Sky coverages on ELTs with a reference area much larger than the compensated one

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Abstract. Sky coverage for MCAO systems has been the subject of a large number of studies in the past decade or so. The resulting figures, further to have the chance of being refined by actual measurements carried out at the largest 8m class telescopes, have to be updated and validated for the most recent approaches in ELT adaptive optics corrections. In particular, techniques employing the use of several virtual deformable mirrors can take advantage of a field of view, inside which references can be found, that is much larger than the area where the correction is actually made. While a parallel with similar studies for Multi Objects AO can be traced down, we revise here the various proposed approaches and we show the results of similar computations using the novel concepts and gauging the outcome with the more recent on-sky available data.

1 Introduction

The main limit of the classical Single Conjugated Adaptive Optics (SCAO) is the small corrected Field of View (FoV). The light coming from the science target and the one of the reference star cross slightly different cylinders of atmosphere before reaching the telescope entrance pupil and undergo different distortions, mainly when very high and strong turbulent layers are present. This effect is called angular anisoplanatism. Because of this limitation, the reference object is required to be very close to the science target. Of course the smaller the isoplanatic patch (usually only a few tens of arcseconds in the NIR band [1]), the more difficult to find a suitable reference (for classic AO the typical limiting magnitude is about 15 - 16 mag, depending on the system) close to the scientific target. This finally limits the sky coverage which can be achieved with classical AO systems. Consequently, with SCAO it is not possible to correct for an appreciably wide FoV, which is a limit for several science cases. Multi-Conjugated Adaptive Optics (MCAO) technique was initially introduced by Beckers in 1988 [3] and it is based on the concept of using more than one guide star as a reference, to sense the turbulence effect in various directions and obtain a sort of 3D map of the atmospheric perturbation, employing more than a Deformable Mirror (DM) conjugated to different heights along the line of sight of the telescope, to perform the AO correction. Sky coverage of an Adaptive Optics system consists in the fraction of the sky in which references, matching previously defined conditions, can be found, in order to achieve the required performance of the system. In the past decades, different approaches to quantify the sky coverage of an AO system have been proposed, based both on star counts and on simulated fields. The conditions, over which a field has been considered as compliant with the AO system requirements, have changed from work to work, sometimes giving results which are difficult to be compared. These conditions, in fact, strongly depend on the considered system. The limiting magnitude, for example, depends on the WFS sensitivity and it can considerably change, switching from a Star Oriented MCAO system to a Layer Oriented (LO) one [5], in which the optical co-addition of the light coming from the guide stars can increase the overall sky coverage. Generally speaking, sky coverage for MCAO is strictly related to the number and magnitude of the Natural Guide Stars (NGSs) which can be found in the FoV and these parameter have always been the basis of this kind of studies [4]. During the last decade, other parameters have been taken into account in the proposed sky coverage algorithms,

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like the limiting magnitude difference between the NGSs, the integrated magnitude and the NGSs separation ([6], [7], [8]). In this work we use the metapupil coverage as the key parameter for the AO correction, considering an ELT-like telescope case, equipped with an AO system whose concept is similar to the Multi-Object AO (MOAO) approach, for which some sky coverage studies have already been carried out [12].

2 From Large telescopes to Extremely large telescopes: gain in sky coverage

The introduction of MCAO potentially enlarges the FoV in which is possible to search for suitable NGSs, leading to a discussion about which sky coverage can be achieved with solely NGSs. While, for Ground Layer correction, the dependence of the availability of NGSs on the FoV size has already been clearly pointed out, since the pupils superimposition is always almost complete, the same cannot be said for the WFSs conjugated to the high altitude layers. The geometrical distance, at which the pupils do no longer overlap at a certain height, defines a limit, over which there is no more gain into enlarging the FoV. This angle is of the order of 2 arcmin for an 8m telescope and scales to 10 arcmin for a 40m-class telescope. Considering a LO approach , the FoV enlargement causes a reduction of the depth of focus of the WFS, accordingly to the so-called *FoV vs thickness* rule [11], because the turbulence effect is smoothed out for layers close to the the WFS-DM conjugation height with a smoothing cone which enlarges as the FoV increases.

