Sky coverage and SR uniformity in Layer-Oriented MCAO

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ABSTRACT

The sky coverage and the Strehl Ratio (SR) uniformity over Field of Views (FoV) of some arcmin are two key points for the development of Natural Guide Star (NGS) based Multi-Conjugate Adaptive Optics (MCAO) systems. We developed a numerical code able to simulate the behavior and to evaluate the performance of MCAO Layer-Oriented systems. In this paper we study the two issues and present the results of the simulations. In particular we consider the Multiple Field of View (MFoV) version of the Layer-Oriented concept. This technique allows looking for the reference stars in sky-areas bigger than the FoV corrected by the adaptive system, with a considerable gain in term of sky coverage. In the MFoV approach of the Layer-Oriented the NGS are selected in two or more concentric annular FoVs. In the configuration we take into account the guide stars are chosen in two different FoVs. The references for the ground layer loop are chosen in an annular FoV which inner diameter has the dimension of the scientific one. This annulus has only technical purposes and only a ground layer correction is applied in those sky directions. The reference stars for the highest loop are selected, as usual, in the corrected FoV. First we take into account the sky coverage considering different galactic latitude cases and studying the results distribution of the simulated cases. In order to enable a statistical approach to the problem we considered a big number of NGS configurations for each galactic latitude case considered. Then we take into account the level of SR uniformity in the cases where a useful correction is achieved. We define a function to quantify the SR uniformity over the FoV and we study its distribution using the results computed by the numerical simulations.

Keywords: Multi-Conjugate Adaptive Optics systems, Layer oriented MCAO, Wavefront Sensors, Sky Coverage.

1. INTRODUCTION

The Adaptive Optics (AO) technique (Babcock, 1953) allows correcting the effect of the atmospheric optical aberration on the wave-front (WF) of the stars. This goal is achieved by means of one deformable mirror (DM) that performs the correction of the aberration introduced on the star WF in its path. The correction to be applied is computed by the adaptive system composed principally by the wave-front sensor (WFS), by the real time computer (RTC) and the DM. These systems composed by one DM and one WFS correct the aberration only in the direction of the star used as light-source for the WF sensing and the level of the correction decreases very quickly with the distance from this reference. In this case the angular size of the sky where the correction is correctly performed (better than 1 rad in rms in the phase residual), called isoplanatic angle, is usually of 20-30 arcsec in the K band with the typical seeing of the astronomical sites. However also in this isoplanatic patch angle the correction is not uniform and it is related to the off-axis angle from the reference stars by an exponential relation, if the performances are expressed in terms of Strehl Ratio (SR). In order to measure with a significant accuracy the reference WF the magnitude of the star cannot be too high (the value of this brightness value depends on the characteristics of the telescope and on the WFS used). This implies a limitation on the coverage of the sky useful with respect to this technique. But, even if limited by the sky coverage because of the brightness of the reference star, V = 17.6 to reach SR =0.6 for NAOS/CONICA (Rousset et al, 2002), these systems

