UCLA
Adaptive Optics for Extremely Large Telescopes 4 – Conference Proceedings

Title
Statistical and morphological analysis of mock galactic fields in the Global-MCAO perspective

Authors
Portaluri, Elisa
Viotto, Valentina
Bergomi, Maria
et al.

Peer reviewed

Statistical and morphological analysis of mock galactic fields in the Global-MCAO perspective

Elisa Portaluri[*a], Valentina Viotto[a], Maria Bergomi[a], Federico Biondi[a], Marco Dima[a], Jacopo Farinato[a], Davide Greggio[a,b], Demetrio Magrin[a], and Roberto Ragazzoni[a]

[a]Istituto Nazionale di Astrofisica - OAPD, vicolo dell'Osservatorio 5, Padova, Italy
[b]Università degli Studi di Padova Dipartimento di Fisica e Astronomia G. Galilei, Vicolo dell'Osservatorio 3, Padova, Italy

ABSTRACT

Enabling accurate morphological and photometric analysis across a wide Field of View (FoV) is one of the key science requirement for multi-conjugate adaptive optics systems. With this motivation we present a study aimed at the investigation of the performance of Global-MCAO (GMCAO). Such an innovative concept, based on natural guide stars in a wide technical FoV, addresses the need for an increase of the sky coverage, which is a key ingredient for future MCAO-based VLT instruments and for the forthcoming E-ELT. Using a tomographic simulation tool, we compute a map of the Strehl Ratio in a $250'' \times 250''$ area, matching the Chandra Deep Field South survey. Mock images of star and galactic fields are then built using such a map and analyzed as if they were real and observed with the E-ELT instrumentation. We perform the source detection and two-dimensional light-profile modeling using the IRAF/ELLIPSE code and we then compare the recovered parameters with the intrinsic data. The good match of our results claims that GMCAO is a reliable approach that can rebuild the AO concepts and can provide a frame of reference for a number of science cases.

Keywords: Global-MCAO, E-ELT, Galaxy: Simulation, Galaxy: Photometry

1. INTRODUCTION

Since the work by [1], Multi Conjugate Adaptive Optics (MCAO) renovated classic Adaptive Optics (AO), especially improving the capability of overcoming Field of View (FOV) restrictions.[2] There are several ways to realize and develop the MCAO theory, with several possible configurations.[3] In fact, MCAO refers essentially to the way in which DMs are introduced in the optical path, but a key role is represented by the way in which the WFSs operate and the DMs are controlled.

In classical AO systems, reference stars with a brightness higher than a certain magnitude are needed, a constraint that leads to a limited sky coverage, *i.e.* the fraction of the whole sky in which the system can work granting a high Strehl Ratio (SR) corrected image. Obviously, the sky coverage depends on the considered area of the sky, since the probability to find a suitable reference depends on the galactic coordinates of the region that is considered. In particular, the lowest sky coverage occurs at the galactic poles (0.1% in the V-band and 0.5% in the K-band[4]), since the statistical density of stars is lower than in all the other directions. On the other hand, the maximum sky coverage will be given for the galactic equatorial areas (1% in V-band and 4% in K-band[4]). The main adopted solution to increase the sky coverage and elude the problem of the availability of NGSs in a certain FoV is to create an artificial reference at the required position in the sky, the so-called Laser Guide Star (LGS). This represents a crucial point, especially for extragalactic research, which is focused in observing regions with low density of stars. Therefore, NGSs are needed in any case. But the LGS solution gave rise to a number of well-known problems,[5–7] usually overcome combining both NGSs and LGSs.

The Global-MCAO (GMCAO) is a new method proposed by [8], based on the idea of using the largest possible FoV, to maximize the chance to find suitable reference stars, but correcting only a central smaller FoV. It involves both several well-known AO concepts and innovative ideas, *i.e.* a number of Very Linear Wavefront Sensors[9] working in open loop and coupled with NGSs that can be found in a wide technical FoV, considering

*elisa.portaluri@oapd.inaf.it

a LO system. Their measurements guide a number of continuously updated virtual deformable mirrors, and are finally projected onto few real deformable mirrors to achieve the best performance in a smaller Scientific FoV area.

In a feasibility study, the work we presented in [10] simulated a complete system based on GMCAO concept mounted on a ELT, showing that the sky coverage can be increased at the galactic Pole reaching SR up to 24%, as also shown in [11]. We carefully examined the main parameters involved in such a system, from technical issues to scientific performances. They implemented a simulation code to compute the estimation of the SR over the FoV for several NGSs configurations.

