E-ELT PROGRAMME

MICADO Phase A
Photometric Study

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ABBREVIATIONS AND ACRONYMS

AO	adaptive optics
CAD	computer aided design
CAE	computer aided engineering
CMD	colour-magnitude diagram
ECSS	European Cooperation for Space Standardization
E-ELT	European Extremely Large Telescope
ESO	European Southern Observatory
FDR	Final Design Review
FoV	Field of View
FTE	Full Time Equivalent (year)
GLAO	ground layer adaptive optics
GMT	Giant Magellan Telescope
JWST	James Web Space Telescope
LESIA	Laboratoire d'Etudes Spatiales et Instrumentations pour l'Astrophysique
LTAO	laser tomography adaptive optics
MAIT	Manufacture, Assembly, Integration, Test
MAORY	Multi-conjugate Adaptive Optics Relay
MCAO	multi-conjugate adaptive optics
MICADO	Multi-adaptive optics Imaging Camera for Deep Observations
MPE	Max-Planck-Institut für extraterrestrische Physik
MPIA	Max-Planck-Institut für Astronomie
NOVA	Nederlandse Onderzoekschool voor Astronomie
OAPD	Osservatorio Astronomico di Padova
PAE	Preliminary Acceptance in Europe
PAO	Preliminary Acceptance at the Observatory
PA/QA	Product Assurance / Quality Assurance
PDR	Preliminary Design Review
PSF	Point Spread Function
RTD	Real Time Display
SCAO	single-conjugate adaptive optics
TMT	Thirty Meter Telescope
USM	Universitäts-Sternwarte München
WP	Workpackage

1 SCOPE

This document addresses the question of whether MICADO on the E-ELT will be able to obtain colour-magnitude diagrams of resolved stellar populations at the distance of the Virgo cluster with sufficiently high photometric accuracy to derive star formation histories. Implicit in this question, and dealt with here explicitly, are the issues of: (i) the complex PSF delivered by the MCAO system, (ii) the impact of anisoplanatism during early operation with SCAO, (iii) whether current photometric packages are sufficient, and (iv) the high surface brightness (due to extreme crowding) of the galaxies themselves.

2 APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable Documents

The following applicable documents form a part of the present document to the extent specified herein. In the event of conflict between applicable documents and the content of the present document, the present document shall be taken as superseding.

AD1 Common definitions and acronyms, E-ESO-SPE-313-0066, Issue 1

AD2 E-ELT Interfaces for Scientific Instruments, E-TRE-ESO-586-0252, issue 1

AD3 Call for Proposal For a Phase A Study of a High Angular Resolution Camera for the E-ELT, Specifications of the Instrument to be studied, E-ESO-SPE-561-0097, v2.0

AD4 Statement of Work for the Phase A Design of MICADO, E-SOW-ESO-561-0127, v1.0

2.2 Reference Documents

RD1 MICADO Instrument Development and Management Plan, E-PLA-MCD-561-0001, v1.0

RD2 MICADO Scientific Analysis Report, E-TRE-MCD-561-0007, v 2.0

RD3 MICADO System Overview, E-TRE-MCD-561-0009, v 2.0

RD4 MAORY Phase A study: Status at mid-term progress meeting, E-TRE-INA-528-0021, v 1.0

RD5 MICADO Opto-Mechanical Design and Analysis, E-TRE-MCD-561-0011, v 5.0

3 PROJECT OVERVIEW

MICADO is the Multi-AO Imaging Camera for Deep Observations, which has been designed for the E-ELT. The instrument is able to image, through selected wide and narrow-band filters, a 53”×53” field of view at the diffraction limit of the E-ELT. It is primarily intended to work with the MCAO system MAORY; but it is also able to interface to, and deliver high quality images from, other AO systems. In particular, it includes its own SCAO module for initial operations. During this early phase, the development plan is that only the central 26”×26” field will be covered with detectors since anisoplanatism will limit the performance further off axis. The remainder of the detectors will be installed during the upgrade to MCAO operations.

4 SCIENTIFIC RATIONALE

One of the primary science goals of an ELT is to be able to resolve and study the stellar population, star by star, in an Elliptical galaxy. Elliptical galaxies represent a large fraction of the luminous mass in the Universe and all indirect observational indications, from the discovery of Elliptical galaxies in high red-shift surveys, to studies of integrated stellar populations, suggest that they are predominantly very old systems. However, the main theory of galaxy formation predicts that they assembled relatively recently, and should therefore be dynamically young. It is important to accurately quantify this apparent contradiction. One piece of the puzzle is the detailed and accurate star formation history from studies of resolved stellar populations. Color-Magnitude Diagrams can tell us when and under what conditions Elliptical galaxies formed most of their stars, using techniques developed for studies of Local Group galaxies. There is no giant Elliptical galaxy in the nearby Universe that can be resolved into individual stars. The closest region of the Universe with a selection of “normal” Elliptical galaxies is the Virgo cluster, 18Mpc away. The aim of this report is to understand if it is possible to obtain CMDs with a sufficiently high photometric accuracy at this distance with a complex AO PSF. In this context, ‘sufficiently accurate’ implies the ability to determine a star formation history and determine if a galaxy is predominantly young or old. It is of course also interesting to study the range of galaxy types found in the Universe that are less distant than the Virgo cluster. Hence, partly as a comparison but also as a point of relevance for science cases relating to other types of galaxies we also simulate galaxies at 3Mpc distance. It is important to determine under which conditions accurate photometry can be obtained. Specifically the surface brightness limit combined with the crowding limit will tell us the fraction of the galaxy for which we can hope to obtain accurate photometry and how many stars we can hope to detect at different magnitudes in a given amount of telescope time. One of the crucial aspects is to understand how close to the centre of typical galaxies we can photometer stars with sufficient accuracy to determine the detailed properties of the stellar population. This document is primarily an initial test of the ability of current photometric tools to be able to cope with a MAORY-like PSF in a number of straightforward but scientifically important examples.

