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EST: the largest and most sensitive spectropolarimeter

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Abstract

Magnetic field plays a crucial role to understand most phenomena happening in the solar atmosphere. Sunspots, flares, prominences, coronal mass ejections are well known examples of its interaction with the solar plasma. To study the properties of this interaction, one needs to analyze the imprint it leaves in the radiation through the polarization induced in spectral lines, via the Zeeman and Hanle effects. Outside sunspots, the polarization degree of the emitted light is usually well below one part in one thousand, which requires sophisticated techniques to measure it accurately. To further complicate the situation, telescopes use mirrors and these introduce undesired polarization which is two or three orders of magnitude larger than that caused by the magnetic field of solar structures. For this reason, present telescopes doing polarimetry require an adequate modelling to correct the measured data from these spurious effects. In addition, most of the magnetic field interactions with the plasma take place at small scales. The best achievable angular resolution is mandatory to adequately study magnetic phenomena. The European solar Telescope (EST) has been defined to overcome these difficulties. Here, some aspects of the design are described.

1 Introduction

The European Solar Telescope (EST, [8]) is a joint project of several leading European research institutions to design and build a 4-meter class solar telescope and its instrumentation suite. EST is intended to be an infrastructure to study the Sun in a way that has never been done before. EST will improve the presently achieved spatial resolution by a considerable factor. In addition, the operation of several narrow-band tunable visible and near-infrared imaging instruments together with grating spectrographs, all with polarimetric capabilities, and large format broad-band imagers, will make it possible the simultaneous observations of photospheric and chromospheric layers and the study of the temporal evolution of the three-dimensional structure of solar magnetic fields. These combined aspects will make of EST a unique infrastructure.

The complementary performance of the instruments of EST will allow scientists to produce a three-dimensional view of regions on the solar atmosphere with unprecedented spatial, temporal, and spectral resolution. Imaging instruments will have the capability to take the performance of the telescope to the limit and reach the diffraction limit of its optics. They will facilitate the study of the details of the interaction between the plasma and the magnetic fields that are unresolved in current observations. Spectrometers have the complementary property that the full information along a spectral line is obtained, guaranteeing that the relevant physical information (temperature, velocity, magnetic field vector, etc.) may be retrieved. By using all these instruments together, the amount of information extracted from the observational data will be maximized. At present, no other solar telescope has, or plans to have, such a large amount of different and simultaneous instruments as planned for EST. The various EST instruments will operate in particular wavelengths to provide adequate sampling of different layers of the solar atmosphere. With its instruments, one may say that EST will make it possible to observe the Sun in depth, to connect the physical processes that take place at different layers. EST will facilitate to observe the Sun from the photosphere (where the properties of the magnetic field are governed by the plasma dynamics and thermodynamics) to the chromosphere (where, on the contrary, the plasma behaviour is governed by the magnetic field topology). Magnetic energy is stored below and at the photosphere, and is transported and released in the upper layers. EST will make it feasible to study all these interactions at their finest scales, where the fundamental processes take place.

Two main requirements are imposed to the technical design to achieve the ambitious goals of EST. On the one hand, EST will have a powerful multi-conjugate adaptive optics system like no other telescope has or will have in the near future. The atmosphere above the telescope distorts the incoming wavefront of the light and deteriorates image quality. This degradation depends on the altitude of the turbulence, making it necessary to devise correction mechanisms for turbulence varying in height. At present, no common-use MCAO system exists at any solar or night-time telescope, although experiments to develop it are being carried out at different institutions. Correlation trackers started to be common at telescopes some twenty years ago, or even earlier. Nowadays, solar telescopes require adaptive optics to correct ground-layer turbulence effects. EST, which is planned to start operation by the end of this decade, goes a step further and introduces in the optical path a complex, innovative and powerful set of deformable mirrors to correct for the effect of low and high altitude turbulence.

To maximize efficiency, the optical design of the telescope integrates in a natural way all the necessary active and adaptive optics, minimizing the number of optical surfaces. Strenuous efforts have been made to reach this goal. It comes with two advantages: on the one hand, the total throughput of the system and photon transmission is maximized; on the other hand, wavefront distortions introduced by the optical surfaces are kept to a minimum. A superb image quality will be one of the major strengths of EST.