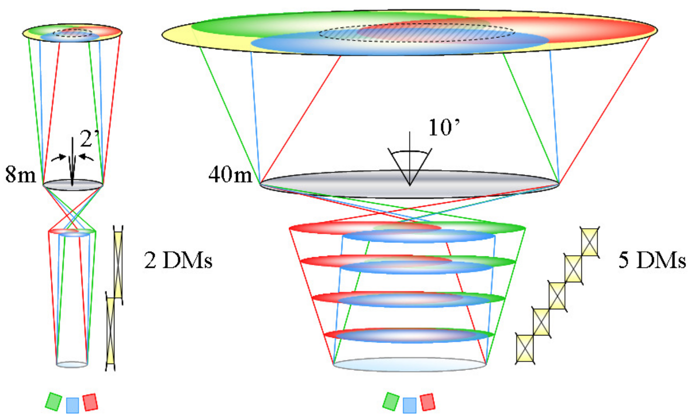

Fig. 1. Enlarging the telescope entrance pupil allows to search for the same number of guide stars in a wider FoV to sense the same fraction of the metapupil at a given height (2' in a 8m-class telescope vs 10' in a 40m-class telescope). More DMs (real or virtual) are needed, because of the FoV vs thickness rule. This Figure shows the comparison between a 2' FoV for a 8m-class telescope and a 10' FoV for a 40m-class telescope.

Figure 1 shows how enlarging the telescope entrance pupil allows to search for the same number of guide stars in a wider FoV to sense the same fraction of the metapupil at a given height. Because of the *FoV vs thickness* rule, however, the required number of DMs increases with the FoV enlargement, translating into a potential show-stopper for using NGSs for MCAO in ELTs. The introduction of techniques employing the use of several virtual deformable mirrors allows to take advantage of a FoV, inside which references can be found, that is much larger than the area where the correction is actually made, in a way very similar to the one already adopted for Multi Objects AO [13]. Provided that the number of DMs is not a problem anymore, the probability to find N stars in a certain FoV can be simulated using a Poisson distribution of the stars with a mean stellar density provided by the Bahcall-Soneira Galactic model [2]. Some examples of the results of these simulations are reported in Figure 2, in which the probability to find 3 stars of a least a certain magnitude inside a 2 arcminute FoV

(8m-class telescopes case) is compared with the one to find the same number of stars in a 10 arcmin FoV (40m-class telescopes case), for different distances of the FoV from the Galactic plane, showing an evident (and obvious) increase in sky coverage for 40m-class telescopes.

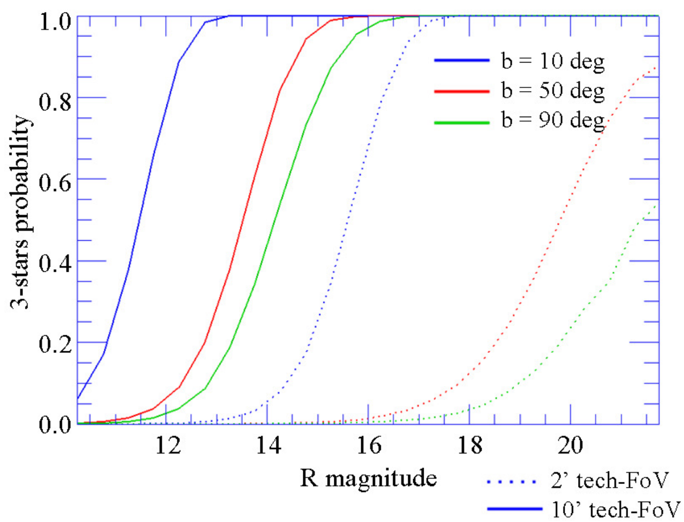

Fig. 2. Simulations with Poisson stars distribution (mean stellar density provided by the Bahcall-Soneira Galactic model)on the probability to find 3 reference stars varying the FoV size and galactic latitude.

3 Metapupil covered fraction

In MCAO, from the point of view of the turbulence sensing, a fundamental parameter is the coverage of the metapupil, namely the projection of the telescope entrance pupil over the FoV to be corrected, since this coverage is strictly related to the fraction of the volume of atmosphere perturbing the wavefronts which is sensed by the WFS. The metapupil covered fraction depends on the height of the highest layer to be sensed, the number of reference inside the FoV and the relative position of these references, namely the *asterism* of the NGSs. Figure 3 shows two extreme cases of 3-stars asterism, with all the stars very close to the center of the field (corresponding to the SCAO case) and with the three stars positioned in the FoV so as to give the maximum possible pupil coverage, and reports the resulting metapupil covered fractions for a 10 arcmin and a 2 arcmin metapupils, respectively.