We used that work as a starting point and investigated the performance of the GMCAO in an extragalactic science case: we implemented a simulation code to build mock images of extragalactic fields as if they were observed by a 40 m class telescope using a GMCAO approach. The details of the procedure are given in Section 2. The photometric analysis of the mock images is described in Section 3. Section 4 shows and discusses the results and then in Section 5 the implications and the progress of this work are presented.

2. GALAXY SIMULATION

In order to investigate the performance of GMCAO in the characterization of galactic properties, like size and morphology, we built a simulated image of an extragalactic field with 5 galaxies ranging between several possible photometric profiles, as discussed in Section 2.1, and adopting a number of reasonable parameters, as shown in Section 2.2. We then convolved the image with two different Point Spread Functions (PSFs), planning to analyze our results as usually done with common observed images of extragalactic fields.

2.1 Photometric profiles

The input photometric profiles we simulated were obtained starting from the Sérsic law,[12] defined as:

$$\log\left(\frac{I(r)}{I_e}\right) = -b_n\left[\left(\frac{r}{r_e}\right)^{\frac{1}{n}} - 1\right] \tag{1}$$

where r_e is the effective radius of the galaxy, i.e. the radius that contains the half of the total light of the galaxy, n is the Sérsic index that is the shape parameter and is linked to b_n with the formula $b_n = 1.999n - 0.327$, and I_e is the surface brightness at r_e. The larger n, the more concentrated the light profile is in the central part, therefore the higher is the surface brightness at larger radii. The Sérsic law provides a convenient parameterization of the light profiles of galaxies, and can be used to classify them, by getting the best fit of their light profile and thus discriminating between Hubble morphological types. In fact, if $n = 4$, the Equation 1 reduces to the de Vaucouleurs law,[13] typical of elliptical galaxies, whereas for $n = 1$ an exponential surface brightness distribution is obtained,[14] which is characteristic of the disk of spiral galaxies. We also adopted $n = 2.5$ to represent an intermediate class of morphology, like pseudo-bulge galaxies (hereafter we call them Sérsic galaxies).

2.2 Mock observations

We generated 5 galaxies with different inputs, spanning in a range of typical K-band observing parameters, as listed in Table 1: the magnitudes were between 16 and 19 and the effective radius between 0.″5 and 3.″5. The galaxies were uniformly distributed in a FoV of 50″ × 50″and a pixel scale of 0.″0035 px^{-1}, chosen to have a similarity with the MICADO camera that will be mounted on E-ELT. We used a gain equal to 1 and simulated an exposure time of 1000 seconds, reaching a $S/N = 100$ and considering a background=0.011 count px^{-1}.

2.2.1 PSF Convolution

To simulate real images, the map of the surface-brightness distribution should be convolved with the effects of the instrumental point spread function (PSF). In this sense it is crucial to derive a proper PSF, making some assumptions and calculations. We decided to make a first approximation in order to test our method, convolving the whole galactic field with a unique PSF, built from a given value of SR. Such a value was obtained running

Table 1. Input parameters for the simulated galaxies. Column 1: Simulated galaxy ID number. Column 2: Morphological Type. Column 3: K-band magnitude at the effective radius. Column 4: Effective radius. Column 5: axial ratio, i.e. minor axis above major axis. Column 6: Position angle with respect to the North. The orientation is assumed to be eastward.

Galaxy	Morph. Type	I_e [mag]	r_e ["]	ϵ	PA $^\circ$
#1	pseudo-bulge	16.481	1.73	0.778	3.2
#2	spiral	17.156	2.60	0.222	256.6
#3	elliptical	16.992	1.93	0.808	355.0
#4	elliptical	16.536	3.08	0.545	160.9
#5	elliptical	17.601	1.32	0.909	48.7

the IDL[*] Simulation Tool that simulates the GMCAO system on a 40-meters telescope pointing at the Chandra Deep Field South.[10] The details of the procedure to build a PSF starting from the wavefronts and SRs obtained from our simulation tool are described in a forthcoming paper.[15]

