The Polarization Optics for the European Solar Telescope

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Abstract. EST, the European Solar Telescope, is a 4-m class solar telescope, which will be located at the Canary Islands. It is currently in the conceptual design phase as a European funded project. In order to fulfill the stringent requirements for polarimetric sensitivity and accuracy, the polarimetry has been included in the design work from the very beginning. The overall philosophy has been to use a combination of techniques, which includes a telescope with low (and stable) instrumental polarization, optimal full Stokes polarimeters, differential measurement schemes, fast modulation and demodulation, and accurate calibration, and at the same time not giving up flexibility.

The current baseline optical layout consists of a 14-mirror layout, which is polarimetrically compensated and non-varying in time. At instrument level the s-, and p-planes of individual components are aligned, resulting in a system in which eigenvectors can travel undisturbed through the system.

1. Introduction

Understanding the processes that generate, concentrate and transport magnetic energy -observable through the polarization of spectral line profiles- at this very moment is one of the most challenging problems in solar physics. It requires 4 m class telescopes with excellent polarimetric performance. EST, the European Solar Telescope, together with ATST (Advanced Technology Solar Telescope (Rimmele & the ATST Team 2008)), represents the major effort in this sense by the worldwide ground-based solar physics community. EST is a telescope that aims at the best polarimetric performance together
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with high spectral, spatial and temporal resolution observations in the solar photosphere and chromosphere, using a suite of instruments (broad-band imagers, narrow-band tunable filter spectropolarimeters, grating spectropolarimeters), that can efficiently produce two-dimensional spectropolarimetric information of the thermal, dynamic and magnetic properties of the plasma over many scale heights, ranging from $\lambda =350$ until 2300 nm (and $\lambda =315$ nm until 20 $\mu$m without Adaptive Optics). It is an ambitious project, which is currently in the conceptual design phase (Collados et al. 2010a,b). The EU funded study is a 3-year project led by the Instituto de Astrofísica de Canarias, involving 30 partners (universities, institutions, and industry) and 7 collaborating institutions from 15 different countries in total. EST is promoted by the European Association of Solar Telescopes (EAST), formed by 15 research institutions from Austria, Croatia, Czech Republic, France, Germany, Great Britain, Hungary, Italy, The Netherlands, Norway, Poland, Slovakia, Spain, Sweden and Switzerland.

2. Telescope overview

EST’s baseline design (Figure 1) includes an on-axis Gregorian optical layout, in alt-azimuth configuration. The telescope assembly has an open configuration and operates in the free air. A Rocking Chair mount configuration, together with fast tip-tilt of the secondary mirror M2 and light weighted M1 provides sufficient protection against wind loading. The enclosure is of the retractable type and allows for optimal wind flushing of the telescope structure, minimizing local seeing effects. M1 is cooled through pockets in the backside of the mirror, with an air knife at the frontside and is located above the elevation axis to enhance natural flushing. Both adaptive optics (AO) as well as multi-conjugate adaptive optics (MCAO), consisting of several deformable mirrors (DM) at conjugated heights (currently on an altitude of 5, 9, 15 and 30 km, but a topic of study), aim at correcting for the diurnal variation of the distance to the turbulence layers over a wide field of view and are part of the main optical train. The aim is to make the MCAO train also by-passable, enabling higher throughput at the price of correction of a smaller field of view. The MCAO optics are accommodated in the transfer optics tube in the pier, which sends the light beam from telescope to instrument lab, which is accommodated in a controlled environment at the bottom of the telescope. The transfer optics assembly and instrument lab have both options for derotation and are topic of further investigation. Three types of instruments are being studied: broad-band imagers, narrow-band tunable filter spectropolarimeters and grating spectropolarimeters, with each instrument operating in several channels at different wavelengths. A flexible light distribution system composed of dichroic and intensity beamsplitters feeds the instruments channels, making it feasible to have different paths of light distribution.

