HIGH-RESOLUTION GROUND-BASED EUROPEAN SOLAR PHYSICS

MANUEL COLLADOS
Instituto de Astrofísica de Canarias, E-38205, La Laguna, SPAIN
and THE EST TEAM

Abstract: This communication reviews some of the most challenging topics in high-resolution ground-based Solar Physics. The most powerful European facilities are described, together with their capabilities and skills gained in Europe using them. The reasons for a large-aperture solar telescope are outlined, based on present scientific needs, which have led to the joint project EST (European Solar Telescope), in which the most prestigious European Solar Physics research institutions participate. Some technical challenges of a such a large telescope are mentioned.

Keywords: Sun – Solar Telescopes – Instrumentation – High Resolution – Magnetic Fields

1 Introduction: The Sun as a three-fold star

Understanding the processes that take place in our Sun is crucial for many reasons. Firstly, there is a fundamental *Solar-terrestrial connection.* The Sun is of paramount importance because it sustains life on Earth. Changes in its conditions may have dramatic consequences for us. Large amounts of energy, derived from the magnetic energy stored in the fields, are deposited into the plasma on very short timescales of seconds to minutes. These flares can accelerate plasma to velocities up to a significant fraction of the speed of light, and if the bulk of the accelerated plasma (in the form of a coronal mass ejection) hits the magnetopause of the earth, it creates fascinating events (Aurorae) and also potentially hazardous phenomena for our living environment (damage to satellites, overload of power lines, increased radiation dose for aircraft/ISS crew, etc.). It is thus fundamental to study these processes in order to be able to predict them. The question of how both long and short-term changes in the solar irradiance can affect the terrestrial climate system is also clearly one of great importance for the accurate prediction of future trends in global warming. To do this requires a much clearer understanding of how changes in the magnetic field affect the solar irradiance than we currently have through the combined efforts of observation and modelling. However, the characteristic spatial and temporal scales of the physical processes in the solar atmosphere are often determined by the magnetic field and are typically so small that their study is impossible due to lack of photons. Large collecting areas are absolutely necessary for a final understanding of the physics of magnetised solar plasma.

Secondly, there is the *planetary and astrophysical connection*. The Sun has a direct influence on all the planets in the heliosphere and there are many parallels between the processes that occur in the solar atmosphere and in planetary magnetospheres, including our own. The Sun is a star and has been used many times to guide stellar evolution models. Many stars are known to have magnetic cycles similar to that of the Sun, and starspots are beginning to be detected thanks to special techniques like Doppler imaging. The feedback between solar and stellar observations is crucial in allowing us to determine how our Sun will evolve in the future. Magnetic fields are also of critical importance in understanding most astrophysical systems, e.g. in the formation of jets observed in many astrophysical objects. They may also play an important role in galaxy evolution. These are only a few examples in which solar studies can help in understanding our universe.

Finally, there is a question of *basic science*. The Sun is the only place where we can study in detail the interaction of plasma and magnetic field, and, as such, it can be considered as a fundamental physics laboratory. Because of its tremendous size, magnetic diffusivity times are very large making it possible to follow the evolution of this interaction in a way that is impossible to reproduce in a laboratory. Consequently, the Sun is the only place where phenomena like conversion of mechanical energy into magnetic energy, conversion of magnetic energy into thermal energy, or particle kinetic energy can be studied by direct observation and in detail. Our Sun is unique in that it is currently the only star with a surface that can be spatially resolved at a level approaching that at which physical processes occur.

2 Present situation of ground-based high-resolution European solar physics

During the last 20 years, a number of European countries have constructed powerful ground-based telescopes that have increased our knowledge of the Sun. The most advanced European facilities are presently located in the Canary Islands observatories. Table 1.1 lists the nowadays existing, or foreseen for a very near future, European high-resolution solar telescopes, together with some of their most powerful capabilities. They lie in the 0.5-1.5 metre range.

On the basis of their existing observing facilities, European solar astronomers have gained leadership positions in several areas of instrumentation and data analysis. These areas include high resolution bi-dimensional spectroscopy (Italy and Germany), polarimetry at visible and infrared wavelengths (France, Spain, Italy, and Switzer-

Facility (Location)	Aperture [m]	Wavelength range (μm)	Capabilities
Dutch Open Telescope (La Palma, Spain)	0.45	0.35 – 0.8	High resolution imaging
Vacuum Tower Telescope (Tenerife, Spain)	0.7	0.35 – 2.3	High resolution imaging Adaptive optics Spectropolarimetry
THÉMIS (Tenerife, Spain)	0.9	0.40 – 1.2	Spectropolarimetry
Swedish Solar Telescope (La Palma, Spain)	1.0	0.35 – 1.1	High resolution imaging Adaptive optics Spectropolarimetry
GREGOR (Tenerife, Spain)	1.5	0.35 – 12	High resolution imaging Adaptive optics Spectropolarimetry

Table 1: European high resolution research telescopes and their capabilities.

land), adaptive optics development (Sweden and Germany), and post-processing techniques for diffraction-limited imaging (Sweden, Germany and The Netherlands).

