

WaveFront Sensing on 100m scale

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ABSTRACT

It is shown that one can build a 100m-class wavefront sensing with today existing components and that 100m-scale wavefront sensing of layers in the atmosphere is also possible with today existing technology.

Keywords: Extremely Large Telescopes, Site testing, WaveFront Sensors, Multi Conjugated Adaptive Optics

1. INTRODUCTION

There is a rather general consensus that Adaptive Optics for next generation of Extremely Large Telescopes (ELTs) is essential for diameters larger than about 50m, like for the Euro50¹ and OWL² projects, and remains an important ingredient of a 20..30m class telescope (like TMT³) although these telescopes can still benefit from seeing limited instrumentation. In this framework Wavefront Sensing (WFS), as well as Wavefront (WF) Reconstruction and the related Deformable Mirrors (DMs) issues are key development areas where one should point attention. While WF Reconstruction can benefit from the Moore's law, and the DM issue is addressed elsewhere I will point my attention here on the WFS alone. Specifically I would like to sketch approaches to make a 100m-class WFS feasible today, with existing components (rather than existing technology), both in the form of a multiple star-oriented WFSs, like Shack-Hartmanns (SHs) or Pyramids⁴, or a layer-oriented⁵ one. Finally, I would like to describe a kind of experiment one can achieve in order to carry out real 100m-scale wavefront sensing, without the obvious need for a 100m class telescopes and it will briefly discussed which are the potential advantages of such an experiment.

2. THE DETECTOR'S DILEMMA

Regardless of which kind of WFS one would like to adopt for an ELT the problem of the overall number of pixels remains. If one would like to push ELTs in the visible or at least in a regime where not only exceptional seeing is exploited, one should consider subapertures in the range 10..30cm. For a 100m class telescope this translates into a pupil subdivision of the order of 300..1000 subapertures in a diagonal. A pupil plane WFS with a single pupil imagery (like the Smartt one) will require a detector with at least the same number of pixels. A Pyramid WFS would require a twice size, although one can easily imagine to split the light of the four pupils into four different detectors. For a single SH, assuming a 2x2 pixel per subaperture and a single guard edges of pixel around each of these, one turn out with the monsters need of a 1200..4000 pixel size fast readout, low noise, detector. While there is some development on CCDs of size 256x256 or 512x512, both on the areas of fast conventional CCDs (like the popular EEV39 and EEV60) and of the novel concepts one (like the L3 one) there is little hope to have devices with such a size on the horizon. The answer to this alibi is clearly in segmentation of the image plane (whatever this is a pupil one, actually, or a sets of SH spots) by means of lenslet arrays as envisaged in what has been introduced as Smart Fast Camera (SFC). It will be useful to recall the SFC concept, although it is described elsewhere⁶ in more detail. It basically consists into a number of focal reducers built up by assembling a minimum of two lenslet arrays (one building up an array of collimators and one building up an array of cameras). The image lying in the plane where the first lenslet array is placed is reimaged into a number of segmented, non-contiguous portions into the

