PWFSs on GMCAO: a different approach to the non-linearity issue

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ABSTRACT

In the last years, the Pyramid WFS finally proved itself to be a very powerful tool for wavefront retrieval, in different applications, inside and outside Astronomy, often showing outstanding results. However, being intrinsically a non-linear WFS, the P-WFS non-linearity error starts to play a role when the AO loop is not closed on the sensor zero-WFE point. This led to the need to elaborate new concepts when trying to apply the P-WFS to open (or partially open) loop based techniques, not to trade sensitivity for linearity. This was the case for GMCAO, in which the reference stars are selected on a wide technical area of the sky, outside the FoV to be optimized, limiting the correction experienced by the WFSs to poor Strehl Ratio regime. While, in the recent past, we proposed a solution based on the Very Linear WFS, a sub-system that locally closes the loop on the Pyramid pin to let the sensor operate in its best regime, we now explore a different approach in which the P-WFS non-linearity is continuously measured, injecting a known aberration onto the sensor. In particular, we evaluate in this paper the possibility to apply basic PWFSs to the GMCAO technique, measuring the non-linearity of the sensor and taking it into account in the wavefront computation, with an approach similar to what already proposed in the LBT AO facility FLAO for the non-common path aberrations correction.

Keywords: Adaptive Optics, Pyramid wavefront sensor

1. INTRODUCTION

The Global-MCAO[1] (GMCAO) technique is the combination of a number of Adaptive Optics concepts working in a numerical Layer-Oriented[2] fashion, proposed as a way to increase the sky coverage, in the Extremely Large Telescopes era. It assumes to access a very large Technical Field of View (FoV) to find Natural Guide Stars (NGS), while performing Multi-Conjugated AO[3] (MCAO) on a relatively small Scientific FoV. Figure 1 shows a comparison between the order of magnitude Technical FoV envisaged for GMCAO reconstruction and the typical MCAO FoV. The GMCAO technique assumes the use of Wavefront Sensors (WFSs) in open loop, since the reference stars are outside the scientific FoV to be optimized, so the system delivers only a partial correction to the WFSs themselves. For this reason, the WFSs will always see a quite large aberration[4]. The goal to optimize the sky coverage implies that we need to push the single WFS limiting magnitude toward fainter stars. For this reason, it has always been considered the possibility to take advantage of the good performance of the Pyramid WFS[5] (P-WFS), since it has been recognized that it can be much more sensitive[6],[7] than the Shack-Hartmann WFS[8]. This has been demonstrated to be true, however, only if the pyramid works in closed loop. For this reason a Very Linear Wavefront Sensor[9] (VL-WFS) has been proposed to allow the P-WFS working in its best regime. This can be achieved with a local closed loop, in which the P-WFS measurements are used to close the loop with a local Deformable Mirror (DM) that brings the PSF to a high Strehl Ratio (SR) regime, as sketched in Figure 2. In this way, the VL-WFS is characterized by both wide linearity range and high sensitivity: as said, the linearity will allow retrieving accurate measurements of the wavefront in open loop, while the sensitivity will push the limiting magnitude to higher values. In this paper, we explore a different possible approach to the pyramid non-linearity issue, which consists in measuring the non-linearity of the sensor and considering it in the wavefront computation.

Adaptive Optics Systems V, edited by Enrico Marchetti, Laird M. Close, Jean-Pierre Véran, Proc. of SPIE Vol. 9909, 99096H
 · doi: 10.1117/12.2232834

