Performance of a NGS-based MCAO demonstrator: the NGC3366 and NGC2346 simulations

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Beyond Conventional Adaptive Optics

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ABSTRACT

Multi–conjugate adaptive optics [MCAO] is announced as the next generation of adaptive optics systems [AOS]. MCAO will be almost mandatory for extremely large telescopes [ELTs] because it permits to compensate the corrugation of the phase of the wave front on a larger field–of–view than can be done with classical AOS.
The knowledge of the performance that can be expected from MCAO on the 8–10 m class telescopes using natural guide stars [NGSs] is important since it is related to the sky coverage of NGS MCAO on this kind of telescopes.
We give here the expected performance of an MCAO systeme on 8–10 m telescopes from the point of view of imagery and spectroscopy over two real extended objects, NGC3366 and NGC2346. The performance is evaluated with the calculation of the Strehl ratio [SR], the full-width-half-maximum [FWHM] and diameter that encircles the 50% of the energy. These quantities are computed using a measured C_n^2 profile and for asterisms of natural guide stars.

1. INTRODUCTION

Classical adaptive optics systems are now working on a large number of ground based telescopes. These systems provide corrected images in a field of view that does not exceed the size of the isoplanatic patch. This is sufficient for a large number of scientific programs, but there are others that would benefit from having wide field near diffraction limited images. We have identified the HII regions in galaxies and the shock boundaries in planetary nebula as regions that would benefit from wide field corrected images. The study of the images could provide information for the analysis of the morphology of the source as well as the history of the object. On the other hand, in spectroscopy, the study of emission lines provides a useful tool for many aspects of the study of the object. The dynamical behaviour of the source can be studied from the shape and width of the emission lines, while their intensity provide information about the temperature and chemical composition. MCAO systems employ several guide stars allowing a tomographic measurement of the volume of turbulence and attempt to correct this volume using a number of deformable mirrors [DM] conjugated at different altitude layers. This technique permits to extend the corrected field of view, allowing to obtain high spatial resolution images and spectra of extended objects.

After the current generation of 8–10 m class telescopes, there are plans to built a new generation of ground based telescopes with diameters that range from 30 to 100 m. Moreover, these systems will be equiped with multi-conjugated adaptive optics systems in order order to obtain a good correction in a large field of view. In the classical adaptive optics systems the problem of sky coverage posed by the use of NGSs can be overcome employing artificially created laser guide stars [LGS]. This is the case also of the proposed MCAO system for the Gemini telescope (Rigaut, 2001) which will employ an asterism of 5 LGSs. The necessity of employing LGS

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for the MCAO systems for the ELTs is still an open question as the sky coverage for these systems should be larger than for classical AOS (Raggazzoni, 2000).

A MCAO demonstrator system has been proposed in the framework of the Research and Training Network on "Adaptive Optics for the Extremely Large Telescopes" funded by the European Community. It will be developed for the VLT telescopes as a prototype of the future MCAO systems for the ELTs (Hubin et al., 2001) . This prototype will work with NGSs. Marchetti et al. (2001) have selected stars in the USNO A2 catalogue to get asterisms of three stars with adequate geometry and magnitude for MCAO purpose. Some of these asterisms contain, within the field of view, interesting objects from an astronomical point of view. We have selected two of these objects to provide an example of the performance that such a system could achieve both in H and K bands. The performance is given in terms of Strehl ratio, full width at half maximum, and diameter that encircles the 50% of the energy. The performance of a classical AOS using one star among those in the field is also given for comparison.

2. MCAO PRINCIPLE AND SIMULATIONS

The turbulence profile at Cerro Pachon was adopted as C_n^2 profile. It has been modeled with 7 turbulent layers and an outer scale of 25 m. The phase screens on each layer were generated from the theoretical Komogorov power spectral power density by the Fast Fourier Transform method. The diameter is 8 m and the overall D/r_0 is 9 in the K band, corresponding to 0.7 arcsec seeing. The phase measurements are made on 3 NGSs surrounding the object of interest (Figure 1 (b) and Figure 5 (b)) The noise on these measurements corresponds to that of a 9x9 sub-aperture Shack-Hartmann wavefront sensor (one per star) with a 250 Hz sampling frequency and a $3e^-$ read–out noise detector with a quantum efficiency of 50%, leading to various signal to noise ratio depending on the guide star magnitudes.

