HARPS Polarimeter Option

Prof. Nikolai Piskunov (Uppsala), Dr. Oleg Kochukhov (Uppsala)
Prof. Christoph Keller (Utrecht), MSc. Frans Snik (Utrecht), Dr. Sandra Jeffers (Utrecht),
Dr. Jeff Valenti (STScI), Dr. Christopher Johns-Krull (Rice)

May 8, 2009

Contents

Chapter 1

Proposal summary

Circular polarimetry at high spectral resolution measures stellar magnetic geometry and net longitudinal field strength, providing clues about stellar dynamos, coronal heating, angular momentum evolution, etc. Linear polarimetry measures scattering by circumstellar material, providing clues about protoplanetary disks, asymmetric mass loss, etc. Astrophysically important polarimetric signals are almost always much less than 1%. Achieving 0.01% precision requires careful instrumental design and observational techniques.

Based on previous experience, we have designed and are currently building a polarimeter that is specifically designed to feed the ultra-precise HARPS spectrograph. We are independently funding all design and construction costs, but request engineering support from ESO to integrate polarimeter into the HARPS interface and to commission the instrument. Before beginning this project, we obtained approval from ESO and Prof. Michel Mayor, who relies on the long-term stability of HARPS for an important planet search program.

Chapter 2

Proposed HARPS upgrade

2.1 Optical design

This section presents the optical design of the polarimetric upgrade to HARPS[1].

2.1.1 Requirements

1. The goal of the project is to upgrade HARPS to a full Stokes spectropolarimeter without compromising the current observational capabilities and operations of HARPS.

2. This is achieved by replacing the obsolete Iodine cell with a new assembly containing the polarimetric components. The existing slider for the Iodine cell will be used to position the polarization optics in and out of the beam, just before the fiber head at the Cassegrain focus.

3. Both fibers will be used to feed the light of two perpendicular polarization directions to the spectrograph.

4. The polarimeter needs to be designed such that the return beam to the guider camera remains unblocked.

5. The full wavelength range of HARPS ($380 - 690$ nm) will be covered.

6. The full polarization state according to the Stokes formalism $(I, Q, U, V)^T$ shall be measured to enable complete diagnostics of magnetic field and scattering topologies.

7. The polarimetric sensitivity is $\sim 10^{-4}$ in order to observe polarized Zeeman profiles in individual lines. The polarimetric sensitivity is defined as the noise level of an observation of a bright star for a sufficient amount of time. Down to this level the noise should be dominated by photometric (Poisson) noise.

8. The polarimetric accuracy needs to be $\sim 5\%$ in order to obtain reliable inversions. This accuracy requirement drives the precision of the polarimetric calibration for taking out instrumental polarization and for putting the measured polarization on an absolute scale. The instrumental polarization of all the optics up until the polarimeter should therefore be minimized. Fortunately, the instrumental polarization at the Cassegrain focus is already minimal because the system is fully rotationally symmetric, except for the atmospheric dispersion corrector (ADC), which has some small-angle refractions.

[1] http://www.ls.eso.org/lasilla/sciops/3p6/harps/

9. The amplitude of intensity and polarized fringes has to be minimized.

2.1.2 Polarimetric design

Polarimetry is by definition differential photometry, i.e. at least two measurements have to be performed and subtracted in order to determine the polarization in one 'direction' (Stokes Q, the difference of linear polarization measurements at 0 and 90°; U, idem at 45 and $-45°$; and V, with measurements of right and left circular polarization). Therefore the measurement of small polarization signals is always hampered by noise. The noise needs to be minimized by an appropriate choice of the polarization modulation. Two classical methods for modulating can be discerned:

1. *Spatial modulation.* A polarizing beam-splitter divides a beam according to their polarization state, for instance linear polarization at 0° ($\frac{1}{2}I+Q$) and at 90° ($\frac{1}{2}I-Q$). By simultaneously measuring the intensity of both beams, the polarization degree Q/I is obtained from $\frac{I^L-I^R}{I^L+I^R}$, L and R denoting the left and right beam. However, spurious signals can be introduced by differential transmissions and aberrations between the two optical systems and by gain table effects in both images by inaccurate flat fielding.

2. *Temporal modulation.* The observable polarization direction is converted to the fixed linear polarization direction of a regular polarizer by a retarder. This would be a half-wave plate (HWP) for modulation of Stokes Q and U, and a quarter-wave plate (QWP) in case of circular polarimetry (Stokes V). The modulation is obtained by rotating the wave plate. The modulated intensity is recorded sequentially at one image plane and therefore the obtained degrees of polarization are independent on gain table effect. However, such a scheme is prone to spurious signals introduced by varying sky transmission, seeing and drifts in the optical system, unless the modulation can be performed at kHz rates, like for the ZIMPOL system [**?**].

Both methods have considerable disadvantages and are known to be limited in sensitivity at the $\sim 10^{-3}$-level by the discussed systematic errors. It was shown [34] that a combination of the two modulation techniques is insensitive to all these noise sources to first order. In this "beam-exchange technique" a dual beam system is also modulated in time by a rotating wave plate. By taking ratios of the four intensity measurements as in equation 2.1, a very sensitive determination of the polarization degree of one Stokes parameter $X = Q, U, V$ is obtained, e.g. [16].

	L	R
$t = 1$	$S = \frac{1}{2}(I + X)$	$S = \frac{1}{2}(I - X)$
$t = 2$	$S = \frac{1}{2}(I - X)$	$S = \frac{1}{2}(I + X)$

$$\frac{1}{4}\left(\frac{S_1^L}{S_2^L}\frac{S_2^R}{S_1^R} - 1\right) \approx \frac{1}{2}\left(\frac{X_1}{I_1} + \frac{X_2}{I_2}\right) \tag{2.1}$$

Using a rotating HWP and formula 2.1, it takes four sequential observations to determine $\frac{Q}{I}$ and $\frac{U}{I}$ (three parameters). A less time-consuming and equally efficient modulation scheme is obtained by rotating the HWP to positions 0° and ±30° with respect to the direction of $+Q$ and combining the three intensity measurements according to equations 2.2 and 2.3. This scheme is also equally well balanced against linear intensity variations with time.

	L	R
$t = 1$	$S = \frac{1}{2}(I + Q)$	$S = \frac{1}{2}(I - Q)$
$t = 2$	$S = \frac{1}{2}(I - \frac{1}{2}Q + \frac{1}{2}\sqrt{3}U)$	$S = \frac{1}{2}(I + \frac{1}{2}Q - \frac{1}{2}\sqrt{3}U)$
$t = 3$	$S = \frac{1}{2}(I - \frac{1}{2}Q - \frac{1}{2}\sqrt{3}U)$	$S = \frac{1}{2}(I + \frac{1}{2}Q + \frac{1}{2}\sqrt{3}U)$

$$\frac{1}{4}/\frac{1}{2}\sqrt{3}\left(\frac{S_2^L}{S_3^L}\frac{S_3^R}{S_2^R}-1\right) \approx \frac{1}{2}\left(\frac{U_2}{I_2}+\frac{U_3}{I_3}\right) \tag{2.2}$$

$$\frac{1}{6}\left(\frac{S_1^L}{S_2^L}\frac{S_2^R}{S_1^R}+\frac{S_1^L}{S_3^L}\frac{S_3^R}{S_1^R}-2\right) \approx \frac{1}{6}\left(4\frac{Q_1}{I_1}+\frac{Q_2}{I_2}+\frac{Q_3}{I_3}\right) \tag{2.3}$$

The proposed polarimetric extension for HARPS actually consists of two separate beam-exchange polarimeters: one circular polarimeter consisting of a rotating QWP and a polarizing beam-splitter and one linear polarimeter consisting of a rotating HWP and an identical polarizing beam-splitter. The optical design is presented in figure 2.1.

