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LIST OF ABBREVIATIONS

AFDT  Auxiliary Full-Disk Telescope
ALT-AZ ALTitude AZimuth
AIV   Assembly, integration and verification
aO    Active Optics
AO    Adaptive Optics
ATST  Advanced Technology Solar Telescope
BASS  Bases de données Solaires Sol (Ground Solar Data Base)
BB    Broad Band imager
CCD   Charge Coupled Device
CFD   Computational Fluid Dynamics
CIMNE International Center for Numerical Methods in Engineering
CM    Collimated mount
CMOS  Complementary Metal Oxide Semiconductor
CORBA Common Object Request Broker Architecture
CoG   Centre of Gravity
COTS  Commercial Off The Shelves
C³Po  Charge Caching CMOS detector for Polarimetry
CVD SiC Chemical Vapour Deposition Silicon Carbide
DCS   Distributive Control System
DoF   Degrees of Freedom
DOT   Dutch Open Telescope
DM    Deformable Mirror
DST   Dunn Solar Tower
ECS   EST Control System
ESO   European Southern Observatory
EST   European Solar Telescope
<table>
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<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>ETH</td>
<td>Eidgenössische Technische Hochschule or Swiss Federal Inst. of Technology</td>
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<tr>
<td>FE</td>
<td>Finite-element</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<tr>
<td>FLC</td>
<td>Ferro-electric Liquid Crystal</td>
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<tr>
<td>FOSP</td>
<td>Fiber-Optics based Spectrograph</td>
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<tr>
<td>FoV</td>
<td>Field Of View</td>
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<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
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<tr>
<td>FPI</td>
<td>Fabry Perot Interferometer</td>
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<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
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<tr>
<td>GLAO</td>
<td>Ground Layer Adaptive Optics</td>
</tr>
<tr>
<td>GPU</td>
<td>Graphics Processing Units</td>
</tr>
<tr>
<td>GTC</td>
<td>Gran Telescopio Canarias (Large Telescope of Canary Island)</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>IAC</td>
<td>Instituto de Astrofisica de Canarias</td>
</tr>
<tr>
<td>IBIS</td>
<td>Interferometric BIdimensional Spectrometer</td>
</tr>
<tr>
<td>IFU</td>
<td>Integral Field Unit</td>
</tr>
<tr>
<td>IR</td>
<td>Infra Red</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
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<tr>
<td>LsSS</td>
<td>Long-Slit Standard Spectrograph</td>
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<tr>
<td>M1</td>
<td>Primary Mirror</td>
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<td>M2</td>
<td>Secondary Mirror</td>
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<tr>
<td>MCAO</td>
<td>Multi Conjugated Adaptive Optics</td>
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<tr>
<td>MIR</td>
<td>Mid Infra-Red</td>
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<tr>
<td>MOMFBD</td>
<td>Multi-Object Multi-Frame Blind Deconvolution</td>
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<tr>
<td>MSDP</td>
<td>Multi-channel Subtractive Double Pass spectrograph</td>
</tr>
<tr>
<td>MSDP-NG</td>
<td>Multi-channel Subtractive Double Pass spectrograph New Generation</td>
</tr>
<tr>
<td>MSMWSP</td>
<td>Multi-Slit Multi-Wavelength SPectrograph</td>
</tr>
<tr>
<td>MT EST</td>
<td>Main Telescope of EST</td>
</tr>
<tr>
<td>MTF</td>
<td>Modulation Transfer Function</td>
</tr>
<tr>
<td>NB</td>
<td>Narrow Band tunable filter spectropolarimeter (also Narrow Band imager)</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infra Red</td>
</tr>
<tr>
<td>NSO</td>
<td>National Solar Observatory</td>
</tr>
<tr>
<td>ORM</td>
<td>Observatorio del Roque de los Muchachos (Roque de los Muchachos Observatory)</td>
</tr>
<tr>
<td>OT</td>
<td>Observatorio del Teide (Teide Observatory)</td>
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1 SUMMARY

This document presents a summary of the results of the Conceptual Design Study of the European Solar Telescope (EST), a project for a 4-metre telescope to be located in the Canary Islands. This project is promoted by the European Association for Solar Telescopes (EAST), which is a consortium formed by a number of research organizations from fifteen European countries (Austria, Croatia, the Czech Republic, France, Germany, Hungary, Italy, the Netherlands, Norway, Poland, the Slovak Republic, Spain, Sweden, Switzerland and the United Kingdom). The Conceptual Design has been possible thanks to the co-financing allocated specifically by the EU and the combined efforts of many people committed to developing new ideas to make this telescope a unique infrastructure to study the Sun. The participation in the Design Study of fifteen private companies, with their expertise and knowledge in particular areas, has also been crucial for the successful achievements described in the following pages and in the large number of technical documents produced since the project started three years ago. The funds received from the EU, through an FP-7 Collaborative Project, have made it possible to join together all these research institutions and private companies, with their scientific and technical skills.

In the following sections, a short description of the proposed solution for the telescope itself and all its subsystems is presented. This description is derived from the best alternatives found for each subsystem during the Design Study. More detailed explanations can be found in the documents produced by the different work-packages on each subject.
2 INTRODUCTION

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 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 two combined aspects will make of EST a unique infrastructure.

The complementary performance of the instruments of EST will allow us to produce a three-dimensional view of regions on the solar atmosphere with unprecedented spatial, temporal, and spectral resolution. Imaging instruments have the capability to take the performance of the telescope to the limit and reach the diffraction limit of its optics. They will enable us to study details of the interaction between the plasma and the magnetic fields that are unresolved in current observations. Spectrometers moreover have the 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 allow us 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 in the photosphere, transported, and then 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 on the technical design to achieve the ambitious goal of EST. On the one hand, EST will have a powerful multi-conjugate adaptive optics system the like of which no other telescope has or will have in the near future. The atmosphere above the telescope distorts the incoming wavefront of the light, resulting the deterioration of 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.
The aperture of a telescope is the essential characteristic in determining its resolving power, but until recently ground-based solar telescopes have been more limited by the effects of atmospheric distortions that disturb the incoming wavefront. New powerful adaptive optics systems are now able to overcome a large fraction of the atmospheric distortion. This has not only given us tantalizing glimpses into the very fine scale structures on the solar surface, but has also shown that these systems are now so mature that our ability to resolve small details is now limited by the size of the telescopes themselves, and not by the atmospheric distortions. We are now poised to probe some of the most essential questions about the physics of solar activity and variability.

On the other hand, the magnetic field plays a fundamental role in the physical processes taking place in the solar atmosphere and leaves its imprint on the polarization of the light coming from the Sun. Consequently, 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 thus 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.

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. A site-testing campaign has been started during the Design Study to compare the two locations and find the optimum site. This campaign will be extended for several years to increase the statistical significance of the differences between the observatories, should they exist. The final decision on the site will have to be taken some time before construction starts.

With EST, Europe will be at the frontier of Solar Physics research, vindicating the philosophy that joint European efforts are worthwhile and necessary.
3 BASELINE CONFIGURATION

EST is a 4-metre class solar telescope with an on-axis Gregory configuration, aiming at superb polarimetric performance. It will have a main instrumentation station at the Coudé focus with three types of instruments, each one composed of different channels to observe different wavelengths: broad-band imagers, narrow-band tunable filter spectropolarimeters and grating spectropolarimeters.

The telescope includes active and multi-conjugate adaptive optics integrated in the telescope optical path between the primary mirror and the instrument focal plane in order to maximize the telescope throughput and provide a corrected image at the Coudé focus for the three types of instruments simultaneously. The active optics system is composed of M1, M2 and different mirrors of the optical path. The adaptive optics system is composed of a fast tip-tilt mirror and a pupil deformable mirror (DM), and up to four DMs conjugated at different heights.

The optical design is based on an aplanatic Gregorian telescope with three magnification stages which finally yield an f/50 telecentric science focus. 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. This configuration allows the maximum number of capabilities: polarization compensation (Mueller matrix of the optical design ~1), integrated optical field de-rotation capabilities, telecentric design, collimated beam at AO system and four MCAO DM mirrors conjugated at different heights.

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 1.5m 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. The 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.

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 (2 or 3 TBC). 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.

The 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 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 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. The alternative of providing a rotating instrument platform in the Coudé room to compensate the field rotation has also been developed during this design study, but was not preferred because of the limitations it implies for the instrumentation.

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. Fast tip-tilt and focus correction capabilities will be provided additionally to M2 in order to correct these effects at the Nasmyth focal station, which cannot take advantage of the correction of the AO system placed in the Coudé path.

The baseline telescope enclosure is completely foldable. 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, 33-38m 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.

A building containing the required control and support installations and facilities will be attached to the tower, providing access to the telescope pier. An additional auxiliary building containing the facilities which might otherwise degrade the telescope performance (due to vibration or air heating produced by the power plant, pumps, water coolers, etc.) will be placed far enough from the telescope tower in order to have no impact on local seeing.

The EST facilities will include an auxiliary full disc telescope that will be used to give the observer a global context of the solar activity and for precise coordinate measurements.
Figure 3.1. Section of EST.
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.

Figures 3.1, 3.2, and 3.3 show sections of the telescope and the facilities that host it.
Figure 3.3. View of EST facilities.
4 OPTICS

4.1 Optical Design

The EST optical design will form an image of the Sun at its Science Coudé Focus providing the scientific instrumentation with an object plane. This chapter describes the EST optical design and optical elements (mirrors), some of which are also used as active and adaptive elements. The active optics scheme is also presented.

4.1.1 Design requirements

The design of the optical system of EST is constrained mainly by the science requirements. However, there are also some fundamental requirements that drive the design:

1. EST must have an entrance-pupil equivalent to a circular aperture of diameter 4 metres. With this, it will provide a significantly improved angular resolution over what is achievable with the current 1-metre class telescopes. The increase in resolution will allow reaching the small spatial scales required to study the solar magnetic phenomena.

2. EST must cancel the instrumental polarization introduced by the telescope. This entails the polarization of the incoming light not being modified, independently of the pointing of the telescope to any direction on the sky. This property must hold for all wavelengths.

3. EST must provide excellent image quality, limited by diffraction over a circular FoV of 1 arcmin in diameter through a wavelength range from 0.39 \( \mu \text{m} \) to 2.3 \( \mu \text{m} \). The system must be seeing-limited in an unvignetted FoV of 2\( \times \)2 arcmin\(^2\).

4. EST must have high-order AO and MCAO systems integrated into the main telescope light path to provide the highest possible spatial resolution.

5. EST must be optimized to give a high throughput, being composed of a minimum number of optical surfaces.

6. The Science instruments of EST have to operate simultaneously to maximize operational efficiency.

4.1.2 General description of the optical system

EST will have an on-axis Gregorian configuration in its main telescope to achieve, after two additional main optical subsystems, a diffraction-limited Coudé Focus in a spectral range from 0.39 \( \mu \text{m} \) to 2.3 \( \mu \text{m} \) that also shows a good polarimetric performance. It will supply a main station with three types of instruments (broad-band imagers, narrow-band tunable filter spectropolarimeters and grating spectropolarimeters) each one comprising different channels to observe different wavelengths simultaneously.

The telescope includes a multi-conjugate adaptive optics system that is integrated into the telescope optical path. This provides simultaneously a corrected image at the Coudé Focus for the three types of instruments mounted on the instrument platform.

EST can be divided into three main subsystems (see Figure 4.1), where each one has a relative movement with respect to the others:
1) The first is the **main telescope** (M1 and M2) defined by an on-axis Gregorian configuration.

2) The second is the **main axes subsystem** (M3 to M8) and integrates those mirrors that define the elevation and azimuth axes. This subsystem houses an on-axis magnification stage (M5) to produce the pupil used by the AO system.

3) The third is the **transfer optics subsystem** (M9 to M14) whose mirrors transfer the light from the main axes subsystem to the Science Coudé Focus. In addition, this assembly integrates the MCAO mirrors inside its light path and also works as the field de-rotator of the telescope. This subsystem houses two off-axis magnification stages (M9 and M13) to get an adequate f-ratio at the MCAO post-focus DMs and the Science Coudé Focus.

EST will have active optics in open and closed loop fed, respectively, by the telescope behaviour model and by the measurements of two wavefront sensors. The latter, which also closes the AO loop, are located before and after the transfer optics subsystem reporting the Science Coudé Focus performance and the correction capabilities of the active and adaptive elements.

The instruments, placed at the Science Coudé Focus and consisting of different channels, will be enclosed in an instrumentation laboratory with a controlled environment. A light distribution unit consisting of dichroic and intensity beam–splitters will be placed at the Science Coudé Focus feeding different instrument channels and accomplishing different ways of light distribution using a flexible number of simultaneous instruments/channels.

### 4.1.3 Optical configuration

Figure 4.1 shows the complete layout of the EST optical design. The different subsystems of the nominal design are detailed below:

#### 4.1.3.1 Main telescope subsystem

Table 4.1 details the surface data summary of the elements integrating this subsystem. The on-axis Gregorian main telescope integrates an f/1.5 primary mirror (M1) and a secondary (M2), defined as the aperture stop of the whole system, which gives an f/11.8 Gregorian 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 $2 \times 2$ 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, typical from the Gregorian aperture stop, has been increased in the EST optical design from 148 mm to 260 mm in diameter, the reason being the necessity of providing a reasonable envelope for the heat rejecter.

M2 will be mounted on a hexapod, with 5 degrees of freedom (piston, $\delta x$, $\delta y$ 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 for M2 would provide an adaptive correction for the Nasmyth station.
Table 4.1. Surface data summary of the elements of the main telescope.

<table>
<thead>
<tr>
<th>Element</th>
<th>Radius (mm)</th>
<th>Distance to next element (mm)</th>
<th>Diameter (mm)</th>
<th>Conic constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>-12426.51</td>
<td>6213.25</td>
<td>4100.16</td>
<td>-0.9946</td>
</tr>
<tr>
<td>F1 (Heat Rejecter)</td>
<td></td>
<td>1186.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>2102.31</td>
<td>8900.00</td>
<td>775.15</td>
<td>-0.6146</td>
</tr>
</tbody>
</table>

The fulfilment of the envelope diameter (225 mm) for the heat rejecter leads to an M1 hole increased by 290 mm with respect to the M2 diameter, giving an inner hole of 677 mm in radius.

The telescope elevation axis is located 1.5 m below the primary mirror vertex and the azimuth and elevation axes are decentred with respect to the optical axis of the main telescope because the optical path is folded in an asymmetric way to produce a polarimetrically compensated performance, with a telescope Mueller matrix that is independent of the telescope elevation and azimuth angles, for all wavelengths.
4.1.3.2 Main axes subsystem

Table 4.2 details the surface data summary of the elements integrated in this subsystem. For the purpose of analysing the polarimetric performance of the rest of the telescope, a truly polarization-free focus just before M3 is foreseen. Only the rotationally symmetric M1 and M2 and its spider, which is also symmetric, will be located in front of it. Here, a polarization calibration unit will be located.

After the polarization unit, the elevation axis is defined by the flat mirrors M3 and M4 (see Figure 4.2). Both 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. The on-axis parabolic collimator mirror M5 generates a pupil in M7 (pupil DM) through a nearby flat M6 which, if necessary, will have pupil fast tip-tilt correction capabilities.

<table>
<thead>
<tr>
<th>Element</th>
<th>Radius (mm)</th>
<th>Distance to next element (mm)</th>
<th>Diameter (mm)</th>
<th>Conic constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3</td>
<td>Infinity</td>
<td>100</td>
<td>75.47</td>
<td>0</td>
</tr>
<tr>
<td>M4 (Elevation axis)</td>
<td>Infinity</td>
<td>200</td>
<td>63.22</td>
<td>0</td>
</tr>
<tr>
<td>F2 (f/11.8)</td>
<td></td>
<td>2150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td>-4300</td>
<td>1985</td>
<td>216.93</td>
<td>-1</td>
</tr>
<tr>
<td>M6 (Tip-Tilt)</td>
<td>Infinity</td>
<td>667.45</td>
<td>275.82</td>
<td>0</td>
</tr>
<tr>
<td>M7 (Pupil DM)</td>
<td>Infinity</td>
<td>19000</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.2. Surface data summary of the elements of the main axes subsystem.
4.1.3.3 Transfer optics subsystem

Table 4.3 details the surface data summary of the elements integrated in this subsystem. The MCAO stage has been integrated in the transfer optics, after the main axes subsystem, in order to keep the pupil well stabilized. Nineteen metres further on from the main axes subsystem, the transfer optics subsystem has a tilted 2-metre off-axis ellipsoid (M8) allowing the post-focus location of the four MCAO DMs (M9, M10, M11 and M12 respectively), conjugated at 30, 15, 9 and 5 km (see Figure 4.3). The exact heights and the number of mirrors may change depending on future MCAO studies and turbulence measurements at the Canarian observatories. The current MCAO assembly has its mirrors tilted 45 degrees in perpendicular planes to keep the instrumental light polarization invariable. One of the advantages of this design is that the exact tuning with height of the DMs does not have any impact on the optical concept of the telescope, in the current phase.

The second magnification stage of the transfer optics includes a tilted off-axis ellipsoid (M13) that conjugates the MCAO focus into the f/50 Science Coudé Focus through the flat M14. This is assembled to send the Coudé Focus light downward in the same direction as the light path that goes to M8 in order to provide field de-rotation capabilities.
### 4.1.3.4 Optical design criteria and image performance

Several designs were analyzed during the EST project. The optical design described above, with a total of 14 reflections proved to fulfill all the required functionalities with the least number of elements. These functionalities are: polarization compensation, optical field de-rotation, a pupil deformable mirror in a collimated beam, and an MCAO system with 4 mirrors conjugate at different altitudes. In addition, the multi-conjugate adaptive optics system is integrated into the telescope optical path and simultaneously provides a corrected image at the Coudé Focus for the three types of instruments settled in the instrument platform.

The minimum required number of mirrors in the EST baseline design is eleven: five mirrors with power to generate the four focal planes and the pupil plane, and six mirrors for the AO and MCAO systems (one tip-tilt mirror and five DMs - one for the ground layer and four conjugated at different high-altitude layers). For the EST optical design, three additional flat mirrors (M3, M4 and M14) were also added to its basic layout. The first two, M3 and M4, balanced in polarimetry due to their incidence-reflection perpendicular planes, define the elevation axis of the telescope. M14 sends the light in a suitable direction towards the instrument platform.

Making the length of the M13-M14-F4 light path as long as possible was mandatory in order to provide space to distribute the light to the science instruments.

Since the off-axis elements of the system have been de-centred from the Y axis, the telescope shows symmetry around the X axis. This behavior is transferred to the image in F4 whose diagram is symmetric about the X axis.

In accordance with the specifications, the Science Coudé Focus (F4) performance gives an f/50 light cone with a theoretical effective focal length of 194345 mm, giving rise to a plate scale of 1.06 ”/mm. The main contributions to the F4 image aberrations in full field come from tilt Y (Z5), coma Y (Z7) and astigmatism X (Z4). Of all of these, the largest contribution is caused by tilt Y (Z5), generated by the two off-axis conics M9 and M13. This gives rise to a geometrical spot size of 0.025 arcsec diameter (centroid RMS) at a 1 arcmin field diameter (limited by diffraction) and 0.127 arcsec diameter (centroid RMS) at a 2×2 arcmin field (limited by seeing).
The relative energy transferred from the PSF central disc to its ring area drops the peak intensity to a Strehl ratio (SR) of 0.91 (at 0.4 μm) in the EST diffraction-limited field-of-view.

The previous descriptions consider a circular pupil without apodization. However, the pupil obstruction produced by the heat rejecter and the spiders are factors in the system that also affect the intensity distribution within the diffraction pattern, apart from the wavefront aberrations. The central obscuration of the aperture stop, which in EST covers 11.14% of the total area of M1, degrades the image in F4 causing a reduction in the Strehl ratio and a decrease in mid-spatial frequencies in the MTF. The annular pupil gives rise to larger values of the MTF at high frequencies (between 30 mm⁻¹ and 40 mm⁻¹) but lower values at low frequencies (below 30 mm⁻¹), compared to the MTF for the corresponding circular pupil. Figure 4.4 shows the MTF diagram in F4 for the diffraction-limited FoV of Ø 1' where the effects of the EST annular pupil have been taken into account.

![Figure 4.4. MTF diagram in the Science Coudé Focus F4 for the diffraction-limited FoV of Ø 1'](image)

4.2 Adaptive Optics

In order to achieve the highest possible spatial resolution, EST shall be provided with powerful adaptive optics. 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 1arcmin x 1arcmin. 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. It will be crucial to provide the possibility of correcting them continuously with the active optics system and the tip-tilt mirror. AO and aO shall work as a single system, with the aO integrated into the AO architecture.

The high level requirements specify the optical quality of the images when the MCAO is operating in closed loop: a spatial resolution of 0.04" (with a goal 0.03") must be achieved at a wavelength of 500 nm. The requirement has been translated (see Table 4.4) into a value of SR=0.4 within a FoV of Ø30 arcmin and SR = 0.3 within a FoV of Ø1 arcmin, for \( r_0 \geq 20 \) cm at \( \lambda = 500 \) nm up to the instruments detector plane. An additional requirement has been included to define the optical quality for closed loop MCAO operation in normal seeing conditions \( (r_0=10\, \text{cm}) \). The proposed requirement is SR = 0.25 (TBC) within a FoV of Ø30 arcmin and SR=0.15 (TBC) within a FOV of Ø1 arcmin for \( r_0 > 10 \) cm at \( \lambda = 500 \) nm up to the instruments detector plane.

<table>
<thead>
<tr>
<th>( r_0(\text{cm}) )</th>
<th>20</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.4</td>
<td>0.25</td>
</tr>
<tr>
<td>60</td>
<td>0.3</td>
<td>0.15</td>
</tr>
</tbody>
</table>

*Table 4.4: Optical quality requirements when the MCAO is operating, for two different seeing conditions and corrected FoV, at a wavelength of 500 nm.*

4.2.1 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. According to the optical design, the actuator pitch will be 5 mm in one axis and 3.6 mm in the other axis, which are feasible values for conventional piezoelectric-actuator deformable mirrors (e.g. CILAS or Xinetics). The stroke required for the DM actuators is, approximately, 12 µm peak-to-valley, which is also a feasible value for conventional piezoelectric mirrors with the required pitch. Approximately, 50% of this stroke will be dedicated to compensating for atmospheric effects and 50% to telescope effects. This value of the stroke includes the extra stroke required due to the placement of the DM at 45° with respect to the optical beam.

CILAS has developed liquid-cooled prototypes of DM mirrors for solar application and these are considered for the application in EST.

The tip-tilt mirror can 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 (Ø800 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. M6 is located at, approximately, 700 mm from the pupil M7, hence it is close enough to the pupil position to be used as a tip-tilt mirror. Should a sufficient bandwidth be achieved with M2, this mirror will be used as the main AO tip-tilt mirror, avoiding the implementation of M6 as tip-tilt mirror.

4.2.2 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 position of the conjugate DMs were initially fixed at 5, 9, 15 and 30 km for the optical design, being optimized during the design study. The optimal positions obtained are 1, 3, 13 and 25 km, hence the optical design shall be updated for these optimized positions. The optical design allows some flexibility to adapt the position of the conjugated DMs without dramatic changes in the optical layout. The spatial sampling assumed on the pupil is 10, 17, 34 and 56 cm respectively, corresponding to a mirror actuator pitch of 3 mm in one axis and 4.2 mm in the other axis for all the mirrors.

The MCAO conjugated mirrors can be by-passed by flattening them whenever the MCAO is not used. Since the MCAO will only correct a partial region of the FoV of the telescope, and to make their operation compatible with a FoV of 2'x2', the DMs must be manufactured with a deformable central area Ø1.4 arcmin (1'x1'), the outer part of the mirror being non-deformable and flat.

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.

4.2.3 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.

The motion and aberrations of the image and the pupil are caused by the perturbations and misalignments originating from the operation of the telescope. The active optics compensators needed to correct the image quality and position, and the pupil position are shown in Table 4.5. The compensators have been selected according to their direct implementation for the effect to be corrected.
Effect to correct | Compensator
---|---
Image motion in F2 | Telescope Guiding
Lateral pupil motion in DM0 | Dx and Dy in M2
Image Quality in F4 (Science Focus) | M2-Dz, M2-TiltX, M2-TiltY, M1-Figure (Z4, Z5, Z8, Z9, Z10)
Image motion in F4 (ref. chief ray) | M6-TiltX, M6-TiltY
Centroid Pupil motion in F4 | M14-TiltX, M14-TiltY
FoV centering on MCAO’s DMs | To Be Confirmed

Table 4.5. Effects of the perturbations in the system and compensators defined to re-balance the optical performance.

Through the control loops, depending on the frequency domain of the correction, some effects (perturbations) can be dispatched to other alternative compensators different from those defined in Table 4.5. 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. However, 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 to 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. The effect-compensator pairs are defined in Table 4.5.

4.2.4 Wavefront sensing

The light required for the wavefront sensor needed to provide feedback for the aO and AO systems shall be taken from the optical path at appropriate locations, at F3 and F4. The wavefront sensor shall be able to provide sensing for different observing modes.

The operation of the active optics needs feedback from the wavefront sensor in order to guarantee performance, so the wavefront sensing shall be in operation although the telescope is operating without AO system. Otherwise, the active optics operation must rely on previously established tables with the modelled behavior of the telescope alignment and mirrors figure for different telescope conditions (elevation angle and temperature). This operation without wavefront sensor feedback can only correct for effects produced by very repeatable conditions and not, for example, for the effect of wind buffeting.

The proposed WFS is a Shack-Hartmann sensor, well known in solar telescopes. It allows operation down to η = 6 cm, tracking on granulation at λ = 500 nm. The main drawback of this sensor is the large number of pixels required for the WFS camera and the high computational power required. A completely new sensor, based on a CAFADIS camera, where microlens arrays are placed in the image plane instead of the pupil plane, is also being investigated, although the baseline for EST is Shack-Hartmann since there is no practical experience using CAFADIS cameras in adaptive optics.
4.2.4.1 Position and geometry of the Shack-Hartmann Wavefront Sensors

The proposed sensor configuration is composed of one narrow field high order sensor for the centre of the field of view and one wide field low-order (less apertures) sensor that samples the field-dependent and weaker aberrations of the high-altitude turbulence. The high order WFS will be placed at F3 after the pupil DM whereas the low-order WFS will be placed at the science focus F4 in order to take into account the wavefront degradation produced along the complete telescope optical path (see Figure 4.5). Both wavefront sensors will be used for pupil guiding also.

The main design driving parameter for a Shack-Hartmann sensor (see Figure 4.6) is the size of the lenslet array. The main component which determines the performance of the WFS is the WFS camera. For EST it has to be large (> 1200 x 1200 pixel) and fast (> 2 kHz).

Based on the design philosophy, which is also followed in GREGOR and the VTT, the WFS configurations are described in Tables 4.6 and 4.7.

![Figure 4.5. Layout of DMs and WFSs placement.](image)

![Figure 4.6. Optical scheme for the EST WFS](image)

The appropriate number of subapertures across the telescope diameter is 50. As an example we choose a lenslet size of 0.4 mm. This yields a pupil diameter of 20 mm. The ground layer WFS (narrow field) will be placed in F3. Here, a collimator focal length of 550 mm is needed to obtain the desired pupil size. The total length of the unfolded WFS will be in the order of 1 m.
The WFSs shall keep the orientation of the microlens patterns with respect to the actuator patterns of the respective mirrors. Due to the proposed design of the transfer optics as a de-rotator, if the high-order WFS is placed at F3 inside the transfer optics, it will be necessary to de-rotate it in order to keep the orientation with respect to the pupil DM, which is fixed to the telescope structure. In the same way, if the low-order WFS is placed at F4 in the Coudé room, it will be necessary to rotate it to keep the orientation with respect to the MCAO DMs, which rotate with the transfer optics system.

4.2.4.2 The cross-correlating Shack-Hartmann sensor

The proposed cross-correlation technique is based on a difference-squared correlation combined with 2D quadratic interpolation, which provides the most exact shift measurement. The size of the correlation function could be ±4-5 pixels, which is sufficient for a stable closed-loop operation and does not cause computational problems. The FoV of the correlation field should be about 10°, sampled in 2×20 or better 24×24 pixels, depending on the WFS cameras available.
in the future. If 24×24 pixels are used, the FFT-based cross-correlation is also possible, with the advantage of providing the full 24×24 pixel correlation function.

4.2.5 Wavefront reconstruction

4.2.5.1 Reconstruction algorithms

Present high performance AO systems are based on a modal approach that allows better optimization and real time control as compared to non-modal control. The optimum set of modes is the one where, for each mode, the DM removes as much phase variance as possible from the atmosphere. The modal basis is therefore the result of diagonalizing the statistical (atmospheric) covariance matrix and the geometrical (DM) covariance matrix simultaneously. This kind of DM-based optimized modal basis is presently being used at the Keck AO and at the VLT NAOS, and therefore both effective and well understood.

The actual reconstruction is done in two steps:

First, the shift vector (containing the shifts of all WFS cameras) is converted into the mode vector (containing the modes of all DMs + tip-tilt mirror). The invoked matrix depends on the geometry of the WFS(s) with respect to the DMs and changes, e.g. if subapertures get obstructed/re-illuminated by the rotating spider. Furthermore, concerning the MCAO, it also depends on the way of separating and distributing the turbulence on the DMs (tomography). During an MCAO test run at the NSO Dunn Solar Telescope, Sacramento Peak, in 2009, two different methods were tried successfully. The final analysis of the data is still pending. Furthermore, the MCAO test-bed of the GREGOR telescope is operational and will allow optimization of the shifts-to-modes reconstruction.

Secondly, after applying the modal gains / filters, the resulting mode vector is converted into the actuator vector (again, containing the actuators of all DMs + tip-tilt mirror). The invoked matrix is fixed (except for broken actuators, etc.) because it only depends on the DM / actuator geometries and the atmospheric statistics, assumed to be Kolmogorov.

At present, advanced reconstructors that adapt to the turbulence statistics are being analysed and tested. However, during real observations the improvement turns out to be only minor, whereas the system / reconstruction complexity grows considerably. Therefore, telescopes such as the VLT or Keck still apply the above reconstruction scheme, together with a simple PI (proportional / integral) servo.

4.2.5.2 Performance simulation

Performance simulations of the EST MCAO system have been carried out using CIBOLA software and CAOS software.

The impact on the MCAO performance of different system configurations has been evaluated:

- Different number of apertures and aperture size
- Different Cn² profiles
- Different number of sensing fields at WFS
- Different spatial sampling at conjugated DMs
- Different number and positions of DMs
- Performance at different zenith angles
The best results show $SR = 0.82$ at the centre of the field for $r_0 = 20$ cm with a wind speed of 10 m/s, for a pupil sampling of 8 cm and a bandwidth (-3 dB) of 300 Hz (see Figure 4.7).

![Figure 4.7](image1)

*Figure 4.7. MCAO performance simulation for different subaperture sizes as function of $r_0$ for a wind speed of 10 m/s and a bandwidth (-3 dB) of 300 Hz. Larger subapertures give rise to lower values of $r_0$*

The best results obtained in the complete field of view of $\theta 1$ arcmin, for telescope pointing to a zenithal angle of 60º, assuming the pupil DM and four conjugated DMs at the optimized positions (1, 3, 13 and 25 km) and WFS sensing on 19 sensing fields, are $SR = 0.7$ at the centre of the field of view and $SR = 0.5$ at the border for $r_0 = 20$ cm, and $SR = 0.35$ at the centre and $SR = 0.2$ at the border for $r_0 = 10$ cm (see Figure 4.8).

![Figure 4.8](image2)

*Figure 4.8. MCAO performance for the complete corrected FoV=1arcmin at 60º zenith angle for $r_0=10$ cm, 15 cm and 20 cm. Large $r_0$ values give rise to large Strehl ratios.*
Reducing the corrected field of view from 1 arcmin to 30 arcsec, the MCAO performance also improves at the border of the field of view (see Figure 4.9). This operation can be performed on the fly, selecting a smaller field of view in the wavefront sensor.

In conclusion, even though more tests are needed to optimize the performance of the MCAO system, the simulations demonstrate that, for the worse situation with a zenithal angle of 60°, the requirements can be achieved for both seeing conditions ($r_0 = 20$ cm and $r_0 = 10$ cm) and both corrected FoV (30 and 60 arcsec). Smaller zenithal angles lead to better SR values.

### 4.3 Polarimetry

This section contains the aspects that have impact on the polarimetry. It analyses the possibilities for a conceptual polarimeter design, estimates its performance and concludes with a baseline design.

#### 4.3.1 Requirements

Precise and sensitive polarimetry forms a cornerstone for EST. For this reason, we have analysed the polarimetric characteristics from the very beginning in the conceptual design process, both in terms of the optical design (with its Adaptive Optics and Multi-Conjugate Adaptive Optics systems), the location of the calibrators and modulators, as well as calibration strategies and the choice of coatings and detector types.