A second critical goal of EST is related to polarimetric measurements. The magnetic field plays a fundamental role in the physical processes taking place in the solar atmosphere and leaves its imprint on the polarization state of the light coming from the Sun. Magnetic fields are detected by measuring the polarization of magnetically sensitive spectral lines. The fraction of the light in a spectral line that is polarized is tiny (sometimes below 10^{-3}). The precision of such measurements is fundamentally limited by photon statistics. A larger aperture collects more photons from a given area on the solar surface, permitting the required precision for polarimetric measurements. The optical design of EST puts special emphasis on a polarimetrically compensated distribution of the optical elements. With this design, the polarization of the light as it comes from the Sun will be modified to a minimum extent. The interpretation of the solar data will thus be simpler and more accurate, without the parasitic contamination introduced by oblique reflections on mirrors.

These two aspects (superb spatial resolution and accurate polarization measurements), solved in an innovative way during the Design Study, will make EST a unique infrastructure in terms of performance.

For the design of EST, many other issues have been analysed, always keeping in mind the best optical and polarimetric behaviour; e.g., thermal effects on the telescope environment, dynamic effects produced by the wind, deformations introduced by the varying gravity vector on the telescope structure, optimum reflective coatings to maximize the throughput and minimize the polarimetric impact, novel philosophies for polarimetric measurements, an effective light distribution system to maximize the light sent to the instruments, flexibility enabling the use combined or individual instruments taking into account particular scientific objectives, and a complex control system to handle all aspects of the data acquisition and on-site handling.

The result of all these studies is an infrastructure which brings together the best of all existing solar telescopes, while incorporating new concepts to satisfy the future scientific needs of the European Solar Physics community during the coming decades. As a complement to make feasible the achievement of the scientific and technical goals, the telescope will be located in the best European location: the Canary Islands. There, two observatories (the Observatorio del Roque de los Muchachos, on the island of La Palma, and the Observatorio del Teide, on Tenerife) host a number of telescopes that have repeatedly demonstrated their excellent quality for day and night astronomical observations. The final decision on the definite site will be taken some time before construction starts.

2 Baseline configuration

EST is a 4-metre class solar telescope with an on-axis Gregory configuration. The telescope includes active, adaptive (AO) and multi-conjugate adaptive optics (MCAO) integrated in the telescope optical path between the primary mirror and the instrument focal plane in order to provide simultaneously all instruments with a corrected image at the Coudé focus. The active optics system is mainly composed of the primary (M1) and secondary (M2) mirrors, although other mirrors of the optical path may also play a role in the active compensation. The adaptive optics system is composed of a fast tip-tilt mirror, a pupil deformable mirror (DM), and up to four DMs conjugated at different heights in the atmosphere.

The optical design is based on an aplanatic Gregory-type telescope with three magnification stages which finally yield an f/50 telecentric science focus [11]. The design includes 14 reflections in total, arranged in pairs with incidence-reflection planes perpendicular to one another in order to compensate their instrumental polarization [4]. This configuration allows the maximum number of capabilities: polarization compensation (Mueller matrix of the optical design very close to unity), integrated optical field-of-view rotation capabilities, telecentric design, collimated beam at the AO system and four MCAO DM mirrors.

The telescope mechanical configuration is alt-azimuthal given that it allows a simpler and more compact system, with better primary mirror air flushing, making it possible to achieve a polarimetrically compensated optical design. The configuration of the telescope structure is determined by the optical layout. The elevation axis has been placed 1.5 m below the M1 vertex in order to facilitate M1 air flushing, also allowing space enough for the M1 cell and for an adequate placement of the transfer optics train vertically from the telescope to the Coudé focus where the instruments are placed. This unusual configuration of the elevation axis below M1 produces a large unbalanced weight around the elevation axis, which is compensated by the structure below M1. In addition, the azimuth and elevation axes are decentred with respect to the telescope optical axis because the optical path is folded in an asymmetric way to produce a polarimetrically compensated layout, with a telescope Mueller matrix that is nearly independent of the telescope elevation and azimuth angles, and for all wavelengths [3].

