Large field-of-view configurations for large-telescope adaptive optics systems:advantages and tradeoffs

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ABSTRACT

In order to achieve high sky coverage with natural guide star adaptive optics systems, the reference stars need to be chosen over a large field of view. But the size of the optical beam can become unmanageably large in current and planned future giant telescopes. This can render the optics unaffordable. To solve this issue, we have adopted two approaches - multiple fields of view and star-enlargers - for the LINC-NIRVANA layer-oriented, multiple-conjugated adaptive optics system. In this paper, we compare and contrast the advantages and disadvantages of various optical configurations for wide-field, natural guide star acquisition on current 8-meter and future 25-40 meter extremely large telescopes.

Keywords: large field of view, large telescope, adaptive optics, sky coverage, optical configuration, LINC-NIRVANA

1. INTRODUCTION

To reach diffraction-limited imaging performance with large ground-based telescopes, adaptive optics (AO) systems, which remove the atmospheric turbulence, are mandatory. In current traditional AO systems, only one guide star (GS) is used to sense the turbulence, and the corresponding turbulence is corrected via a deformable mirror (DM). Since the GS needs to be bright enough to provide a certain level of signal to noise ratio for the AO system, only a small fraction of sky can be covered in the traditional single GS AO systems.

To achieve large sky coverage, multiple GSs AO systems, which select multiple NGSs in a large field of view (FoV), are being developed, examples include, the multi-conjugate adaptive optics (MCAO) [1] systems, ground layer adaptive optics (GLAO) [11] and multiple-object adaptive optics (MOAO) [5].

But the size of the optical beam increases with the FoV and the size of the telescope. In current and planned future giant telescopes, the size can become unmanageably large and the cost of optics becomes unaffordable. For instance, in the Nasmyth focus (F/17.7) of the European Extremely Large Telescope (E-ELT) [4], 1 arcsecond on sky corresponds to 3.6 mm in the focal plane, so the 6 arcminute FoV corresponds to almost 1.3 meters. The Large Binocular Telescopes faces a similar problem, and to solve this issue, we apply two approaches – multiple fields of view [9] and star-enlargers [10].

Section 2 of this paper describes the multiple-field-of-view and star-enlarger design for the LINC-NIRVANA system. The various optical configurations with multiple natural guide stars on current 8-meter and future 25-40 meter extremely large telescopes, together with the advantages and disadvantages of various optical configurations, appear in section 3. Section 4 gives the conclusions.

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2. TWO APPROACHES IN LINC-NIRVANA

