Design of an adaptable Stokes polarimeter for exploring chromospheric magnetism

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Abstract

The chromosphere is a highly complex and dynamic layer of the Sun, that serves as a conduit for mass and energy supply between two, very distinct regions of the solar atmosphere, namely, the photosphere and corona. Inferring magnetic fields in the chromosphere, has thus become an important topic, that can be addressed with large-aperture solar telescopes to carry out highly sensitive polarimetric measurements. In this article, we present a design of a polarimeter for investigating the chromospheric magnetic field. The instrument consists of a number of lenses, two ferro-electric liquid crystals, a Wollaston prism, and a CCD camera. The optical design is similar to that of a commercial zoom lens which allows a variable f\# while maintaining focus and aberrations well within the Airy disc. The optical design of the Adaptable ChRomOspheric POLarimeter (ACROPOL) makes use of off-the-shelf components and is described for the 70 cm Vacuum Tower Telescope and the 1.5 m GREGOR telescope at Observatorio del Teide, Tenerife, Spain. Our design shows that the optical train can be separated into two units where the first unit, consisting of a single lens, has to be changed while going from the VTT to the GREGOR configuration. We also discuss the tolerances within which, diffraction limited performance can be

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achieved with our design.

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1. Introduction

The chromosphere couples the photosphere to the corona. It represents an important region in the solar atmosphere where nearly all of the mechanical energy that drives solar activity is converted into heat and radiation, with only a small fraction leaking through to heat the overlying corona and power the solar wind (Withbroe & Noyes, 1977). Several processes, such as wave propagation and dissipation (McIntosh & Judge, 2001), electrical currents (Judge & Centeno, 2008), and magnetic reconnection occur in the chromosphere, which regulate the mass and energy supply to the corona. However, the relative contribution of the individual processes, their dependence on local conditions, and the nature of non-thermal to thermal energy conversion, remains an open question. Thus, understanding the chromosphere and its magnetism is a significant necessity for explaining the corona and heliosphere (De Pontieu et al., 2014).

As the pressure scale height in the solar atmosphere is about 150 km (Durant, 1988), the chromospheric density is about four orders of magnitude lower than that in the photosphere. Subsequently, the Alfvén and sound speeds in the chromosphere necessitate measurements at high temporal and spatial resolution so as to resolve gas, plasma, and wave motions (Kano et al., 2012). Diagnosis of the chromospheric magnetic field is mainly done through spectro-polarimetry in spectral lines formed under non-LTE conditions (Socas-Navarro et al., 2000). More importantly, the chromospheric signature in these spectral lines is only evident in a narrow range around the line core, where the photon flux is only 10-20% of the continuum intensity. A polarimetric sensitivity of the order of $10^{-4}$ is required to detect weak chromospheric fields (Socas-Navarro, 2010). The extraction of the chromospheric magnetic field at high spatial and temporal res-
olution is quintessential to shed light into this complex region of the Sun and requires large-aperture solar telescopes with photon-efficient instruments. While the 4-m Daniel K. Inouye Solar Telescope (DKIST, previously ATST; Rimmele & ATST Team, 2008), and the 4-m European Solar Telescope (EST; Collados et al., 2013) are important steps in this direction, the former is presently under construction and it will be several years until the latter is realised. As Europe’s largest operational solar telescope, the 1.5-m GREGOR (Schmidt et al., 2012), at Observatorio del Teide, is pivotal for exploring chromospheric magnetism and on the verge of creating several important scientific milestones which will serve as a foundation for future large-aperture solar telescopes.

A design for a dual-beam polarimeter is presented in this article which will probe the chromospheric magnetic field using the Ca II infrared line at 854.2 nm. The aim of this work is to determine the feasibility of designing a single optical configuration that can modify the f# at the detector plane, analogous to commercial zoom lenses. In this article we discuss the design specifically for different input f-numbers corresponding to the 70 cm Vacuum Tower Telescope (VTT) and the 1.5 m GREGOR.