Figure 1 shows the 2-dimensional PSF and its radial profile obtained for the average value of the SR map of the Chandra Deep Field South, 17%: therefore $\frac{M_{\mathrm{SIM}}}{M_{\mathrm{DL}}} = 0.17$, where M_{SIM} and M_{DL} are the peaks of the simulated and the Diffraction Limit PSF, respectively. To test our model, we decided also to convolve the simulated map with a Gaussian PSF, making comparison between the results obtained using the GMCAO PSF and the analytical one.
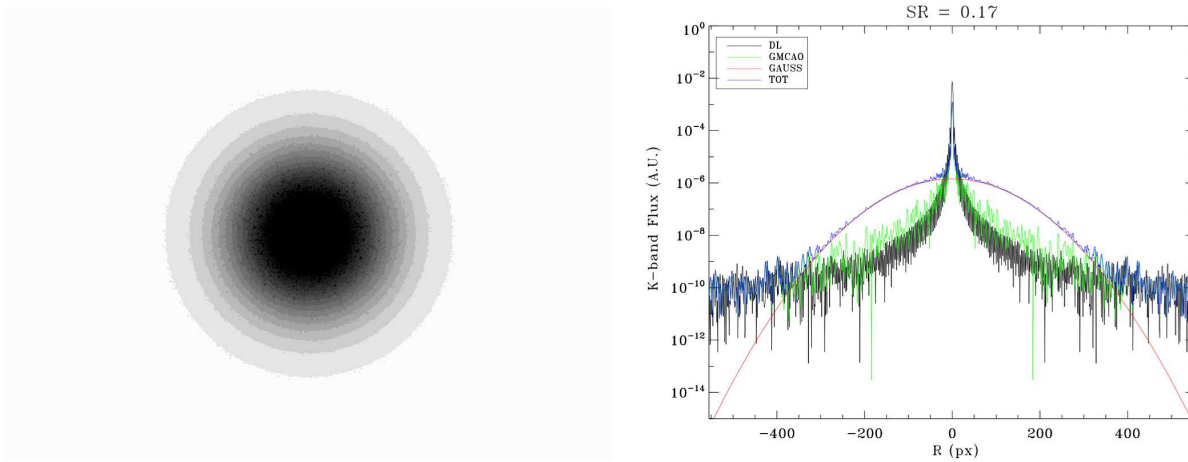

Figure 1. Left-hand panel: 2-dimensional simulated PSF. The field of view is $3.''4 \times 2.''4$. Right-hand panel: Radial profile of the simulated PSF. The legend shows how the final (total) function is built, i.e. as a sum of a the GMCAO PSF obtained from the wavefronts generated by the IDL Simulation Tool and a Gaussian PSF in order to have the typical shape of an AO PSF.

3. PHOTOMETRIC ANALYSIS

At that point we had 3 different images:

1. the "naked" simulation, without any convolution, hereafter called "simulation image"

---

[*]Interactive Data Language is distributed by Research System Inc.

2. the image convolved with the Gaussian PSF, hereafter called "analytical image"

3. the image convolved with the GMCAO PSF, hereafter called "GMCAO image".

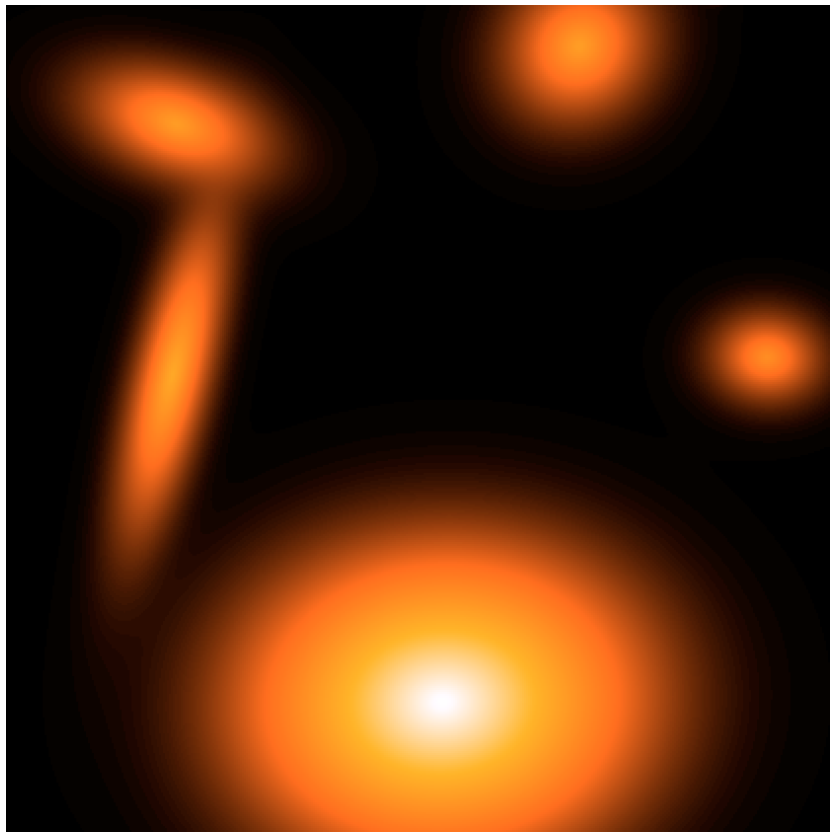Figure 2 shows the resulting GMCAO image with the 5 galaxies of our sample listed in Table 1.