5 SIMULATION AND PHOTOMETRY

All the simulations for this document have been made using the IRAF package *artdata* (artificial data). Most of the parameters such as background, pixel scale, read-noise, throughput etc have been chosen so that the simulated image will resemble as closely as possible what might be expected from MICADO (see Table 1 and Table 2). The exposure time has been taken to be 1 hour for each simulation. For the simulations we have used either a 3×3 arcsec FoV, which corresponds to 1000×1000 pixels on the detector, or a 0.75×0.75 arcsec FoV, which is 250×250 pixels. This is a small but representative fraction of the larger FoV expected for MICADO. We stick to a one hour exposure as a representative image depth to determine the generic effects of crowding, and photometric errors.

Photometry of resolved stellar populations has to date been predominantly carried out in optical filters (e.g., BVI). This is certainly the easier regime to carry out accurate deep photometry because the sky background is relatively faint and stable, and excellent image quality has been obtained for deep exposures at good sites with active image correction on the ground (e.g. Paranal) and most notably from space (HST). However MICADO on the E-ELT will be much more efficient at infra-red wavelengths, as AO works best at longer wavelengths. The bluest filter presumed to be available with a minimum acceptable AO performance is Johnson-Cousins I. This is also the bluest MAORY PSF that was provided. On the other hand, a much better performance is expected in JHK filters. We have therefore chosen to carry out our initial simulations in I and Ks filters which are at the extremes of the wavelength of operation of MICADO.

Table 1: Telescope and instrument parameters.

Parameter	Unit	Value
Collecting area	m^2	1275
Telescope throughput		0.74
AO throughput		0.80
Instrument throughput		0.60
Total throughput (including detective QE)		0.40
Read noise	e^-	5

Table 2: Filter characteristics (Vega magnitudes)

Filter	Units	I	J	H	Ks
Filter centre	μm	0.900	1.215	1.650	2.160
Filter width	μm	0.24	0.26	0.29	0.32
Zero magnitude	ph/s/m^2/μm	3.76E+10	2.02E+10	9.56E+09	4.66E+09
Sky brightness	mag/$arcsec^2$	19.7	16.5	14.4	13.5
Background	e^-/s/pixel	0.6	5.8	20.9	25.7

5.1 Limiting Magnitudes

Figure 1 shows the limiting magnitude that can theoretically be achieved with MICADO+MAORY as a function of time for S/N ~ 5. It can be seen that limiting magnitudes

(Vega) of **29.3** and **27.0** can be achieved for I and Ks filters for an exposure time of 1 hour (this is the exposure time adopted for all simulations in this document). The following equations have been used to convert from AB to Vega magnitudes.

$$I(AB) = I(Vega) + 0.3$$

$$K(AB) = K(Vega) + 1.9$$

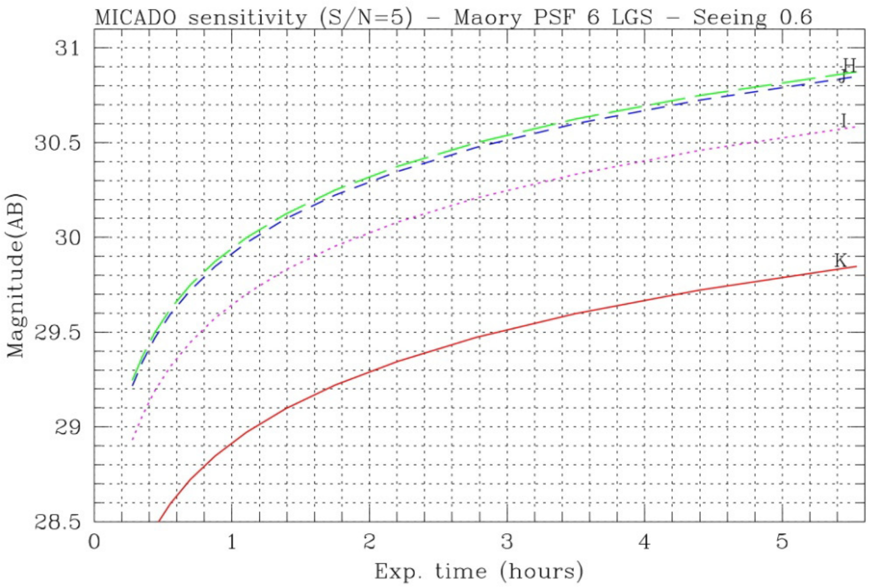

Figure 1: Limiting magnitudes for I, J, H and Ks filters (AB magnitudes) as a function of time for S/N=5. The sensitivities have been calculated using MAORY PSFs that were created with a seeing of 0.6 arcsec.

5.2 PSFs

Two different adaptive optics models of MICADO have been considered in this study, MCAO and SCAO. The majority of the detailed simulations have been carried out with MCAO PSFs that were kindly provided by the MAORY consortium, such as those shown in Figure 2. In Figure 3 we show the simulated image of a small region in an old galaxy at 18Mpc using these PSFs. The I-band image shown there, and the corresponding Ks band image, were analysed using the photometry package Starfinder (developed by E. Diolaitti). The PSF for doing photometry was in each case extracted directly from the simulated field and *not* assumed a priori. Figure 4 shows how this extracted PSF compares to the original input PSF. We also carried out a similar comparison with the more commonly used DAOPHOT/Allstar (P.Stetson).

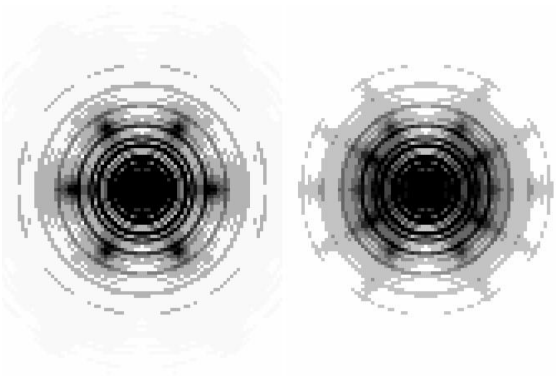

Figure 2: MCAO PSFs provided by the MAORY consortium. The 2 PSFs corresponds to the centre of the field (left) and the edge of the field (right), 30arcsec from the centre. These are I band PSFs created for a seeing of 0.6arcsec.