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detector's plane. As each of the focal reducer obeys to Lagrange invariant rules there is a direct relationship between the focal reducer ratio and the filling factor of the CCDs in the focal plane. Taking existing EEV60 (128x128 24um pixel size) as final detectors one can see that a minimum ratio of 10 is necessary in order to allow for an array of such a CCDs to physically coexist. As one can envisage a camera focal ratio of F/1 to F/2 (although these are very fast numbers it is to be noted that it is not unrealistic to achieve such a performance, as the physical Field of View is very limited, given the small absolute size of the sensitive part of the CCD) a minimum entrance focal ratio of the order of F/10 to F/20 should be assumed. Also, the equivalent pixel size with which one has to design the lenslet array for an hypothetical gigantic SH-WFS is the pixel size of the final CCD multiplied by the same ratio. So, assuming a final F/1 ratio and an incoming F/20 one an equivalent pixel size of about 240 um is to be considered. Assuming a 20cm subaperture with an equivalent diffraction limited imaging of half an arcsec at visible wavelength this will correspond to a lenslet array with F/500 for each equivalent subaperture. Assuming a total of 4x4 pixel per subaperture, including the guard ring, this translates into an array of 16x16 EEV60 CCDs. (see Fig. 1) Each 128x128 CCD is receiving light from one lenslet arm of the SFC and comply with 32x32 subapertures and related SH spots. Physically such a device will be roughly 500x500mm in size while the lenslet array (that can be segmented too, of course) has a subaperture of roughly 960um and a focal length of the order of half a meter too. So, the final WFS optomechanics will roughly size as a cube of half a meter in diameter, at least as an order of magnitude. Electronic readout should be massively designed in order to read 256 detectors simultaneously without significant cross-talking, at least to the level of not producing great noise. As all the spots are, roughly, of the same brightness one can easily conclude that cross-talk rejection is not really a huge issue, in contrast with scientific camera where the dynamic range of true sky imagery can easily reach several orders of magnitude. A single clocking mechanism with local buffers and a massive parallel readout would allow for an easier job for the WF reconstruction too.

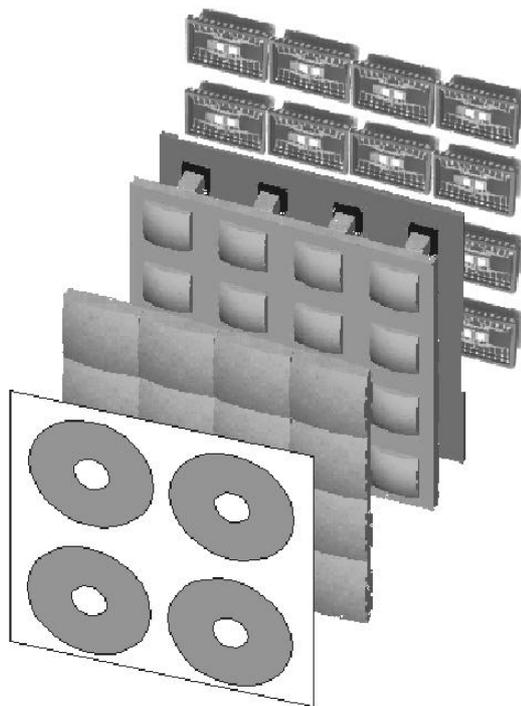


Fig. 1. Four pupils of a single star, or a Layer-Oriented multiple stars WFS is feeding a Smart Fast Camera equipped with a number of low read-out noise, high speed, EEV60. In the example depicted in the figure an equivalent of a 512x512 CCD is piled up. This could be enough, for instance, to sense a 30m class telescope at visible wavelength, or a 100m class one at NIR wavelengths.

3. THE FAST OPTICS FOR LO-WFS DILEMMA

Layer-oriented (LO) techniques could allow for significant sky coverage with solely Natural Guide Stars (NGSs) provided that collection of starlight with a significant portion of the sky is used to concur to the WF estimation⁷. Recently we looked into further FoV segmentations that shows some indication we could actually achieve such a goal with a small number of Field of Views each of size of the order of a couple of arcmin. In the following we concentrate onto this figure and of course one should eventually scale the resulting dimensions in case different patches of the sky are to be used. Basically the main problem is that in the LO approach the size of the pupil can be too large for existing detectors and one is forced to both make very fast optics and to introduce stars enlargers. These makes the mechanics more complex and positioning introduce an additional trouble consisting into the maximum allowable tip-tilt of each stars enlarger. Such a constraint scales linearly with the diameter of the telescope such that while this is doable with off-the-shelf component for 8m class telescopes, is still mechanically doable with custom designed linear stages for 24m-class telescope, will probably requires active tip-tilt mechanisms for 100m-class telescopes. The latter has been shown to be feasible. However, if one is sampling the pupil with a 10cm subaperture without any stars enlarger (making the tip-tilt requirement on their positioning a hugely coarse one, and simplifying by orders of magnitude the related mechanics) one is required to have an F/10 optics and an SFC with a final camera F/ of 0.82. The latter is really an extreme, although doable, figure. In this approach the number of pixel requirements still remain unchanged with respect to the SH case mentioned in the previous section and one can envisage a similar number of CCDs and related optomechanics. In this case, however, a full coverage of four pupils and an half a meter sized optics for illuminating the pyramid is required. The last optics will be at the level of F/10 so it is rather easy to achieve and it is less demanding than the current Prime Focus units for 8m class telescopes, that exists.