The organisation of this article is as follows: diagnostics for chromospheric spectro-polarimetry and some key scientific questions which could be addressed, are presented in Sects. 2 and 3, respectively. The instrument and its performance are described in Sect. 4, and the concluding remarks are highlighted in Sect. 5.

2. Diagnostics for chromospheric spectro-polarimetry

There are a number of spectral lines that can be used for chromospheric observations. The Hydrogen Hα Balmer line at 656 nm is historically significant and has been traditionally used for flare, spicule, and prominence/filament studies. Despite this, its interpretation is enormously challenging as the population of the excited \( n = 3 \) level is strongly dependent on the temperature and radiative conditions in the solar atmosphere, with quantitative estimates confined to simplistic assumptions such as the cloud model (Beckers, 1964).
prominent spectral lines are the Ca II H&K lines at 390 nm, the NaD line pair at 589 nm, the Mg I B2 at 517 nm, the He I D3 at 588 nm, the Ca II infrared triplet at 850 nm, and the He I infrared triplet at 1083 nm. The Ca II and He I infrared lines have gained considerable importance over the last decade due to sensitive polarimeters (references provided below) and the availability of standard inversion codes (Asensio Ramos et al., 2008; Lagg et al., 2009; Socas-Navarro et al., 2015) that provide physical parameters in the relevant part of the solar atmosphere.

The He I 1083 nm line forms through ionisation by coronal ultra-violet (UV) radiation, thus forming in a narrow region in the upper layers of the chromosphere (Mohler & Goldberg, 1956; Harvey & Sheeley, 1977; Venkatakrishnan et al., 1992; Fontenla et al., 1993). While the line is free from photospheric contamination, it is extremely weak in the quiet Sun. The Ca II infrared triplet on the other hand, has a low excitation potential of 1.69 eV and extends from the upper photosphere well into the chromosphere. For instance, at ±60 pm from the line core, one can probe the photosphere at a height of about 200 km which exhibits reversed granulation. The “knees” of the intensity profile at around ±30 pm sample the temperature minimum region, some 500 km above the continuum forming layer. The line core, representing heights of approximately 1300 km, is purely chromospheric (Leenaarts et al., 2009). Thus, the Ca II infrared line has the advantage, that it can be combined with photospheric observations to extract the stratification of physical parameters over a large height range in the atmosphere. The sensitivity of the Ca II infrared line to longitudinal and transverse magnetic fields has been recently studied by Quintero Noda et al. (2016) and the authors conclude that the line is mostly sensitive to the layers between log τ = 0 and log τ = −5.5, under the prescribed conditions in their model atmospheres.

Several instruments at various ground-based telescopes observe the He I infrared triplet. They are the Spectro-Polarimeter for Infrared and Optical Regions (SPINOR; Socas-Navarro et al., 2006), the Facility Infrared Spectropolarimeter (FIRS; Jaeggli et al., 2010), and the SOLIS Vector SpectroMagneto-
graph (VSM; Henney et al., 2006) at the National Solar Observatory (NSO), and the The Near-InfraRed Imaging Spectropolarimeter (NIRIS; Cao et al., 2012) at the Big Bear Solar Observatory. Observations in the Ca II infrared line are done with the Interferometric BIdimensional Spectrometer (IBIS Cavallini, 2006) and SPINOR at NSO, as well as with the CRisp Imaging SpectroPolarimeter (CRISP; Scharmer et al., 2008) at the Swedish Solar Telescope.

The 1.5-m GREGOR Infrared Spectrograph (GRIS; Collados et al., 2012) is routinely providing observations of the He I infrared triplet, in continuation to the Tenerife Infrared Polarimeter (TIP-I/II; Collados et al., 2007), which was operational at the adjacent 70 cm VTT for more than a decade. Our optical design for the polarimeter, allows it to be mounted at the VTT or GREGOR, which will provide a comprehensive coverage of the solar chromosphere and significantly reinforce the instrumentation capability of the two telescopes.