Both polarimeters can be positioned into the beam by the Iodine slider. One additional mechanism needs to be added to drive the rotation of both wave plates by a belt. They can be rotated together since only one polarimeter can be active at any given time.

The amount of defocus caused by the planar components of the polarimeter can be compensated for by moving back M2 by ~ 2 mm.

Wave plates

Wave plates are by nature chromatic. However, several techniques exist to significantly reduce the chromatism by stacking retarder plates from different materials and/or with different orientations. We choose "superachromatic" HWPs and QWPs from AstroPribor [2] which are manufactured from five zero-order polymer retarder films [33] (a double-Pancharatnam design). Two such superachromatic QWPs and two HWPs have already been purchased by the consortium. The deviations of the retarder value and the fast axis orientation from ideal values are measured to be $\pm 3°$ and $\pm 2°$ respectively for all wave plates over the entire wavelength range.

The substrate material for the wave plates is fused silica, which is known to be very resilient against stress birefringence.

Polarizing beam-splitter

No solution was found for a single off-the-shelf polarizing beam-splitter that could separate and focus the beams onto the two fibers and ensure an overall polarimeter design that would fit in the volume space of the Iodine cell. Therefore, custom components are being manufactured by Halle. The splitting according to perpendicular linear polarization states is performed by a Foster prism [3], a modified Glan-Thompson prism which also transmits the reflected beam at a 45° angle. The extinction ratios for a Foster prism are typically $\sim 10^{-6}$ for the transmitted beam and $\sim 10^{-3}$ (380 nm) -10^{-4} (690 nm) for the reflected beam. The straight-through beam suffers from crystal astigmatism, which is compensated by a fused silica cylindrical lens on the Foster prism's exit face.
A second prism out of CaF_2 guides the light of the second beam into the second fiber. This prism's function is fourfold:

1. It reflects the beam through 135° with a total internal reflection (TIR).
2. The TIR and the material choice maximizes the transmission of the second beam.
3. It compensates for the focal shift between the two beams due to the additional path length.
4. The precise prism positioning allows for fine-tuning of the beam separation.

[2] http://www.mao.kiev.ua/astropribor/

[3] http://www.b-halle.de http://www.b-halle.de/EN/Catalog/Polarizers/Foster_Polarizing_Beamsplitters.php

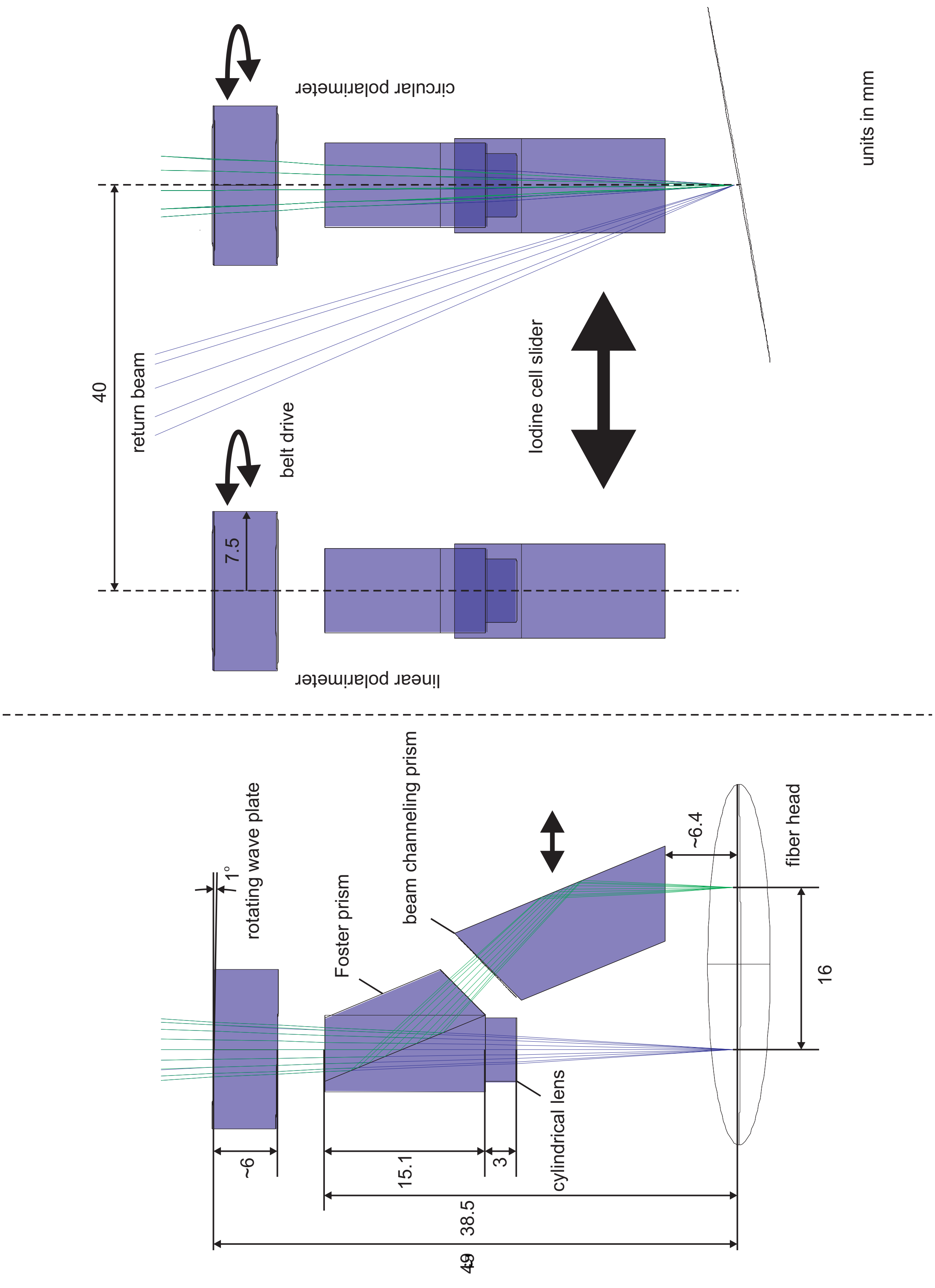

Figure 2.1: Optical design for the HARPS polarimeter. The individual components are discussed in the text.

Instrumental polarization

Positioning the polarimeter in the Cassegrain focus is polarimetrically the optimal situation, since the instrumental polarization due to M1 and M2 is negligible for symmetry reasons and no other oblique reflection is present as would be the case for a Nasmyth instrument. The only potential sources of instrumental polarization are the atmospheric dispersion corrector (ADC) and the polarimeters themselves. The ADC is expected to introduce a small amount of linear polarization due to its small-angle refractions ($\sim 0.3\%$ from the ZEMAX model) which depends on the zenith angle and some linear$\leftrightarrow$circular polarization cross-talk due to inherent and mechanical stress birefringence. The ADC can be taken out in order to absolutely minimize the instrumental polarization. This is at the expense of limiting the observation to targets close to zenith or at the expense of spectral range. By accurately pointing into the dispersed stellar image, a certain wavelength range may be selected.

The instrumental polarization due to the polarimeters is due the deviations from the ideal values of the QWP and the HWP. All these effects are to be taken out by calibration, see section 2.3.5. The angle of $+Q$ can be freely chosen and is defined here as the polarization direction transmitted straight-through by the Foster prism. Since the 3.6 m host telescope has an equatorial mounting, the angle of $+Q$ on the sky is invariant.

Demodulation

There are two ways to demodulate the signals in time. The first way is to read out the entire CCD containing the spectra from both fiber at one modulation time-step. Not only does the read-out cycle take a considerable amount of time (> 10 s), but also it takes a long time to build up sufficient S/N for one modulation step. This has as a result that the two or three modulation step are separated in time by possible more than 10 minutes. A highly variable source or highly variable seeing can therefore degrade the observation.