Furthermore it would be extremely easy to divide the WFS into four units, each for a single pupil, leading to four separate units, each with 8x8 CCDs. It is worth pointing out that the development of, say, 512x512 CCDs with similar performances, will dramatically reduce the overall number of CCDs and segments, to the range of 4x4 per each WFS. The former approach is doable today, while the latter one does probably requires the completion of some CCD development already underway today or the adoption of similar formats of CCDs envisaged for the L3 approach.

4. THE 100M TELESCOPE DILEMMA

Finally one could argue that all the WFSs described above have sense only with a 100m telescope able to feed them with enough photons! This is not completely true. In fact we traced out a series of approaches to use a number of medium and large sized telescopes in order to achieve WF sensing at a certain range on a patch whose size is of the order of 100m. The footprint of a number of 8m clustered telescopes (like VLTs) and of properly positioned Auxiliary Telescopes (ATs, existing too) looking to an enough large FoV will start to intersect one to each other and, at a minimum range that can be realistically made as small as a few km, can leads to an irregular surface whose size is in the range of 50..100m (Fig. 2). There are a number of reasons to achieve such an experiment. One of the most important is, probably, a direct, interpretation-free, measurement of the Taylor's frozen hypothesis. It is important, in fact, to point out that the degree of compliance to the Taylor hypothesis would dramatically change the effective sky coverage of any technique massively using such a feature. The latter statement is especially true for ELTs where edge effects are smaller. The direct measurement of the physics of turbulence to such a scales is also relevant for ELT design and this can be achieved without indirect interpretation on snapshots of wavefront on much smaller scales as it is unavoidably done today.

Another aspect that one should not discard is that such an experiment could demonstrate on the field our ability (or inability, actually...) to measure the WF on such a scale. On the technical side one should figure out in which way to perform such a WFsensing. In principle WF sensing of a large number of stars, and averaging through a layer-oriented scheme (not necessarily in an optical fashion) would suffice. As the number of stars involved in the experiment, in order to achieve a decent coverage and overlap exceeds one hundred, the optical co-addition is strongly preferred and still leads unsolved issues. The straight Layer-Oriented approach, in fact, would envisage a number of pyramids pre-mounted on their proper place on the focal plane. We initially designed such an architecture using a piezo-driven device (normally used to move biological samples in microscopy) to oscillate the whole pyramidic set. One should note that there is no strictly speaking requirements neither of extremely short exposures neither of efficient duty cycles. In fact, assuming normal wind speed of 20..30m/s an exposure per second could be

enough to trace the movement of the turbulence at a specific layer as the latter will move (at least in the Taylor hypothesis) of a fraction of the overall sampled patch.