3. Scientific outlook

In this section, the usefulness of our instrument is briefly described for a few research areas in solar physics.

3.1. The 3D structure of sunspots

Understanding the thermal, magnetic, and kinematic structure of sunspots has been one of the frontier topics in solar physics. While the magnetic field can be inferred with high spatial resolution in the photosphere owing to large telescopes and sensitive polarimeters, the vector magnetic field is only known at a single height or as a function of optical depth. Puschmann et al. (2010) carried out a geometrical transformation for a small penumbral region, allowing physical quantities such as the electrical current density, helicity, Wilson depression, plasma $\beta$, etc. to be derived. However, to do the same for a full sunspot, one requires inverting spectral lines spanning a large height range in the solar atmosphere, so as to satisfy the condition of force balance between structures such as the umbra and penumbra, that are relatively depressed by
about 300 km (Mathew et al., 2004). The above underscores the importance of
the chromospheric magnetic field to extract basic physical quantities associated
with sunspots.

3.2. Spectro-polarimetry of PILs in complex active regions

Solar eruptions can be triggered through the emergence of flux which occur
when newly emerged magnetic fields appear in a region of pre-existing flux, often
in, or in close proximity to, a filament channel (Rust, 1972). This can lead to
the formation of a magnetic flux rope through bodily emergence (Low, 1996),
by reconnection within an emerged magnetic arcade (Manchester et al., 2004),
or by reconnection with the pre-existing flux (Kusano et al., 2012). The source
regions comprise highly sheared magnetic fields in the corona which overlie a
photospheric polarity inversion line (PIL; Martres et al., 1968; Hagyard et al.,
1990). These locations inevitably show a filament channel in the chromosphere
and often contain a filament or prominence in the corona above (Martin, 1998).
It is widely (but not universally) accepted that a filament represents a weakly
twisted magnetic flux rope holding the cool material (Mackay et al., 2010). The
formation and instability of a flux rope is a key element of storage-and-release
eruption models (van Tend & Kuperus, 1978; Forbes & Priest, 1995; Mackay &
van Ballegooijen, 2006; Kliem & Török, 2006).

Multi-wavelength observations offer the possibility to study the formation
of flux ropes at PILs through the process of flux emergence, especially in the
vicinity of active regions (ARs; Louis et al., 2014, 2015). The formation of
PILs in δ-spots (Balthasar et al., 2014), in particular, is highly interesting and
important because of the presence of strong magnetic fields that can store large
amounts of free magnetic energy, which can be impulsively released at the time
of flares. Combining the photospheric and chromospheric magnetic field allows
for accurate estimates of the free magnetic energy which can help constrain
existing flare models and in determining the processes which destabilise the
magnetic field at PILs.
3.3. Establishment of chirality in AR filaments

Chromospheric Hα observations often show filaments having a magnetic pattern of handedness or “chirality”. When the axial field is directed rightward, when viewed by an observer at the positive-polarity side, the filament is said to be ‘dextral’ (Zirker et al., 1997). On the other hand, if the axial field is directed leftward from the same perspective, the filament is called ‘sinistral’. Chae (2000) showed that filament chirality bears a close correspondence to the sign of magnetic helicity in ARs, wherein sinistral and dextral filaments had positive and negative magnetic helicity, respectively. Classifying filaments as sinistral or dextral requires identifying the orientation of bright and dark filament threads from EUV images. A combination of localised heating and energy transport along the field lines could render filament threads to appear in emission, which can only be confirmed using chromospheric spectro-polarimetry. Thus, it is necessary to determine the boundary conditions and small-scale instabilities that influence filament chirality which would be critical for understanding the relation of erupting filaments to CMEs, as well as to the magnetic structure and formation of AR filaments themselves.