Two DMs conjugated at 0 and 10 km are employed. The phase is reconstructed on each DM using a 66 Zernike polynomial decomposition. Temporal issues are not modeled, hence each frame corresponds to an open loop measurement, and the final results are obtained with the average of one hundred frames.

The phase on the deformable mirror is reconstructed optimally. This means that we minimize the mean residual variance in the FOV of interest, obtaining the best image quality in the field of view. This reconstructor is shown to be equivalent to a two step reconstruction (Conan et al., 2001, Fusco et al.,2001): first a reconstruction of the turbulent volume over each of the turbulent layers, and second a projection of this solution onto the space of modes of the deformable mirrors employed to correct the turbulence volume.

Two different codes were employed to perform the simulations. One of them has been developed by T. Fusco (2000). It is a Monte Carlo simulation modeling the guide stars geometry, the wavefront sensor noise, the turbulent profile and the corrections applied by the deformable mirrors. The other one has been developed by A. Tokovinin, M. Le Louarn ,E. Viard and R. Conan (Tokovinin et al., 2001). It is an anlytical simulation which permits to compute the optimized command matrix knowing the same parameters as those used in the Monte Carlo simulation. The optimization is performed in order to minimize the variance of the residual phase fluctuation along particular directions within the field of view depending of the morphology of the scientific target. These two codes were previously cross–checked to verify the good agreement between both.

The first code was employed to simulate the performance obtained over the first object: NGC3366, while the other code was employed for the second object: NGC2346.

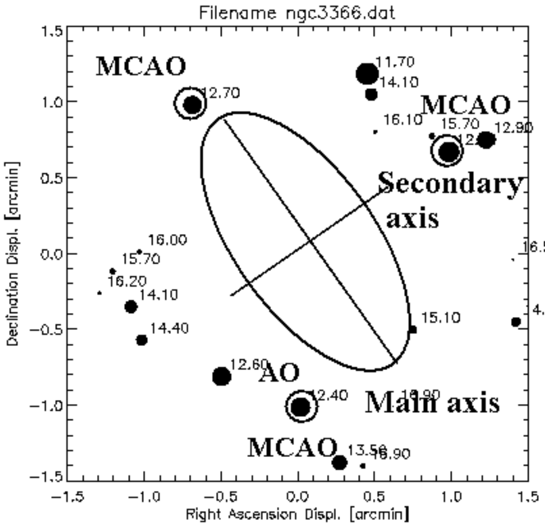
λ	λ/D [mas]
1.65μm (H)	42.54
2.20μm (K)	56.72

Table 1. λ/D values for H and K bands.

3. NGC3366 SIMULATION

Figure 1 (a) shows the image of NGC3366, a spiral galaxy in the southern hemisphere, taken from the Digital Sky Survey (DSS2 red band) of ESO/ST-ECF archive. The ellipse in figure 1 (b) represents the object which is in this case the field of view of interest. The figure shows also the field of stars surrounding the object and the asterism of NGS (labeled MCAO)) we have selected to test the performance of the system over the real

(a) Photograph of the galaxy NGC3366.



(b) Stars surrounding the galaxy NGC3366. The position of the galaxy is drawn in the center of the figure as an ellipse. The NGSs for AO and MCAO are surrounded with a circle. The two axis were the performance of the system is given are also drawn.

Figure 1.

object. The star magnitudes are 12.70, 12.20, and 12.40. The 12.40 magnitude star (labeled AO) is selected to estimate the performance in classical AO for comparison. The different parameters will be given along the main and secondary axis of the galaxy, from the bottom to the top for the main axis and from left to right for the secondary axis. The size of the main axis is 120 arcsec, while the secondary axis is 50 arcsec long.

Figure 2 shows the Strehl ratio of the MCAO system (continuous line) and of the AO system (dashed line) in both H and K bands and on the main and secondary axis respectively. The Strehl ratio varies between 20% and 30% in K band and between 10% and 20% in H band for MCAO. In AO the Strehl ratio varies from 0.8% to 13% in K band and from 0.05% to 3% in H band.