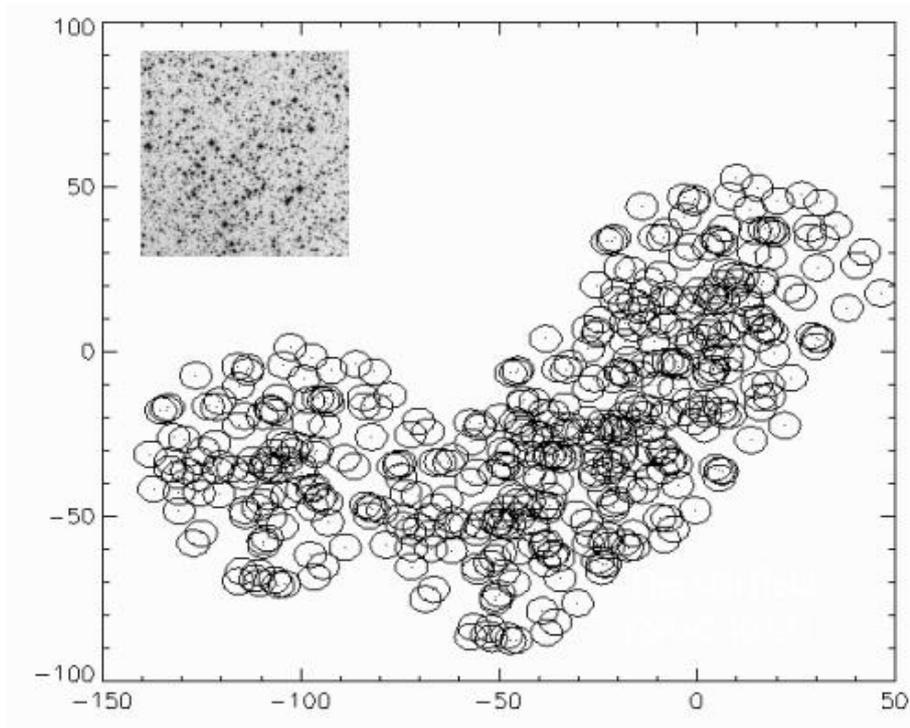


Fig. 2. The open cluster NGC4052 (in the inset) imaged through the four VLTs would produce, at a range of about 5km, the footprints shown here. With a large overlap it is possible to derive the contribution to the wavefront from such a layer for patches of ELTs class size (scales are in meters measured orthogonal to the common line of sight of the various telescopes).

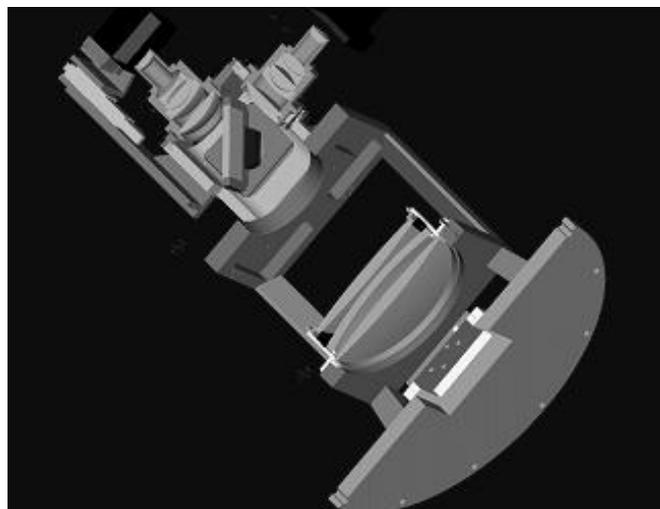


Fig. 3. A CAD drawing of a preliminary concept for sensing a large Field of View in order to exploit 100m-class wavefront sensing. The plate on the entrance flange has pre-mounted a number of pyramids and a dedicated piezo device vibrates it.