Obviously, to completely cover a 10 arcmin metapupil at a certain altitude, more references than the ones required to fully cover a 2 arcmin metapupil are necessary. Considering the more generic case of N stars in the technical 10 arcmin FoV of a 40m-class telescope, which is the probability to cover a certain metapupil fraction, with the best 3-stars constellation? Let's consider the metapupil projection at a 9 km altitude and simulated fields including N reference stars randomly positioned. Figure 4 shows the results of the simulations in which the covered fraction of the metapupil of a 2' and a 10' scientific FoV, with the best-disposed three references, is computed for randomly positioned N-references fields. While the performance of a 40m-class telescope in terms of metapupil coverage with a scientific FoV equal to the technical 10 arcmin FoV are the same as an 8m-class telescope with a scientific FoV equal to the technical 2 arcmin FoV, there is a great improvement in the maximum achievable metapupil coverage if considering an E-ELT-like case, in which the technical FoV and the scientific FoV, to be corrected with AO, are 10 arcmin and 2 arcmin wide, respectively.

In other words, while, for a 10' scientific FoV, the probability to cover a fraction of the metapupil higher than 0.8 with an ELT is lower than 10% up to $N = 8$ stars, if only the inner 2' FoV is considered,

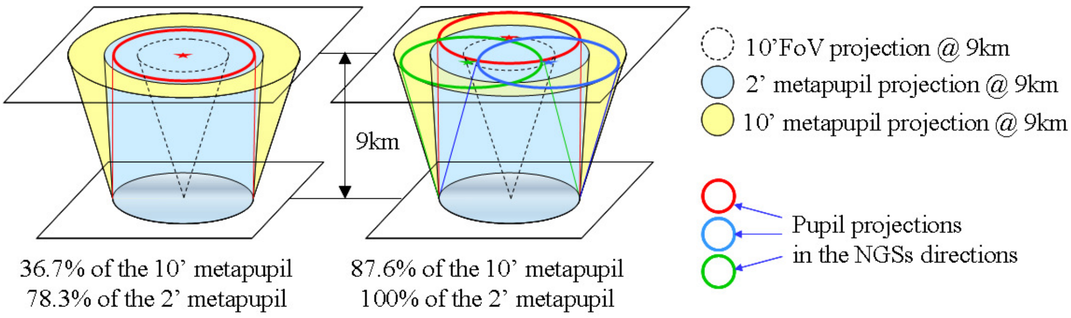

Fig. 3. Metapupil coverage at 9km height: 3 NGSs extreme cases.

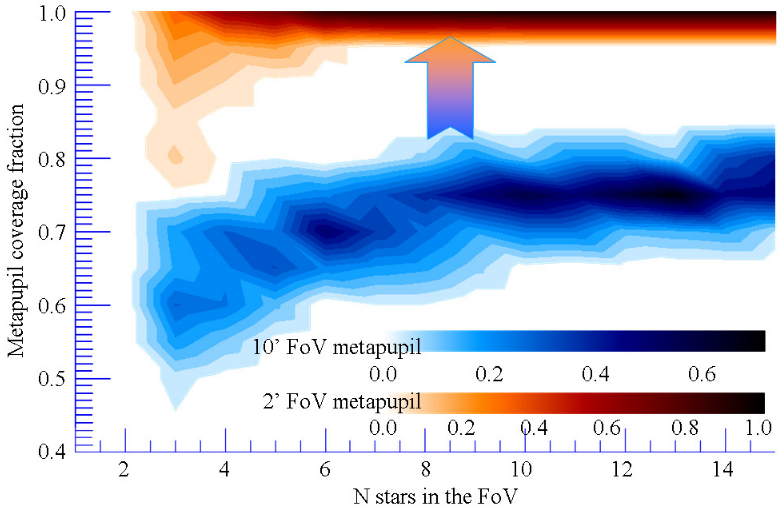

Fig. 4. Probability to cover a certain fraction of the metapupil with the best 3-stars asterism, selected from N suitable references randomly distributed inside the FoV. With respect to the predicted performances for a 40m telescope equipped with a 3-stars AO system with a technical FoV=scientific FoV=10 arcmin (same performances of a 8m telescope with a technical FoV=scientific FoV=2 arcmin), there is a great improvement in the maximum achievable metapupil coverage if considering the actual E-ELT case, in which the technical FoV and the scientific FoV, to be corrected with AO, are 10 arcmin and 2 arcmin wide, respectively.

this probability becomes 0.9, and only $N = 3$ references are required to be found in the 10' technical FoV.