High-precision visible and near-infrared spectropolarimetry is now routinely performed at the German Vacuum Tower Telescope (VTT) and at the French-Italian THÉMIS telescope. Accurate spectropolarimetry (10^{-3} sensitivity or better) is very photon demanding and integration times of at least several seconds are required to detect the necessary number of photons to reduce noise to acceptable levels. Only very recently, with the development of powerful adaptive optics systems has it been possible to increase the spatial resolution of spectropolarimetric data. But, even today, observations with a spatial resolution better than 0.3-0.5 arcsec are scarce. Improving this situation will only be possible if a strong effort is made to increase the telescope aperture, thus making possible the detection of a larger number of photons from smaller solar areas, complemented with a multi-adaptive conjugate adaptive system to increase the size of the corrected field of view (see Fig. 1).

Near-infrared observations offer several advantages over standard visible techniques. One of them is their larger magnetic sensitivity. Magnetic fields are better detected and studied in this wavelength range. A second argument in favour of infrared observations is the reduced sensitivity to atmospheric disturbances. However, due to the dependence of the diffraction limit on wavelength, a larger telescope is required to observe the Sun in the near-infrared with a spatial resolution of, say, 0.1 arcsec.

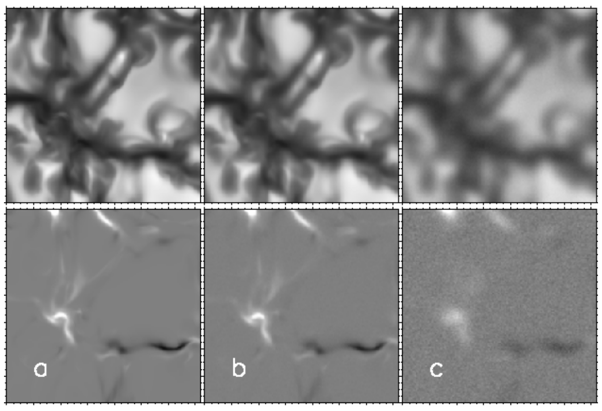

Figure 1: *a)* A frame taken from a 3-D simulation (20 km grid) of magneto-convection near the solar surface (courtesy of E. Khomenko). Each box is 3000 km (4 arcsec) wide and shows a snapshot of the intensity (top) and vertical magnetic field strength (bottom) as it would appear looking down on the simulation. *b)* The same areas seen through a diffraction-limited 4m telescope at a wavelength of 630 nm (a noise of 10^{-3} has been added to simulate an observation in a realistic way) and, *c)* Same images as seen with a 0.75m telescope at the same wavelength (noise has been added as if the images had been taken with the same integration time as in b). The model predicts rapidly evolving, highly mixed, bipolar fields that are twisted by strong turbulent downflows. A 4-meter class telescope is required to measure both the spatial and temporal characteristic of the magnetic field associated with this small-scale dynamo process which current telescopes cannot detect and resolve.

Numerical magnetohydrodynamical simulations presently achieve a degree of complexity that allows direct comparison with observations. In fact, numerical spatial resolutions, of the order of 10 km, are better than the observations and the simulations need to be degraded for an adequate comparison. The interaction of convective flows with magnetic fields has been reproduced, showing how plasma motions sweep the magnetic field to converging flow regions (downflows) where the field is concentrated and intensified. Small-scale magnetic field structures channel energy and seem to be the fundamental key for understanding how the chromosphere and corona are heated. Simulations, together with high-spatial resolution observations, will ultimately reveal e.g. the origin of the energy deficit in the umbra of sunspots or the energy excess in sunspot penumbrae. The spatial resolution of observational data is today signifi-

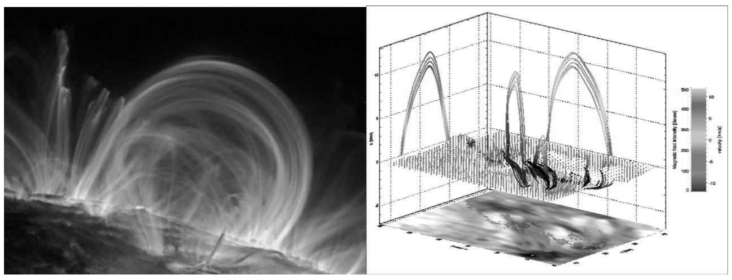

Figure 2: *Left*: Loops observed in the solar corona by the satellite TRACE. *Right*: Magnetic field configuration of an emerging region, showing similar loops as those observed by TRACE. These results have been obtained using near-infrared spectropolarimetric data taken at the German VTT.

