

# First successful deployment of the ZIMPOL-3 system at the GREGOR telescope

Renzo Ramelli<sup>a</sup>, Daniel Gisler<sup>a,b</sup>, Michele Bianda<sup>a</sup>, Nazaret Bello González<sup>b</sup>, Svetlana Berdyugina<sup>b</sup>, Dirk Soltau<sup>b</sup>

<sup>a</sup>Istituto Ricerche Solari Locarno, Via Patocchi 57, Locarno, Switzerland;

<sup>b</sup>Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany

## ABSTRACT

Since several years the Zurich Imaging polarimeter (ZIMPOL) system is successfully used as a high sensitivity polarimeter. The polarimeter system, which is mainly based on a fast modulator and a special demodulating camera with a masked CCD, has been continuously improved. The third version of the system (ZIMPOL-3) is routinely used at IRSOL, Locarno. The fast modulation allows to “freeze” intensity variations due to seeing, and to achieve a polarimetric sensitivity below  $10^{-5}$  if the photon statistics is large enough. In October 2013 the ZIMPOL system has been brought and installed for the first time at the GREGOR telescope in Tenerife for a spectropolarimetric observing campaign. There, the system configuration took advantage from the calibration unit installed at the primary focus of the GREGOR telescope, while the analyzer was inserted in the optical path just before the spectrograph slit after several folding mirrors. This setup has been tested successfully by the authors for the first time in this occasion.

**Keywords:** Instrumentation, Polarimeter, Solar Spectropolarimetry, ZIMPOL, GREGOR telescope

## 1. INTRODUCTION

The Zurich Imaging Polarimeter (ZIMPOL)<sup>1-3</sup> allows to obtain solar observations with high polarimetric sensitivity. If photon statistics allows, a polarimetric precision below  $10^{-5}$  can be reached. It is thus possible the exploration of a wealth of phenomena that generate a low amount of polarization such as elusive quantum mechanics interference effects in scattering processes and the Hanle effect. This gives a deep insight in the complex structures of the solar magnetic field.<sup>4</sup>

The high polarimetric sensitivity is obtained thanks to fast modulation in the kHz regime followed by a synchronous demodulation obtained with a special camera with a masked CCD sensor.<sup>3</sup> This allows to avoid spurious effects induced by intensity variations due to seeing.

First developed at the Institute of Astronomy at ETH Zurich, the ZIMPOL system for solar observations is now further developed and maintained by Istituto Ricerche Solari Locarno (IRSOL) in collaboration with University of Applied Sciences and Arts of Southern Switzerland (SUPSI). Since 1998 ZIMPOL has its permanent base at IRSOL where it is regularly used for scientific observations. The past versions of the ZIMPOL system has been installed several times for dedicated observing campaigns at large solar facilities (Dunn Solar Telescope, McMath-Pierce Telescope, Swedish Solar Telescope and THEMIS).

Here we describe the first experience installing ZIMPOL at the GREGOR telescope, which is also the first time that the new ZIMPOL-3 version<sup>3</sup> has been brought to an external facility. The main goal of the observing campaign has been to test the setup from the technical point of view and to learn about its capabilities. This has been the first step of a collaboration between IRSOL and the Kiepenheuer-Institut für Sonnenphysik (KIS) that aims at bringing a full ZIMPOL system permanently at the GREGOR telescope. This will allow to combine high spatial resolution with high sensitive spectropolarimetry mainly in the visible and in the near UV.