A second option for demodulation is to store the 2×2 spectra on the CCD and interleave the two modulation states in time. For example:

1. A short exposure is made at wave plate position #1.
2. All charges on the CCD are shifted by an amount n in the spatial dimension.
3. A short exposure is made at wave plate position #2.
4. All charges on the CCD are shifted back by an amount n in the other direction.

This procedure is repeated until sufficient S/N is obtained in all spectra. This on-chip demodulation needs a modification to the camera interface, since charges are moved around in both directions without reading out the CCD. Specific care has to be taken against overlapping of the spectra and the double influence of stray light. Calibration spectra from HARPS with Tungsten illumination on both fibers show that no overlapping occurs anywhere on the CCD for $n = 8$ and that the stray light contribution is $< 1\%$. This demodulation scheme is not possible with the three-step scheme of equations 2.2 and 2.3.

The polarimetric technique has been shown to reach the required sensitivity [16]. The separate components are based on proven technologies and therefore pose no significant risk. With a minimal amount of instrumental polarization, calibration routines do not have to be very intricate in order to reach the required accuracy.

2.1.3 Optical performance

The spot diagrams of both beams of the polarimeter from the ZEMAX model are given in figure 2.2 for the full wavelength range. The glasses were chosen such that the spot diagrams in both beams were similar. It is clear that the true spot size (and therefore the fiber coupling efficiency) is determined by the seeing. It has to be investigated whether certain seeing conditions cause variable fiber coupling efficiencies between both beams.

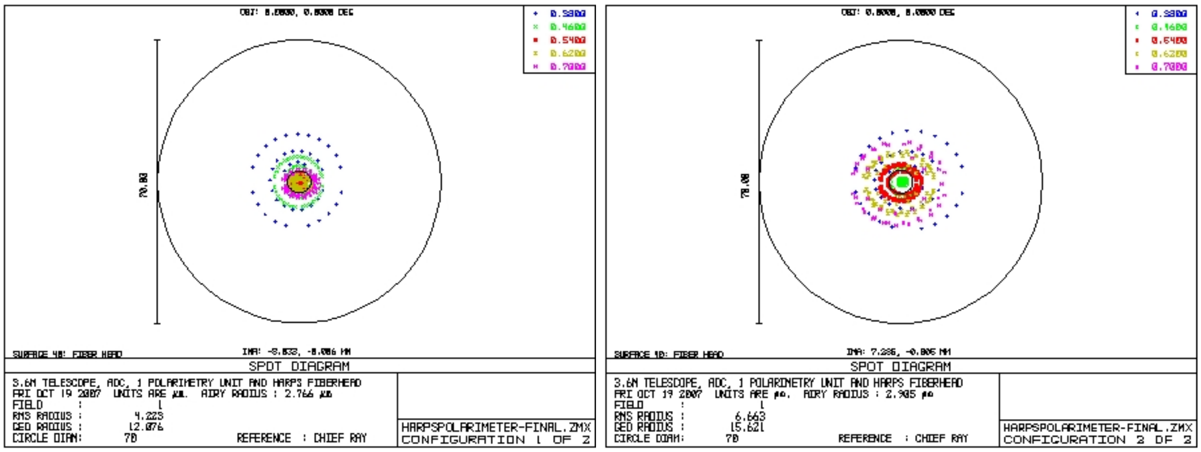

Figure 2.2: Spot diagrams from ZEMAX for the optical design of figure 2.1. Left image: the beam transmitted through the Foster prism. Right image: the beam reflected within the Foster prism. The inner circles represent the Airy disks; the outer circles represent the fiber core size. Note that the light collection area of the fiber head is enlarged by a microlens.

With a high-resolution spectrograph like HARPS particular care has to be taken not to introduce fringes due to multiple reflections. When multiple reflections occur within birefringent media, these fringes also become polarized. The following design choices have been made in order to minimize intensity and polarized fringes.

1. The wave plates consist of thin polymer layers. Therefore the cavity length for internal reflections is minimal and the reflectivity of the layer interfaces is reduced because of the nearly matched indices of refraction. It is observed that such wave plates reduce the polarized fringe pattern down to an amplitude of $< 10^{-3}$ [20].

2. The wave plates are so thin that they can be mounted at a tilting angle of 1°. This avoids a multiple reflection between the wave plates' exit face and the Foster prism's entrance face.

3. The entrance face of the beam-channeling prims is wedged by 1° for the same reason.

2.2 Mechanical design

The proposed polarimeter will replace the existing iodine cell unit which is inserted at the side of the HARPS Cassegrain Fiber Adapter (HCFA) of the 3.6m telescope. The new unit consists of a slider (practically identical to the one move the iodine cell) with three positions: no beam splitter (all current HARPS operation modes except those involving the iodine cell), first beam splitter is in the beam (circular polarization) and second beam splitter is in the beam (linear polarization). Figure 2.3 shows the CAD view of the polarimeter. The switch between modulations of polarization is achieved by rotating the retarder plates located above beam splitters into one of the preset positions. The retarders are moved by a belt drive rotating both plates with a single motor. The accuracy and repeatability of the drive

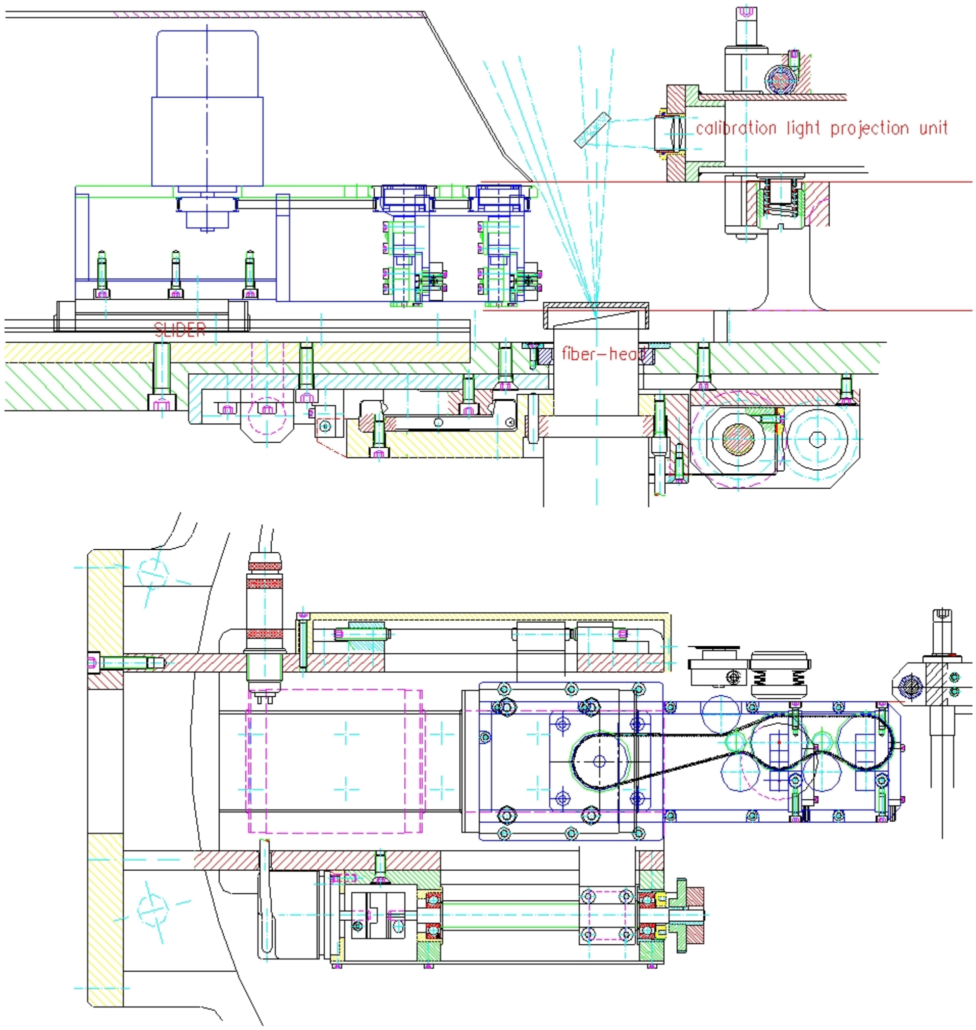

Figure 2.3: Upper panel: side view of the central part of the Cassegrain adapter with the polarimeter removed from the beam. Lower panel: top view of the central part of the Cassegrain adapter with one the beam splitters in the beam sending light into two fibers.

required to reach the specified polarization precision are achieved by installing the encoder on the motor axis and restricting the motion to one direction.