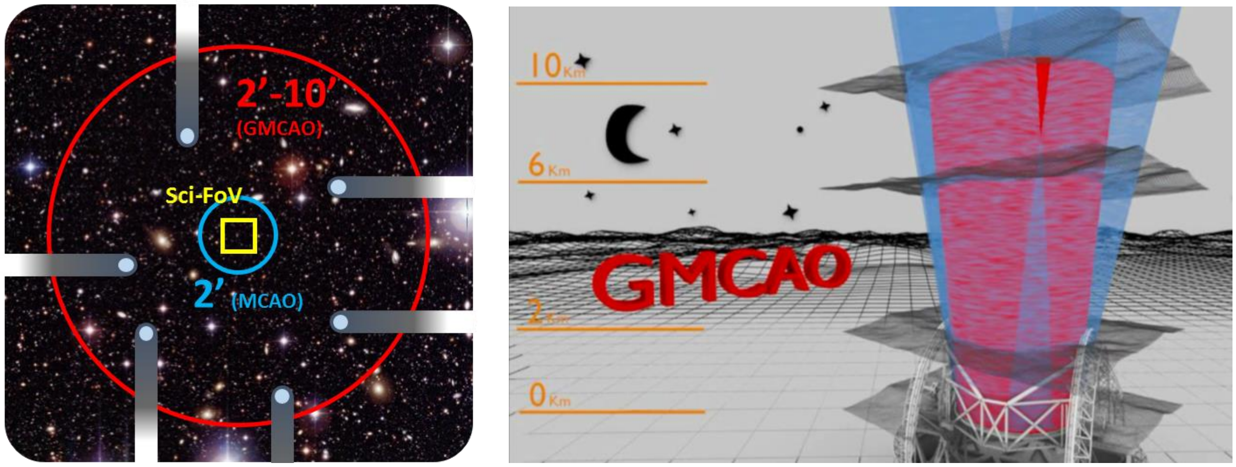

Figure 1 *Left:* GMCAO Technical FoV compared with typical MCAO FoV and with the Scientific FoV to be corrected. *Right:* high pupil projections overlap for a 10' FoV in a 40m-class telescope. In red, the inner 2' FoV, untouched by the GMCAO probes.

2. THE WAVEFRONT SENSING LINEARITY ISSUE

As described in the previous Section, the VL-WFS solves the issue related to the non-linear response of the P-WFS in open loop. It is achieved with the contributions of two WFSs working together: the P-WFS working in a locally closed loop with the DM, to take advantage of the increase in the sensitivity, and a monitoring system directly looking at the shape of the mirror in open loop. For this latter purpose, we always mentioned the YAW WFS[10], but the measurement could in principle either be retrieved with whichever referencing system or with capacitive sensors on the DM itself, and could even be totally avoided, if the DM reliability was proved to be high enough. The residual of the wavefront shape, measured by the pyramid, is then combined with the actual DM shape. It shall be noticed that the pyramid is working in closed loop with a correcting device that can allow for a wavefront correction only up to certain spatial scale, depending on its number of actuators. Because of this, the P-WFS will still measure higher orders aberrations, even in the ideal case in which the modes accessible to the DM itself are *perfectly* corrected.

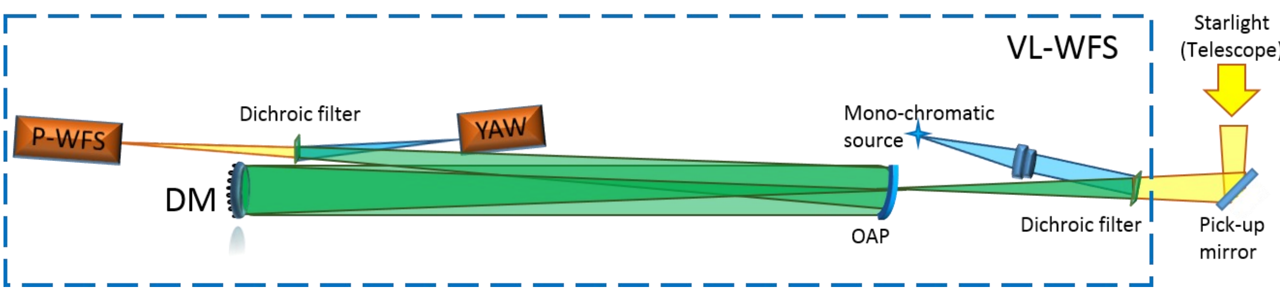

Figure 2 sketch of a possible layout of the VL-WFS.

The VL-WFS will be actually linear (in the context in which the sensor is used) only if it guarantees the proper minimum SR on the vertex of the pyramid. This minimum SR will depend on the linearity error that can be accepted and it is related to the specific application. For the GMCAO, in [7], we developed a full simulation with Fourier wave-optics propagation of a perfect P-WFS, assuming a given input atmospheric model (ESO Paranal 40 layers C_n^2 model, see original paper for details), because the non-linearity error computed for a given mode depends on the absolute input aberration. Finally, we computed the residual global non-linearity error, estimated as the cumulative RMS sum of non-corrected modes, assuming an AO system perfectly correcting the wavefront aberration up to a certain radial order, which we can assume as half the number of actuators on a diameter. As shown in Figure 3, we found that, if 20 radial orders are perfectly corrected, a residual non-linearity wavefront error (WFE) of about 16 nm will affect the measurements, which we considered a reasonable value to be accepted, taking into account the goals of GMCAO. If we could introduce a small modulation term on the pyramid, the residual error would furtherly decrease, but this is not baseline for VL-WFS, since it would increase the system complexity. To correct 20 radial orders of polynomials (we assumed Zernike's orthogonal basis in our simulation), however, about 40 actuators on a pupil diameter will be needed, as a first approximation. Even if we already found solutions which will allow to satisfy it[9], this can be a tight requirement for the selection of the local DM to be implemented inside the VL-WFS.

