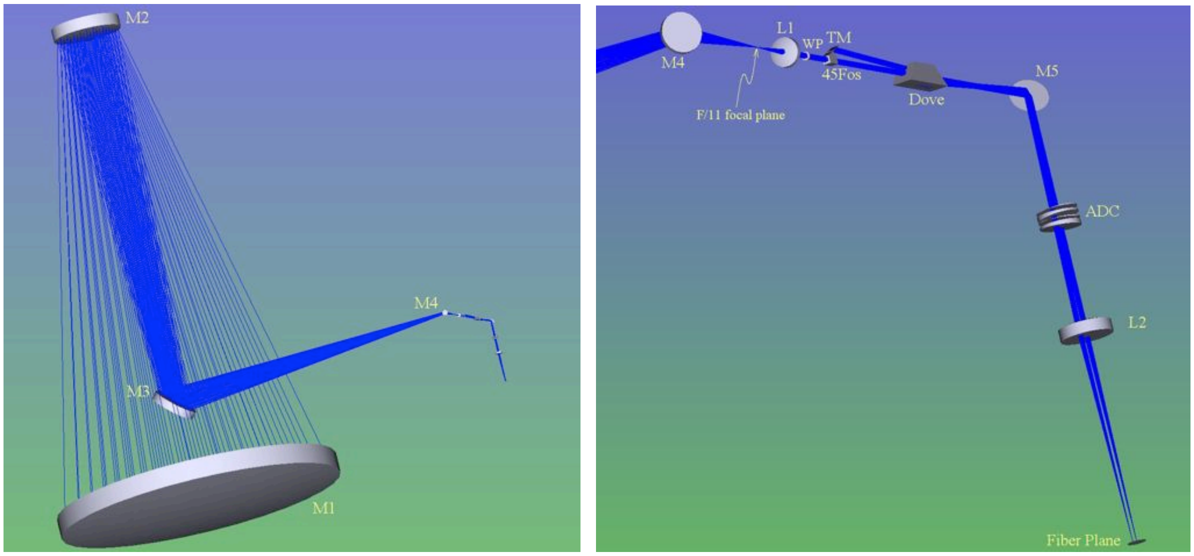

Figure 2. The HARPS-North polarimeter (HANPO) is located after a folding prism (M4) that feeds the spectrograph. A lens (L1) collimates the F/11 telescope beam after focal plane and drives it through the waveplate (WP). A Foster polarizer displaces the ordinary and the extraordinary beams forming a 45° angle. A mirror bends the extraordinary beam to be almost parallel (2.6°) to the ordinary one and then both enter in a Dove prism that is necessary to fixed them onto the corresponding HARPS-North fiber as the retarders and the Foster jointly and synchronously rotate to compensate the apparent sky rotation due to the alt-azimuth telescope mount. The two fixed beams are real-time locked onto the fiber by the tip-tilt M5 mirror. Before to reach the fibers, the ordinary and the extraordinary beams go through the Atmospheric Dispersion Corrector (ADC) and L2 camera lens.

As previously pointed out, the polarisation analyser consists of a $\lambda/4$ retarder or a $\lambda/2$ retarder and a Foster polarizer as beam displacer (Fig. 2). Pancharatnam superachromatic retarders in principle were acceptable within the covered spectral range. However, Donati et al.[9] reported that superachromatic retarders generate ripples. Such ripples are expected to limit the polarimetric capability at high resolution. Unfortunately, because of the limited available space, we could not adopt a K-prism as a $\lambda/4$ retarder and a Fresnel prism as $\lambda/2$ retarder which would be ideal items for their phase retardation with wavelengths (Leone et al.[2]).

For this reason we finally selected achromatic quartz and MgF_2 retarders by the *Bernhard Halle Nachfl. GmbH* whose path-difference is correct within 3% in the spectral range of 450-700 nm. Retarders are mounted on rotary stages, so that when the $\lambda/4$ retarder is inserted along the telescope beam and its axis forms a 45^o degree angle with respect to the beam displacer (Foster polarizer) optical axis, the V Stokes parameter is measured. While the $\lambda/2$ retarder can assume the 0^o, 22.5^o, 45^o and 67.5^o angles to measure the Q and U Stokes parameters. Because of the 16 mm distance between the two HARPS-North fibers on the telescope side it was not possible to use a standard birifrangent plate. We adopted a Foster polarizer with a mirror folding the extraordinary beam with such angle to be focused onto the fiber B by the HARPS-North L2 camera lens (Fig. 3). Still because of the large spectral range a cubic beam splitter, certainly easily to be handled, could not be adopted. To face the field of view rotation, the Foster polarizer is also mounted on a rotary stage in order to have its optical axis fixed on the sky along the acquisiton time. In principle, Stokes parameters could be acquired at any angle between the Foster optical axis and sky reference system being possible to rotate them. However we prefer to jointly and synchronously rotate the Foster and retarders to avoid any smearing of Q and U Stokes parameters during exposure. The ordinary and the extraordinary beams emerging from the Foster polarizer are subsequently *derotated* by a Dove prism to be aligned with respect to the two fixed fibers feeding the HARPS-North spectrograph. All rotary stages can be positioned with an angular precision of 10^{-3} degrees.