To estimate the actual probability to cover the metapupil, we converted the results showed in Figure 4 into cumulative probability functions, and weighted them with the probability to find N stars in the FoV, retrieved simulating a Poisson stars distribution with the mean stellar density provided by the Bahcall-Soneira Galactic model. Figure 5, *upper image*, shows the probability to cover a fraction of the 2' metapupil (always considering a 40m-class telescope) with a 3-NGSs asterism, selected from a sample of N randomly distributed stars in the 10' technical FoV. A limiting magnitude of $R_{max} = 15.25$ mag has been used to select suitable reference inside the FoV, since the virtual mirrors technique WFSs work like star oriented open loop WFSs. The conservative case of a FoV very close to the Galactic Pole is considered. Figure 5 also shows the same results obtained for 5 and 7 stars asterisms. To retrieve the actual searched probability, the superior of the results obtained for all the possible m-stars asterisms should be considered. In Figure 6, for example, the superior of 3,5,7 stars constellations (please note that these cases can be considered as representative of the all 3 to 7 WFSs range, since only the superior

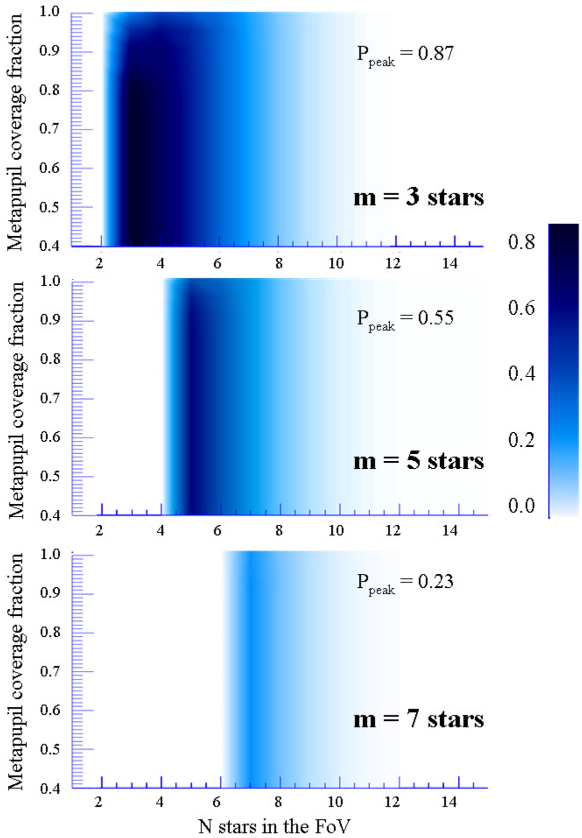

Fig. 5. Probability to cover a certain fraction of the 2' metapupil with the best m-stars asterism, selected from N suitable references randomly distributed inside the 10' technical FoV. The probability to actually find N suitable references ($R < 15.25$ mag) is retrieved with a simulation of a Poisson distribution with the mean stellar density provided by the Bahcall-Soneira Galactic model. The conservative case of $b = 90$ deg is considered.

of the retrieved values is considered) results are shown, for $b = 90$ deg. The graphs in Figure 6 show that the higher probability to cover a wide fraction of the metapupil corresponds to the 3 NGSs case.

3.1 Results and conclusions

Considering a 2' scientific FoV at a Galactic Latitude $b = 90$deg (extreme case), observed with a 40m-class telescope, if 3 suitable stars are found in the technical 10' FoV, the metapupil coverage is always higher than 70%, so the probability to cover such a fraction of the metapupil only depends on the probability to find 3 stars in the technical FoV (87%). If other cases, in which more references are required, are considered, the probability to cover a high fraction of the metapupil decreases, since it always has to be weighted with the probability to find a higher number of suitable reference stars. Of course, for lower latitude fields, it becomes more likely to find a high number of suitable references. Figure 7 shows the $b = 50$deg latitude case, in which, however, a conservative limiting magnitude of 14.25 mag has been used as a threshold. In this case, the probability to find a suitable 4-stars asterism is considerably higher than in the $b = 90$ deg case, and so on for decreasing latitudes. Finally, in a star oriented AO system, applied to a 40m-class telescope, a very high number of WFSs is not required to obtain a uniform correction (related to the metapupil coverage). This is true because of the pupil diameter of the telescope, which is more than 7 times wider than the scientific FoV projection at a 9km altitude. Because of this, the pupil size dominates on the probability to find many references for