LINC-NIRVANA [7], a Fizeau interferometer imager on the Large Binocular Telescope (LBT), employs a two-layer (ground-layer and high-layer) multiple-conjugated adaptive optics system to achieve 10 mas resolution. For the ground layer, up to 12 GSs in a 2-6 arcminute FoV can be used to sense the turbulence and correct it via the adaptive secondary mirror; for the high layer, up to 8 GSs can be used to sense the aberrations and remove them via a Xinetics-349 DM. Following the MCAO correction, the piston error is removed by a delay line. A schematic of LINC-NIRVANA appears in figure 1.
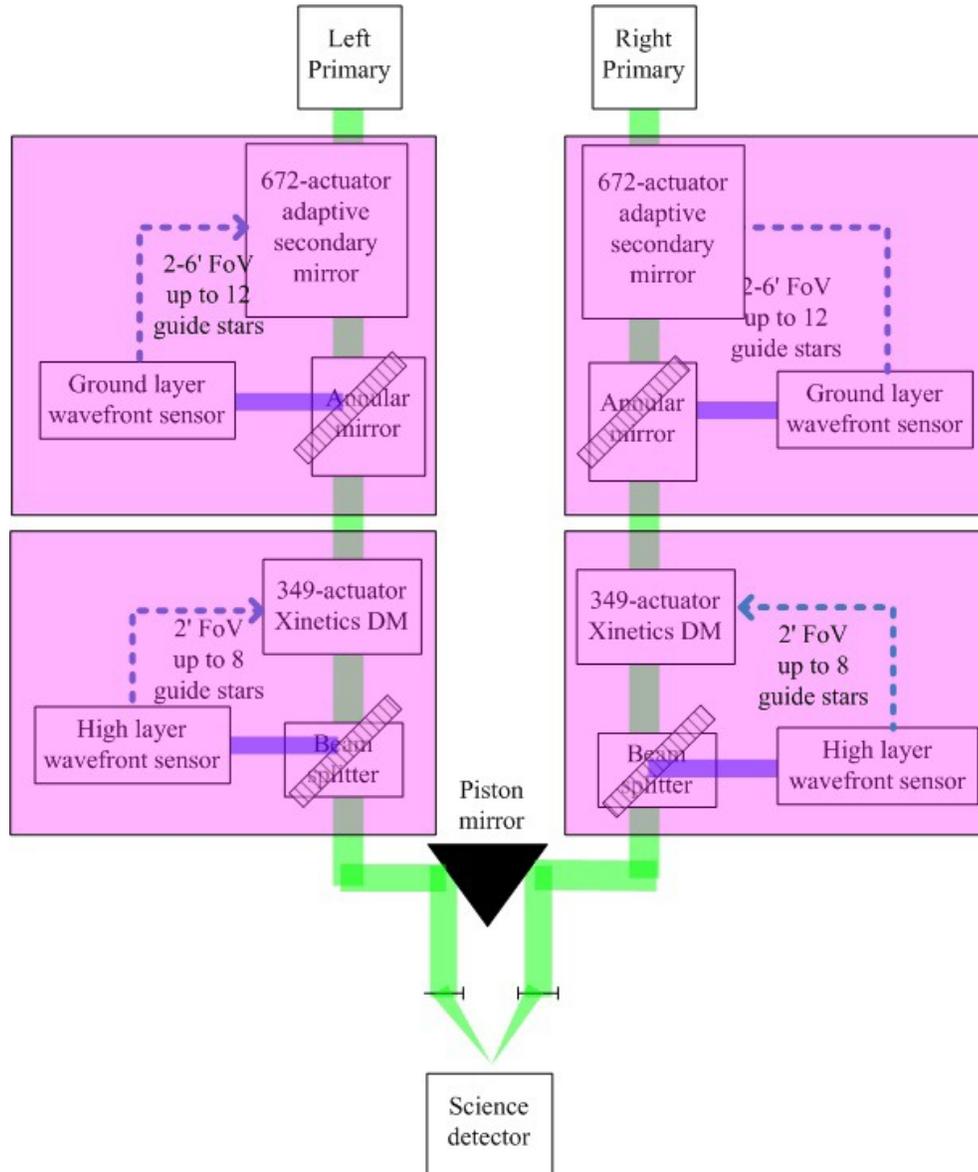

Figure 1. Schematic of LINC-NIRVANA system[12].

2.1 Multiple field of view

As seen in figure 1, an annular mirror provides different FoVs to the ground and high layer wavefront sensors. This approval concept, in which different fields of view are used for different layers, is called the multiple fields of view [9].

In this way, splitting of the light between detectors is avoided, so fainter stars can be used as GSs, and the sky coverage can be increased.