cantly poorer than that possible with numerical simulations, preventing progress in our understanding of, e.g., the internal structure of thin flux tubes or the propagation of different MHD waves in magnetic structures. Simulations will undoubtedly continue to improve, thanks to increasingly powerful computers and better modelling of radiative transfer. Better quality data than currently available is then essential to observe the phenomena that are only accessible today via numerical calculations. Unexpected findings, when increasing the spatial and temporal resolution of observational data, are to be expected, which will in turn also serve as input for improving simulations. This has been the case, for instance, with the discovery of penumbral dark cores, which were only discovered when observations with a spatial resolution of 0.1 arcsec were achieved. Their magnetic properties remain unknown, however, because of the inherent difficulty of reaching such a resolution with currently available spectropolarimetric data. There will certainly be a mutual benefit between numerical simulations and high quality observations obtained with a large aperture telescope.

The theory of radiative transfer in a magnetised medium was developed several decades ago. The formation of spectral lines under LTE conditions giving rise to polarised spectral lines via the Zeeman effect is very well understood. Inversion codes exist that retrieve the solar atmospheric conditions under which the spectral lines are formed. Temperature, velocity and magnetic field stratifications are routinely calculated in the photosphere. However, only now are we starting to understand and reproduce the formation of spectral lines in the chromosphere, where non-LTE conditions prevail (see Fig. 2). The Hanle effect has also been demonstrated to leave its imprint on spectral lines, and extremely weak magnetic fields can be detected with it. The foundations are now in place for the development of the tools required

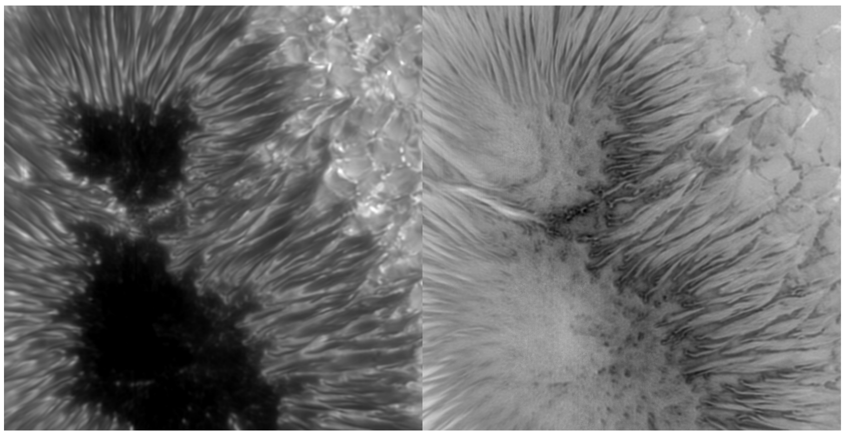

Figure 3: Sunspot recorded by the SST in the blue and red wings of the magnetically sensitive Fe I line at 630.2 nm on Sept 12, 2006. The left-hand image represents the average intensity, the right-hand image the difference in circular polarization (normalised to the intensity) of the two wings. The spatial resolution of these images, consisting of over 500 individual exposures, is the result of adaptive optics and image restoration techniques (developed by Löfdahl and van Noort) and is close to 0".2. Dark penumbra cores, discovered with the SST, are seen clearly in both intensity and polarization signal (Michiel van Noort, Institute for Solar Physics)

to diagnose the magnetic field in the solar chromosphere. These will be a fundamental key for the correct interpretation of observational data corresponding to this highly dynamic layer.

The 1-metre Swedish Solar Telescope (SST) presently produces the sharpest images of the Sun ever obtained (see Figs. 3 and 4). Not even space missions, free from atmospheric turbulence, can reach that degree of detail, because of the smaller size of the telescopes that can be launched. Such diffraction-limited observations require excellent optics and effective adaptive optics working on an extended object to counter the disturbances in the Earth's atmosphere. Post-facto reconstructions also help reach this high image quality. The 45-cm Dutch Open Telescope (DOT) has proven that an open telescope is capable of obtaining excellent results. GREGOR, with its 1.5 metre aperture and open structure, will represent an intermediate step towards a larger telescope and will serve as a test bench for the development of new generation high-order multi-conjugate adaptive optics.