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now are used with success in several astronomical observatories. The sky coverage and the correction uniformity limits are overriden by the multi-conjugate adaptive optics (MCAO) technique (Beckers, 1988, 1989, Ellerbroek 1994). In this case sensing reference stars at different angle in Field of View (FoV) of 1-2 arcmin it is possible to measure the 3-dimensional distribution of the turbulence in the atmosphere volume between the telescope and the observed object. MCAO uses more WFS to sense the light from the references and several DMs to apply the correction. In this way it is possible to look for the reference stars in a sky area tens times bigger than the one useful for the classical AO and to obtain a more uniform correction over the scientific FoV. The Layer-Oriented (LO) (Ragazzoni, Farinato and Marchetti, 2000, Ragazzoni 2000) is a MCAO technique where the light coming from different sky-directions inside the scientific FoV is co-added on the WFSs that are conjugated to specific turbulent layer. The information retrieved by the WFSs is used to reconstruct the WF distortion introduced by the atmospheric layers close to the conjugated planes and then used to drive the DMs conjugated to these planes in a closed-loop way. In LO it is possible to realize both the optical and numerical co-addition of the references WF but with the difference that in this last case the number of WFSs grows up with the number of reference stars to be used. In this paper we take into account the optical co-addition only, but the same approach described here to study sky coverage and uniformity could be used for the numerical case. One of the more interesting features of the LO with respect to other MCAO techniques is the possibility to tune the spatial-temporal parameters used to sense and to correct each couple WFS-DM to the statistical characteristics of the conjugated atmospheric layer as the wind speed and the Fried parameter (r_0). This is possible because of each conjugated couple is independent from the hardware and RTC points of view (Figure 1). A natural WFS device for the LO is the Pyramidic WF sensor (Ragazzoni, 1996, Ragazzoni and Farinato, 1999) that, using as many pyramids as reference stars, produces on the sensor, for every Natural Guide Stars (NGS), four pupil images (one for each quadrant of the pyramids). The pupil images of different stars are optically super-imposed on the WFSs. The projection of all possible stars inside the FoV defines on the conjugated plane the metapupil. Each sensor measures the illumination on the four metapupil and the difference between them permits to compute the X and Y derivatives of the WF. But because of the optical co-addition the phase information retrieved are weighted for the star brightness and this can be disadvantage. In fact the bright stars on the field drive the correction on their directions more than the fainter stars. This effect is visible especially if there is among the NGS one star brighter than the other ones at least of 3-4 magnitude. This effect produces a no-uniformity on the correction that results peaked in the direction of the bright star. In order to avoid this effect is better to select the references in a small range of magnitude (3-4 mag). Of course this constrains decreases the sky-coverage and it will be take into account in the following sections. However this effect is smoothed in the Multiple Field of View (MFoV) version of LO (Ragazzoni et al, 2002). In this approach the reference stars for the ground layer loop are selected in a FoV bigger than the corrected one. This is possible because the position on the sensor of the stars footprint relative to the ground is independent on the reference direction and then all star pupil images are perfectly super-imposed on the metapupil. The MFoV approach uses a large FoV to look for the references and then it increases the probability to find several bright enough stars, at least for the ground loop. In this configuration it is useful not to split the light of the central FoV between the high and ground loop, but to send all the light collected from these NGS to drive the high only and then to consider as references for the ground the stars in the ring with inner radius equal to the corrected field and outer radius to the dimension of the external FoV. But the size of this ring is not arbitrary because increasing the FoV the thickness of the atmospheric region in focus on the sensor decreases (Diolaiti et al, 2001), limiting the achievable correction. Even if the MCAO technique is a development of the single reference AO also it suffers the same kind of limitations of the oldest one because, of course, it is limited by the number of the references photon flux received by the sensor and on the number and configuration of the NGS. In this paper we study the effective sky-coverage and correction uniformity with respect to the LO MFoV approach using the LOST simulation tool, elsewhere presented (Arcidiacono et al, 2003). We evaluate the performance of a specific system on a set of real fields considering the stars data obtained by the USNO-B catalogue version 1.0 (Monet et al, 2001). Finally we use this data to compute the sky-coverage and SR uniformity for these fields.

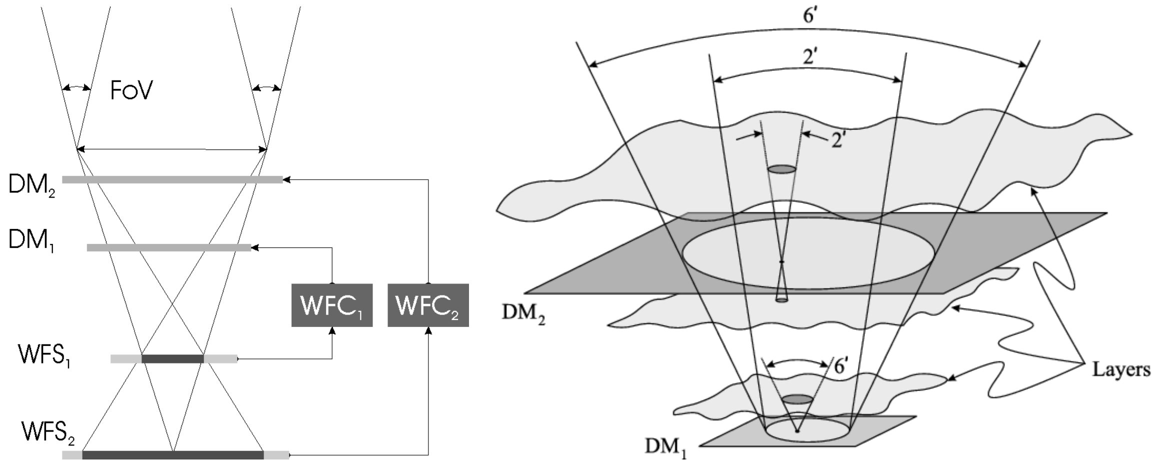

Figure 1 Thes figures show the scheme of the LO approach in the case of two conjugation planes (left) and the MFoV scheme (right). The labels WFS, DM and WFC indicate respectively the wave-front sensors, the deformable mirrors and the WF computers (one for each loop). The subscript 1 refers to ground conjugated plane while 2 to the high layer. The darkest regions on the WFS represent the projection of the metapupils on the sensor. In the MFoV approach the stars in ring region in between the 2 arcmin circle and the 6 arcmin circle will drive the ground correction while the stars in the central 2 arcmin FoV are the references for the high loop.

2.THE LOST CODE

The Layer Oriented Simulation Tool (LOST) is an end-to-end simulation code developed to study the performance of the LO system. It simulates the atmosphere by generating phase screens by Fourier Transform procedure with Kolmogorov or Von Karman power spectrum as well. During the simulation the atmosphere is moving in a very precise way by shifting and interpolating for the not integer part, restoring at each iteration of the loop the original set of phase screens. The atmosphere is characterized also by the r_0 and by the wind speed altitude profile. The WF of the NGS are collected by considering the footprints of the stars on the phase screens and on the deformable mirrors. These WF are arranged on the simulated metapupil following the LO scheme and sampled according to the spatial-characteristic of the sensor. For each loop of the simulation the WF of the reference stars (and of the test stars used to compute the SR) retrieved are used to compute the Point Spread Function (PSF) that are integrated for the overall time of the simulation and finally saved to a file.