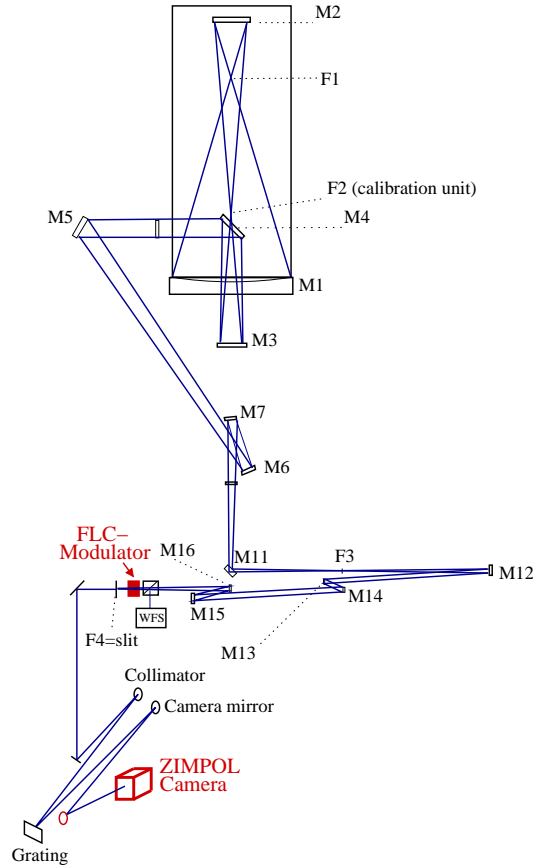


Figure 1. Optical layout scheme showing the ZIMPOL setup at the GREGOR telescope.

## 2. THE INSTALLATION CONFIGURATION OF ZIMPOL AT GREGOR

The observing campaign with ZIMPOL at the GREGOR telescope described here has been carried out from 21st to 31st October 2013. Figure 1 shows how the ZIMPOL system has been integrated in the GREGOR optical design.<sup>5</sup> As analyzer we used a liquid crystal modulator package (see section 3), which has been installed just before the spectrograph slit and after the beam splitter feeding the adaptive optics (AO) system<sup>6</sup> (see Figure 2). The dichroic pentaprism which is usually installed to allow simultaneous observations with the GREGOR Fabry-Pérot Interferometer (GFPI)<sup>7</sup> and the GREGOR Infrared Spectrograph (GRIS)<sup>8</sup> has been removed in order to allow the usage of the spectrograph in the visual range. The resulting change in optical length has been well compensated by the ZIMPOL modulator package itself, so that no further adjustments for the focalization have been needed.

The ZIMPOL camera has been installed on the spectrograph optical table. An additional flat mirror has been installed on the light path after the camera mirror in order to deviate the light beam into the ZIMPOL camera.

At the time of the observing campaign described here the derotator was not yet available. Thus it has not been possible to orient the solar image as desired with respect to the spectrograph limb. In addition the image rotation could not be compensated. To obtain observations with the slit orientated parallel or perpendicular to the solar limb in a given moment, we selected the particular points on the solar disc allowing that.

## 3. THE MODULATOR PACKAGE

For the ZIMPOL system the used modulator package consists either of a photo-elastic modulator (PEM) or a liquid crystal modulator. The modulator is followed by a linear polarizer.