Critical design goal is the efficiency of fiber coupling in the situation when fibers are not rigidly attached to a beam splitter unit. The proposed optical solution allows to achieve this goal by requesting that he separation and the orientation of the two emergent beams are fixed. This drives the requirement of the rigidity against rotation in he plane of the table to be <10". The separation of the two beams is tuned by a linear table during commissioning, see below. The positioning of the star of the ordinary beam onto the fiber is ensured by spill-over guiding on the return beam. The off-axis guiding system the keeps the star on its position. The rigidity requirement in combination with the stiffness of the slider ensures stability of the optical axis. The orientation requirement of ¡30" is trivially met by the proposal mechanical solution.

The polarimeter unit replaces the iodine cell and during conventional operations is retracted into the parking position not affecting HARPS observations in any way. During polarization measurements one of the beam splitters is inserted in to the beam between the fiber head and the 45deg mirror of the calibration light projection unit.

Mechanically polarimeter unit consists of a flange to be mounted on the HCFA in place of the iodine cell. This flange carries a slider performing translation motion of the beam splitter encloser.

The slider mechanism (a THK linear guide system model 2RSR15WC1+190LH-1) can be moved into any of the three preset positions: parking, linear and circular polarizations. The slider is similar to the one described in 3.1.2 of HCFA and Calibration Unit Design, Analysis and Performance Report, Doc. Nr. 3M6-TRE-HAR-33106-0002. The drive consists of a Faulhaber 24 V DC-motor (8000 R/min) with attached tacho generator and a gear unit (43:1). A standard preloaded ball screw spindle (2 mm pitch), which is free of backlash is driven by two gear wheels. The one on the motor shaft is equipped with a friction coupling. A Heidenhain incremental encoder (1000 lines) is connected directly to the ball screw (spindle). The nut of the spindle attaches the carriage to the THK linear guide by a spring steel tappet eliminating backlash. The speed of positioning is 6 mm/sec and the repeatability is 10 μ. The two mechanical stops and the two precision limit switches MY-COM B50/80 [4] are mounted on both sides of the carriage. Precision limit switches are activated before the stops are reached and the remaining kinetic energy of the motor will be absorbed by the friction coupling. One of the limit switches is used as initialization switch.

At any of the three positions a cut-off voltage (about 1 V) as applied to keep the carriage in place. The voltage is lower than the nominal driving voltage ensuring no excessive heat inside the HCFA during the observations but sufficient for keep the position carriage fixed. The proposed design permits the guiding camera to have an unobstructed view of the fiber head at all 3 fixed positions of the slider.

The beam splitter enclosure installed on the carriage houses two optical tables and the retarder plate rotation mechanism. In the current version the beam splitter encloser consists of the bottom flange, the walls parallel to the sliding direction and the cover. The bottom flange is attached to the rails of the slider and to a ball screw drive mechanism. The cover of the unit carries the belt drive rollers and the motor for rotating the retarder plates. The rigidity of the assembly is ensured by mounting the optical tables for the two beam splitters inside the encloser perpendicular to the sliding direction.

The rails attachments and ball screw mechanisms are preloaded to avoid backlashes and keep the orientation of the beam splitter encloser relative to the HCFA within a few arcseconds (< 10") at any orientation of the telescope.

Each of the optical assemblies is mounted on a separate optical table (see Figure 2.4. The mount provides fine adjustments for the alignment of the optical components relative to each other and relative to the encloser. These alignments will mostly be performed in the lab (hopefully once) and only fine corrections will have to be done on the telescope during the commissioning.

The two retarder plates (half-wave and quarter-wave) are used to change the orientation of linear

[4] http://www.baumerelectric.com

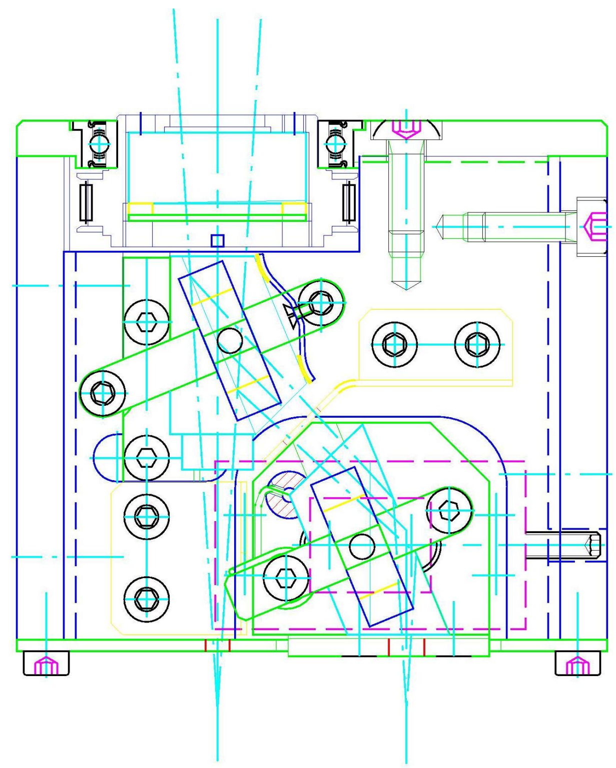

Figure 2.4: One of the optical tables carrying the retarder plate at the top and the beam splitter (Foster prism + beam channeling prism).

polarization or convert circular polarization to linear. Both plates are rotated simultaneously by a single stepping motor with a timing belt drive. The motor is a hybrid stepping motor 17PU-H301V with stepping angle of 3.75deg from NMB Technologies Co. [5]. The belt is polyurethane timing belt FTH-1 type (pitch 1 mm), which provides accurate positioning due to reduced backlash, higher carrying torque and smoother running [6].

The optical elements on each optical table (polarimeter) include a polarizing beam splitter (Foster prism + beam channeling prism) and a retarder plate. The ordinary beam continues along the original optical axis to the fiber head. The extraordinary beam is deflected to a beam channeling prism which corrects the focal length. It is also used for fine alignment of the beam with the second fiber. This is achieved with a manual linear stage MS-125X from Newport. Prisms are fixed in all directions on the optical table by spring-loaded support excluding mechanical and thermal stresses. Particular care is taken in order not to damage the fragile calcite Foster prism. The optical table also carries several baffles to minimize the amount of scattered light.

Due to a manufacturing error of the cylindrical lenses attached to the Foster prisms an additional 1 mm fused silica plate will be added to the ordinary beams of both polarimeters. This allows for an eventual fine-tuning of the focus difference compensation between the two beams. The plates will be positioned before the exit baffle of the ordinary beam, such that both light paths are closed against air circulation.

2.2.1 Stability of the Polarimeter

The thermal and mechanical stability of the polarimeter is achieved by high rigidity of the beam splitter enclosure, small weight of movable elements of the device and application of preloaded mechanisms such as THK linear guide system, ball screw spindle, linear stage MS-125X, which are completely free of backlash in any orientation.