The Science requirements for EST list specifications for both the polarimetric sensitivity and accuracy. The polarimetric sensitivity of EST should be $3 \times 10^{-5}$ S/I, where S is any Stokes parameter. The accuracy is expressed in a Mueller matrix and should be better than:
Other requirements that have been defined are: 1) the system shall deliver polarization modulation for all polarimetric instruments (it has to be decided whether the modulation is performed in the main optical train or at instrument level); 2) functionalities for polarimetric calibration of the whole optical system should be included (in principle the polarimetric calibration assembly shall be located before any folding mirror); 3) the polarization optics will be integrated in the optical path and should be removable; and 4) the footprint of the light beam entering the polarimetric calibration assembly should not be bigger than 100 mm.

4.3.2 Concept

Figure 4.10 shows the general layout of the EST polarimeter concept. Just after the axisymmetric mirrors M1 and M2, close to the instrumental polarization-“free” secondary focus F2, space is reserved for calibration optics and modulators, which can be slid in and out of the beam. Modulators can be of any type, optimized, for example, for efficiency or wavelength coverage, a polychromatic type with switching capabilities being one option. The complete optics train up to the science focus, including both elevation and azimuth mirrors, and the AO and MCAO system, is polarimetrically compensated. After the science focus, all optical elements are statically aligned, with the s- and p- planes being the eigenvectors of the total system after the science focus. The analysers are placed at each instrument and send the light as dual beam to the demodulating detectors. A second modulator can be located also at instrument level, as well as extra calibration optics and/or polarimetric compensators. The great advantage in also locating polarimeter components at each instrument is flexibility.

![Figure 4.10. General concept for the polarimetric setup of EST.](image)
The main mirror and the secondary mirror form a Gregory system and, as such, are rotationally symmetric. Therefore, they do not introduce any instrumental polarization: all locally introduced polarization due to an inclined mirror surface, e.g. on the rim of M1, cancels out due to the rotational symmetry. Due to the arrangement of M1 and M2, the secondary focus is still polarization free. Here the polarization package will be located, containing both modulator and calibration optics. It is the preferred place for a large aperture solar telescope. In order to eliminate the effects of seeing it is preferable to measure the various polarimetric states within the time that the seeing changes. For this reason fast modulation and fast readout is to be preferred.

The aim of the optical design of EST is to get the lowest possible instrumental polarization, which is a strong requirement for accurate measurements. Variations in time are particularly to be avoided since calibration quickly becomes a time-demanding (and thus expensive) task and reduces the calibration accuracy. Obtaining low instrumental polarization is realized by: 1) a minimal number of optical components; 2) a minimal number of oblique reflections; the use of rotational symmetric optics where possible; 3) oblique reflections arranged such that they compensate each other; and 4) the use of appropriate coatings. The baseline optical design of EST consists of 14 mirrors. The layout of the optics is such that pairs of mirrors are orientated in a way that they compensate each other’s polarization. For the fold mirrors with 45° incidence angle this occurs when the incidence-reflection planes are perpendicular. Since different parts of the telescope rotate at different rates (elevation axis, azimuth axis, de-rotator unit), compensation for the system as a whole also requires that all subsystems in themselves are compensated, which is also included in the optical design. It makes the telescope polarization time invariant to first order. In order to maximize the throughput of the telescope (hence also the polarimetric sensitivity), adding extra compensation mirrors (with no other function) is seen as a drawback. For the current baseline design only one extra mirror is needed to achieve complete compensation.

After the science focus, all mirrors can be statically aligned according to their individual eigenvectors. The modulator in front of the instruments transfers the polarization to be measured into the eigenvector of the optical train, which creates a very robust, insensitive polarimetric system. The (unknown) instrumental polarization in the (s-, p-) directions cancels out after a regular beam-exchange with the modulator.

Dual beam polarimetry is preferred for high-accuracy polarimetry because two measurements are done in parallel, providing measurements of a Stokes parameter with no time delay in between. Dual beam polarimetry can compensate for instrumental effects by swapping the s- and p- direction periodically. Unlike single-beam polarimetry all the photons are used, thus maximizing sensitivity.

In the dual beam concept (and, when possible, where no strongly polarizing elements exist in the optical beam), it is easier to have the analyser just before the detector(s) in order to avoid complications with the AO optics and instruments, as otherwise two beams have to travel through the system. Separating the modulator from the analyser and putting it much more in front (i.e. in F2), has the great advantage that the instrumental polarization of all optics behind the modulator has a lower impact on the polarization accuracy.

By using modulators at various locations in the optical train, which switch the sign of polarization periodically, and then subtracting sequential images, spurious polarization signals of parts of the telescope can be subtracted. The modulator in F2 could act as a “switch” to change the sign of real polarization with respect to instrumental polarization. When combined
with the beam exchange method, the real polarization then follows, together with “switching” from a “triple difference”.

The main calibration unit will be located at the F2 location, which is the ideal place just after the symmetric M1 and M2 to be able to calibrate the maximum number of optical components. The procedure is not different from other telescopes. The calibration unit defines the performance of the polarimeters by generating defined states of polarization.

4.3.3 Performance estimation

4.3.3.1 Sensitivity

The sensitivity aim is a signal-to-noise requirement. The obtained sensitivity depends on the exposure time, spatial resolution, spectral bandwidth and instrument efficiency, and is usually a trade-off between these parameters. To reach a sensitivity of $3 \times 10^{-5}$ with a 4-metre telescope, an instrument efficiency of 10% (and all the light going to a single instrument), a filter bandwidth of 33 mÅ, a detector efficiency of 100%, and a polarimetric efficiency of 50%, a trade-off has been made. $3 \times 10^{-5}$ sensitivity at 0.05" is reached after 500 s of exposure time; and within 20 s when sampled at 0.3".

The spurious polarization related to atmospheric turbulence, often called seeing-induced crosstalk, has a direct impact on sensitivity. It is caused by different effects. The first cause is due to the variations of the atmosphere during the modulation cycle. A second cause of seeing-induced crosstalk is more appropriately been called “bloosoming”. A localized source of significant polarization in the solar surface will be convolved by the PSF of the telescope and instrument, but also by the equivalent PSF of the turbulent atmosphere, and be seen to spread to
adjacent regions of the image. Finally, the light can also become polarized due to the breaking of symmetry across the pupil.

An AO system will both help to improve effect 1) and 2), but effect 3) is not corrected by usual image correction systems, since they are placed at locations in the optical path far from the primary mirror.

Simulations have been done to simulate the effect of the atmosphere including AO to estimate the impact on a 4-metre class telescope. The results are shown in Figure 4.11. Modulator frequencies of, approximately, 50 Hz (for rotating waveplates) are needed to fulfil the sensitivity requirement. The cross-talk terms are almost constant irrespective of the number of low order terms compensated by the AO. The cross-talk terms depend only on the modulation frequency and do not depend on number of Zernike terms compensated, at least up to 120, for a 4-metre class telescope. We think that this is due to two competing effects. With an increasing number of AO-compensated Zernike terms, the spatial resolution improves which results in higher intensity gradients in the Stokes images. On the other hand, the seeing-induced fluctuations in the images are reduced.

<table>
<thead>
<tr>
<th></th>
<th>Max Q/U-&gt;V</th>
<th>Max I-&gt;Q/U</th>
<th># components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrumental polarization</td>
<td>1E-03</td>
<td>5E-04</td>
<td>-</td>
</tr>
<tr>
<td>Dust</td>
<td>6E-05</td>
<td>2E-02</td>
<td>14</td>
</tr>
<tr>
<td>Coatings</td>
<td>1.6E-03*</td>
<td>&lt;1E-04</td>
<td>14/2</td>
</tr>
<tr>
<td>Window (mechanical induced stress)</td>
<td>8E-03</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Window (Thermal induced stress)</td>
<td>9E-05</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Window (inherent birefringence)</td>
<td>0 to 6E-02</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>WFS beamsplitter (mechanical induced stress)</td>
<td>8E-05</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>WFS beamsplitter (thermal induced stress)</td>
<td>9E-05</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>WFS beamsplitter (inherent birefringence)</td>
<td>0 to 6E-02</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td><strong>TOTAL STATIC (all components)</strong></td>
<td><strong>1E-01</strong></td>
<td><strong>7E-02</strong></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL DYNAMIC (all components)</strong></td>
<td><strong>1.3E-04</strong></td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.8. Overview of instrumental errors. Static and quasi static errors are in normal font; dynamical errors are in italic
4.3.3.2 Accuracy

To estimate the accuracy, polarimetric error budgeting should be carried out. To that aim, the complete polarimetric train has to be divided into its building blocks, each with its own errors. The total propagated error should be within the requirements value. Building blocks for EST have been made, but thorough error budgeting has only just started, and needs to be continued into the next design phase. Instead, we have estimated a number of aspects (instrumental polarization, coatings, dust, birefringence), divided into static and dynamic errors. The results are summarized in Table 4.8.

The static Q/U→V effect is easily dominated by the birefringence in windows. This implies that we should aim at substrates with low birefringence. Nevertheless, the factor between the sum of the static error sources and requirement value is not more than a factor 20, which means that with a calibration accuracy of a few per cent, the error seems manageable. The dynamic (difficult to calibrate) Q/U→V effect is more than a factor 10 smaller than the requirement, which is fine in itself. The static I→Q/U effect is dominated by dust. The difference between the sum of the static errors and requirement is a factor 140, which is just below what we can reach with 1% calibration accuracy. It demands proper dust control by frequent cleaning, recoating, and proper covering when not in use.

4.3.4 Final design

Modulator package

An initial estimate for the envelope of the unit for the modulator and calibrator around F2 was made, based on the optical layout of a preliminary M1 cell design. A cylinder with a diameter 1.2 m and a height of 1 m has been devised, located in the central area of the M1 mirror cell. The envelope can accommodate four “polarimetric optics” wheels, with up to ~700 mm diameter each and with a minimum of four positions (Figure 4.12), both for a range of modulators and calibration optics. Apart from the F2 unit, also modulator (and/or calibrator) components can be placed at the science focus or instrument foci. For this reason one position in each wheel in the F2 package is open.

![Figure 4.12. Left) Engineer’s drawing of the F2 polarimetric unit with modulator wheels and calibrators; (Right) location of the F2 unit in the telescope.](image)

- Figure 4.12. Left) Engineer’s drawing of the F2 polarimetric unit with modulator wheels and calibrators; (Right) location of the F2 unit in the telescope.
Figure 4.13. Results of the final calculation (after a limited iteration time) of the total modulator, which is both athermal and polychromatic. I efficiency: black solid; Q efficiency: red dashed; U efficiency: green dashed; V efficiency: blue solid; total polarimetric efficiency: black dotted. The theoretical maximum I efficiency = 1; maximum total polarimetric efficiency = 1; maximum equal efficiencies for Q, U and V: 1/√3 = 0.58.

Modulator design

A range of classic modulators are proposed (rotating retarders, a Pockels cell and SLCVRs, for several wavelength ranges), all housed in the wheel assemblies. Also a variable compensator (“tackler”) is under consideration to compensate any potential crosstalk introduced by the optics train between the Sun and the analyser. Finally a “switch” has been proposed to invert the incoming (solar) Q, U, V periodically, but leaving the telescope/instrument polarization (which are constant or very slow varying) the same to disentangle solar from instrumental polarization.

An alternative that we have studied in more detail is a modulator that works at more than one wavelength, but which is not achromatic, although efficient at all wavelengths of interest. Massive computation is needed to find the optimum solution. Such modulators have also been built and tested. For EST, a modulator has been designed that is: a) efficient in the wavelength range 380–2000 nm, b) working with a beam divergence of f/11 (EST F2 focus), c) a-thermic, which is done by choosing complementary materials. It results in a temperature-insensitive modulator, which is important to maintain retardance, necessary for a solar telescope, since this adds actively heat to the modulator. Figure 4.13 shows an acceptable design.

Coatings

The baseline choice for coating is Al for M1 and protected Ag for all other mirrors. This choice seems to be the best trade-off between throughput, polarization and manufacturing.

Detectors
Fast modulation requires fast (kilohertz) recording. Fast demodulating detectors (ZIMPOL, C³Po) are not readily available yet for the projected detector size for EST (~4k × 4k). Study and development is beyond the scope of this Design Study but should continue in the next phase.

A conclusion of the analyses performed is that it seems possible to realize an extremely flexible polarimeter for EST thanks to the voluminous space in F2. The (fast) modulator will be located either at F2, at instrument level or a combination of at both locations. The required sensitivity goal is within reach but requires a trade-off (between spatial resolution, integration time and sensitivity) due to photon noise and seeing. With (MC)AO included, modulator frequencies of approximately 50 Hz (rotating waveplates) are needed and detector readout in the kHz range.

The accuracy requirement is within reach thanks to the low instrumental polarization in combination with common calibration techniques. Birefringence and dust control need particular attention, however.

4.4 Primary Mirror

4.4.1 General

The EST optical configuration is Gregorian. Therefore, the primary (f/1.55) is an on-axis mirror with a central obscuration. The outer diameter of the optical used area is about 4.1 m, the obscuration has a diameter of about 1.4 m.

Sunlight will heat up the mirror surface without cooling. A cooling device at the back of the mirror will cool it to near ambient temperature. Remaining warm air on the illuminated front side will be removed by a flushing system.

The primary mirror and mirror cell are mounted above the elevation axis and are directly exposed to the wind. The mirror will be supported by a stiff active axial support system which compensates for all static or slow changing deformations. The active system is also able to compensate for aberrations introduced by the optical elements within the remaining light path.

4.4.2 Mirror design

The mirror design is driven by the stiffness and cooling capabilities. Either a thin monolithic mirror or a thicker light-weighted mirror is possible. Investigations showed that a light weight, meniscus-shaped mirror with a moderate number of actively controlled axial actuators provides the best performance. The stiffness and cooling performance is better than for a monolithic mirror but the complexity to light weight and manufacture the mirror is much higher.

The light-weighting patterns (see Figure 4.14) are hexagonal cells (about 640 in total) with an inner diameter of 125 mm (72 mm cell side). The weight of the mirror is 2514 kg. The constant height of the mirror is 246 mm, the rib wall thickness 18 mm and the constant front sheet thickness 22 mm. The backs of the mirror cells have no undercuts. The mirror is supported by 96 independent axial supporting points and 30 lateral supporting points attached to the mirror cell (see image on the right of Figure 4.14).

The first two fundamental mirror frequencies (free-free conditions) are 33.7 Hz. Mode 3 and 4 have 90.5 Hz.
4.4.3 **Mirror cell**

The mirror cell shall provide the high stiff support when the mirror blank faces the dynamic effect of the wind load. It shall accommodate the other subsystems: the cooling system, the suction systems and the support elements (actuators).

The M1 mirror cell is a dodecagon welded steel structure (see Figure 4.15). The total weight is about 9.5 t. The diameter of the inner hole is 1300 mm; the maximum diameter is 4.9 m. The nominal rib wall has 15 mm, the inner wall 20 mm, and the back plate 10 mm thickness.

The M1 cell structure attaches to the telescope structure at three main attachment points, providing an isostatic constraint.

The mean local stiffness at the actuators mounting points is $4 \cdot 10^8$ N, this is more than an order of magnitude higher than the stiffness of the actuators ($10^7$ N).

The 96 axial actuators are installed inside cylinder tubes and react against the back plate of the cell structure. They could be installed and removed without dismounting the primary mirror blank. The axial actuators are individually active controlled.

The 30 lateral actuators are attached to the outer edge of the mirror cell. The lateral actuator is a passive hydraulic system. The directions of forces are according to the Schwesinger concept.
Figure 4.15. Mirror Cell.

Figure 4.16. Mirror surface deformation under a dynamic wind distribution. The upper figure shows the raw deformation corresponding to 1250 nm rms, the lower figure shows the surface deformation after compensation of piston, tip-tilt and focus, corresponding to 230 nm rms.
4.4.4 **Performance**

Preliminary analyses of the mirror surface deformation under gravity, wind buffeting and thermal effects show deformation within the limits defined in the error budget. The gravity surface deformation obtained is 40 nm rms after compensation with the active optics system up to trefoil. The dynamic wind buffeting deformation obtained is 230 nm rms under a dynamic wind pressure distribution of 64 Pa rms, corresponding to a mean wind velocity of 15 m/s with variance of 30% (see Figure 4.16). In the case of dynamic wind load, only piston, tip-tilt and focus are compensated, assuming that the M1 active optics has an insufficient bandwidth to compensate for this effect. The thermal print-through obtained due to the local effect of the discrete impingement jets of the thermal control system is below 0.1 nm rms.

A modal analysis in isostatic condition of the mirror mounted in the mirror cell shows the modes listed in Table 4.9.

<table>
<thead>
<tr>
<th>Mode</th>
<th>frequency</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.1</td>
<td>Mirror in-plane</td>
</tr>
<tr>
<td>2</td>
<td>30.7</td>
<td>Mirror – Cell couple in plane</td>
</tr>
<tr>
<td>3</td>
<td>46.6</td>
<td>Astigmatism</td>
</tr>
<tr>
<td>4</td>
<td>48.2</td>
<td>Astigmatism</td>
</tr>
<tr>
<td>5</td>
<td>61.8</td>
<td>Mirror defocus</td>
</tr>
<tr>
<td>6</td>
<td>63.2</td>
<td>Mirror in-plane</td>
</tr>
<tr>
<td>7</td>
<td>84.0</td>
<td>Torsional mirror</td>
</tr>
<tr>
<td>8</td>
<td>93.3</td>
<td>Mirror rolling in X</td>
</tr>
<tr>
<td>9</td>
<td>99.8</td>
<td>Coupled flexural</td>
</tr>
<tr>
<td>10</td>
<td>103.7</td>
<td>Coupled flexural</td>
</tr>
</tbody>
</table>

*Table 4.9. M1 Assembly eigenmodes (isostatic constrains).*

4.4.5 **Cooling**

The temperature difference between the primary mirror surface and ambient shall be only a few degrees. Pre-cooled air is blown into the cells at the back of the primary by individual nozzles. The cold and heated air is distributed and removed by dedicated channels in the mirror cell (see Figure 4.17).

The cooling of the mirror is fast enough to follow most daily ambient temperature changes. Because the thermal expansion coefficient of Zerodur is very low, the deformations through thermal gradient are also very low (<1 nm RMS).

In case of strong thermal gradients of the ambient temperatures the thermal reaction is to slow and the mirror surface temperatures could be higher than a few degree Celsius. An air flushing system was introduced to avoid warm air bubbles on top of the mirror surface. From the outer border of the mirror air with ambient temperature is blown radially into the direction of the inner hole through air knives (see Figure 4.18). The airstream removes remaining warm air from the face sheet. A suction system around the inner hole will collect the flushed air (see Figure 4.19). The flushing system will work also under different elevation angles and wind conditions (see Figure 4.20).
Figure 4.17. Primary mirror, cooling system, and flushing system in mirror cell integrated (lateral actuators are not shown)

Figure 4.18. Suction/Flushing System
4.5 Secondary Mirror

The secondary mirror is a Ø800 mm concave ellipsoid which defines the telescope pupil. It includes slow alignment drives to keep the optical alignment and fast tip-tilt and focus drives to correct dynamic perturbations (see Figure 4.21).

Assuming the open air baseline configuration for the telescope, the wind load on the telescope structure and primary mirror will be a dominant error source in the image motion and image quality budgets. Fast drives are needed to correct dynamic effects at the Nasmyth focal station, which cannot take advantage of the AO system correction. For the Coudé focal station, providing fast tip-tilt and focus capabilities to M2 will allow compensation of part of the wind effects, reducing the load on the AO system.

In the design study the feasibility has been evaluated to achieve a bandwidth of 150 Hz (-3 dB) for the M2 tip-tilt drives to use it as the main tip-tilt mirror of the AO system. In case a higher bandwidth is needed, the possibility exists to implement an additional faster tip-tilt mirror already foreseen in the optical train (M6).

The implementation of fast drives at the M2 with the required bandwidth requires an extremely light and stiff mirror. In case the open air configuration is not finally implemented in favour of a conventional configuration with dome, reducing drastically the wind effects, the necessity to include fast drives at the M2 will be reconsidered. In this case a more conventional mirror with lower dynamic requirements can be implemented.
In the design study the performance has been evaluated of a high stiffness light-weight silicon carbide mirror for the case of providing fast drives and a more conventional Zerodur mirror for the case that fast drives will not be provided.

4.5.1 Mirror

The proposed design for the mirror is a silicon carbide (SiC) open back light-weight substrate with ribs defining triangular cells. SiC is proposed due to its high specific stiffness, high thermal diffusivity and low thermal expansion, taking into account that SiC mirrors below Ø1 m are well within the current mirror manufacturing technology. The open back substrate is proposed for optimal stiffness and to facilitate mirror cooling. Triangular cells are proposed since they provide optimal stiffness compared to other patterns. Chemical Vapor Composite (CVC) SiC ($E = 457$ GPa, $\rho = 3210$ kg/m$^3$) has been considered in this study, but it is also possible to use other SiC materials with similar properties.

The mirror is axially supported on three points, and laterally supported by a diaphragm placed in a central cavity. The tip-tilt mechanism is integrated into the mirror mount.

The mirror substrate has been optimized for the required gravity deformation with minimum mass. The active primary mirror can compensate low-frequency wavefront distortions by deforming the mirror in a proper way. This capability allows the correction of quasi-static errors of the secondary mirror surface, such as gravity effects and other low-frequency errors, relaxing the requirements on the mirror surface deformation. The requirements for the maximum gravity surface deformation derive from the telescope image quality error budgets, which assign a maximum total surface error for the secondary mirror of 91 nm rms after active optics correction and 230 nm rms before active optics compensation. From these values, 40 nm rms...
are allowed for gravity deformation after active optics correction and 120 nm rms before active optics compensation. Table 4.10 shows the secondary mirror physical properties.

<table>
<thead>
<tr>
<th>Mirror mechanical diameter</th>
<th>Ø800mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical shape</td>
<td>Concave ellipsoid</td>
</tr>
<tr>
<td>Curvature radius</td>
<td>2220mm</td>
</tr>
<tr>
<td>Conical constant</td>
<td>-0.6</td>
</tr>
<tr>
<td>Front face thickness</td>
<td>5mm</td>
</tr>
<tr>
<td>Ribs thickness (triangular pattern)</td>
<td>3mm</td>
</tr>
<tr>
<td>Central rib height</td>
<td>80mm</td>
</tr>
<tr>
<td>Border rib height</td>
<td>25mm</td>
</tr>
<tr>
<td>Central cavity diameter for diaphragm</td>
<td>180mm</td>
</tr>
<tr>
<td>Mass</td>
<td>23.2kg</td>
</tr>
<tr>
<td>Centre of gravity from mirror vertex</td>
<td>10.6mm</td>
</tr>
<tr>
<td>Moment of inertia around tilt axis $I_{CoG}$</td>
<td>0.91Kgm$^2$</td>
</tr>
</tbody>
</table>

Table 4.10. M2 substrate characteristics.

4.5.2 Tip-tilt stage

The tip-tilt mechanism is composed of three piezo actuators fixed directly to the back of the mirror by means of flexible joints (see Figure 4.22), thus minimizing the moments introduced on the mirror during the tip-tilt movement. The selected actuators provide a linear stroke of 180 µm which allows a maximum tip-tilt range of ±60 arcsec (±24 arcsec image motion). If the tip-tilt range is reduced to the minimum required value of ±15 arcsec (±6 arcsec image motion), it will also allow additional fast focus correction range of ±65 µm, which corresponds to 1800 nm rms of wavefront focus correction capabilities. The actuator resolution is 2.4 nm, which allows a theoretical image tip-tilt resolution of 1.6 marcsec.

The central diaphragm placed in the mirror core supports laterally the mirror and performs the tip-tilt flexure join, provided that this element is laterally stiff and axially flexible. The proposed design includes radial flexures which allow absorbing a differential thermal expansion between the diaphragm and the mirror. The membrane is provided with apertures in order to allow cooling of the mirror. The membrane is placed at the position of the mirror centre of gravity avoiding lateral forces which appear on the system when the centre of gravity is out of the pivot point. The centre of gravity of the mirror is placed close to the mirror vertex, so lateral displacements of the mirror vertex produced by the small tip-tilt motion are negligible. Additionally a tangential bar provides torsional stiffness to the assembly.

Since the mass and moment of inertia of the mirror are small, no reaction mass is needed for the tip-tilt stage to compensate the inertia forces produced by the expected accelerations during the
image motion correction. The maximum inertia force transmitted by each actuator to the structure is below 1 N for the more demanding focus and tilt acceleration needed.

A finite-element (FE) analysis of the complete mechanism including mirror and mount with real flexibility of the actuators and joins has been performed in order to evaluate the eigenfrequencies of the tip-tilt system. The results show that the axial modes of the system (piston and tip-tilt), which limit the bandwidth of the mechanism, are above 400 Hz.

The proposed control loop for the tip-tilt mechanism is based on position feedback obtained from the internal sensors included in the piezo actuators and velocity feedback obtained from accelerometers (see Figure 4.23). Preliminary performance has been evaluated with a model based on a detailed FE model of the mirror and tip-tilt stage. With these premises the closed loop bandwidth (-3 dB) obtained for the system are 175 Hz for Tip, 178 Hz for Tilt, and 29 Hz for Focus. Difference between Tip and Tilt performance are related to the asymmetry introduced by the tangential bar. Figure 4.24 shows the closed loop transfer function for the tip-tilt mechanism.
4.5.3 Alignment system

The alignment system is composed of a hexapod implemented by means of 6 linear actuators, which allow the alignment of the mirror in 6 DoF (only 5 are used since the rotation around the optical axis is not useful). This kind of mechanism is a standard system extensively used as the M2 alignment mechanism in many telescopes.

The linear actuators are joined to the platforms using flexures to avoid play and stick-slip effects. The alignment system is designed to allow XYZ movement range of ±10 mm and XY rotations of ±1.5 mrad.

Standard actuators are proposed for the hexapod. These actuators are composed of a preloaded planetary rollerscrew driven by a brushless servomotor including a safety brake.

Preliminary FE analyses of the hexapod show the feasibility to obtain axial eigenmodes larger than 60 Hz.

4.5.4 Thermal control

The proposed design for thermal control system is based on impingement air jets blowing air inside the mirror core cells, where every cell has its own impinging jet and hoses are distributed to pick up the heated air (see Figure 4.25). This system is proposed since a non-contact system is needed to avoid affecting the tip-tilt mechanism.
Two air plenums are attached to the output stage of the hexapod. The inlet plenum distributes the cooled air among all the impinging jets. The return plenum collects the heated air from aspiration hoses. In order to ensure that cooled air from the back of the mirror does not leak out into the light path, a suction mechanism aspirates air at the gap between the mirror and the cover, preventing the heated air from leaving the cover environment. The air aspirated through the gap tends to avoid the separation of the boundary layer from the mirror surface, hence reducing the turbulence at the mirror edge. An aspiration device is proposed instead of a rubber seal in order not to affect the tip-tilt mechanism.

Simulations of thermal performance, with a lumped masses model assuming typical daily ambient temperature and solar irradiation profiles, show that a simple PID temperature controller can follow the daily temperature with maximum differences between the mirror surface and the ambient air below 0.2 °C.

Analyses of the temperature distribution in the mirror cells have been performed using a complete mirror FE model assuming a heat flux of 40 W/m². Inside the cell the forced convection coefficient of the impingement jets is considered changing radially from 67 W/m²K to 36 W/m²K to take into account the effect of the limited size of jet tubes with respect to the cell size. 5 W/m²K is assumed for the rib walls not affected by forced convection. The thermal print-through calculated using this model is 0.4 nm rms assuming the figure compensation by the M1 active optics up to trefoil.

### 4.6 Heat Stop

The Heat Rejecter (HR) lies at the prime focus of the telescope and operates as first field stop of the optical system. The aim of the HR is to reject the solar radiation falling outside the selected Field Of View, avoiding the development of thermal plumes, i.e. avoiding internal seeing.
The science requirements state that observations up to a distance of 200 arcsec from the solar limb should be possible. Figure 4.26 shows a scheme of the field of view that must be covered by the heat stop. Various concepts were analysed to meet the requirement. The flat heat rejecter alternative was chosen as the most suitable for the telescope configuration (see Figure 4.27). The flat heat rejecter consists essentially in a flat reflective surface inclined at 45º to the optical axis and will be described in the following.

The solar radiation, in the optical layout of the telescope, generates a total thermal load on the heat rejecter of about 13.4 kW assuming a ~95% reflectivity for the primary mirror (M1). The M1 has a diameter of 4.1 m with a central hole of 1.358 m and a focal length of about 6.2 m. Accordingly, the sun image size at the focal plane is about 59.1 mm and the heat load ranges between 2016 W and 672 W, for an HR surface reflectivity of 85% and 95%, respectively.

The cooling system required to remove the HR thermal load has been designed to avoid the formation of air turbulence in the optical path due to the temperature increment on the HR heated surface. Due to the large heat load applied on the HR heated surface, the proposed cooling system combines a liquid cooling system and an air suction system.
In the design process, the following guidelines were taken into account: a) coolant flow velocity below 5 m/s in all circuit parts in order to avoid vibrations and reduce surface washout; and b) coolant bulk temperature equal to ambient temperature in order to avoid internal seeing and prevent moisture condensation.

4.6.1 Cooling system

To prevent atmospheric moisture condensation, an efficient way to cool the HR front face is to increase the fluid Heat Transfer Coefficient (HTC) rather than to lower fluid bulk temperature. The jet impingement method has been chosen for this purpose.

Jet impingement involves a water-based cooling fluid, forced to pass through an orifice and impact at high speed on the target to be cooled. Although this method allows optimal heat exchange, it could be not sufficient to keep the HR front surface temperature in the required range. An additional air sucking system avoids the generation of air plumes by sucking the air layer in contact with the HR front surface.

The jet impingement method is implemented inside the HR using a nozzle plate, which contains the holes necessary to accelerate the cooling fluid (see Figure 4.28). The hole distribution on the nozzle plate is designed to obtain the desired HTC values.

The air flow around the HR is confined by a shroud as shown in Figure 4.29.

![Figure 4.28: Coolant path inside the HR: blue lines show the cool fluid, red lines show the warmed-up fluid](image1)

![Figure 4.29: Air path inside the HR (red lines locate the warm air pattern inside the shroud)](image2)

The liquid cooling system main specifications are the following:

- Volume Flow Rate (VFR): 1.2 l/s (0.15 l/s per pipe)
- Coolant velocity (pipe section): 5.31 m/s
- Coolant pressure (pipe section): 2.5 bar
- Coolant pressure drop (estimated): ~0.5 bar
- Expected HTC value: between 43 kW/m²°C and 25 kW/m²°C

The air suction system main specifications are:
- VFR: 10 m³/h each spider [2.78 l/s], 40 m³/h total [11.12 l/s]
- Head loss (approx.) ~10.70 Pa

4.6.2 **Design of the heat rejecter**

The principal dimensions of the HR are listed below:

1. Minor axis: 215 mm
2. Major axis: 304.1 mm
3. Overall thickness: 58 mm (vertical dir.), 48 mm (45° dir.)
4. Spiders: 4×10 mm² thick

![Figure 4.30. Exploded view of the Heat Rejecter](image1)

![Figure 4.31. HR assembly (the yellow cone shows the light passing through the heat rejecter)](image2)

Due to the large temperature increment which will occur in case of failure of the cooling system, both the front surface and the inner cone are made of Glidcop (copper with dispersed alumina), which has excellent properties both at ambient and high temperatures. The other HR surfaces, the support system, the four spiders, and the coolant pipes are made of stainless steel.

The HR, shown in Figure 4.30, is made of a bottom elliptical surface (coated to increase reflectivity) that receives the heat load, another elliptical surface containing the nozzles necessary to realize the jet impingement cooling system (the nozzle plate) and a top elliptical surface that covers the HR and contains the connections to the coolant inlet and outlet pipes. An inner cone (with the same shape as the optical beam) connects all the surfaces and confines the coolant; inside the HR, an elliptical ring divides the coolant entering the nozzle plate and the coolant returning to the spiders.
The HR is connected to the four spiders by a support ring. Coolant pipes run inside the four spiders and then connect to the HR top surface directly. Figure 4.31 shows the HR assembly. A shroud, covering the support ring, pipes and HR itself, confines the air and creates the window for the air suction system. The air sucked from the HR will be removed through the same spider arms. To minimize vibrations, the velocity of the air inside the spiders has to be kept below 5m/s.

4.6.3 Thermal analysis

Thermal analyses have been performed in different conditions, both steady state and transient. Two cases were analysed: 95% of reflectivity value of the heated surface (simulating a nominal coating) and 85% of the reflectivity value (simulating a worn coating). The heat flux at the focal plane is approximately 175 kW/m² and 520 kW/m² for reflectivities of 95% and 85%, respectively.