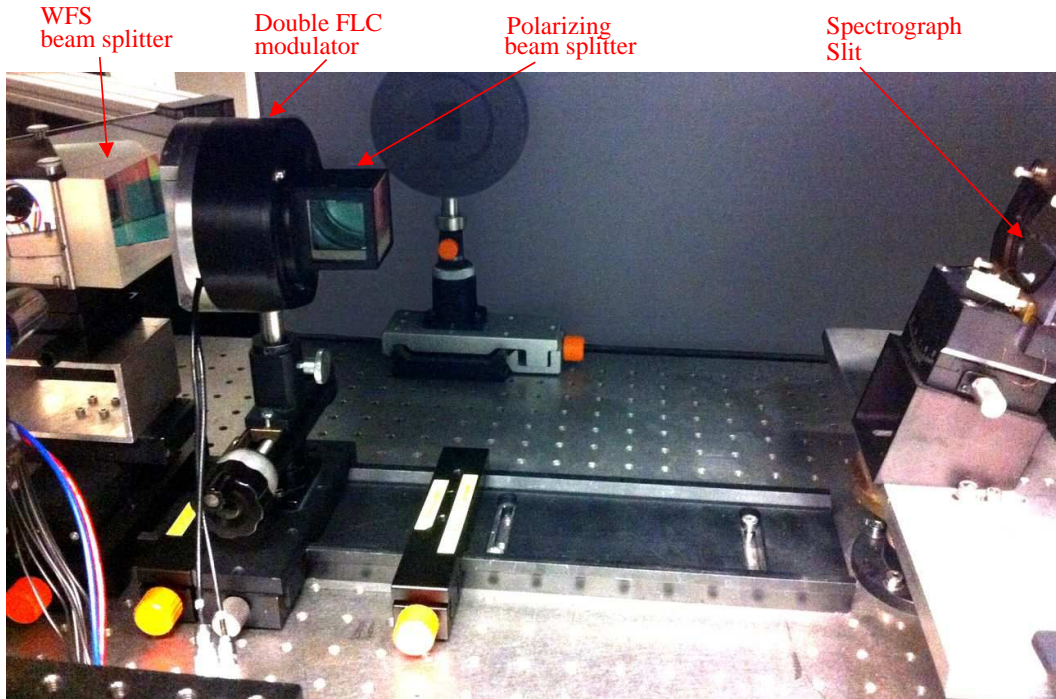


Figure 2. The ZIMPOL modulator package consisting of a double ferroelectric liquid crystal modulator and a polarizing beam-splitter installed before the spectrograph slit and after the beam-splitter feeding the wave front sensor of the adaptive optics system.

For most measurements with ZIMPOL the PEM is used. Because due to its high optical quality it achieves the highest polarimetric sensitivity. But it has also the major drawback that measuring the full Stokes vector simultaneously is not possible. Because of this and some additional smaller disadvantages, we decided to use at GREGOR a liquid crystal modulator.

For that we use two ferro-electric liquid crystal retarders (FLCs) (Figure 3). If an electric field is applied, these elements work like a zero-order retarder. If the sign of the electric field is changed the optical axis of the retarder changes to an about 45 degree rotated position. The time to change between these two positions is about  $100\mu\text{s}$  which allows a modulation frequency of up to 1kHz. Two of these elements can easily be combined: one with half-wave and a second one with quarter-wave retardation would be required to modulate the Stokes vector. As any other zero-order retarder, a FLC retarder has a wavelength dependent retardance proportional to about  $\lambda_0/\lambda$ . Therefore a high polarimetric efficiency can only be achieved around wavelength  $\lambda_0$ .

### 3.1 Achromatic design of the modulator

To make the modulator more achromatic two standard zero-order retarders are added (for GREGOR we use retarders made of quartz crystal due to its high transmission in the UV). This four element system has eight free parameters (4 retardations and 4 angles). With help of a simple model and an optimization software routine, an achromatic system with high polarimetric efficiency can be found in a given wavelength range. For the modulator prepared for GREGOR we decided to optimize the wavelength range 390 to 700 nm.

The optimization has been done in three steps. Technically it is difficult and expensive to build FLC retarders with a very accurate phase shift at a given wavelength. Therefore in the first step the optimum phase shift of the FLC retarder has been calculated but with the restriction that the retardation of both FLC retarders should be equal. After purchase of the FLC retarders, the wavelength dependence of the retardance has been measured and given into the model. The second step has been then to calculate the optimum retardance of the two quartz retarders. Here one can choose for each retarder a different phase shift since they can be fabricated very