When considering spectroscopy it is however more adequate to give the performance of the system in terms of point spread function [PSF] characteristics such as the FWHM and the diameter that encircles a certain amount of the energy. We have chosen the 50% of the energy in this case. The results are shown in figure 3 and figure 4, in units of λ/D. The corresponding values of λ/D for the H and K band are given in table 1. Continuous lines correspond to the MCAO case while dashed lines correspond to the classical AO case. The difference between the two cases is important for the two bands, but more significant for the H band, where the PSF core quickly spreads out when we move away from the GS.

4. NGC2346 SIMULATION

The planetary nebula NGC2346 (Fig. 5 (a)) has been chosen due to the number of NGSs (Fig. 5 (b)) in its neighborhood with the adequate magnitude, distance to and position around the scientific target.

The MCAO simulation is performed in order to obtain the best and the most uniform performance on the two axis drawn in Fig. 5 (b). The asterism formed with the three NGSs labeled MCAO provides the reference stars for this simulation, magnitudes 14.00, 14.50 and 14.80. The performance is compared to that of a classical AO system using a unique NGS labeled AO on Fig. 5 (b) and of magnitude 13.30. The performance, given in terms of SR, FWHM and diameter that encircles the 50% of the energy will be given along this two axis browsing them for the top to the bottom for the main axis and from the right to the left for the secondary axis.

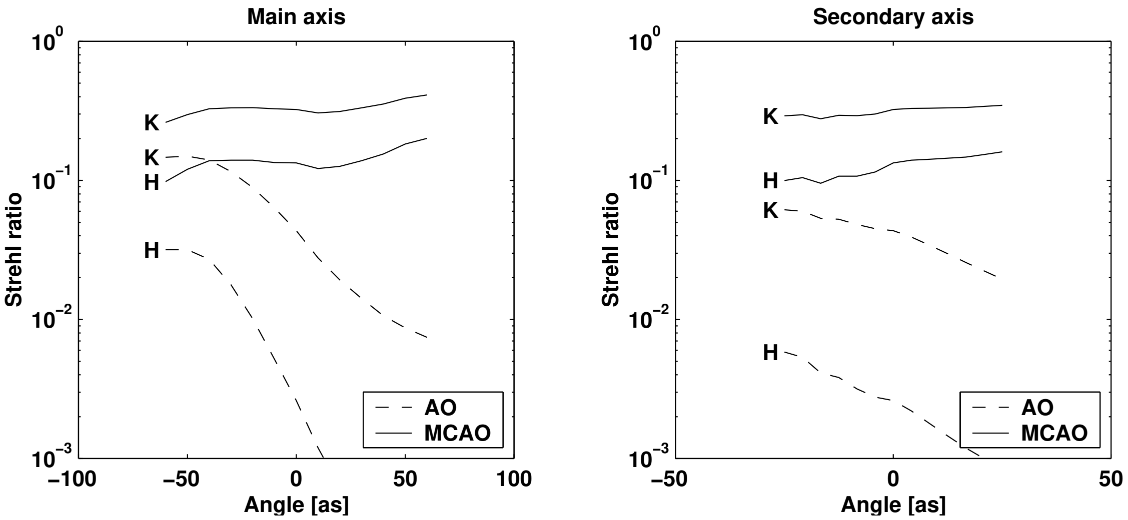


Figure 2. Strehl ratio for the main and the secondary axis of NGC3366. Dashed lines show AO performance and full lines MCAO results.