Figure 2. Mock image of the simulated extragalactic field obtained convolving the simulation image with the GMCAO PSF.

As a preliminary study, we decided to perform the photometric analysis of the surface brightness of the galaxies in our sample using the isophote approximation, without distinguish between different morphological types. The isophotes of a galaxy connect points characterised by the same surface brightness. To describe in a quantitative way the light distribution of a galaxy we usually interpolate the isophotes with ellipses. This technique allowed us to extract the radial profiles that describe the behaviour of the surface brightness, μ, ellipticity, ϵ, major-axis position angle, PA, and Fourier coefficients, A_n and B_n (with n > 3) that parametrize the deviations of the isophotal shape from a perfect ellipse. Usually, the isophotes of a bulge or of an elliptical galaxy are expected to be nearly elliptical, even if the ellipticity changes with radius.

We fitted isophotes to the model images using the IRAF[†] task ELLIPSE.[16] They are fitted with ellipses, allowing their centres to vary in order to look for asymmetries in the light distribution. Within the errors of the fits we found no evidence of variations in the fitted centres. The ellipse fitting was then repeated with the ellipse centres fixed. The resulting azimuthally-averaged surface brightness, ellipticity, and position angle of the Galaxy # 1 are presented in Figure 3 for the 3 mock images. The figure shows also the 2-dimensional map

---

[†]The Imaging Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.
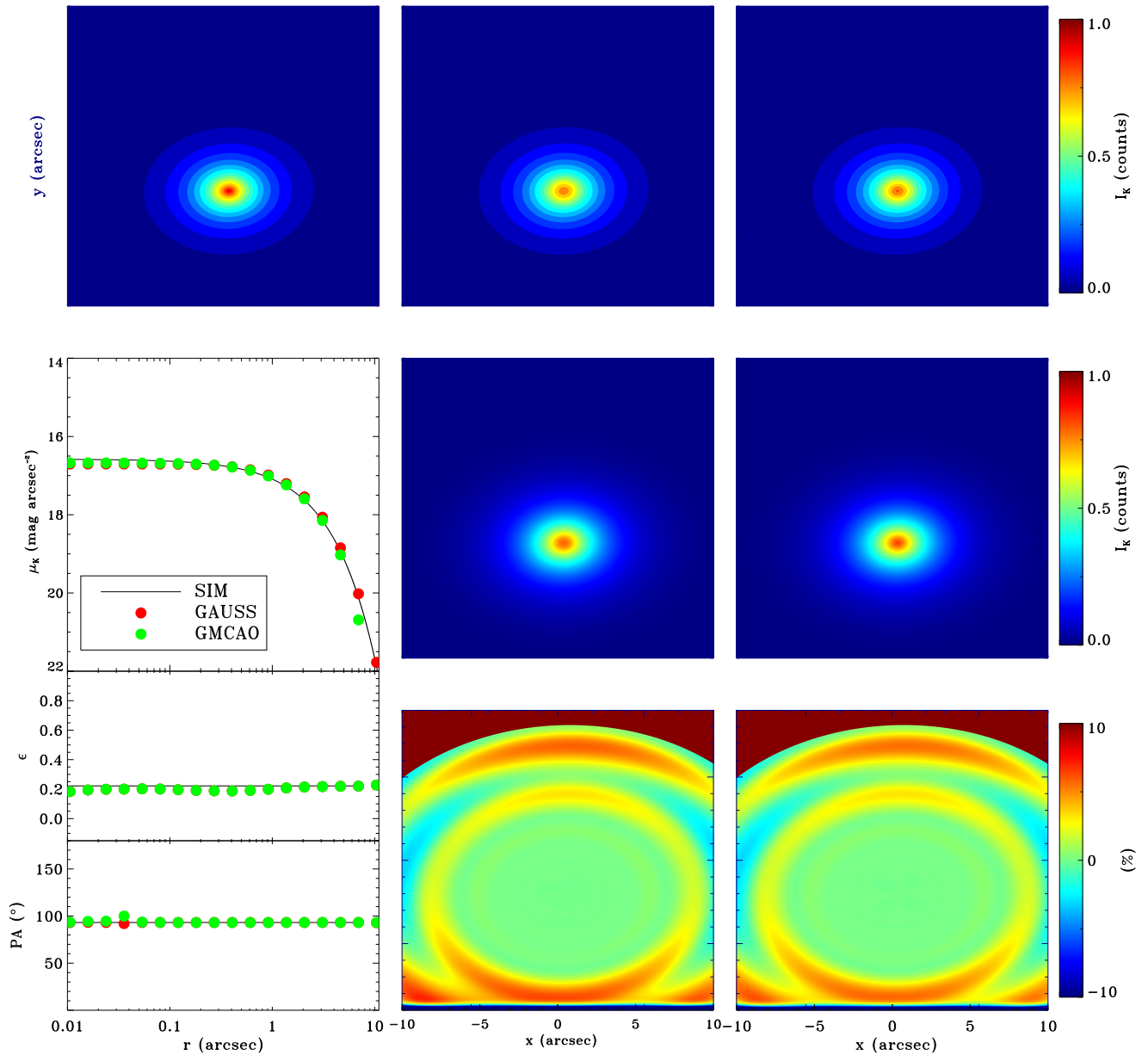
Figure 3. Top panels: 2-dimensional map of the surface brightness of Galaxy #1 in the simulation, analytical, and GMCAO image (left-hand, central, and right-hand panel, respectively). The central and bottom panels are divided in two blocks. The 1-dimensional plot (left-hand) represents the isophotal parameters of the Galaxy #1 of our sample as a function of the isophotal semi-major axis based on the analysis of the surface-brightness distribution obtained for the image simulation (black line), analytical and GMCAO image (red and green points, respectively). From top to bottom: Radial profiles of the surface brightness, ellipticity, and position angle. The 2-dimensional model and residual maps obtained using the IRAF task BMODEL are shown on the right with their colorbar.