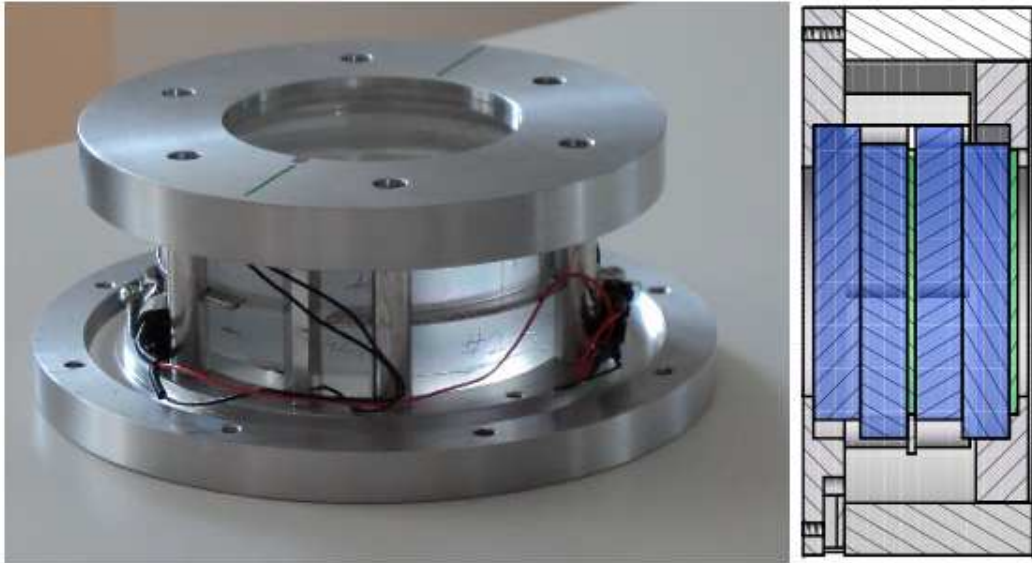


Figure 3. Open housing of the assembled modulator package (without polarizer). The drawing on the right side shows the position of the FLC retarders (blue) and the quartz retarders (green).

accurately. The wavelength dependence of those retarders has been measured too and in the third step finally the four angles have been calculated.<sup>9</sup>

### 3.2 Opto-mechanical design

Together with the polarizer, the modulator package consists of 5 optical elements with ten surfaces. Reflections between the surface can induce strong polarized fringes. Instead of mounting them individually and suppress reflections with a broadband anti-reflex (AR) coating, FLC and fixed retarders have been stacked together to a single element. The space between the elements is filled with a thin film of a refraction index matching silicon oil. This allows also to minimize the required space for the modulator. The modulator has a clear aperture of 45mm and a thickness of 44mm (without polarizer).

### 3.3 Performance

Figure 4 shows the measured total polarimetric efficiency. The modulator achieves an averaged efficiency of about 0.8 in the wavelength range 400 to 700nm. The efficiency is almost equally shared by the different Stokes parameters. Generally FLC retarders do not work in the UV range. With this device the shortest possible wavelength is about 385nm.

## 4. THE COMMUNICATION INTERFACE BETWEEN ZIMPOL AND GREGOR SOFTWARE

The ZIMPOL-3 hardware components are controlled by a Command Script Interpreter (CSI) whose main task is to coordinate concurrent actions, check their completion and store data. Commands can be sent through both scripts and interactive client entries (GUI or command line). The CSI communicate with different hardware subsystems through TCP/IP connections using a dedicated simple communication protocol. More details on the CSI are described in the paper by Ramelli et al. 2010.<sup>3</sup>

In order to coordinate the ZIMPOL system actions with the GREGOR systems a dedicated *ZIMPOL to GREGOR software interface* (ZGSI) written in C++ has been developed. This interface acts as a server of the CSI and as a client of the GREGOR control system.<sup>10</sup> The ZGSI is able to translate the commands from the ZIMPOL communication protocol to the GREGOR communication protocol.