3. Design strategy

Telescopes, in general, are not designed for polarimetric measurements, which reduces the performance and requires frequent and precise calibration (Skumanich et al. 1997). Also, because the captured light is only slightly polarized, polarimetry requires many photons for reducing the noise level clearly below the polarimetric signal (Collados et al. 2010b). For this reason we have included the polarimetric characteristics from the
very beginning. The design study focus on two main aspects: 1) an optimum design, meaning that all elements in the telescope are the best choice for polarimetry, i.e. both in terms of the optical layout, the location of the calibrators and modulators, the choice of coatings and detector types, as well as calibration strategies, modulation schemes and processing pipeline; 2) characterization of the design by simulating the output as delivered by the total system, including seeing and its AO/MCAO correction as well as performing error budgeting of the total system. Both give information how well we are able to reach the scientific requirements and what the critical areas are. In order to be able to achieve the requirements, the overall philosophy is to use a combination of techniques, rather than focusing on one or two. This means that the EST polarization system will aim at combining: a low polarization telescope and instrumentation (which is also constant over the course of the day), high detector linearity, accurate calibration, differential measurement schemes, switching, and solid image processing software. At the same time we will try to maintain the flexibility of the whole system, allowing for different setups, optimally tuned for different programs and instruments with also ample room for future technological development.

4. Requirements

The science requirements for EST contain specifications for both the polarimetric sensitivity and accuracy, with polarimetric sensitivity defined as the noise level above which a real polarization signal can be measured and polarimetric accuracy describing to what extent the real polarization signals (e.g. on the Sun) are actually reproduced by the po-
larimetric system. Solar polarimetry in most cases aims at measuring the full set of Stokes vectors \((I, Q, U, V)\). As such, the accuracy is best described by the matrix \((X)\), being the relation between the real and measured Stokes components and containing the relative errors to the measurement scale at its diagonal elements, the offsets to the zero point at the \(I \rightarrow Q, U, V\) components and general cross-talk at the other non-diagonal components (Ichimoto et al. 2008). The science requirements dictate that after calibration: 1) the polarimetric accuracy should be better than:

\[
\Delta X < \begin{pmatrix}
10^{-2} & 1 & 1 & 0.1 \\
5 \times 10^{-4} & 10^{-2} & 5 \times 10^{-3} & 5 \times 10^{-3} \\
5 \times 10^{-4} & 5 \times 10^{-2} & 10^{-2} & 5 \times 10^{-3} \\
5 \times 10^{-3} & 5 \times 10^{-1} & 5 \times 10^{-1} & 10^{-2}
\end{pmatrix}
\]

with \(\Delta X(i,j)\) being the maximal allowed difference between the measured and real Stokes vector components \(I, Q, U, V\).

2) the polarimetric sensitivity of EST should be better than \(3 \times 10^{-5} S / I\) (in the continuum), where \(S\) is any Stokes parameter. The obtainable sensitivity depends on the chosen resolution, integration time and telescope-instrument efficiency, see Figure 3. The aim is to reach a telescope-instrument efficiency of 10%.

5. Design

Not different from polarimeters elsewhere, the EST polarimeters will consist of a) a modulator, b) an analyzer (polarizer or polarizing beam-splitter) and c) a demodulator (detector). The role of the modulator is to transfer the to be measured polarization into a (fixed) linear polarization state (e.g. \(Q\)). The role of the analyzer is to transfer that linear polarization state into intensity, being the quantity to be measured by the camera. In order to measure the full Stokes vector, generally a sequence of exposures is required that together measure different polarization states. In the following subsections we will detail the design considerations.

5.1. Sensitivity

Sensitivity is affected by both atmospheric seeing and systematic effects. The influence of seeing is minimized if the subsequent measurements are performed with little time separation, preferably in the milliseconds range, or alternatively simultaneously (although other differential effects limit the sensitivity in this case). Kilohertz recording requires both fast modulators and demodulating detectors e.g. ZIMPOL (Povel et al. 1994) and C3Po (Keller 2005), but both are not readily available yet for the projected detector size for EST (4k x 4k). Also instantaneous measurement of one Stokes vector is possible (even without a modulator) by using polarizing beam splitters that split the light up in two opposite polarization states, both feeding their own detector system, called dual beam polarimetry. By swapping periodically the polarization between the two beams, the systematic effects can then be cancelled out (Semel et al. 1993). Contrary to single beam polarimetry, all photons are used. Dual beam polarimetry together with a modulator is the baseline option for EST. The very best we can do is to combine fast modulation and dual-beam.
5.2. Accuracy

Accuracy is limited by not knowing precisely all instrumental properties. For maximizing the accuracy we could think of the following strategies:
1. the minimizing of instrumental polarization, by use of a) a polarization free focus; b) compensating mirrors; c) polarization compensation; d) appropriate coatings; e) avoiding of windows.
2. calibration of instrumental polarization.
3. multiple-stage modulation and switching of sign to cancel out instrumental polarization.
4. use geometry of mirror train to advantage eigenvectors.
All could in principle be used together. In the next sections we will describe them successively.