recostruction obtained using the IRAF task BMODEL from the fitted ellipse values, and the percentage residuals obtained by measuring $I_{\text{res}} = \frac{I_{\text{image}} - I_{\text{model}}}{I_{\text{image}}} \times 100$.

4. RESULTS AND DISCUSSIONS

As shown in Figure 3, the surface photometry of the three images does not show significant differences. In the next subsections we discuss the results for each image.

4.1 Simulation image

Galaxy #1 is a galaxy with a Sérsic index $n = 2.5$, so it is an intermediate type, often interpreted as having a pseudobulge. It is the most luminous galaxy of our sample, with a central surface brightness of 16.481 mag in K band. It has an effective radius of $1.''73$ and an ellipticity of 0.788, as listed in Table 1. In the image of Figure 3 (left side), no source of noise was added, but only the background contribution.

4.2 Analytical image

The radial profiles of the analytical image of Galaxy #1 are in good agreement with those of the simulation image. We were able to retrieve $n = 2.51$, so we can confirm also *a posteriori* that it is a galaxy that hosts a pseudobulge. The effective radius we measured, $r_{\text{e}} = 1.''74$ is also in good agreement, therefore the convolution between the image simulation with a Gaussian function does not affect the retrievements of the size of an object. The central surface brightness seems to be the only parameter we investigated that is slightly different from the input one of about 15%.

4.3 GMCAO image

Also in this case, the radial profiles of the GMCAO image of Galaxy #1 are still in good agreement with those of the simulation image, but the surface brightness profile of the external regions of the galaxy seems to be slightly different. Again, we can conclude from this analysis that the galaxy has a pseudobulge ($n = 2.49$) and that has a dimension similar to the original one ($r_{\text{e}} = 1.''74$). Also in this analysis the surface brightness is the parameter with the biggest difference from the one we used as input in the simulation, being different of slightly more than 13%.

4.4 Other galaxies

Figure 4 shows the results obtained for all the galaxies of the sample, considering r_{e} and n.

Galaxy #1 that we have discussed previously is the best fitted object, but other galaxies are not significantly different from the simulation counterparts. The worst case is for Galaxy #2, mainly because it is a spiral and the approximation of elliptical isophote is not very representative for late-type galaxies. This pushed us to decide to improve our analysis in a detailed study,[15] performing 2-dimensional fits of the objects with available programs, like GALFIT[17] or GALAPAGOS.[18]

However, more broadly, the fit done on the analytical image seems to be better than the one we made using the GMCAO image, but to quantify this assertion we need a proper study of the errors. As a general conclusion, neglecting Galaxy #2, the differences between the input parameters and the fitted ones are less than 10%, confirming the reliability of the GMCAO approach and encouraging a further study to better test this technique.

5. CONCLUSIONS

The study is aimed at investigating the photometric properties of the galaxies in an extragalactic field to evaluate the performance of the Global-MCAO, a new technique proposed in the work of [8], capable to correct for the atmospheric turbolence on ELTs and to increase the sky coverage because of the enlargment of the technical FoV used to find NGSs.