Moreover the instantaneous PSF are used to compute the SR and these values are saved for each star and for each iteration. The evolution time step is usually smaller than the integration time used for the WFS. In this way is implicitly considered the blurring by the temporal evolution. At each integration time step of the WFS is added the phase noise to the LO measurements. The phase-noise model used for the WFS is a phase sensor based on the implementation of the noise propagation coefficients of the Shack Hartmann (Rousset, 1999), given here in terms of variance in a sub-aperture:

- Photon noise $\sigma^2 = \frac{\pi^2}{2}\frac{1}{n_{ph}}\left(\frac{N_T}{N_D}\right)^2$
- Dark and Ron $\sigma^2 = \frac{\pi^2}{3}\frac{{\sigma_e}^2}{{n_{ph}}^2}\left(\frac{{N_S}^2}{N_D}\right)^2$
- Sky background $\sigma^2 = \frac{\pi^2}{3}\frac{n_{bg}}{{n_{ph}}^2}\left(\frac{N_S}{N_D}\right)^2$

where n_{ph} is the number of photons detected in the sub-aperture, N_S^2 is the total number of pixels per sub-aperture, and σ_e is the standard deviation relative to Read Out Noise (RON) and dark current, N_T is the image full width half maximum (FWHM). This is about the ratio λ/r_0, where λ is the WF sensing wavelength, if it is true that r_0 is bigger than the dimension of the sub-aperture, d, while N_D is the FWHM of the diffraction pattern of one sub-aperture, $N_D \approx \lambda/D$. The n_{bg} is the number of photons detected by a sub-aperture from the sky background. This model has been extended to the pyramid WFS, but neglecting in this case the gain in limiting magnitude with respect to the Shack Hartmann and without considering any modulation of the pyramids. The LO noisy measurements relative to each conjugation plane are used to reconstruct the WF on the conjugated plane. The LO measurements are interpolated with a set of Zernike modes or a set of user defined modes (ad example the measured mirror modes). This interpolation is obtained with a least square solution of the system that relates the measured WF and the modes using a generalized inverse of the interaction matrix method.

3.THE CATALOGUE

This study is strictly dependent on the initial parameter considered, and dramatically on the reference stars selection. We considered several 1 square degree real sky-field reading the stars data in the USNO-B catalogue (version 1.0). In this catalogue are listed the detected object identified scanning Schmidt plates taken in the last 50 years. These data cover all the galactic latitude and longitude and it presents lists, proper motions, magnitudes in various optical pass bands, and a star/galaxy estimator for more than 1 billion objects. This catalogue has an accuracy of about 0.2 arcsec for astrometry, 0.3 in photometry and 85 percent in star/galaxy classification. It supposed to be completed until the magnitude 21 in the V band. We consider from the catalogue the information about the R magnitude and the object classification. But we discarded more or less the 12 percent of the star because they has only blue magnitude. Never less we considered them but taking into account that in this way we introduce an error because the R magnitude is, in average, 2 mag brighter than the blue.

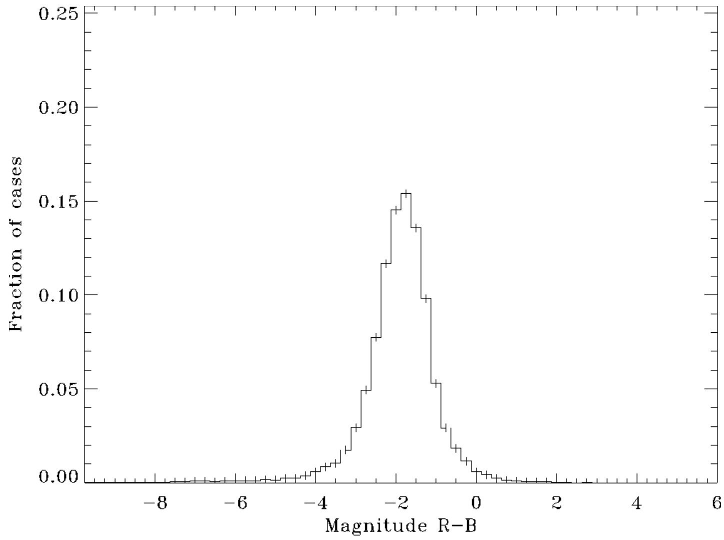

Figure 2 The normalized distribution of the R minus B difference for the star data in the catalogue USNO-B for the stars in the 1deg square field around the galactic anti-centre. In average the R magnitude is 2 mag brighter than the B.