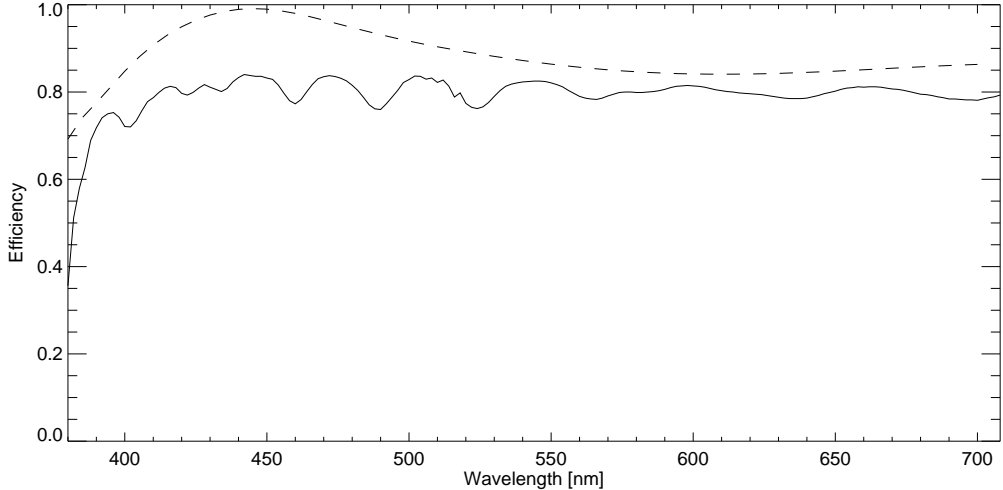


Figure 4. Laboratory measurement of the polarization efficiency of the modulator (solid line) in comparison with the model calculation (dashed line).

The ZGSI has been particularly helpful to automatize the acquisition of the polarimetric calibration measurement allowing the CSI scripts to control the filters in the calibration unit.<sup>11</sup>

## 5. THE ZIMPOL CALIBRATION

The ZIMPOL-CCD sensor<sup>3</sup> is equipped with a mask that, for each set of four neighbour rows, covers three rows and let one row free. With a proper shifting of the electron charges between a set of four rows, synchronized with the modulation, it is thus possible to record for each free pixel four intensities in correspondence with four modulator states. Let's indicate with  $\vec{I}$  the 4-component vector of the measured intensities in one pixel. The modulation  $4 \times 4$ -matrix  $\mathbf{O}_{\text{mod}}$  models how  $\vec{I}$  linearly depends on the Stokes vector  $\vec{S}_{\text{in}}$  of the beam coming in the modulator

$$\vec{I} = \mathbf{O}_{\text{mod}} \vec{S}_{\text{in}} \quad (1)$$

The demodulation matrix  $\mathbf{D}_{\text{mod}} = (\mathbf{O}_{\text{mod}})^{-1}$  allows to obtain the incoming Stokes vector  $\vec{S}_{\text{in}}$  from the measured intensities  $\vec{I}$ .

$$\vec{S}_{\text{in}} = \mathbf{D}_{\text{mod}} \vec{I} \quad (2)$$

The goal of the polarimetric calibration is to obtain the matrices  $\mathbf{O}_{\text{mod}}$  and  $\mathbf{D}_{\text{mod}}$ . This is achieved measuring the reaction of the polarimeter to different reference polarization states  $\vec{S}_{\text{in}}$  generated inserting the calibration optics, which usually is composed by a linear polarizer and a quarter wave plate. Typically the calibration is obtained measuring the six polarization states with  $Q/I = +1$ ,  $Q/I = -1$ ,  $U/I = +1$ ,  $U/I = -1$ ,  $V/I = +1$  and  $V/I = -1$ . The calibration reduction procedure is done applying a technique based on a singular value decomposition (SVD) as described by Feller.<sup>12</sup>

One has however also to consider that the “true” Stokes vector  $\vec{S}$  of the solar light is altered by the instrumental polarization of the telescope as described by the Mueller matrix  $\mathbf{M}_{\text{tel}}$ . Then the Stokes vector reaching the modulator is given by

$$\vec{S}_{\text{in}} = \mathbf{M}_{\text{tel}} \vec{S}. \quad (3)$$

The intensity vector recorded by the polarimeter is thus

$$\vec{I} = \mathbf{O}_{\text{mod}} \cdot \mathbf{M}_{\text{tel}} \cdot \vec{S}. \quad (4)$$

In practice it is often not an easy task to handle the corrections of the instrumental polarization, specially when  $\mathbf{M}_{\text{tel}}$  is highly time dependent. This leads easily to a remarkable increase of the systematic uncertainties.

There are different methods to handle the corrections of the instrumental polarization. A possibility is to determine the Mueller matrix through a calibration or considering a telescope model. Cross-talk corrections between the Stokes parameters and in particular from circular to linear polarization and vice-versa are often also done considering theoretical assumptions on the polarimetric signal shapes, in particular in the patterns produced by Zeeman effect (see e.g. Stenflo 2001<sup>13</sup>).