We have built three K-band mock images of an ordinary extragalactic field. It consists of 5 galaxies with typical luminosities and sizes of nearby observed galaxies. The difference bewteen them is the fact that they are:
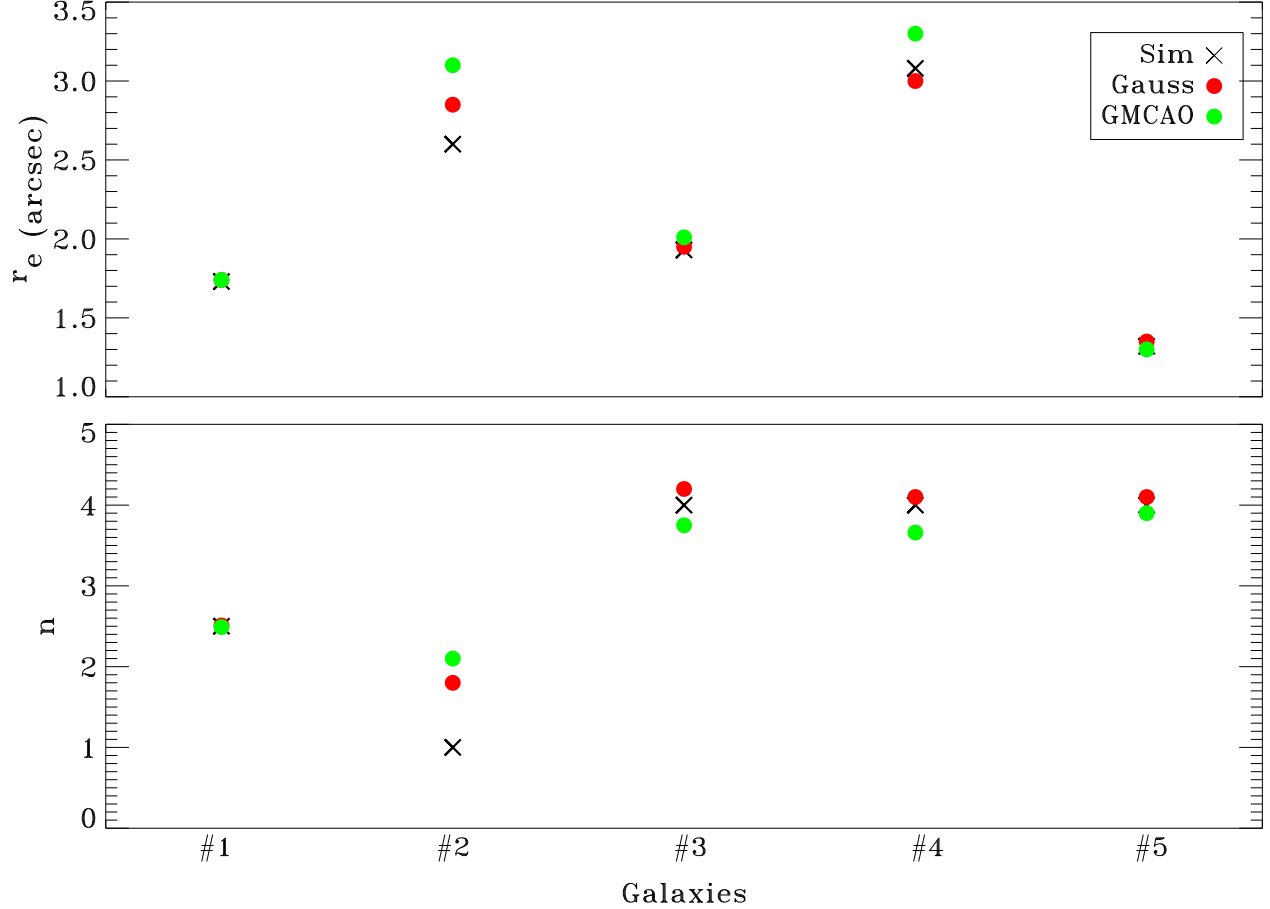
Figure 4. Results from the photometric analysis of the 5 galaxies of our sample. Comparison of the r_e (Top panel) and n (Bottom panel). Black crosses represent the parameters used as input in the simulation while red and green points are the results obtained from the analysis of the analytical and GMCAO image, respectively.

- not convolved

- convolved with a Gaussian PSF

- convolved with a PSF obtained simulating 40-m telescope system that uses the GMCAO technique, and pointing to the Chandra Deep Field South region.