2.2 Star-enlarger

To match the optical path with the WFS CCD, a suitable size of the f/ratio is required. The LINC-NIRVANA requires a f/ratio of 225, but this would correspond to more than three meters for a 6 arcminute FoV. This means the cost of optics becomes unacceptable. To solve this issue, locally changing the f/ratio for the GSs is introduced, i.e., the star-enlarger [10], as shown in figure 2.
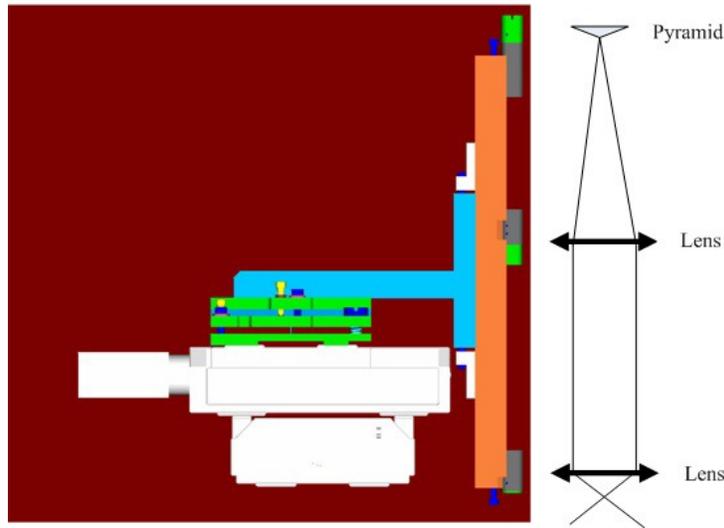

Figure 2. The opto-mechanical design of the star-enlarger. The star-enlarger contains two lenses and one pyramid; The mechanics and motors are used to hold and position the star-enlarger.

3. OPTICAL CONFIGURATIONS

In this section, we examine these two approaches - multiple fields of view and star-enlargers - to solve the large optics size issue for the multiple GSs systems in giant telescopes with a wide FoV. As in LINC-NIRVANA's MCAO system, a lens is placed in a correct position to form a suitable collimated beam size, then a mirror is used to fold the beam to the wavefront sensor. As seen in figure 3, in the Shack-Hartmann wavefront sensor case, each collimated beam is folded to the lenslet; in the pyramid wavefront sensor case, an additional lens is needed to form a suitable f/ratio and form a desirable PSF size. With the fold mirror, the heavy and large size wavefront sensor can be fixed. So the mechanical requirements on the wavefront sensor, especially the long distance and accurate motors for positioning, are extremely decreased. Note that a rotating stage is needed for positioning and folding the mirror to put the light of GS in the wavefront sensor. This introduces additional complexity in the system.
The corresponding optical configurations of multiple GSs (MCAO, MOAO and GLAO) systems with the concepts of multiple fields of view and star-enlarger appear in below.

3.1 Multi-conjugate adaptive optics

MCAO systems use multiple GSs to reconstruct the three-dimensional atmospheric turbulence, and to remove the corresponding turbulence via several DMs. Then the high sky coverage and uniform AO correction in a large FoV are achieved [8, 13]. MCAO systems have several possible configurations. Here, we give the optical configurations of the star-oriented (SO) [2] and layer-oriented (LO) [8] approaches (see descriptions below), which are popularly implemented in current MCAO systems.
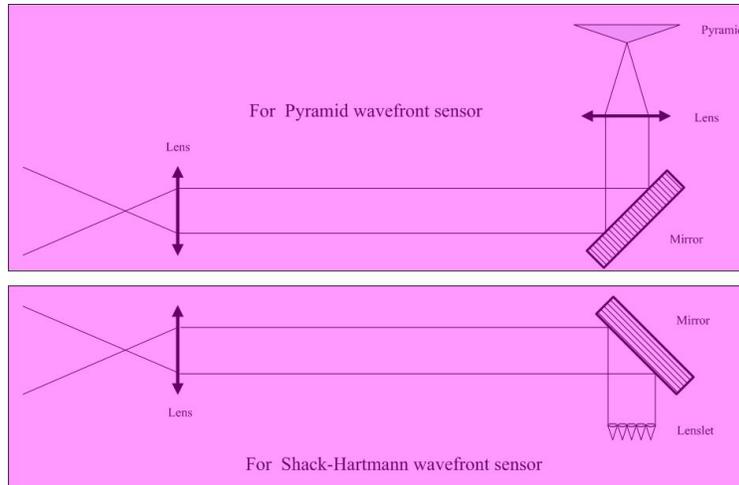
Figure 3. Optical design of star-enlarger with a fold mirror used for the Shack-Hartmann (upper image) and pyramid (lower image) wavefront sensor.