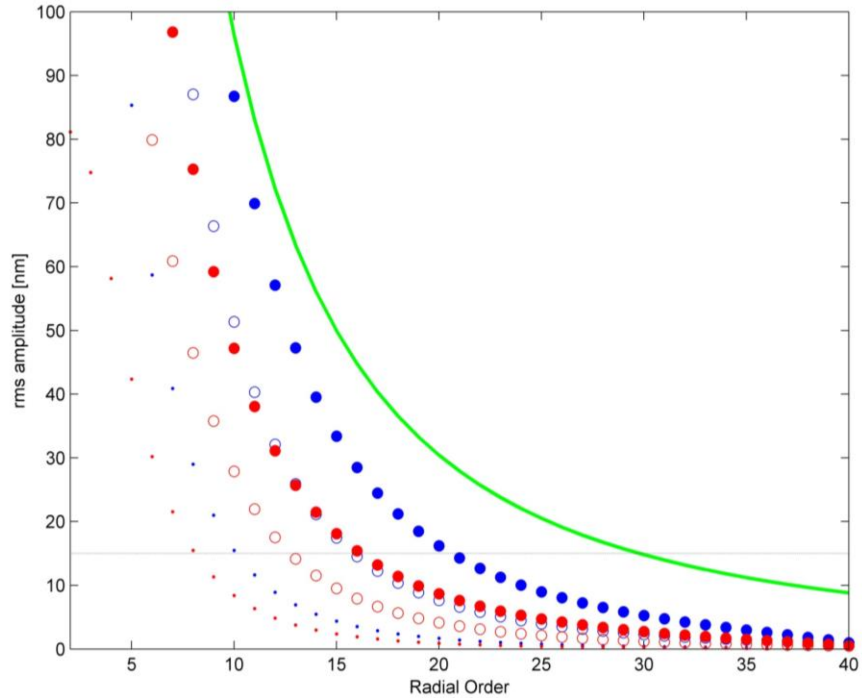

Figure 3 Non-linearity error of an ideal P-WFS, as retrieved in [7] at λ=1.4µm. The *green line* represents a considered amplitude for the incoming atmospheric aberration on a single mode (Von Karman spectrum), while the *dots* show the aberrations for a non-modulated (*blue*) and a $3\lambda/D$ modulation (*red*) cases. The *small dots* report the single mode non linearity error, the *empty circles* represent the overall effect on each radial order and the *filled circles* are the cumulative residual non linearity error, once the lower radial orders are perfectly corrected by the system.

3. A DIFFERENT APPROACH

There are, however, other ways to attack the issue. Another approach could be, in fact, to measure the non-linearity of the WFS on-line. If this can be done, the retrieved non-linearity factor could then be applied as a variable gain to the WFS measurements, in order to compensate for the non-linearity before sending the commands to the DM. This measurement could be performed injecting a known aberration in the loop, using the DM, and then comparing the measured deformation with the input one, so that we are able to retrieve a gain. This approach, if applied to a generic AO system mounted on a telescope, has the limitation that the injected signal shall be small enough to have a negligible effect in the scientific image. In the VL-WFS configuration, however, the injected aberration will never reach the scientific focal plane, being applied inside the VL-WFS locally closed loop. This approach was mentioned in [11], where we were assuming, however, we had to readout the CCD at a double speed and clock it with the aberration at a high time frequency, to avoid measurements deterioration. An analogous technique, with a different and more suitable way to inject the aberrations in the loop, has recently been tested[12] on FLAO[13], the Large Binocular Telescope[14] AO facility. The goal of the mentioned test was to quantify the optical gain to be used to translate the P-WFS into commands for the Adaptive Secondary Mirror[15], to compensate for Non-Common-Path Aberrations (NCPA). In that case, a single mode has been introduced with an amplitude varying sinusoidally with time, but in a way to always be negligible (few nm) with respect to the overall WFE. This is important not to deteriorate the scientific image more than the improvement that the gain characterization can introduce, so that the technique still shows improvements on the final performance.