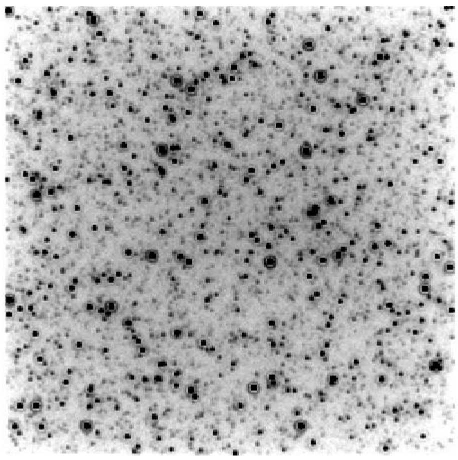

Figure 3: A simulated MICADO I band image of an old galaxy at 18 Mpc in a field of view of 0.75×0.75 arcsec (250×250 pixels), made using MAORY PSFs. The exposure time is 1 hour. The surface brightness of the galaxy at this position is ~20 mag/arcsec^2 in I band. 1200 stars were detected in the image using Starfinder (out of 200,000 populated stars going 7mags below the detection limit).

Figure 4: PSFs corresponding to the simulations shown in Figure 3, and other similar simulations: that extracted by Starfinder (left) and the original PSF used to make each simulation (right). The sizes of the images are 0.15 arcsec.

In addition to the MCAO simulations, we also performed an analysis of images made from the types of PSF one can expect from SCAO (see Figure 5), focussing on anisoplanatism, which is the major difference with MCAO. For SCAO, the PSFs we used were computed using the simulator PAOLA (developed by L. Jolissaint). As before, we have simulated an old galaxy at a distance of 18Mpc, this time using on-axis and off-axis SCAO PSFs. The resulting images are shown in Figure 6.

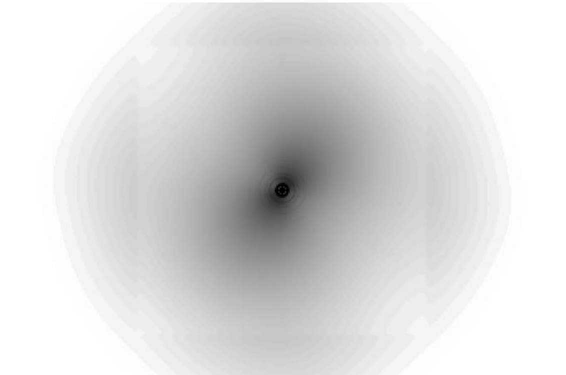

Figure 5: SCAO PSF simulation for the I band using PAOLA. The science target (i.e. this star) is at an angle of 5 arcsec from the guide star. A seeing of 0.6arcsec has been considered.

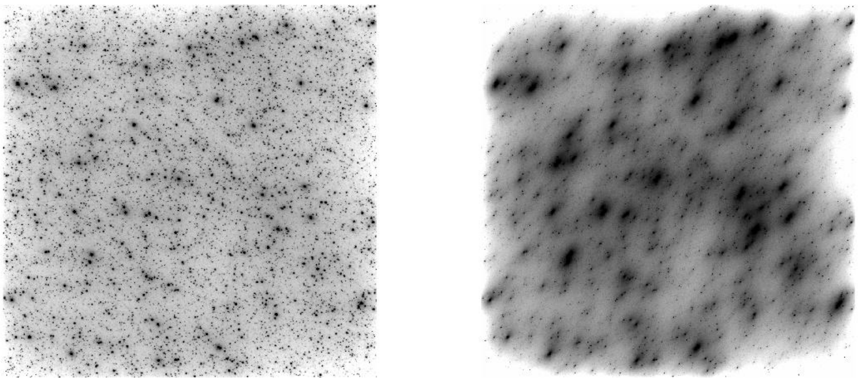

Figure 6: Simulated I band image of a 3×3arcsec field in an old galaxy at a distance of 18 Mpc using SCAO PSFs. On the left is the central 3×3arcsec and on the right is a similar field 15arcsec off-axis.

6 METHODOLOGY

The simulations are carried out using IRAF task *mkobjects.* As input we used, for each case, a list of stellar absolute magnitudes as derived from a simple theoretical synthetic population (from IACstar, which is available at http://iac-star.iac.es/). We created a "complete" stellar population down to the lowest mass objects for an assumed star formation history. We have chosen to simulate four generic examples relating to potential science cases in MCAO mode:

- An old galaxy at 18 Mpc
- An old galaxy at 3 Mpc
- A young galaxy at 18 Mpc
- A young galaxy at 3 Mpc

For each simulation a 1000×1000 pixel (3×3 arcsec FoV) or a 250×250 pixel (0.75×0.75 arcsec FoV) fits file is created in each of the I and Ks filters for the adopted exposure time of one hour. This means that these simulations are not testing the limit of what is possible but trying to understand how well photometry can be done under more reasonable and simple assumptions. The number of stars put down on each image is typically 200,000. However, to study crowding effects this number is varied from 25,000 to 100 million stars. In all cases most remain undetected and merely add to the spatially variable (stellar) background flux.

To detect and measure the magnitudes of the stars in our simulated images, we primarily used Starfinder (E. Diolaiti, 2000), a code developed to perform PSF photometry on stellar AO images. This software is able to take into account the variation of the PSF across the image. We also performed photometry with DAOPHOT/Allstar (P. B. Stetson 1987, 1994) one of the most commonly used photometric packages. Since it returned very similar results to Starfinder, here we only discuss the Starfinder results. In this way we photometered all the simulated images, and considered the general effects of a peculiar AO PSF combined with crowding and distance on the photometric results (see Figures 7-14). We note that these are not very deep images, nor is extreme crowding considered. But this is primarily a test of the ability of current photometric tools to be able to cope with a MAORY-like PSF; and the impact of more extreme crowding is addressed in Section 9.