3.1.1 Star-oriented multi-conjugate adaptive optics

In the SO approach, each GS is detected by its sensor. With the multiple FoVs concept, the optical configuration of the SO approach in large FoV appears in figure 4. Thanks to the fold mirror in the star-enlarger, the SO approach can also be achieved with a single detector CCD, as shown in figure 5. The single CCD configuration can reduce the complexity in the mechanical, control and electronic systems. The disadvantage of a single CCD configuration is that the limited CCD size leads to a limited number of GSs which can be used.
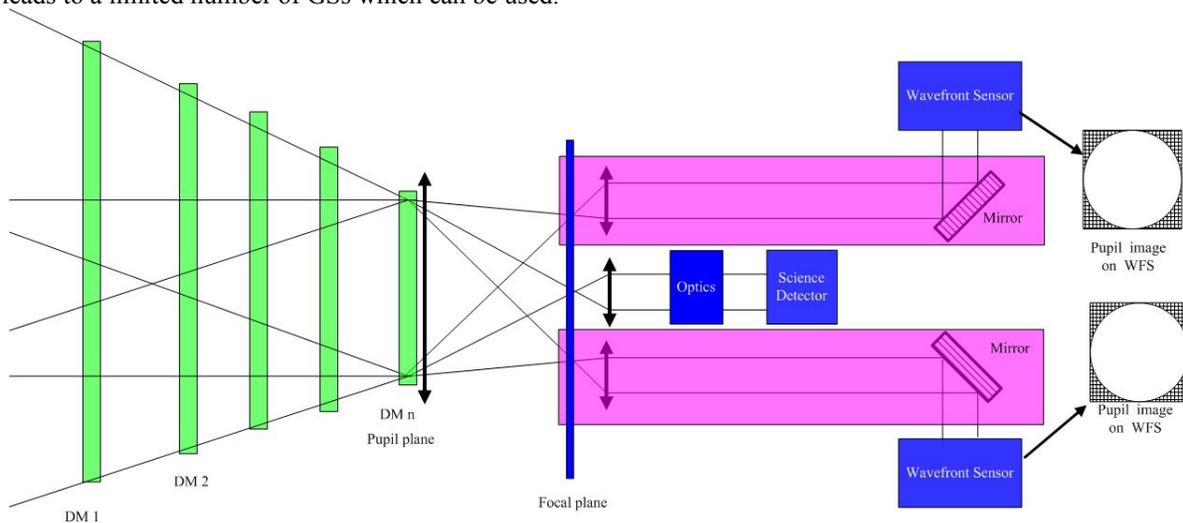

Figure 4. Optical configuration of star-oriented multiple-conjugate adaptive optics with multiple CCDs. Each guide star is required in the focal plane and folded to its corresponding wavefront sensor CCD. Note that the images on the wavefront sensor are for the Shack-Hartmann wavefront sensor; with the pyramid wavefront senor, each circle contains four small circles.

As seen in figures 4 and 5, the science target cannot be selected as the GS. This issue can be solved by introducing a beam splitter (see figure 6). The disadvantages of this configuration are that the light is split and the system is more complex.

