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List of abbreviations

EST	European Solar Telescope
DM	Deformable mirror
AO	Adaptive Optics
MCAO	Multi-conjugated AO
FoV	Field-of-view
WFS	wavefront sensor
SH-WFS	Shack-Hartmann WFS
CAO	Conventional AO
LO-WFS	Low Order WFS
NCPA	non-common path aberration
FPGA	field-programmable gate array

1. Introduction

In order to meet its science requirements, EST will be equipped with a state-of-the-art MCAO system composed of 5 DMs, conjugated at different heights, and two SH-WFSs; a small FoV high order WFS covering 10-12 arcsec and a large FoV low order WFS with 60-70 arcsec, allowing a real-time correction over such a large FoV [see RD1 for an complete review of the technical requirements].

On top of this, its overall optical configuration is completely polarization-free, enabling high polarimetric sensitivity and accuracy observation of the solar atmosphere.

However, the most challenging technical requirements of the MCAO system are represented by the SR=0.3 for r0=7 cm, and SR=0.6 for r0=20 cm [RD2]. Indeed, in consideration of the required wavelength coverage, which has to extend down to 500 nm, and the extended corrected FoV mentioned above, this translates into the need for specific wavefront sensing technical solutions with detectors able to run up to 2 kHz and formats > 1000 x 1000 pixels. Indeed, such a high speed and large format camera technology is not available on the market, and specific developments need to be done. One possible solution to overcome this limitation of off-the-shelf devices, is represented by the use of a multi-camera system, where two or more detectors are simultaneously used to sample different regions of the pupil plane and provide a large format wavefront sensing solution, able to run at the required correction frequencies.

The scope of WP7.4 is to investigate the possibility of a multiplexed WFS solution and its scalability. More specifically a laboratory prototype, based on the simplest configuration with two cameras, will be constructed making use of commercial parts with the aim of testing the solution and the control scheme, in terms of data handling, of the device.

In this document we describe the main technical specifications of the hardware components selected for the demonstrator, the proposed approach for their control, and the overall design.

2. The EST MCAO and wavefront sensing

In Fig. 1, we show the EST optical scheme together with the location of the DMs and the SH-WFSs as in [RD2].

Between the collimator M5 and reimager M8, a tip-tilt mirror (M6) and ground layer DM (M7) are foreseen, although a secondary deformable mirror able to replace the two is currently under evaluation. These two active elements constitute the conventional AO (CAO) system and are driven by the CAO WFS at F3.

In addition, four MCAO DMs conjugated at different heights are placed in a direct order (from the higher altitude DM to lower altitude DM) after the focus, in such a way that reimaging for each of them is not necessary. This configuration was successfully validated, through simulations, in [RD3] and [RD4].

Last, a wide field low order SH-WFS is located at F4 to drive the MCAO DMs. This WFS, hereafter LO-WFS, should accommodate 13 subapertures across the pupil, each one with a FoV of 70 arcsec. This requires an effective detector format of at least 1 k x 1 k pixel. In contrast to conventional SH-WFS, in the LO-WFS each subaperture image is subdivided in several smaller parts (24 x 24 pixel each), which are cross-correlated with the other subimages of the other subapertures to improve the reconstruction of the turbulence in different directions.

Currently up and running solar AO systems are all employing cross-correlating SH sensors with typical subapertures of the order of 10-15 arcsec, while the EST LO-WFS will have subaperture images larger than 100x100 pixels. Although many wavefront sensing interesting approaches were proposed (see for instance [RD4]), a SH-WFS appears the most reliable technology at the moment, due to the long experience acquired operating and developing AO system based on that. For this reason, the EST MCAO will also be based on the same solution. However, due to the intrinsic low contrast of the solar granulation (13-14 %) at visible wavelengths, which further reduces to a few percents when the sub-pupil MTF is considered, a good telescope optics and a high full well capacity (ideally larger than 50 ke-) of the camera are required in order to get a reasonably high contrast to perform cross-correlations. Unfortunately, a high full well capacity and bit depth pose limitations to the acquisition speed.