![Figure 4.32. Heat transfer coefficient distribution on the heat rejecter heated surface (values range between 43 kW/m²°C and 25 kW/m²°C)](image)

Three observational cases were investigated: Sun centred on the rejecter and Sun off-centre in the X and Y directions (corresponding to the observation of the solar disc centre and two coronal observations) to evaluate the steady-state equilibrium temperatures over the heat rejecter. Figure 4.32 shows the heat transfer coefficient for the Sun-centred case. The retrieved temperatures for steady situation are given in Table 4.11.

<table>
<thead>
<tr>
<th>Reflectivity</th>
<th>Sun centre</th>
<th>Coronal, X-dir.</th>
<th>Coronal, Y-dir.</th>
</tr>
</thead>
<tbody>
<tr>
<td>85%</td>
<td>36.3</td>
<td>41.2</td>
<td>41.8</td>
</tr>
<tr>
<td>95%</td>
<td>25.5</td>
<td>27.1</td>
<td>27.3</td>
</tr>
</tbody>
</table>

Table 4.11. Maximum temperatures for the thermal steady-state analyses [°C]

Transient analyses have been performed in order to verify the maximum HR lifetime in the case of a cooling system failure. The analysis time is set to 60 s, the time required by the telescope for an emergency shutdown. The temperatures from the transient analyses are given in Table 4.12.

<table>
<thead>
<tr>
<th>Reflectivity</th>
<th>Sun centre</th>
<th>Coronal X-dir.</th>
<th>Coronal Y-dir.</th>
</tr>
</thead>
<tbody>
<tr>
<td>85%</td>
<td>475.2</td>
<td>543.5</td>
<td>553.7</td>
</tr>
<tr>
<td>95%</td>
<td>171.7</td>
<td>194.5</td>
<td>197.9</td>
</tr>
</tbody>
</table>

Table 4.12. Thermal transient analyses maximum temperatures [°C] after 60 s

Although the maximum temperatures reached in 60 s by the front surface are far below the melting point of both the materials used, the coolant will reach its boiling point in a few
seconds, depending also on the effective value of the reflectivity of the HR surface. The possibility of this event has to be considered among the most severe safety issues.

4.6.4 CFD Analysis

Computational Fluid Dynamics (CFD) simulations have been performed for different telescope zenithal angle configurations: 0° (observing at the Zenith), 30°, 60° and 90° (observing at the horizon) to evaluate the efficiency of the air suction system in different observing conditions. The suction window is placed all around the elliptical edge of the HR heated surface.

The results of analyses showed that the air suction is fully capable of avoiding the formation of air plumes inside the optical cone and provided the sucked air VFR and air velocity at spider section (cooling system specifications).

4.7 Transfer Optics

The transfer optics includes all the optics between the M3 and the instrument focal plane at the Coudé focus. In the current optical design, mirrors M3 to M7 are located on the telescope structure, defining the telescope main axes, while mirrors M8 to M14 are distributed in a long chamber below the telescope level. This chamber is a cylindrical volume of Ø5×25 m³, approximately, enclosed by the concrete pier, where the optical path has a length of approximately 70 m.

4.7.1 Field-of-view de-rotator

Mirrors M8 to M14 are arranged such that the input and output optical axes of the chamber coincide with the telescope azimuth axis. This arrangement allows this system of seven mirrors to work as an optical FoV de-rotator, rotating these mirrors around the optical axis at the appropriate rate.

The arrangement of the transfer optics as an FoV de-rotator avoids the necessity of providing a large rotating platform for the instrumentation, which is advantageous in terms of simplicity, instruments stability, cost and flexibility to allow future instrumentation upgrades.

Arranging the transfer optics as an FoV de-rotator, the mirrors composing the field de-rotator rotate at a different rate than the mirrors supported on the telescope structure. In this case, a differential rotation is produced during the telescope operation between the AO pupil DM (M7) and the DMs composing the MCAO system (M9-M12). The effect of this differential rotation on the AO performance has been analysed and considered minor if each DM keeps the orientation of its actuator pattern with respect to its respective WFS. Keeping the orientation of each DM with respect to its WFS is compatible with the performance of the transfer optics as a FoV de-rotator, by providing additional optical de-rotators in the WFS.

The proposed design for the transfer optics FoV de-rotator is based on an open framework structure Ø3×20 m³, approximately, connected to the concrete pier at the upper end and guided at both ends by roller bearings (see Figure 4.33). Mirrors M8 to M14 are attached to the rotating structure.

Considering the limited diameter of the required bearings (Ø500 mm approx.) and the limited weight of the rotating structure, roller bearings are proposed for simplicity instead of hydrostatic bearings. A self-aligned spherical roller thrust is proposed at the upper end to support axial and radial loads and a radial roller bearing is proposed at the lower end to support radial loads only.
This bearing arrangement provides an isostatic configuration which facilitates the system alignment and which allows differential thermal expansion between the transfer optics structure and the concrete pier without overloading the system.

Supporting the rotating structure with a single large slewing bearing placed at the centre of the structure instead of two bearings at the ends was also considered as an alternative. The main advantage of supporting and guiding the structure from the centre is the simplicity of the system, since it is possible to integrate support, guiding and drive at the central slewing bearing.

The advantages of guiding the rotating structure at the two ends are related to the long distance between the guiding points (approx. 20 m). The long distance between guiding points reduces the wobble produced during the rotation and allows a higher accuracy in the alignment of the rotation axis with respect to the telescope azimuth axis.

The drive proposed for the transfer optics de-rotator is based on a pinion-gear system with two preloaded servomotors to avoid backlash (see Figure 4.34). Pinion-gear is proposed for simplicity and cost, although a direct drive alternative is also feasible. The drive unit is integrated at the upper end of the system, where the system is supported. Considering that the transfer optics de-rotator is located in a protected environment inside the pier, not affected by external disturbance, pinion-gear is a feasible solution, even if this has a lower dynamic performance when compared to direct drives.

The system shall include a cable wrap composed of cable chains to rotate the cables corresponding to the DMs (M9-M12) and coolant hoses needed for the mirrors.

4.7.2 Thermal control

Thermal control based on a liquid coolant is proposed for each mirror of the transfer optics to avoid mirror seeing. The mirrors located on the telescope structure will operate in open air conditions, as M1 and M2, hence they will take advantage additionally of natural wind flushing to reduce mirror seeing. An air conditioning system is proposed in the transfer optics chamber to reduce local seeing in the long optical path enclosed in the chamber. The air conditioning system will guarantee at the same time a certain air flushing on the enclosed mirrors to reduce the mirror seeing.
Figure 4.33. Transfer optics de-rotator.

Figure 4.34. Transfer optics de-rotator drive.
4.8 Optical Coatings

During the design study we carried out an extensive technology review of metallic coatings, focusing on published experiences with telescope mirrors. In the process, we identified several promising coating types to be further studied: the classical and well-proven bare Al coating, Ag coatings with different dielectric multilayers for protection and UV enhancement, and combined Al-Ag coatings.

Small coated mirror samples from different experienced coating manufacturers (SAGEM, SESO and IOF Jena) were tested under realistic observing conditions, with repeated exposure periods of several months at the VTT solar telescope of the Observatorio de Tenerife, between 2009 and 2011. Some samples were illuminated directly by sunlight, while others were put aside and intentionally shadowed to study the dependence of the reflectivity with time under different conditions. The durability test was accompanied by regular reflectivity measurements at IOF Jena, over the full EST spectral range, i.e. from about 300 nm up to 20 µm. The results permit us to assess ageing effects and to make predictions on the frequency of re-coating cycles. In addition, we have measured the polarization properties of the coating samples vs. angle of incidence. The results are a valuable input for the telescope polarization model, which is needed for EST optical design, to fulfil the stringent requirements on polarimetric accuracy.

After analysis of the test results, we can give the following coating recommendations for the EST mirrors.

For M1 we recommend a bare Al coating, for several reasons. (1) From a scientific point of view, the dip at 850 nm is unfavourable, as it affects the Ca II IR triplet (see Figure 4.35, for the sun-illuminated samples and those kept at the shadow). However, if no other Al-coated mirrors than M1 and maybe M2 are used in the beam path of an NIR channel, the losses in throughput are acceptable. (2) Al re-coating can be easily performed at a local facility, e.g. the coating chamber of the William Herschel Telescope (WHT) on La Palma. In contrast, a complex Ag-based coating has to be renewed at the facilities of the coating manufacturer, which involves a major logistical effort and significant maintenance costs. (3) In the near future it is not expected that European manufacturers will be able to apply protected or enhanced Ag coatings to mirrors with a diameter larger than about 2.2 m.

The coating strategy for the other mirrors should take into account the different spectral channels. The white-light mirrors, located before the spectral partitioning (dichroics), are most critical. If Al coatings are used for several of them, the throughput loss at 850 nm is severe.

Among the coatings of our durability test, the enhanced Ag coatings “GAIA” from SAGEM (see Figure 4.36), and the new enhanced Ag coating from SESO are most favourable. In the NUV down to 300 nm, the reflectivity of the “X-shooter” coating is (locally) higher, but the reflectivity curve shows strong oscillations. In addition, the polarization properties of the X-Shooter coating have a stronger angle dependence, which renders the polarimetric accuracy much less predictable. The enhanced Ag coating from SESO shows a loss in reflectivity in the 350 nm - 400 nm region, comparable to the losses of Al around 850 nm, which calls for a trade-off between those spectral bands.

Since neither of the coatings studied in this work yields an entirely satisfactory performance for the white-light mirrors over the full EST spectral range, we advise that further coating options shall be explored for those specific mirrors, in terms of an extended study. One possibility would be to aim for a special Al coating with additional dielectric layers, enhancing the reflectivity around 850 nm.
For the mirrors located after the spectral partitioning, specific coatings shall be used, with an increased reflectivity in the spectral band of interest. For the VIS above 400 nm and for the IR channels, protected Ag shall be considered. In the IR, bare Au can also be used as an alternative. An Au coating is very robust and does not need a protective layer. In the blue and near-UV region below 400 nm, bare Al is clearly the coating of choice.

Concerning the polarization properties, we emphasize two effects. (1) For angles of incidence larger than about 30°, the protected and enhanced Ag coatings show significant deviations from theoretical bare Ag (see Figure 4.37). This should be kept in mind when modelling the polarimetric performance of the telescope. (2) Enhanced Ag coatings show strong gradients in the angular dependence of the crosstalk between linear and circular polarization. The location of the strongest gradient is wavelength dependent. The exact behaviour of the mirrors in this angle range is therefore very difficult to predict. Further, the strong gradients can result in a significant field-dependence of the telescope polarization.
Bare Al coatings on outdoor mirrors have to be renewed every 1-3 years, depending on the variable environmental conditions. For indoor Al coatings, re-coating cycles may be less frequent. Under outdoor conditions, the protected and enhanced Ag coatings show yearly reflectivity losses of several percent, and up to 10% in the case of the older SESO enhanced Ag coating used by THEMIS. This rate of degradation requires an almost yearly re-coating. However, under indoor conditions, the reflectivity losses of enhanced Ag coatings are much less severe, suggesting a typical life-span of about 10 years.

Figure 4.37. Measured Muller Matrix values for protected SAGEM-GAIA coating as function of the incidence angle.

4.9 Auxiliary Telescope

The Auxiliary Full-Disc Telescope (AFDT) will be used for the orientation of the observer on the solar disc and in its surroundings, for an easy guidance of the main telescope (MT EST) to a selected target and for precise coordinate measurements. The AFDT will also be used as an autonomous robotic telescope for synoptic observations and records of solar activity even when no observations are carried out at MT EST. Since the AFDT is designed primarily for solar observations, its aiming is limited to the belt ± 26° around the celestial equator. The following baseline concepts are adopted:
(1) The AFDT will be located separately, without connection to the MT EST structure. This allows using it as an independent coordinate reference system. The AFDT will not serve as a closed-loop guider for MT EST but it will be capable of introducing corrections into the MT EST positional control system.

(2) The magnification of the AFDT is such that the solar disc covers the major part of the its FoV, and the maximum resolution provided by digital camera chips is utilized. Therefore, the AFDT must track the Sun to keep the full solar disc inside the FoV in most cases.

(3) The solar tracking is based on calculated solar ephemeris (including a pointing model and refraction) and utilizes a guiding signal for corrections.

(4) In order to ensure the maximum positional stability, the concept of the AFDT is based on a classical refractor optical system embedded in an autonomous compact mechanical structure rotating around the polar axis and fed by a built-in flat mirror (equatorial mount).

4.9.1 **Required functions and properties**

The AFDT will perform the following functions:

- Image acquisition and visualization of the solar disc and its surroundings simultaneously in spectral channels Hα, Ca II H(K), and in white light (450–460 nm band), with spatial resolution 1" (arcsec).

- Telescope pointing and tracking: The standard telescope pointing is made according to the calculated ephemeris, including the pointing model and refraction. Manual telescope pointing is used only in exceptional cases. The telescope tracking is done according to calculated ephemeris and is usually corrected by the guiding signal obtained from the white-light channel. The slow component of deviations between the calculated and observed position is compensated mechanically and the fast one numerically. Required resolution in telescope position reading is 0.25" or better in both axes.

- Absolute measurement of positions: The absolute accuracy is better than 3" in equatorial and horizontal coordinates. The following coordinate systems are used: heliographic, Carrington, polar, Cartesian, equatorial and horizontal.

- Cooperation with MT EST: Equal image orientation on AFDT and MT EST monitors. Highlight of the actual MT EST FoV on all AFDT monitors. Setting of MT EST FoV centre to a selected target. Check and correction of accuracy of the positional control systems of AFDT and MT EST, corrections of the MT EST coordinate system.

- Automatic recording of solar active phenomena: Selection of best full-disc images in the intervals of 1 second, including tests for clouds. Automatic recognition of active phenomena (flares). Record of the evolution of the active phenomenon including the period of 15 minutes before its onset. The archives of solar active phenomena collect the recordings of fast active processes on the Sun. Each phenomenon has its own archive.

- Automatic recording of long-term history of solar activity: The archive of long-term history of solar activity documents the evolution of slow processes on the Sun. The observations are sampled continuously, in real time, with a frequency of 1 frame per 30 minutes in each optical channel.
- Resistibility to external environment: the AFDT is not protected by an enclosure or dome.
- Operation modes: Robotic (fully automatic), user (for the EST observer), and service mode.

4.9.2 Optical design

The angular resolution limit of 1" implies a diameter of the AFDT aperture of $d = 150$ mm. The telescope works in three spectral channels: Ca II K (394 nm), H-alpha (656.3 nm), and white light (continuum 450–460 nm). The field of view is 1°. Particularly, the FoV on a square detector chip shall be $51' \times 51'$, this means the circular FoV with diameter of 72" (1.2°).

The correct sampling with a pixel size of 0.5" will be achieved with chips of 6120 x 6120 pixels. The size of the chip determines the required equivalent focal length of the telescope. Since the chip size is currently unknown, the optical system was calculated for two chip sizes: (i) 28 x 28 mm² – short variant $f' = 1550$ mm and (ii) 60 x 60 mm² – long variant $f' = 2650$ mm. The detectors still have to be specified. For example, the chip KODAK KAF-50100-AAA has a resolution of 6132 x 8176 pixels, a chip size of 37 x 49 mm², balanced spectral sensitivity and a frame rate of 1 frame/s, which is too low.

The telescope is designed as a refactor with spectral filters located in collimated beams. The main optical components (see Figure 4.38) are: flat mirror, neutral-density and heat-blocking filters, main objective, collimator lens, beam-splitting cube, spectral filters (two narrow-band and one broad-band), neutral filters and three imaging objectives for individual spectral channels. The flat mirror, the neutral-density and heat-blocking filters, the main objective and the detectors are attached to the telescope structure. The rest of optical components is mounted on a common optical table and aligned with accuracy of manufacture.

The rectangular (300 x 160 mm) or circular ($d = 300$ mm) flat mirror provides a $d = 150$ mm reflected beam parallel to the optical axis of the telescope. The $d = 160$ mm neutral-density filter with a reflecting surface is located behind the flat mirror and in front of the heat-blocking filter. When flat-field images are taken, the neutral-density filter is removed and replaced by a light diffuser to provide a homogeneous illumination of the optical system. The heat-blocking filter KG3, band 330–700 nm, is located behind the neutral-density filter in front of the main objective. The main objective is designed as a general doublet with $d = 150$ mm and primary focal length 2380 mm (long variant for chips 60 x 60 mm²) or 2232 mm (short variant for chips 28 x 28 mm²). The following three elements are located in the primary focus: the field stop, the shutter used to take dark frames and the transparent target used for optical alignment and
focusing of detectors. The collimator is designed as a \( d = 75 \) mm doublet. The three spectral channels are separated by the beam-splitting cube. The designed cube has a coated reflecting side that is opposite to the entering beam. This way it will provide the required third beam. The imaging objectives form the real images with the required parameters on the detector chips. It was necessary to design them as general quadruplets, \( d = 40–60 \) mm, in order to have a sufficient number of parameters to compensate optical aberrations.

Spectral filters: A broad-band Fabry-Perot dielectric filter centred at 456 nm with FWHM 5 nm will be used for the white-light (continuum) channel. For the Ca II K(H) and H\( \alpha \) channels, the \( d = 32 \) mm thermally stabilized off-shelf Barr®, DayStar®, or Solar Spectrum® narrow-band filters are expected to be used, with bandpasses of 0.2–0.3 nm (Ca II K) and 0.05–0.07 nm (H\( \alpha \)).

Both calculated variants of the optical system (for chip sizes 28 x 28 and 60 x 60 mm; see example in Figure 4.39) have geometrical images better than the diffraction limit in the full FoV and in all spectral regions. The final variant has to be calculated with the knowledge of the actual dimensions of the narrow-band filters and detectors.

4.9.3 Mechanical design

The mechanical structure of the AFDT must be compact, stiff and stable. Since the telescope does not feed any static post-focus device, the optical system can be located firmly in the telescope tube. The tube is collocated in two bearings and rotates around its longitudinal axis, which is parallel with the polar axis. A flat mirror feeds the optical system. It is mounted in the tube and rotates around an axis perpendicular to the tube axis. The solar disc can be moved in two perpendicular directions by rotating the tube and the mirror. The AFDT mount is equatorial and the solar image does not rotate. The tilt of the flat mirror ranges from 32º to 58º with respect to the tube axis, making it possible to observe the zone ±26º around the celestial equator.

The telescope consists of a tube and a mount. The telescope tube is composed of two framed structures (cages) connected by a thick-walled cylindrical barrel. The lower (entrance) cage supports the flat mirror, the upper cage (box) contains the optical table and detectors (see Figures 4.40 and 4.41). The tube is about 4.5 m long with a diameter of, approximately, 0.5 m. The expected length of the telescope with mount is 5.6 m and the height is 3.3 m. The maximum expected total mass of the telescope and mount is 1000 kg.
In order to inhibit fast temperature changes during the observation and during the day/night cycle, all optical elements except the flat mirror, the neutral-density filter, and the heat-blocking filter are encased in a closed space thermally insulated from the external environment. Internal walls of the closed space have a high thermal capacity to minimize internal temperature fluctuations. They also serve as a supporting element. These walls are covered by an insulation layer. The insulation layer is protected by a thin sheet-metal layer on the surface of the telescope with a high reflectivity to reduce heating by sunlight and a low thermal capacity to avoid water condensation. The closed space is thermally stabilized and the air inside it is dried. A slow air circulation is driven in order to remove temperature gradients and to prevent pressure gradients. The pressure balancing between the closed space and the external environment is made through an air filter, where the incoming air is also dried.

4.9.4 Location

The location of AFDT must meet the following conditions:

(a) Its entrance beam is free, not obstructed by other parts of the EST structure or building. An unobstructed view to the zenith and ±120° from the southern direction is required.

(b) The entrance beam is undisturbed by hot air streams around the building, enclosure, and the EST structure. For this reason, the entrance part of AFDT may extend out from the EST pier.

(c) The angular position of the tube rotational axis is ensured with long-term accuracy of ±10°, including thermal effects, heating by solar radiation, and wind gusts.

The proposed baseline for the AFDT location is to place it at a separate tower in order to avoid constraining the design of the main telescope platform. It is proposed to locate the AFDT on a 15 m high tower with open structure analogous to the tower of the Dutch Open Telescope at La
Palma. Although if the final design of the telescope platform is compatible with the placement of the AFDT, the location of the AFDT on the main telescope tower can be reconsidered.

4.9.5 **Control system**

The AFDT control system has two key parts: positioning/guiding and solar activity monitoring.

The standard positioning and guiding is based on a combination of (1) real-time calculation of position using solar ephemeris, including a pointing model and refraction corrections, and (2) a self-guiding, i.e. real-time evaluation of the observed position of the solar disc centre using white-light images. The guiding is enabled only when the full solar disc is inside the AFDT FoV and when it is not disturbed by clouds. Its precision is better than the spatial resolution (1''). The guiding signal is used to correct the calculated position numerically (short-term deviations) and mechanically by slow telescope motions (long-term deviations and trends). The AFDT coordinate systems are related to the corrected, real position of the solar disc centre.

The current position of the MT EST FoV is outlined by a rectangle on the AFDT monitors, which show the three spectral channels. The observing target for EST can be selected by a cursor in any spectral channel. The target-corrected coordinates are calculated and, if required, transferred to MT EST. In case of a correct alignment, the target should be seen in the centre of the MT EST FoV. If the target is located at some distance from it, this distance represents the positional error of MT EST.

The manual control of AFDT motions is used only in exceptional cases, when a target far from the solar limb is observed. The activation of the manual control automatically disables the guiding system. The guiding of the AFDT is determined using the calculated position of the solar disc centre, the latest-known guiding correction, and the signal from the manual control. When the manual regime terminates, the telescope control automatically returns to the standard positioning and guiding.

The solar activity monitoring is fully automatic, without the necessity of observer intervention. Solar activity processes run on different time scales, from seconds (flares) to days (sunspots). To avoid the accumulation of useless information, only images containing changes of the observed scene should be stored. The evolution of fast active phenomena like flares must be recorded with high frame rate and completely, including a pre-defined period before the onset. The records produced by the AFDT are of two types: records of particular fast active phenomena, stored in activity archives, and a record of the long-term history of solar activity, stored in an history archive. The solar activity monitoring is disabled in the manual regime.

The frame acquisition includes a test for clouds (decisive for enabling/disabling the guiding), frame selection based on image sharpness (1 frame per 1 s period), flatfielding and alignment of selected frames, and their storage in a temporary FIFO buffer. Intensity (eventually structural) changes in frames stored in the buffer are evaluated by a fast-phenomena recognition algorithm. If a fast phenomenon is detected, frames of all spectral channels are stored in an activity archive with a cadence depending on the rate of evolution (maximum 1 frame/s). Frames acquired before the fast phenomenon onset, contained in the buffer, are also stored. The record is finished with the end of the phenomenon. To record the long-term history of solar activity, a set of selected, flatfielded, and aligned frames from all spectral channels is stored in the history archive every 30 minutes.

This scheme provides coverage of all important activity phenomena with minimum requirements to the storage capacity. The frame-selection algorithm is available. The cloud-testing and fast-phenomena recognition algorithms are feasible and under development.
5 TELESCOPE MECHANICS

5.1 Structure

The configuration of the telescope structure is determined by the defined optical layout (see Figure 5.1). The optical layout has the elevation axis placed 1.5 m below the M1 vertex in order to facilitate M1 air flushing, allowing space enough for the M1 cell and for a more convenient disposition 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 imbalance around the elevation axis due to high weight of the M1 assembly (13 ton), which shall be balanced by the structure below M1, large elevation wheels and additional ballast. On the other hand azimuth and elevation axis also are placed decentred with respect to the telescope optical axis because the optical path is folded in an asymmetric way to produce a polarimetrically compensated layout independent of the telescope elevation and azimuth angles.

The design of the elevation structure is based on two large wheels with a cage structure built around and below M1 leaving enough free space to avoid interference with the optical path of the transfer optics. A cage structure is designed instead of a more conventional elevation ring in order to facilitate air flushing and allow for an easier M1 dismounting from the side, since the structure and the optics below M1 makes difficult to dismount M1 downwards, as is usually done in alt-az telescopes. The upper tube structure is a Serrurier type structure since this is an efficient and light structure and is at the same time very open facilitating air flushing. The large elevation wheels balance the large M1 moment by including additional ballast at the wheels rims, allowing a balanced design.

Three alternative configurations have been evaluated to implement the elevation and azimuth axes: conventional yoke, rocking chair concept and gantry concept (see Figure 5.2).

In the yoke concept, the telescope tube is supported by trunnions on the two arms of the azimuth platform and the azimuth platform transfers loads to the azimuth bearing. In this design, the azimuth platform supports large bending loads from the elevation arms which shall be transferred to the azimuth bearing, hence the azimuth platform shall be a very stiff and massive structure. This has been the conventional mount design for alt-az telescopes during the last 50 years.

In the rocking chair concept (also known as Dobsonian mount), the telescope tube is supported directly on the azimuth platform by the large wheels, avoiding the elevation trunnions and the yoke arms. Load from the elevation wheels is transferred directly to the azimuth bearing on discrete pads, avoiding the necessity to provide a very stiff azimuth platform.

In the gantry concept, the telescope tube is supported by trunnions on two arms of the azimuth platform as for the yoke concept. The main difference is that the load of each arm is transferred directly to a large double track azimuth bearing, so each arm is supported independently on the azimuth bearing. In this design, the azimuth platform only provides stiffness in plane and it does not need high bending stiffness, since the bending from each elevation arm is directly transferred to the azimuth bearing. This concept was used in the VLT telescope.

The three structure concepts are considered feasible. The rocking chair and the gantry concepts are considered more efficient than the yoke configuration, since they have a very direct load path from the elevation bearings to the azimuth bearing thus avoiding the necessity for the azimuth platform to support bending loads. The efficiency of these designs results in stiffer and lighter structures reducing the cost with respect to the yoke configuration.
Figure 5.1. Telescope optical layout and envelopes.

Figure 5.2. Telescope structure alternatives: Yoke, Rocking Chair and Gantry (from left to right).
Preliminary analyses of rocking chair and gantry concepts show similar performance in terms of eigenfrequencies and wind shake deformation. The main advantages of the gantry concept are that it allows the use of conventional elevation bearings, and that the gantry arms provide a natural support for the Nasmyth platform. The use of conventional elevation bearings permits a compact design integrating the elevation drives also, which simplifies the assembly and alignment procedures. In the case of the rocking chair configuration, the main advantage is that it does not include arms supporting the elevation axis, so the design of the azimuth platform is simpler and the telescope exposure to wind flushing is maximized. The main drawback of the rocking chair concept is the complexity of assembling and aligning the elevation bearings on the wheels.

The eigenfrequencies obtained for rocking chair and gantry structures are 10 Hz about the elevation axis. For lateral modes related to the Nasmyth platform, they have values of 8 Hz for the rocking chair and 8.7 Hz for the gantry configuration. It is expected that the eigenfrequencies can be increased up to 12 Hz after optimization.

The rocking chair is the proposed baseline, due to its lower cost related to the simpler design of the azimuth platform, although it is proposed to analyse the rocking chair and gantry concepts in more detail in the next project phases. The configuration is presented in Figure 5.3.

Figure 5.3. Rocking chair telescope baseline configuration.
5.2 Bearings and Drives

During the design study the possibility has been analysed of using passive bearings for the telescope main axes instead of the hydraulic bearings commonly used in telescopes of similar or larger size. An example of a 4-metre class telescope with passive bearings built during the last decade is the SOAR telescope which uses roller bearings in the azimuth and elevation axes reporting a tracking jitter below 0.1 arcsec rms.

Hydraulic bearings provide the best performance in terms of stick-slip friction and stiffness. The main drawbacks are the complex auxiliary equipment required, the maintenance required, the power consumption, the necessity of especial protection to prevent oil contamination operating in open air conditions and the risk of leaks.

The passive bearing alternatives considered for the azimuth axis were large diameter roller bearing and the curved rail guides. The large diameter roller bearing is suitable for application in the yoke and rocking chair configurations, while the curved rail guides are suitable for application in the rocking chair and gantry configurations.

The diameter of the large roller bearing for the azimuth axis is limited to Ø6 m for transport limitations, although diameters larger than Ø8 m are feasible from Rothe-Erde. The stiffness provided by a Ø 6 m roller bearing is compatible with the required stiffness for the telescope structure.

The curved rail guides (see Figure 5.4) are off-the-shelf elements supplied in a large number of diameters which are extensively used in machine tools. The curved roller guides are available with diameter up to 10 m, being supplied in segments to be assembled on-site, there is no limitation on their transport. The tracks of the curved rail guides are less stiff than the large roller bearings since the roller elements have lower diameter. This effect can be compensated by the increase of the bearing diameter for the rail guide and supporting the structure on several tracks. The friction of rail guides is lower than the friction of the large bearing due to the smaller diameter of the roller elements and the presence of rolling elements in the tracks placed at discrete points only, not in the complete rail, as in the case of roller bearings.

Curved rail guides are proposed as the baseline for the azimuth bearing, because it allows a larger diameter than the roller bearing, which improves the stiffness of the structure, without transport limitation. The larger bearing diameter allows a more direct load path from the elevation axis to the azimuth bearing, simplifying the design of the azimuth platform, thereby saving mass and reducing its cost. Two concentric curved rail guides are proposed for the
azimuth bearing to implement the double track bearing needed for the gantry concept. A double track allows one to distribute the load on several tracks increasing the stiffness of the assembly.

The passive bearings alternatives considered for the elevation axis were the small diameter (approximately, 1 m) roller bearings and the curved rail guides. The roller bearings are suitable for application in the yoke and gantry configurations, while the curved rail guides are suitable for the rocking chair configuration. Two concentric curved rail guides are proposed in each wheel for the rocking chair configuration.

The main advantage of the small diameter roller bearing for the gantry concept is that it is a well proven concept using also off-the-shelf elements. The small diameter of the bearings reduces the effect of stick-slip friction with respect to the large roller bearing considered in the azimuth axis.

Direct drives are proposed for the main telescope axes. Direct drives provide maximum stiffness since they avoid the flexibility of the transmission trains. They avoid also inaccuracies and friction related to the transmissions.

One large diameter motor is proposed for the azimuth drive and one motor at each side of the structure is proposed for the elevation drive. Direct drives shall be installed segmented in the case of the azimuth axis and the elevation axis for the rocking chair structure. In the case of the elevation axis for the gantry concept, the direct motor can be arranged in a closed compact assembly with the elevation bearings which can be preassembled at the factory (Figure 5.5).

Figure 5.5. Azimuth direct drive (left) and elevation bearing and drive assembly proposed for the Gantry structure configuration (right).

5.3 Auxiliary equipment

5.3.1 Thermal control

Sunshields are envisaged to protect the telescope structure from the solar irradiation, as shown in Figure 5.6. Sunshades are needed to avoid warming up of the telescope structure, thereby producing thermal deformations and degrading the local seeing. A small individual sunshade for each beam is proposed avoiding large sunshades that would make the telescope more sensitive to wind shake.
Since the telescope structure is very close to the optical beam, it is required to keep it close to ambient temperature to avoid local seeing degradation. The preliminary requirement allows a maximum temperature difference for the structure of ±1 °C with respect to ambient.

Preliminary thermal analysis of the telescope structure during the observation cycle shows that although the sunshields are painted in white, with high visible reflectivity and infrared emissivity paint, their temperature increases by more than 5 °C with respect to the ambient temperature in low wind periods. In order to keep the temperature of the sunshields within ±1 °C with respect to the ambient temperature it is proposed to provide liquid cooling to the sunshields. Liquid cooling by plate coils is also proposed for the azimuth platform.

Figure 5.6. Sunshield structure proposal.

5.3.2 Cable wraps

Cable wraps with cable chains are proposed for the elevation and azimuth axes. Active cable wraps are proposed in both axes to avoid introducing additional load and perturbations on the telescope main axis. The elevation cable wrap moves 90°, while the azimuth cable wrap moves ±270°.

It is proposed to install the elevation cable wrap at the opposing site of the Nasmyth platform (Figure 5.7), while two alternative placements are feasible for the azimuth cable wrap, depending of the final diameter of the azimuth bearing and the required space for the transfer optics (Figure 5.8). In the case that the azimuth bearing is limited to Ø 6 m, as is the case for the roller bearing, the cable wrap can be placed around the upper part of the telescope pier. For a Ø 10 m azimuth bearing, as is the proposed configuration with rail guides, the cable wrap can be placed inside the telescope pier.
Figure 5.7. Elevation cable wrap.

Figure 5.8. Alternative placements of the azimuth cable wrap depending on the size of the azimuth bearing.
5.3.3 M1 cover

The M1 cover is a safety element which has two functions: protect M1 when the telescope is not in operation and prevent dangerous concentrated solar irradiation from M1 arriving directly to M2 or the telescope structure without passing through the heat rejecter when the telescope is passing through a forbidden area away from the solar disc.

The proposed design is a curtain made of plates which can be coiled around a spindle (see Figure 5.9). The curtain also covers one side of the mirror cell, protecting the upper part of the mirror when the telescope is in the parking position, pointing to horizon. When the curtain is completely coiled up, it allows free space for the side extraction of M1 from the structure.