3.1.2 Layer-oriented multi-conjugate adaptive optics

In the LO approach, the detectors are conjugated to suitable atmosphere altitudes, and multiple GSs are used at each altitude. Then the different layer atmospheric turbulence is removed via its corresponding conjugated DM. The optical configuration with concepts of multiple FoVs and star-enlarger is shown in figure 7.
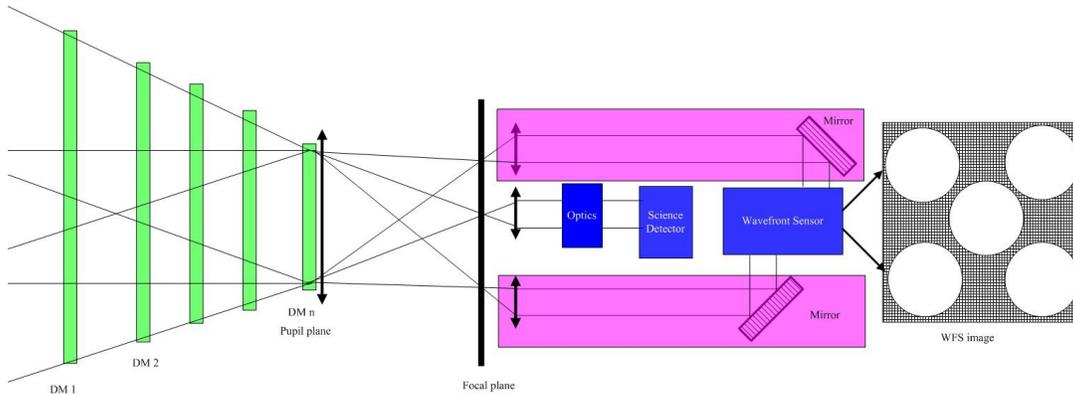
Figure 5. Optical configuration of star-oriented multiple-conjugate adaptive optics with a single CCD. Each guide star is required in the focal plane and folded to the same wavefront sensor CCD.
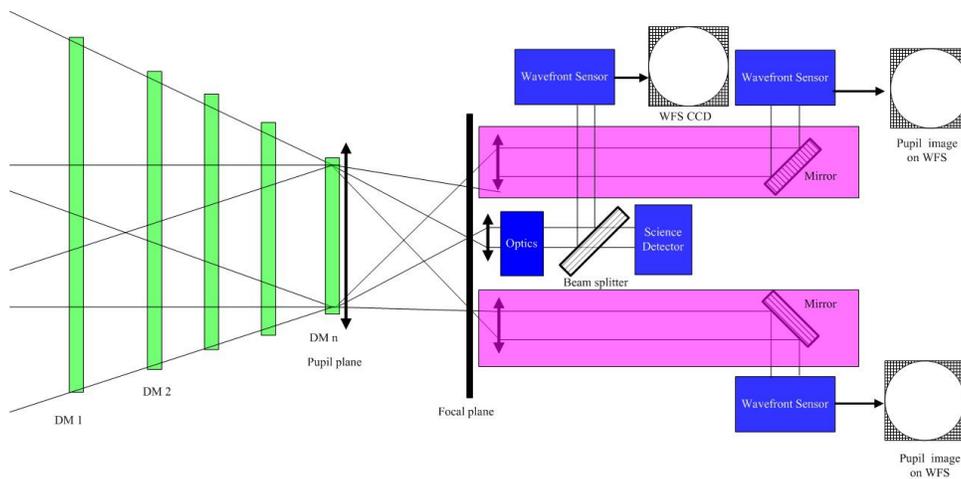