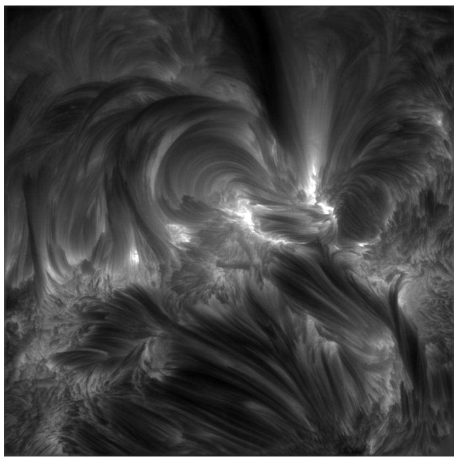

Figure 4: Hα line core image of an active region observed with the SST on 04-Oct-2005. The FOV is 64x64 arcsec. The spatial resolution is close to the diffraction limit of the telescope ($\sim$ 120 km) which was achieved with the aid of adaptive optics and post-processing techniques (Multi-object Multi-Frame Blind Deconvolution).

3 Future perspective

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 distortion that disturb the incoming wavefront. New and more powerful adaptive optics systems installed at some of the principal solar telescopes, including the German Vacuum Tower Telescope and the Swedish Solar Telescope, 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 shown that these systems are now so mature that our ability to resolve small detail is now limited by the size of the telescopes themselves, and not by the atmospheric distortions.

Besides spatial resolution, the light collecting power of a large aperture is crucial for solar research, quite contrary to the perception that sunlight is bright. Magnetic fields are detected by measuring the polarisation of magnetically sensitive spectral lines. The fraction of the light in a spectral line that is polarised 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 of one part in 10^4. The timescales with which solar features change are related to the speed of sound in the solar atmosphere (about 7 km/s), so smaller features evolve faster than larger ones. The required time resolution amounts to just a few seconds, making a large aperture even more necessary.

In view of all these arguments, solar astronomers world-wide are unanimously in agreement that a much larger step in observational capability is needed to fully understand the fundamental processes of plasma physics that are at work in the outer layers of our star, and, in particular, to begin an in depth study of the magnetic coupling of the solar atmosphere by simultaneously observing the photosphere and the chromosphere, with high spatial resolution (to see details smaller than 100 km), high spectropolarimetric accuracy (for an accurate determination of magnetic fields and velocities) and high temporal resolution (for evolutionary studies at time scales of a few seconds). Numerical simulations and radiative transfer calculations, taking into account the Zeeman and Hanle effects, will help interpret the observational data. A large aperture telescope is thus required to meet these requirements.

Following this trend, many leading European solar astronomers decided to form the consortium EAST (European Association for Solar Telescopes) to keep Europe in the frontier of international solar physics. Among others, one of the aims of this consortium is to develop, construct and operate a next generation large aperture telescope (EST, European Solar Telescope) in the Canaries. This telescope should be optimised for studies of magnetic coupling between the deep photosphere and upper chromosphere. This will require diagnostics of the thermal, dynamic and magnetic properties of the plasma over many scale heights, by using multiple wavelength imaging, spectroscopy and spectropolarimetry. The EST design will therefore strongly emphasise the use of a large number of instruments simultaneously, thereby improving photon efficiency and diagnostic capabilities relative to other existing or proposed ground-based or space-borne solar telescopes. To implement the EST science goals, also high spatial and temporal resolution will be needed.

4 Some science cases for EST

Some examples where a large aperture solar telescope is necessary to make significant progress are the following:

- Magnetic flux removal from active regions

  The magnetic field generated during one solar cycle must disappear from the surface before the opposite-polarity field of the next cycle can appear, i.e., a removal of the photospheric field is required for the dynamo to operate. Active regions and sunspots are observed to slowly decay with time: their size and magnetic flux start to decrease as soon as they are fully formed. Part of the flux lost by sunspots migrates to the poles through random walk diffusion, producing the magnetic field reversal observed in the polar caps around the maximum of sunspot activity. The fate of the remaining sunspot flux is unknown.

Magnetic flux can be eliminated from the photosphere by in-situ small-scale reconnection processes or by the rise (submergence) of field lines to higher (deeper) layers. The edge of the moat surrounding sunspots is known to be the site of many flux cancellation events, i.e., the disappearance of flux concentrations of opposite polarity as they come into close contact. Often, moving magnetic features associated with the sunspot cancel when they hit existing plate elements of opposite polarity at the boundary of the moat. It has been suggested that these cancellations may explain the decay of sunspots and hence the removal from the solar surface of a significant fraction of the magnetic flux in active regions. With current or upcoming observations, however, it is difficult to determine whether these small-scale cancellations are the result of magnetic reconnection, the rise of U-loops, or the submergence of Ω-loops. All three processes may be a source of chromospheric/coronal heating (due to the release of magnetic energy), and of transient events in the upper atmosphere. To distinguish among the different possibilities, simultaneous observations of the photosphere and chromosphere need to be carried out at the highest angular resolution possible. By analyzing the photospheric and chromospheric flow fields at the cancellation sites, and the timing difference between the events occurring in the different layers, it will be possible to draw definite conclusions about which mechanism is actually responsible for the removal of magnetic flux.