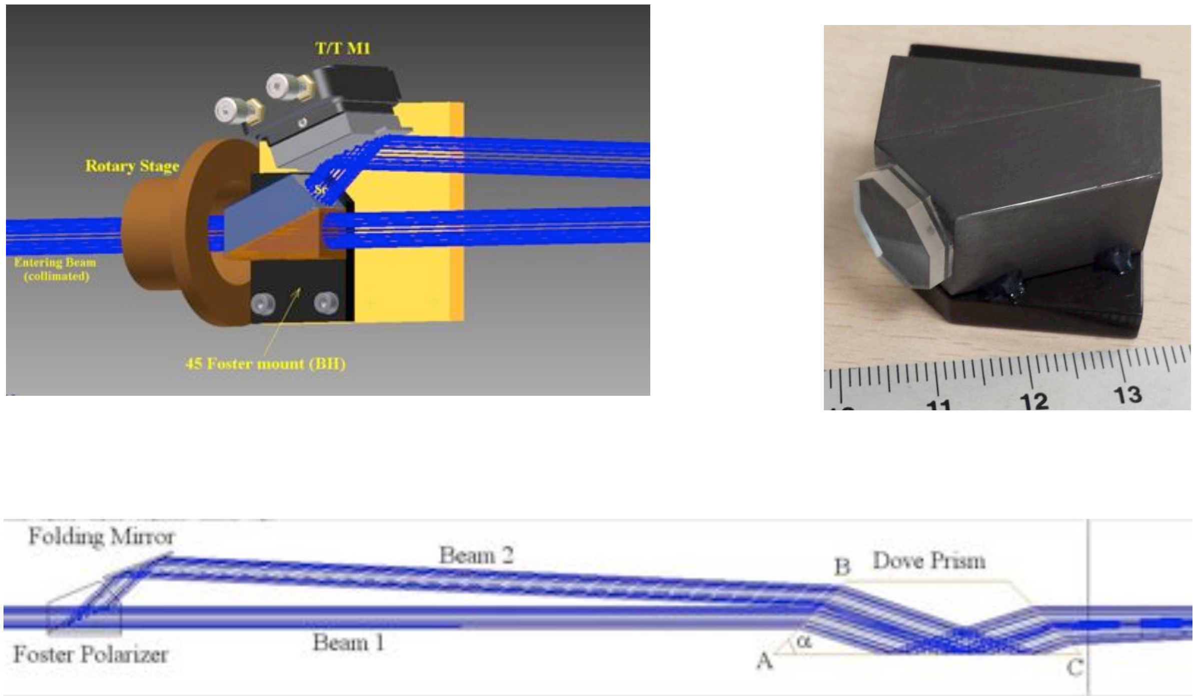

Figure 3. To match the very separated (16 mm) HARPS-North fibers on the focal plane, a Foster prism combined with a Dove prism have been selected. The fine M5 tip-tilt mirror integrated in the HARPS-North Front End Unit (FEU) will fix the two spots on them. A λ/2 retarder (top-right) has been glued on the 45^{o} exit face of the Foster prism to maximize the reflection onto the mirror. To fix the polarimeter optical axis on the sky reference system despite the Alt-Azimuth mount, the Foster prism rotates as the parallactic angle. The emerging ordinary and extraordinary beams go through a Dove prism that properly anticounter-rotates to feed HARPS-North fibers.

In order to interfere at minimum with the observations of HARPS-North (Cosentino et al.[14]) we took advantage of the decommissioning of the High Resolution Spectrograph SARG (Gratton et al.[15]) and put a mechanical interface between the mechanical derotator of the telescope and the F/11 focal plane (Fig.4).