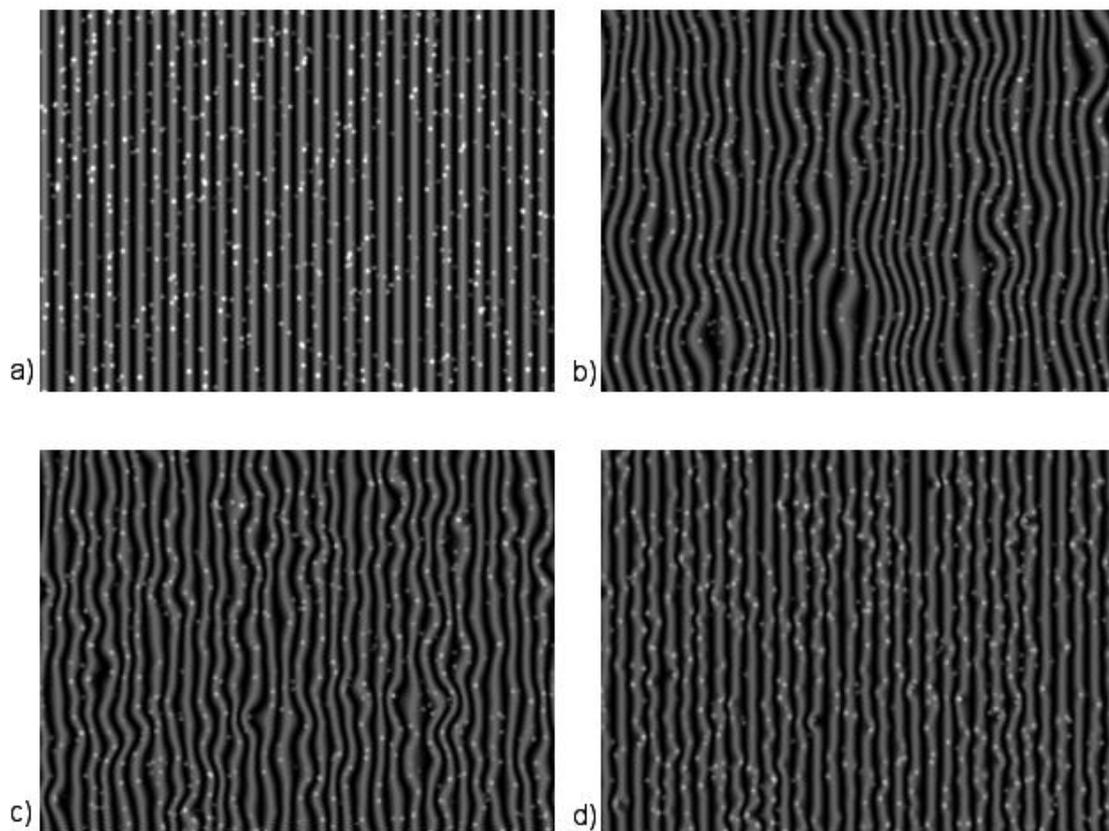


Fig. 4. A star-field is shown superimposed on a sinusoidal pattern described in the text for whole star-field wavefront sensing. In a) the pattern is straight. The signal strength is small but does not depend upon the position of the stars inside the pattern. From b) to d) an increasing tuning of the distortion will make the signal stronger and stronger, but requiring more and more precise alignment with the star-field.

We figured out, however, a novel concept for WF sensing (that could turn out to be useful also in other kind of applications, like MCAO in remote places, like Antarctica) based on a sinusoidal grating placed on the focal plane of a pupil reimager. As the detector is placed in the pupil plane (or, in layer-oriented fashion, conjugated at any specific range) one can focus on the light collected from a single subaperture where, for the purpose of the WF sensing, we are interested solely in tip-tilt. Such a tip-tilt, at least along the axis orthogonal to the sinusoidal modulation pattern, will translate into a modulation of light into the pupil plane detector. Such a modulation will show up half of the light of the star in the considered subaperture, plus the projection along one fixed axis of a vector whose length is again equal to half of the light of the star, rotated by an amount corresponding to the phase of the sinusoidal pattern where the star light is falling over. If one positions the star just on, or close to, the point of maximum variation of the transparency with the tip-tilt movement, the gain will be surely enough to detect the local tip-tilt. The step of the sinusoidal pattern should be enough long to avoid wrapping around of this information and not so large that the signal becomes too weak. In practice as a rule of thumb the rms of the tip-tilt fluctuation should be of the same order of one radian phase. In other words the step of the pattern will be of the order of six times the seeing in the conditions of the measure. What happens if a large number of stars is now in place? Simply each of these stars will contribute to the formation of the pupil image and each of them will be modulated by local tip-tilt in the same fashion. While the half of the light of the whole set of stars will permanently reach the detector the other half is piled up, generally speaking, in a random-walk summation way. It is easy to see (but the details are left for a future work on the topic) that in this way the sensitivity of the WFS is equivalent to the one looking at the average star in the FoV (however with a depth of focus given by the number of collected stars). Although this has the merit of working well with any kind of star-field, there are ways to improve it just by distorting the pattern in order to match the chosen star-