- Flux emergence and cancellation in the quiet sun

  The two sources of flux for the network are the dispersal of flux from active regions and ephemeral regions. Ephemeral regions are bipolar magnetic concentrations with sizes typically less than 20000 km that appear over the entire quiet Sun and, subject to granular motions, merge and cancel with other network flux concentrations. They are short-lived, with an average lifetime of 4.4 hours. Through cancellation processes, ephemeral regions replace the total flux of the quiet sun in 8-19 hours. We still do not know if ephemeral regions and internet work fields are produced by the global dynamo, a local dynamo, or both. To answer this question, it is important to follow their temporal evolution during emergence and to determine their magnetic field topology and connectivity in the different layers of the atmosphere. It has been suggested that, in general, all flux emergences above 10^{18} Maxwell are associated with coronal brightening in Fe XII ($\sim$1.6 MK). Emerging loop structures first become visible in the corona when the separation of the two poles of the ephemeral region reach 4.5-8.5 Mm, and then remain visible for 5-12 h. These results suggest that there is magnetic field connectivity between the photosphere and corona at the location of ephemeral regions, but no further studies have been carried out so far, partly because of the lack of reliable magnetic field measurements in the chromosphere (the interface layer between photosphere and corona). Whether this connectivity is able to provide a heating mechanism to the corona remains unclear.

Flux cancellations are very frequent in the quiet Sun. Many of these events involve one of the poles of an ephemeral region and a network element of opposite polarity. As a result of the cancellation, the network element disappears and is effectively replaced by the other pole of the ephemeral region. The reconfiguration of the photospheric field can result in localised heating in the chromosphere and corona by field braiding. Brightenings in the chromosphere and corona are indeed observed during quiet Sun cancellation events, but it is not clear whether they are caused by field braiding, the retraction of Ω-loops, the emergence of U-loops, or photospheric reconnection. EST will clarify this issue by making it possible to investigate the time difference between events in the photosphere and chromosphere, and by providing information about the connectivity of the field in the photosphere and upper layers by direct measurements of the magnetic field. Once this fundamental problem is solved, it will be possible to assess the potential of cancellation events as a source of atmospheric heating in the quiet Sun.

- Wave propagation in different magnetic structures

Waves are one of the most promising candidates for upper atmospheric heating. It has been suggested that acoustic waves are generated by the turbulent convection in the sub-photospheric layers. In a stratified solar atmosphere, an acoustic cut-off frequency exists producing a reflection of the low-frequency waves back to the lower atmosphere and convection zone. Only high-frequency waves above the cut-off frequency can propagate outwards. These high-frequency waves can propagate to the chromosphere, steepen into shocks and dissipate their energy there. However, the acoustic energy flux of these waves has been found to be at least ten times lower than required to balance the radiative losses in the solar chromosphere.

Magnetic fields play an important role in modifying the properties of the acoustic oscillations. In the presence of a magnetic field, a new characteristic wave propagation speed appears: the Alf’̌en speed. In those layers where both acoustic and Alfvén speeds are similar, the energy of acoustic waves can be effectively transformed into the energy of magneto-acoustic waves. Magneto-acoustic waves can also be generated by the random motion of the photospheric footpoints of the fields, which are stochastically shuffled around by the surrounding convective flows. Since the fields connect photosphere and chromosphere, they provide channels for energy transport to the upper layers.

However, the efficiency of mode conversion or the excitation of magnetoacoustic waves depends on the size of the magnetic structures. For weak inter-network fields and the magnetic network with field strength up to 1.5 kG, plasma motions determine the field topology, whereas the strong fields of pores and sunspots suppress the convection and direct the flows along their field lines. While the number of sunspots changes with the solar cycle, the small-scale network flux tubes and the internetwork flux are always present on the solar surface. To address the role of magnetic fields in chromospheric heating, one thus has to determine both the relative contribution of the different kind of magnetic structures to the heating, and the actual way of energy transport in each of them. This leads to the following list of questions:

- What types of waves are transmitted by the different kind of the magnetic structures of different sizes and magnetic field strength?
- At what height do waves develop shocks? How is the wave energy dissipated into the medium?
- How do the frequency spectra change with height in the magnetic structures of different types? What are the mechanisms of these changes? Can direct evidence for mode conversion be found?
- What is the contribution of different frequency ranges to the chromospheric heating?
- Can the photospheric sources of the chromospheric oscillations be uniquely identified? Can direct links between these two layers be found?
- What are the respective contributions of acoustic and magnetic heating?

In order to find the answers to these questions, it is of crucial importance to observe simultaneously several photospheric and chromospheric spectral lines. The topology, field strength, and magnetic flux of the magnetic fields have to be known in the photosphere and in the chromosphere. The evolution of the fields has to be followed closely, as well as that of the purely thermodynamic quantities like temperature and flows. Regardless of the type of magnetic structure observed, high spatial and temporal resolution, large field of view, and high spectropolarimetric precision are always required.