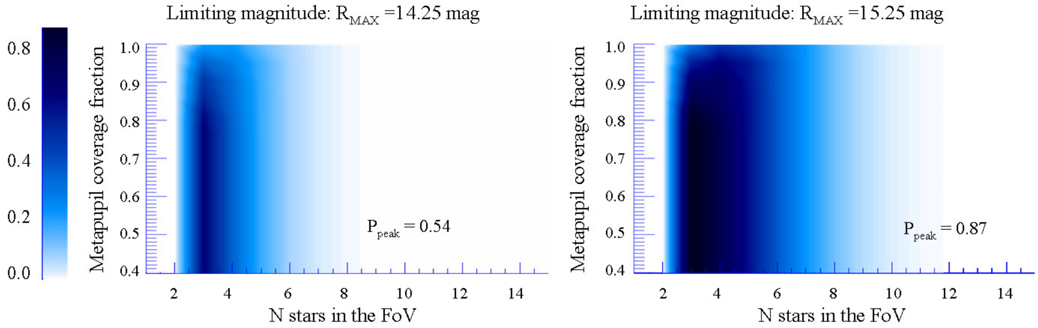

Fig. 6. Superior of 3,5,7 stars constellations results, as presented in Figure 5, for b = 90 deg.

most of the Galactic latitudes (b > 25 deg, but this number depends on the limiting magnitude, on the metapupil coverage threshold and so on..), even if the technical FoV becomes wide (10').

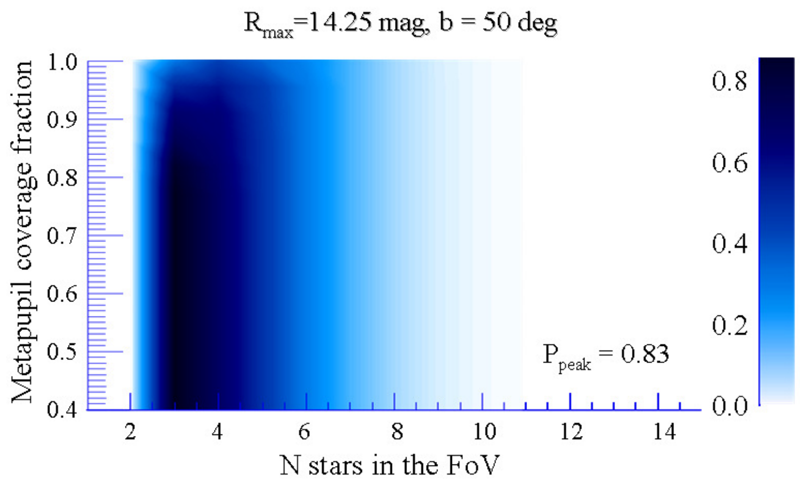

Fig. 7. Probability to caver a certain fraction of the metapupil at a 9km altitude, with N stars in the FoV. Conservative case: (R_{max} = 14.25 mag, b = 50 deg).

In this paper has been presented a statistical analysis on the sky coverage of a 40m-class telescope, intended as the probability to cover a certain fraction of the metapupil up to a given altitude (9km in this work) and based on simulated fields computed considering a Poisson distribution of the stars with a mean stellar density provided by the Bahcall-Soneira Galactic model. The actual sky coverage can be computed defining a threshold on the metapupil fraction to be sensed by the AO WFS, in a way similar to other works based on the estimated Strehl Ratio (SR) delivered by the system. The detailed analysis of the link between metapupil coverage and achievable SR depends not only on the NGSs positions, but also on their brightness, and it is beyond the goal of this work, in which we only considered the limiting magnitude as a threshold for the references selection. To give an idea of the performance in term of AO correction which could be achieved with a certain covered metapupil fraction, we can consider some scientific results obtained with an already existing MCAO system: MAD at VLT. In the work by Wong et al. [9], for example, scientifically relevant results have been obtained from 1'×1' images of Jupiter taken with MAD in its Star Oriented mode, delivering a FWHM between 0.1 and 0.16 arcsec inside the whole FoV. In this case, only 2 NGSs were used for the AO sensing, giving a metapupil coverage at the same altitude we considered for all the computations of this paper (9km) of less than 66%, as shown in Figure 8.