The vibrations from the stepping motor rotating the retarder plates are expected to be insignificant as the polyurethane timing belt FTH-1 has the smallest possible pitch and the geometry of the belt allows smoother running. Moreover, the use of the stepping motor in a microstep mode dramatically reduces the amplitude of vibrations. During exposures motors are not running generating no vibrations.

Temperature changes will not affect the geometry of the polarimeter because the largest dimensions of the enclosure and the slider are 200 mm or smaller. The expansion coefficient for aluminum is 2×10^{-5} cm K-1 thus the maximum change of the whole unit is 4 micron per 1 degree perpendicular to the optical axis and less than 1 micron along the optical axis. The expansion perpendicular to the optical axis can compensated by the slider control and the necessity of such compensation will be further investigated.

2.3 Impact on HARPS

The proposed upgrade will affect the following areas:

- Optomechanics of the HCFA.
- Control electronics.
- Instrument control software.
- Operation, calibration and maintenance procedures.
- Instrument templates.

[5] http://www.nmbtc.com
[6] http://www.fennerprecision.com

The proposed upgrade is aimed at reaching highest polarization precision while minimizing the impact on the current HARPS operation as detailed below.

2.3.1 Changes to the HCFA

The optical and mechanical design confine the upgrade to a single compact module that fits in place of the existing iodine cell unit. No mechanical modifications to the CFA is needed and the change is fully reversible.

2.3.2 Changes to the control electronics

The polarization module has two precision moving functions: moving the beam splitters in and out of the beam and rotating the retarder plates. The first function is very similar to the slider of the iodine cell except that it has 3 positions: out, circular, linear. This function thus can be operated by the same MACCON controller that drives the iodine cell with a minor change to the software. The servo positioning accuracy of 0.01 mm is quite sufficient for the optical alignment. The rotation function uses a single motor and a belt drive to position the two retarder plates (see Section 2.3). The encoder will be installed on the axis of the motor and in combination a MACCON controller will provide the required resolution and repeatability. The circular function thus requires one additional MACCON controller to be installed in the HCFA rack. A separate signal cable will have to be installed to connect this controller with the polarimeter unit.

The interlock function between the iodine cell and the fiber dust cover remains needed. Due to mechanical and operational similarities between the iodine cell and the polarimeter unit no changes in the interlock functionality is anticipated.

The last new signal to be generated in the HCFA electronic rack is an identification bit signalling that the polarimeter unit is installed. The lack of such signal will correspond to the configuration with the iodine cell.

2.3.3 Changes to the ICS

Instrument control software should provide functionality of additional templates described in Section 2.3.6.

2.3.4 Changes to the operation, calibration and maintenance procedures

Two separate polarimetric modes will be added with the design of figure 2.1: circular spectropolarimetry and linear spectropolarimetry.

The sequencing for circular polarimetry is described by the formula 2.1:

1. Exposure with the QWP at +45°: $S^L = \frac{1}{2}(I+V)$, $S^R = \frac{1}{2}(I-V)$.
2. Exposure with the QWP at −45°: $S^L = \frac{1}{2}(I-V)$, $S^R = \frac{1}{2}(I+V)$.

The sequencing for linear polarimetry is either cf. equation 2.1:

1. Exposure with the HWP at 0° : $S^L = \frac{1}{2}(I+Q)$, $S^R = \frac{1}{2}(I-Q)$.
2. Exposure with the HWP at +45° : $S^L = \frac{1}{2}(I-Q)$, $S^R = \frac{1}{2}(I+Q)$.
3. Exposure with the HWP at +22.5°: $S^L = \frac{1}{2}(I+U)$, $S^R = \frac{1}{2}(I-U)$.
4. Exposure with the HWP at −22.5°: $S^L = \frac{1}{2}(I-U)$, $S^R = \frac{1}{2}(I+U)$.

Or to save time it can be performed cf. equations 2.2 & 2.3:

1. Exposure with the HWP at 0°.
2. Exposure with the HWP at +30°.
3. Exposure with the HWP at −30°.

Additional options that can be selected by the observer are:

- On-chip demodulation on/off.
- ADC in/out. This minimized the instrumental polarization at the expense of spectral range.
- X mode. This comprises the insertion of two different fibers with larger core size. This increases the light gathering power and there the S/N in the spectra at the expense of spectral resolution.
- ThAr source in/out (for calibration; see section 2.3.5)
- Tungsten source in/out (for calibration; see section 2.3.5)

2.3.5 Calibration plan

Despite a careful design, the accuracy of the polarimeter is limited by the accuracy of its calibration. The options for inserting additional calibration components are very limited. Therefore the following calibration approaches using the available components are considered.

Wavelength calibration

Using the beam-exchange technique, differences in wavelength sampling between the two beams as well as spectrograph drift are taken out to first order. Nevertheless ThAr reference spectra will be obtained on both fibers for acquiring the wavelength sampling in order to prevent spectral smearing after combining data from both beams.

Polarimetric calibrations

Both polarimeters will be carefully calibrated in the lab with standard calibration components and techniques during the AIT phase.

The most straightforward technique for calibrating the polarimeters and the instrumental polarization after commissioning is to observe standard polarized and unpolarized stars. Sufficient number of targets with known linear polarization are available [19]. Standard stars for circular polarimetry calibration are not available, since the magnetic fields that produce circular polarization through the Zeeman effect are highly variable. Induced polarization ($I \rightarrow Q, U, V$ cross-talk) is easily recognized as the polarization level of the continuum (provided the continuum is known to be unpolarized).

Another way of calibrating the polarimeters is to make use of the standard calibration components available for HARPS. Light from the ThAr or the Tungsten source can be inserted into the main beam (and therefore into both fibers) by a 45° mirror. Since such a reflection polarizes the light by several percent in the $-Q$ direction, this can be used to calibrate the linear polarimeter. The mirror also produces some cross-talk $U \rightarrow V$, so if the calibration light is to some degree (made to be) linearly polarized in the $\pm U$ direction, the calibration beam will be slightly circularly polarized, which can be used for the calibration of the circular polarimeter. The polarization properties of the mirror depend on the coating, which slowly degrades with time. But if the mirror has not been recently aluminized ($>$ 1 yr), its properties are to a large degree remain constant, provided it is kept clean from dust.