- How do active regions emerge from the convection zone?

The origin of active regions is thought to be the emergence of toroidal flux tubes initially stored at the bottom of the convection zone, the site of the solar dynamo. After being amplified at the bottom of the convection zone, the toroidal magnetic field becomes unstable and rises buoyantly to the solar surface, where it emerges in the form of bipolar active regions. The growth of active regions is rapid and complex, affecting the photosphere, the chromosphere and the corona. At moderate spatial resolution, one observes the formation of arch filament systems in the chromosphere, strong flows in the photosphere and chromosphere (suggesting the occurrence of convective collapse), and flare activity. So far, the interrelation of these events and the topology of the field during the emergence of active regions have not been well characterised because of three main reasons: (a) no ground-based telescope or spacecraft has the capability to measure magnetic fields in the photosphere and chromosphere simultaneously, with high temporal and angular resolution; (b) the evolution of the region must be followed for at least the first 2-3 days; and (c) quite large fields of view are required to cover the full active region.

Observations with EST can be used to understand the sequence of events during the emergence of active regions at their intrinsic scales, to determine the evolution of the photospheric magnetic field and flows, and to investigate the interaction of the newly emerged flux with the pre-existing chromospheric magnetic field (a potential source of heating in the upper layers via magnetic reconnection). The observations will make it possible to test the predictions of 3D MHD simulations of the eruption of flux tubes from below the photosphere into the upper atmospheric layers.

Some important parameters related to the working of the solar dynamo that should be investigated with EST include: (a) the amount of twist in the flux tubes that rise buoyantly from the convection zone; (b) the onset of fragmentation processes and the occurrence of convective collapse as flux tubes reach the photosphere; (c) the changes in magnetic connectivity taking place in the photosphere and chromosphere during the emergence; and (d) the rate of chromospheric heating due to magnetic reconnection.

To achieve all these aims, and others, EST must combine the best of present European facilities:

- Excellent narrow-band and polarimetric imaging capabilities, such as those of the 1-m Swedish Solar Telescope (SST), by using simple optical design and highly performing adaptive optics.

- Open design, as that of the Dutch Open Telescope (DOT), to exploit the favourable winds at the Canary Islands.

- Robust and user-friendly adaptive optics systems, such as the one operating at the German VTT .
- Multi-line spectroscopy, such as that operated by THÉMIS. .
- Visible and near-infrared simultaneous spectropolarimetry, such as the combination of Visible Polarimeters (VIP)-Tenerife Infrared Polarimeter (TIP) and Polarimetric Littrow Spectrograph (POLIS)-TIP at the VTT.
- Efficient narrow-band tunable filters, such as the Interferometric BIdimensional Spectrometer (IBIS) or the Triple Etalon SOlar Spectrometer (TESOS).
- Simultaneous control of polarimetric imaging and spectrograph instruments, such as in the VTT.
- Post-processing techniques to compensate for residual seeing effects in multi-wavelength polarimetric images, such as developed for the SST.

EST is expected to improve by a considerable factor the presently achieved spatial resolution. The operation of several narrow-band tunable visible and near-infrared imaging instruments together with grating spectrographs, all with polarimetric capabilities, will make EST a unique telescope for simultaneous observations of photospheric and chromospheric layers and for studies of the time evolution of the three-dimensional structure of solar magnetic fields. Its performance will only be comparable to that of the American ATST. Solar studies will benefit tremendously from having two telescopes with a similar power capable of giving an almost full temporal coverage of solar phenomena. Unlike ATST, EST will not have special requirements to observe the solar corona, making a simpler optomechanical design feasible, with an on-axis structure and less stringent stray light constraints. With this solution, the polarimetric calibration of the telescope, which is fundamental for an accurate determination of the magnetic field vector, will be easier than for off-axis telescopes. A single polarimetric unit may be located in the primary focus. This polarimetric unit would be shared by all instruments (or those selected by the observer). Another option is that each instrument may have its own polarimeter. In this case a unit for polarimetric calibration may be placed in the primary focus. Again this is a flexible setup and observers may decide the optimum configuration for their interests.

Flexible setups will allow the observer to use multiple configurations with minimal optical changes. The observer may decide to use many instruments simultaneously, with broad-band beam splitters for sharing light between the instruments, or, choose to use dichroic beam splitters to distribute all light of a specific wavelength to a specific instrument, thereby maximising the photon flux for each wavelength.

To maximise the efficiency, the optical design of the telescope must integrate in a natural way all the active and adaptive optics, minimising the number of optical surfaces. This optimisation comes with two advantages. On the one hand, the total throughput of the system and photon transmission will be maximised. On the other hand, wavefront distortions introduced by the optical surfaces will be kept to a minimum. A superb image quality must be one of the major strengths of EST.