The instruments will be enclosed in the Coudé instrumentation laboratory in a controlled environment. Since each instrument is composed of several channels, the space required in the Coudé room is huge. To accommodate all the instrument channels, they are distributed on different floors. A configurable light distribution system composed of dichroics and beam-splitters will be placed at the Coudé focus in order to feed different instrument channels, making it feasible to have different ways of light distribution for simultaneous observations using a flexible number of instruments/channels.

Image rotation will be compensated at the Coudé focus in order to feed the instruments with a stable image. The proposed baseline to compensate the field-of-view rotation is based on an optical de-rotator integrated in the telescope optical path. The seven mirrors of the transfer optics between the telescope and the Coudé focus, including the MCAO DMs, are arranged in way such that their input and output optical axes are coincident with the telescope optical axis. This arrangement allows this system of seven mirrors to work as an optical field-of-view de-rotator, rotating these mirrors around the optical axis at an appropriate rate. In addition, this design is also compensated under a polarimetric point of view, without introducing additional flat mirrors in the optical path. The arrangement of the transfer optics as a field de-rotator avoids the necessity to use a large rotating platform for the instrumentation, which is advantageous in terms of simplicity, instrument stability, cost and flexibility to allow future instrumentation upgrades.

Given the alt-azimuthal configuration, a Nasmyth platform will be provided as an auxiliary focal station for a medium infrared or ultraviolet instrument that will be fed directly with telescope light without passing through the complete transfer optics.

The baseline telescope enclosure is completely foldable [2]. This option has been selected since it maximizes natural wind flushing of the telescope, improving the local seeing conditions with less effort than with a conventional dome. The conventional dome requires a cooled skin, combined with many vent openings, requiring a complex and demanding installation. An important advantage of the completely foldable enclosure is that it allows the use of a reflecting heat rejecter at the Gregory focus, while with a conventional dome, it is necessary to absorb the heat inside the dome. The drawback of the open-air configuration is the higher wind effect on the image quality produced by wind shake on the telescope structure and wind buffeting deformation of the primary mirror. The wind effect has been taken into account from the beginning of the design, maximizing the stiffness of the telescope structure and primary mirror support, improving the bandwidth of the telescope drives, and providing fast tip-tilt and focus correction capabilities to the secondary mirror. The residual errors from wind effect can be corrected by the deformable mirrors of the AO system, although it is necessary to keep residual wind errors limited in order to avoid overloading the AO system. Additionally, a shield is proposed to reduce wind effects.

The telescope will be placed on the top of a tower to improve the local seeing conditions. The tower also supports the telescope enclosure. The Coudé instruments laboratory will be placed at the base of the tower. The transfer optics, including the MCAO system, will be distributed inside a chamber between the telescope and the instrument laboratory. The baseline for the telescope tower is a concrete tower that will enclose the instrument laboratory and the transfer optics, while providing the necessary stiffness to the telescope azimuth base. Since the instruments will be placed at the Coudé station at the base of the tower, it is important to minimize the tilt between the telescope and the Coudé focus and the lateral displacement.

A conical shape is proposed for the tower, in which the upper concrete part has a reduced diameter. The enclosure is supported with a transparent framework structure, to reduce the air obstruction and the turbulence at the telescope area. The optical layout is arranged on a tower height of, approximately, 33–38 m between the base of the Coudé laboratory and the telescope platform, which is adequate for reducing the ground layer effect on the local seeing conditions.

The EST facilities will include an auxiliary full disc telescope [12] that will be used to give the observer a global context of the solar activity and for precise coordinate measurements. The operation of the EST infrastructure, as well as the supervision of all its sub-systems as a whole, shall be carried out by an integrated control system, which will be characterized by a distributed, object-oriented architecture and a common software employed in the entire system. The EST control system shall also provide efficient management of the data and metadata produced by the facility, and their transmission from each sub-system to a real-time repository, as well as to users and to temporary and permanent archives [9]. Figure 1 show sections of the telescope and the facilities that host it.

Figure 1: Sketch showing the telescope, transfer optics, instrument platform, pier and building of EST.