4. NON-LINEARITY VS. ABERRATION ORDER

An approach similar to what mentioned in the previous Section could allow quantifying the non-linearity of the P-WFS response.

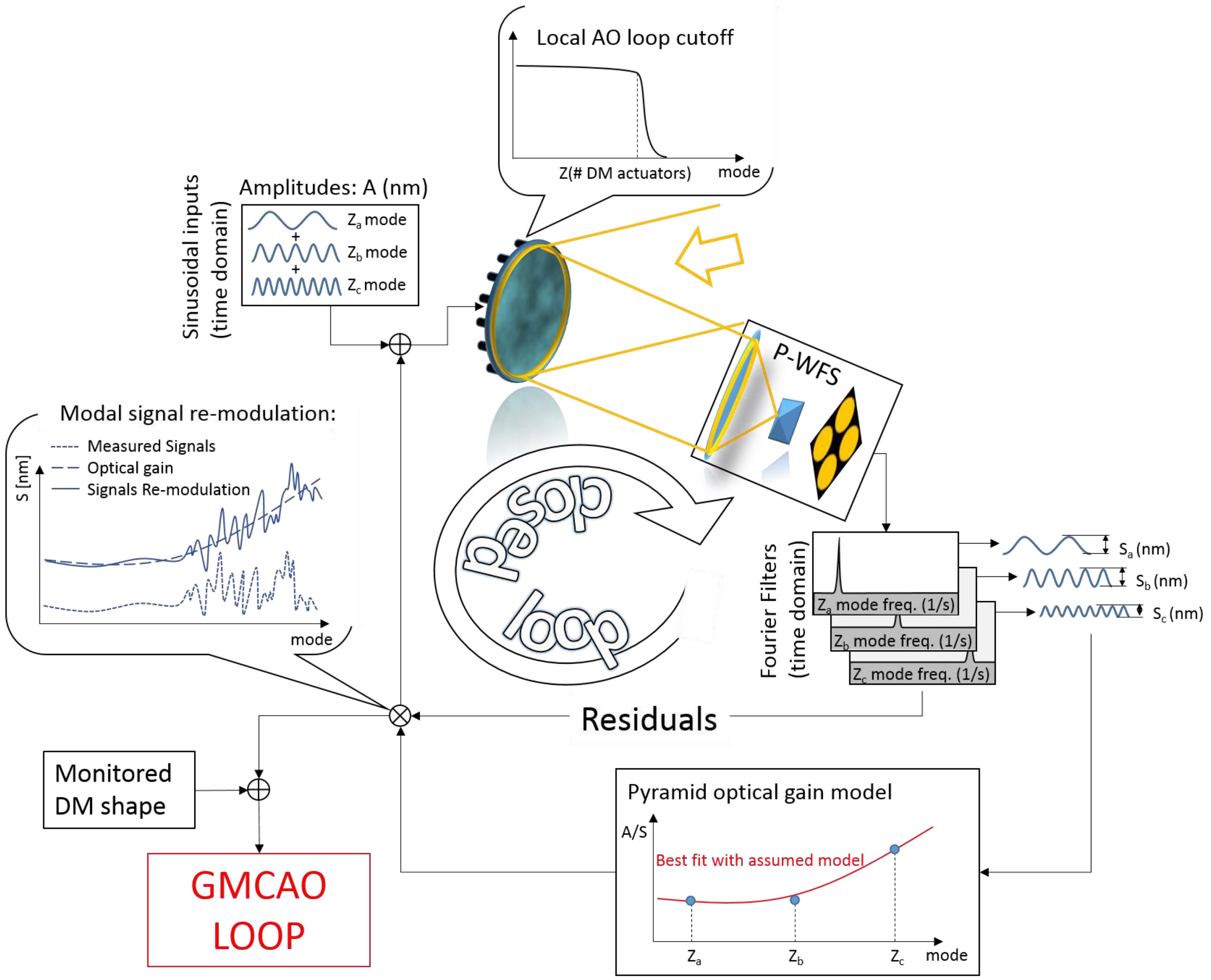

Figure 4 Schematic view of the local loop assuming signal re-modulation with measured optical gain.