With the setup at this observing campaign at GREGOR we used another approach. Instead of placing a calibration optics just before the modulator package as usually, we used the calibration unit installed at the focal point F2.<sup>11</sup> In such a way the telescope Mueller matrix  $\mathbf{M}_{\text{tel}}$  could be considered as becoming part of the modulation matrix of the system so that the polarimetric calibration delivered directly

$$\mathbf{O}_{\text{tot}} = \mathbf{O}_{\text{mod}} \cdot \mathbf{M}_{\text{tel}}. \quad (5)$$

To note that F2 is located before any folding mirrors and thus the instrumental polarization up to this point can be neglected.

It is the first time that such a configuration was used in combination with ZIMPOL. The results obtained in this way (see next section) are very satisfactory and clean from evident cross-talks effects between circular and linear polarization. The only drawback is that the calibration is time dependent. Thus calibrations loose quickly their validity and one needs frequent calibration measurements. During this first test observing campaign the observations were relatively short and lasted for few minutes. Thus it was not difficult to obtain a calibration measurement just before or after the science observations. If in the future observing campaigns, observations with long exposure times will be obtained, one could develop a data reduction procedure based on a time dependent interpolation of the calibration coefficients.

### 5.1 Correction of the polarization offset

Usually, an offset in the absolute polarization measurements  $Q/I$ ,  $U/I$  and  $V/I$  are generated by the polarimetric system itself and by the instrumental polarization as described by the parameters in the first column of the telescope Mueller matrix  $\mathbf{M}_{\text{tel}}$ . In the measurements obtained with the FLC-modulator, the offset are often not perfectly constant over the spatial direction. In order to correct for this offset, a flat-field recording near disc center is obtained. The Stokes images of the flat-field recordings shows the same offset patterns and they can be used to correct the polarization offsets present in the scientific measurements.

Another consequence of the polarization offset is that the CCD pixel rows are not illuminated homogeneously so that the measured intensity components of  $\vec{I}$  strongly differ among them. Strong intensity variations are easily the cause of possible systematic effects.<sup>9</sup> A solution to that problem, is provided by the new version of the polarimetric system ZIMPOL-3 that allows to program small delays in the cyclic timing of the photo-charges shifts between the masked and unmasked rows for the demodulation. The basic idea of this electronic compensation is to arrange the exposure times of each row of charges so that on average the four intensity components of  $\vec{I}$  become nearly equal. The suitable time delays can be determined taking few exposures at disc center before starting calibrations and measurements and applying a quick optimization procedure.<sup>14</sup>

## 6. EXAMPLE OF OBSERVATIONAL RESULT

During the campaign we could preform several observations in different spectral regions and on different targets (e.g. solar limb, sunspots, prominences). Figure 5 shows, as a representative example, the four Stokes images of an observation recorded around the  $\text{Sr}_I$  4607Å line on 30 October 2013. The measurement has been obtained near the solar limb with a total exposure time of 1 minute. The sharpness of the structures seen in the spatial direction, indicates how the observing conditions allowed to reach a high spatial resolution, also thanks to the