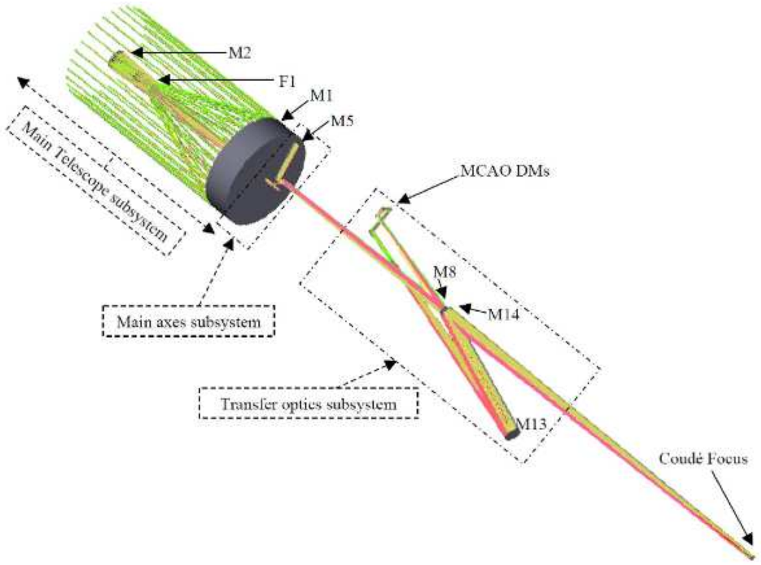

Figure 2: Optical path of EST showing the main telescope and the main axes and transfer optics subsystems, with all their optical elements.

3 Optical design

The main telescope has an on-axis Gregory-type configurationsee [11]. After two additional main optical subsystems, a diffraction-limited Coudé Focus is achieved in a spectral range from 0.39 μm to 2.3 μm. The optical design of EST can be divided into three main subsystems (see Fig. 2), where each one has a relative movement with respect to the others:

1. Main telescope (M1 and M2) defined by an on-axis Gregory-type configuration.
2. Main axes subsystem (M3 to M8), which integrates those mirrors that define the elevation and azimuth axes. This subsystem houses an on-axis magnification stage to produce the pupil used by the AO system.
3. Transfer optics subsystem (M9 to M14), whose mirrors transfer the light from the main axes subsystem to the Science Coudé Focus. This assembly integrates the MCAO mirrors in its light path and also works as the field-of-view de-rotator of the telescope.

The main telescope integrates an f/1.5 primary mirror. The secondary mirror defines the aperture stop of the whole system and produces an f/11.8 beam at the secondary focus (F2). A heat rejecter that also works as a field-stop is located at the primary focus (F1) to limit the field of view to the required unvignetted 2×2 arcmin^2. The entrance pupil of the system, which has a diameter of 4070 mm, is defined by the conjugation of the aperture stop

(M2) (whose diameter is limited to 800 mm) through M1, with 4100 mm in diameter. The inner central circular obscuration has been increased in the EST optical design from 148mm to 260 mm in diameter to provide a reasonable envelope for the heat rejecter.

M2 will be mounted on a hexapod [7], with 5 degrees of freedom (piston, δx, δy and slow tip-tilt) to perform active optics tasks. Besides, M2 could be used as a fast AO tip-tilt mirror, with a limited bandwidth. If a larger bandwidth is required, a second smaller and faster tip-tilt mirror, M6 (which is located in the main axes subsystem), will be used. Including fast tip-tilt and piston capabilities at M2 would provide an adaptive correction for the Nasmyth station.

M3 and M4 are tilted 45 degrees in perpendicular planes to auto-balance their instrumental polarization provided their reflection coatings have the same properties. This is the philosophy applied to the whole design in order to cancel the instrumental polarization introduced by the telescope. In the main axes subsystem, the ground-layer turbulence correction is also accomplished

4 Adaptive optics

In order to achieve the highest possible spatial resolution, EST shall be provided with powerful adaptive optics [1, 13]. On the one hand, it will have a ground layer adaptive optics system (GLAO), composed of a deformable mirror located at a pupil position, and a fast tip-tilt mirror. On the other hand, additional deformable mirrors are needed to increase the size of the corrected field of view. These DMs will be placed at positions which correspond to certain heights in the atmosphere. Such a multi-conjugate adaptive optics system is mandatory to achieve the required corrected FoV of 1 arcmin $\times$ 1 arcmin. The AO system will be integrated in the main telescope optical path in order to minimize the number of optical surfaces.