4. METHOD DESCRIPTION

The sky-coverage problem regarding the LO and MFoV approach to MCAO has been studied (Marchetti, Ragazzoni and Diolaiti, 2002) using a statistical approach based on the Bahcall and Soneira star density function (Bahcall and Soneira, 1980) and an analytical model for the Pyramidic WFS. It was find out that the limiting integrated magnitude to

have a degradation of 0.5 in SR with respect to the case with infinite bright reference stars are 14.5 for the ground loop and 16.5 for the high loop. There was found out sky coverage of 20% for the galactic poles. But in this paper we follow a different approach: we consider as parameter the average SR computed over the scientific FoV (2 arcmin in the simulated cases) and we define that there is sky coverage if the average SR is bigger than a fixed amount: 5% or 10%. Our method follows several steps. First of all we consider real 1 square degree fields, from the USNO-B catalogue, around the Galactic poles, North (NGP) and South (SGP) and the Galactic anti-Centre (GAC) and then we define on them a square grid of 32×32 points (see Figure 4). In this way we have a reasonable grid-step of about 2 arcmin, equal to the dimension of the smallest FoV considered. Every grid point represents the on-axis direction used to center the FoV circles of 2 and 6 arcmin.
But in the USNO-B catalogue are listed also extended non-stellar objects that cannot be references for MCAO, then we discard these objects from the field data considering as parameter the star/galaxy estimator of the catalogue. In this way we have the "raw" data for the analysis of the field stars distribution and characteristics.

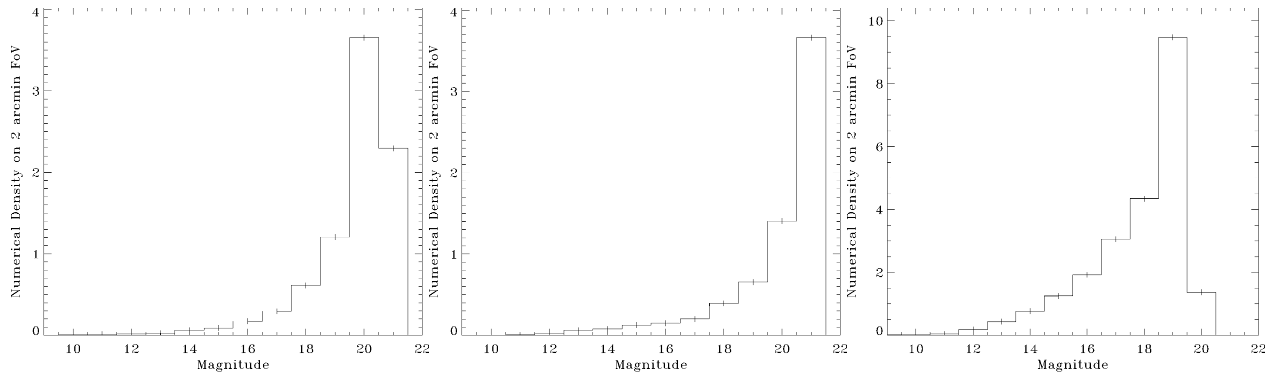

Figure 3 The distribution of the numerical density of the stars in the catalogue with respect to the magnitude respectively for the cases (from the left): North Galactic Pole, South Galactic Pole and Galactic anti-centre. The numerical density represents the average number of stars over 2 arcmin FoV for each unit magnitude range.

Field	Number of stars	Magnitude density for square degree
NGP	9687	5.91
SGP	7760	6.30
45	13112	6.27
GAC	26258	3.13

Table 1 Statistical data regarding the selected fields. Here is considered also a 45 degree field

The reference stars are selected (if any) simultaneously in the two FoV of 2 and 6 arcmin and according to the constrains summarized in Table 2. The constrain on the maximum range of variation for the references selection usually tends to decrease the probability to find very bright star (brighter than 12-13 mag) in the central 2 arcmin FoV because the other stars lying in the Field are "statistically" more faint than 3 magnitudes.
The stars are selected in order to obtain the brightest as possible asterism considering the limits given by the constrains. Another limit to the sky-coverage is the minimum distance that separates two close references. This is due to the physical dimension of the tube containing the pyramid positioned on the focal plane of the telescope. These values depend on the system and, usually, are about 20 arcsec for the high WFS and 30 arcsec for the ground.

Limit magnitude single NGS	Min Separation GL	Min Separation HL	Max magnitude range	Min NGS number GL and HL	Max NGS number GL	Max NGS number HL
R = 21	30“	20“	3.5 mag	3	12	8

Table 2 List of the constrains used on the selection of the NGS. All this condition must be true simultaneously in order that the star asterism is selected for a simulation run. If no asterism verifies the constrains in that region there is not sky coverage for sure and uniformity is not considered.

Then a simulation run is performed for each grid-point where a suitable asterism has been found, retrieving in this way a 1 degree grid of SR map computed on the 2 arcmin central FoV (see Figure 5). Finally the simulation outputs are the data for the analysis of sky-coverage and SR uniformity.