4. Adaptable ChRomOspheric POLarimeter (ACROPOL)

The plate scale for post-focus instruments is determined by the telescope diameter and the pixel size of the detector. In order to convert the f# at the instrument plane to that at the detector, a pair of relay lenses are often used, where one serves as the collimator and the other as the imager. As is evident, this configuration is unique to the telescope diameter and f#, assuming the detector size remains unchanged. The concept of an Adaptable ChRomOspheric POLarimeter (ACROPOL) was introduced to explore the possibility of a design, wherein the above limitation could be overcome, with a single post-focus instrument. In other words, the optics in the instrument operate much the same way as commercial zoom lenses which allow a variable f# and plate scale. Fig. 1 shows the working of a simple zoom lens, in which the movement of one of the
Figure 1: Illustration of zoom lens principle. The zoom lens consists of several lenses, some of which can be moved back and forth to change the magnification. In this simple example the magnification is changed by moving the second lens L2 while maintaining focus at the image plane (IP). The red and blue lines correspond to different field points.

Figure 2: Block diagram illustrating the placement of ACROPOL in a general optical setup. The arrow indicates the direction of light. IFP and SFP refer to the instrument focal plane and spectrograph focal plane, respectively.

lenses (lens L2 in the figure) allows the f# to change while keeping the focal plane unaltered. Such a system is referred to as a parfocal system. Along with a number of lenses, ACROPOL comprises polarizing optics – two Ferroelectric Liquid Crystals (FLCs) as polarization modulators and a Wollaston prism (WP) to produce the orthogonal polarized components, and a CCD camera as
A number of requirements had to be met by the instrument. These included, diffraction limited performance, using off-the-shelf components, adaptability to an existing set-up, compactness, portability, and cost effectiveness. While ACROPOL is intended to operate at any existing solar facility, the design study presented here, was carried out for the GREGOR and VTT. Figure 2 shows the block diagram of the setup where ACROPOL will be deployed. This layout is common for both the VTT and the GREGOR. The instrument will be mounted at the spectrograph focal plane (SFP in Fig. 2), thus complementing the GREGOR Fabry-Pérot Interferometer (GFPI; Puschmann et al., 2012) and the Triple Etalon SOLar Spectrometer (TESOS; Tritschler et al., 2002), but nothing prevents it from being used at the focal plane of a 2-dimensional imaging spectrometer. The choice of using ACROPOL with a spectrograph is to keep the interfacing with the image scanning mechanism as simple and minimal as possible. We now proceed to describe the functionality of the individual components of ACROPOL.

4.1. Optics

The optical design of ACROPOL is intended for a range of plate scales without compromising the image quality, and the parfocal design should ensure that the focal plane of the detector remains unchanged. Table 1 summarises the telescope parameters and the design requirements. The inputs for the design are the wavelength of interest, field-of-view (FOV), magnification, detector size, and minimum separation between the two beams. The optical design was carried out using ZEMAX® for 854±1 nm and the ray diagrams are shown in Fig. 3. The design includes two configurations, one changing the f#33 beam to f#23 for the VTT, and the other converting an f#40 beam to an f#17 beam for GREGOR.

The telecentric beam from the spectrograph (SFP in Fig. 3) is re-imaged onto the detector using a number of lenses. A Wollaston prism (WP) is placed in the optical path to obtain both states of polarization simultaneously. Initially, we tried to use four or five lenses to vary the f# for different configurations, by sys-
### Telescope and Image Dimensions

|                          | VTT  | GREGOR |
|--------------------------|------|--------|
| Telescope diameter (mm)  | 700  | 1440   |
| f# at spectrograph slit  | 66   | 40     |
| Mag. between coll. and camera mirror | 0.5  | 1      |
| f# at instrument focal plane | 33  | 40     |
| FOV (")                 | 72   | 50     |
| Size of above FOV at instrument focal plane (mm) | 8.07 | 14.04 |
| f# at CCD focal plane    | 23   | 17     |
| Diffraction limit at 8542 Å (") | 0.31 | 0.15   |
| Image size on CCD (mm)   | 12.5 | 12.7   |
| Spatial sampling at CCD ("/pixel) | 0.15 | 0.102  |
| Separation between two beams (mm) | 0.85 | 0.6    |