However, numerical simulations and experience operating AO systems demonstrated that 8 bits and a full well capacity of 25 ke- are already sufficient to close the loop in a solar AO [RD2].

The selection of the hardware components, which will be used in the laboratory to study the multiplexing configuration reflected these requirements (see below), although the main scope of this study is not to produce a WFS prototype ready for onsky testing, but to verify the feasibility of the overall approach and, in particular, the data handling from the two specular cameras.

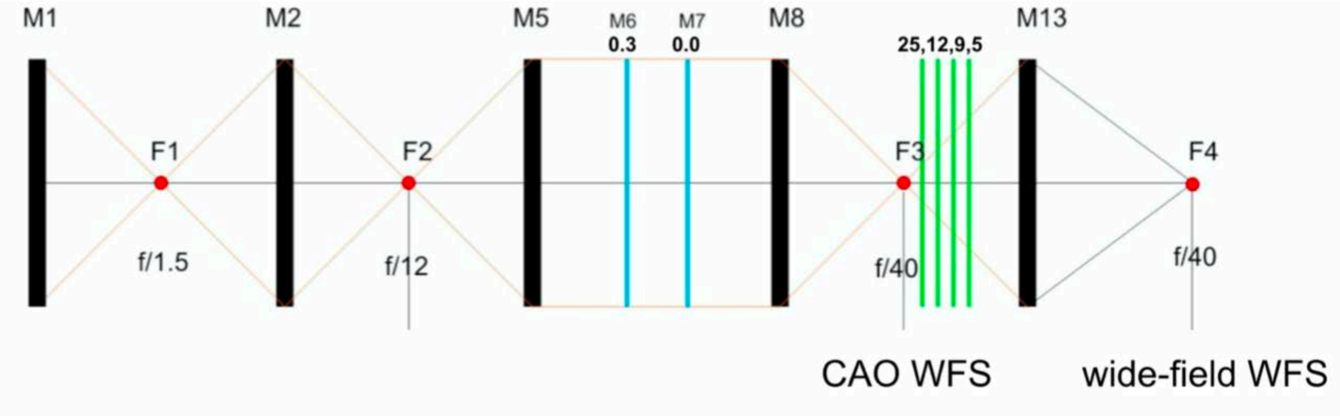

Fig. 1 EST optical scheme and MCAO DMs location (from Berkefeld et al. 2017)

3. Selected hardware

The hardware selection resulted from a detailed trade-off analysis conducted on the basis of the technical specifications of hardware parts available on the market and minimal technical requirements allowing the characterization and study, in conditions that can reproduce on-sky operations, of the data handling approach. More in detail, in order to validate the multiplexed approach, it was necessary to have a two camera system able to deliver combined data streams with an effective format of 1 k x 1k and acquisition cadence of at least 1 kHz, the latter being a tradeoff between current hardware possibilities and the minimal bandwidth requirements usually needed for on-sky operations [RD6].

The trade-off analysis which brought to the final hardware selection was primarily based on these two parameters, plus an additional requirement on the real-time availability of the data stream. Indeed, most of the large format commercial high speed cameras are recording cameras, not real-time cameras. They make use of an internal memory, where the high speed data stream is stored before being downloaded to the computer memory afterwards. In this case, acquired images are not immediately available to provide the real-time commands to be sent to the DM. On the other hand, truly high speed and real-time cameras, commonly used in machine vision applications, are generally able to operate up to 1 kHz, but with a limited format (VGA 640x408 pixels), thus not matching our goals. Combining more than one of these cameras, appears a natural solution to overcome the limitations imposed by the limited bandwidth that prevents the

Fig. 2 Image of the selected CMOS camera EoSens 3CXP.

real-time transfer of the data stream to the computer memory. Indeed, given the minimal bit depth, the format and the high cadence required, the real-time data transfer represents the main bottleneck for the data.

According to all the above points, the primary aim of this study, and the technology currently available on the market, the final choice is represented by the camera EoSens 3CXP (Fig. 2) produced by Mikrotron GmbH, which is based on the CMOS technology and is able to deliver, no considering multiplexing, data streams at about 1 kHz with a maximum format of 1024x768 pixels.