With this solution the original optomechanical configuration for the observations with HARPS-North is combined with a substantially different configuration when using HANPO. In particular:

(i) the M4 mirror is substituted with a 2" folding prism; both are mounted on a translation stage 300mm before the F/11 focal plane but after collecting the light from the M3 tertiary mirror they send the beam radially towards the border of the derotator at two different angles (roughly 11^{o} apart each other);

(ii) the derotator thus needs to be positioned in two different angles in order to feed the light inside the HARPS-North Front End Unit (FEU) depending on whether the spectrograph or the spectropolarimeter is planned to be used.

The swap between these two configurations is nonetheless automatic and is completed in less than a minute. The limited space available forced us to find a compact solution for the polarimeter that could be easily aligned in the laboratory and reduced at minimum the need of optical fine adjustment once mounted at the telescope. There are less than 100 mm of space between the external part of the Dove prism and the entrance of the FEU so that it would be very problematic to adjust some optical component after the mounting of the system inside the derotator or during the night.

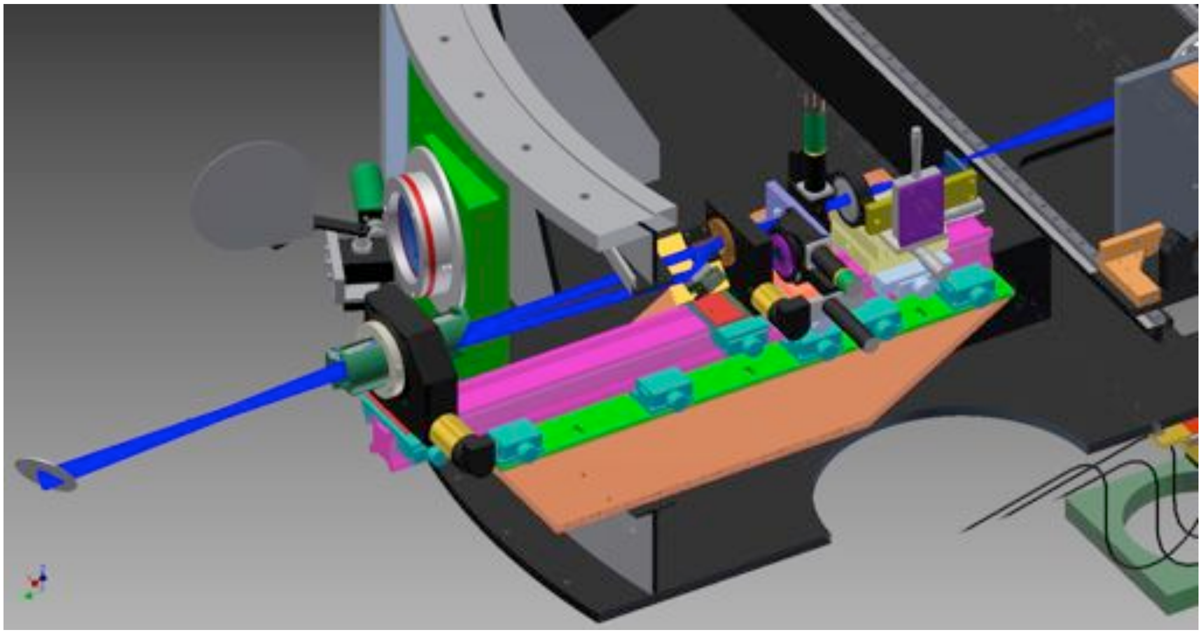

Figure 4. Mechanical drawing of the whole polarimeter HANPO inside the derotator B. From the right to left: M4 folding prism (not completely visible), F/11 telescope focal plane where beam is focused and a lens to convert the diverging beam in a collimated one. Then retarders, Foster polarizer and optical (Dove prism) derotator. Finally, on the left, M5 tip/tilt mirror inside the HARPS-North Front End Unit. The overall instrument is mounted on a Newport optical rail (magenta) which is inserted through 5 clamps fixed on a board (green) attached to the interface with the derotator (light brown).

We chose a 4 sided cruciform aluminium optical rail from Newport (X48, Newport[16]) as the mechanical pin of our system. Then we machined in-house all the interfaces between the optomechanical components and the dovetail carriers (CXL48-50 and CXL 48-80). We also built a mechanical flange to be the interface between the flange attached to the derotator and the X48 rail. The rail can slide over 5 clamps which are fixed to the flange and in this way we can firstly adjust the axis of the rail by moving the flange and lastly mount the whole polarimetric unit (with the optomechanics previously aligned as respect to the rail in the optical laboratory) just by sliding the rail inside the 5 clamps.