Figure 4 shows a schematic view of the concept. The technique is based on the injection in the loop, as modes applied to the local DM, of a certain number of known aberrations, with a sinusoidal amplitude, at a certain frequency (one for each injected mode). The amplitude of the sinusoid shall be small enough not to let the aberration to push the pyramid to the edge of its dynamic range, but, as already mentioned, there are no restrictions related to the quality of the image, since the modes are only injected into the local loop and never degrade the scientific PSF. It has to be taken into account, however, that the non-linearity error of the P-WFS depends also on the amplitude of the injected aberration, as discussed in [7]. This means that either it is possible to scale the P-WFS response with a given amount of aberration to the actual incoming wavefront amplitude, or the injected signal shall have a power comparable with the pure residual aberrations inside the loop. The limited number of actuators in the local DM will act as a cut-off filter for the higher modes, and then of course the selected input modes shall lay in the available spatial frequency domain. Then, the P-WFS measurements will need to be filtered in the Fourier time space, in order to select (and subtract from the residuals) the sinusoidal outputs of the modes used as gauges for the optical gain estimation. The retrieved maximum signals will differ from the input amplitudes for a factor (different for each considered mode), which represents the effect of the non-linear response of the P-WFS to the incoming aberration modes. Once the damping factors are computed, they can be used to best-fit a pyramid optical gain analytical model (whose shape is not yet confirmed at the moment of this writing), which will then be applied to the residuals, measured by the P-WFS, providing a re-modulated modal signal. Then, such signal will be, on one side, re-injected into the closed loop and, at the same time, combined with the actual DM monitored shape, to retrieve the single GMCAO arm measurement, which will then be injected into the global loop. Being the one described above just a concept, it is clear that all the details and implications still need to be further investigated. In fact, some main parameters, as the number of injected modes and optimum amplitudes of the sinusoids, shall be tuned on the shape of the assumed optical gain model. Even if a reasonable analysis has already been performed in the FLAO framework to derive the shape of this model, further analysis still need to be done and confirmed with actual either laboratory or on-sky measurements.

5. WAY FORWARD

All the parameters mentioned above are described in a heuristic way but, of course, they will hold true up to a certain extent and under some assumptions. In particular, an uncertainty will be associated to each step and parameter in the loop presented in the previous Sections. The corresponding errors should be quantified, e.g., in terms of the reliability of the model used in the VL-WFS closed loop in matching the non-linearity term. Furthermore, there will be an additional associated noise because some of the driving parameters will be only estimated to a certain extent. All these contributions will build up an error budget, in which the effects of non-linearity are modelled with a resulting uncertainty that is to be balanced against the other parameters in the design, optimization and operation of the VL-WFS. A preliminary assessment of such an error budget could be obtainable through an end-to-end simulation. On the other hand, the results obtained so far on sky[12] are essentially based on these numerical model, and their validation is obtained just realizing that the overall performance on the instrument focal plane is (significantly) better than without any attempt to model the non-linearity. It is to be recalled that, in the VL-WFS, any injection of a small and known perturbation does not influence at all the scientific image, although it can deteriorate the performance of the P-WFS, for instance in terms of limiting magnitude. On the contrary, in the NCPA compensation such a modulation is directly injected into the final scientific image, so that the improvement that is obtained with the characterization shall be higher than the modulation figure, in order to be effective. In principle, one could use the results obtained with FLAO in order to formulate, or at least to give a crude estimation, of an upper limit to the errors obtainable by the described technique. However, the variables that are not monitored or under control are such that this estimation is likely to be wildly undefined and, after some preliminary attempt, we preferred not to try such a direction. The best approach to validate this, without of course building a full VL-WFS, is just to measure in the actual FLAO system the non-linearity of several modes by explicitly and directly modulating them at different temporal frequencies and with different amplitudes, under controlled conditions. With these measurements, it will be possible to quantify directly the spread of the model used for the non-linearity effect in the various modes. Moreover, this will allow to measure any possible cross term between various modes, as the non-linearity of some modes could be influenced by the injection of other modes, or to define a threshold at which this effect becomes noticeable and requires modelling.