With the aim of overcoming the aforementioned bandwidth limitations in the case of the above high data volume, the EoSens 3CXP will be equipped with a high-performance frame grabber able to handle the required data volume and with an FPGA unit onboard (Fig. 3). The frame grabber is based on the CoaXpress technology, with a four parallel channel interface, which allows a data transfer capability of 4 x 6.25 Gbit/s, thus enough to sustain a high data stream, when operated in the multiplexed configuration with two cameras and relative frame grabber.

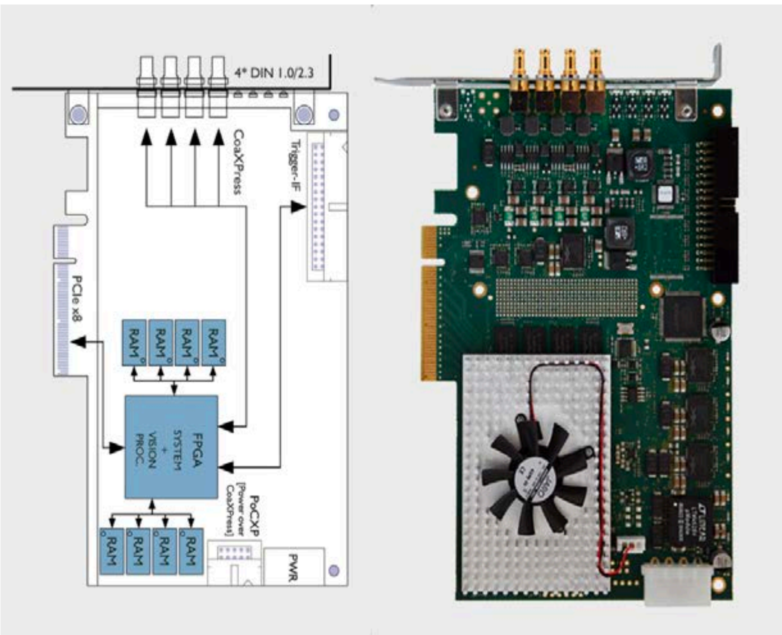

Fig. 3 SiLi MicroEnable 5 frame grabber equipped with an onboard FPGA unit and CoaXpress 4x interface.

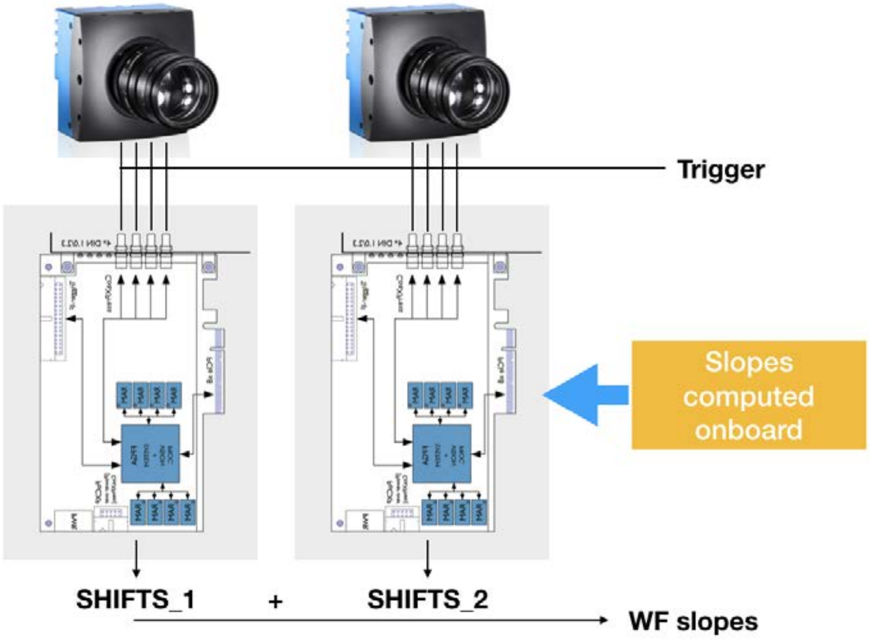

Fig. 4 Camera interface scheme. Each camera is interfaced to a single frame grabber equipped with an onboard FPGA unit. Each unit provides the necessary computational performance to handle the data stream and allows a first pro-processing of the data stream itself to reduce the load on the CPU.