So HANPO has 4 rotary stages (Dove prism, Foster polarizer/folding mirror and 2 laminas), one translation stage for the choice between $\lambda/2$ and $\lambda/4$ and another rotary stage for the insertion of a fiber at the focal plane for calibration purposes (lamps). All these movements are controlled with a custom control box based on Arduino Uno rev.3 (Fig.5).

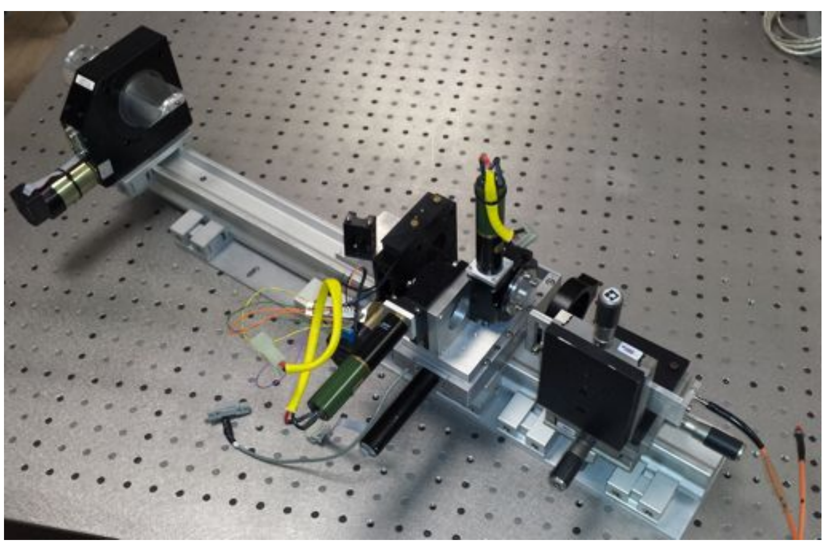

Figure 5. Mechanical setup of the whole polarimeter HANPO.

To align the mechanical interface of the instrument to the optical axis of the telescope we first adjusted an on-axis laser beam to fall into Fiber A in the classical optical configuration for HARPS-N. We then swapped to the HANPO configuration and adjusted the prism to send the light towards the FEU and again onto Fiber A. We obtained in this way the reference beam onto which make measurements and fine adjust the position of the optical axis of the polarimetric unit (Fig.6).