The telescope will also include active optics (aO) in order to maintain the alignment of the primary and secondary mirrors and the optical figure of the former, and to take into account alignment tolerances, changes of the gravity vector with elevation angle, temperature variations, or wind buffeting deformation. Continuous operation of the active optics system will be needed during all the telescope operation to guarantee the optical quality of the telescope, even when the adaptive optics in not in operation. Due to the baseline open air configuration of EST, dynamic effects derived from wind shake on the telescope structure and M1 wind buffeting deformation will degrade the optical quality of telescope.

4.1 GLAO

The GLAO is composed of the pupil DM and the tip-tilt mirror. According to the optical design, the pupil DM is M7 which is located at a pupil position. The optimum subaperture size that has been obtained, after a trade-off analysis between resolution (larger apertures) and degrees of freedom (smaller apertures), is 8 cm, corresponding to 50 subapertures across the pupil mirror, which means 51 actuators across the DM diameter. Approximately, 50% of the stroke of the actuators will be dedicated to compensating for atmospheric effects and

50% to telescope effects.

The tip-tilt mirror may be implemented at M2 or at M6 (or at both positions, if two tip-tilt mirrors are considered). M2 defines the telescope pupil and will include fast tip-tilt and focus capabilities in order to provide some wavefront correction to the Nasmyth focus, which cannot take advantage of the AO system correction. M2 fast tip-tilt and focus correction capabilities will compensate for a large fraction of the wavefront distortions produced by the deformation of M1 induced by wind buffeting in open air conditions, since it makes feasible the correction for piston and focus errors, in addition to the tip-tilt components. These capabilities are also useful for the Coudé path, since fast capabilities of M2 can reduce the load on the rest of the AO system. Due to the large size of M2 (800 mm), the correction bandwidth of this mirror will be limited. Consequently, the possibility to implement a second smaller and faster tip-tilt mirror at M6 has been foreseen.

4.2 MCAO

The MCAO optical design (and especially the number and size of the conjugate high altitude DMs) depends on the turbulence (Cn2) stratification with height above the telescope site. An obstacle lies in the large zenith angles (in the morning) that are typical for solar observations, leading to effective turbulence heights varying over a wide range. The proposed configuration is based on four conjugated DMs (M9-M12) at fixed positions, in order to reduce the height mismatch between the DMs and the turbulence layers caused by a zenith angle varying during the day. The optical design allows some flexibility to adapt the position of the conjugated DMs without dramatic changes in the optical layout.

Due to the proposed design of the transfer optics system as a de-rotator, a relative rotation will be produced between the pupil DM and the MCAO DMs during telescope operation. The effect of the differential rotation on the MCAO performance has been analysed and considered minor if each DM keeps the orientation of its actuator pattern with respect to the respective WFS.

4.3 Active optics

Considering the size of the telescope and primary mirror, the telescope shall include active optics in order to keep the alignment and optical figure of the mirror compensating for initial alignment tolerances, changes in the gravity vector with elevation angle, temperature variations or wind buffeting. Continuous operation of the active optics system will be needed throughout the telescope operation in order to guarantee the optical quality of the telescope, and also when the adaptive optics is not operated.

Through the control loops, depending on the frequency domain of the correction, some effects (perturbations) can be dispatched to alternative compensators. At the first stage, the image motion generated by predictable low frequency perturbations will be controlled by the telescope guiding or the M6 tip-tilt mirror, with a range up to few arcsec. Unexpected perturbations and residuals of medium frequency should be corrected in closed-loop by a second stage. These medium frequency residuals cannot be controlled by the guiding system and the M2 tip-tilt mirror could be in charge of this correction. This correction would penalize the image quality, though, by increasing the coma of the image, and corrections in the range ± 3 arcsec, approximately, are allowed to fulfill the image quality requirement. The final stage of corrections, where the higher frequencies are compensated, is definitely accomplished by the DMs of the AO system.