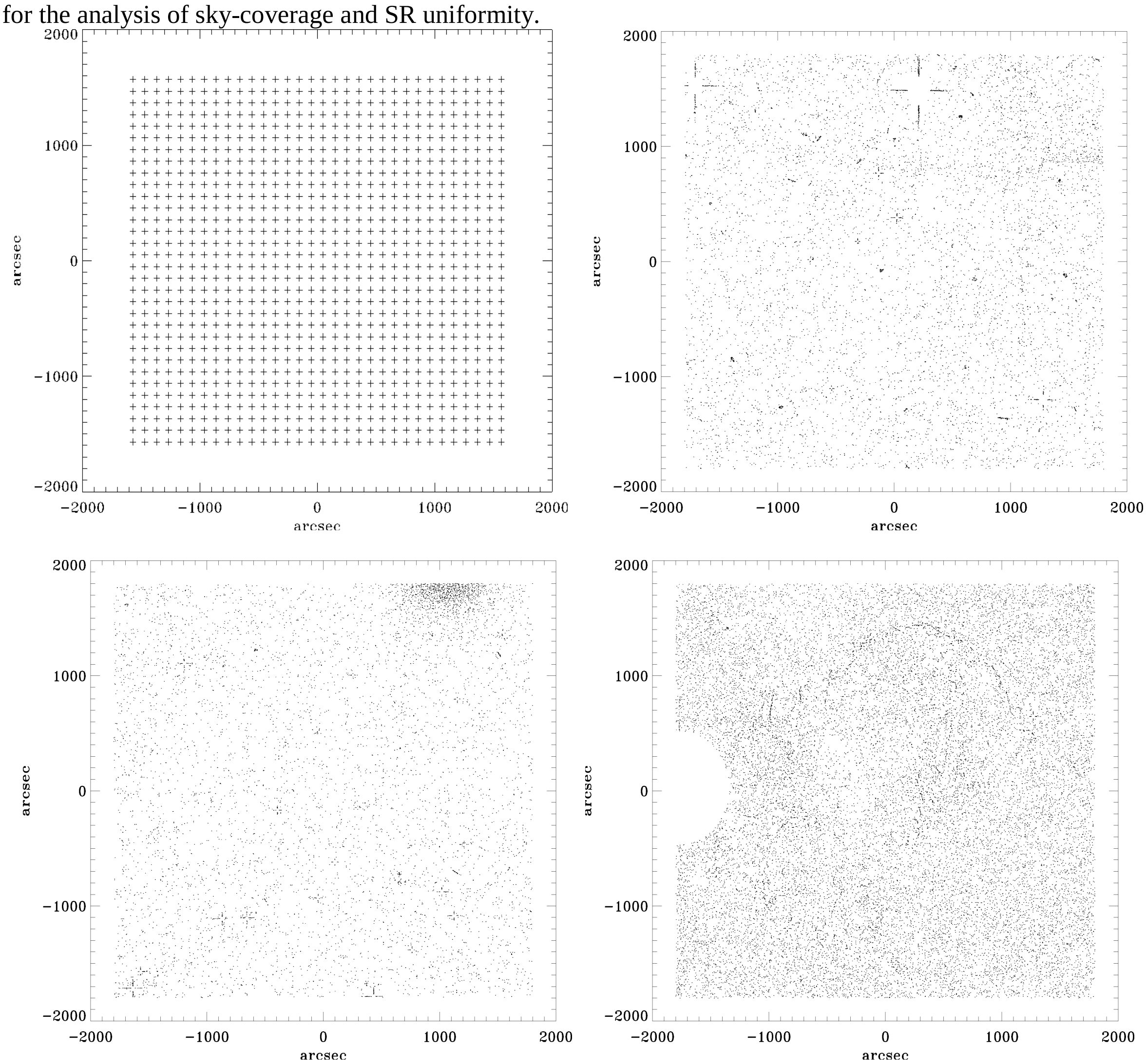

Figure 4 In the top-left plot the "+" sign defines the direction where the 2' and 6' are has been centered. Over these fixed directions the SR is computed also on the NGS. On the top-right is shown the NGP field, on bottom left the SGP and on bottom-right the Galactic anti-centre. In the GAC is visible a hole in the catalogue due to the diffracted light of a bright star.

In order to compare the results obtained on different asterism of the same 1 deg field the characteristics of the LO system and of the atmosphere must be keep fixed. We consider an 8-meter telescope and the median turbulence profile typical of the Paranal (Table 5), characterized by an average seeing value at the V band of 0.73 arcsec equivalent to an overall r_0 of 0.14 meters (in the V band). In both cases the results are computed at the K band, 2.2μm, with a correspondent $r_{0,K}$=0.83 meters. We consider a MFoV system with 2 DM conjugated to 0 and 8.5 km. The spatial geometry of the system has been taken fixed to a sampling 8×8 for the ground and 7×7 for the high in order to be deep in term of limiting magnitude but not optimizing for the achievable SR. The other MCAO system parameters are listed in Table 3. Each simulation covers an elapsed time of 0.5 seconds and then the last 0.4 are taken in to account for the computation of the long exposure SR.