![Figure 5.9. M1 protecting curtain.](image)

5.4 Performance

Performance of pointing and tracking has been estimated based on the FE model of the telescope structure. The calculated motions of optical elements are transferred into image motion in the Coudé focal plane by the sensibility matrix of the optical design. An integrated end-to-end model of the telescope mechanics and main axes controllers was developed for a more detailed analysis of the pointing and tracking performance (Figure 5.10). Preliminary results of the end-to-end model are already available, although the model must be tuned to improve the performance.

Pointing and tracking errors are dominated by wind shake produced in open air configuration and friction and servo errors related to bearings and drives. Wind load considered in this study corresponds to the maximum nominal wind speed of 15 m/s without considering any attenuation by the wind shield (see Figure 5.11). The raw image motion calculated due to the wind load corresponding to the maximum nominal wind speed is 3 arcsec, including steady state wind component and gusts. The wind image motion can be partially compensated by the telescope main axes within their bandwidth with flexible body control techniques. Flexible body control by feed-forward of the main axes motor torques is proposed to compensate steady state and low frequency wind gusts. With this technique, torques measured at the main axes will be correlated to the wind moments on the structure and used for open loop correction of the related pointing influence. According to experiences in other projects it is expected that 90% of the steady state and low frequency wind components can be compensated with this method.
Effect of bearings and drives on the tracking error is estimated 0.36 arcsec for each axis due to friction effects and servo controller error, based on preliminary results of the telescope mechanics end-to-end model. It is expected that this performance can be improved, based on the reported tracking performance of telescopes of similar size built during the last years.

Based on these results it is expected that a tracking error below 0.8 arcsec rms according to the requirements can be achieved for the complete telescope mechanics in the highest nominal wind conditions. This value could be considered high compared to the performance of other telescopes of similar size operating with a conventional dome, but it is well within the correction capabilities of the tip-tilt mirror of the AO system.
5.5 M1 removal

Due to the optical configuration with the elevation axis below M1 and the structure required below M1 to provide stiffness to tube, it is proposed to remove M1 from the side instead of downwards, as is usually done in alt-az telescopes.

The cage structure designed around M1 allows dismounting some of the beams to allow the extraction of the complete M1 assembly. It is proposed to extract M1 with the telescope positioned in parking position pointing towards the horizon or a few degrees above the horizon and handling M1 with the main crane of the enclosure platform, as depicted in Figure 5.12.

Figure 5.12. M1 extraction process.
6 INSTRUMENTS

6.1 Light Distribution System

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 (number of channels-volumes-entrance focus position-optical axis height-spectral range) and the possibility of adding 2 additional guest instruments (one in the visible beam and one in the NIR beam. The light distribution system includes all mechanisms (with exchangeable beamsplitters/dichroics/mirrors/compensators needed to achieve flexible combinations) and the electronic cabinets for the instruments and light distribution mechanism.

The instrument layout has been designed for two cases: with the instruments static on a concrete slab (field rotation being provided by transfer optics) and with the instruments installed on a rotating platform (for alignment purposes and to compensate for image rotation). At the end of this Design Study, the former was found to be preferred, since it minimizes the number of elements to be rotated, giving more flexibility to the instruments design and for four future developments and upgrades.

The light coming from the telescope is shared among the following instruments channels:

- 3 visible broad band imager channels,
- 5 narrow band imager channels: 3 operating in visible wavelengths and 2 in the near-infrared,
- 4 grating spectrographs: 2 for the visible spectral range and 2 for the NIR. These spectrographs are versatile and can operate in different configurations, using adequate additional modules. There are four possible configurations:
  - Long-slit Standard Spectrograph (LsSS),
  - Multi-Slit Multi Wavelength SPectrograph equipped with an integral Field Unit (IFU-MSMWSP),
  - Tunable Universal Narrow band Imaging Spectrograph (TUNIS),
  - and Multi-channel Subtractive Double Pass, New Generation (MSDP-NG).

The light distribution among the instruments (Figure 6.1) 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 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, as depicted in Figure 6.2. By moving the first pair of mirror in a direction parallel to the line that joins them, the image is displaced in that direction. The same can be applied to a second pair of mirrors. 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 6.1: Functional diagram of light distribution for instruments/channels at Coudé focus.

Figure 6.2: Sketch of the quad-mirror scanning system with its four flat mirrors used for 2-D scanning at the spectrographs. The incidence-reflection plan at M3 and M4 is in perpendicular to that of M1 and M2. They have been displayed parallel for the sake of simplicity. By moving together M1 and M2 along the line that connects them, the image at the focal plane is displaced in that direction, without changing its focus or the properties of the incoming beam. The same applies to M3 and M4, to scan the image in the perpendicular direction. The distance from M2 and M3 controls the position of the focus at the entrance of the spectrograph.
<table>
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<tr>
<th>Intersection</th>
<th>Instruments/channels (Reflection/Transmission)</th>
<th>Mechanism Number of positions (one open for free transmission)</th>
<th>Splitter type</th>
</tr>
</thead>
</table>
| D1           | R: Visible station                             | 3                                                             | a) Dichroic Reflection λ<800 nm  
b) Dichroic Reflection λ<900 nm |
|              | T: NIR station                                 |                                                               |               |
| BS1          | R: SP VIS I–SP VIS II                         | 5                                                             | a) Beamsplitter R=0.25 and T=0.75  
b) Dichroic Reflection λ<600 nm  
c) Dichroic Reflection λ>600 nm  
d) Mirror |
| D2           | R: NB1–BB1–BB2                                | 2                                                             | Dichroic Reflection λ<500 nm |
|              | T: BB3–NB2–NB3                                |                                                               |               |
| BS2          | R: BB1–BB2                                    | 3                                                             | a) Beamsplitter R=0.10 and T=0.90  
b) Mirror |
|              | T: BB1                                        |                                                               |               |
| BS3          | R: BB2                                        | 3                                                             | a) Beamsplitter R=0.30 and T=0.70  
b) Mirror (optional) |
|              | T: BB1                                        |                                                               |               |
| FM           | For BB2                                       | 1 (Fixed)                                                     | Mirror |
| FM1g         | For guest instrument                           | 2                                                             | a) Mirror |
| BS4          | R: BB3                                        | 3                                                             | a) Beamsplitter R=0.10 and T=0.90  
b) Mirror |
|              | T: NB2–NB3                                    |                                                               |               |
| D3           | R: NB2                                        | 2                                                             | Dichroic Reflection λ<620 nm |
|              | T: NB3                                        |                                                               |               |
| BS5          | R: NIR NB1–NIR NB2                            | 3                                                             | a) Beamsplitter R=0.75 and T=0.25  
b) Mirror |
|              | T: SP NIR I–SP NIR II                         |                                                               |               |
| D4           | R: NIR NB1                                    | 2                                                             | Dichroic Reflection λ<1100 nm |
|              | T: NIR NB2                                    |                                                               |               |
| FM2g         | For guest instrument                           | 2                                                             | Mirror |
| FM3g         | For guest instrument                           | 2                                                             | Mirror |

Table 6.1: Splitters type and number of mechanism positions proposed at each intersection between instruments/channels of the light distribution diagram shown in figure 6.1.
Dichroics and beamsplitters are inserted in the last five metres of the telescope optical beam in front of the f/50 focus and distribute the light to each instrument channel. This study considers that these splitters to be plates rather than cubes, due to the large beam size. As these splitters are plates placed at 45 deg in the beam, they can introduce astigmatism and polarization. This double effect might be compensated, if necessary, by inserting a compensator at the entrance of each channel. This compensator is a transparent plate with the same thickness as the splitter introducing the astigmatism and orientated at 45 deg in a direction perpendicular to the splitter introducing the astigmatism/polarization. To really compensate from the polarization effect, the compensator/splitter correcting it shall have the same coating type as the polarizing splitter.

Table 6.1 summarizes the different types of splitters needed at each instrument/channel intersection for the light distribution shown in Figure 6.1. At each intersection, the splitter can be removed from the beam or exchanged to maximize the light sent to each observing channel taking into account the demands of each observational programme. The second column gives the number of positions for each mechanism, exchangeable using a remote-controlled motorized staged, including one position without splitter. The reflectivity and transmission values of each beamsplitter are indicative and should be adjusted taking into account the photon flux estimation for the different instruments and the science goals.

An estimate of the throughput of the light distribution elements is presented in two cases (see Table 6.2):

- When all the instruments work simultaneously with transmission and reflection of the beamsplitters as proposed in Table 6.1.
- When each instrument is used alone

The following reflectivities and transmissions are considered to calculate the total throughput of the light distribution system:

- R = 95% and T = 90% are considered for each dichroic all over the spectral range 380 nm to 2300 nm.
- For each beamsplitter, an additional loss of 5% is assumed in reflection and 10% in transmission, with respect to the values shown in Table 6.1.
- For the compensators, the transmission is estimated equal to 90%.

The instrument distribution at the Coudé room is shown in Figures 6.3, 6.4 and 6.5 for the static option.
## Light Distribution System

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<th>BS1</th>
<th>D2</th>
<th>BS2</th>
<th>BS3</th>
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<tr>
<td>1800-2300</td>
<td>90.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>22.5%</td>
<td>2</td>
<td>90.3%</td>
<td></td>
</tr>
<tr>
<td><strong>NIR NB1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>800-1100</td>
<td>90.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td><strong>NIR NB2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500-1800</td>
<td>90.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 6.2. Throughput of the light distribution subsystem when all the instruments/channels are used simultaneously and when one instrument/channel is used alone.
Figure 6.3: Two different views of the instrument distribution at the (non-rotating) Coudé room

Figure 6.4: Left: Instrument distribution on the upper floor. Right: Splitters and their mechanisms for the light distribution among the imagers on the upper floor (the numbers in brackets give the number of positions for each mechanism)

Figure 6.5: Layout of the grating spectrographs on the lower floor.
6.2 Broad-Band Imager

The broad-band imagers are responsible for photospheric and chromospheric observations at selected (non-tunable) continuum wavelengths and spectral line cores. Some of the main requirements that have led to the proposed design are:

- **Different resolution modes**: a high resolution mode (1 x 1 arcmin^2, 0.015 arcsec/pix, 4k x 4k detectors), to exploit the diffraction limited quality of the telescope+MCAO system, and a large field of view mode (2 x 2 arcmin^2, 0.03 arcsec/pix, 4k x 4k detectors), to exploit the full telescope field of view, are requested. A single mode covering the full FoV at the maximum resolution is not feasible right now because either the detector and/or the filters are not manufacturable with the required size and properties. To ensure the maximum, the two modes will have to be available independently to the user. This way, the observer can decide the appropriate image scale on each channel. It may turn out that some channel is more useful at high resolution mode while another is most appropriate in maximum FoV mode, or any combination.

- **Image reconstruction techniques**: Even if no final decision about the post facto image reconstruction techniques has been taken, it may be foreseen that MOMFBD will be used for chromospheric filters and phase diversity for continuum filters. These solutions imply that for each chromospheric channel one will need a continuum channel for reference which, in turn, will be split into two (in and out of focus) for phase diversity reconstruction.

- **Telecentric configuration**: continuum windows will be used as reference for speckle reconstruction. To that aim, the aberrations of the narrow-band channel must be the same as those of the corresponding continuum channel (at each spatial point), implying that they need to share the same optics. This means that the filters have to be located after the beam separation, and given that this separation is done near the instrument focal plane, the filters must be located near the detector.

The BBI has three channels. Two channels are placed on the “blue” (\(\lambda \leq 550\) nm) arm of EST while the third one is on the “red” (\(\lambda \geq 550\) nm) arm (see Figure 6.1). The blue and red channels are fed through beam splitters (BS2 and BS4) that are not part of the BBI but of the common path of the light distribution system. The number of channels has been defined on the basis of the observational programs that require simultaneous observations in different bands. These requirements have led also to the distribution of filters among the various channels (see Table 6.3).

<table>
<thead>
<tr>
<th>Blue Arm</th>
<th>Red Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channel 1</strong></td>
<td><strong>Channel 2</strong></td>
</tr>
<tr>
<td>Ca II core</td>
<td>Ca II wing</td>
</tr>
<tr>
<td>Ca II continuum</td>
<td>G Band</td>
</tr>
<tr>
<td>CN band head</td>
<td>Brackett continuum</td>
</tr>
<tr>
<td>Paschen continuum</td>
<td>H(_\alpha) continuum</td>
</tr>
<tr>
<td>G band continuum</td>
<td></td>
</tr>
<tr>
<td>Ca II continuum</td>
<td></td>
</tr>
</tbody>
</table>

*Table 6.3. Filters distribution among the BBI channels*

Each of the three channels has two different resolution modes: a high resolution mode (small FoV) to exploit the diffraction-limited quality of the telescope + MCAO system and a large field
of view mode to exploit the full telescope field of view. A summary of the constraints for the instrument is presented in Table 6.4.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Telecentricity</td>
<td>Yes</td>
</tr>
<tr>
<td>Pixel size</td>
<td>10 micron</td>
</tr>
<tr>
<td>CCD format</td>
<td>4k x 4k</td>
</tr>
<tr>
<td>CCD dimension</td>
<td>4cm side</td>
</tr>
<tr>
<td>High Resolution Mode f/#</td>
<td>32</td>
</tr>
<tr>
<td>Large FoV Mode f/#</td>
<td>17.2</td>
</tr>
<tr>
<td>Back Focal Distance</td>
<td>500mm</td>
</tr>
<tr>
<td>Maximum envelope</td>
<td>6\times6\times1m^3</td>
</tr>
<tr>
<td>High Resolution Mode FoV</td>
<td>1.075' side</td>
</tr>
<tr>
<td>Large FoV Mode FoV</td>
<td>2' side</td>
</tr>
</tbody>
</table>

Table 6.4. Summary of the constraints for the BBI design

Each channel is split into three sub-channels. The three sub-channels share the same optics to have the same aberrations. Out of the three sub–channels of each channel, the first one hosts narrow band filters for chromospheric observations, the second one hosts wide band filters used as reference for speckle reconstruction and photospheric observations and the third one generates an out-of-focus wide-band image for phase diversity reconstruction. Figures 6.6 and 6.7 show the layout for a BBI generic channel.

In the design, only refractive elements have optical power. In particular there are three doublets. The first doublet is common to the two operational modes (see Figure 6.8) and makes a pupil, while the second and the third doublet are placed along two different optical paths. Looking
again at Figure 6.8, the direct path is the one for the large FoV mode. The folded path is, instead, the one for the high resolution mode. To fold the optical beam, there are two pick-up relays. The first one is composed of two flat mirrors at 45° with respect to the optical axis and the second one by a flat mirror and a beam splitter. In the first pick relay, one of the mirrors (the upper one) is fixed, the other one is movable (via a linear or rotary stage), allowing the beam to be intercepted and redirected along the high resolution mode path.

![Figure 6.8: One of the channels of the BBI. Blue rays are for the large FoV mode and light-blue rays for the high resolution mode.](image)

The mechanical components and assemblies included in each BBI channel are: optical bench, entrance shutter, optical mountings, mechanisms, and detector cryostat. All the external surfaces of the optical elements will be covered with a protection stopper in order to prevent dust contamination during alignment phases and for the handling/shipping operations. Standard commercial components, where possible, have been selected.

Figure 6.9 shows a preliminary conceptual layout for one of the BBI channels. Filters holders and detectors are not shown.

Spot diagrams and PSFs show that the high resolution mode is diffraction-limited (see Figure 6.10). The large FoV mode also has excellent performances, with a SR often being the SR greater than 0.8. The RMS wavefront error for the high resolution mode is 0.03-0.04 waves, while for the large FoV mode is 0.1 waves.

![Figure 6.9: BBI channel conceptual mechanical layout. Filter holders and detectors are not shown.](image)
Paschen continuum | Hα | Brackett continuum
---|---|---
![Spot diagram](image1)

Large FoV mode

Paschen continuum | Hα | Brackett continuum
---|---|---
![Spot diagram](image2)

Table 6.5 gives preliminary estimates of the transmission and the photon flux detected (at zenith for single-instrument configuration and for simultaneous observations with other Coudé instruments/channels) for the BB3 channel observing the solar line Hα in both resolution modes for the three sub-channels. Table 6.6 shows these estimates for BB2 channel observing the wing of the Ca II H line.

Figure 6.10: Spot diagrams for the two BBI observational modes. Black rings represent the Airy disk.
### BB3 with Halpha (656.3 nm)

<table>
<thead>
<tr>
<th>BB3 Elements</th>
<th>Low Resolution Mode</th>
<th>High Resolution Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st SubChannel</td>
<td>2d SubChannel</td>
</tr>
<tr>
<td></td>
<td>(focus)</td>
<td>(post focus)</td>
</tr>
<tr>
<td>L1S1</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L1G</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L1S2</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L2S1</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L2S2</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>M1</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>M2</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>L3S1</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L3S2</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L4S1</td>
<td>99.5%</td>
<td>99.5%</td>
</tr>
<tr>
<td>L4S2</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L5S1</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>L5S2</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>M3</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>BS1</td>
<td>90.0%</td>
<td>10.0%</td>
</tr>
<tr>
<td>BS2 (values TBC)</td>
<td>100.0%</td>
<td>50.0%</td>
</tr>
</tbody>
</table>

**Subtotal without filters**

|                | 78.5%               | 4.4%                 | 4.4%          | 66.9%           | 3.7%           | 3.7%          |

**FILTER Halpha 0.1 nm**  
Transmission (TBC)

|                | 40.0%               | 40.0%                | 40.0%         | 40.0%           | 40.0%          | 40.0%         |

**Filter Halpha continuum 1 nm**

|                | 100.0%              | 90.0%                | 90.0%         | 100.0%          | 90.0%          | 90.0%         |

**BB3 Halpha transmission Total**

|                | 31.5%               | 3.9%                 | 3.9%          | 31.5%           | 3.9%           | 3.9%          |

**Detected photons flux Zenith for each BB3 subchannel**

### Current estimate

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.404E+08</td>
<td>2.404E+08</td>
<td>2.404E+08</td>
<td>6.010E+07</td>
<td>6.010E+07</td>
<td>6.010E+07</td>
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<tr>
<td>BB3 Halpha transmission Total</td>
<td>31.5%</td>
<td>3.9%</td>
<td>3.9%</td>
<td>31.5%</td>
<td>3.9%</td>
<td>3.9%</td>
</tr>
<tr>
<td>Correction Halphacontinuum</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Factor Halpha line intensity &amp; continuum</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Detected photons flux Zenith by EST-BB3 single obs.* (Nph/s/px)</td>
<td>3.025E+07</td>
<td>1.890E+08</td>
<td>1.890E+08</td>
<td>6.43E+08</td>
<td>4.023E+07</td>
<td>4.023E+07</td>
</tr>
<tr>
<td>BB3 Halpha transmission Total</td>
<td>31.5%</td>
<td>3.9%</td>
<td>3.9%</td>
<td>31.5%</td>
<td>3.9%</td>
<td>3.9%</td>
</tr>
<tr>
<td>Correction Halphacontinuum</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Factor Halpha line intensity &amp; continuum</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Detected photons flux Zenith-BB3 simul.Obs.* (Nph/s/px)</td>
<td>1.446E+07</td>
<td>1.446E+07</td>
<td>1.446E+07</td>
<td>3.651E+06</td>
<td>3.651E+06</td>
<td>3.651E+06</td>
</tr>
<tr>
<td>BB3 Halpha transmission Total</td>
<td>31.5%</td>
<td>3.9%</td>
<td>3.9%</td>
<td>31.5%</td>
<td>3.9%</td>
<td>3.9%</td>
</tr>
<tr>
<td>Correction Halphacontinuum</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Factor Halpha line intensity &amp; continuum</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Detected photons flux Zenith-BB2 simul.Obs.(ph/s/px)</td>
<td>1.831E+06</td>
<td>1.148E+06</td>
<td>1.148E+06</td>
<td>3.91E+05</td>
<td>2.344E+06</td>
<td>2.344E+06</td>
</tr>
</tbody>
</table>

* estimate from EST error budgets /throughput budget without Tinstrument

**Table 6.5 Preliminary estimates of transmission and detected photons flux (at Zenith) for BB3 channel observing Halpha**
### BB2 with CaIIH wing (396.4nm)

<table>
<thead>
<tr>
<th>BB2 Elements</th>
<th>Low Resolution Mode</th>
<th>High Resolution Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st SubChannel</td>
<td>2d SubChannel (focus)</td>
</tr>
<tr>
<td>L1S1</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L1S</td>
<td>89.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L1S2</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L2G</td>
<td>86.0%</td>
<td>86.0%</td>
</tr>
<tr>
<td>L2S2</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>M1</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>M2</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>L1S1</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L1S2</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L2S</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>L2G</td>
<td>86.0%</td>
<td>86.0%</td>
</tr>
<tr>
<td>L2S2</td>
<td>99.0%</td>
<td>99.0%</td>
</tr>
<tr>
<td>M3</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>BS1</td>
<td>90.0%</td>
<td>10.0%</td>
</tr>
<tr>
<td>BS2</td>
<td>100.0%</td>
<td>50.0%</td>
</tr>
<tr>
<td>Subtotal without filters</td>
<td>50.3%</td>
<td>2.8%</td>
</tr>
<tr>
<td>FILTER CaIIH continuum 0.5 nm (Transmission TBC)</td>
<td>30.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>BB2 CaIIH wing transmission Total</td>
<td>15.1%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

**Detected photons flux Zenith for each BB2 subchannel**

| BB2 CaIIH wing transmission Total | 15.1% | 2.5% | 2.5% | 12.8% | 1.7% | 1.7% |

**Current estimate**

| BB2 CaIIH wing transmission Total | 15.1% | 2.5% | 2.5% | 12.8% | 1.7% | 1.7% |

**Correction**

| Detector efficiency/continuum | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

**Detected photons flux Zenith -BB2 Single Observ. (Nphs.pixel)**

| BB2 CaIIH wing transmission Total | 15.1% | 2.5% | 2.5% | 12.8% | 1.7% | 1.7% |

**Correlation**

| BB2 CaIIH wing transmission Total | 15.1% | 2.5% | 2.5% | 12.8% | 1.7% | 1.7% |

**Factor**

| BB2 CaIIH wing transmission Total | 15.1% | 2.5% | 2.5% | 12.8% | 1.7% | 1.7% |

**Detected photons flux Zenith -BB2 Simult. Observ. (Nphs.pixel)**

| BB2 CaIIH wing transmission Total | 15.1% | 2.5% | 2.5% | 12.8% | 1.7% | 1.7% |

**Correlation**

| BB2 CaIIH wing transmission Total | 15.1% | 2.5% | 2.5% | 12.8% | 1.7% | 1.7% |

**Factor**

| BB2 CaIIH wing transmission Total | 15.1% | 2.5% | 2.5% | 12.8% | 1.7% | 1.7% |

*estimate from EST error budgets /throughput budget without Tinstrument

Table 6.6 Preliminary estimates of transmission and detected photons flux (at Zenith) for BB2 channel observing Ca II H wing.
6.3 **Narrow-Band Spectropolarimeter**

The mission of this instrument is to spectrally isolate narrow-bandpass images of the Sun at the highest possible spatial and temporal resolution. Observations with this instrument should allow rapid imaging spectrometry, Stokes imaging polarimetry, accurate surface photometry and spectroheliograms that will result in Doppler velocity maps, transverse flows and imaging magnetograms that track evolutionary changes of solar activity.

The technical feasibility of a narrow-band tunable-filter imaging system has been studied. From the analysis, it turns out that only a Fabry-Perot interferometer-based design with air gaps can meet most of the science requirements. There are two different philosophies in mounting the etalons within the optical light beam. In the collimated version, the etalons are mounted in the parallel light beam near an image of the telescope entrance pupil; in the telecentric configuration the etalons are mounted in the convergent light beam near an image plane. Both configurations have their own advantages and disadvantages and put similar demands on the quality and size of the required etalons.

Fabry Perot interferometers have a very small free spectral range. So, an ordinary interference filter cannot be used as an order sorter. A solution to this problem is the use of multiple etalons in series.

The requirements for the instrument are:

- **Spectral Resolution:** 150,000 at 525 nm, 630 nm (visible channels), 854 nm, 1565 nm (infrared channels), with goal at 1083 nm and TBD at 396 nm (CaH, K channel).
- **Polarimetric SNR in 1 sec at 0.04" resolution and at 500 nm:** 1000
- **Instrument Transmission:** >30 %
- **Spectral S/N ratio:** >100 (TBC)
- **Max Ghost:** <1 % (TBC)
- **Max. Interetalon Ghost:** < 0.5 % (TBC)
- **FoV:** 60 arcsec
- **F-Ratio@Etalons:** 200 (TBC)
- **Max. Etalon mismatch:** < 1% (TBC)
- **Polarimetric accuracy:** 3e-5
- **Spectral Stability:** 1% of spectral FWHM
- **Strehl intensity:** 90 % minimum

On the one hand, a triple-etalon telecentric design is proposed. Air gap separation ratios, coating reflectivities and f-ratio issues have been analysed. The effect of coating inhomogeneities and plate imperfections and their impact on the instrument performance has been evaluated. A first optical design has been presented and the required space within the observing room discussed. A preliminary estimate on the total transmission and on the exposure time required to meet the scientific requirements has been done. The necessary alignment and setup procedures for this
design have also been described, together with a summary of all calibration, setup and observing modes.

On the other hand, a collimated, tandem design for the wavelength range between 850 and 1100 nm with is also included, with a discussion on parasitic light and ghost contributions.

6.3.1 **Triple etalon telecentric design**

There are a few existing and working solar, Fabry Perot etalons-based spectrometers. Scaling up such devices to very large solar telescopes needs a reconsideration of some design issues. Basic issues are

- Etalon size, pupil apodization (telecentric), FoV wavelength shift (collimated)
- Etalon coatings
- Spacing ratios
- Inter etalon ghosts

It seems possible to design a triple-etalon system that can meet the requirements on spectral resolution and the property that both, the inter-etalon ghosts and the orange skin effect, are minimized. It is possible to tilt two etalons to get rid of inter-etalon ghosts completely. This can be done with the combination of one high-reflectivity etalon and two “low” (R = 0.8) finesse FPIs. There are several spacing ratios which can meet the requirements on spectral stray light, max ghost, and the required spectral resolution. To decide on the ideal ratios, a more detailed analysis has to be done. A tandem system is not desirable because the required spectral signal-to-noise ratio cannot be fulfilled, especially at shorter wavelengths. Special attention has to be turned to whether coatings with reduced micro-roughness can be obtained.

The plate separations are very small (1, 0.15, 0.1 mm). If oil-filled etalons were planned, these gap separations would be halved. It is unlikely to be feasible to fill such small gaps with highly viscous oil (without bubbles). Dynamic fast gap control would be impossible due to the oil viscosity.

Etalons with a maximum diameter of 250 mm are needed for a field of view of 60 arcsec. Together with the extra room needed for control equipment the total diameter of the plates will reach 300 mm. Superb polishing has to be reached to get a substrate flatness of $\lambda/400$. To minimize gravitational bending, the plates have to be mounted horizontally.

Ion sputtering deposition has to be used instead of an e-beam for the etalon coatings. RMS surface roughness below 0.1 nm and increased reflection homogeneity will help to reduce the orange skin intensity variation to below 1%. The coatings have to be designed in such a way that the stresses introduced from reflection and anti-reflection films are equal. Here extensive tests have to be performed.

The baseline for the optical design is:

- F#50 telescope beam feed
- Plate scale telescope focus: ~1 arcsec/mm
  - Telecentric configuration.
  - F# (at FPI): 200
Horizontal FPI mount
- FoV: ~1 arcmin (photometric mode), 1 arcmin x 40 arcsec (polarimetric mode)
- 4k camera with 12 μm pixels.
- Dual-beam polarimetry.
- Minimize intern polarization.
- Diffraction limited imaging
- Auxiliary channels:
  - Continuum channel
  - Laser adjustment channel
  - Wavelength calibration channel
  - Video context channel

Starting from the EST science focus with an f-ratio of 50, the beam has to be slowed down to an f-ratio of 200 at the positions of the etalons. This is done by one achromatic doublet with a focal length of 1250 mm and a spherical mirror with a focal length of 5000 mm. The focal length ratio of both components is 4. The setup is telecentric. In order to account for the oblique reflection within the imaging mirror, the powered mirrors will be slightly toric. The solar image within the Fabry-Perot package will be picked up by another toric mirror of the same focal length. At the end, a second achromat with a focal length of 800 mm reimages the Sun onto the CCD-sensor. In order to minimize internal polarization every sagittal 90° reflection will be followed by a tangential 90° reflection (M1 + M2, M4 + M5, M6 + M7, M9 + M10). Important is that both reflections happen within a beam of the same f-ratio (Figures 6.11 and 6.12).

A stop wheel is located at the telescope focal plane (F1 in Figures 6.11 and 6.12). It is motorized and maintains 4 different positions.
- Field Stop for photometric observations (1 arcmin diameter)
- Field stop for polarimetric observations (1 arc min x 40 arcsec)
- Pinhole for setup purposes.
- USAF target for alignment purposes.

For the narrow-band instrument interference filters with a FWHM of 1 nm and 3 cavities have to be used. These filters can be mounted in a motorized filter wheel. This wheel is located either near the focal plane F1 or near the first pupil plane F2. What position is to be preferred depends on the optical quality and size of the available interference filters. If the filters are mounted near F1, an optical quality of λ/4 is sufficient but the clear aperture should be about 70 mm. Such filters are available at the moment but only with a flatness λ/4 per inch. The optical quality should be much better (λ/10) if the filter is mounted near the pupil image P2. On the other hand, the clear aperture of such filters can be much smaller (approximately, 35 mm).
Figure 6.11: Top view of the filter instrument.
Figure 6.12: Side view of the filter instrument
It is not clear up to now if the telescope own modulator package can be used for the tunable filter. To be on the safe side, a package of 2 swift retarders is envisaged. These retarders are located just behind the first field stop. They should have a clear aperture of 80 mm.

Polarimetry is done by a dual beam approach. Beam splitting is done with a Wollaston prism located at the second pupil image just in front of the camera lens. To minimize different image distortion which can be introduced by such polarizing beam splitters, the Wollaston has to be fabricated from calcite. The beam splitting has to be approx. 1.8° so the cut angle between both crystals has to be 5.1°.

The diffraction-limited spatial resolution of EST at 600 nm is 0.038 arcsec. In order to stay diffraction-limited this has to be sampled with two camera pixels minimum. With a plate scale of 1 arcsec/mm in F1 and a collimation focal lens of L1 of 1250 mm, the focal lens of L2 has to be 789 mm if the camera has 12 μm pixels. If a 4 k × 4 k camera is used, the maximum possible field of view will be 78 × 78 arcsec², which has to be compared to the 1 arcmin circular field which is driven by the etalon size and the required f-ratio. Dual beam polarimetry on one camera reduces this FoV. So, with a 4 k × 4 k camera it will only be possible to observe a field of 60 × 39 arcsec². An observation of the entire 60 arcsec circular field is only possible with a camera of 3160 × 6310 pixels.

It could be useful to have the full circular 60 arcsec field (or even more) on the continuum camera while the polarimetric field is reduced. For this, the field stop in the stop wheel should have a diameter of 60 mm while there is has to be a second field stop for the filtergram channel. This stop has to be located at F2 between the etalon FPI2 and the etalon FPI3.

Most of the optical components can be housed in a box with dimensions 1800 x 2000 x 1300 mm³ (Optics Box, see Figure 6.13). Light entry is on the side. Lost heat from the cameras is actively transported to outside the box. The etalon package itself is mounted in a separate box with dimensions 900 x 1000 x 800 mm³ (Etalon Box). This box is temperature and pressure stabilized. Mounting the etalons in a horizontal direction is crucial. Therefore the reflective imaging optics has to be orientated vertically. This is done inside the mirror box (500 x 800 x 4000 mm³). It goes from the optical table down to the basement below the observing room. There is a rigid connection to the floor and the optical table. The box is closed so there can be stable air stratification. Because the light enters the box “pre-filtered” there is no heat dissipation in it.