<table>
<tr><td>INS.OPTI2.NAME</td><td>HARPS|AUX</td><td>Fiber head selector</td></tr>
<tr><td>INS.OPTI3.NAME</td><td>IN|OUT</td><td>Fiber head dust cover</td></tr>
<tr><td>INS.ADCS.NAME</td><td>IN|OUT</td><td>Atmospheric dispersion corrector slide</td></tr>
<tr><td>INS.ADC1.MODE</td><td>OFF|AUTO</td><td>ADC prism 1</td></tr>
<tr><td>INS.ADC2.MODE</td><td>OFF|AUTO</td><td>ADC prism 2</td></tr>
<tr><td>INS.LAMP4.ST</td><td>T|F (ON|OFF)</td><td>THAR1 lamp</td></tr>
<tr><td>INS.LAMP5.ST</td><td>T|F (ON|OFF)</td><td>THAR2 lamp</td></tr>
<tr><td>INS.MIRR1.NAME</td><td>FIBA|BOTH|FIBB|NONE</td><td>Calibration mirror</td></tr>
<tr><td>~~INS.OPTI4.NAME~~</td><td>~~IN|OUT~~</td><td>~~I_2 cell~~</td></tr>
<tr><td>INS.OPTI7.NAME</td><td>CIRPOL|LINPOL|OUT</td><td>Polarimeter</td></tr>
<tr><td>INS.OPTI5.NAME</td><td>NONE|TUN1|SPARE|
~~I2CELL~~|THAR1|THAR2</td><td>Calibration lamp A selector</td></tr>
<tr><td>INS.OPTI6.NAME</td><td>NONE|TUN1|SPARE|
~~I2CELL~~|THAR1|THAR2</td><td>Calibration lamp B selector</td></tr>
<tr><td>INS.RET25.POS</td><td>0|22.5|30|45|60|67.5|90|112.5|120|135|
150|157.5|180|202.5|210|225|240|247.5|
270|292.5|300|315|330|337.5</td><td>Absolute position of the retarder plate 1</td></tr>
<tr><td>INS.RET50.POS</td><td>0|22.5|30|45|60|67.5|90|112.5|120|135|
150|157.5|180|202.5|210|225|240|247.5|
270|292.5|300|315|330|337.5</td><td>Position angle of the retarder plate 2</td></tr>
<tr><td>INS.RET.RPOS</td><td>0|22.5|30|45</td><td>Relative rotation of the selected retarder plate</td></tr>
<tr><td>INS.ROT1.POS</td><td>0-2.132 (0)</td><td>Neutral Density Filter Wheel</td></tr>
<tr><td>INS.LAMP1.ST</td><td>T|F (ON|OFF)</td><td>TUN1</td></tr>
<tr><td>~~INS.LAMP2.ST~~</td><td>~~T|F (ON|OFF)~~</td><td>~~Calibration I_2 cell lamp~~</td></tr>
<tr><td>~~INS.LAMP6.ST~~</td><td>~~T|F (ON|OFF)~~</td><td>~~Calibration I_2 cell heating~~</td></tr>
<tr><td>~~INS.LAMP7.ST~~</td><td>~~T|F (ON|OFF)~~</td><td>~~Scientific I_2 cell heating~~</td></tr>
<tr><td>DET1.WIN1.UIT1</td><td><Range></td><td>Exposure time (sec)</td></tr>
<tr><td>SEQ.NEXPO</td><td>1-100</td><td>Number of Repeated exposures</td></tr>
<tr><td>DET1.READ.SPEED</td><td><mode></td><td>CCD Readout mode</td></tr>
<tr><td>DET1.EXP.TYPE</td><td>NORMAL|DARK</td><td>Exposure type</td></tr>
</table>

Table 2.1: The different devices that can be operated via templates and the corresponding ICD keywords.

Stray light calibration

Stray light contamination between the two signals and between the various spectral orders on the camera will also result in instrumental (de)polarization. It can be calibrated to some degree by examining a measurement with illumination from the Tungsten source (on both fibers).

2.3.6 HAPRS templates

In the description of the new templates we follow the ESO document 3M6-TRE-HAR-33110-0008, Issue 4. This document describes various operation modes of the HARPS in two general configurations: precision radial velocity mode "HARPS" and high-efficiency mode "EGGS". The opto-mechanical design of the polarimeter unit is incompatible with the high efficiency mode, therefore, only those "EGGS" templates that have I_2 cell off will be available (which is in fact a normal practice even today).

Templates are classified in four groups: acquisition templates, observation templates, calibration templates and maintenance templates. In the table 2.3.6 (equivalent to the Table 2.1 in the 3M6-TRE-HAR-33110-0008) we list the existing and the new interface control document keywords responsible for the moving parts in the HARPS and their values.

The retarder positioning system will be initialized every time the polarimeter is move from the parking

Template=TPL.NAME	INS.MODE	DPR.TECH	DPR.TYPE
HARPS_ech_acq_thosimult	"HARPS"	"ECHELLE"	"STAR,WAVE,<sp. type>"
~~HARPS_ech_acq_I2cell~~	~~"HARPS"~~	~~"ECHELLE, ABS..._CELL"~~	~~"STAR,DARK,<sp. type>"~~
HARPS_ech_acq_cirpol	"HARPS"	"ECHELLE, CIRPOL"	"STAR,<sp. type>,<ret. angle>"
HARPS_ech_acq_linpol	"HARPS"	"ECHELLE, LINPOL"	"STAR,<sp. type>,<ret. angle>"
HARPS_ech_acq_objA	"HARPS"	"ECHELLE"	"STAR,DARK,<sp. type>"
HARPS_ech_acq_objAB	"HARPS"	"ECHELLE"	"STAR,SKY,<sp. type>"
HARPS_eggs_acq_thosimult	"EGGS"	"ECHELLE"	"STAR,WAVE,<sp. type>"
~~HARPS_eggs_acq_I2cell~~	~~"EGGS"~~	~~"ECHELLE,ABS..._CELL"~~	~~"STAR,DARK,<sp. type>"~~
HARPS_eggs_acq_objA	"EGGS"	"ECHELLE"	"STAR,DARK,<sp. type>"
HARPS_eggs_acq_objAB	"EGGS"	"ECHELLE"	"STAR,SKY,<sp. type>"

Table 2.2: The values of the data product keywords generated by the acquisition templates. The keywords describe the light source and the light path.

position into the beam and remembered while the polarimeter is in. The rotation of the retarder plates is not interfering with the movement of the polarimeter carriage and therefore those two motions can be combined to improve the duty cycle.

Acquisition templates. The acquisition templates are used for fully configuring the HARPS before the science exposure starts. There will be a set of five (currently it is four) templates for high precision HARPS mode:

1. Acquisition for accurate RV measurement (acq_thosimult)
2. ~~Acquisition for spectroscopy with I2 (acq_I2cell)~~
   Acquisition for circular spectropolarimetry (acq_cirpol)
3. Acquisition for linear spectropolarimetry (acq_linpol)
4. Acquisition for spectroscopy of object only on fiber A (acq_objA)
5. Acquisition for spectroscopy of object on fiber A and sky on fiber B (acq_objAB).

In the "EGGS" mode neither the polarimeter not the Iodine cell will be available thus the number of acquisition templates will be reduced to three:

1. Acquisition for accurate RV measurement (acq_thosimult)
   ~~Acquisition for spectroscopy with I2 (acq_I2cell)~~
2. Acquisition for spectroscopy of object only on fiber A (acq_objA)
3. Acquisition for spectroscopy of object on fiber A and sky on fiber B (acq_objAB).

Each acquisition template defines and stores in the instrument database four keywords TPL.NAME, INS.MODE, DPR.TECH and DPR.TYPE, containing the type of observation and the information regarding the objects seen by the fibers. The observation templates recover from the ICSDB these values, and insert them to the FITS header of the data frames. Table 2.3.6 illustrates the changes to the keyword values used by the acquisition templates with the proposed upgrade. Note that we plan to follow the existing operation logic of HARPS leaving minimum of configuration function to the observation templates.

Observation template. The complete configuration of the instrument is done by the acquisition template. Currently the only instrument function that could be adjusted at this stage is the ThAr lamp attenuator whose value is function of the exposure time and of the instrument mode. There is only one observation template per mode ("HARPS" or "EGGS"), whose goal is to define the exposure characteristics and to launch it. With an addition of the polarization mode we will ne be able to use simultaneous ThAr calibration but we will use sequences of exposures for different position of the retarder plate. Thus we propose to introduce a new observing template HARPS_polarim_obs_all that is capable of initiating a number of exposures adjusting the retarder position during detector readout.

Calibration templates. The calibration templates set provides exposures to fully characterize HARPS and to obtain the best quality reduction of science exposures. The following templates existing today are fully sufficient (see Section 2.3.5) for the reduction of the polarization data:

1. Calibration of detector bias (cal_bias).
2. Calibration of detector dark current (cal_dark).
3. Calibration exposures for fiber A and B orders geometry taken separately (cal_tun).
4. Calibration exposure for spectral flat field for both fibers (cal_tunAB).
5. Calibration exposure of tungsten lamp in free settings (cal_tunUSER).
6. Calibration exposure for wavelength calibration (cal_thoAB).
7. ~~Calibration exposure of continuum lamp with I_2 (cal_tunAI2).~~

Template cal_tunAI2 will not be functional and will not be needed when the polarimeter is installed.

Maintenance templates. The proposed polarization upgrade of the HARPS does not require any additional maintenance templates. The existing once can used for periodic verification of the zero point for the retarder plates and the optimal positioning of the polarimeters in the beam.