Figure 6. Optical configuration of star-oriented multiple-conjugate adaptive optics including the FoV of science targets, each guide star with its CCD.
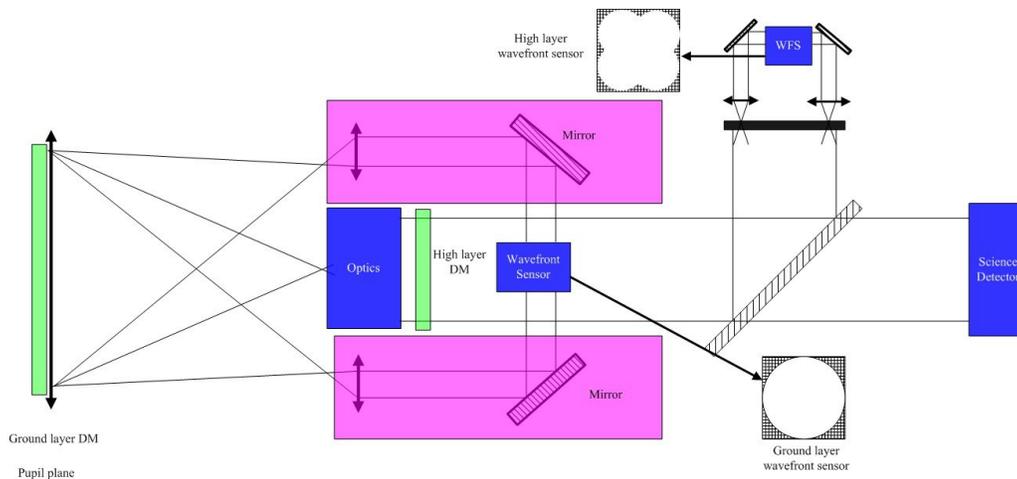

Figure 7. Optical configuration of layer-oriented multiple-conjugate adaptive optics. On the ground layer, the multiple GSs are well overlapped; while on the high layer wavefront sensor, the multiple GSs are partial overlapped. Note that with the exception of the fold mirror in the star-enlarges, the optical configuration of LINC-NIRVANA system is the same as shown in the figure.

3.2 Multiple-object adaptive optics

The MOAO systems employ multiple GSs in a large FoV to retrieve the atmospheric disturbances in small distributed FoV. And the atmosphere aberration in small FoV is removed via a small DM. The optical configurations of MOAO systems are similar to the SO-MCAO systems. For clarity, only the optical configuration of MOAO system including the FoV of science targets is shown here (see figure 8).
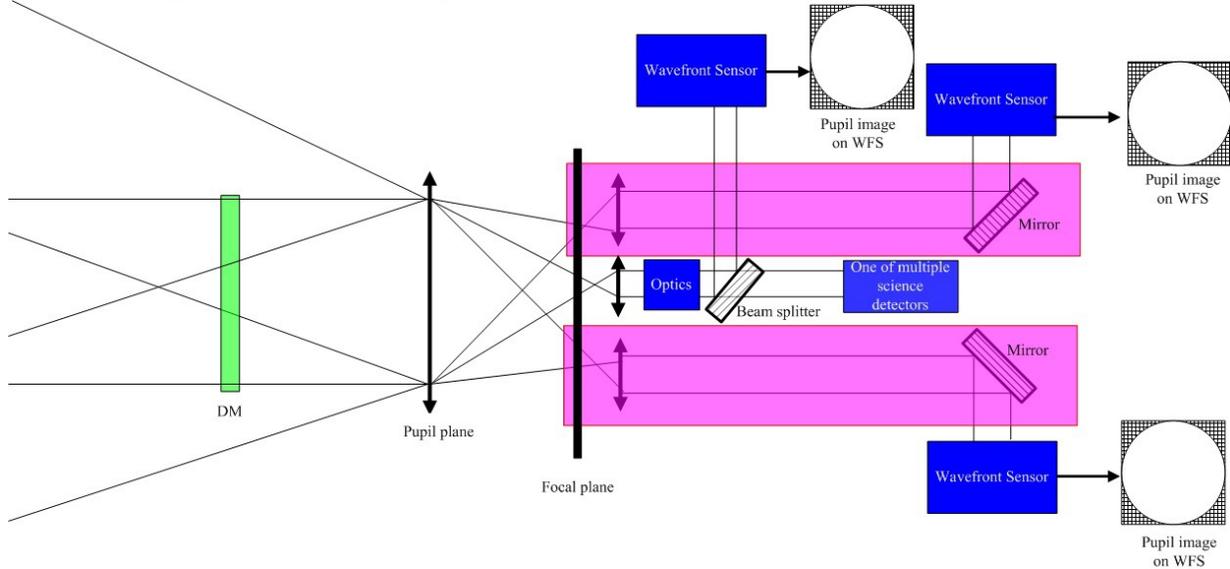

Figure 8. Optical configuration of multiple-object adaptive optics system including the FoV of science targets.