6. CONCLUSIONS

Provided the technique described above turns out to be of some effectiveness, its beneficial effects in GMCAO are twofold. On one hand, the VL-WFS can be technologically simplified, the most obvious argument being the requirement of a smaller number of actuators in the local DM. A further argument has a more fundamental nature because, once the non-linearity can be controlled, the potential need for modulation (with the corresponding deterioration of the limiting magnitude performance of the pyramid) would become less frequent. In order to investigate the feasibility of this approach, it will be necessary to have analytical evidences that there is a fixed pattern in the optical gain as a function of the spatial scale, depending on the input aberration power, in order to be able to assume a reliable the gain model. Once the shape of the model function is known, the optimum number of input test modes to have a good fit can be selected. A detailed analysis of the impact of all the described effects requires the consolidation of the performances of the technique and this is likely to be possible only after some ad-hoc experiment on sky, for validation and assessment of the associated noise contributions.

REFERENCES

[1] Ragazzoni, R., Arcidiacono, C., Dima, M., Farinato, J., Magrin, D. and Viotto V., "Adaptive optics with solely natural guide stars for an extremely large telescope," in Proc. SPIE 7736, 23 (2010).

[2] Ragazzoni, R., Farinato, J., and Marchetti, E., "Adaptive optics for 100-m-class telescopes: new challenges require new solutions," in Proc. SPIE 4007, 1076 (2000).

[3] Beckers, J.M., "Increasing the Size of the Isoplanatic Patch with Multi-Conjugate Adaptive Optics," ESO Conference and Workshop Proceedings 30, 693 (1988).

[4] Viotto, V., Bergomi, M., Portaluri, E., Dima, M., Farinato, J., Greggio, D., Magrin, D., and Ragazzoni, R., "GMCAO for E-ELT: a feasibility study," Proc. Fourth AO4ELT Conf., (2015).

[5] Ragazzoni, R., "Pupil plane wavefront sensing with an oscillating prism," Journal of Modern Optics 43, 289 (1996).

[6] Ragazzoni, R., and Farinato, J., "Sensitivity of a pyramidic Wave Front Sensor in closed loop Adaptive Optics," A&A 350, L23 (1999)

[7] Viotto, V., Magrin, D., Bergomi, M., Dima, M., Farinato, J., Marafatto, L. and Ragazzoni, R., "A study of Pyramid WFS behavior under imperfect illumination," Proc. Third AO4ELT Conf., 38 (2013).

[8] Shack, R.V., "Production and use of a lenticular Hartmann screen," Journal of the Optical Society of America (Oral presentation) 61, 656 (1971).

[9] Greggio, D., Magrin, D., Farinato, J., Ragazzoni, R., Bergomi, M., Dima, M., Marafatto, L., and Viotto, V., "Avoiding to trade sensitivity for linearity in a real world WFS," Proc. Third AO4ELT Conf., 36 (2013).

[10] Gendron, E., Brangier, M., Chenegros, G., Vidal, F., Hubert, Z., Rousset, G., and Pouplard, F., "A new sensor for laser tomography on ELTs," Proc. First AO4ELT Conf., 5003 (2010).

[11] Ragazzoni, R., Bergomi, M., Brunelli, A., Dima, M., Farinato, J., Magrin, D., Marafatto, L., and Viotto, V., "Global wavefront sensing for extremely large telescopes," Proc. SPIE 8447, 2I (2012).

[12] Esposito, S., Puglisi, A., Pinna, E., Agapito, G., Veran, J.P., and Herriot, G., "Non common path aberration correction with nonlinear WFSs," Proc. Fourth AO4ELT Conf., (2015).

[13] Esposito, S., Riccardi, A., Pinna, E., Puglisi, A., Quirós-Pacheco, F., Arcidiacono, C., Xompero, M., Briguglio, R., Agapito, G., Busoni, L., Fini, L., Argomedo, J., Gherardi, A., Brusa, G., Miller, D., Guerra, J. C., Stefanini, P., and Salinari, P. "Large Binocular Telescope Adaptive Optics System: new achievements and perspectives in adaptive optics," Proc. SPIE 8149, 2 (2011).

[14] Hill, J., and Salinari, P., "Large Binocular Telescope project," in Proc. SPIE 4004, 36 (2000).

[15] Riccardi, A. Xompero, M., Briguglio, R., Quirós-Pacheco, F., Busoni, L., Fini, L., Puglisi, A., Esposito, S., Arcidiacono, C., Pinna, E., Ranfagni, P., Salinari, P., Brusa, G., Demers, R., Biasi, R., and Gallieni, D., "The adaptive secondary mirror for the Large Binocular Telescope: optical acceptance test and preliminary on-sky commissioning results," Proc. SPIE 7736, 79 (2010).