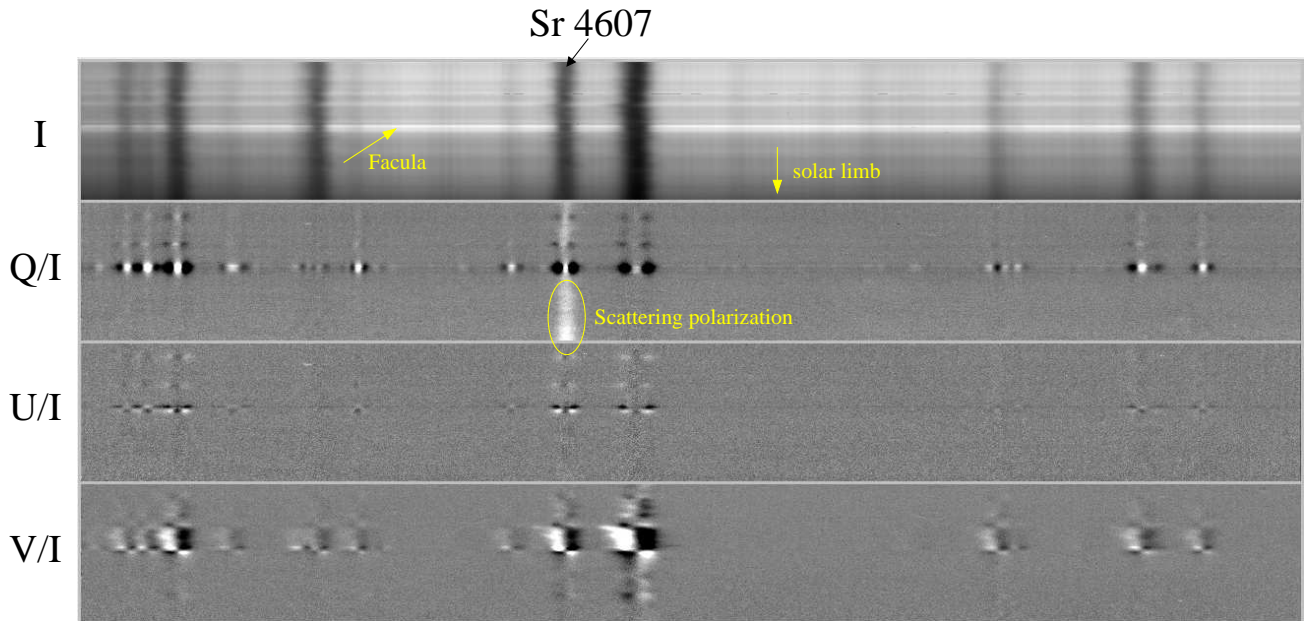


Figure 5. Example of full-Stokes observation taken around the  $\text{Sr}_I$  4607 Å line. During this observation the adaptive optics system was in closed loop.

usage of the adaptive optics system.<sup>6</sup> The solar limb is located in the bottom direction, while the horizontal bright line in the  $I$ -image corresponds to a facular region. Positive Stokes  $Q$  is defined parallel to the nearest limb point. It is interesting to see how the scattering polarization signal in the Stokes  $Q/I$  image is increasing noticeably when approaching the limb, as expected from the theory. In the magnetic regions, clear signals from the Zeeman effect can be seen as symmetric patterns in the linear polarization (Stokes  $Q/I$  and  $U/I$ ) and as antisymmetric patterns in the circular polarization. The lowest polarization signal detectable in the image has an amplitude of 0.01%.

## 7. CONCLUSION AND OUTLOOK

This first observing campaign has shown that the ZIMPOL-3 system works very well at the GREGOR telescope. The installation of the system did not present any difficult technical problem. We found, that the setup with the polarimetric analyzer just before the spectrograph slit in combination with the calibration unit at the focal point F2 installed before any folding mirror was very convenient. The calibration allowed to obtain observations where Zeeman effect signals did not show any evident sign of crosstalk from circular to linear polarization and vice-versa.

While the aim of the first observing campaign with ZIMPOL was mainly to test the instrumental capabilities, in 2014 we are planning a new campaign more oriented on selected scientific topics. In the near future we plan that a ZIMPOL system will be permanently available at GREGOR. We expect also to benefit of further developments of the instrumentation at GREGOR such as the slit jaw scanner and the image derotator that will give the possibility to perform scientific observations involving longer exposure times.

## ACKNOWLEDGMENTS

The authors thank the technical staff at the GREGOR telescope and the mechanical workshop at KIS for their support.

The ZIMPOL-3 project started at Institute of Astronomy at ETH-Zurich in the group of Prof. Jan O. Stenflo. After the retirement of Prof. Stenflo the continuation of the project has been taken over by IRSOL and University

of Applied Sciences of Southern Switzerland (SUPSI). The SUPSI team is led by Ivan Defilippis and Diego Barrettino.

IRSOL activity is supported by State Secretariat for Education, Research and Innovation (SERI), Canton Ticino, City of Locarno together with the municipalities affiliated to CISL and the Aldo e Cele Daccò Foundation. This project has been supported by Swiss National Science Foundation grant 200021-138016 and by Solarnet. RR acknowledges financial support by the Carlo e Albina Cavargna foundation.

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