field. This can be done with different degree of accuracy, leading to pattern that can loosely match the star-field and others requiring careful matching. The latter will exhibit a much larger sensitivity (approaching the ultimate ones, equivalent to a full set of SH but without reaching the ultimate pyramids ones⁸) but requires a very precise superposition of the pattern with star-field, while the former can be placed with a much coarser precision although sensitivity will be smaller. A trade off to establish the right amount of perturbation is required to figure out the exact distortion to be applied. The algorithm for the pattern deformation is surprisingly simple and it can be implemented in a couple of lines of an IDL-code to generate the mentioned sinusoidal pattern. Although details, again, are demanded to a further work on this kind of WFS, we just outline that the phase is perturbed with a Gaussian shaped pattern whose peak intensity is given by the derivative of the original, unperturbed pattern, in the positions where each star is placed. As the derivative is a measure of how much the star is away from the proper position to achieve the better sensitivity, the final effect is the one depicted in Fig.4. It is noticeable that the size of the Gaussian shape will tune the details of how much precisely the pattern matches the star-field. Crowding of stars is automatically taken into consideration as the Gaussian shapes overlap and pile up algebraically. One can choose different forms of weightings, for instance including or not the brightness of the stars in the computation of the amount of distortion in order to privilege the brightest stars.

5. CONCLUSIONS

ELTs are a formidable technological challenge from several conceptual and engineering viewpoints. WFSensing is among one of these. However we believe that we have sketched at least one way to achieve such a task using existing components, leading to devices whose physical size is much smaller than a cubic meter. While research and development on the WFSensing field must continue and surely several other better options exist and must be worked out, the former is not, definitively, a showstopper for ELTs.

6. ACKNOWLEDGEMENTS

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REFERENCES

1. Andersen T.E., Ardeberg A., Enmark A., Knutsson P., Morau D., Owner-Petersen M., Riewaldt H. "Status of the Euro50 project", *Proc. SPIE* **5489**-24 (this Conference).
2. Brunetto E.T., Dierickx P., Gilmozzi R. "OWL Phase A status report", *Proc. SPIE* **5489**-23 (this Conference)
3. Nelson J.E. "TMT status" SPIE **5489**-27 (this Conference).
4. Ragazzoni R., "Pupil plane wave front sensing with an oscillating prism", *J. of Mod. Opt.* **43**, pp. 289-293, 1996.
5. Ragazzoni R., Farinato J. and Marchetti E., "Adaptive optics for 100-m-class telescopes: new challenges require new solutions", *Proc. SPIE* **4007**, pp. 1076-1087, 2000.
6. Ragazzoni R., Arcidiacono C., Diolaiti E., Farinato J., Moore A., Soci R. "A Smart Fast Camera", *Proc. SPIE* **5492**-12 (this Conference)-
7. Arcidiacono C., Diolaiti E., Ragazzoni R., Farinato J., Vernet E., "Sky coverage for Layer Oriented MCAO: a detailed analytical and numerical study", *Proc. SPIE* **5490**-94 (this Conference)
8. Ragazzoni R., Farinato J., "Sensitivity of a pyramidal wavefront sensor in closed loop adaptive optics", *A&A* **350**, pp. L23-L26, 1999.