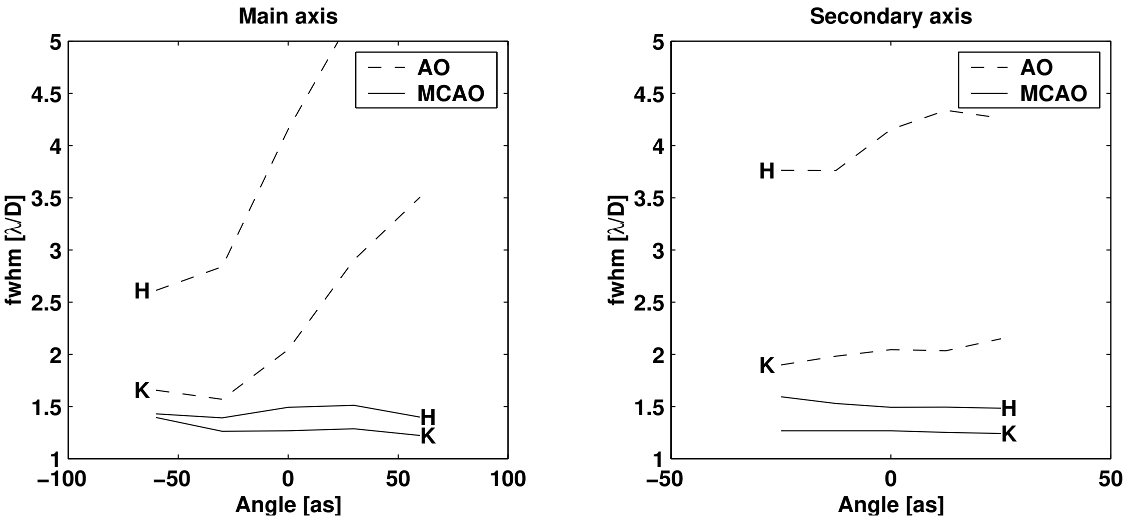


Figure 3. Azimuthal average of the full width half maximum for the main and the secondary axis of NGC3366 in units of λ/D. Dashed lines show AO performance and full lines MCAO results.

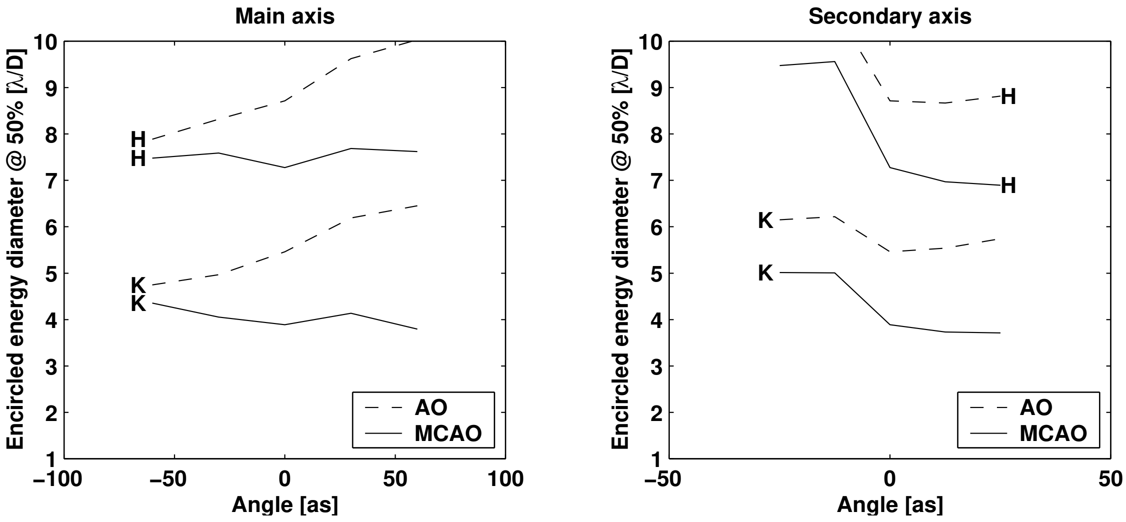
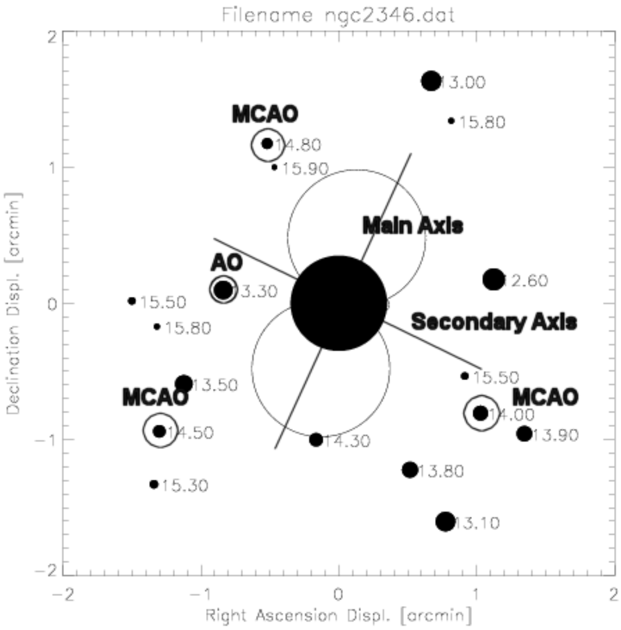


Figure 4. Encircled energy for the main and the secondary axis of NGC3366 in units of λ/D. Dashed lines show AO performance and full lines MCAO results.