As a preliminary study, here we have adopted a PSF that is uniform over the field, planning to improve and strenghten our results in a further study.[15]

We have then analyzed the images as if they were real using the IRAF task ELLIPSE, obtaining the photometric radial profiles of the main structural parameters that characterize a galaxy. We focused expecially on the effective radius and the Sérsic index, in order to access to the information about the size and morphology of the objects.

Comparing the parameters obtained analyzing the two convolved images to those we used as input in our simulation, we can conclude that they are strongly consistent within 15%. The analytical image seems to give the best results, in the sense that it is more comparable to the simulation image. However, a detailed study of the errors is missing, so the small differences between the two convolved images could be negligible when considering the error bars.

These results give us a strong hint on the fact that the GMCAO system can produce robust results in the extragalactic photometry field and can provide a frame of reference for a number of science cases. The first application we have in mind is to make extragalactic surveys, a key tool for modern extragalactic research. In fact, determining the size of massive galaxies at different redshift will provide strong constraints on galaxy formation,[19–21] allowing astronomers to discriminate between the hierarchical and monolithic processes that are the 2 main proposed scenarios for the formation of elliptical galaxies. Moreover, the identification of the morphological types of galaxies is fundamental to study the effect of the environment in shaping the galaxies, as claimed from the so-called morphological type-density relation, which is well studied in a lot of aspects.[22–24] For example, in a semplified version, spiral galaxies reside in crowded field, like galaxy clusters, while ellipticals seem to prefer isolated region.

However, as this was a preliminary test on the performance of GMCAO, we refer to a more completed and detailed study we are doing on the importance of GMCAO for extragalactic science.[15] There, we consider the non uniformity of the PSF over the field and we build an image of galaxies at high redshift. Another improvement we are planning to do is the implementation of the GALFIT code in order to perform the 2-dimensional photometric decompositions of the objects in the field, and better address the problem of the analysis of late-type galaxies.

Overcoming all the limitations related to LGSs and at the same time offering a large sky coverage are the requests for the future of AO Astonomy in the ELTs era. Therefore, even if we are still working on that, the first results on GMCAO performances are very promising and claim that this technique is a reliable approach that can rebuild the AO concept and can provide a frame of reference for a number of science topics.

REFERENCES

[1] Beckers, J. M. and Merkle, F., "Adaptive optics for large telescopes," *Ap&SS* **160**, 345–351 (Oct. 1989).

[2] Beckers, J. M., "Adaptive optics for astronomy - Principles, performance, and applications," *ARA&A* **31**, 13–62 (1993).

[3] Ragazzoni, R., Farinato, J., and Marchetti, E., "Adaptive optics for 100-m-class telescopes: new challenges require new solutions," in [*Adaptive Optical Systems Technology*], Wizinowich, P. L., ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4007**, 1076–1087 (July 2000).

[4] Arcidiacono, C., Diolaiti, E., Ragazzoni, R., Farinato, J., and Vernet-Viard, E., "Sky coverage for layer-oriented MCAO: a detailed analytical and numerical study," in [*Advancements in Adaptive Optics*], Bonaccini Calia, D., Ellerbroek, B. L., and Ragazzoni, R., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5490**, 563–573 (Oct. 2004).

[5] Fried, D. L., "Focus anisoplanatism in the limit of infinitely many artificial-guide-star reference spots.," *Journal of the Optical Society of America A* **12**, 939–949 (May 1995).

[6] Pfrommer, T., Hickson, P., and She, C.-Y., "A large-aperture sodium fluorescence lidar with very high resolution for mesopause dynamics and adaptive optics studies," *Geophys. Res. Lett.* **36**, 15831 (Aug. 2009).

[7] Diolaiti, E., Schreiber, L., Foppiani, I., and Lombini, M., "Dual-channel multiple natural guide star wavefront sensor for the E-ELT multiconjugate adaptive optics module," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8447**, 1 (July 2012).

[8] Ragazzoni, R., Arcidiacono, C., Dima, M., Dri, P., Farinato, J., Gentile, G., Magrin, D., and Viotto, V., "How to break the FoV versus thickness rule in MCAO," in [*Adaptative Optics for Extremely Large Telescopes*], 2003 (2010).

[9] Viotto, V., Magrin, D., Bergomi, M., Dima, M., Farinato, J., Marafatto, L., and Ragazzoni, R., "A study of Pyramid WFS behaviour under imperfect illumination," in [*Proceedings of the Third AO4ELT Conference*], Esposito, S. and Fini, L., eds., 38 (Dec. 2013).