Future state-of-the-art ground-based telescopes that will be operating in the coming decades (e.g. GREGOR or ATST) share some of the science goals of EST. EST will have the capability to operate several of its focal-plane instruments simultaneously, and thus allow to study the magnetic connection of the solar magnetic field throughout the solar atmosphere and the interaction of the magnetic field with the moving plasma. This will ensure that these facilities are complementary, resulting in greater scientific return.

Space missions are usually intended to observe wavelengths not accessible from the ground (such as X-rays or the far ultraviolet). Our knowledge of the corona has considerably increased as a result of these instruments. Nonetheless, even if the magnetic connectivity between the different layers of the solar atmosphere is the primary goal of most of them, the study of the deep atmosphere is generally limited to photospheric longitudinal or vector magnetograms (difficult to calibrate accurately in terms of magnetic field) with moderate spatial resolution. The recently launched Hinode mission, with its 50-cm optical telescope, is equipped with a visible spectropolarimeter with a spatial resolution of 0.3 arcsec, to study the photospheric magnetism. The 1-metre balloon-borne solar telescope SUNRISE, will measure the photospheric and the chromospheric magnetic field, but only during its 10 day mission in 2009. There are no currently planned missions that will achieve the resolution of EST in this area during the next decade. To achieve a complete understanding of solar magnetism and its effects in the heliosphere it is necessary to make the connection between all the layers of the atmosphere by combining ground-based and space-based observations.

5 Technical challenges for EST

From a technical point of view, a 4-metre class solar telescope is a challenge. Despite all the knowledge and expertise in building and operating solar telescopes that has been acquired in Europe during the last decades, the construction of a large facility is not without risks, and a substantial effort must be made to make it a reality. Presently, there are no operational telescopes of this category in the world.

Thermal effects due to solar radiation are tremendous. To minimise the wavefront distortion in the telescope itself and its surroundings, a careful thermal control of the environment of the telescope is critical. Mirror seeing, turbulence induced by the telescope structure and the floor on which it stands, and wind buffeting on the mirrors and the structure (causing spatial and temporal vibrations) are, among other problems, to be studied together as a single system to get a coherent design. All these issues are directly related to the existence or not of a dome protecting the telescope during diurnal operation.

Analyses have demonstrated that mirror surfaces need to be cooled to a temperature very close (~ 0.3 degrees) to ambient air temperature for an efficient reduction of turbulence close to them. This cooling may need to be combined with an additional, natural or forced, air flow to sweep any residual turbulent cells. An open telescope can take advantage of natural winds better than a dome-based solution, even if this has flaps with controlled openings. Since the ambient temperature varies considerably along the day, the mirrors have to be constantly tuned to maintain the required temperature difference. Also, there always exists a time lag between the moment when the cooling system is set to a given temperature and the moment when the mirrors reach it. The inertia of the mirrors to temperature changes has to be taken into account, so that at every instant the temperature difference is always kept within specifications. Mirror thicknesses and materials are thus closely tied-up to their corresponding cooling mechanisms.

The heat load on the primary mirror, M1, is determined by the solar radiation and can consequently by analysed independently of the rest of the system. This is not the case for the rest of the optical surfaces. The amount of radiation they receive depends directly on the field-of-view that is transmitted by the heat rejector. A trade-off must be reached to have the largest possible field of view, without compromising the scientific objectives and the technical solutions for an efficient cooling.

The deformation of the figure of the primary mirror is also a subject that requires a close analysis. Since it is expected that it will be a light mirror, to reduce the overall mass of the telescope and to reduce the heat capacity of the mirror, it will tend to change its shape under conditions of varying gravity vector, as the telescope changes elevation during a diurnal observation. This deformation can be measured and corrected by means of a look-up table. More critically, its low weight and large surface will make it very sensitive to deformations due to wind effects. The buffeting will produce a vibrational spatio-temporal spectrum that will depend on the material and thickness of the mirror. An active compensation of M1 will be required to maintain its figure, using an accurate wavefront sensor. The optimum location of the actuators and their specifications will be obtained after a careful finite-element analysis. To avoid any mechanical or thermal incompatibility between the support of M1 and its cooling mechanism, they will need to be designed together.

The deformation of other mirrors (especially that of the secondary, M2, or of the tertiary, M3, which deviates the beam along the elevation axis) cannot be ignored, but it is substantially less critical, since it depends on the mirror aspect ratio. However, thermal conduction is related to their absolute thickness. M2 and M3 can thus be relatively thicker thereby reducing deformation while having tolerable thermal properties.