Overall efficiency	Sensing wavelength	Scientific wavelength	Bandwidth	Conjugated Plane	RON	Dark Current	Delay time	Max # Zernike modes
0.2	0.7μm	2.2μm	0.4μm	0 km	3.0	200 e^-/sec	2 msec	59
				8.5 km	3.0	200 e^-/sec	2 msec	45

Table 3 In this table are presented the main characteristic of the MCAO system considered. Here we remember that we simulate an MFoV system with scientific field of 2 arcmin and a technical FoV for the NGS relative to the ground loop of 6 arcmin.

The integration times applied to the two WFS are tuned to the integrated magnitude on the 6' ring and on the 2' FoV for the ground and the high respectively. In this way, as in the case of the spatial sampling, we prefer to have a high limiting magnitude than a high SR. The values of the integrated time are listed in Table 4.

Ground Loop	R_{int} < 11	11 < R_{int}<13	13 < R_{int}<15	15 < R_{int}<16.5	R > 16.5
	2 msec	4 msec	10 msec	20 msec	40 msec
High Loop	R_{int} < 10	10 < R_{int}<12	12 < R_{int}<14	14 < R_{int}<16.5	R > 16.5
	2 msec	4 msec	10 msec	20 msec	40 msec

Table 4 In this table are listed the integration times used for the two WFS with respect to the integrated magnitude of the both references asterism. The values are tuned to the statistical characteristics of the conjugated planes.

Layer	Layer Altitude [m]	D/r_0 @ K	Wind [$^m/_s$]
1	0	7.38	6.6
2	1800	2.11	12.4
3	3200	2.67	8.0
4	5800	1.28	33.7
5	7400	1.05	23.2
6	13800	2.11	22.2
7	15800	0.77	8.0

Table 5 Here are listed the atmospheric parameters used in the simulations. For each layer an outer-scale of 20 m has been considered. The isoplanatic angle for the overall atmosphere is about 15 arcsec at the 2.2μm pass band.

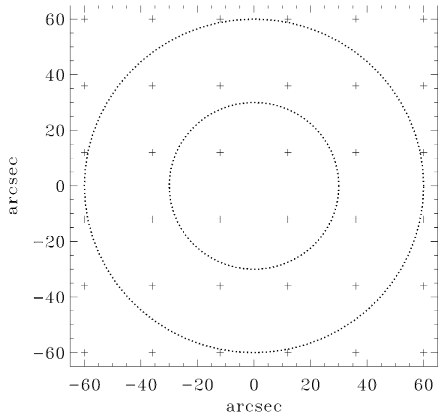

Figure 5 In this plot the "+" sign defines the direction where the SR is computed in all the simulated cases and the two circles represent the 1 arcmin field and the 2 arcmin corrected FoV.

An automatic procedure drives all the steps described above in this section retrieving finally the results. In the next section we analyze the distribution of the references asterism founded over the 1 deg fields and we study the long exposure SR results obtained by the simulations.

5. SKY-COVERAGE AND STREHL UNIFORMITY ANALYSIS

The number and the brightness of the references asterism founded change a lot with the galactic latitude: in Figure 6 and Figure 7 are presented the integrated luminosity function of the reference asterisms founded, normalized for the overall number of grid points (1024) taken in to account for each field. All the curves show a plateau for high integrated magnitude values both in 2 and 6 arcmin FoV cases. The level of this plateau indicates the maximum fraction of grid point that can be set as centre of the two FoVs. Theoretically the plateau should tend to the unitary value: the sky-coverage tends to be 100% increasing the limit magnitude. But we fixed a reasonable threshold in the faintness of each reference (R<21) and in this way we implicitly limit the sky coverage. While on the galactic plane the limit on the sky coverage is close to the unit (93%), the coverage for the galactic pole is in average of about the 50%. These values of course refer to a case not limited by the signal to noise ratio (SNR) on the WFS. We want to stress that both FoV cases (2' and 6') present for each field the same plateau level because they has been computed simultaneously and if not enough stars are selected in one of the two field then both are not considered in the sky coverage computation.