The MCAO systems remove the three-dimensional atmospheric turbulence in a large FoV via multiple large DMs, and AO correction is achieved in a large FoV. With a lower cost, the MOAO systems only remove the atmospheric turbulence in a small FoV via a small DM, so the AO correction can be achieved only in the small FoV.

3.3 Ground layer adaptive optics

As is well known, the turbulence in the ground layer (including mirror and dome seeing) contributes most of the total atmospheric turbulence [3]. If the ground layer turbulence is removed, the system can achieve a significant uniform correction in a large FoV [6]. This is the concept of GLAO.

Since the non-ground layer atmospheric turbulence still remains in the system, diffraction-limited imaging cannot be reached by the GLAO. The advantage of GLAO systems is that it provides acceptable image quality, particularly for spectroscopy, and high sky coverage with a low cost. The optical configuration of a GLAO system (as shown in figure 9) can be considered as the simple ground layer version of the LO-MCAO system.
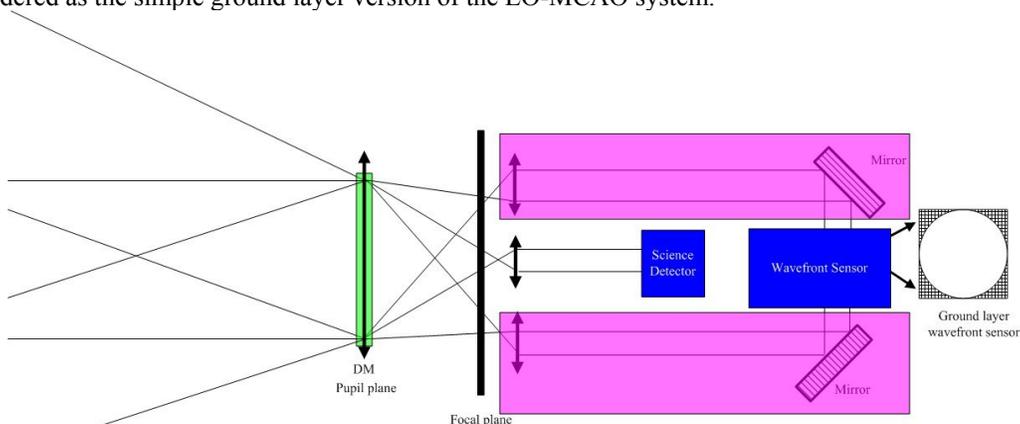

Figure 9. Optical configuration of ground layer adaptive optics system.

4. CONCLUSIONS

On one side, the size of the optical beam increases with the FoV, f/ratio and the size of telescope. As a consequence, the optics can become unaffordable large on current 8-meter and future 25-40 meter extremely large telescopes with large FoV. On the other side, to realize high sky coverage for AO systems, acquiring several GSs in the large FoV is compulsory. We give a possible solution for this issue in this paper.

We apply the multiple fields of view and star-enlarger approaches from the LINC-NIRVANA system to other extremely large telescope multiple GSs systems. The corresponding optical configurations of MCAO, MOAO and GLAO are given as examples. The advantages and disadvantages of various optical configurations are compared as well. Hopefully, this paper can give some ideas for achieving the wide field AO on the extremely large telescope systems.