The telescope structure is also affected by thermal effects and wind buffeting. Direct sunlight will make it suffer expansions and contractions throughout the day that will modify the separation between the primary and secondary mirrors. Differential heating, or slight inhomogeneities, of the structure will also produce changes in the relative orientation between them. An active M2, built on a hexapod, is necessary to keep fixed its distance and orientation with respect to M1.

Wind has two effects on the telescope structure. On the one hand, it will excite its natural eigenfrequencies. The active supports of M1 and M2 will be in charge of the compensation of these vibrations. A careful control of the spatio-temporal variations will be required, to determine which actuators are to be applied. On the other hand, a laminar flow crossing the telescope will be deformed by the presence of the bars of the structure, giving rise to a turbulent flow. Temperature fluctuations associated with this flow should be kept to a minimum, since they are the responsible for refractive index and optical length variations, i.e., for the distortion of the wavefront.

The spider supporting M2 also needs special consideration. It needs to be stiff enough to minimise its deformation but must have a small cross-section because its shadow will be seen by the subaperture images generated with the adaptive optics system. An alt-azimuthal structure is expected for EST, due to its large size and weight, and will give rise to a rotation of the pupil in a fixed reference frame, such as the location of the wavefront sensor. The spider projection on each subpupil of the AO system should represent a small fraction of the subpupil area, so that they are all useful at every instant. The cooling system of M2 will be guided through the telescope structure and, in particular, through the spider. A large flux of the cooling fluid implies a large section of the spider, with a negative impact on the AO performance. Since the field of view determines how much energy needs to be removed from M2 to keep it at the desired temperature, a close relation between the designs of the heat rejector, the spider and AO system is mandatory.

Following all the above reasoning, telescope structure (including the spider for M2), the active system of M1 and M2, the mirror cooling mechanisms, the heat rejector and the AO system are part of the same system and must be designed very tightly to match each other and minimise the impact of heat and wind loads.

There is another factor that critically affects the mentioned subsystems: the dome. The DOT has demonstrated that an open telescope can operate very efficiently and, with the help of natural wind, diffraction-limited images can be obtained. It is not clear whether this experience can be extrapolated to a 4-metre class telescope and an in-depth analysis needs to be performed. In an open telescope, the whole telescope (structure and mirrors) is affected by wind. The image-quality performance of the telescope must be guaranteed for all possible wind directions and telescope orientations. In addition, the whole floor where the telescope is located is heated by the solar radiation and must be actively cooled to avoid locally generated seeing. If a dome is installed to protect the telescope from wind, then the problem is transferred to the local seeing generated by the dome itself. A critical decision about the dome must be made by the project, since directly affects the technical requirements of the whole telescope and AO systems.

The pier and the building have to be designed in such a way that the vibrations of the building or the pier induced by wind are small enough to be corrected by the AO.

As mentioned above, the adaptive optics system is responsible for evaluating the control signals of M1 and M2 and sending them to their actuators in case the mirrors or the structure itself suffer from deformations. The AO must, in addition, evaluate the wavefront distortions induced by the air along the optical path, inside the telescope, in its surroundings and in the free atmosphere. Turbulence has typical variation frequencies of a few hundred Hz, larger than those of mechanical vibrations of solid structures. For this reason, a fast tip-tilt mirror and, at least, one deformable mirror are required in the optical path to compensate for turbulence-induced wavefront inclination and deformation. At visible wavelengths, the isoplanatic angle is expected to be rather small for a 4-metre class telescope (a few arcsec). A Multi-Conjugate AO (MCAO) system with, at least, a second deformable mirror, is required to have a larger diffraction-limited field of view. In the near-infrared, this parameter is expected to be considerable larger. The number of layers of the atmosphere that need to be corrected is at present unknown.

Finally, instruments must be addressed as a whole. These include broad-band imagers, with phase diversity and/or speckle imaging capabilities, in several wavelengths. Etalon-based tunable imagers, covering from short visible wavelengths to the near-infrared, seem to be the most promising candidates for narrow band imaging. Independently of whether a collimated or a telecentric solution is adopted, the selected field of view will be critical. In addition, one or several long-slit or integral-field spectrographs must also be included. Narrow-band imagers usually give much better imaging quality than spectrographs, but these give more coherent spectral information. For this reason, the combination of narrow band imaging filters and spectrographs will be fundamental for many observing programs. The telescope optical design must give the capability of using all these instruments simultaneously or only a few of them, with an optimised light distribution.

Acknowledgements: This report is the consequence of the work of many people, whole names can not be explicitly listed without surpassing the space reserved to the author's list. Spanish solar astronomers first contributed to the document “Spanish Science Vision for EST: Magnetic coupling of the solar atmosphere”. Later, many european solar astronomers contributed to complement and improve it for the presentation of the EST project to the EC under the FP-7 programme. This report is based on these two documents.