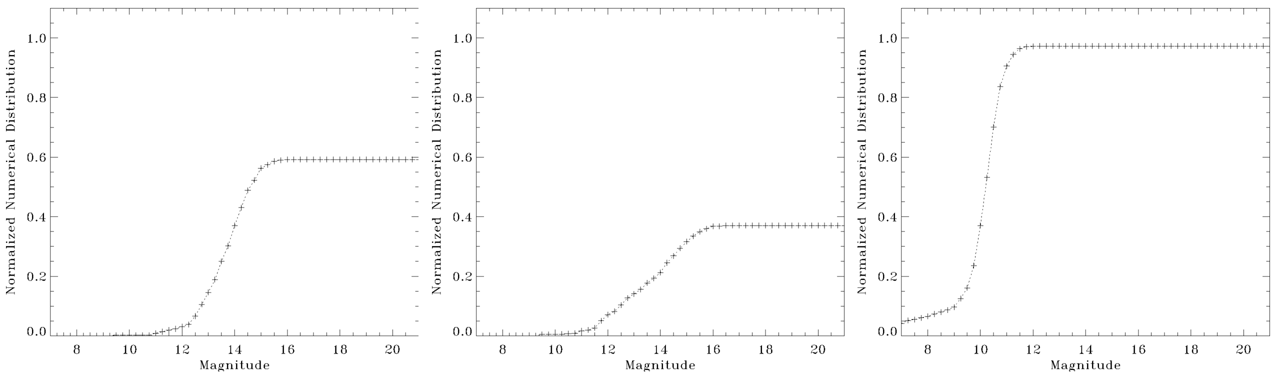

Figure 6 These three pictures show the integrated distribution of the integrated magnitude of the stars in the 6 arcmin ring for, from the left, the NGP, SGP and Galactic anti-centre. The curves represent the grid point fraction where an asterism has been found for different integrated magnitude threshold.

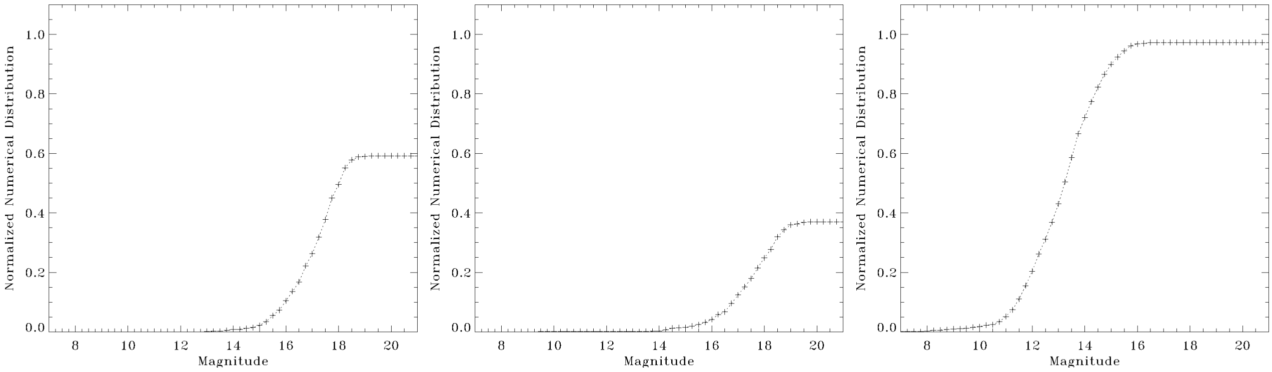

Figure 7 These three pictures show the integrated distribution of the integrated magnitude of the stars in the central 2 arcmin FoV for, from the left, the NGP, SGP and Galactic anti-centre. The curves represent the grid points fraction where at least an asterism has been found with respect to different integrated magnitude thresholds.

The results of the simulations must be interpreted taking in to account that we try to optimize the MCAO system parameters for the loop closure and the robustness of the correction and we do not point out our attention to the performance in term of SR achieved. In the conditions here used the best way to compute the effective sky coverage is to confront the performance obtained on each 2 arcmin FoV with a low average SR = 5-10% that however it is enough to indicate that loop is closed properly and to science purposes. We want to point out that with an optimization of the system parameters, as the number of DM modes used or the spatial sampling, better SR performance can be simulated, especially for the cases characterized by faint magnitude (and low SR) where the optimization is more important.

	NGP	SGP	GAC
Average SR > 5%	35 %	13 %	91 %
Average SR > 10%	25 %	8 %	89 %

Table 6 In this table are presented the values for the sky coverage respectively for 5% and 10% average SR computed over the central 2 arcmin FoV of the selected fields.

The average SR can be an interesting parameter in the astronomical cases where a good level correction is requested over the 2 armin FoV, as in the case of the extended (more than 1 arcmin) object. But in the case of a specific small object (at least 10 arcsec) the SR in a specific point of the field can be a interesting term: the probability to obtain a certain level of correction in the centre of the FoV is equal to the probability to obtain a SR value for a small object pointed by the telescope exactly at the centre of the field (see Table 7).

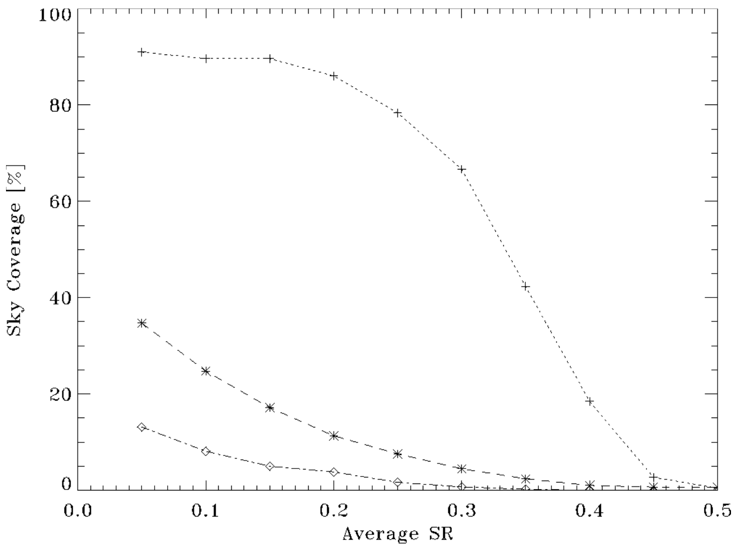

Figure 8 This figure shows the sky coverage with respect to the average SR computed on the 2 arcmin FoV. With the MCAO system parameters used the theoretical maximum SR achievable is about the 0.6. The plus sign refers to the GAC, the asterisk to the NGP and the diamond to the SGP.