Table 6.7 shows the transmission contributions for the filter instrument. All reflecting surfaces are coated with protected silver. The refracting surfaces all have a broadband anti-reflection film. The transmission of the prefilters is assumed to be 75%. In total, a transmission of 16% is reached.
Figure 6.13: Mechanical envelope of the EST narrow band instrument

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
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<td>105</td>
<td>Homosil</td>
<td>0.98</td>
<td>0.02</td>
<td>0.86</td>
</tr>
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<td>2</td>
<td>Interference Filter</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Swift1</td>
<td></td>
<td></td>
<td>0.95</td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>Swift2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>5</td>
<td>L1</td>
<td>14</td>
<td>SF2</td>
<td>0.99</td>
<td>0.01</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Bk10</td>
<td>0.99</td>
<td>0.01</td>
<td>0.98</td>
</tr>
<tr>
<td>6</td>
<td>M1</td>
<td></td>
<td>Ag</td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>7</td>
<td>M2</td>
<td></td>
<td>Ag</td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>8</td>
<td>M3</td>
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<td>Ag</td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>9</td>
<td>Window 1</td>
<td>20</td>
<td>Homosil</td>
<td>0.99</td>
<td>0.02</td>
<td>0.98</td>
</tr>
<tr>
<td>10</td>
<td>FPI1</td>
<td>100</td>
<td>Homosil</td>
<td>0.98</td>
<td>0.9</td>
<td>0.88</td>
</tr>
<tr>
<td>11</td>
<td>M4</td>
<td></td>
<td>Ag</td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>12</td>
<td>M5</td>
<td></td>
<td>Ag</td>
<td></td>
<td></td>
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</tr>
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<td>Ag</td>
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<td></td>
<td>0.98</td>
</tr>
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<td>Ag</td>
<td></td>
<td></td>
<td>0.98</td>
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<td>FPI2</td>
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<td>Homosil</td>
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<td>0.96</td>
<td>0.94</td>
</tr>
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<td>16</td>
<td>FPI3</td>
<td>100</td>
<td>Homosil</td>
<td>0.98</td>
<td>0.96</td>
<td>0.94</td>
</tr>
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<td>17</td>
<td>Window 2</td>
<td>20</td>
<td>Homosil</td>
<td>0.99</td>
<td>0.02</td>
<td>0.98</td>
</tr>
<tr>
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<td>M8</td>
<td></td>
<td>Ag</td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
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<td>19</td>
<td>M9</td>
<td></td>
<td>Ag</td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>20</td>
<td>Wollaston</td>
<td>12</td>
<td>Calcite</td>
<td></td>
<td>0.02</td>
<td>0.49</td>
</tr>
<tr>
<td>21</td>
<td>M10</td>
<td></td>
<td>Ag</td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>22</td>
<td>L2</td>
<td>20</td>
<td>BK7</td>
<td>0.99</td>
<td>0.01</td>
<td>0.97</td>
</tr>
<tr>
<td>23</td>
<td>L3</td>
<td>5</td>
<td>SF12</td>
<td>0.99</td>
<td>0.01</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Total Transmission: 0.16213552
6.3.2 Double-etalon collimated design

For a collimated mount (CM), the diameter of the plates is obtained as the best trade-off between the field of view (FoV) and the maximum admitted field-dependent blue shift, typical of this mount. If the requirement is imposed that the latter parameter is not larger than two spectral points at the maximum spectral resolution ($\Delta \lambda \leq 2$ FWHM), we obtain:

$$\beta \leq 4 \frac{\Phi_{FP}}{\sqrt{R \Phi_T}}$$

where $\beta$ is the FoV, $R$ the spectral resolving power and $\Phi_{FP}$ and $\Phi_T$ respectively are the FPI and the telescope pupil diameter.

The feasibility of a double-etalon in collimated mount is presented, following the requirements listed in Table 6.8.

<table>
<thead>
<tr>
<th>Wavelength range</th>
<th>850 – 1100 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral resolving power</td>
<td>150000 @ 850 nm</td>
</tr>
<tr>
<td>Parasitic light</td>
<td>$\leq 1%$</td>
</tr>
<tr>
<td>Ghosts</td>
<td>$\leq 0.5%$</td>
</tr>
<tr>
<td>Exposure time (S/N = 100)</td>
<td>$\leq 10$ ms</td>
</tr>
<tr>
<td>Spatial sampling</td>
<td>$\geq 2$ pixel/ res. el.</td>
</tr>
<tr>
<td>Field of view</td>
<td>$\geq 60^\circ$</td>
</tr>
<tr>
<td>Field-dependent blue-shift</td>
<td>$\leq 2$ FWHM</td>
</tr>
</tbody>
</table>

Table 6.8. Required instrumental characteristics used for the design of the FPI in collimated mount

Figure 6.14: $P_1$ is an image of the entrance pupil of the telescope. $P_2$ is a new image formed on the interference filter by the two lenses $L_1$ and $L_2$. 
The reduction of the ghosts obtained in CM by inserting interference filters between the two interferometers requires filter diameters similar to those of the FPIs (200 mm). However, since the spectral and optical quality of these filters decreases with their increasing size, reducing the instrumental performance, a suitable optics is needed to allow the use of smaller filters. For this purpose, an optical system (pupil adapter) has been developed to reduce the size of the pupil image on the pre-filters (see Figure 6.14). A second equal pair of lenses, but in inverted order, then is able to form on FPI2 a pupil image equal to P1 (see Figure 6.15).

CM and TM (telecentric mount) are not equivalent, also for ideal interferometers, and a choice between them should be done on the basis of the scientific requirements. This choice, however, is complicated by the different effects on both mounts due to the cavity defects and by the impossibility of knowing in advance their size and distribution. So, the general conclusion is that a decision will can be only made once the interferometers have been manufactured and their cavity errors fully quantified.

### 6.4 Grating Spectropolarimeter

Four configurations of grating spectrographs are presented to fulfil the EST grating spectropolarimeter requirements:

- Long-slit Standard Spectrograph, LsSS,
- Multi-Slit Multi-Wavelength Spectrograph fed with an Integral Field Unit, IFU-MSMWSP,
- Tunable Universal Narrowband Imaging Spectrograph, TUNIS,
- Multi-channel Subtractive Double Pass, New Generation, MSDP-NG.
These four configurations use the same spectrographs, hereinafter named as “main spectrographs”: two for the visible range of the spectrum and another two for the near-infrared. By inserting the adequate optical elements, each spectrograph can independently operate in any of the above mentioned configurations.

The design drivers for the main spectrographs are:
- each main SP shall be designed with commercial gratings,
- each main SP shall be as compact as possible,
- each main SP shall be a static module, common to the four spectrograph configurations mentioned above,
- the combination of these main SPs shall cover simultaneously all the solar lines observations specified in the Science Requirements Document.

The design study has led to 4 main spectrographs with their main parameters summarized in Table 6.9.

<table>
<thead>
<tr>
<th>SPs</th>
<th>VIS-I</th>
<th>VIS-II</th>
<th>NIR-I</th>
<th>NIR-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newport Echelle Grating size (mm x mm)</td>
<td>204×408</td>
<td>310×413</td>
<td>210×411</td>
<td>210×411</td>
</tr>
<tr>
<td>Grating constant (grooves/mm)</td>
<td>316</td>
<td>110</td>
<td>79</td>
<td>79</td>
</tr>
<tr>
<td>Blaze angle (º)</td>
<td>63</td>
<td>64</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>7500</td>
<td>7000</td>
<td>8000</td>
<td>7000</td>
</tr>
<tr>
<td>Pupil size (mm) with f/40 input beam</td>
<td>187.5</td>
<td>175</td>
<td>200</td>
<td>175</td>
</tr>
<tr>
<td>Pupil size (mm) with f/50 input beam</td>
<td>150</td>
<td>140</td>
<td>160</td>
<td>140</td>
</tr>
<tr>
<td>Diameter collimator mirror (mm)</td>
<td>460</td>
<td>400</td>
<td>700</td>
<td>500</td>
</tr>
<tr>
<td>Diameter camera mirror (mm)</td>
<td>890</td>
<td>600</td>
<td>660</td>
<td>380</td>
</tr>
<tr>
<td>Spectral range (nm)</td>
<td>390-560</td>
<td>560-1100</td>
<td>700-1600</td>
<td>1000-2300</td>
</tr>
</tbody>
</table>

Table 6.9. Parameters of the main spectrographs

The size of the optics of the spectrographs has been designed to accommodate an f/40 beam, even though the telescope delivers an f/50 beam. This slight oversize of the optical elements does not have a significant impact of the total cost and allows the beam to illuminate completely the standard gratings that are available in the Newport catalogue, shown in Table 6.9. The additional modules required by some configurations (IFU-MSMWSP and MSDP-NG) change the input f/50 beam of the telescope to f/40, without introducing extra optical elements. The LsSS and TUNIS configurations use directly the telescope f/50 beam to feed the spectrograph.
and do not completely illuminate the grating. Their spectral resolution, however, still meets the science requirements, as will be shown below, since their performance is not limited by the resolution of the grating.

The main characteristics of the four configurations of the spectrographs are given below. The detailed description can be found in their corresponding documents.

6.4.1 **LsSS**

The image on the left in Figure 6.16 shows one of the main spectrographs used in the Long-slit Standard configuration. The entrance field-of-view is a 2-arcmin long slit, and the different orders produced by the diffraction grating are separated by an interference filter located near the detector. An atmospheric dispersion corrector may be located in front of the spectrograph slits to correct for differential refraction and make sure that the FoV of the four spectrographs is the same.

6.4.2 **Integral Field Multi Slit Multi Wavelength Spectrograph (IFU-MSMWSP)**

This configuration uses an integral field unit to rearrange an input FoV of $12.6'' \times 6.3''$ into 8 parallel long slits which are used to illuminate the main spectrographs. The IFU is based on a multi-slicer concept, similar to the night-time devices MUSE and FISICA, but adequately adapted to the spectrographs of EST with the necessary changes and optimizations. To avoid overlapping between the spectra of the eight slits, a grating predisperser is used in front of the spectrograph, with the required mask at its output focal plane to restrict the transmitted wavelength range. The right image in Figure 6.16 shows one spectrograph used in this configuration. The integral field unit changes the input f/50 of the telescope to f/40.

*Figure 6.16: One main spectrograph used in LsSS configuration (left) and using the integral filed unit (right)*
6.4.3 TUNIS

This configuration is based on the selection of a small wavelength range of the spectrum of a wide 2D field-of-view formed by the main spectrograph. This light is then re-injected back on to the spectrograph to compensate for the dispersion, thus forming an image of the input 2D field-of-view with monochromatic pixels (see Figure 6.17). The full spectral information at each point of the 2D FoV is obtained by rotating the grating. Multiplexing with Hadamard masks at the focal plane of the spectrograph, before the second pass, may be implemented to measure several wavelengths simultaneously at each observed point. Moving the Hadamard mask changes the particular wavelengths that are observed at each point and makes it possible to
separate the contribution of each of them. This way, the rotation of the grating would no longer be necessary to obtain the full Spectral profiles.

The field of view of this configuration is 1'×2' and consequently does not need scanning to observe a large FoV.

6.4.4 **MSDP New Generation**

This configuration uses a beam slicer based on thin blades located in the focal plane of the spectrograph (see Figure 6.18) before re-injecting the light back into the main spectrograph for a second pass. Multiple monochromatic images of a large 2D field-of-view are formed and a full spectral line is measured simultaneously at all observed points. The “natural” entrance FoV of this option is 8"×120". A FoV re-arranger may be included at the entrance of the spectrograph, to convert a 32"×30" to that an equivalent 8"×120" FoV and, at the same time, convert the input f/50 delivered by the telescope to the maximum f/40 acceptable by the spectrograph.

6.4.5 **Performance**

The optical quality of the proposed spectrograph configurations is excellent. Figures 6.19 and 6.20 show the spot diagrams of one main spectrograph used in LsSS configuration and with the integral field unit (including the predisperser), respectively. As can been seen, all rays lie within the Airy disc.

Table 6.10 gives the spectral resolution obtained with the different configurations of the spectrographs. The spectral lines described in the Science Requirements Document have been used to evaluate that the spectral resolution requirement is fulfilled at most wavelengths. The total contribution from the slit, the grating and the detector sampling has been taken into account by adding them quadratically. For the LsSS configuration, the spectral resolution is limited by the width of slit (a value of 0.1 arcsec has been taken). For the TUNIS and IFU-MSMWSP configurations, the limit is imposed by the detector sampling (2 spectral pixels have been used in the calculations). In the case of MSDP-NG, the limit is imposed by the minimum size of the blades of the slicer that can be manufactured. We expect to reach a spectral resolution in the range [1-1.5]×10^5 for all wavelengths in this configuration.

Tables 6.11 and 6.12 give the transmission contributions for the spectrograph VIS-II used in the four configurations (LsSS, IFU-MSMWSP, TUNIS and MSDP-NG) at several reference wavelengths. The throughput values for the three spectrographs (VIS-I, NIR-I, and NIR-II) are similar, except for wavelengths below 400 nm with VIS-I, where the total transmission lies between 5% and 10%.
Figure 6.19: Spot diagrams for VIS-I, used in LsSS configuration, at 517.7 nm and 525.0 nm.

Figure 6.20: Spot diagrams for VIS-I, obtained with the IFU and the predisperser configuration, giving rise to eight parallel entrance slit at the main spectrograph. The eight columns at the left correspond to 517.7 nm, while the eight at the right correspond to 525.0 nm.
### Table 6.10. Spectral resolution for the spectrograph configurations LsSS, IFU-MSMWSP, and TUNIS. The last column at the right describes the scientific programs that require each different spectral line.

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>Spectrograph</th>
<th>LsSS</th>
<th>IFU-MSMWSP</th>
<th>TUNIS</th>
<th>Science Program</th>
</tr>
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<tr>
<td>393.3</td>
<td>VIS-I</td>
<td>2.84×10⁶</td>
<td>3.09×10⁶</td>
<td>Hanle, flares</td>
<td></td>
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<tr>
<td>396.8</td>
<td>VIS-I</td>
<td>3.06×10⁶</td>
<td>3.27×10⁶</td>
<td>Hanle, flares</td>
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<td>410.2</td>
<td>VIS-I</td>
<td>4.77×10⁶</td>
<td>4.44×10⁶</td>
<td>Flares</td>
<td></td>
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<tr>
<td>422.7</td>
<td>VIS-I</td>
<td>2.59×10⁶</td>
<td>3.05×10⁶</td>
<td>Planets</td>
<td></td>
</tr>
<tr>
<td>517.7</td>
<td>VIS-I</td>
<td>3.36×10⁶</td>
<td>4.04×10⁶</td>
<td>Flux tubes</td>
<td></td>
</tr>
<tr>
<td>525.0</td>
<td>VIS-I</td>
<td>4.02×10⁶</td>
<td>4.78×10⁶</td>
<td>Flux tubes</td>
<td></td>
</tr>
<tr>
<td>557.6</td>
<td>VIS-I</td>
<td>2.80×10⁶</td>
<td>3.36×10⁶</td>
<td>Network</td>
<td></td>
</tr>
<tr>
<td>589.0</td>
<td>VIS-II</td>
<td>3.27×10⁶</td>
<td>3.99×10⁶</td>
<td>Planets</td>
<td></td>
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<td>589.6</td>
<td>VIS-II</td>
<td>3.31×10⁶</td>
<td>3.99×10⁶</td>
<td>Magnetic canopies, planets</td>
<td></td>
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<tr>
<td>630.2</td>
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<td>3.68×10⁶</td>
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<td>VIS-II</td>
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<td>3.55×10⁶</td>
<td>Hanle</td>
<td></td>
</tr>
<tr>
<td>849.8</td>
<td>NIR-I</td>
<td>3.22×10⁶</td>
<td>3.45×10⁶</td>
<td>Magnetic canopies</td>
<td></td>
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<tr>
<td>854.2</td>
<td>NIR-I</td>
<td>3.37×10⁶</td>
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### SP VIS-II

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<td>M1</td>
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<td>0.63</td>
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*Table 6.11: Transmission budget of the common elements for all configurations with spectrograph VIS-II.*
### Table 6.12. Transmission budget of the particular modules of the LsSS, IFU-MSMWSP, TUNIS and MSDP-NG configurations with spectrograph VIS-II. The total throughput values include the common modules listed in Table 6.11.

<table>
<thead>
<tr>
<th>λ (Å)</th>
<th>5889,9</th>
<th>5896</th>
<th>6302,5</th>
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<td><strong>IFU MSMWSP Modules</strong></td>
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<td>1 macro slicer+slicer mirror</td>
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<td>0.84</td>
<td>0.83</td>
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<td><strong>MSDP beam slicer module</strong></td>
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<td>0.84</td>
<td>0.83</td>
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</table>
7 ENCLOSURE AND BUILDINGS

7.1 Enclosure

7.1.1 Trade off

During the study several types of enclosures have been suggested. Two main alternatives have been studied in detail: a ventilated/cooled permanent dome around the telescope and a retractable enclosure. Topics that have been investigated are thermal characteristics, wind load reduction, technical feasibility and costs. The comparison between both alternatives are shown in Table 7.1. Based on the results a trade-off has been made.

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<th>Comments</th>
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<td>Local seeing</td>
<td>-</td>
<td>+</td>
<td>Retractable always best. More effort needed in case of dome.</td>
</tr>
<tr>
<td>Wind shake</td>
<td>+</td>
<td>=</td>
<td>Stiffer telescope needed. Effect can be mitigated with windshield.</td>
</tr>
<tr>
<td>Primary focus heat stop</td>
<td>-</td>
<td>+</td>
<td>Heat rejector possible. Safer.</td>
</tr>
<tr>
<td>Telescope mobility</td>
<td>+</td>
<td>-</td>
<td>For full range, larger diameter required for retractable variant.</td>
</tr>
<tr>
<td>Handling equipment</td>
<td>+</td>
<td>-</td>
<td>The dome can easily provide crane facilities.</td>
</tr>
<tr>
<td>Safety</td>
<td>=</td>
<td>=</td>
<td>Dome more complex system, due to cooling. Both need redundant safety systems.</td>
</tr>
<tr>
<td>Cost</td>
<td>-</td>
<td>+</td>
<td>Dome more expensive, even when including extra costs for stiffer telescope.</td>
</tr>
</tbody>
</table>

Table 7.1: Comparison of strength and weakness of the dome concept and retractable enclosure.

It was concluded that both a cooled hemispherical and a retractable enclosure based on membrane technology are technically realistic concepts. The retractable enclosure was chosen as the baseline concept, because its has better seeing properties (no dome seeing, no shell seeing, only floor seeing instead, easier to keep within seeing requirements) and its major drawback, the windshake on the telescope, seemed to be under control based on first results based on calculations of the telescope pointing performance, with an optional wind shield as a backup plan. Retractable enclosures are also cheaper than ventilated domes and the retractable enclosure allows the use of a reflecting heat rejecter at the Gregory focus. Stringent safety issues both for the ventilated dome and retractable enclosure exist, which are of similar magnitude.
Considering the above arguments, it was concluded that the retractable enclosure is to be considered as the less risky alternative, since it allows easier local seeing control with less effort and it allows the use of the safer reflecting solution for the heat stop.

7.1.2 Proposed Design

The proposed design is based on a Ø28 m retractable enclosure, which allows full telescope movement in azimuth and an elevation movement up to 15°.

The retractable enclosure concept has been developed based on the 7 m and 9 m retractable enclosures for the DOT and GREGOR solar telescopes. Although novel in their construction, both enclosures have been in operation for up to 15 years, with broad experience available. Calculations show that, until ~30 m diameter, no principal changes in the design are necessary. Larger sizes also seem within reach based on light-weight civil building technology, but need more motorized bows.

The EST enclosure has been designed to withstand hurricanes (70 m/s) to be opened and closed with wind speeds up to 30 m/s. The enclosure consists of rotatable bows (Figures 7.1 and 7.2), which are encapsulated in a spanned membrane. The two main bows are driven by a very compact drive system near the hinges of the bows with electrically driven actuators. All other bows between the different cloth segments are undriven. They rotate solely on hinges at the bow ends. During opening and closing, the upper cloth segments are tensioned because of the weight of these in-between bows. It avoids flapping of the cloth during opening and closing without the need of a complex drive system for the in-between bows.

Figure 7.1: Model of the enclosure with telescope inside.
For opening and closing, 180 kW motor power (4×200 Tons) is available to close the enclosure in 3 minutes. Three clamps on the main bows, each 4 kW with 12 ton, help span the membrane. The total weight of the enclosure is 131 tons.

The membrane is double layer with an air gap in between to improve insulation. It is needed to maintain the telescope temperature during night at early morning temperature. The membrane material is prestretched, frost, UV and ozone-proof, and guaranteed and tested for 20 year lifetime. Ice deposition during winter is minimal due to a PVDF coating on the membrane material. FE calculations on the enclosure and membrane have been done, and curvature, membrane thickness and pretension were optimized. The maximum stress at survival wind (70 m/s) is below 50% of the allowable stress (Figure 7.3).

![Figure 7.2: Model of the enclosure in closed and open position.](image)

![Figure 7.3: Wind load simulation on the enclosure with stress in the membrane in the two membrane weave directions. The maximum stress is 75 kN/m.](image)
The design of the enclosure is such that, when fully opened, the bows and membrane are “stored” below the telescope platform, which enhances flushing and avoids the formation of air pockets with deviating temperature.

The enclosure is manufactured in small parts, which can be assembled on-site, and weather-proofed by use of a duplex coating system. The enclosure is almost maintenance-free.

7.1.3 Windshield

Around the enclosure, there is an external rotatable windshield (Figure 7.4). The windshield reduces the wind load on the telescope and also stratifies the air behind the screen, reducing the platform boundary layer and as such keeps the platform seeing further away from the optical beam (Figure 7.5). The reduction in wind load is in the order of 3-5 following from simulations, with in situ measurements suggesting a larger reduction factor.

We have chosen to locate the windscreen outside the enclosure. This does not set constraints on the size on the enclosure, but it does need to be outdoor resistant and thus able to withstand 70 m/s with heavy ice deposition (screen fully iced).

The proposed design is composed of a screen of vertical poles placed on an 180° carousel that can rotate on a circular rail in order to turn the shield towards the actual wind direction. The poles generate small scale eddies, forming directly behind the windshield that efficiently dissipate the kinetic energy, with the vertical pole orientation maintaining the horizontally stratified air mass.

The shield consists of two parts (each spanning 90° in azimuth) with screen heights of of 6 m and 4 m. A higher height gives a better shielding effect but hinders telescope operation at lower elevation angles. The 4 m height is too low to cover the M1 completely but is a better compromise when observing upwind at low elevation angles.

The selected gap width is 200 mm (hence, 200 mm closed, 200 mm open). The choice is based on measurements on a range of gaps and can be further optimized in future research. More work (both simulations and in situ measurements) is needed for characterizing the flow through and above the screen.
7.2 Pier

7.2.1 Trade off

The basic function of the pier is to support the telescope and the enclosure. It forms the connection between telescope/enclosure and ground. At the bottom of the pier the instrument (Coudé) room is located, which has dimensions of approximately 16 m × 10 m (diameter x height) and influences on the design of the pier. The pier is divided into two parts: a lower and an upper pier. The lower part houses the instrument room; the upper part accommodates the transfer optics.

The error budget specifies three values for the pier. The first is the budget for thermal aspects, and specified as a contribution to image blur of 0.038". The second is the budget for windshake, which is defined as: 1.0" pointing accuracy for wind and 0.2" tracking accuracy for wind (10 minute interval). Finally, the thermal stability should be better than 0.5" pointing accuracy for thermal effects and 0.1" tracking accuracy for thermal effects (10 minute interval).

A trade-off was made, which included stability, thermal aspects (stability, seeing), height and overall construction issues, and costs. Analysed have been: solid piers (concrete, in cylindrical, rectangular, conical shape), open frame piers (made of steel, transparent to wind), double tower (internal pier, supporting pier and external pier supporting the enclosure), and hybrid type, consisting of a concrete lower part and open framework upper part. Both plates, as well as deep (pole) foundations, have been studies on both weak and stiffer underground.

In terms of wind load, all alternatives easily fulfil the requirements. The “cone tower” is the best single tower, which can be explained by the smaller surface that is exposed to wind.

Regarding seeing, the lower part of the pier is not critical because it is too far away from the optical telescope beam. For the upper pier half the situation is different and becomes comparable with shell seeing. It is found that in order to reach the error budget of 0.03" an air temperature difference of ~0.5 °C is allowed, and a pier temperature difference of ~1.5 °C.

Flow patterns around the pier have been computed with CFD, which showed that 1) on the top of the pier a boundary layer builds up, which for full diameter pier (diameter 20-28 m), can easily reach the height of M1; 2) the wind flow that impinges on the pier has a slight vertical component at the upper part of the pier. This is next to buoyancy, a second mechanism to transport air with deviating temperature up to the telescope.
It was concluded that a pier top a) that is small in diameter and b) that does not extend to the top as a massive part are the best solution.

Site testing measurements have demonstrated that the local seeing improves with increasing height of the tower.

7.2.2 Proposed Design

The proposed design (Figure 7.6) incorporates a cone-shaped pier top, which is the stiffest pier design. At the top, the diameter was derived from the size of the azimuth bearing of the telescope and transfer optics. Around the cone a steel framework is erected that supports the enclosure platform. Together they form a good alternative for reducing pier seeing.

The height of the pier is set at 38 m. It leads to a design where the instrument lab is above ground level, with only a service floor level underground. 38 m is also the largest height that a local mobile crane can reach. The final design has a cylindrical base that surrounds the instrument lab. A cylindrical base fits better to the building, otherwise also a complete cone could be chosen. Around the top of the pier a ø33 m steel platform is located. The preference is to attach the building to the pier, with some of the facilities housed inside the pier. There is no indication from the CFD analysis that the building has a negative impact on the generated turbulence, since it is well below the telescope level.

The framework is bolted together on site, all elements dip zinc and TiO2 coated. After assembly the construction is maintenance free and does not need periodic repainting.

Figure 7.6: Model of the proposed pier design.
Simulations have been done to study the thermal behaviour of the pier. These include a bare white concrete pier, an insulated pier and an insulated pier surrounded by a second thinner (150 mm concrete wall). The simulations (Figure 7.7) show that a thick concrete pier cools down and has average temperatures of 5°C below ambient at daytime. An insulated pier with aluminium plating heats up, but above ambient, most of the day, at 2°C. With a second concrete wall the temperature behavior is also very good, and can even be tuned by the thickness. Note, however, that the pier will have no homogenous temperature (we are looking here at average temperatures), and that at different parts of the pier the differences can easily be a few degrees centigrade. This is also confirmed by measurements.

A second wall with a thickness of 150 mm was also studied, but its contribution to the costs was significant because of its complexity. Furthermore, the 150 mm wall was demonstrated not to be sufficient as a stand-alone cone over the full height, and required studs in between. Baffles around the external surface assist in adding rigidity and they also serve as a protection against updrafts of warm air. As a cheaper alternative to the double wall, insulation with white aluminium plating is proposed (sandwich system). Insulation of the main pier is also needed to maintain thermal stability, mainly in terms of pointing.

7.2.3 Platform

The floor of the telescope platform is an important source of seeing in the retractable enclosure. The floor is also illuminated by sunlight, and thus the floor temperature should be maintained. A floor that is too warm is the worst scenario, but also a floor which is too cold is to be avoided, since cold air can be transported upwards by large scale eddies or counter flows.

From CFD simulations, it was also concluded that an open floor has advantages: it improves the homogeneity of the airflow and also limits the boundary layer. A completely open platform floor is nevertheless not possible but also apertures in the floor avoid the airflow to be detached from the telescope floor improving also the flushing of the telescope floor in a similar way as the wind shield.
Figure 7.8 illustrates the basic layout of the platform. The platform consists of a double-layered construction, consisting of an upper and a lower floor. The upper one is the telescope platform and the lower one is used for accommodating cable wraps and auxiliary equipment. The outer part of the platform construction consists of a tub, which is used for storage of the enclosure membrane when the enclosure is open. It is important that the airflow above the floor is disturbed as little as possible, i.e. that no large eddies or counter flows are developed that push the floor seeing into the optical beam. The floor is located such that the enclosure is at the same height as the platform floor. The tub is filled with the membrane when the enclosure is open, approaching a smooth surface.

Louvers in the bottom are included, both in upper and lower platform, which can be opened during observations, and closed overnight and at bad weather. It allows for optimization, since closed vents can have also effect on preventing buoyancy from the ground layer at certain conditions. The louvers consist of roller blades, with a grid on top for walking on.

![Figure 7.8: Concept of the platform floor. The brown panels represent the louvers.](image)

### 7.3 Building

The building includes the facilities and services (control room, stores, workshops, laboratories, offices, power plant, water coolers, lifting elements, fire prevention, coating facilities, etc.) required for the normal telescope operation, support and maintenance. Considering the current design of the telescope pier composed of a conical concrete tower approx. 30 m high containing the Coudé room with instruments at its base, it is proposed to attach the main building containing the required facilities to the pier. In order to minimize vibration and local seeing degradation, the services generating heat, smoke or vibration will be placed in an additional auxiliary building placed in the downwind direction away from the telescope location. This building will be connected to the telescope building by means of a supply gallery. Additionally, all the surroundings of the telescope will have to be urbanized to provide access to both pedestrians and traffic, including lorries.
During the design study, the effect of the shape of the building on the air turbulence generated at the telescope level has been analysed, comparing a box-shaped building and a more aerodynamic circular building distributed around the pier. Since the turbulence obtained is similar for both configurations, if the pier is high enough, it is proposed to attach the building concentrating the facilities to one side of the pier in order to improve functionality. In order to improve the observing conditions during most of the day, it is proposed to place the building in the west, where it can be flushed by the predominant northerly wind without affecting the telescope environment. A western orientation can be changed from north-west to south-west depending on the telescope site that is finally selected.

The telescope urbanization (Figure 7.9) include work areas on the south and west sides of the main building in order to work with the enclosure crane and to facilitate the access of lorries. The ground of the urbanized area around the telescope will be coated with a white concrete apron or white paving stones to improve the local seeing.

The following services shall be provided by the building to the telescope:

- Heating, ventilating and air conditioning (HVAC) and cooling. It will provide thermal control to the transfer optics chamber, Coudé room, and additional laboratories. It also will provide comfortable environmental conditions in all the telescope facilities. This system will provide the required coolant supply for the local cooling systems of the different telescope subsystems: mirrors, heat stop, sunshields, electronics cabinets, etc.

- Electrical power and lighting. The electrical supply comprises three main categories: clean power supply (filtered by isolating transformers), non-clean supply (directly from
the transformer station) and the UPS power supply (from an autonomous generating equipment).

- Fire systems.
- Water and sanitation.
- Networks and communications.
- Dry compressed air lines.
- Handling and lifting equipment: Several handling devices are required for the telescope operation. The most relevant ones are a large crane (15 ton, 24 m) at the telescope platform, two small foldable cranes inside the enclosure, a large bridge crane (15 ton) at the receiving area, a large lifting platform (5 ton, 5×4 m) inside the building and an elevator for personnel and loads inside the pier (2 ton, 3×2 m²) to access to the telescope level.

Disturbing services which will be located in the auxiliary building are the following:

- Power supply: including transformers and diesel engine
- Water supply room: including hydraulic pumps
- Air conditioning equipment room, including fans
- Fire prevention equipment room, including hydraulic pumps

7.3.1 Building layout

The design of the main building is based on organic geometry, linked to the vernacular architecture, which provides greater flexibility than orthogonal geometry and facilitates integration with the conical pier (see Figure 7.10). A small rotation of volume is proposed to provide a dynamic look related with the dynamic phenomena produced in the Sun, allowing an artistic integration of the entire system. This rotation generates terraces where façade openings can be located for access and views.

The building is organized in four floors above ground and an additional underground service floor. The 4 floors above ground are needed in order to access the floor above the Coudé laboratory inside the telescope pier, from where there is access to the telescope platform. The building is layered in order to reduce the impact of wind flow. The facilities inside the building are distributed, placing the hard working areas on the north side and the inhabited areas on south side for greater comfort (leeward, warmer and more illuminated).

The vertical communications and handling core is placed in the centre of the building to work as the organizer of all the surrounding areas. The 5 ton large lift, the stairs and the services shafts are located together in the heart of the building and directly connect all the levels inside the telescope pier with the exterior access. The communications between the different areas and the telescope pier will be through an optimized direct corridor, minimizing the ratio between constructed and service-dedicated surface.

Access to the telescope platform is provided inside the pier, from the floor above the Coudé room (Figure 7.11). Stairs and an elevator for persons and loads up to 2 ton are planned inside the pier to access the telescope platform. Inside the enclosure, the loads can be handled by two cranes on the telescope platform. The main advantage of providing access from inside the pier is the possibility of accessing the telescope platform for persons and loads keeping the telescope
enclosure closed. Large loads (> 2 ton) shall be handled with the large crane of the enclosure platform, requiring in this case to open the enclosure to access the telescope platform (see Figure 7.12).

*Figure 7.10: Views of the building attached to the telescope pier.*
The underground floor includes service areas such as a water supply room, the hydraulic pumps and compressor rooms and the Air Conditioning (AC) room (Figure 7.13). The AC room is located close to the pier to optimize the air duct dimensions. A services gallery is proposed to connect with the Auxiliary building. The septic tank can be buried outside the building.

The ground floor (Figure 7.14) includes the accesses, receiving areas for lorries and persons, Reception, Cleaning and First-aid room, Toilets and the hard work areas (Mirror washing and Coating areas, Mechanical workshop and Storing area). Some of these areas have double height.
The first floor, orientated south (Figure 7.15), includes all the rest areas (Kitchen and Living Room), Changing room and offices, and the Gases room orientated north. The corridor that provides access to the office has a long window providing views for personnel and visitors to the hard work areas at the ground level. A glazed partition could also provide views from the office.