### Dimensions of Optical Components

|                          | VTT  | GREGOR |
|--------------------------|------|--------|
| L1 focal length (mm)     | 40   | 63     |
| Edmund Optics            | 45801| 49797  |
| L2 focal length (mm)     | 50   | 50     |
| Edmund Optics            | 32478| 32478  |
| L3 focal length (mm)     | 60   | 60     |
| Edmund Optics            | 45128| 45128  |
| Tilt of WP (°)           | 24.5 | 24.5   |
| WP (mm)                  | 11×11| 11×11  |
| Thorlabs                 | WPA10| WPA10  |
| Distance between instrument focal plane and L1 (mm) | 34.5 | 64.7   |
| Combined focal length of L2 & L3 | 27.5 | 27.5   |
| Distance between L1 and WP | 43   | 43     |
| Distance between WP and L2/L3 | 11   | 11     |
| Distance between L2/L3 and sensor | 22.7 | 22.7   |

Table 1: Image dimensions and f# conversion using ACROPOL at the VTT and GREGOR. The stock numbers for the optical components have also been included.

Systematically adjusting the distance between the individual lenses. However, due to the small size of commercial off-the-shelf Wollaston prisms, and the separa-
Figure 3: Ray diagram of ACROPOL for the VTT (above) and GREGOR (below) configurations depicting, dual-beam polarimetry. The incident beam enters the optical train at the spectrograph focal plane (SFP) on the left. The ray propagation is along the $z$-axis and the $x$-axis is perpendicular to the plane of the paper. In the figure the wedge angle of the WP is rotated by $24.5\degree$ to produce the required separation of the ordinary and extra-ordinary rays and to avoid change in f# of the O and E rays. The rotation of the wedge angle w.r.t to the $y$-axis is only for illustration, whereas during alignment the WP will be rotated w.r.t to the $x$-axis for mounting purposes.

Diffraction limited performance could not be achieved. In the present design, diffraction limited performance could be achieved with only three lenses. However, one of the lenses has to be changed between the VTT and GREGOR configurations, while the position of all the remaining components remains unaltered.

The lenses are indexed L1, L2, and L3, with the suffix ‘V’ and ‘G’ reserved for the first lens L1, when used in the VTT and GREGOR configurations, respectively. All the lenses are off-the-shelf components from Edmund Optics with a diameter of 25 mm. The lenses L1V and L1G are achromatic doublets with a NIR II and MgF$_2$ coating, respectively. The lenses L2 and L3 are plano-convex, with a MgF$_2$ coating. All lenses have a scratch-dig of 40–20, as specified by the vendor. The average reflectivity of the lenses at 850 nm is less than 1.75%. The lenses L2 and L3 are separated by a distance of 0.3 mm and de-centred from the optic axis by 2 mm. The WP is at a distance of 40 mm from the lens L1 and the f# of the input beam to WP is more than 350 (i.e., the beam is nearly...
Figure 4: Simulation results showing anamorphism and its effect on the f# of a system consisting of a WP illuminated in a collimated beam, followed by a lens with a focal length of 100 mm. The WP is tilted from 0–30° in steps of 3° and the ratio of beam diameters along x and y-directions is measured to obtain the eccentricity of the beam for both E- and O-rays (left panel). The change in f# due to the anamorphic beam is shown on the right. In order to minimise the change in f-numbers of the O- and E-rays, the WP must be tilted by around 24°.

collimated). Thus, the combined unit of WP–L2–L3–Detector is common to both the VTT and GREGOR configurations that can be mounted together, while the lens L1 can be a separate unit that can be interchanged between the two configurations.