[10] Viotto, V., Bergomi, M., Portaluri, E., Dima, M., Farinato, J., Greggio, D., Magrin, D., and Ragazzoni, R., "GMCAO for E-ELT: a feasibility study," in [*Adaptive Optics for Extremely Large Telescopes 4*], (2015).

[11] Viotto, V., Ragazzoni, R., Magrin, D., Bergomi, M., Dima, M., Farinato, J., Marafatto, L., and Greggio, D., "Modelling global multi-conjugated adaptive optics," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9148**, 6 (Aug. 2014).

[12] Sérsic, J. L., [*Atlas de galaxias australes*], Cordoba, Argentina: Observatorio Astronomico, 1968 (1968).

[13] de Vaucouleurs, G., de Vaucouleurs, A., Corwin, Jr., H. G., Buta, R. J., Paturel, G., and Fouque, P., [*Third Reference Catalogue of Bright Galaxies*], Volume 1-3, XII, 2069 pp. 7 figs.. Springer-Verlag Berlin Heidelberg New York (1991).

[14] Freeman, K. C., "On the Disks of Spiral and so Galaxies," *ApJ* **160**, 811–+ (June 1970).

[15] Portaluri, E., Viotto, V., Bergomi, M., Biondi, F., Dima, M., Farinato, J., Greggio, D., Gullieuszik, M., Magrin, D., and Ragazzoni, R., "Performance of a GMCAO on E-ELT: a case study of Chandra Deep Field," in prep. (2016).

[16] Jedrzejewski, R. I., "CCD surface photometry of elliptical galaxies. I - Observations, reduction and results," *MNRAS* **226**, 747–768 (June 1987).

[17] Peng, C. Y., Ho, L. C., Impey, C. D., and Rix, H.-W., "Detailed Structural Decomposition of Galaxy Images," *AJ* **124**, 266–293 (July 2002).

[18] Barden, M., Häußler, B., Peng, C. Y., McIntosh, D. H., and Guo, Y., "GALAPAGOS: from pixels to parameters," *MNRAS* **422**, 449–468 (May 2012).

[19] Buitrago, F., Trujillo, I., Conselice, C. J., Bouwens, R. J., Dickinson, M., and Yan, H., "Size Evolution of the Most Massive Galaxies at $1.7 < z < 3$ from GOODS NICMOS Survey Imaging," *ApJ* **687**, L61–L64 (Nov. 2008).

[20] van Dokkum, P. G., Franx, M., Kriek, M., Holden, B., Illingworth, G. D., Magee, D., Bouwens, R., Marchesini, D., Quadri, R., Rudnick, G., Taylor, E. N., and Toft, S., "Confirmation of the Remarkable Compactness of Massive Quiescent Galaxies at z ~ 2.3: Early-Type Galaxies Did not Form in a Simple Monolithic Collapse," *ApJ* **677**, L5–L8 (Apr. 2008).

[21] van der Wel, A., Franx, M., van Dokkum, P. G., Skelton, R. E., Momcheva, I. G., Whitaker, K. E., Brammer, G. B., Bell, E. F., Rix, H.-W., Wuyts, S., Ferguson, H. C., Holden, B. P., Barro, G., Koekemoer, A. M., Chang, Y.-Y., McGrath, E. J., Häussler, B., Dekel, A., Behroozi, P., Fumagalli, M., Leja, J., Lundgren, B. F., Maseda, M. V., Nelson, E. J., Wake, D. A., Patel, S. G., Labbé, I., Faber, S. M., Grogin, N. A., and Kocevski, D. D., "3D-HST+CANDELS: The Evolution of the Galaxy Size-Mass Distribution since z = 3," *ApJ* **788**, 28 (June 2014).

[22] Dressler, A., "Galaxy morphology in rich clusters - Implications for the formation and evolution of galaxies," *ApJ* **236**, 351–365 (Mar. 1980).

[23] Dressler, A., Oemler, Jr., A., Couch, W. J., Smail, I., Ellis, R. S., Barger, A., Butcher, H., Poggianti, B. M., and Sharples, R. M., "Evolution since z = 0.5 of the Morphology-Density Relation for Clusters of Galaxies," *ApJ* **490**, 577–591 (Dec. 1997).

[24] Fasano, G., Poggianti, B. M., Bettoni, D., D'Onofrio, M., Dressler, A., Vulcani, B., Moretti, A., Gullieuszik, M., Fritz, J., Omizzolo, A., Cava, A., Couch, W. J., Ramella, M., and Biviano, A., "Morphological fractions of galaxies in WINGS clusters: revisiting the morphology-density paradigm," *MNRAS* **449**, 3927–3944 (June 2015).