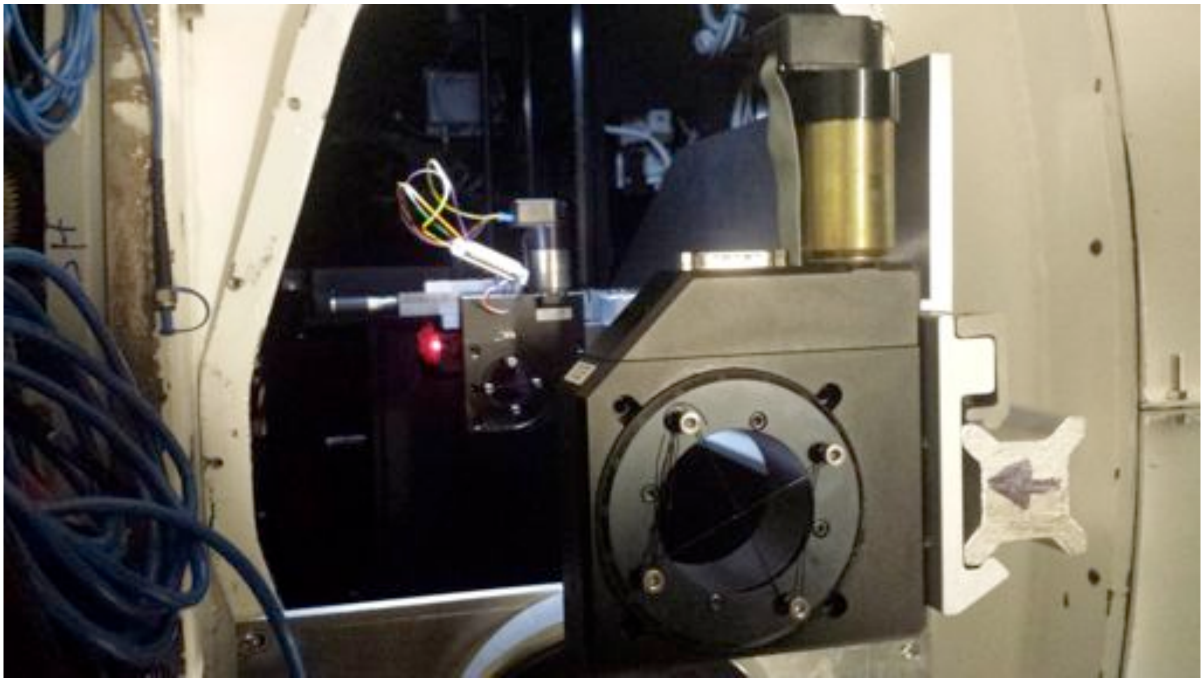

Figure 6. HANPO inserted into the derotator by sliding through the 5 clamps. The overall instrument was aligned by means of a laser beam as coming from the telescope.

4. OPTICAL TEST & ALIGNMENT

Since the errors on the Dove prism geometry (see Fig. 7) reported by the company did not correspond to the required one, we tried to directly test this optical device in our optical laboratory to verify if it could work for our purposes as well.

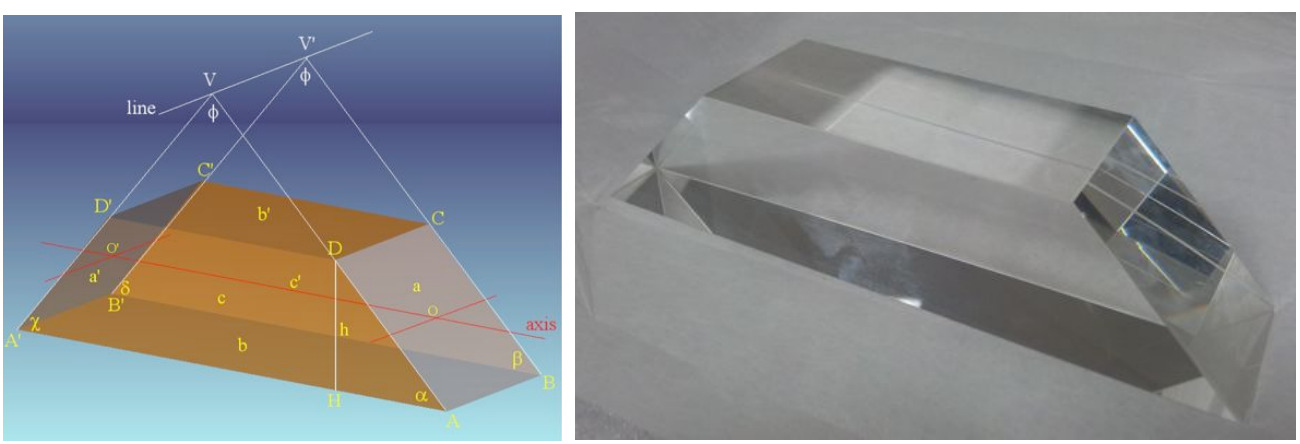

Figure 7. The geometry and accuracies of the Dove prism have been selected to fulfil the optical and volume requirements to adapt the polarimeter (Left)

We locked the Dove prism inside its mechanical mount and this on its rotary stage. Then, we mounted the overall system on an external tilting stage. A 10mm diameter collimated beam entered the Dove prism. The exiting beam was focused by a 1000mm focal length lens onto a CCD camera with 7um pixels. By tilting the overall system and the single Dove prism mount in respect of the rotary stage, we checked the maximum deviation of the output beam onto CCD.
At first, some exposures have been done while Dove prism rotating. The image does a complete round for a 180^o rotation of the Dove prism. So, two image circles appear if we sum the images obtained during a 360^o Dove prism rotation (Fig. 8 left). Then, single exposures have been done for fixed Dove prism position angles (Fig. 8 centre). After many attempts, a maximum output beam deviation of less than 0.4mm was obtained which corresponds to a less than 1.5 arcmin angular deviation at the given 1000mm focal length (Fig. 8 right).