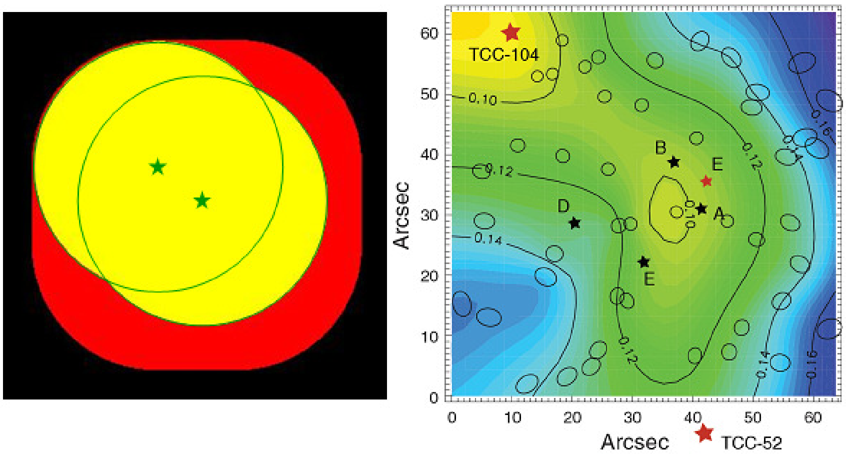

Fig. 8. Metapupil coverage in Wong et al. [9]. *Left*: the red area represents the metapupil projection at a 9km altitude, the green circles represent the entrance pupil projections in the NGSs directions and the yellow area shows the metapupil covered fraction. *Right*: the FWHM map as reported in Wong et al. [9].

Another example of scientific result obtained thanks to MCAO is reported in Moretti et al. [10], in which the K_s band photometry obtained with MAD has been combined with ACS/HST F606W photometry in order to construct a color-magnitude diagram of the Galactic Globular Cluster NGC6388. In this case, the field reported in the work from Moretti et al. has been corrected with AO taking advantage of 5 NGSs, uniformly distributed over a technical FoV wider than the scientific one. This was possible because the AO system was working in its layer oriented mode, so it could take advantage of references with a brightness lower than 15 mag (in the F606W band). In this case the metapupil coverage is really high, resulting in about 95%, since a lot of references have been used, looking for them in a technical FoV wider than the scientific one (as we discussed in the previous sections, this not only increases the metapupil coverage but also considerably improves the sky coverage). The achieved FWHM are higher (0.14 to 0.16) than the one obtained in Wong et al. (please note that the FWHM minimum values of Wong's work correspond to the refence stars positions, which were inside the scientific FoV), however, the field correction is more uniform.

Looking at these results, we can notice that the correspondence between the metapupil coverage and the AO correction in terms of achievable SR or FWHM is not straightforward, however, as expected, a good metapupil coverage translates into an uniform AO correction over the scientific FoV.

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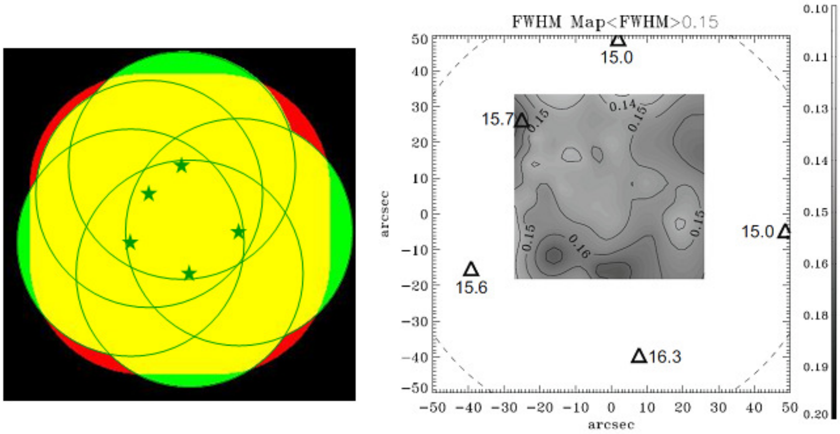

Fig. 9. Metapupil coverage in Moretti et al. [10]. *Left*: the red area represents the metapupil projection at a 9km altitude, the green circles represent the entrance pupil projections in the NGSs directions and the yellow area shows the metapupil covered fraction. *Right*: the FWHM map as reported in Moretti et al. [10].

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