Field	$SR_{on\ axis} > 10\%$
NGP	12 %
SGP	4 %
GAC	90 %

Table 7 Here are listed the probability to find a SR value more than 10% on the on axis direction for each 1 deg field. The SR values are computed for the K band.

In order to study the level of uniformity we consider only the sky region where the LO correction has been performed successfully with average SR higher than 5%. We define a general parameter, *s*, defined by the fraction of area of the corrected field that presents a difference in terms of residual phase rms that belongs to a 1 radian range centered on its median value.

$$s = \frac{Area(|\sigma_\varphi - \sigma_{\varphi,median}| < 0.5rad)}{Area}$$

Where σ_φ is the residual phase rms, *Area* is the area of corrected field and $Area(|\sigma_\varphi - \sigma_{\varphi,median}| < 0.5rad)$ is the area of corrected field with σ_φ belonging to the range $\lfloor \sigma_{\varphi,median} - 0.5, \sigma_{\varphi,median} + 0.5 \rfloor$. A completely uniform correction is characterized (according to this definition) by *s*=1. In other words a completely uniform field correction presents a variation in the residual phase rms in a range smaller than 1 radian centered on the median value of that.

In this manuscript the *s* parameter takes in to account the uniformity of the SR over the scientific 2 arcmin FoV. We measure this value on the simulated cases retrieving the distribution of this parameter for each 1 degreee field, see Figure 9. We retrieve from the analysis of these cases that the uniformity of the correction is quite high over all the corrected fields: in the about 80 %, the 80% (*s*>0.8) of the directions in the central 2 arcmin FoV presents a difference in residual phase less than half radian.

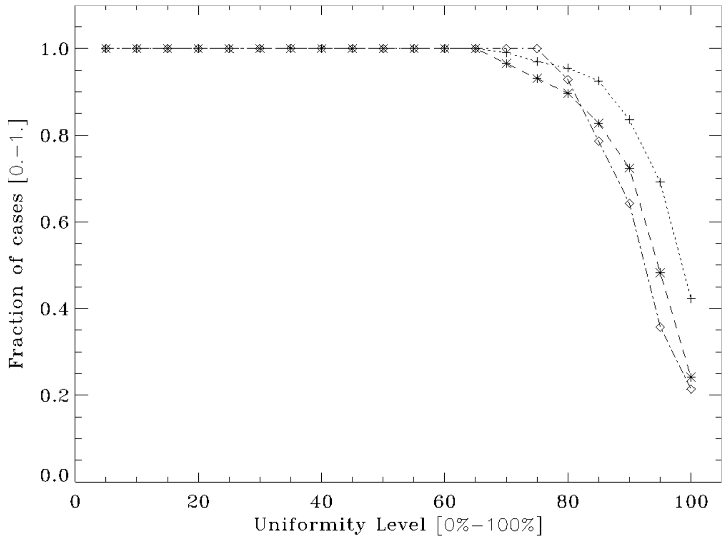

Figure 9 This figure shows the fraction of cases that presents a uniformity level, measured on the simulated cases (with average SR > 5%), bigger than a threshold value. A 100% completely uniform correction has an *s* parameter equal to 1, and this means that all the directions in the 2 arcmin central FoV have a variation in rms value of the residual phase among 1 rad range centered on the median value. The plus sign refers to the GAC, the asterisk to the NGP and the diamond to the SGP.

6. CONCLUSIONS

In this paper we described the main feature of the LOST simulation code used to simulate a MFoV Layer-Oriented MCAO system and we presented the results about sky coverage and SR uniformity values over the North and South Galactic Pole, and on the Galactic anti-centre. It was found that also considering several realistic technical constrain on the number, the distance and the magnitude range of the reference stars the probability to find an asterism for the MFoV is very high (more than 50% at the posssles and 90% on the galactic plane). Then we showed the results of the simulations for these fields and we got that the probability to achieve a correction is between 10 and 30 percent for the poles and more than 90 % for the galactic plane. We defined a parameter, *s*, to measure the uniformity of the correction over the scientific FoV: on the simulated cases we computed this value and we found out that a high level of uniformity (80%) can be achieved in more than 80% of the asterism. So we checked numerically that with MFoV version of LO is possible to reach satisfying sky coverage values and really uniform correction over 2 arcmin FoV.

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