ACKNOWLEDGMENTS

REFERENCES

1   Beckers, J. M., "Increasing the size of the isoplanatic patch with multiconjugate adaptive optics," *Very Large Telescopes and their Instrumentation*, 2, 693-703 (1988).
2   Diolaiti, E., Ragazzoni, R. and Tordi, M., "Closed loop performance of a layer-oriented multi-conjugate adaptive optics system," *Astronomy & Astrophysics*, 372, 710-718 (2001).
3   Egner, S. E., Masciadri, E. and McKenna, D., "Generalized SCIDAR Measurements at Mount Graham," *Publications of the Astronomical Society of the Pacific*, 119, 669-686 (2007).
4   ESO, "The European Extremely Large Telescope," *http://www.eso.org/public/teles-instr/e-elt.html* (2012)
5   Hammer, F., Sayède, F., Gendron, E., Fusco, T., Burgarella, D., Cayatte, V., Conan, J.-M., Courbin, F., Flores, H., Guinouard, I., Jocou, L., Lançon, A., Monnet, G., Mouhcine, M., Rigaud, F., Rouan, D., Rousset, G., Buat, V. and Zamkotsian, F., "The FALCON Concept: Multi-Object Spectroscopy Combined with MCAO in Near-IR," *Scientific Drivers for ESO Future VLT/VLTI Instrumentation*, 139-148 (2002).
6   Hart, M., Milton, N. M., Baranec, C., Powell, K., Stalcup, T., McCarthy, D., Kulesa, C. and Bendek, E., "A ground-layer adaptive optics system with multiple laser guide stars," *Nature*, 466, 727-729 (2010).
7   Herbst, T., "Interferometry with the Large Binocular Telescope," *Astrophysics and Space Science*, 286, 45-53 (2003).
8   Marchetti, E., Brast, R., Delabre, B., Donaldson, R., Fedrigo, E., Frank, C., Hubin, N., Kolb, J., Lizon, J.-L., Marchesi, M., Oberti, S., Reiss, R., Santos, J., Soenke, C., Tordo, S., Baruffolo, A., Bagnara, P. and The CAMCAO Consortium, "On-sky Testing of the Multi-Conjugate Adaptive Optics Demonstrator," *The Messenger*, 129, 8-13 (2007).
9   Ragazzoni, R., Diolaiti, E., Farinato, J., Fedrigo, E., Marchetti, E., Tordi, M. and Kirkman, D., "Multiple field of view layer-oriented adaptive optics," *Astronomy & Astrophysics*, 396, 731-744 (2002).
10   Ragazzoni, R., Diolaiti, E., Vernet, E., Farinato, J., Marchetti, E. and Arcidiacono, C., "Arbitrarily Small Pupils in Layer-Oriented Multi-Conjugate Adaptive Optics," *Publications of the Astronomical Society of the Pacific*, 117, 860-869 (2005).
11   Tokovinin, A., "Seeing Improvement with Ground-Layer Adaptive Optics," *Publications of the Astronomical Society of the Pacific*, 116:941-951 (2004).
12   Xianyu Zhang, Carmelo Arcidiacono, Albert R. Conrad, Thomas M. Herbst, Wolfgang Gaessler, Thomas Bertram, Roberto Ragazzoni, Laura Schreiber, Emiliano Diolaiti, Martin Kuerster, Peter Bizenberger, Daniel Meschke, Hans-Walter Rix, Changhui Rao, Lars Mohr, Florian Briegel, Frank Kittmann, Juergen Berwein, and Jan Trowitzsch, "Calibrating the interaction matrix with LINC-NIRVANA high layer wavefront sensor," *Opt. Express*, 20(7), 8078-8092 (2012).
13   Xianyu Zhang, Wolfgang Gaessler, Albert R. Conrad, Thomas Bertram, Carmelo Arcidiacono, Thomas M. Herbst, Martin Kuerster, Peter Bizenberger, Daniel Meschke, Hans-Walter Rix, Changhui Rao, Lars Mohr, Florian Briegel, Frank Kittmann, Juergen Berwein, Jan Trowitzsch, Laura Schreiber, Roberto Ragazzoni, and Emiliano Diolaiti, "First laboratory results with the LINC-NIRVANA high layer wavefront sensor," *Opt. Express*, 19(17), 16087-16095 (2011).