7 MCAO RESULTS

To determine the properties of resolved stellar populations in distant galaxies, spatial resolution and sensitivity are important. However it is also equally important that images can be accurately photometered over a FoV large enough to include a significant number of stars to populate a CMD. Accurate photometry requires a PSF that is stable and can be modelled. The major emphasis of this report is on MCAO imaging which offers the best and most stable image quality over the widest FoV. We have used MAORY PSFs provided to us by the MAORY consortium to simulate the images. The aim is that the combination of MICADO and MAORY will allow us, for the first time, to be able to observe crowded resolved stellar fields in galaxies out to and beyond the distance of the Virgo cluster.

Each of the simulations listed in Section 6 refers to a specific case and distance, and assumes a position within the galaxy that has a given surface brightness. For each case, we show 2 figures. The first contains a pair of CMDs. In the left-hand panel is the input CMD in I and Ks (both Vega magnitudes). In the right-hand panel is the CMD retrieved from the simulated image (measured by Starfinder). To quantify the quality of the photometry we matched the input and retrieved (output) catalogues to each other, and plotted the difference for each filter in the 2 panels of the second figure. This is, by definition, the ‘photometric error’ we achieve. It can be seen that the measured magnitudes do not go deeper than about I=29.5mag for a limiting error of 0.2mag (which is 20% photometry or a 5σ detection), which is consistent with the magnitude limits predicted in Figure 1. The features in the retrieved CMD are well defined up to this limit, which means that an acceptable photometric accuracy is achieved. As expected, the error becomes steadily larger towards fainter magnitudes. We computed a mean error for each magnitude and these values are over plotted in red on the measurements.

7.1 Results: Old Galaxy, 18Mpc away

The results of the simulation of an old galaxy 18 Mpc distant (input and output CMDs) are shown in Figure 7, and the direct comparisons between the input and output magnitudes are shown in Figure 8. It should be borne in mind that an Elliptical galaxy typically has a central surface brightness closer to 15mag/arcsec^2, significantly brighter than that used in this simulation. As such, these images are not particularly deep nor is the surface brightness – i.e. crowding regime – especially demanding (this issue is studied in Section 9). Instead they indicate what should be possible slightly out from the centre of the galaxy, perhaps at $2R_{eff}$. Here, we find that the limiting factor in obtaining a sufficiently deep CMD at this surface brightness is the Ks image depth. The Horizontal Branch is at I~31.3 and Ks ~ 30.6 at a distance of 18 Mpc (m-M = 31.3). If we scale the integration time we can expect to be able detect the presence of a Horizontal Branch in I with an acceptable photometric accuracy at this surface brightness in an integration time of about 15 hours. However detecting it in K is unlikely to be possible. The sensitivity determinations shown in Figure 1 indicate that Ks = 30.6 is out of reach of MICADO/MAORY. On the other hand, sufficient sensitivity should be achievable in the H filter. And so perhaps I-H is a better combination to detect the Horizontal Branch at the distance of Virgo. On the basis of these simulations we can expect to detect in the Horizontal Branch quite clearly in the I-filter luminosity distribution.

7.2 Results: Old Galaxy, 3Mpc away

The results of the simulation of an old galaxy 3Mpc distant (input and output CMDs) are shown in Figure 9, and the direct comparisons between the input and output magnitudes are shown in Figure 10. As for the previous case, these images are not particularly deep nor is the surface brightness (crowding regime) especially demanding, but even so quite a bit more detail can be seen compared to Figure 7. The limiting factor is again the Ks image depth, but despite this the Horizontal Branch is clearly and accurately detected (at I=27.3 and K=26.7). If we scale the integration time, we can expect to probe deeper down the Main Sequence, to the oldest turn-offs. To do so in the I filter would require about 15 hours of integration time. Thus the oldest Main Sequence Turnoffs at 3Mpc are at a comparable photometric depth to the Horizontal Branch at 18Mpc. But the crowding effects are less at 3Mpc because the number of undetected stars at fainter magnitudes is smaller and hence the stellar background light is less. As a result, the limiting magnitude of the detected stars is fainter. This appears to be the case, comparing Figures 8 and 10. Although detecting the oldest Main Sequence Turnoffs in K will be impossible, it is possible in H filter. Thus I-H is a better combination to *detect* the oldest Main Sequence turnoffs to 3Mpc distance.