(a) Photograph of the nebula NGC2346.



(b) Stars surrounding the nebula NGC2346. The position of the nebula is drawn in the center of the figure. The NGSs for AO and MCAO are surrounded with a circle. The two axis on which the performance of the MCAO system are optimized are also drawn.

Figure 5.

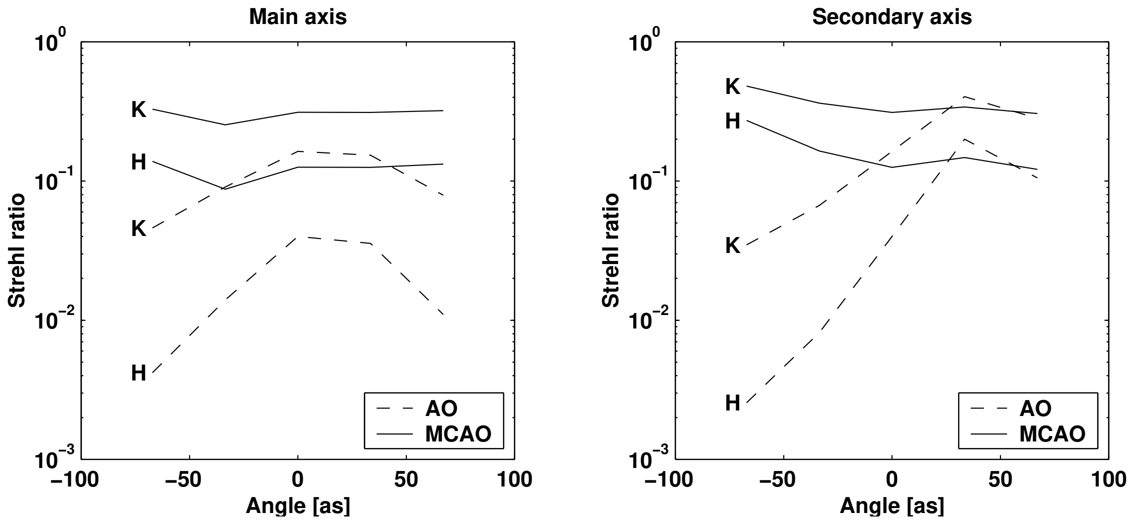


Figure 6. Strehl ratio for the main and the secondary axis of NGC2346. Dashed lines show AO performance and full lines MCAO results.

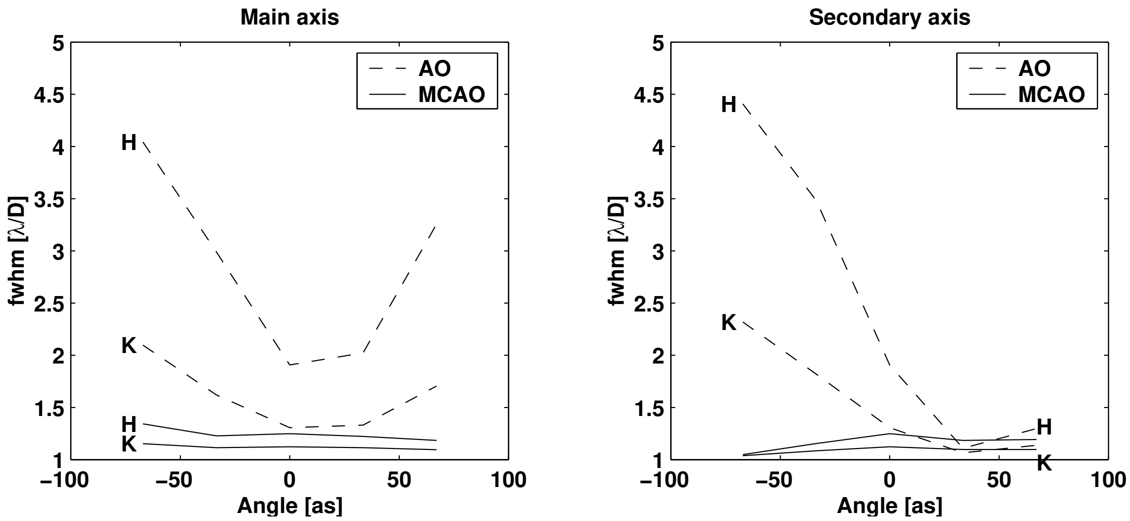


Figure 7. Azimuthal average of the full width half maximum for the main and the secondary axis of NGC2346 in units of λ/D. Dashed lines show AO performance and full lines MCAO results.