5 Instruments

The instruments are distributed in the Coudé room in two floors, the upper one dedicated to imagers and the lower one to grating spectrographs. The instrument layout takes into account the current design of each instrument type and the possibility of adding two additional guest instruments (one in the visible beam and one in the NIR beam).

The instrument layout has been designed with the instruments static on a concrete slab (field rotation being provided by transfer optics). The light coming from the telescope is shared among the following instruments channels:

- Three visible broad-band imaging channels [10].
- Five narrow-band imager channels: three operating in visible wavelengths and two in the near-infrared (NIR).
- Four grating spectrographs: two for the visible spectral range and two for the NIR. These spectrographs are versatile and can operate in different configurations, using adequate additional modules. There are four possible configurations [5]:
  - Long-slit standard spectrograph.
  - Multi-slit multi-Wavelength spectrograph equipped with an integral field unit [6].
  - Tunable universal narrow-band imaging spectrograph.
  - Multi-channel subtractive double-pass spectrograph of new generation.

The light distribution among the instruments (see Fig. 3) is based on a division of the main beam coming from the transfer optics by a main dichroic D1 in two spectral stations: one for visible wavelengths and another for near-infrared. This division makes it possible to optimize the light flux transmission (after the beam separation, coating optics can be optimized for the selected spectral range at each station).

After the intensity beam-splitter BS5, the transmitted beam goes to the scanning unit of the two NIR spectrographs (a single unit for both). This unit is based on a quad-mirror (i.e. two pairs of 45-incidence mirrors, for which the lines that connect the centre of the mirrors of each pair are perpendicular to each other. This way, the FoV of the telescope can be scanned in both directions to select the adequate FoV for the spectrograph without affecting the imaging instruments. For the visible branch, one similar quad-mirror is located in the beam reflected by BS1 to scan the entrance FoV of the visible spectrographs. In addition, these quad-mirror scanning systems can also focus the image at the entrance focal plane of the spectrographs.

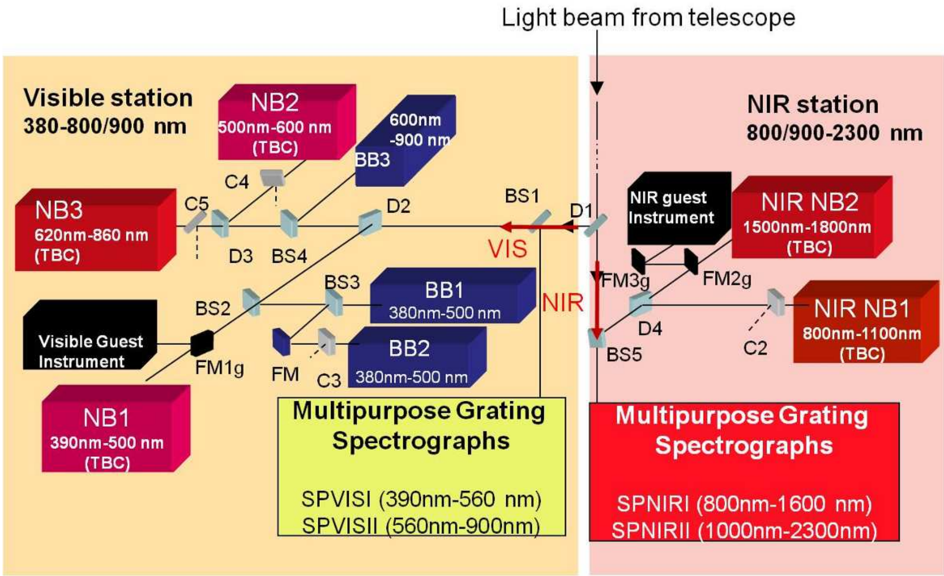

Figure 3: Light distribution for the instruments of EST. Labels Dn correspond to dichroic mirrors splitting light in wavelength, labels BSn stand for intensity beamsplitters, and labels FM refer to folding mirrors. BBn indicate the broad-band imagers, NBn the narrow-band instruments and SPn the spectrographs.

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