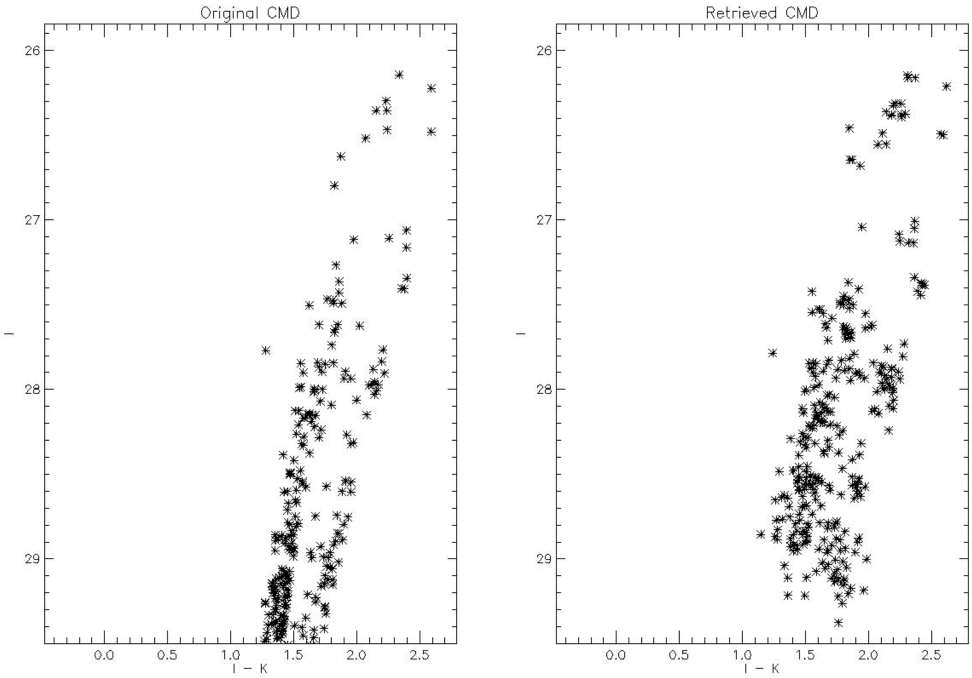

Figure 7: CMD (I vs. I-Ks) in Vega mag for an old galaxy at 18 Mpc: input (left) and retrieved (right). The surface brightness is $\mu_I = 19.8$ mag/arcsec^2 and $\mu_K = 18.4$ mag/arcsec^2. There are 200 000 stars in the field of view of 0.75 x 0.75 arcsec, going down 7 mags below the detection limit. 1300 stars could be detected using Starfinder.

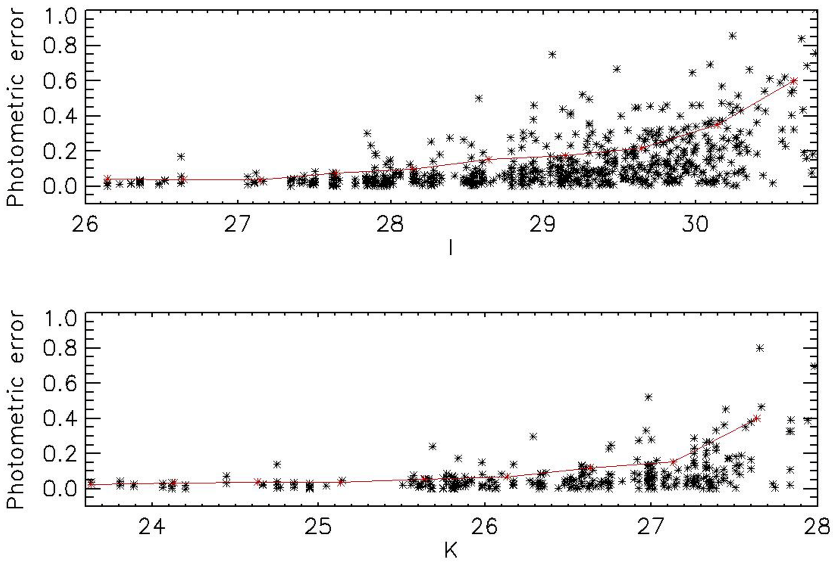

Figure 8: Difference in magnitudes (photometric error) between the input and output I and Ks catalogues of Figure 7. Over-plotted in red are RMS errors in 0.5 mag bins. There are 1300 stars in the upper panel and 700 stars in the lower panel.

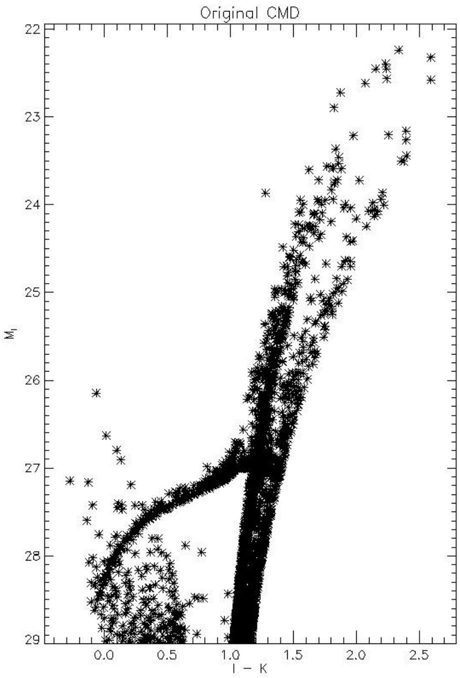

Figure 9: CMD (I vs. I-Ks) in Vega mag for an old galaxy at 3 Mpc: input (left) and retrieved (right). The Surface brightness is $\mu_I = 19.9$ mag/arcsec^2 and $\mu_K = 18.3$ mag/arcsec^2. There are 200 000 stars in the field of view of 3×3 arcsec, going down 7mags below the detection limit. 14 000 stars could be detected using Starfinder.

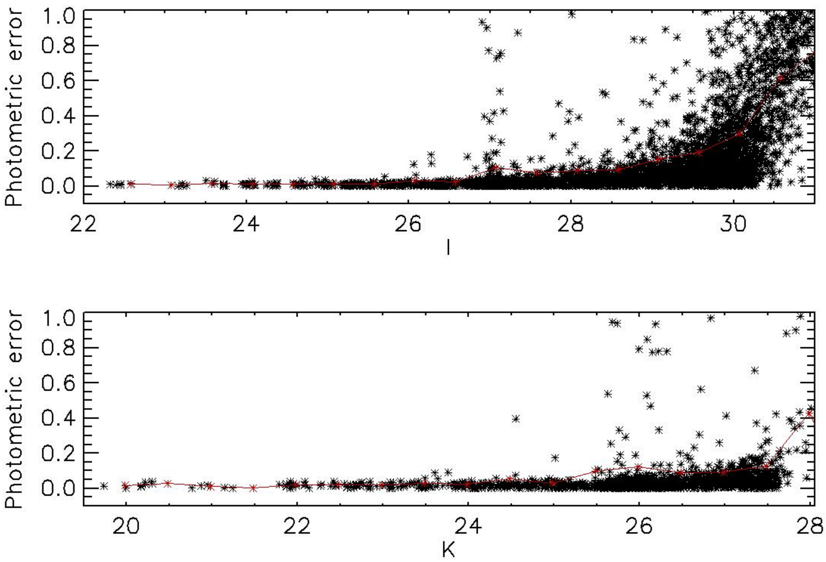

Figure 10: Difference in magnitudes (photometric error) between the input and output I and Ks catalogues of Figure 9. Over-plotted in red are RMS errors in bins of 0.5 mag. There are 14 000 stars in the upper panel and 6000 stars in the lower panel.