The onboard FPGA unit provides the necessary data processing capabilities to handle the high cadence stream and offers the additional advantage of enabling the possibility of a nearly real-time onboard processing.

The advantage of the FPGA unit is twofold. On one hand, it enables the aforementioned capability to handle the high data stream from the two cameras; on the other hand, it offers the additional possibility of an onboard wavefront pro-analysis to reduce the computational load on the CPU and provide a real-time data product ready to be used in the AO loop (e.g. wavefront slopes, see Fig. 4).

4. Proposed laboratory configurations

As already said, the aim of this study is to investigate efficient data handling approaches of a multiplexed WFS configuration and possible opto-mechanics configurations. To this aim, we start from two simple optical configurations that will be explored in detail through laboratory activities.

These two configurations are shown in Fig. 5 and 6. Both schemes are based on a simple approach employing a cube beam splitter to split the light among the two detectors. In the case of a two camera system this equally splits the light between the two channels, but in the case of a multi-camera system, a series of beam splitters with different fractions of the splitted light can be employed in order to maintain a constant intensity on all detectors. This simple configuration was proposed for the DKIST MCAO system and discussed more in detail in [RD7]. It is trivial that every approach to the segmentation of the pupil by means of splitters will affect the WFS global throughput and sensitivity by a factor inversely proportional to the numbers of the splitters in the field; the team was preliminary exploring alternative approaches but to provide a fast assessment of the concept of synchronous multi-detector readout we decided to follow the cheapest and simplest way despite its low efficiency.

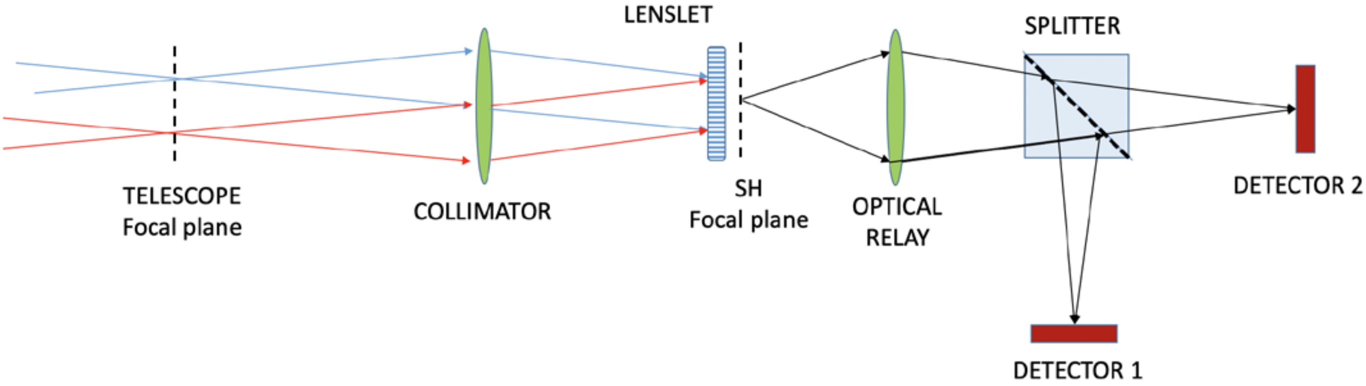

Fig. 5 Baseline optical layout.

The use of a cube beam splitter is due because it is an optical component that is not injecting low order aberration as typical of “membranes” or “plates” that respectively insert defocus or astigmatism and coma in the reflected or transmitted beam. Cubes, when well machined, may insert just a bit of high orders NCPA that can be compensated during the zero calibration on a reference source or preliminary measured during the laboratory characterization. Furthermore, they will be positioned as far as possible from the pupil plane to minimize any possible aberration effects.