The second floor (Figure 7.16) includes the fine work areas such as the Control and Computer room, Networks and telephone room, Electrical Workshop, and Instrument laboratory. This time, the corridor glazed partitions provide views to the Control and Computer rooms and to the Instrument Laboratory. An additional window can be installed in the pier corridor to provide views of the second level of the Coudé room. All these windows will be equipped with shutters or roller blinds to allow visiting the facilities without disturbing the normal work or to avoid illumination when needed.

The third floor (Figure 7.17) allows the access inside the pier above the Coudé room where an additional Instruments laboratory and long term storing areas are proposed. The additional Instruments laboratory located above the Coudé room can be used for fine instruments tests before installation in the Coudé room, and it could be used to install visiting instruments also. This laboratory could be fed by light coming from the transfer optics, although the use of this optical path will not be compatible with observations in the Coudé room at the same time, and a dedicated optical de-rotator will be needed inside the laboratory to compensate the FoV rotation. This floor includes additionally Visitors Gallery and Meeting room located in the south area, where a glazed door provides natural light to the area and access to the terrace. An additional Auxiliary equipment area is located on the north side close to the pier.

Figure 7.13: Underground floor.
Figure 7.14: Ground floor.

Figure 7.15: First floor.
Figure 7.16: Second floor.

Figure 7.17: Third floor.
7.3.2 Structure

A structure based on flat concrete slabs supported on a concrete column grid is proposed as baseline solution. Additional supports are provided by the lateral walls of the lifting platform and the some of the walls of the stairs. These walls will also act as the lateral stability core of the building against both wind and seismic loads.

General benefits of full concrete structures include the simplicity of their implementation and the competitive price of the materials, which leads to inexpensive erection costs, and optimum behaviour in fire conditions, leading to resistance times far beyond 90 minutes.

Steel structure should be a competitive solution in order to avoid the transportation of concrete to the observatory. In any case, the large scale use of concrete for the pier structure and for the foundations of the main building will require the installation of a concrete plant on site.

The external façades are proposed in precast concrete panels painted in white. Concrete walls provide high thermal inertia which facilitates to keep the external surfaces of the building below the ambient temperature most of the day, avoiding local seeing degradation. The solution of precast panels is economically more competitive than concrete walls cast on site and allows faster construction since the panels can be supplied finished from workshop. The panels include a layer of insulation inside, although in the inhabited areas additional thermal insulation with plaster board should be added in the inner face for a greater comfort.

An alternative considered to the precast concrete panels are local volcanic concrete blocks. The concrete blocks solution is cheaper than precast panels, but the faster construction of the precast blocks compensates the cost and, at the end, the concrete panels are economically competitive.

The roofing proposed is Mediterranean terrace composed of a water-proofed concrete slab covered with either white gravel or white tiles, which also provides high thermal inertia.

7.4 Local Seeing Control

7.4.1 Telescope structure

The proposed baseline to control the local seeing around the telescope structure is to locate the telescope in open air conditions with a completely foldable enclosure. Under these conditions the telescope environment benefits from optimal natural air flushing, as well as during low wind periods, which prevent hot air plumes degrading the local seeing.

With the telescope placed in open air, it is necessary to provide liquid-cooled sunshields to the telescope structure to protect it from the solar irradiation.

The telescope mirrors shall be cooled to avoid mirror seeing, although they take advantage of natural air flushing provided in open-air conditions to reduce the mirror seeing. Mirror cooling by air impingement jets at the back of the mirror is proposed for M1 and M2 due to the compatibility with the mirror actuators, while liquid cooling is proposed for the remaining mirrors in the optical path. Additionally, a dedicated air flushing system is proposed on the M1 surface in order to guarantee the mirror flushing in very low wind periods. The flushing of the M1 surface is crucial since M1 supports the maximum heat load and the size of the mirror is large, being subjected to air temperature gradients that affect the local seeing.
The heat stop placed at the prime focus receives the maximum heat density. The open air configuration allows implementing a reflecting heat rejecter, reflecting away most of the heat load. If the telescope were to operate with a conventional enclosure, it would be necessary to implement a heat trap absorbing all received heat load at the primary focus, thereby increasing dramatically the heat that would need to be removed by the cooling system. An air suction system is additionally proposed around the heat rejecter surface to absorb any warmer air from the surface to avoid crossing the optical beam.

Liquid cooling by plate coils is also proposed for the telescope platform. Preliminary thermal analysis of the telescope platform shows that its temperature increases by up to 7 °C with respect to the ambient temperature in low wind conditions if thermal control is not provided (see Figure 7.18), even if it is painted in white with high visible reflectivity and infrared emissivity paint.

Working in open air conditions, it is observed that the solar radiation reflected on the telescope platform warms up the lower part of the telescope structure, producing a similar effect as direct solar radiation; hence, it will also be necessary to provide sunshades for the lower part of the structure to protect it from the reflected radiation. Painting the telescope platform in white with high visible reflectivity and infrared emissivity paint to reduce the thermal load to be removed by its liquid cooling system produces a greenhouse effect on the lower part of the telescope structure, since the platform reflects the solar radiation on the telescope structure but prevents infrared exchange between the structure and the cold sky. To avoid this effect, it is proposed to paint the telescope azimuth platform in silver (see Figure 7.19), with low infrared emissivity, which will allow the infrared exchange between the lower part of the structure and the sky, although it will increase the thermal load to be removed by the thermal control of the azimuth platform.
From CFD simulations (Figure 7.20), it was concluded that an open floor has advantages: it improves the homogeneity of the airflow and also limits the boundary layer. A completely open platform floor is nevertheless not possible, but also apertures in the floor prevent the airflow from being detached from the telescope floor improving also the flushing of the telescope floor in similar way as the wind shield. It is proposed to include large venting apertures at the fixed part of the telescope platform, to improve the natural flushing of the telescope platform and lower part of the telescope structure. The venting apertures will include louvers to be able to regulate the lifting flow or close the apertures if needed to avoid the arrival of ground layer air plumes at telescope level.
7.4.2 Transfer optics and Coudé laboratory

It is proposed to implement an air conditioning system in the long transfer optics chamber and the large Coudé laboratory to control the local seeing (Figure 7.21). Additionally, liquid cooling is proposed for each mirror in the transfer optics to avoid mirror seeing, and the electronics racks will have their own thermal control also, hence the air conditioning system will remove only residual heat not removed by the local thermal control of each component.

A vacuum chamber, instead of air conditioning, was also considered as an alternative for seeing control of the enclosed transfer optics chamber. Considering the small diameter of the transfer optics path, the windows needed for the vacuum chamber would be relatively small and thin, but they would produce some effect on the telescope throughput and polarimetric performance. An air conditioning system is proposed as baseline, since this makes it possible to eliminate the windows and allows better accessibility to the transfer optics systems.

The proposed design of the air conditioning system consists of a circular plenum located in the upper part of the Transfer Optic Chamber supplying air at 1 m/s and another circular plenum hanging from the ceiling of the Coudé laboratory supplying air at 0.2 m/s. Both of them supply a vertical laminar air flux, covering the complete workspace. The flow from the two input plenums is collected by the output plenum below the Coudé laboratory.

Three air handling units (AHU) of 80,000 m³/hour are needed to supply the required air flow, one for the upper plenum and two for the Coudé plenum.

An air curtain is proposed at the top of the transfer optics chamber to isolate the enclosed controlled environment and the outer environment of the telescope platform. The implementation of the air curtain is proposed by a supply of a horizontal laminar flow at 10 m/s, which is collected by a grille arranged in the opposite side. The air curtain avoids the necessity to close the environment by a glass window, which would have some effect on the polarimetry performance and optical throughput. Nevertheless, the possibility of closing the environment with a glass window is still open, since the dichroic needed for the pupil DM WFS could be used also as a window to close the environment.

A preliminary estimate has been made of the local seeing degradation in the transfer optics path and Coudé laboratory using CFD analysis (see Figure 7.22) to obtain an average seeing degradation of 0.0002 arcsec per metre of optical path, which results in 0.014 arcsec rms for the complete optical path length. CFD analysis shows an additional local seeing degradation of 0.01 arcsec corresponding to the air curtain. These values are well in agreement with the requirement of 0.048 arcsec rms local seeing degradation due to the air conditioning system of the transfer optics chamber and Coudé laboratory.
7.4.3 **Pier and building**

The local seeing in the telescope environment is controlled providing a high pier to reduce the effect of the ground layer. Measurements performed for the ATST site campaign at different sites shows the improvement of seeing conditions with increasing pier height (Figure 7.23). An increase from 28 to 38 metres could provide an increase in science output of 17%, related to the increase of periods with seeing better than 6 cm, which is assumed the limit of operation of the AO system.
According to the current optical design, the height needed to accommodate the transfer optics chamber and the Coudé laboratory, between the telescope platform and the lower floor of the Coudé laboratory is 33 or 38 metres, depending on the final arrangement of the Coudé laboratory in two or three floors. The primary mirror is located approx. 5 m above the telescope platform. In order to take advantage of the best seeing conditions it is proposed to build the pier arranging the lower floor of the Coudé at the ground level, which would place the primary mirror approx. at 38 m or 43 m above ground level.

Figure 7.23. $r_0$ measurements from the ATST site campaign. At 8m height, 13% of the data has seeing better than 6cm, at 18m height, 26% of the data has seeing better than 6cm, at 28m height, 36% of the data has seeing better than 6cm, at 38m height, 42% of the data has seeing better than 6cm.

The proposed shape of the pier is conical, in order to reduce as much as possible the wind resistance and the turbulence generated at the top of the tower. It is proposed to support the enclosure platform by an independent framework structure to the pier base to minimize the flow resistance. The reduction of the diameter at the upper part of the pier, while keeping larger the telescope platform diameter, prevents the possible arrival of the ground layer plumes up to telescope level.

The building attached to the pier is half of the pier height, keeping the upper part of the pier free of building structures, to minimize the wind flow disturbance. To improve the observing conditions during most of the day, it is proposed to place the building to the west, where it can be flushed by the predominant northerly wind without affecting the telescope environment. The west orientation can be changed from north-west to south-west depending of the telescope site finally selected.

Additionally, an auxiliary building containing the services which can generate heat, smoke or vibration will be placed in the downwind direction away from the telescope location.

It is advantageous that the surfaces below the telescope level such as the pier, building and urbanization are kept a few degrees below the ambient temperature in order to prevent hot air
plumes appearing. These elements can be kept most of the day below the ambient temperature if they have high thermal inertia, since they can take advantage of sub-cooling during night. The high thermal inertia of these elements provides a slow temperature increase during daytime, slower than the heating of the ambient air, keeping its temperature below the ambient into the afternoon. These elements shall be finished in white in order to maximize the radiation thermal exchange with the cold sky, minimizing the absorption of solar irradiation.

In the case of the telescope pier, it is proposed to provide an external white concrete wall isolated from the structural pier, in order to protect the pier structure from solar irradiation, thereby avoiding gradients that would affect the telescope pointing. The thickness of the external wall can be optimized in order to improve temperature evolution during the day.

It is proposed to cover the telescope urbanization with white concrete apron or white concrete paving stones in order to provide a white area surrounding the pier. The white ground allows keeping the urbanization area a few degrees below the ambient temperature most of the day, while the raw ground increases its temperature due to its lower reflectivity.

Preliminary thermal analyses (see Figure 7.24) have been performed in order to obtain the daily temperature evolution of the external surfaces of the pier building and surrounding ground in different conditions. Based on these thermal results, the local seeing degradation due to the pier and building effects has been estimated by CFD analysis and some results are shown in Figure 7.25.

Figure 7.24. Temperature maps obtained for a simplified model of the telescope environment at sunrise (left) and noon (right).
Figure 7.25. 48 hours evolution of averaged temperature difference between the pier and building elements (pier, building, urbanization ground and raw ground) and ambient air for 2 m/s wind in summer conditions. It is observed that the averaged temperature of the threatened elements is kept below the ambient during most of the day. The temperature differences are reduced in higher wind conditions, due to the higher convection. High temperature increase is observed in the raw ground (Tfar) with respect to the urbanization ground (Tcloser), due to its low reflectivity assumed.
8 CONTROL SYSTEM AND DATA HANDLING

The EST Control System (hereafter ECS) shall be used for the operation and overall supervision of all the subsystems, components and elements forming the EST facility. The EST shall physically consist of the following high-level sub-systems, each one consisting of several components:

- Telescope mechanics (Mount, Heat rejecter);
- Telescope Optics (Primary mirror, Secondary mirror, Transfer optics, Polarization optics, WFS, MCAO);
- Science Instruments (Broad Band Imager [BBI], Narrow Band tunable filter spectro-polarimeter [NBI], Grating Spectropolarimeter [GS], Detectors);
- Enclosure (Enclosure, Windshield, Building);
- Control facilities (Interconnected computers, Electronic equipments);
- Auxiliary installations (Auxiliary full-disk telescope, Meteorological Station).

The ECS must allow to operate all the EST parts listed above by dealings with the following additional elements of the EST facility:

- Users
- Common software
- External databases;
- Data analysis applications
- Safety facilities
- Monitoring facilities
- UPS and power generators

The ECS shall consist of the EST control facilities and of some of the elements listed above, specifically the common software, the safety and monitoring facilities, and a sub-set of data analysis applications. It shall allow EST users to manage the flux of information generated by the EST facility. The term User encompasses the five categories: engineers, technical operators, staff astronomers, responsible for the operation of the EST, visiting astronomers. EST Users and ECS sub-systems are hereafter referred to as EST actors. The flux of information generated by the facility shall consist of science data, metadata, and monitoring data. Figure 8.1 shows the high-level sub-systems of the EST, by picking out the role of ECS within the EST.

The general strategy for controlling the observatory during the operational phase needs to consider efficient means both to transmit and share data and metadata generated by the EST facility, from telescope, instruments, enclosure and environment to a real-time repository, as well as to users and to temporary and permanent archives. At any stage of the observatory operation it shall be possible to visualize and store a subset of transmitted data, both for system monitoring and for evaluation of data quality.
The analysis of control alternatives carried out for the conceptual design of ECS indicates that astronomical observatories are moving towards establishing common software across their entire domain, by adopting both open-source and commercial solutions. Distributed control has become a standard. The analysis also indicates the well-established trend to model the various software packages forming the control system of complex facilities with the component-container model. The analysis indicates that the ECS architecture could be based on:

- systems specifically developed for this project;
- complete open source systems developed for other projects, e.g., for data handling and control of other astronomical facilities such as ALMA, ATST, GTC, which could provide both architecture and tools to realize a control system fulfilling the specifications and requirements of the EST;
- complete commercial solutions;
- hybrid solutions, with an architecture based on both open source existing systems and commercial solutions, the latter utilized for the low-level control of elements in the various sub-systems.

Among the various alternatives for the ECS design, open source systems and hybrid solutions promise fulfillment of all the system characteristics listed for ECS together with lower cost and greater reliability. The current design envisages that an open, flexible, distributed and object-oriented architecture shall be adopted for the ECS in order to provide location-transparent access to the set of physically distributed interconnected sub-systems forming the EST. The implementation of the ECS architecture shall be simplified through the use of a distributed middleware that shall ensure availability of necessary resources to all the tasks accomplished by ECS.
Among complete open-source solutions, the ALMA Common Software (ACS) offers several basic services for object-oriented distributed computing, e.g. transparent remote object invocation, object deployment and location, distributed error, alarm handling, logging and events. Although developed for the ALMA, ACS concepts are now used by several other projects worldwide, including ATST. Similarly, the GTC developed an SW infrastructure akin to that provided by ACS. ACS provides an application architecture based on the Component Containe paradigm. ACS Containers are implemented in C++, Java, Python. Within ACS, developers need only to implement the functional aspects of the various Components.

The distributed middleware service behind ACS is CORBA (Common Object Request Broker Architecture), which shapes the architecture of a system according to a client-server communication model. This model describes the relationship between two computer programs in which the client program makes a service request to the server program. ATST adopted this communication model. On the other hand, the Data-Distribution Service (DDS) middleware allows to address publish-subscribe communications for real-time and embedded systems.

To date, it seems appropriate to base the ECS design on the concepts presented above, specifically a distributed and object-oriented architecture founded on the component/container model, the open source-solution of either ACS or ATST and the middleware services provided by CORBA (ACE/TAO, ICE) and DDS for the flow of operational and science data, respectively.

### 8.1 ECS Architecture

The ECS architecture looks at the organization of the various parts forming the EST facility, as well as to their interaction during EST operation. The term architecture indicates the hierarchical frame of elements forming the ECS, hereafter referred to as components. Each component is defined by a set of attributes that include name, responsibility, content, constraints, dependencies, and interfaces; the latter attribute indicates the elements utilized by each component to interact with other ECS components. Each component could comprise an aggregate of other components (e.g. an application consisting of several executables).

The ECS architecture is presented in the following by means of five models:

- the package model that describes all high level sub-systems forming the ECS
- the reference model that describes all high level functions expected from the ECS
- the logical model that describes the connections among the various sub-systems forming the ECS
- the development model that describes the arrangement of the control software forming ECS
- the physical model that describes the arrangement of the control hardware forming ECS
8.1.1 Package Model

The ECS shall consist of four main blocks:

- Observatory control
- Instrument control
- Data handling
- Telescope control

Figure 8.2 shows the main blocks of the ECS.

The partition of the ECS into these main blocks derives from the topological, functional and management reasons described below. These four blocks have to work in a coordinated manner although they are to a certain degree independent of each other. In particular, the Observatory, Instrument, and Telescope Control blocks are required to enable EST to execute various modes of both operation (classically scheduled, queue observing service, engineering) and observation (day-time solar observation, day-time non-solar observation, night-time observation), by various users (engineers, technical operators, staff astronomers, visiting astronomers responsible for EST operation). This implies control, monitoring and operation of all the various main parts of the EST. These blocks are also required to enable EST to point and track a position in various coordinate systems (none, sidereal, heliocentric, heliographic) and to perform observations with different instrument setups, also in the framework of simultaneous and coordinated campaigns carried out with various instruments and other telescopes. Moreover, the Data handling block of the ECS shall provide for the recording of all the data and metadata acquired by the telescope and instruments for the access and display of the data needed to facilitate telescope operations, and for the transfer of the data produced away from the telescope to intermediate and then to long-term data archiving facilities. The facilities dedicated to data handling at the telescope and other sites shall allow for the re-processing and re-use of old data; in addition, they shall serve as dispenser of Science-ready data (VO-compliant) and processing tools. They shall also allow for the publication of data into VO and the interoperability with databases produced by other facilities. The display of the data generated by the EST shall provide near real-time feedback to the operators and users about the telescope operations. The data display may have to combine the raw data stored on disc with metadata extracted from the repository in order to provide a coherent set of information to the users, also for engineering purposes. In addition, it may be necessary to have some subset of the acquired data processed at the telescope prior to moving it off the summit. The purposes of such processing might include:
− Data quality assurance
− Data volume reduction
− Evaluation of the solar structures being observed

The data volume could be reduced to 2/3 with evaluation of observations quality and to 1-5 to 1/10, depending on the instrument, with on-site data processing. In addition, a lossless data compression can be applied to the data, such as that performed by JPEG-2000 or FPACK, to compress most integer-format data by a factor of approximately two. The JPEG-2000 is a lossless wavelet-based compression algorithm already applied to SDO/AIA data and tested on data set such as the one that shall be generated with the EST. It is worth considering that the data production by the LHC project LHC (basically 1 DVD/s, ~5 GB/s) is currently managed by using grid computing, state-of-the-art data storage facilities, and high-bandwidth networks. Therefore, independent of the capacity to reduce the EST data volume (~80 GB/s) on-site and of the improvement of information technologies by the start of EST operation, the management of data generated by the EST shall rely also on European e-Infrastructures (e.g. http://cordis.europa.eu/fp7/ict/e-infrastructure/home_en.html).

![Figure 8.3.High-level sub-systems of ECS.](image_url)

The four main blocks of ECS consist of 16 sub-systems, hereafter referred to as high-level sub-systems of ECS, and are arranged as sketched out in Figure 8.3. The high-level sub-systems comprise:

− The Supervisor Sub-system (SS) shall allow EST Actors to manage actions affecting the functionality of the whole EST infrastructure, as well as to report and to act on the state of each component and software block running in the system. In particular, the SS shall be responsible for:
  o coordinating the start up and shutdown of the ECS System
− The Inspector Sub-system (IS) shall provide the EST Users with the graphical tools required to interact with the EST. The IS shall be the main interface of Users with the EST. Therefore, it shall facilitate

  o Operation of the ECS
  o Display of the state of its various Sub-system and components
  o The sending of engineering commands to the various ECS Sub-systems and EST components

− The Scheduler Sub-System (SCS) shall be responsible for establishing the sequence of operations that forms the observation queue, which is the ordered list of observations awaiting execution. The sequences shall be generated by matching the conditions requested for a given observation (target, instrument configuration, observing conditions, etc.) with current or expected conditions. Therefore, the main service of the SCS consists of the generation of operation sequences to be executed with the EST. The sequences shall be based on both the approved observations and expected conditions of the EST facility. They shall guarantee the observations are performed under the most adequate conditions, with a high operational efficiency, by accomplishing both the science priority assigned to a given observation by the TAC and the weighting rules defined by the policy of the EST resource use. The weighting rules indicate the importance of a given selection criterion with respect to the others considered for the scheduling.

− The Sequencer Sub-system (SES) shall guarantee safe and coordinated work of the various parts forming the EST during EST operation. The Sequencer shall manage the ordering of concurrent commands and the sequential execution of the operations carried out by all the ECS Sub-systems contributing to EST operation.

− The Telescope Control Sub-system (TCS) shall allow the coordinated operation of various telescope sub-systems (responsible in turn to control the associated hardware). Moreover, it shall allow the pointing and tracking of the telescope in a range of coordinate systems fulfilling given requirements in terms of accuracy and stability, as well as the monitoring and control of thermal loads and of adaptive optics sub-system in order to allow EST to deliver high-quality science data.
The Instrument Control Sub-system (ICS) shall guarantee a safe and stable management of the three types of instruments that will be located at the focal plane of the EST. The three types of instruments shall include the Broad-Band imager, the narrow-band tunable spectro-polarimeter and the grating spectrograph, each consisting of various channels and detectors. ICS shall have to coordinate, control, and monitor the instrument functioning. The ICS shall also handle all errors coming from the various ICS sub-systems, hardware devices, and their interlock, log information, handle alarms and maintenance aspects.

The Operation Repository Sub-system (OR) shall allow storing all the data generated by the EST operation. The OR shall guarantee the proper handling and efficient access to large amounts of data.

The Logging and Alarms Service Sub-system (LAS) shall guarantee the reception, the storing and the propagation of all alarms and log messages generated during the operation of the EST.

The Configuration Service Sub-system (CS) shall enable the storage properties of the EST components, arranging them in blocks called configurations, to work on these properties (e.g. editing, displaying, storing, etc.).

The Observing Engine Sub-system (OE) shall allow managing the coordination among various sub-systems responsible for the operation of the whole telescope and of instruments.

The Observing Programme Management Subsystem (OPMS) shall provide EST users with the tools needed for the creation, modification and submission of observing proposals. It shall allow the EST end users (Principal Investigator, PI) to plan observations, as well as to monitor the status of granted observations.

The Database Management Sub-system (DMS) shall provide the EST end users with the access to the scientific and operational data generated by the EST through remote internet access, or through the transfer of physical media if necessary. All these data will become public after a proprietary period during which the PI will have exclusive right to the data. The EST database will contain the raw science data (TBC), the reduced science data, the calibration data (TBC) and all the ancillary data concerning observing conditions.

The Data Processing Sub-system (hereafter DPS) shall allow processing both scientific and engineering data, to perform Quality Control (hereafter QC) of science data, and to archive the data managed. The DPS shall provide a common framework for the processing of the science data, including quick-look analysis and reduction. This system shall be a distributed facility since some of the data processing tasks might be executed at different processing nodes to improve the system performance. The instrument teams shall have to provide the specific reduction templates of science data, i.e. the set of rules to be followed and codes to be applied for the reduction of the science data taken with a given instrument.

The Time service Sub-system (TS) shall guarantee both the command and synchronization of actions carried out by several ECS sub-systems, including all the actions required on real-time operations.
− The Monitoring Sub-system (MS) shall allow managing the status data generated by the hardware and software sub-systems of EST and ECS. The MS shall provide ECS and EST with all the data critical for the EST operation.

− The Sub-system for the Acquisition of Calibration Data (ACDS) shall allow managing the acquisition of calibration data for each observation performed with the EST.

To date, the most important operational aspects of the ECS high-level sub-systems have been described with more than 170 Use Cases. The interactions among the various sub-systems during EST operation are sketched out in the reference and logical models presented in the following.

8.1.2 Reference Model

The Principal Investigator shall prepare its observation programme by using the Observing Programme Management tools. The observation programme shall consist of a set of individual Observation Sequences. The Observing Programme Management shall provide tools for the submission of both Phase I and Phase II proposals. The submission shall result in a script to be executed automatically. The script shall contain commands for the execution of the observation and a description of the observation; it shall be stored in the Operation Repository. Staff Astronomers and TAC shall be allowed to browse all Observations stored in the Operation Repository by using the Inspector. Staff Astronomer shall be allowed to prepare long- to mid-term plans for telescope operation based on accepted observations and other defined constraints by using the Scheduler.

At the time the accepted observation shall be carried out in queued observing mode, the scheduler shall select the best candidate observation that matches the actual observing conditions and the ones required in the submitted proposal; then it shall pass the observation to the sequencer. The Sequencer shall take as input the observation description and depending of the required instruments, observing mode, and observation set-up, it shall coordinate the various subsystems that shall control the operation of telescope and instruments to perform the observation with the required conditions. This shall include sending of the configuration, pointing and guiding commands to the Observing Engine.

The Observing Engine shall manage to coordinate operation of all the sub-systems controlled by the Telescope Control System and by the Instrument Control System during the execution of the observation sequence. During the execution of the observation, the Observing Engine shall be provided with the outcomes of some common services e.g. by the Logging and Alarms, Monitoring, Configuring service Sub-systems.

The science data shall be generated during the execution of the observation sequence by the Detector Control Service that shall be coordinated by the Instrument Control Sub-system. Metadata describing telescope and environmental conditions during the observation execution shall be also generated; they shall be associated with the corresponding science data most probably only after completion of the observation run and stored in the Operation Repository.

Once the raw science data have been generated, they may be processed with the Data processing Sub-system for quick-look analysis and quality control, by using, e.g. most recent relevant calibration data stored in the Operation Repository. Staff Astronomers and Visiting Astronomers shall be allowed to display the result of the data processing and to apply quick-
look analysis on them, by using the tools provided by the Data Processing and Inspector Sub-systems.

After completion of observation sequences and telescope operations, all the science data generated by the EST shall be associated with the corresponding metadata, and analysed with the tools provided by the Data Processing and Data Management Sub-systems to reduce the data volume on-site. Then the data shall be moved to the first-support data centre for completion of the data processing and for reduction of the volume of the data to be distributed to other processing centres with the tools provided by the Data Archive Management Sub-system. With some intermediate processing steps, the data shall be processed and formatted with VO compliant standards, then distributed by the Science Database following the policy that shall be defined for the distribution of EST data.

Figure 8.4 shows the actors and the main sequence of events described in the reference model.

![Figure 8.4. Reference model.](image)

### 8.1.3 Logical Model

The high-level sub-systems of ECS can be ordered in two coherent blocks:

- **Observing Workshop block** comprising the sub-systems with the graphical applications that shall allow users to access any components of the EST facility. This block includes the Inspector, Observing Program Management, Database Management sub-systems, which are not required to provide services to other ECS sub-systems.

- **Operations Coordination block** comprising the various sub-systems that shall provide all the high level services related with the operation of the telescope, e.g. execution of observations, data processing, other. This sub-system block shall provide services for
telescope operation (observing and engineering), scheduling of observations and sequencing of operations. This block shall include, e.g. the Observing Engine in charge of the Real-time coordination of several lower-level control sub-systems, and the Sequencer that shall be responsible of high level observatory operations.

The visualization and coordination functionalities expected from the ECS shall derive from the services provided by the Observing Workshop and Operations Coordination blocks, together with the ones derived from the sub-systems of the Equipment Control and Monitoring block. This block shall comprise the logical equivalent of the various low-level control devices of the EST facility. Figure 8.5 shows the ordering of the high-level and Equipment sub-systems on the three logical blocks introduced above.

The communication among the various sub-systems of the three logical blocks shall follow the publish-subscribe model. It shall occur through connections between the various ECS components and interoperability services provided by the ECS. Figure 8.6 shows the connections among the various high- and low-level sub-systems of ECS shown on Figure 8.5. For clarity, the connection is traced with point-to-point links for all the sub-systems, but the Supervisor, Operation Repository, Time service, and Monitoring that communicate with all the remaining sub-systems of the Observing workshop and Operations coordination block inside the orange box.
The Observations coordination and Equipment control and monitoring blocks form a two level hierarchy of control sub-systems (hereafter controllers). Figure 8.7 sketches out this hierarchy. The Observations Coordination block forms the upper level of this hierarchy. This level includes:

a) Real-Time controllers, e.g. the ones of the Observing Engine in charge of the Real-Time coordination of various sub-systems;

b) High level operation sequencing controllers, e.g. the ones of the Scheduler, which is responsible for long- to short-term scheduling of observations, and the controllers of the Sequencer in charge of high level operation coordination.

The Equipment Control and Monitoring block form the lower level of the control sub-system hierarchy, by comprising the devices and tools inside each equipment sub-system responsible for the coordination of local mechanisms. This block includes two classes of controllers:

a) Device controllers: to manage the hardware devices

b) Sub-system controllers: to manage the coordination of various devices inside a sub-system and to implement subsystem-level operations
8.1.4 Development Model

The software components of the ECS shall be arranged in three coherent layers, as shown in Figure 8.8.

The application layer shall contain all the applications that shall be developed to accomplish the specific functionalities expected from the ECS. To date, it is assumed that these applications shall be built by direct implementation of the component-container model on the composition of the underlying software layers. The application layer shall provide the tools utilized by the Users to operate the EST facility. The Observing Workshop (containing the Inspector, the Observing Proposal Management Tools, the Archive Management Tools), the Operation Coordination Applications (Sequencer, Scheduler, Observing Engine and others) and the Equipment Control and Monitoring (M1 control system, M2 control system, Transfer Optics control system, Heat Rejeter control system, and others) shall belong to the application layer. The application layer shall also include the user interfaces and the interfaces between ECS and other external systems.

The service layer shall provide the set of basic software services that are specifically utilized for the control of a telescope facility as to the EST, and missing on the COTS products employed to implement e.g. the database, communication and other EST functionalities. These services shall be provided by software packages grouped in tool kits (e.g. library for GUI, motor control, CCD, image viewers, data processing, data access, other).

The base layer shall provide basic common services. This layer shall consist of the operating system (from both real-time and conventional operating systems) and distributed middleware services.
8.1.5 Physical Model

The hardware components of ECS shall be arranged to form a hierarchy of control systems. These systems, hereafter referred to as control nodes, shall comprise computers, local control units (LCUs), electronic equipment, sensors, and actuators. The various nodes shall be responsible for direct control of the various parts forming the EST; some nodes shall have real-time processing capacity. The node hierarchy shall include:

- A top layer with Human Machine Interfaces (HMI) that shall be utilized by the EST User to access, to operate, and to monitor the EST
- A middle layer comprising programmable logic controllers and other controllers (PLC, VME, PXI, custom controllers)
- A lower layer comprising sensors, actuators, electric motors, switches, contactors, other and the field bus (e.g. CAN bus, Profibus, WorldFIP) linking the controllers to these lower-level components

The control nodes shall be interconnected by means of the various LANs (Local Area Networks) that shall form the control network. This network shall consist of two main segments assigned to the transfer of control commands and of data, respectively. Depending on the node, the LAN shall be based on either fibre-optics connection or metal wires, by adopting both non-time-critical (e.g. Ethernet) and real-time communication systems (e.g. Profinet, EtherCAT) to link the various LCUs and lower layer devices, respectively. The use of fibre-optics interfaces (e.g. SCI, Fiber Channel) shall assure large bandwidth and protection against many of the possible sources of electromagnetic interference. However, for all the applications requiring small bandwidth cheaper interfaces (e.g. Ethernet, Fast-Ethernet) shall be used. The control network shall have to guarantee the dynamical configuration of communication traffic to provide each node with the adequate bandwidth. Figure 8.9 shows the structure of ECS hardware components. Figure 8.10 delineates the interconnection among the various control sub-systems.
8.2 Telescope Control Design

TCS shall provide the coordinated operation of various telescope sub-systems (responsible in turn for controlling the associated hardware), the pointing and tracking of the telescope in a range of coordinate systems fulfilling given requirements in terms of accuracy and stability, the monitoring and control of thermal loads and of adaptive optics sub-system in order to allow EST to deliver high-quality science data.

Figures 8.11 to 8.17 show the proposed TCS Architecture based on the technologies described in the previous sections and on the TCS Design document.
Figure 8.11. TCS Control Architecture. The sub-systems represented with blue boxes are directly controlled by the Telescope Control System.