7.3 Results: Young Galaxy, 18Mpc away

The results of the simulation of a young galaxy 18Mpc distant (input and output CMDs) are shown in Figure 11, and the direct comparisons between the input and output magnitudes are shown in Figure 12. As before, the limiting factor in obtaining a sufficiently deep CMD at this surface brightness is the Ks image depth, and the bluest main sequence stars are not detected in this band. It is possible to determine the difference (even by eye) between the features in the right-hand CMDs in Figures 7 and 11. The bright blue-loop stars are clearly visible in Figure 11, distinguishing this as a galaxy that contains a young stellar population. Of course the challenge remains to determine the properties of the underlying older stellar population in this predominantly young galaxy and work out the relative fraction of both. This requires the same photometric depth as for the old galaxy, but in this case the crowding will be more severe because there are more bright stars whose wings will hamper accurate photometry at faint magnitudes and increase the background. As with the simulation in Section 7.1, if we scale the integration time to 15 hours, we can still expect to be able detect the presence of a Horizontal Branch in I with an acceptable photometric accuracy at this surface brightness. Again, the H filter might be a better choice to determine more detail in the CMD to a greater depth.

7.4 Results: Young Galaxy, 3Mpc away

The results of the simulation of a young galaxy 3Mpc distant (input and output CMDs) are shown in Figure 13, and the direct comparisons between the input and output magnitudes are shown in Figure 14. Due to the proximity of the galaxy, much more detail can be seen than in Figure 11. Again the large numbers of bright blue stars clearly distinguish this from a galaxy dominated by old stars at the same distance (e.g. Figure 9). The limiting factor is again the Ks image depth. The Horizontal Branch is barely detected (at I=27.3 and K=26.7), although the red clump is quite clearly visible. This is due to additional crowding from the large numbers of very bright stars in these images. This means that the photometric accuracy is less than it is for a predominantly older system where there are very few bright stars. Although the brightest blue-loop stars and (blue) main sequence stars are detected, the Ks magnitude limit has a clear effect on reducing the fraction of the Main Sequence stars that are detected. If we scale the I-band integration time to 15 hours, we can expect to probe deeper down the Main Sequence to the oldest turn-offs – although it will be more challenging than the case in Section 7.2 because of the additional crowding from bright stars. It is again possible that the H filter is a better choice, allowing the *detection* of the oldest Main Sequence turnoffs at 3Mpc distance in a galaxy dominated by bright young stars. However this statement must be made cautiously since it may be difficult to *interpret* these turnoffs in great detail because of the lack of colour baseline to spread out the Main Sequence and the brighter features in the CMD sufficiently. Instead, it might be possible to at least estimate the relative fraction of old and young stars in a currently star forming galaxy, even if one cannot derive a full and accurate star formation history down to the oldest main sequence turn-offs.

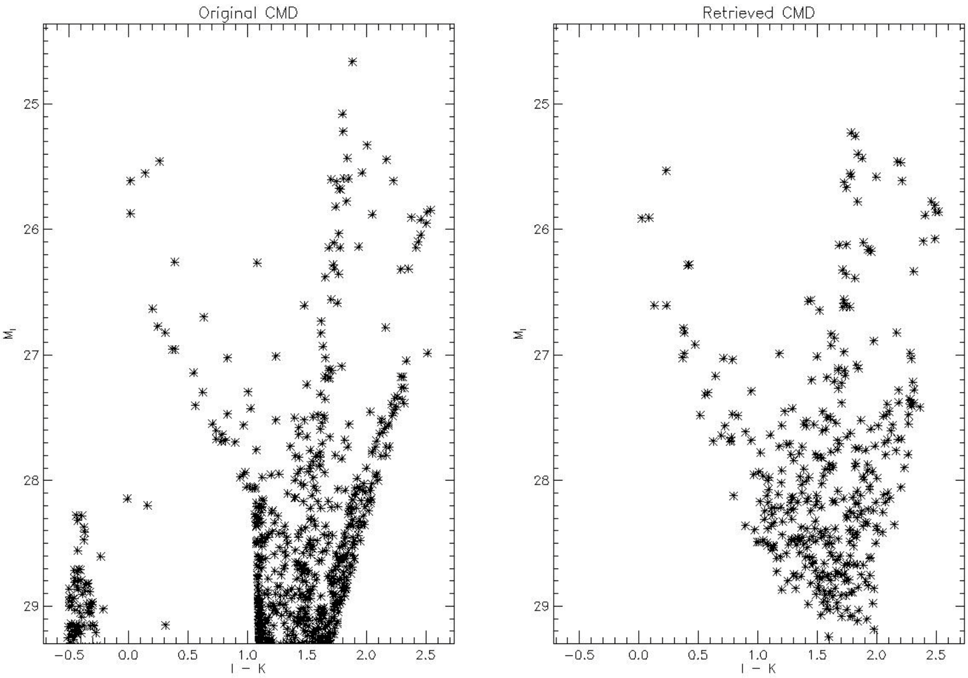

Figure 11: CMD (I vs. I-Ks) in Vega mag for a young galaxy at 18 Mpc: input (left) and retrieved (right). The Surface brightness is, $\mu_I = 18.3$ mag/arcsec^2 and $\mu_K = 17.1$ mag/arcsec^2. There are 200 000 stars place in the field of view of 0.75×0.75 arcsec, going down 7 mags below the detection limit. 1500 stars could be detected using starfinder.