The WP from Thorlabs uses scatter-free α−BBO crystal as the substrate, with an extinction ratio greater than 100000:1, and a scratch-dig of 20–10. We selected this prism from different off-the-shelf components for the required beam separation in the image plane. The beam separation is 20° at 250 nm and 15° at 854 nm. The wedge angle of the WP is rotated by 24.5° with respect to the x-axis and it produces a separation of 0.85 mm and 0.6 mm between the two orthogonal beams for the VTT and GREGOR configurations, respectively. The rotation of the WP affects the f# of the O- and E-rays, thereby producing different magnifications in the two beams. This effect can be attributed to anamorphism (Fig. 4), wherein a WP in normal incidence causes the beam to be compressed along one direction (Simon, 1986). The effect of the rotation of
the WP, as shown in Fig. 3 is to mitigate the above effect. A preliminary analysis of the design for polarization measurements using ZEMAX, shows that there will not be any cross-talk between the $s$ and $p$ polarization states, irrespective of the rotation of the WP. However, this rotation reduces the transmittance nominally. This analysis excludes the effect of coating of the WP surfaces.

Figures 5 and 6 show the spot diagrams for different points in the FOV for the O- and E-rays for both configurations. As is evident, all the aberrations are well within the Airy disc and the design can be considered as diffraction-limited. Figure 7 shows that the $rms$ wavefront error is well within the diffraction limit, corresponding to a Strehl ratio of 0.82, for the FOV considered in the two configurations. The present optical setup would be useful for a range of input $f$-numbers varying from 25–40 and 30–50 for the VTT and GREGOR, respectively, with a change in the position of lens L1. The adaptability is also illustrated in Fig. 8 which shows the permissible FOV for different $f$-numbers and telescope diameters that satisfy the following two conditions, (i) the $f\#$ of the telescope-spectrograph system (i.e. at SFP) should be larger than 25, and (ii) the image size at SFP should be less than 14 mm. Using the above conditions, we arrive at $\Theta \times F < 48000$, where $\Theta$ is the FOV in arcmin and $F$ is focal length at SFP in mm. Our proposed design is applicable for any FOV and $f\#$ that satisfies the above condition, and will be nearly diffraction limited with a minor adjustment in the position of the first lens.

We also performed a tolerance analysis for our design. We set the following criteria for determining the tolerances, namely, the minimum beam separation should be 0.5 mm, the image size should be will within the detector size, the change in $f\#$ between O and E-rays should be minimal, and the performance of the lens system should be diffraction limited. With these conditions, we obtain the following tolerances. The permissible changes in tilt and de-centre of the individual components are $30^\prime$ and $\pm 1$ mm, respectively. The distance between the components, L1–WP and WP–L2, can vary around 10% of the actual value. The distance between L2 and L3 can be $\pm 0.2$ mm. All these changes affect the $f\#$ of the system, but equally for both the O and E-rays. The
tolerance for the WP rotation is $\pm 3^\circ$, which causes a change in the f# for both beams differentially. However, the consequent change in plate scales in less than $0''005$. The above tolerances imply that the setup can be easily aligned without compromising the performance of the system.

It is to be noted that, by changing L1 and its position, the WP-L2-L3-Detector unit can be utilised for another telescope with a different diameter. For example, using either L1V or L1G, and changing its position, the same setup can be used for a 1 m telescope with an f# varying from 20–50, and a FOV of $50''$ to $80''$. 

Figure 5: ZEMAX spot diagrams for the VTT configuration at 854 nm. The left and right panels correspond to the O- and E-rays, respectively.