2.3.7 New templates

Acquisition templates

The two new acquisition templates HARPS_ech_acq_cirpol and HARPS_ech_acq_linpol will be available to the observers in order to create their OBs in the HARPS instrument mode only! We rely on the same mechanism as the existing HARPS acquisition templates, namely, that the new template will store its name in the instrument database, where it will then be found by the observation templates.

HARPS_ech_acq_cirpol

This template is similar to the existing HARPS_ech_acq_I2cell in that it requires to insert an extra device in to the telescope beam and that this device will change the focus and the position of the target on the fiber(s).

TPL.NAME	"HARPS_ech_acq_cirpol"	Observation mode
DPR.TECH	"ECHELLE,CIRPOL"	Observation technique
DPR.TYPE	"STAR,<sp>,<angle>" (G2V,45)	Object, sp. type and retarder angle
INS.MODE	"HARPSpol"	Instrument mode
TEL.TARG.RADVEL	radvel ("NONE")	Target radial velocity (why is it here?)

The three first keywords are stored in the ICS online database. After the telescope preset to the specified RA and DEC, the polarimeter "1" is inserted. The insertion will modify the focus of the telescope and the position of an already centered star.

INS.OPTI7.NAME	"CIRPOL"	Circular polarization

The target is acquired, then the optical paths are setup to have the target in one circular polarization in fiber A and the opposite polarization in fiber B.

INS.RET25.POS	<retarder angle>	Retarder position

The retarder plate is positioned in one of the preset positions from 0deg to 360deg with a step of 22.5deg, the image of the fiber entrance taken with a technical CCD is saved, then a pop-up window asks the operator to verify star centering/focusing and start guiding.

HARPS_ech_acq_linpol

This template nearly identical to the HARPS_ech_acq_cirpol described above.

TPL.NAME	"HARPS_ech_acq_cirpol"	Observation mode
DPR.TECH	"ECHELLE,LINPOL"	Observation technique
DPR.TYPE	"STAR,<sp>,<angle>" (G2V,0)	Object, sp. type and retarder angle
INS.MODE	"HARPSpol"	Instrument mode
TEL.TARG.RADVEL	radvel ("NONE")	Target radial velocity

The three first keywords are stored in the ICS online database. After the telescope preset to the specified RA and DEC, the polarimeter "2" is inserted. The insertion will modify the focus of the telescope and the position of an already centered star.

INS.OPTI7.NAME	"LINPOL"	Linear polarization

The target is acquired, then the optical paths are setup to have the target in one circular polarization in fiber A and the opposite polarization in fiber B.

INS.RET50.POS	<retarder angle>	Retarder position

The retarder plate is positioned in one of the preset positions from 0deg to 360deg with a step of 22.5deg, the image of the fiber entrance taken with a technical CCD is saved, then a pop-up window asks the operator to verify star centering/focusing and start guiding.

The parameters to be included in the corresponding .ref and .tsf files are listed in Table 2.3.7.

Observation templates

HARPS_polarim_obs_all.

The sequence described by this template is very similar to the existing HARPS_ech_obs_all. The template reads the observation mode back from the ICS online database, where it was stored as the name of the acquisition template. The keyword TPL.NAME is then constructed to give a pseudo observation template name HARPS_polarim_obs_XXXX, where XXXX is the last extension of the acquisition template name.

TPL.NAME	"HARPS_polarim_obs_XXXX"	Observation mode

The DPR.TECH and the DPR.TYPE keywords are also read in and passed to the OS, in order to inform the DRS about the kind of object acquired by the acquisition template, as well as the technique of observation. The DPR.CATG is set to "SCIENCE".

HARPS_ech_acq_cirpol.tsf		
Parameter	Range (Default)	Label
DPR.TYPE	"STAR,<sp>,<angle>" (G2V,0)	Objects Type, Spectral Type and retarder angle
TEL.TARG.RADVEL	radvel ()	Target Radial Velocity
TEL.TARG.ALPHA	ra (000000.0)	Target R.A.
TEL.TARG.DELTA	dec (-850000.0)	Target Decl.
TEL.TARG.EQUINOX	year (2000.0)	Coordinates Equinox
TEL.TARG.PMA	pm ra (0 arcsec/year)	Alpha Proper Motion
TEL.TARG.PMD	pm dec (0 arcsec/year)	Delta Proper Motion

HARPS_ech_acq_cirpol.ref		
Parameter	Value	Label
INS.MODE	HARPSpol	Instrument Mode
TPL.NAME	HARPS_ech_acq_cirpol	Observation Mode
DPR.TECH	ECHELLE,CIRPOL	Observation Technique
INS.MIRR1.NAME	FIBB	Calibration Mirror
INS.OPTI2.NAME	HARPS	Fiber Head Selector
INS.OPTI3.NAME	OUT	Fiber Head Dust Cover
INS.OPTI4.NAME	IN	Circular polarimeter
INS.OPTI6.NAME	NONE	Calibration Lamp B Selector
INS.OPTI7.NAME	CIRPOL	Circular polarization

HARPS_ech_acq_linpol.tsf		
Parameter	Range (Default)	Label
DPR.TYPE	"STAR,<sp>,<angle>" (G2V,0)	Objects Type, Spectral Type and retarder angle
TEL.TARG.RADVEL	radvel ()	Target Radial Velocity
TEL.TARG.ALPHA	ra (000000.0)	Target R.A.
TEL.TARG.DELTA	dec (-850000.0)	Target Decl.
TEL.TARG.EQUINOX	year (2000.0)	Coordinates Equinox
TEL.TARG.PMA	pm ra (0 arcsec/year)	Alpha Proper Motion
TEL.TARG.PMD	pm dec (0 arcsec/year)	Delta Proper Motion

HARPS_ech_acq_linpol.ref		
Parameter	Value	Label
INS.MODE	HARPSpol	Instrument Mode
TPL.NAME	HARPS_ech_acq_linpol	Observation Mode
DPR.TECH	ECHELLE,LINPOL	Observation Technique
INS.MIRR1.NAME	FIBB	Calibration Mirror
INS.OPTI2.NAME	HARPS	Fiber Head Selector
INS.OPTI3.NAME	OUT	Fiber Head Dust Cover
INS.OPTI4.NAME	IN	Circular polarimeter
INS.OPTI6.NAME	NONE	Calibration Lamp B Selector
INS.OPTI7.NAME	LINPOL	Circular polarization

Table 2.3: The parameters to be included in the Template Signature Files and the Reference Setup Files for the new acquisition templates.

HARPS_polarim_obs_all.tsf		
Parameter	Range (Default)	Label
SEQ.NEXPO	1-100 (1)	Number of Repeated Exposures
DET1.WIN1.UIT1	seconds (0)	Exposure Time (sec)
DET1.READ.SPEED	<mode>	CCD ReadOut Mode
INS.RET.RPOS	0|22.5|30|45	Rotation of the retarder plate between exposures

HARPS_polarim_obs_all.ref		
Parameter	Value	Label
INS.MODE	HARPS	Instrument Mode
DPR.CATG	"SCIENCE"	Observation Category
DET1.EXP.TYPE	NORMAL	Exposure Type
DET1.EXP.NREP	1	Number of Exposures
DET1.WIN1.BINX	1	Binning factor along X
DET1.WIN1.BINY	1	Binning factor along Y
INS.ADCS.NAME	IN	Atmospheric Dispersion Corrector Slide
INS.ADC1.MODE	AUTO	Atmospheric Dispersion Corrector Prism 1
INS.ADC2.MODE	AUTO	Atmospheric Dispersion Corrector Prism 2

Computed by HARPS_polarim_obs_all.seq		
Parameter	Value	Label
TPL.NAME	HARPS_polarim_obs_XXXX	Observation Mode
DPR.TECH	"<obs. technique>"	Observation Technique
DPR.TYPE	"<obj>,<sp>,<angle>"	Object, Spectral Type and retarder angle
INS.ROT1.POS	0-2.132 (0)	Neutral Density Filter Wheel

Table 2.4: The parameters to be included in the Template Signature Files, the Reference Setup Files and passed to the sequencer script for the new observation template.