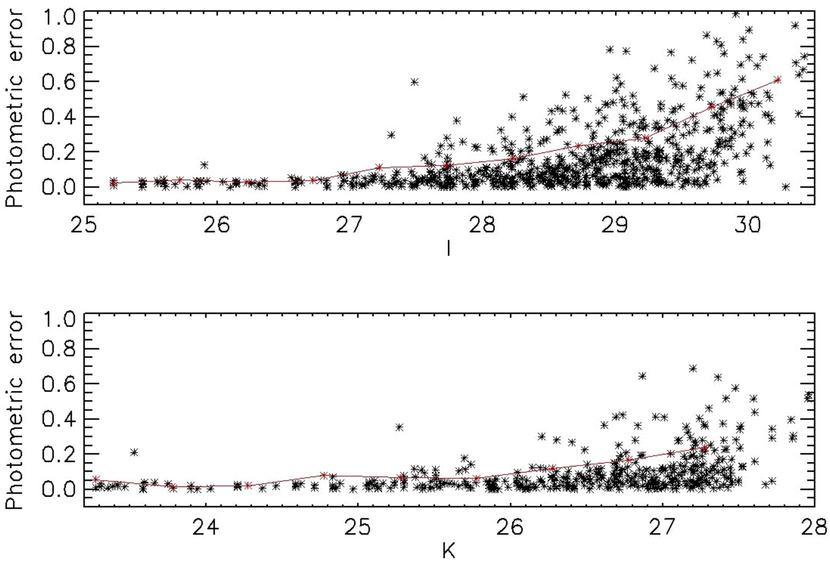

Figure 12: Difference in magnitudes (photometric error) between the input and output I and Ks catalogues of Figure 11. Over-plotted in red are RMS errors in 0.5 mag bins. There are 1500 stars in upper panel and 800 stars in lower panel.

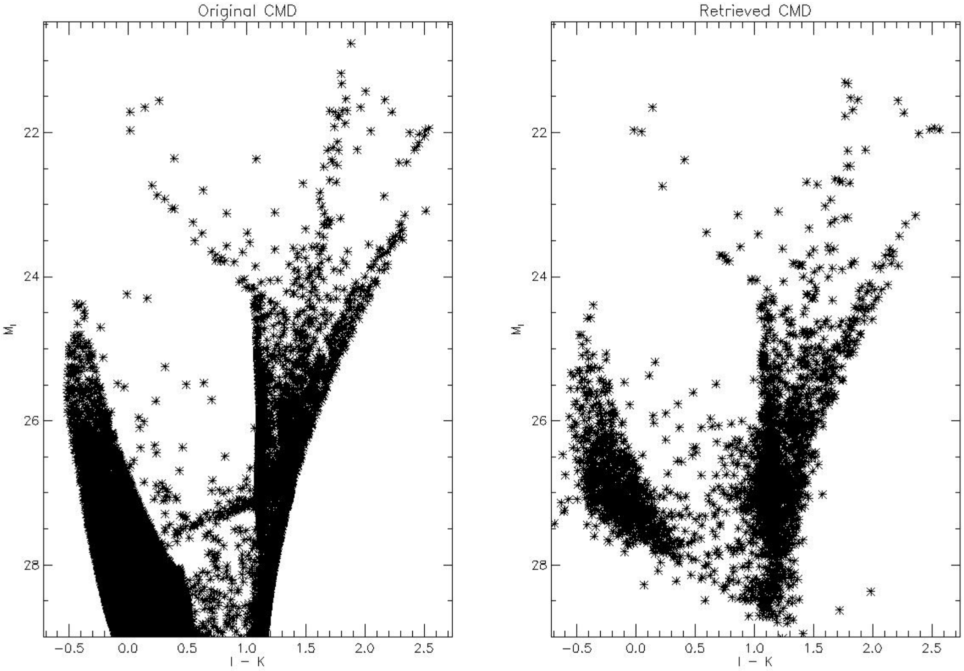

Figure 13: CMD (I vs. I-Ks) in Vega mag for a young galaxy at 3 Mpc: input (left) and retrieved (right). Surface brightness is $\mu_I = 18.9$ mag/arcsec^2 and $\mu_K = 17.7$ mag/arcsec^2. There are 100 000 stars in the field of view of 3×3 arcsec down to a magnitude limit 7 mags below the detection threshold. Around 24 000 stars were detected using Starfinder.

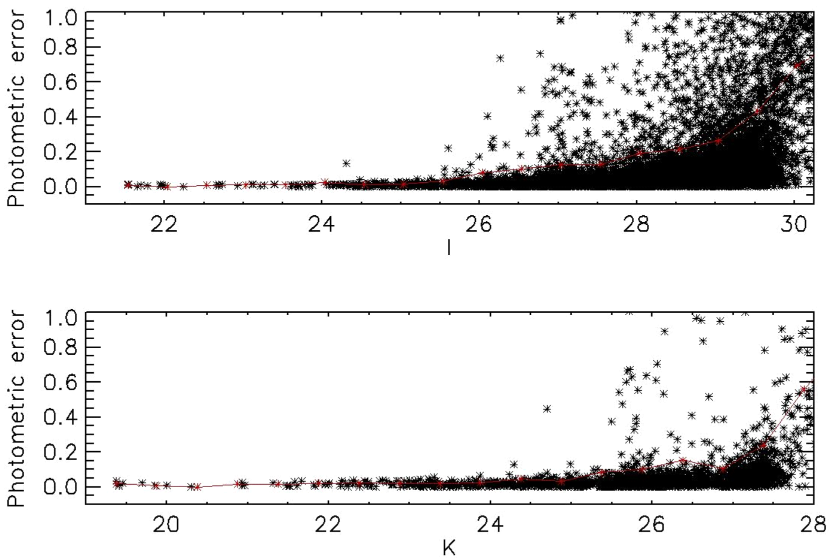

Figure 14: Difference in magnitudes (photometric error) between the input and output I and Ks catalogues of Figure 13. Over-plotted in red are RMS errors in 0.5 mag bins. There are 24 000 stars in upper panel and 8000 stars in lower panel.