In the first layout (Fig. 5) we propose to use a single lenslet array, placed at the pupil plane and then relay and split its focal plane to two different detectors. The relay optics is common to both arms and it can help to adapt the pixel scale to the size of the telescope pupil, because it is expected that a standard fast detector has too small pixels for a good sampling of the SH focal plane, hence the optical relay will help to squeeze the image. The two detectors will be offset until each one of the two will record one half of the SH focal plane.

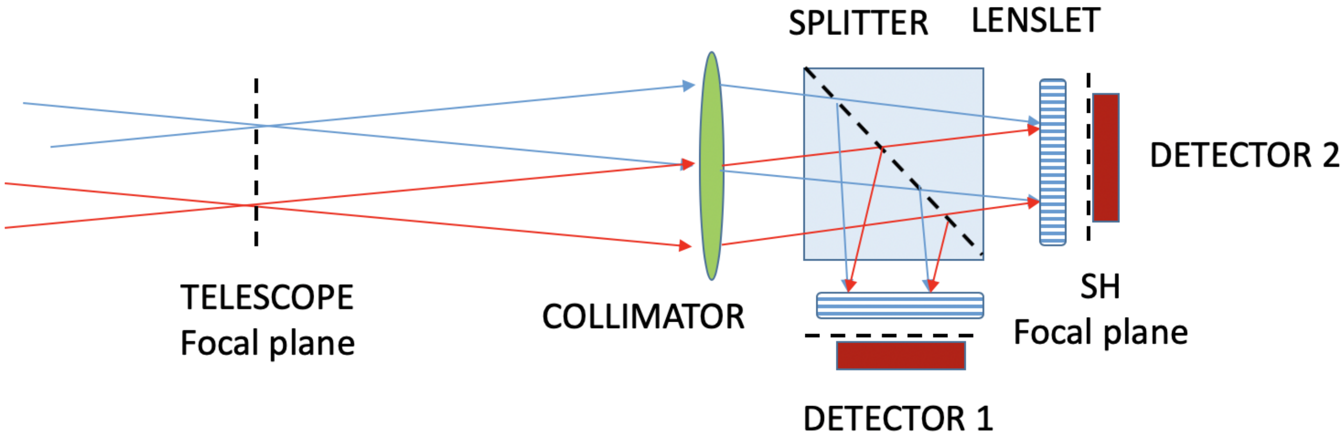

Fig. 6 Alternative optical layout.

The second, alternative, layout (Fig. 6) eliminates the use of an optical relay but it needs two lenslet (to be installed very close to the detector planes) and constraints the assembly of the two cameras with the lenslets. This may create some difficulties for the mounting of this devices internally to the cameras case and it is not more possible to adapt the pixel scale to the sub apertures of the SH without using a couple of relay lenses in between the SH focal plane and the detectors (not shown in the figure).

5. Summary

WP 7.4 aims at studying the feasibility of a multi-plexed WFS, made by several cameras operated simultaneously in parallel to correctly handle the high frame rate and effective detector format required for the EST WFS. In this document we have summarized the main specifications of the laboratory demonstrator, which will be the main focus of the activities in the next months, and will be based on a two-camera system operated in parallel thanks to a high-speed CoaXpress interface.

The selection of the opto-mechanical components, although reflecting the limited market offer in relation to the demanding requirements of the EST WFS, still allows the investigation of the data handling strategy of a multi-camera WFS system and its peculiarities. Furthermore, the onboard FPGA units of the acquisition system, allows the additional exploration of new real-time data pre-processing schemes, which can offer additional advantages in terms of speed and bandwidth of the AO loop. This task, although not foreseen in the original proposal, appears feasible with selected hardware parts. The possibility to provide a first insight into these additional FPGA approaches for wavefront sensing will be assessed over the next months.

Finally, in order to ensure a high readiness level, the proposed configuration is based on a SH-WFS and two simple optical schemes derived from approaches already studied in the literature.

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