Figure 8.12. TCS network layout.
The TCS coordinator shall be the entry point for all the external communications of TCS with other ECS sub-systems. It shall provide also the programmatic interface to TCS for external software (applications) that requires TCS functionalities. The TCS coordinator shall accept most (but not all) of TCS commands and/or configurations, it shall check for their correctness and validity and issue an immediate error reply (with no further processing), if any errors are detected.
Figure 8.15. TCS Component/Container deployment.

Figure 8.16. TCS Coordinator class diagram.
8.3 Instrument Control Design

ICS shall be responsible for managing the three types of instruments that will be placed at the focal plane of the EST, specifically the BBI, NBI, and GS, as well as of all associated detectors.

Figures 8.18 to 8.23 show the proposed ICS Architecture based on the technologies described in the previous sections and on the ICS Design document.

The ICS Coordinator shall be the package responsible for coordinating the communication with the other packages devoted to the control of the instruments and with the external subsystems. It is therefore characterized by several operations for the management of several functions.
Figure 8.18. ICS top-level package diagram.

Figure 8.19. ICS deployment diagram.
Figure 8.20. ICS class diagram.

Figure 8.21. ICS BBI class diagram.
Figure 8.22. ICS NBI class diagram.
8.4 Data Handling Control Design

The Data Handling System (DHS) shall manage the flow and local storage of data acquired with the EST instruments and facility systems. It shall also provide the capability to transfer the data efficiently from the telescope to an off-site, first-support data centre for wider distribution to general facility users and long-term storage.

Figures 8.24 to 8.30 show the proposed DHS Architecture based on the technologies described in the previous sections.
Figure 8.25. DHS deployment diagram.

Figure 8.26. DHS Metadata class diagram.

Figure 8.27. DHS Stored image class diagram.
Figure 8.28. DHS Data export class diagram.

Figure 8.29. DHS Observation class diagram.

Figure 8.30. View of the dataflow from the telescope to the first support data centre, dedicated processing centres distributed across Europe and, finally, the EST VOCD (Virtual Observatory Compliant Data Base).
9 SITE SELECTION

Since EST is aimed at obtaining diffraction-limited images, it must be located at a site where atmospheric turbulence above the telescope is minimized. With this in mind, there is unanimous agreement that the Canary Islands are among the best sites in the world for solar observations. The Observatorio del Roque de los Muchachos (ORM, on the island of La Palma) and the Observatorio del Teide (OT, on Tenerife) are the candidate sites to host the EST. For decades, they have demonstrated the excellence of the observatories to study the Sun, having obtained the best solar images ever recorded.

A site-testing campaign has been started within the framework of the Design Study to compare both sites. This campaign not only aims at obtaining information on the ground-layer turbulence but also up to several kilometers above the observatories. To that aim, several scintillometer arrays (two with a long baseline - 3.23 metres - and five with a shorter one - 0.42 metres) and one wide-field wavefront sensor (WFWFS) have been designed and constructed. The WFWFS has been installed at the SST, at the ORM, and operates simultaneously with regular observations. A second unit will be installed soon at Tenerife, either at GREGOR or the German VTT.

Seeing is caused by fluctuations in the index of refraction of air, \( n \). These occur because of the turbulent spectra of temperature fluctuations, \( n \) being primarily a function of temperature. As the index of refraction varies, the incoming light rays are bent in a random manner. Wavefronts that are originally flat when entering the atmosphere become corrugated and distorted. The distortion of the wavefront introduces optical errors when imaging these objects, degrading the spatial resolution of the image. The atmospheric seeing is characterized by the Fried parameter \( r_0 \), which expresses the diameter over which the rms phase distortion is about 1 radian. Since typical values of \( r_0 \) are of the order of 10 cm, this distortion needs to be corrected in order to use current- and next-generation telescopes to their full potential. This can be done by using adaptive optics (AO), where a deformable mirror counters the distortion introduced by the atmosphere on a given point of the field of view. This correction is good on a small field of view, known as isoplanatic angle. Over the years, more elaborate AO systems have been developed to increase the corrected field of view, where knowledge of the (local) seeing and especially the turbulence height-dependence is becoming more and more important.

The variation of \( n \) in the atmosphere is described by the \( C_n^2(h) \) profile (refractive index structure function), which is a function of height. The height dependence shows that the seeing in the atmosphere is layered (see Figure 9.1); during daytime observation there is typically a strong ground layer seeing and a significantly less intense high altitude seeing. The different layers cause different image distortion effects. While the ground layer seeing causes distortion over the whole field of view, the high layer seeing causes differential distortion, the image is warped and differentially blurred. This effect is caused by the fact that different parts of the field of view cross different pockets of air at high altitude, while the complete field of view typically only crosses a single pocket of air at low altitude. The severity of the differential seeing is quantified by the isoplanatic angle, \( \theta_0 \), an angle over which the image distortion is more or less constant.

Mathematically, the relation between the Fried parameter, \( r_0 \), and the \( C_n^2 \) profile is given by the equation

\[
r_{0,-5/3} = \frac{16.7}{\lambda^5} \sec z \int_0^\infty C_n^2(h) \, dh ,
\]

where \( \lambda \) represents wavelength and \( z \) the solar zenith distance.
Following the theory of turbulence, image motion and scintillation can be calculated assuming a Kolmogorov spectrum for the turbulent medium which is traversed by the radiation coming from celestial bodies. In practice, differential measurements are more easily carried out, because they can be freed from instrumental effects such as, for instance, image motion generated by wind shaking of telescope structures. Sarazin and Roddier showed that the relative motion between the images produced by two apertures of diameter $D$, separated by a distance $d$, when observing through a turbulent medium, can be expressed as

$$
\sigma_L^2 = 2\lambda^2 r_0^{-5/3} (0.179 D^{-1/3} - 0.0968 d^{-1/3}),
$$

(2)

$$
\sigma_T^2 = 2\lambda^2 r_0^{-5/3} (0.179 D^{-1/3} - 0.145 d^{-1/3}),
$$

(3)

where $\sigma_L^2$ and $\sigma_T^2$ are the variances of the differential motions measured in the directions parallel and perpendicular to the line joining both apertures, respectively.

Shack-Hartmann wavefront sensors divide the entrance pupil $D$ of a telescope into a number of sub-pupils and create an image of the object through each sub-pupil. Differential motion between the sub-pupils can thus be used to measure the Fried parameter. On the other hand, the instantaneous displacement can be translated into the local slope of the wavefront. This signal is used to adequately modify the shape of a deformable mirror, such that the reflected beam is corrected for the atmospheric turbulence.

For wavefront sensing with an extended target, the averaging area, of diameter $D$, corresponds to the sub-pupil area only close to the telescope. For the correction of high altitude turbulence, one has to take into account that the effective averaging area expands from the pupil and up by an amount that increases with the FoV used for wavefront sensing. Scharmer and van Werkhoven have shown that the theory developed by Fried can be used and Equations 2 and 3 can be applied, taking into account this effect by substituting the subpupil diameter $D$ with an effective diameter.

Furthermore, a theoretical relation between scintillation and the structure function, $C_n^2(h)$, of the turbulent atmosphere has been shown to exist. The covariance $B_t(r)$ of the intensity fluctuations
measured by two detectors separated by a distance $r$ can be calculated using the following expression:

$$B_l(r) = \int_0^\infty W(h,r)C_n^2(h)dh,$$

(4)

where the weighting function $W(h,r)$ can be computed analytically, and depends upon the angular extent and zenithal distance of the Sun, wavelength of observation, and detector separation, $r$. The value corresponding to $r = 0$ is usually known as scintillation.

### 9.1 Wide-Field Wavefront Sensor

The WFWFS is a Shack-Hartmann wavefront sensor (WFS) with a large field of view and a large format camera. Whereas in regular WFSs, subimages are usually limited in number of pixels as to obtain a high frame rate, the subimages in the WFWFS are much larger, 145 by 160 pixels (see Figure 9.2). Because of this, separate parts of the subimage, still large enough to be mutually cross-correlated, can be selected, yielding different subfields. These subfields from one subimage can then be cross-correlated with another subimage-subfield pair to get more accurate data on the wavefront slope over the field of view. As opposed to a regular WFS, this does not yield a number of slope vectors equal to the number of subapertures, but equal to the number of subapertures multiplied with the number of subfields per subimage. This vastly greater amount of data allows for much more accurate reconstruction of the wavefront perturbation. Figure 9.3 shows the expanding beam because of the non-zero angular size of the field of view and the atmospheric layers traversed by the light reaching different subapertures.

![Figure 9.2. Initial data from the WFWFS at the SST, showing the granulation pattern in each subimage. One subimage is blown up to illustrate the large field of view.](image)

Two WFWFSs with similar subaperture size will be mounted on both the SST and the VTT or GREGOR. Even though these telescopes are different, the setups can be made such that the results are compatible. The WFWFS at the SST was installed and tested in depth during summer 2009. The main characteristics of the WFWFS are shown in Table 9.1.
Figure 9.3. Left: Illustration of tomographic analysis of WFWFS data with relevant components indicated. Right: An illustration of the atmosphere model for one subfield in one subaperture, sampling only a few cells in each of the layers.

<table>
<thead>
<tr>
<th>Field of view</th>
<th>50&quot;×55&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subaperture size</td>
<td>9.8 cm</td>
</tr>
<tr>
<td>Lenslets</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Camera</td>
<td>Roper Scientific 4020 CCD, 2048×2048 px, 7.4 μm/px</td>
</tr>
<tr>
<td># Subfields</td>
<td>10×10 independent</td>
</tr>
<tr>
<td>Image scale</td>
<td>0.344&quot;/pixel</td>
</tr>
<tr>
<td>Wavelength</td>
<td>500 nm (10 nm FWHM)</td>
</tr>
<tr>
<td>Integration time</td>
<td>3 ms</td>
</tr>
<tr>
<td>Framerate</td>
<td>9 Hz</td>
</tr>
</tbody>
</table>

Table 9.1. WFWFS Hardware setup
The implications of this hardware setup are that there are 85 usable subapertures at the 1-metre aperture of the SST, and 37 at the 0.7-metre VTT aperture (see Figure 9.4). Each subimage has a resolution of about 145 by 160 pixels. The subfield field of view used for correlation is 5" by 5.5", or 14 by 16 pixels. This means that the optimistic height resolution is about 350 metres and the maximum height will be about 40 kilometres.

At the SST, the wide-field wavefront sensor (WFWFS) is mounted immediately under the vacuum system of the telescope. Light to the WFWFS is fed from a FoV adjacent to the science FoV and deflected horizontally such that the WFWFS beam does not pass through the tip-tilt and AO system. The WFWFS optics consists of a field stop, a collimator lens and an array with 85 hexagonal microlenses. The microlenses have an equivalent diameter close to 9.8 cm.

Finally, the WFWFS has a separate field of view next to the science beam. The WFWFS is therefore not affected by any adaptive optics to prevent contamination of the information on wavefront perturbation.

The analysis procedure of WFWFS data from the SST has been presented by Scharmer and van Werkhoven. Some preliminary results are shown in Figures 9.5 and 9.6. An excellent correlation between WFWFS r_0 measurements and simultaneous measurements of granulation contrast has been shown, demonstrating the good performance of the instrument.
9.2 Long and short SHABARs

The long SHABAR consists of 16 scintillometers that are inserted in holes in a 320 cm long bar, while the short SHABAR has 6 scintillometers in a 50 cm bar. Each sensor cell consists of a cylindrical, weatherproof housing made of anodized aluminium, containing a Hamamatsu S2386-44K photodiode, two bandpass filters (KG3 and BG13), two lenses and a field stop (see Figure 9.7). The photodiode sits in a socket to which a coaxial cable is connected.

The bars hosting the sensor cells are hollow, rectangular profiles bars of anodized aluminium. There are circular holes drilled in it at intervals corresponding to the desired detector separations (see Tables 9.2 and 9.3). Each scintillometer unit fits tightly through a hole, and is fixed with a single screw.
Table 9.2. Positions of the scintillometers of the short SHABARs relative to the start of the bar.

<table>
<thead>
<tr>
<th>Scintillometer</th>
<th>Position (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
</tr>
<tr>
<td>3</td>
<td>55.2</td>
</tr>
<tr>
<td>4</td>
<td>117.7</td>
</tr>
<tr>
<td>5</td>
<td>228.1</td>
</tr>
<tr>
<td>6</td>
<td>423.4</td>
</tr>
</tbody>
</table>

Table 9.3. Positions of the scintillometers of the long SHABARs relative to the start of the bar.

<table>
<thead>
<tr>
<th>Scintillometer</th>
<th>Position (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
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<tr>
<td>3</td>
<td>55.2</td>
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<td>4</td>
<td>117.7</td>
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<tr>
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<td>228.1</td>
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<td>6</td>
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</tr>
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<td>15</td>
<td>3215.6</td>
</tr>
<tr>
<td>16</td>
<td>3230.6</td>
</tr>
</tbody>
</table>

Figure 9.7. One scintillometer unit. Sunlight enters through an objective lens (orange) on the top right, through two filters (green and red), a field stop (beige), and a collimating lens (orange), reimaging the pupil on the photodiode (blue). A coax cable (not drawn) exits through a cable gland on the bottom left.
A camera is mounted on the bar of the short SHABARs, facing in the same direction as the scintillometers, and is used to track the Sun during the day (see Figure 9.8). The camera unit consists of a custom made weatherproof housing created from white arnite. The circuit board of a Logitech QuickCam 3000, with CCD and lens, is put inside the housing. A circular piece of welding glass covers the circuit board, preventing overexposure of the CCD from the Sun, and at the same time blocking out anything else from the image. The whole camera unit is rigidly fixed to the bar with two screws. With the lens that comes with the camera, the field of view of the camera is 54 degrees.

Both, long and short SHABARs use the same scintillometers and amplifiers. The photodiodes are connected to a scintillometer amplifier box especially designed and constructed for these instruments. The photodiodes are driven in photovoltaic mode. The output signal of each photodiode first goes through a pre-amplification stage with configurable gain. A Butterworth filter is used to split the signal into an AC (> 0.1 Hz) component and a low frequency (< 0.1 Hz) DC component. The high frequency component is then again amplified with a fixed gain of 105. The gain of the pre-amplification stage is set such that when the Sun is at zenith on a clear day, the DC output is approximately 7 V. The amplified AC and DC components are then digitized with a 16 bit ADC at a rate of 1 kHz. The ADC, computer, and control and data acquisition program are different for the long and short units.

At the present time, two short SHABARs are completely finished, and have been installed on the DOT and the SST. Since the wind comes mostly from the north, both units have been placed a few meters north of each telescope, so that there is a smaller chance that the low level seeing, as seen by the SHABAR, is disturbed by the telescope structure. A long SHABAR unit is already installed at the OT (right picture of Figure 9.8). The rest of the units will installed during summer 2010. The reduction software has been written and tested and a pipeline for an almost on-line $C_n^2$ determination has been designed for the short SHABAR units. The reduction of the long SHABAR data will be performed from one day to the next.

Figure 9.8. Left: A short SHABAR installed on the DOT. Right: A long SHABAR installed at the OT
Figure 9.9. Two examples of data taken with the long SHABAR of the OT, with medium (upper row) and good seeing (lower row). The x-axis has been expanded on the figures on the right for a better visualization of the curve for small distances between detectors. Symbols represent measured values, and the solid line is the result of the fit. Note that all plots have the same vertical scale.

Figure 9.10: Cn² and r₀ stratifications obtained from the fits shown in Figure 9.9. The solid/dashed line corresponds to the case shown in the upper/lower row of Figure 9.9.

Figures 9.9 and 9.10 show two examples, with medium and good seeing, of the cross-covariances measured with the long SHABAR unit of the OT and the retrieved Cn² and r₀ stratifications obtained from them. Seeing variations are indicated by the different order of magnitude of the measured covariances.

A comparison between the data obtained between the three instruments has been done (see Figure 9.11). To that aim, simultaneous data were inverted to get the Cn² stratification and then integrated to obtain the r₀ value at ground level. For the SHABAR data, two different inversion codes were used, one developed at the IAC (and applied to the long SHABAR data) and the other at Utrecht (and applied to the short SHABAR data). Data were averaged every two seconds to compare the short temporal scales of the seeing variation retrieved by the three
instruments. Despite the SHABAR $C_n^2$ stratifications were derived from scintillation and those of the WFWFS were derived from image motion in the different subfields, the comparison between the retrieved $r_0$ values is excellent. Data will continue to be taken beyond this design study for several years, to get statistically significant results to compare the atmospheric behaviour at the two sites.

![Graphs showing comparison of r0 values](image)

**Figure 9.11.** Some results of the comparison of the r0 values obtained at ground level using the three different instruments: the WFWFS and the short and long SHABARS operated simultaneously at the SST. The two curves on the upper row and the one on the left of the lower rows show the results of the inversions every 2 seconds. Three different inversion codes have been used. The short/long SHABAR results are labeled as UTRECHT/IAC, using the inversion codes of these two institutions, respectively. The right plot on the lower row shows the excellent correlation between the retrieved WFWFS and the IAC r0 values.
10 MANAGEMENT PLAN

10.1 Project Organization

A project office is proposed for the execution of the EST project from the preliminary design up to the construction and starting up of scientific operation. The main responsibility of the project office will be the construction of EST according to the defined science requirements within the defined budgets and according to the defined schedule. The policy of the EST project will try to maximize the participation of industry during the design and construction phases, in order to optimize the effectiveness and efficiency in all these tasks where industry can provide the required expertise. Other tasks, less common in industry and which require specific expertise, can be carried out directly by the project office or by solar physics institutes linked to the project. An example of the latter items are the science instruments, which need to be developed at institutes coordinated by the project office. Nevertheless, for the instruments development, efforts will be done to maximize the implication of industry in several subsystems.

A complex project like EST requires firm management rules in order to control its scope, cost, schedule and quality assurance during all its life cycle, with effectiveness. The proposed organization for the EST project is based on similar experiences of large telescope projects executed during last decades. Figure 10.1 shows a description of the proposed high-level organization chart.

![Figure 10.1. EST project organization chart.](image-url)
The EST Board will be the maximum authority of the EST project. It will be composed of representatives of the different EST project partners. The functions of the board will be the overall control of the project policy and budget. The EST board will be the only body able to approve any change in the project objectives, scheduling and budget. It will be responsible for the reviewing and approving annual and multi-year budgets and for the nomination of the main project positions (project director, project scientist, science advisory committee and any other relevant position).

The Science Advisory Committee will be a committee which will advise the EST Board and the Project Director on all aspects related to the science requirements and objectives of the project. In addition to monitoring the science requirements, the Science Advisory Committee will recommend the scientific priorities to be followed during the project in order to maximize the scientific return, with special attention to instrumentation. The Science Advisory Committee can recommend changes in the science requirements, if considered necessary. The proposed changes must be approved by the EST board. The Science Advisory Committee will be chaired by the Project Scientist, who will periodically inform the Committee on the progress of the project.

The Project Director will be responsible for the running of the project until its completion, leading the Project Office and ensuring that the project objectives are achieved. The director will have wide-ranging authority for managing the project, within the limits established by the Project Board. The Project Director will report to the EST board.

The Project Scientist with the Science Group will be responsible of ensuring that the scientific objectives, specifications and programmes are adequately fulfilled during the design, construction and commissioning of the EST. He/She will work with the Science Advisory Committee and the scientific community to define the scientific requirements of the EST. He/She will work with the other members of the Project Office throughout the construction phase of the project evaluating the consistency of the project plans with the scientific requirements, advising on scientific priorities and identifying and reviewing specific technical approaches to meet the scientific requirements. The Project Scientist will provide advice on scientific aspects to the Project Director and the other members of the project team.

The Project Scientist must be consulted on all aspects of the project that could affect the scientific performance of EST. All major actions, documents, and plans of the project will require the agreement of the Project Scientist.

The Project Scientist will chair the Science Advisory Committee and report to the Committee on the project progress.

The Administration Group will be responsible for the accounts, procurement and contract administration of the project. It will give support on these matters to the project team. The archiving and circulation of appropriate documents, inside and outside the Project Office, and providing computing support for the project staff will also be the responsibility of this group. The Administration Group will report to the Project Director.

The Project Manager will be responsible for managing the engineering activities of the project to achieve the science specifications within the approved schedule and budget, will lead the activities of several engineering groups in charge of different aspects of the project, will work closely with the Project Scientist in all aspects of the project that might significantly affect the scientific performance of the EST, and will report to the Project Director.

The Project Manager will be reported by the various engineering groups in charge of different EST subsystems. Each engineering group will be headed by a group leader and each group will
be responsible of the development of the subsystems within their scope according to the defined requirements, budget and schedule.

The System Engineering Group will be responsible of systems-engineering activities and of the system integration and testing of EST at the observatory. Systems-engineering activities include the configuration and documentation management, the technical requirements and interfaces management and the system performance analysis and budgeting. The system engineering group will develop on site integration and test plans with support of the rest of engineering groups.

The proposed engineering groups in charge of development of EST subsystems are the following:

- Enclosure and Civil works group, in charge of the enclosure, telescope pier, buildings, urbanization and all the services and facilities required for EST operation.
- Optics group, in charge of all the optical systems of EST, including the active and adaptive systems up to the telescope focal planes.
- Telescope mechanics group, in charge of the telescope structure and mechanisms up to the telescope focal planes.
- Instrumentation group, in charge of the EST science instruments.
- Control group, in charge of the control system of the complete observatory, including software and hardware, data handling, processing and archiving.

The Project Office will be a team composed by the Project Director, the Project Scientist and Science group, the Project Manager, the Engineering Groups and the Administration Group. The manpower needed to manage the activities of the EST Project in the Project Office is estimated to be 19 persons, on average, during the project lifetime up to the starting up of scientific operation. This reduced amount is based on maximizing the participation of industry and solar institutes in the EST project.

10.2 Schedule

The schedule for the European Solar Telescope, shown in Figure 10.2, has been elaborated with the inputs of the EST Study Design participants, as well as the information coming from the experience in other similar projects in which the present project team has been involved.

The project starts with the next design phase, which includes the preliminary and the detailed designs and the corresponding two design reviews. The preliminary design will finish the design of all systems and subsystems at components level, and the overall configuration is defined. During the detailed design, every component of every system and subsystem must be specified and drawn at the level they can be manufactured, assembled, integrated and verified. Just after the last design review, the construction and assembly of all the subsystems is planned. The integration and verification on site is the following phase and the commissioning is the last stage.

The estimated time of the whole project is eight years, three years to complete the design, four years for manufacturing and assembly, and other three years for integration, verification and commissioning. This last period overlaps with two years the assembly of some subsystems since it begins when the building, the support facilities and the enclosure are finished.
### Figure 10.2. EST project schedule.
10.3 Cost Estimate

The estimation of costs given in Table 10.1 has taken into account the preliminary and detailed design, the construction and the AIV of the EST, as well as the commissioning phase.

Every system and subsystem cost has been evaluated by the corresponding design team participating in the EST Design Study. The elements costs have been estimated from potential suppliers when possible. In other cases the designers have evaluated the cost based in their own experience in similar projects.

The item named “project office manpower” refers to the tasks to be developed by the project office during the whole project: management, systems engineering, administrative and computer support, etc. Under this item, a project office of 19 persons working during eight years has been taken into account: 2 optical engineers, 2 software engineers, 2 mechanical engineers, 2 electronic engineers, 2 draughtsman, 2 computing common services personnel, 2 administrative personnel, 2 project scientist, 1 project manager, 1 system engineer, 1 coordinator.

Based on the cost estimated for the telescope operation, the cost per person and year, including salaries and taxes, facilities and services, communications, insurances, training, travel and maintenance, is around 115,000 €/person-year.

All numbers are given in Euros 2011 and inflation over the lifetime of the project has not been added. Contingency is estimated as a 20% of the total cost.
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>Total (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>18,700,000</td>
</tr>
<tr>
<td>M2</td>
<td>1,310,000</td>
</tr>
<tr>
<td>HEAT REJECTOR</td>
<td>560,000</td>
</tr>
<tr>
<td>AO/MCAO</td>
<td>6,160,000</td>
</tr>
<tr>
<td>TRANSFER OPTICS</td>
<td>3,007,000</td>
</tr>
<tr>
<td>Auxiliary full disk telescope</td>
<td>650,000</td>
</tr>
<tr>
<td>OPTICS</td>
<td>30,977,000</td>
</tr>
<tr>
<td>TRANSFER OPTICS &amp; INTRUMENT PLATFORM</td>
<td>4,774,380</td>
</tr>
<tr>
<td>TELESCOPE MOUNT</td>
<td>14,748,310</td>
</tr>
<tr>
<td>Tower (AFDT)</td>
<td>325,000</td>
</tr>
<tr>
<td>MECHANICS</td>
<td>19,847,680</td>
</tr>
<tr>
<td>ENCLOSURE</td>
<td>5,834,500</td>
</tr>
<tr>
<td>BUILDING, PIER (30m) &amp; FACILITIES</td>
<td>10,707,258</td>
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<tr>
<td>CIVIL WORK</td>
<td>16,241,758</td>
</tr>
<tr>
<td>INSTRUMENTS</td>
<td>33,076,670</td>
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<tr>
<td>CONTROL</td>
<td>9,772,000</td>
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<tr>
<td>PROJECT OFFICE MANPOWER</td>
<td>17,480,000</td>
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<tr>
<td>SUBTOTAL</td>
<td>127,395,116</td>
</tr>
<tr>
<td>Contingency 20%</td>
<td>25,479,024</td>
</tr>
<tr>
<td>TOTAL (€)</td>
<td>152,874,142</td>
</tr>
</tbody>
</table>

*Table 10.1. Estimated cost for the design and construction of EST.*
10.4 Operation and System Upgrades

10.4.1 Operation requirements

The EST operation will be defined in order to optimize the scientific use of telescope time and maximize its scientific return. The following points give an overview of the operational key-points which can characterize the EST operation:

- EST will be a very sophisticated system. Most users will need a robust user support process (Web portal, central electronic help desk, easy graphical user interfaces, etc).

- High efficiency: EST shall be kept scientifically competitive (new instruments and improvement of the telescope will be necessary). Priority shall be given to maximize the quality of the data.

- High reliability: Limiting time lost during the day due to unscheduled technical failures to under 3% (TBC) of scheduled science operations time; minimizing the number of hours used at day for scheduled technical activity (e.g. mirror re-coating) and minimizing operational overheads required for target acquisition, instrument configuration, and data calibration.

- It will be a priority to use the hours with best seeing conditions (during morning and late afternoon) in science operations. The science programmes which do not need optimal conditions and routine maintenance tasks will be performance at other times with worse seeing (during noon).

- EST safety priorities will be the following: protection of persons, safeguarding the integrity of EST and protection of scientific data.

- EST will have a continuous development programme for new instruments and systems upgrades.

10.4.2 Operation modes

The EST operation modes will be the following:

- **Queue service observing mode**: It will be used with proposals which need an standard configuration or set-up of the telescope and its instruments. The main advantages are the high efficiency and the high flexibility, as it enables that the observations are scheduled in real time taking into account the observing conditions.

- **Classical observing mode**: It is recommended for those programmes that are not adequate for queue service observing mode. Principal Investigator (PI) will be responsible for scientific observation. These programmes will need special configuration or set-up of the telescope and its instruments or will require the use of a visitor instrument.

- **Engineering and maintenance mode**: EST spends observing time in the development and commissioning of any new subsystems or instruments. Calibration of the telescope and scheduled maintenance activities are performed in a regular basis.
10.4.3 Available time

The observing time, in general, will be the time available from the morning astronomical twilight until the evening astronomical twilight, and eventually, there would be allocated night time during part of the year (not more than 50% of the annual nights is foreseen).

A normal day in EST will be divided in the different periods that are shown in Figure 10.3 (commissioning of new subsystems or instrument does not necessary follow the timeline that is shown).

- **Day time**: Science operations and instruments calibrations according to the operational schedule. The analysis of any failure that could have happened during the day or the preparation of the instruments that could be used at day (i.e. checks, fill tanks, etc.) shall be done during the breaks along the day time (normally during the central hours of the day).
- **Night time**: This time would be used to have EST ready and in perfect working order for day-time operations, unless it is dedicated those engineering and maintenance activities which are incompatible with day-time schedule. It is not envisaged to do routine maintenance during the night, except special maintenance tasks that have been scheduled previously. It is expected to perform night-time operations during part of the year.

10.4.4 Science program life cycle overview

The EST Observatory shall explore ways of making the process of proposal solicitation, review and time allocation, as efficient as possible for all parties (Figure 10.4). The result will be a master schedule created and managed by the EST Observatory for each observing period.
10.4.5 Organization

10.4.5.1 Facilities

The facilities of EST will be the following:

- **Observatory**: The telescope facilities and a variety of technical support services and infrastructures (warehousing, technical workshops)

- **Sea Level Base (SLB)**: It shall have offices for a variety for purposes like work space for EST science operations staff performing off-site work and engineering and technical works

- **EST Data Archive**: EST has two options: build its own data center or form a partnership with an existing data centre

These facilities will be proximity to a centre of excellence in astrophysical research such as the IAC. This will be advantageous in simplifying and minimizing the costs for bringing EST into operation and maintenance phase through a possible agreement with the IAC

10.4.5.2 Staff

This section provides a description of the high-level structure of the organization which would be responsible for the EST operational and maintenance phase, as shown in Figure 10.5.

![Figure 10.5. EST organization chart.](image)

- **EST Board** will be the ultimate financial and management authority for the EST Observatory

- **EST Directorate** will hosts the EST Director and support staff necessary for the carrying out of high-level management responsibilities.

- **Administration** will contain all the administrative, financial and logistics services necessary to run the observatory and all activities related to the operation of non-technical facilities.

- **Science Operations** will contain all the system (“telescope”) operators and user support services necessary to support day-time and night-time operations.
- **Engineering & Technical Services** will be responsible for all technical system operations, maintenance and improvement activities. It will contain engineers and technicians in all major engineering disciplines including mechanic, electrical, optics, software, and IT systems.

The EST organization will be able to have different advisory committees. Their main goals would be provided technical and scientific oversight of EST Observatory activity and recommends options for systems optimization and development of new science instruments.

Table 10.2 shows the estimated EST staff needed to guarantee the running and maintenance of the installation once it will be into operation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Total</th>
<th>Sea Level</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Total</td>
<td>Sea Level</td>
<td>Telescope</td>
</tr>
<tr>
<td>DIRECTORATE</td>
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<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Director</td>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Deputy Director</td>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Safety Responsible</td>
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<td>0</td>
</tr>
<tr>
<td>Assistant</td>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>ADMINISTRATION (ADM)</td>
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<td>0</td>
</tr>
<tr>
<td>Administration Manager</td>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Accountants</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Contracts Procurement &amp; Purchasing Responsible</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Logistical Service Responsible</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>SCIENCE OPERATIONS (SCO)</td>
<td>13</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Science Operations Manager</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Support Astronomers</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Systems Operators</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ENGINEERING &amp; TECHNICAL SERVICES (ETS)</td>
<td>26</td>
<td>11</td>
<td>11</td>
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<td>Engineering Manager</td>
<td>1</td>
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<td>0</td>
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<tr>
<td>Engineers</td>
<td>12</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Technicians</td>
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<td>6</td>
</tr>
<tr>
<td>Assistant</td>
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<td>0</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>48</strong></td>
<td><strong>25</strong></td>
<td><strong>15</strong></td>
</tr>
</tbody>
</table>

*Table 10.2. EST estimated staff for operational phase.*
10.4.6 Cost Estimates

Table 10.3 shows the estimated cost of the routine operation and maintenance services of EST.

<table>
<thead>
<tr>
<th>Accountable Items</th>
<th>Estimated Cost (Euros 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel Salary &amp; Taxes</td>
<td>3,000,000</td>
</tr>
<tr>
<td>Facilities Maintenance &amp; Supplies</td>
<td>700,000</td>
</tr>
<tr>
<td>Virtual Observatory Data Base</td>
<td>900,000</td>
</tr>
<tr>
<td>Observatory Residence Services</td>
<td>200,000</td>
</tr>
<tr>
<td>IT &amp; Communications</td>
<td>40,000</td>
</tr>
<tr>
<td>Property Insurances</td>
<td>300,000</td>
</tr>
<tr>
<td>Training</td>
<td>35,000</td>
</tr>
<tr>
<td>Duty Travels</td>
<td>35,000</td>
</tr>
<tr>
<td>Vehicles</td>
<td>80,000</td>
</tr>
<tr>
<td>Technical Consumables</td>
<td>100,000</td>
</tr>
<tr>
<td>Maintenance Technical Services</td>
<td>200,000</td>
</tr>
<tr>
<td>Spares</td>
<td>60,000</td>
</tr>
<tr>
<td>System Upgrades</td>
<td>800,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>6,450,000</strong></td>
</tr>
</tbody>
</table>

Table 10.3 EST estimated costs for operational phase
11 SOCIO-ECONOMIC IMPACT AND FINANCIAL FEASIBILITY

Today, the European Solar Physics community is prominent on the world stage. This is the combined result of the international reputation that research groups in Europe have been building and access to the world's most comprehensive array of solar telescopes at the astrophysical observatories in the Canaries.