In the figures 6, 7 and 8, dashed lines and full lines correspond to the results of AO and MCAO simulations, respectively. The labels H and K are related to results computed for H and K band respectively. The FWHM and EE are given in units of λ/D.

In figure 6 the Strehl ratio varies from 20% to 50% in K band and from 10% to 30% in H band for MCAO. For AO, it varies from 3% to 50% in K band and from 0.2% to 30% in H band. The highest SR in AO is obtained only close to the guide star i.e. close to the left part of the secondary axis.

Figure 7 shows that for MCAO the images resolution is close to the diffraction limit. This is far to be the case for AO in most of the field.

For a point source diffraction limited image, the diameter value that encircles 50% of the energy is close to λ/D. In figure 8 it can be seen that for MCAO, the encircled energy is 4 to 5 times larger in K band and 6 to 7 times larger in H band. This means that even if we have a PSF core close to the one given by the diffraction limit, there is still a large halo. For AO, the energy is much more diluted due to the presence of larger halo and core.

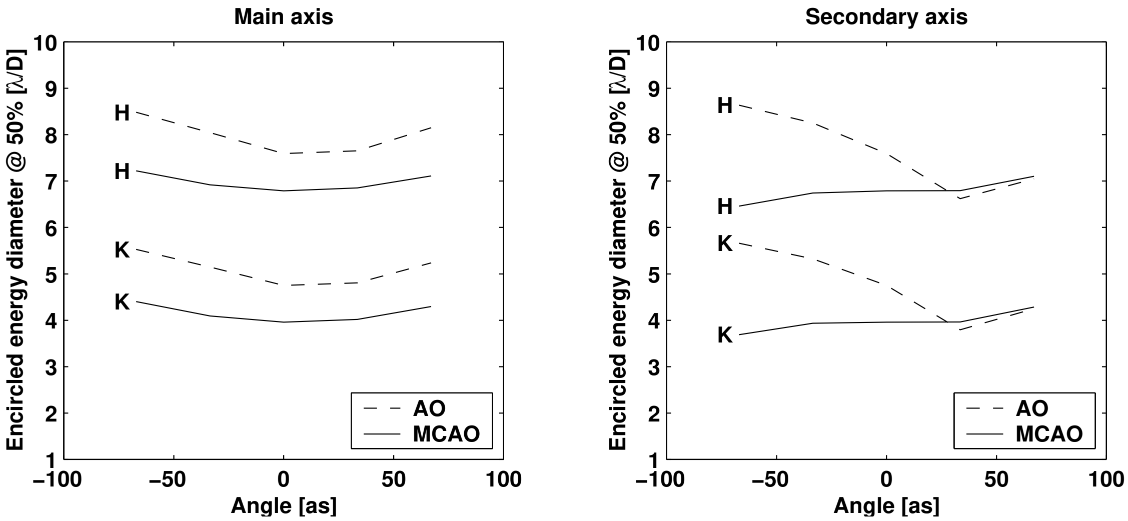


Figure 8. Encircled energy for the main and the secondary axis of NGC2346 in units of λ/D. Dashed lines show AO performance and full lines MCAO results.

5. CONCLUSION

Several authors had previoulsly performed simulations with a regular configuration of guide stars (with a variable number from 3 to 6 stars). These regular geometrical configurations were able to assure a uniformity of the performance over the field of view. When using NGS, irregular configurations have to be employed with varying stars magnitudes. We have picked up two examples and showed that MCAO techniques are still able to provide uniform performance over the field of view with non regular stars configurations. Moreover we have also plotted the results that could be expected for these objects employing classical AO, using as a guide star one of the stars of the field. In this case the results are quickly degraded when moving away from the reference. When we have increased the number of natural guide stars picking up other stars in the field of view, the performance is shown to be better, in the H and K bands.

The results of the simulations show that MCAO techniques in 8 m class telescopes are encouraging for imaging and spectroscopy of extended astronomical objects with a typical field of view of a few arcmins.

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