Figure 6: Same as Fig. 5 but for the GREGOR configuration.
4.2. FLC Modulators

The choice of FLC modulators for ACROPOL is straightforward, as the instrument is intended for a single wavelength operation, similar to GRIS. One of the FLCs serves as a half-wave retarder while the other as a quarter-wave retarder. The switching time of around 0.1 ms is achieved by changing the orientation of the fast axis of the FLCs using a low DC voltage. With two orientations of each FLC, four sets of measurements yield the four Stokes parameters (Sánchez Almeida et al., 1994; Collados, 1999; del Toro Iniesta, 2007). The difference in orientation angles of the optical axis of the two states for both crystals is $45^\circ$. For a set of four measurements, the half-wave and quarter wave FLCs have duty cycles of 25% and 50%, respectively. Standard, mounted FLCs from Meadowlark Optics Inc. have a clear aperture of 17.8 mm and a thickness of 19.05 mm. Taking into account the design parameters described in Table 1 and the size of the FLCs, there will be no vignetting if the crystals are placed just before the instrument focal plane. Since the orientation angle of the optic axis is temperature dependent ($-0.3^\circ/\degree\mathrm{C}$), the FLCs will have to be enclosed
Figure 8: Permissible FOV for different telescope diameters and f-numbers that can be realised with ACROPOL.

in a temperature-controlled oven.

4.3. Detector

A ProEM-HS:1024BX3 EMCCD camera from Princeton Instruments serves as the detector. The CCD has 1024×1024 pixels of 13×13 μm size. The sensor has a quantum efficiency of 95% and 65% at 650 nm and 850 nm, respectively. The camera features a readout speed of 30 MHz with the electron multiplication (EM) gain mode to deliver 25 frames/s, as well as a slow scan normal CCD readout mode with very low read noise for precision photometry applications. The dynamic range of the CCD is 3900 at a readout rate of 30 MHz with 16 bit digitization. The sensor is coated with a patented anti-reflection coating for standard fringe suppression. At full resolution, the camera frame rate is given by
\((t_{\text{exp}} + 0.04)^{-1}\) frames/sec with a readout rate of 30 MHz and a vertical shift rate of 700 ns, where \(t_{\text{exp}}\) is the exposure time in seconds. The desired signal-to-noise ratio can be achieved by modifying the exposure time, the analog-to-digital rate, the vertical shift rate, and the EM gain. Other features of the camera include a Gigabit Ethernet interface for fast data transfer, proprietary data acquisition software, as well as software development kits for custom programming that are compatible with Linux and latest versions of Windows. The functionality of the camera was tested at the spectrograph of the Einstein Tower, Telegrafenberg, Potsdam and a sample spectrum at 630 nm is shown in Fig. 9.

Figure 9: Left: ProEM CCD camera from Princeton Instruments at the focal plane of the Einstein Tower. Right: Unprocessed solar spectrum at 630 nm with an exposure time of 20 ms with the slit passing over a sunspot in NOAA AR 12548 on 2016 May 27. Due to poor observing conditions, calibration data could not be taken that day.
5. Conclusions

We present the design of a polarimeter to investigate the chromospheric magnetic field. The stand-alone instrument consists of three lenses, two ferro-electric liquid crystals, a Wollaston prism, and a CCD camera, allowing standard two-beam polarimetry. The consideration in the optical design was to enable the instrument to adapt to various f-numbers and telescope diameters and provide the necessary plate scale at the detector. To that extent, we describe the design for the 70 cm Vacuum Tower Telescope and the 1.5 m GREGOR solar telescope. In both cases, we obtain a diffraction-limited design, using off-the-shelf components, with an additional constraint that one of the lenses has to be replaced for the two configurations. However, the performance is valid over a range of f-numbers, so either configuration described here could be utilised for any existing solar telescope. We plan to experimentally determine the effect of the rotation of the Wollaston prism on the Muller matrices of the two orthogonal beams. However, since this effect is expected is to be systematic for a fixed rotation angle, it can be corrected by a suitable calibration scheme combining a quarter-wave plate and a linear polariser placed in front of the polarimeter. The budget of the instrument is very modest, the bulk of the expense being the CCD camera. Its compactness and adaptability make it a valuable addition to any solar facility.

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