The strategic advantage presented by the Observatories has helped develop strong relationships across the European solar physics community, creating new observational needs and driving the development of new technology to meet them, thereby creating new opportunities for joint work on high technology projects.

The successes of recent years and the experience gained by the European scientific community in this field mean that the time is now ripe for a major challenge. This is the role of the European Solar Telescope (EST), which would be one of the largest European research instruments in the field of earth-bound solar physics. Building it in the Canaries, at the Observatorio del Roque de los Muchachos (La Palma) or at the Observatorio del Teide (Tenerife), would also stimulate economic and industrial development in this peripheral region as well as in mainland Europe.

The design study has identified the scientific, technical, industrial and socio-economic activities that would arise from the construction and operation of the EST in the Canaries in order to provide information that would be helpful for decision-making when this joint European science project is initiated. This analysis is based on an estimated budget of approximately 150 million Euros needed to accomplish the design and construction.

![Figure 11.1. Estimated spending profile to carry out the several phases of EST, assuming starting in 2015.](image)

It is possible to argue that one of the financial and industrial benefits of involvement in the project for the countries involved (there are over a dozen Member States) could be a return proportionate to the size of their solar physics community, the type of contribution they make (monetary or in kind), the resources they make available for solar physics, or their industrial capacity. For the host country, previous experience with large telescope construction projects
like the GTC combined with the existence of a competitive and specialized nationwide industrial sector and the nature of some of the EST work packets could mean a return in excess of 30%. Similar returns could also be anticipated for any other country with much to offer the project.

However, given the large amount of uncertainty presented by the requirement to advertise many of the tenders and services for the project across the whole of the EU, which would be greater than within the host region alone, basing a framework for returns on GDP and job creation in each individual country (including Spain) would be a complex and unconvincing enterprise.

The EST project will be an important achievement for the Canary Islands, not just for the enormous worldwide scientific importance it would bring to this region in years to come, but also for the considerable positive impact it will have on the regional economy.

From a socio-economic perspective the Canaries would benefit on many levels, in particular from a more diverse economy, increased GDP and the creation of high quality jobs. Given the current state of the economy in the Canaries, with the wider international crisis and the islands’ focus on the services sector, this project is an opportunity that must not be missed. EST will position the Canary Islands as the solar physics capital of the world.

Detailed analysis of the available data suggests that financial returns from the project for the Canaries during the construction phase could be as high as 54 million Euros, rising to some 364 million over the 30 years of the telescope’s lifetime (including the impact on the regional economy). The effect on jobs, again including the impact on the economy, could total some 10,565 new one-year fixed term positions in the Canaries, rising to 10,734 across Spain as a whole (taking into account both the construction period 2015-2020 and the operating phase of up to 30 years). This is equivalent to 213 full-time jobs during the seven-year construction phase and 309 over the telescope 30-year life.

The methodology used (standard, based on Input-Output tables), together with high levels of uncertainty in the estimates for the extent of involvement of the different nations (including the
host nation), makes meaningful projections for impact on GDP and employment across the EC impossible.

The impact of a project like the EST on the reputation of the Observatories in the Canaries should also not be underestimated, as it would confirm their position as a world-class astronomy resource: premium sites for the latest generation telescopes and new instruments, a permanent training facility for young researchers and technologists and a source of new outreach and science tourism initiatives that would have beneficial effects on society.

At global level the EST, as part of the backbone of the European Research Area, would be a driver for the economic development of the countries involved in their construction, favouring the creation of more competitive economies and boosting economic recovery in times of crisis by revitalising the economy.

The technology required to make the EST happen is going to be developed all over Europe. Solar Physics is a modern, high-tech science relying on a strong collaboration with industry to realize challenging large-scale engineering tasks. The EST, considered worldwide as one of the highest priorities in ground-based Solar Physics, is a high technology science-driven project that incorporates many innovative developments, offering possibilities for technological spin-off and transfer, together with challenging technology contract opportunities providing a dramatic showcase for European industry. It will create high technology jobs.

The main features of the Canary Islands Observatories, which make them the optimal location for EST are the following:

- The location of the Canary Islands, with its excellent and plentiful transport links to Europe. This is demonstrated by the constant movement of large numbers of research and technical professionals from Europe to the Observatories of the Canaries for many decades.

- The excellent quality of the sky for astronomy in the Canaries is determined and protected by Law. As a result, the observatories of the Instituto de Astrofísica de Canarias (IAC) are an "astronomy reserve", which has been available to the international community since 1979.

- Technical site properties are assessed through continuous site characterization to provide a historical record of site conditions that will help to select the final location.

- An analysis of geological hazards associated with seismic and volcanic activity (lava flows and ashfall) carried out at selected astronomical sites shows that the lowest geological hazard in both seismic and volcanic activity was found at Roque de los Muchachos observatory, on the island of La Palma. Seismic hazard is also low at the other Canarian site, the Teide Observatory, since seismic activity in the Canary Islands is low in both the number and magnitude of earthquakes.

- The European Solar Telescope (EST) will require exhaustive technical and logistic support when starting its construction and during later scientific operation. To this aim, basic and advanced infrastructures will be required not only at site level but also at regional level (transport, communications, specialized manufacturers and suppliers). Currently, both Canary Islands Observatories have common services and facilities to cover most of the required support infrastructure at site level. Likewise, at sea level the CALP and the IAC Headquarters in La Palma and Tenerife respectively as well as the existing facilities for supercomputing and communication with Europe provide an
excellent baseline for EST requirements since they already house much of the basic and advanced infrastructures needed to build and operate the EST.

- Although there are no compulsory requirements, the EST Site is assumed to have neighbouring communities to provide socio-economic infrastructure. Neighbouring communities are assumed to be not greater than 40 km from the site (or one hour’s travel). In this way, both Tenerife and La Palma fulfil these desirable characteristics without exception.

The Canaries is involved in negotiations for the development of the 2014-2020 strategy for the Ultra-Peripheral Regions, providing them with an unprecedented opportunity to put large research infrastructure projects on the list of funding priorities for the principal structural funds (FEDER and the European Social Fund).

With regard to the cultural impact, and its relation to training and education, it is highlighted that Astronomy, and in particular Solar Physics, contributes to our cultural and economic well-being in a number of ways. It is an integral part of our culture and contributes to a better understanding of our fragile environment. Researchers in this field tackle key questions that challenge our minds and our imagination.

Beyond these questions, astronomy and solar Physics often inspires young people to choose natural sciences as a career, from which they then go on to scientific and technical careers in academia and industry in a wide range of other fields, thus contributing to a balanced, future-orientated society. By means of the joint effort of many research institutions, the Canary Islands as host region offer to young people a unique opportunity to get closer to astronomy and solar physics at various levels of education, as well as offering them a training experience dealing with the most advanced technologies and research infrastructures all over the world.

The main institutional support of the EST project relies on the European Association for Solar Telescopes (EAST), with institutions of 15 European countries and a strategic objective focussed on the access of European solar astronomers to world-class high-resolution ground-based observing facilities. EAST could be the legal body fostering the future construction and operation of the EST. To this aim, a suitable legal framework is being sought at national and international level. In particular, the legal framework put in place by the European Commission for the creation and operation of transnational research infrastructure (ERIC) provides a functional model with sufficient guarantees for the project to go ahead without significant difficulty in this regard. An ERIC can benefit from exemptions from VAT and excise duty in all EU Member States and may adopt its own procurement procedures, which have to respect the principles of transparency, non-discrimination and competition but are not subject to public procurement procedures.

As this report was being produced, the financial regime for economic support for the phases of the project following the Conceptual Design phase had not been determined. It is likely that the member institutions of EAST, via their funding arms and using whatever legal personality is finally adopted, will provide the financial backing for the project.
Figure 11.3. Countries with institutions and companies involved in the Conceptual Design Study of EST: Spain, Germany, France, Italy, United Kingdom, Netherlands, Sweden, Norway, Czech Republic, Poland, Slovakia, Swiss, Austria, Hungary and Croatia.
12 ANNEX I: SCIENCE REQUIREMENTS

The following list summarizes the science requirements and goals for EST:

12.1 Main Telescope Imaging Field of View

- 2'x2' with optimal resolution over 60"x60" for Broad Band imagers
- 1'x1' for the Narrow Band Tunable filter spectropolarimeters
- 3'x3' mosaic mode at optimal resolution (60"x60" patches). For broadband instrument, mosaic detectors may be employed. The gap between two neighboring detectors should not be larger than 1".

Note: The current telescope design do not allow the 3'x3' mosaic mode since the FoV is 2'x2'. The mosaic mode can be performed moving the field of view (moving the telescope), but it means that the WFS shall be moved simultaneously in order to avoid losing the AO closed loop, otherwise the AO closed loop will be lost and reengaged with new target in the new position.

12.2 Finder telescope

- Field of view: 1"x1"
- Spatial resolution: 1.5"
- Spectral channels: CaII H or K, Hα, white light.

12.3 Spectrograph Field of View

- 2' (goal: 3') with optimal resolution over 60"
- User can specify the slit orientation with respect either:
  a) the solar limb (parallel or perpendicular)
  b) the N-S direction
  c) the horizon

12.4 Spatial resolution

- Imaging instruments spatial resolution: 0.04" (goal: 0.03") at 500nm
- Spectrograph spatial resolution: 0.1" from 380nm to 1.6μm, and diffraction limited above 1.6μm
- 0.15" for limb observations. This may require a low-order operational mode for the MCAO in which the wavefront sensor is fed with Hα and/or CaII (H&K or the infrared triplet) light.
- For non-solar targets, the AO should permit observations at 0.2" resolution in visible wavelengths (It means that the AO system should operate, with partial correction, with non-solar targets also).
12.5 Imaging instruments operational modes

The broadband imaging instruments shall have two operation modes:

- Optimal spatial resolution
- Maximum field of view

12.6 Wavelength coverage

- 390nm to 2.3 μm (goal: 350 nm to 2.3 μm) with Adaptive Optics correction with defined resolution and simultaneous instruments operation.
- 315 nm to 20 μm without AO correction and without simultaneous instrument operation

12.7 Light distribution

Instrument stations can observe simultaneously in the visible and infrared. Distribution among instruments can be configured according to the following options:

1) All the light goes to the spectrograph(s).
2) All the light goes to the imager(s).
3) The spectrograph slit-jaw image is reflected into the imager(s).
4) A beamsplitter feeds both the spectrograph and imager with the following possible configurations:
   a. 50%-50%
   b. 70%-30%
   c. 90%-10%

In the visible station, the light that goes to the imagers can also be split to send part of the beam to the broad-band imager. Also at this station, configuration 4 shall have the following additional mode:

   a. A dichroic splits the light between spectrograph(s) and imager(s) at 600nm.

The configuration of beamsplitters and dichroics to share the light between spectrographs and imagers shall be reversible, although in the case of beamsplitters we expect that most applications will have the large fraction of the light going into the spectrograph(s).

Note: The optics required to switch between two of the most frequently used configurations should be mounted on motorized mechanisms so that switching observing modes takes less than one minute of time. Switching to other less frequent modes may require manually swapping optics and could take several hours (ideally this would be done overnight).

12.8 Spectral resolution

- Spectrographs: $\lambda/\delta\lambda = 3 \times 10^5$ (it should be possible to open the slit up to 1" without degrading the spectral resolution)
- Tunable filters: $\lambda/\delta\lambda = 1.5 \times 10^5$ at visible channels : at 396 nm, at 525 nm, at 630 nm, and at infrared channels : at 854 nm, (Goal: 1083 nm, if available) and 1565 nm.
Second and third visible channels shall overlap over a range at least from 525 nm to 653 nm.

- Broadband imager: 0.05 nm for Ca II H and K, 0.1 nm for Hα and ~0.5 nm for various continuous ranges.

12.9 **Maximum bandpass shift of imaging instruments**

- Maximum bandpass shift of imaging instruments over the field of view, specified at 500 nm, 30" away from the field center: 5×10⁻³ nm (goal 3×10⁻³).

12.10 **Minimum spectral coverage for slit spectrograph**

- Minimum spectral coverage for slit spectrograph: 0.5 nm

12.11 **Polarimetric sensitivity**

- Sensitivity: 3×10⁻⁵ in S/I, where S is any Stokes parameter (Polarimetric sensitivity refers to our ability to detect a signal above the noise and is therefore a requirement on the signal-to-noise ratio)

12.12 **Polarimetric accuracy**

This requirement may be defined as the accuracy to which we need to know the crosstalk between any two Stokes parameters. If $O_{ij}$ is the contamination in i due to the cross talk from j, the requirement is defined as:

$$
O = \begin{bmatrix}
10^{-2} & 1 & 1 & 0.1 \\
5\times10^{-4} & 10^{-2} & 5\times10^{-2} & 5\times10^{-3} \\
5\times10^{-4} & 5\times10^{-2} & 10^{-2} & 5\times10^{-3} \\
5\times10^{-3} & 5\times10^{-1} & 5\times10^{-1} & 10^{-2}
\end{bmatrix}
$$

The matrix above implies that:

- Flat-field accuracy needs to be around 10⁻² (it is not possible to specify polarization accuracy without giving this requirement explicitly)

- The residual polarization measured in an unpolarized region must be smaller than 5⋅10⁻⁴

- If Q, U are ~0.1⋅V and V is ~0.1⋅I then the relative contamination from crosstalk is evenly distributed among I, Q, U and V (5%).

12.13 **Scattered light level at 500 nm**

- Scattered light shall be below 10% at a 1" distance from the scattered light source on the science focal plane, and below 1% at a 5" distance. This requirement sets constraints not only on the telescope but also on the instrumentation.

- For coronal observations, the flux from the observed spectral line must amount to more than 1 ADU before the background signal saturates the detector.
12.14 Image rotation

- The image rotation on the science focal plane needs to be corrected.

12.15 Sky coverage

- Ecliptic (goal: full sky, except Ø 2º at the zenith)

12.16 Absolute pointing accuracy

- 3"

12.17 Open-loop absolute tracking accuracy

- 1" over 10 minutes

12.18 Slit scanning

- Scanning steps shall take less than 0.1 s.

- The slit scanning shall be repeatable with an accuracy of 0.002" and a stability of 0.01" over 1 hour.

12.19 Wavelength scanning for tunable filters:

- Scanning of 10 wavelengths along a spectral line in 10s shall be possible for a continuum signal to noise ratio of 1000 in polarimetric mode.

- The scanning shall be repeatable with an accuracy of 1/100th of the spectral resolution profile and a stability of 1/100th over 1 hour.

- All 10 wavelengths shall be available over the entire field of view.

12.20 Absolute timing accuracy

TBD

12.21 Total photon throughput for tunable filters

The total throughput shall be sufficient to reach a signal-to-noise ratio of 1000 in spectropolarimetric observations with 1 s integration time, at a spatial resolution of 0.04" and spectral resolution of 150,000.

12.22 Multi-line and multi-instrument capability

The telescope needs to be able to observe multiple spectral regions simultaneously. The particular combinations will be specified for each instrument individually but the telescope optics needs to provide high image quality at the science focal plane over the entire spectrum.

Simultaneous observations using all instruments shall be possible for instruments observing wavelengths < 2.3μm.

12.23 Number of instrument channels

- Broad-band imager: 3 (goal: 5) channels

- Visible narrow band imager (assuming coverage up to 1100 nm): 3 channels

- IR narrow-band imager (assuming coverage from 700nm): 2 channels
- Visible spectrograph (assuming coverage up to 1100 nm): 5 channels
- IR spectrograph (assuming coverage from 700 nm): 3 channels
- MIR spectrograph and imager (wavelength > 2.3 μm): 3 channels

12.24 Atmospheric Differential refraction at multiple wavelengths

The differential refraction shall be compensated for spectropolarimetric observations with visible and IR spectrographs with the selected combination of wavelengths at any time of the day.

12.25 Alignment of the science focal plane

The image orientation needs to be known with an accuracy of 0.015º (this follows from allowing a misalignment of up to 0.015" over a 1' field of view), both for the finder telescope and for the main telescope (in all channels).

The linear polarization reference axis (e.g. the positive Q axis) needs to be known with 0.5º accuracy.

12.26 Observable radius away from the Sun

- Off limb observation up to 200" from the solar limb
- >5º (goal: >2º) avoiding solar illumination for Mercury observation (Low priority)

12.27 Maximum time between image acquisitions in mosaic mode

- 2s for contiguous sub-fields
- 6s for non contiguous sub-fields
13 ANNEX II: ENVIRONMENTAL CONDITIONS

LOCATION 1: OT (Observatorio del Teide) on Tenerife. The geodetic coordinates are the following:

Longitude  +16º 31’ / Latitude  +28º 18’ / Altitude 2400 m

LOCATION 2: ORM (Observatorio Roque de los Muchachos) on La Palma. The geodetic coordinates are the following:

Longitude  +17º 53’ / Latitude  +28º 45’ / Altitude 2250 m

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>-2 ºC to 25ºC</td>
</tr>
<tr>
<td>Temperature variation</td>
<td>6.3%/hr max.</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>10 % to 80 % (non condensation)</td>
</tr>
<tr>
<td>Wind</td>
<td>0 m/s to 15 m/s</td>
</tr>
<tr>
<td>Irradiance</td>
<td>1300 W/m² max.</td>
</tr>
</tbody>
</table>

*Table 13.1. Nominal conditions*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>-6ºC to 30ºC</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>5% to 90% (non condensation)</td>
</tr>
<tr>
<td>Wind</td>
<td>0 m/s to 25 m/s</td>
</tr>
<tr>
<td>Wind gusts</td>
<td>30 m/s max.</td>
</tr>
<tr>
<td>Saharian Dust</td>
<td>100 mg/m³ max.</td>
</tr>
</tbody>
</table>

*Table 13.2. Operational conditions*
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Survival Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>-15 ºC to +35ºC</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>100% (condensation)</td>
</tr>
<tr>
<td>Wind</td>
<td>55 m/s (averaged over 15 min.)</td>
</tr>
<tr>
<td>Wind gusts</td>
<td>70 m/s</td>
</tr>
<tr>
<td>Rain in 1 hour</td>
<td>120 mm</td>
</tr>
<tr>
<td>Rain in 24 hrs</td>
<td>360 mm</td>
</tr>
<tr>
<td>Ice thickness</td>
<td>0.23 m</td>
</tr>
<tr>
<td>Snow thickness</td>
<td>2.25 m</td>
</tr>
<tr>
<td>Earthquake</td>
<td>According to NCSE 02.</td>
</tr>
</tbody>
</table>

*Table 13.3. Survival limits*
# ANNEX II: ERROR BUDGETS

## 14.1 Image Quality

### SEEING LIMITED IMAGE QUALITY

Image degradation <10% of seeing image quality without OA including instruments: CIR 0.8

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CIR</th>
<th>50% EE (arcsec)</th>
<th>WFE (nm rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Atmosphere</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2 Telescope</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Static errors</td>
<td>0.849</td>
<td>0.23</td>
<td>1082</td>
</tr>
<tr>
<td>2.1.1 Diffraction and optical design image quality</td>
<td>0.849</td>
<td>0.23</td>
<td>1082</td>
</tr>
<tr>
<td>2.1.2 M1</td>
<td>0.997</td>
<td>0.03</td>
<td>150</td>
</tr>
<tr>
<td>2.1.3 M2</td>
<td>0.997</td>
<td>0.03</td>
<td>150</td>
</tr>
<tr>
<td>2.1.4 Transfer optics</td>
<td>0.883</td>
<td>0.20</td>
<td>925</td>
</tr>
<tr>
<td>2.1.5 Active optics system</td>
<td>0.970</td>
<td>0.10</td>
<td>500</td>
</tr>
<tr>
<td>2.1.6 Optical alignment</td>
<td>0.819</td>
<td>0.17</td>
<td>723</td>
</tr>
<tr>
<td>2.2 Dynamic errors</td>
<td>0.883</td>
<td>0.20</td>
<td>925</td>
</tr>
<tr>
<td>2.2.1 Wind buffeting mirrors deformation</td>
<td>0.956</td>
<td>0.12</td>
<td>522</td>
</tr>
<tr>
<td>2.2.2 Environment</td>
<td>0.970</td>
<td>0.10</td>
<td>500</td>
</tr>
<tr>
<td>2.2.2.1 M1</td>
<td>0.895</td>
<td>0.04</td>
<td>200</td>
</tr>
<tr>
<td>2.2.2.2 M2</td>
<td>0.995</td>
<td>0.04</td>
<td>200</td>
</tr>
<tr>
<td>2.2.2.2.3 Heat stop</td>
<td>0.992</td>
<td>0.05</td>
<td>250</td>
</tr>
<tr>
<td>2.2.2.2.4 Transfer optics</td>
<td>0.995</td>
<td>0.04</td>
<td>200</td>
</tr>
<tr>
<td>2.2.2.2.5 Telescope mount</td>
<td>0.995</td>
<td>0.04</td>
<td>200</td>
</tr>
<tr>
<td>2.2.3 Dynamic optical alignment</td>
<td>0.997</td>
<td>0.03</td>
<td>150</td>
</tr>
<tr>
<td>2.2.4 Image jitter</td>
<td>0.993</td>
<td>0.05</td>
<td>245</td>
</tr>
<tr>
<td>2.2.4.1 Wind shake</td>
<td>0.995</td>
<td>0.04</td>
<td>200</td>
</tr>
<tr>
<td>2.2.4.2 Drives jitter</td>
<td>0.999</td>
<td>0.02</td>
<td>100</td>
</tr>
<tr>
<td>2.2.4.3 Thermal control jitter</td>
<td>0.999</td>
<td>0.02</td>
<td>100</td>
</tr>
<tr>
<td>2.2.5 AO system errors</td>
<td>1.000</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td><strong>3 Instruments</strong></td>
<td>0.943</td>
<td>0.14</td>
<td>700</td>
</tr>
</tbody>
</table>

**TOTAL** 0.801 0.63 1619

Table 14.1. Seeing limited image quality error budget at $r_0=20\text{cm}$. 
### Table 14.2. Diffraction limited image quality error budget at \( r_0=20\text{cm} \).

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Seeing Limited</th>
<th>Diffraction Limited at ( \theta^1\text{FOV} )</th>
<th>Diffraction Limited at ( \theta^3\text{FOV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WFE (arcsec)</td>
<td>WFE (arcsec)</td>
<td>%Residual Error</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.21</td>
<td>0.50</td>
<td>18.7%</td>
</tr>
<tr>
<td>Telescope</td>
<td>0.22</td>
<td>0.69</td>
<td>4.9%</td>
</tr>
<tr>
<td>Static errors</td>
<td>0.07</td>
<td>0.95</td>
<td>4.7%</td>
</tr>
<tr>
<td>M1</td>
<td>0.03</td>
<td>1.00</td>
<td>2.7%</td>
</tr>
<tr>
<td>Transfer optics</td>
<td>0.03</td>
<td>0.99</td>
<td>5.3%</td>
</tr>
<tr>
<td>Active optics</td>
<td>0.03</td>
<td>1.00</td>
<td>2.7%</td>
</tr>
<tr>
<td>Optical alignment</td>
<td>0.03</td>
<td>1.00</td>
<td>2.7%</td>
</tr>
<tr>
<td>Dynamic errors</td>
<td>0.20</td>
<td>0.72</td>
<td>4.9%</td>
</tr>
<tr>
<td>Local seeing</td>
<td>0.17</td>
<td>0.93</td>
<td>3.0%</td>
</tr>
<tr>
<td>Environment</td>
<td>0.10</td>
<td>0.98</td>
<td>2.4%</td>
</tr>
<tr>
<td>Telescope</td>
<td>0.12</td>
<td>0.95</td>
<td>3.4%</td>
</tr>
<tr>
<td>M1</td>
<td>0.06</td>
<td>0.98</td>
<td>4.0%</td>
</tr>
<tr>
<td>M2</td>
<td>0.04</td>
<td>1.00</td>
<td>2.5%</td>
</tr>
<tr>
<td>Heat stop</td>
<td>0.04</td>
<td>1.00</td>
<td>2.5%</td>
</tr>
<tr>
<td>Transfer optics</td>
<td>0.05</td>
<td>0.99</td>
<td>3.2%</td>
</tr>
<tr>
<td>Telescope mount</td>
<td>0.04</td>
<td>0.99</td>
<td>4.0%</td>
</tr>
<tr>
<td>Dynamic optical alignment</td>
<td>0.03</td>
<td>0.99</td>
<td>5.3%</td>
</tr>
<tr>
<td>Image jitter</td>
<td>0.05</td>
<td>0.97</td>
<td>6.0%</td>
</tr>
<tr>
<td>Wind shake</td>
<td>0.04</td>
<td>0.98</td>
<td>6.0%</td>
</tr>
<tr>
<td>Drives jitter</td>
<td>0.02</td>
<td>0.99</td>
<td>6.0%</td>
</tr>
<tr>
<td>Thermal control jitter</td>
<td>0.02</td>
<td>0.99</td>
<td>6.0%</td>
</tr>
<tr>
<td>AO system errors</td>
<td>0.14</td>
<td>0.87</td>
<td>4.3%</td>
</tr>
<tr>
<td>Instruments</td>
<td>0.33</td>
<td>0.31</td>
<td>6.9%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1267</strong></td>
<td><strong>97</strong></td>
<td><strong>6.9%</strong></td>
</tr>
</tbody>
</table>

\( r_0=0.2\text{m} \) up to the instruments detector plane for \( \text{FoV}=3\text{0}\text{diam} \)
\( r_0=0.2\text{m} \) up to the instruments detector plane for \( \text{FoV}=1\text{diam} \)
## Table 14.3. Diffraction limited image quality error budget at r₀=10cm.

<table>
<thead>
<tr>
<th></th>
<th>Sealing Limited</th>
<th>Diffraction Limited</th>
<th>Diffraction Limited</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tip-Tilt corrected</td>
<td>Ω1/TOV</td>
<td>%Residual Error</td>
</tr>
<tr>
<td>Limb (arcsec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.41</td>
<td>0.22</td>
<td>0.07</td>
</tr>
<tr>
<td>R/(m)</td>
<td>690</td>
<td>995</td>
<td>367</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>4.9%</td>
<td>4.7%</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>49</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>Telescope</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>2.1</td>
<td>Stare errors</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>2.1.1</td>
<td>Diffraction and optical design image quality</td>
<td>0.03</td>
<td>0.03</td>
</tr>
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<td>Thermal control jitter</td>
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<td>AO system errors</td>
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<td>Instruments</td>
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<td>TOTAL</td>
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14.2 Image Stability

**IMAGE STABILITY**

4 arcsec/10s (goal: 3 arcsec/10s) in diffraction limited conditions

<table>
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<tr>
<th></th>
<th>Diff. Ltd. r0=20cm (arcsec)</th>
<th>Diff. Ltd. r0=7cm (arcsec)</th>
<th>Seeing Ltd. TT-corrected r0=20cm (arcsec)</th>
<th>Seeing Ltd. r0=20cm Raw (arcsec)</th>
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<tr>
<td>1 Atmospheric tip-tilt</td>
<td>0.82</td>
<td>1.97</td>
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<td>2 Telescope image jitter</td>
<td>3.00</td>
<td>3.00</td>
<td>36.00</td>
<td>1000</td>
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<td><strong>TOTAL</strong></td>
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<td><strong>3.59</strong></td>
<td><strong>36.01</strong></td>
<td><strong>1008</strong></td>
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BW-3dB TT1: 150Hz  
BW-3dB TT2(OM); 350Hz

*Table 14.4. Image stability budget.*

14.3 Pointing and Tracking

**POINTING AND TRACKING ERROR**

- Pointing error in open loop < 3arcsec rms
- Tracking error in open loop < 1arcsec rms in 10 minutes

No tip-tilt correction  
Atmosphere not considered

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<th>1</th>
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<th>Track. 10min (arcsec)</th>
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<td>1.2</td>
<td>Wind</td>
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<td>0.20</td>
</tr>
<tr>
<td>1.3</td>
<td>Jitter</td>
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<td>0.10</td>
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<td>2</td>
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<td>Mechanics</td>
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<td>2.1.3</td>
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<td>2.1.4</td>
<td>Az drive</td>
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<td>0.20</td>
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<td>0.20</td>
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*Table 14.5. Open loop pointing and tracking error budget.*
### 14.4 Throughput

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<th>λ BANDS</th>
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<th>14 MIRROR</th>
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<td>85.0%</td>
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<td>81.0%</td>
</tr>
<tr>
<td></td>
<td>400-500</td>
<td>92.0%</td>
<td>95.0%</td>
<td>45.7%</td>
<td>81.0%</td>
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<tr>
<td></td>
<td>500-620</td>
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<td>96.0%</td>
<td>51.9%</td>
<td>65.6%</td>
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<tr>
<td></td>
<td>620-800</td>
<td>88.0%</td>
<td>95.0%</td>
<td>41.0%</td>
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<tr>
<td>NB1</td>
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<td>11.5%</td>
<td>81.0%</td>
</tr>
<tr>
<td></td>
<td>400-500</td>
<td>92.0%</td>
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<tr>
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*Table 14.6. Throughput budget.*

The throughput budget does not include the losses of the polarimetry system. In the case of polarimetric observations, the throughput is reduced 50% due to the polarimetry system throughput.
### 14.5 Photon Flux

Table 14.7. Photon flux budget.

The photon flux budget does not include the losses of the polarimetry system. In the case of polarimetric observations, the photon flux is reduced 50% due to the polarimetry system throughput.
14.6 Polarimetric Accuracy

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<th>Component</th>
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<th>Max I -&gt; Q/U</th>
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<td>Coatings</td>
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<td>Window (mechanical induced stress)</td>
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<tr>
<td>Window (Thermal induced stress)</td>
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<td>-</td>
<td>2</td>
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<tr>
<td>Window (inherent birefringence)</td>
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<td>-</td>
<td>2</td>
</tr>
<tr>
<td>WFS beamsplitter (mechanical induced stress)</td>
<td>8E-05</td>
<td>-</td>
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</tr>
<tr>
<td>WFS beamsplitter (thermal induced stress)</td>
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<td>-</td>
<td>1</td>
</tr>
<tr>
<td>WFS beamsplitter (inherent birefringence)</td>
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<td>-</td>
<td>1</td>
</tr>
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<td><strong>TOTAL STATIC (all components)</strong></td>
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<td>5E-04</td>
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Table 14.8. Polarimetric accuracy budget.
15 AUTHORS

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  - Manuel Collados Vera
  - José Javier Díaz García
  - Christine Grivel
  - Elvio Hernández Suárez
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  - José Marco de la Rosa
  - Yolanda Martín Hernando
  - Iciar Montilla García
  - Esperanza Páez Mana
  - José Peñate Castro
  - R. Ángeles Pérez de Taoro
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  - Gerard van Harten
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  - Frans Snik

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  - Claude Le Men
  - Arturo López Ariste

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- Ales Kucera
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  - David Fischer
  - Hans Kärcher
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  - Joan Manel Casalta
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• AND
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• UFP
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  - Zdenek Rail

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  - Joaquín González
  - Andrea Martín
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  - Germán Prieto
  - José Antonio Rodríguez
  - Benjamin Siegel

• OBSPARIS
  - Jean Aboudarham
  - Jean-Philippe Amans
  - Guillaume Aulanier
  - Jacques Moity
  - Guillaume Molodij
  - Pierre Mein
  - Frédéric Sayède
16 INSTITUTIONS

The following institutions have participated in the Design Study of EST

<table>
<thead>
<tr>
<th>Institution</th>
<th>Country</th>
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<tr>
<td>Instituto de Astrofísica de Canarias</td>
<td>Spain</td>
</tr>
<tr>
<td>Kiepenheuer-Institut für Sonnenphysik</td>
<td>Germany</td>
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<td>Universiteit Utrecht</td>
<td>The Netherlands</td>
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<td>Kungliga Vetenskapsakademien</td>
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<tr>
<td>Université de Paul Sabatier (Toulouse III)</td>
<td>France</td>
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<td>University College London – MSSL</td>
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<td>Astronomical Institute, Academy of Sciences of the Czech Rep., v.v.i.</td>
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<td>Rothe Erde GmbH</td>
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</tr>
<tr>
<td>Siemens Mechanical Drive (previous partner was FLENDER A.G. from month 1 to 27).</td>
<td>Germany</td>
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<td>Bouwstudio PelserHartman b.v.</td>
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<tr>
<td>MT Mechatronics GmbH</td>
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17 ACKNOWLEDGEMENTS

The Conceptual Design has been possible thanks to the efforts of many people who have invested a lot of time and hard work on the development of new ideas to make this telescope a unique infrastructure to study the Sun. The participation in the Design Study of fifteen private companies, with their expertise and knowledge in particular areas, has also been crucial for the successful achievements described in the next pages and in the huge amount of documentation generated since the project started three years ago. The funds received from the EU, through the FP-7 Collaborative Project 212482, have made possible joining together all these research institutions and private companies, with their scientific and technical skills.
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