5.3. Instrumental polarization

The aim for the optical design of EST, up to the science focus, is to get the lowest possible instrumental polarization. An instrumental polarization free telescope transfers all polarization states undisturbed, at any pointing direction of the telescope. Especially variations in time are to be avoided since calibration becomes then quickly a time-demanding task and impacts negatively the calibration accuracy. The baseline optical design of EST (Figure 2) consists currently of 14 mirrors (Collados et al. 2010a,b). Among them are 5 mirrors with power to generate four focus positions and a collimated beam, a ground layer DM (DM0), a tip-tilt mirror (TT) and four MCAO DMs. The optical layout can work without lens or window components (e.g. to close evacuated chambers or beamsplitter cubes to feed wavefront sensors), which eliminates birefringence effects. The design groups the mirrors in pairs, oriented in a way that they compensate each others polarization (Cox 1976). For the fold mirrors with 45° incidence angle this occurs when the incidence-reflection planes are perpendicular. Since different parts of
the telescope rotate with different rates (elevation axis, azimuth axis, derotator), compensation for the system as a whole also requires that all subsystems in themselves are compensated, which also has been realized.

Figure 3. Concept drawing of the geometry of the optical layout of EST. The flat elevation mirrors M3-M4 are polarimetrically compensated as well as the flat azimuth mirrors M6-M7. The transfer optics assembly M8-M14 is compensated in itself too and can work as a derotator. M6 can work as tip-tilt mirror.

For achieving this full compensation only one extra 'dead' mirror is needed, which does not lower the total throughput significantly (important for efficiency and sensitivity). The instrumental polarization has been evaluated with ZEMAX, for different field angles, wavelengths, a variety of coatings and as function of time. Figure 3 shows an example. The results confirmed that the instrumental polarization is indeed extremely low, over the whole field of view (2' x 2'), for all hour angles, at all investigated wavelengths (400 - 1000 nm) and below or close to the requirements for simple coatings. In the calculations nevertheless ideal components are used and in reality performance will be worse, due to differential effects, non-ideal coatings, (differential) aging, dust, etc. (Bettonvil et al. 2010). Over-coatings tend to increase the instrumental polarization, in particular when they are aiming at enhanced reflectivity. Extensive measurements on reflective coatings therefore have been done (and still are ongoing) to learn about polarization properties (Bettonvil et al. 2010). Figure 5 shows a sample of the results. Thin Al$_2$O$_3$ films on top of Al coatings have the least influence, although it has been shown that also these layers do have influence (Van Harten et al. 2009) and easily can exceed the error budget if no compensation of calibration is applied. Dust can change the polarization Mueller matrix elements in the order of 2%, as derived from measurements and modeling (Snik et al.).
5.4. Calibration

Due to the non-ideal behavior we emphasize that calibration is always needed. For this purpose, a calibration package in the F2 focus (Sanchez Almeida & Martinez Pillet 1992) is foreseen, having only the rotationally symmetric M1 and M2 in front (and also the spider, which with its 4 arms is symmetric too) and as such minimal instrumental polarization. A volume of 1 m$^3$ is available to accommodate calibration components as well as modulators (Bettonvil et al. 2010). An overdetermined system allows then for retrieval of non-ideal parameters of calibration components (Skumanich et al. 1997).

5.5. Multiple stage modulation

A classical polarimeter has modulator and analyzer together in one polarimetric package. For EST the (dual beam) analyzer will also be put at the very end in order to eliminate complications with the (MC)AO optics and instruments since otherwise two beams have to travel through the system. For the modulator however two positions are foreseen, 1) at the 'classical' location just just before the analyzer and enabling large flexibility and choice of polarimeter designs for every channel separate; 2) in the very front (i.e. in F2) of the optical train, as e.g. done at THEMIS (López Ariste et al. 2000). This has the great advantage that the instrumental polarization of the all optics behind the modulator does only harm in much lesser way.