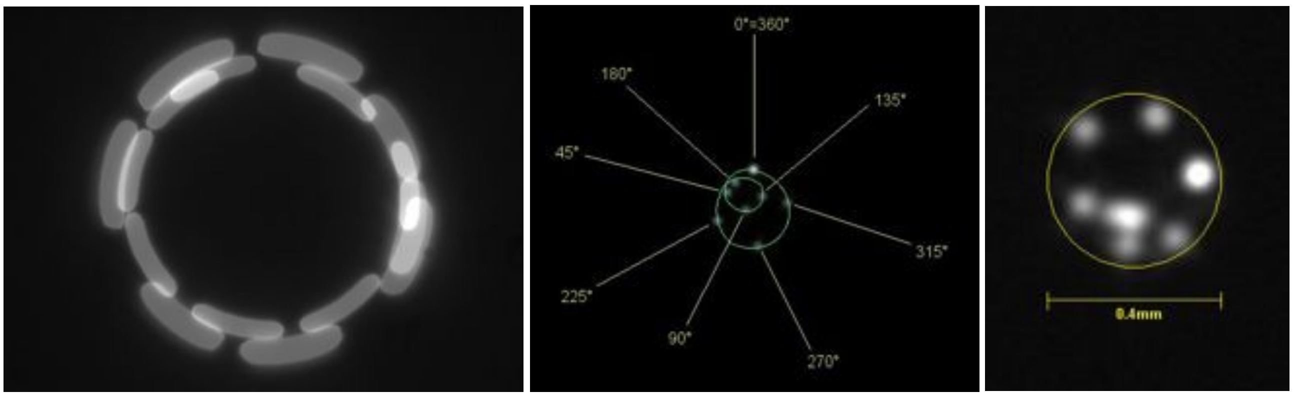

Figure 8. During Dove prism 360^o rotation, output beam prints two circles onto the CCD (left). Spot position have been recorded for given Dove prism position angles (centre) up to minimize the two circles' dimension (right).

Since the maximum stroke of the M5 tip/tilt mirror is 7arcmin, the Dove prism maximum deviation is not critical to allow M5 mirror to maintain the two beams onto their corresponding fibers. Moreover, during a single scientific exposure, field of view will not rotate a lot, especially if far from the meridian, and Dove prism will rotate half that quantity. So the final output beam angle deviation will be even less and easily recoverable by the M5 tip/tilt mirror.

Also the retarders and the Foster polarizer will be similarly tested/mounted/aligned to guarantee the overall maximum output beam deviation will be within 1-2 arcmin to allow M5 tip-tilt mirror to maintain spot centring.

To align the optical axis of retarders with respect to the Foster prism optical axis, we have followed Goodrich et al.[10]. To align the retarders with respect to the Foster prism, a linear polariser was located along a simulated beam at an angle extinguishing the extraordinary beam emerging from the Foster prism. The intensity of the emerging beam was then measured as a function of the rotary stage position, and the Foster axis was fixed at that angle where the intensity was *null*. Then the λ/4 retarder was inserted after the linear polariser and the beam intensity recorded during its rotation. The 45^o angles were fixed determining the maximum intensity of the emerging beam (Fig. 9). Similarly, we have determined the relative position of λ/2 retarder and Foster prism optical axes.

Figure 9. Linearly polarised light is modulated by the relative angle between the λ/4 retarder and Foster axes. Maxima of the extraordinary beam are coincident with multiples of 45^o.

5. INSTRUMENTAL POLARISATION

HARPS-North is fed by means of the M3 tertiary telescope mirror and a further M4 folding prism, so that the instrumental polarisation has to be determined as a function of the target position in the sky. A theoretical polarimetric study of the M3 mirror has already been carried out by Giro et al.[11] where it has been shown that such a polarization can be easily managed by means of the Muller calculus. Leone et al.[2] have extended such a study to a further folding mirror. In the case of HARPS-North polarimeter, the Stokes parameters describing the polarisation state of the observed target have to be rotated of the *parallactic angle*, that is from the equatorial to the alt-azimuth reference system, and then multiplied for the Muller reflection matrix R(*pa*) because of the M3 tertiary mirror where the polarisation is changed according to the reflection matrix T. Because of the reflection on the M4 folding prism, the incidence plane on M3 has to be rotated of $R(\pi/2\text{-}el)$ where *el* is elevation angle. Finally being the polarimeter always oriented to the north, a further passage from the alt-azimuth to the equatorial system is necessary: $IP = R(pa)\ R(\pi/2\text{-}el)\ T(M3)\ R(pa)$. A successfully application of this method is given in Covino et al.[12] as to the polarimeter (PAOLO) of the Low Resolution Spectrograph (LRS) and camera of the TNG.

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