DPR.CATG	"SCIENCE"	Observation category
DPR.TECH	"<obs. technique>"	Observation technique
DPR.TYPE	"<objA>,<sp>,<angle>"	Objects, sp. type and retarder angle
INS.MODE	"HARPSpol"	Instrument mode

The exposure parameters set are: Exposure Type (set to NORMAL for the scientific exposures), CCD ReadOut Mode (according to second column of table 4.1 in 3M6-TRE-HAR-33110-0008), Exposure Time, Number of Repeated Exposures and retarder plate rotation increment.

DET1.EXP.TYPE	NORMAL	Exposure Type
DET1.READ.SPEED	<mode>	CCD ReadOut Mode
DET1.WIN1.UIT1	<exptime>	Exposure Time (sec)
SEQ.NEXPO	1-1000	Number of repeated exposures
INS.RET.RPOS	0|22.5|30|45	Rotation of the retarder plate between exposures

The parameters to be included in the corresponding .ref, .tsf and .seq files are presented in Table 2.3.7.

2.4 Operation, Calibration and Maintenance plan

We do not expect any major changes compared to the existing routines described in 3M6-PLA-HAR-33100-0005 (Issue 1.4). The operation procedures look to be straight forward do to the similarities with the Iodine cell unit. Special data reduction algorithms for polarization signal have been developed and tested by the members of the consortium and will be implemented is part of the HARPS pipeline. Although the exact details of the maintenance routines still have to be worked out they rely on standard calibration frames and on regular (but not often) observations of bright polarization standards. The analysis of these data and the corrections for the zero-points of the retarder plates (if needed) will be done off-line and we plan to automate this procedure as much as possible.

2.5 Project plan and schedule

02/2008 Critical mechanical design

03/2008 Preliminary electrical/electronic design

03/2008 Preliminary software design

04/2008 Formal ESO review

04/2008 Presentation to the STC for recommendation

07/2008 All mechanical parts received in Utrecht

07/2008 All electrical/electronic parts received in Utrecht

08/2008 Assembly, Integration

09/2008 Testing

10/2008 Shipping to La Silla

12/2008 Commissioning

01/2009 First science observations

Bibliography

[1] Alecian, E., Catala, C., Wade, G.A., et al. 2008, MNRAS, accepted, arXiv0712.1746

[2] Babel, J., & Montmerle, T. 1997, A&A, 323, 121

[3] Basri, G., Marcy, G. W., & Valenti, J. A. 1992, ApJ, 390, 622

[4] Bertout, C., Siess, L., & Cabrit, S. 2007, A&A, 473, L21

[5] Bouvier, J., et al. 2007, A&A, 463, 1017

[6] Braithwaite, J., & Spruit, H.C. 2004, Nature, 431, 819

[7] Braithwaite, J., & Spruit, H.C. 2004, Nature, 431, 819

[8] Cellino, A., Hutton, R. et al. 2005, Icarus, 179, 304

[9] Cuntz, M., Saar, S.H., & Musielak, Z.E. 2000, ApJ, 533, L151

[10] Donati, J.-F., Babel, J., Harries, T.J., et al. 2002, MNRAS, 333, 55

[11] Donati, J.-F., Paletou, F., Bouvier, J., & Ferreira, J. 2005, Nature, 438, 466

[12] Dobler, W., Stix, M., & Brandenburg, A. 2006, ApJ, 638, 336

[13] Donati, J.-F., Forveille, T., Cameron, A. C, Barnes, J. R., Delfosse, X., Jardine, M. M., & Valenti, J. A. 2006, Science, 311, 633

[14] Donati, J.-F., Catala, C., Landstreet, J. D., & Petit, P. 2006, Solar Polarization 4, ASP Conf. Series 358, 362

[15] Donati, J.-F., Howarth, I.D., Jardine, M.M., et al. 2006, MNRAS, 370, 629

[16] Donati, J.-F., Jardine, M.M., Gregory, S.G., et al. 2007, MNRAS, 380, 1297

[17] Donati, J.-F., Moutou, C., Farès, R., Bohlender, D., Catala, C., Deleuil, M., Shkolnik, E., Cameron, A.C., Jardine, M.M., Walker, G.A.H. 2008, MNRAS, in press

[18] Ferrario, L., & Wickramasinghe, D. 2006, MNRAS 367, 1323

[19] Heiles, C. *ApJ* **119**, pp. 923-927 (2000)

[20] Ikeda, Y., Akitaya, H., Matsuda, K., Kawabata, K.S., Seki, M., Hirata, R., & Okazaki, A. 2003, Proc. SPIE, 4843, 437

[21] Ip, W.-H., Kopp, A., & Hu, J.-H. 2004, ApJ, 602, L53

[22] Jeffers, S. V., Donati, J.-F., & Cameron, A. C. 2007, MNRAS, 375, 567

[23] Jeffers, S. V., Donati, J.-F. 2008, MNRAS, in press

[24] Kaper, L., & Fullerton, A.W. 1998, Cyclical variability in stellar winds, ESO Workshop

[25] Kochukhov, O., & Piskunov N., 2002, A&A, 288, 868

[26] Kochukhov, O., Bagnulo, S., Wade, G.A., et al. 2004, A&A, 414, 613

[27] Maeder, A., & Meynet, G. 2000, ARA&A, 38, 143

[28] Mestel, L. 2003, in Magnetic fields in O, B and A stars, ASP conference series vol. 305, p. 3

[29] Muzerolle, J., D'Alessio, P., Calvet, N., & Hartmann, L. 2004, ApJ, 617, 406

[30] Monin, J.-L., Menard, F., & Peretto, N. 2006, 446, 201

[31] Piskunov, N., & Kochukhov, O. 2002, A&A, 381, 736

[32] Piskunov, N. E., & Valenti, J. A. 2002, A&A, 385, 1095

[33] Samoylov, A.V., Samoylov, V.S., Vidmachenko, A.P., & Perekhod, A.V. 2004, Journal of Quantitative Spectroscopy & Radiative Transfer, 88, 319

[34] Semel, M., Donati, J.-F., & Rees, D.E. 1993, A&A, 278, 231

[35] Spanò, P., Leone, F., Bruno, P., Catalano, S., Martinetti, E., Scuderi, S. 2006, Mem. della Soc. Astron. Italiana Supp., 9, 481

[36] D. M. Stam; I. Aben; F. Helderman, 2002, JOURNAL OF GEOPHYSICAL RESEARCH, 107, D20

[37] Stelzer, B., Flaccomio, E., Montmerle, T., et al. 2005, ApJS, 160, 557

[38] Strassmeier, K. G., Hofmann, A., Woche, M. F., Rice, J. B., Keller, C. U., Piskunov, N. E., & Pallavicini, R. 2003, SPIE, 4843, 180

[39] Townsend, R.H.D., Owocki, S.P., & ud Doula, A. 2007, MNRAS, 382, 139

[40] Turcotte, S. 2003, in Magnetic fields in O, B and A stars, ASP conference series vol. 305, p. 199

[41] ud Doula, A., Townsend, R.H.D., Owocki, S.P. 2006, ApJ, 640, L191

[42] Wade, G.A., Donati, J.-F., Landstreet, J.D., Shorlin, S.L.S. 2000, MNRAS, 313, 823

[43] Wade, G. A., et al. 2005, A&A, 442, L31

[44] Weber, E.J., & Davis, L. 1967, ApJ, 148, 217

[45] Yang, H., Johns-Krull, C. M., & Valenti, J. A. 2007, AJ, 133, 73