By using modulators at both (or even other) locations in the optical train, and switching the sign of polarization periodically, and then subtracting sequential images, spurious polarization signals of parts of the telescope can be subtracted while the source polarization (i.e. on the Sun) will add, and thus can be discriminated (Tinbergen 2007). The modulator in F2 could act as a switch to change sign of real polarization with respect to instrumental polarization.
5.6. Use of eigenvectors

Behind the science focus the optical layout can be characterized as being complicated, due to the diversity and amount of instruments. For this reason it is more difficult to apply a design strategy, as done for the telescope optics, the more because maximum flexibility is required.

We can however make advantage of the static behavior (no rotating elements, apart from the instrument interior). If we orient all mirrors such that they are aligned according to their individual eigenvectors (being a linear polarization) and put also a modulator in front of the system (i.e. in F2), which transfers the to be measured polarization into the eigenvector of the optical train, we have created a very robust polarimetric system. In such a system light with linear polarization travels along the s- or p- direction, and therefore is never converted into Stokes V or U, because of symmetry reasons, and as such the change of physical properties of the mirror does not have effect on the cross talk (Ichimoto et al. 2008). The (unknown) instrumental polarization in the s-, p- (Q) directions drops out after a regular beam-exchange with the modulator or corrected with a compensator.

6. Concept

Based on the outlined methodology in the previous section, we can sketch the EST polarimeter layout (Figure 6). Just after the axis-symmetric mirrors M1 and M2, close to the instrumental free secondary focus F2, space is reserved for calibration optics and modulators, which can be slided in and out of the beam. Interchangeable polychromatic
modulators (Tomczyk et al. 2010; Xu et al. 2006) with switching capabilities provide for efficient modulation at a combination of wavelengths. The complete optics train, up to the science focus, including elevation and azimuth mirrors and AO and MCAO system is polarimetrically compensated. After the science focus, all optics are static and aligned according to their eigen vectors. After each instrument the analyzers are placed, and then sent as a dual beam to the fast demodulating detectors. Here also a modulator can be located as well as extra calibration optics and/or polarimetric compensators.

Figure 6. General concept for the polarimetric layout of EST.

7. Performance analysis

After the realization of the EST polarimeter concept, the next goal in the design study is predicting its performance. This work is in progress and here we present only the approach. It is divided in two tasks:

1) Numerical simulation of modulation and demodulation under variable seeing conditions with higher order contributions and AO/MCAO performance included, based on synthetic solar images. The outcome has mainly impact on the sensitivity. The purpose of this modeling is to test different polarimeter modulation schemes, study the interaction with the MCAO and test whether the science requirements can be met. Previous work was done by Lites (1987); Judge et al. (2004), which will form the basis.

2) Polarimetric error budgeting, which is needed to quantify the accuracy. It is part of the EST overall error budgeting (Cavaller Marqu´ez & Prieto Labra 2010). Full analysis of error propagation is planned and for this the EST optics will be split up in polarimetric building blocks, each with their own errors, e.g. aging, coating characteristics, pointing influence, dust, temperature effects, birefringence, field effects, calibration issues, etc. The formalism to perform this kind of error budgeting is based
on Stokes-Mueller description and was introduced by Keller & Snik (2009). The final goal is to allow for separate analysis of all propagated errors. By comparing the total contribution of all potential errors with the science requirements, the magnitude of all potential errors can be distributed over the various components and helps identifying critical elements. Monte-Carlo simulations will be used for verifying.

8. Summary and conclusions

We have outlined the current status of the design of the polarization optics for the EST. Sensitive and accurate polarimetry is one of the design goals of the telescope, and as such the polarimetric characteristics have been included from the beginning in all relevant aspects of the EST design study. A general and flexible concept for the polarimeter of EST has been made, with the overall philosophy to use a combination of techniques. The current work in the design study concentrates on predicting the performance. It is done by both numerical simulation of the modulation/demodulation under higher order seeing and polarimetric error budgeting.

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