In addition to these general simulations, we carried out specific tests of the effect of anisoplanatism by looking at 3×3 arcsec fields at different distances from the centre of the MICADO FoV using the appropriate MAORY PSFs. We saw little noticeable effect on the photometry over the MICADO FoV, although obviously the effect increases for faint magnitudes where the varying PSF is more difficult to define. MAORY PSFs are available for different seeing conditions, and we find that the impact on photometry of degrading the seeing from 0.6 arcsec to 0.8 arcsec appears to be small.

8 SCAO

MICADO has its own SCAO module, and the development plan proposes that during early operational phases, MICADO should be use with this simpler and more robust AO system. We have therefore performed a number of simulations appropriate to the SCAO mode, with which we have studied the primary difference between SCAO and MCAO – the ability to carry out accurate photometry when there is strong variation of the PSF with field position. Photometry becomes more difficult because the light of the stars becomes more elongated, or spread out over more pixels the further away it is from the centre of the field. This results in a brighter magnitude limit and/or higher uncertainties in measuring the magnitudes of faint stars.

To determine the effect of the elongated PSF on photometric accuracy, we have simulated cases where stars are photometered in 3×3 arcsec FoV at distances of 5, 10, 15 and 30 arcsec from the guide star at the centre of the field. For the photometry itself, we use only the PSF extracted from a central field. This exercise has been done in both I and Ks filters to compare the impact of anisoplanatism on photometric accuracy at different wavelengths. The resulting CMDs for an old galaxy at a distance of 3Mpc are shown in Figure 15, and the uncertainties for the I-band and K-band in Figure 16 and Figure 17 respectively.

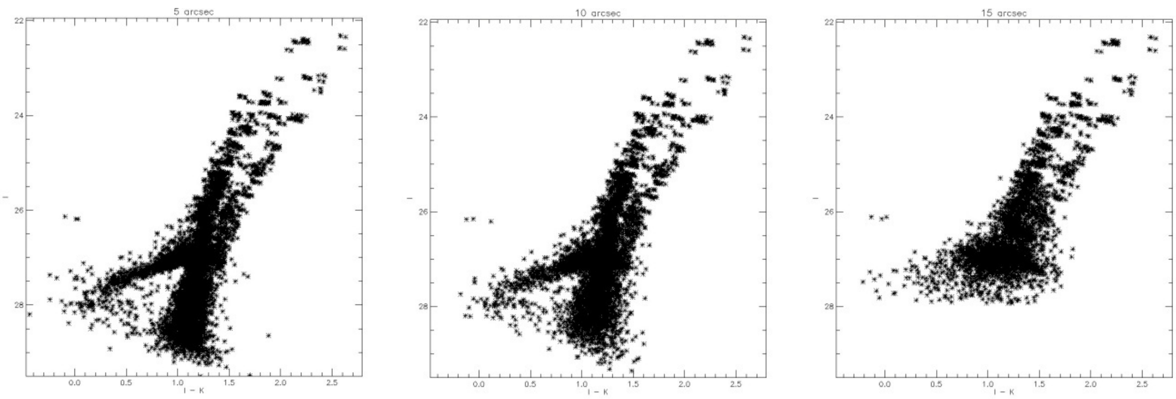

Figure 15: CMDs for single conjugate adaptive optics at 5” (left), 10” (centre), and 15” (right) off-axis. The on-axis CMD is indistinguishable from the left-hand panel. A summary of the photometric errors for the I- and K-bands is given in the following figures. The degradation in photometric accuracy – and hence in quality of the scientific interpretation – is clearly visible beyond 10” off-axis. The useful (i.e. well corrected) field of view for SCAO is well matched to the field covered by the central 2×2 detectors in MICADO.

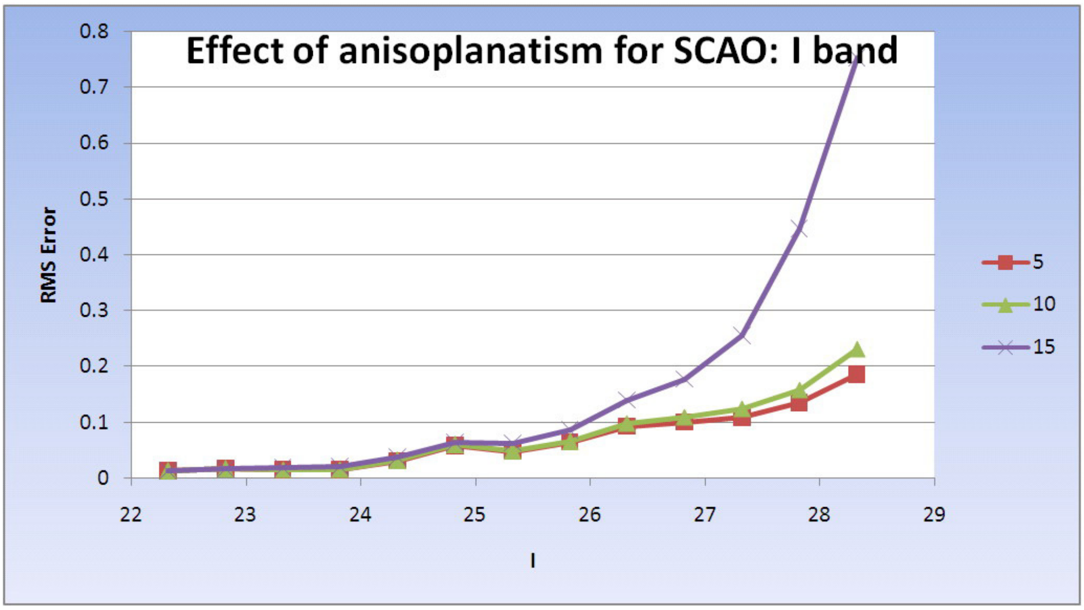

Figure 16: The effect of anisoplanatism on photometric accuracy in the I band. Different coloured lines show the effect of different levels of anisoplanatism when the target is 5, 10 and 15 arcseconds off axis. For a distance of 30 arcseconds off axis there is no useful information.

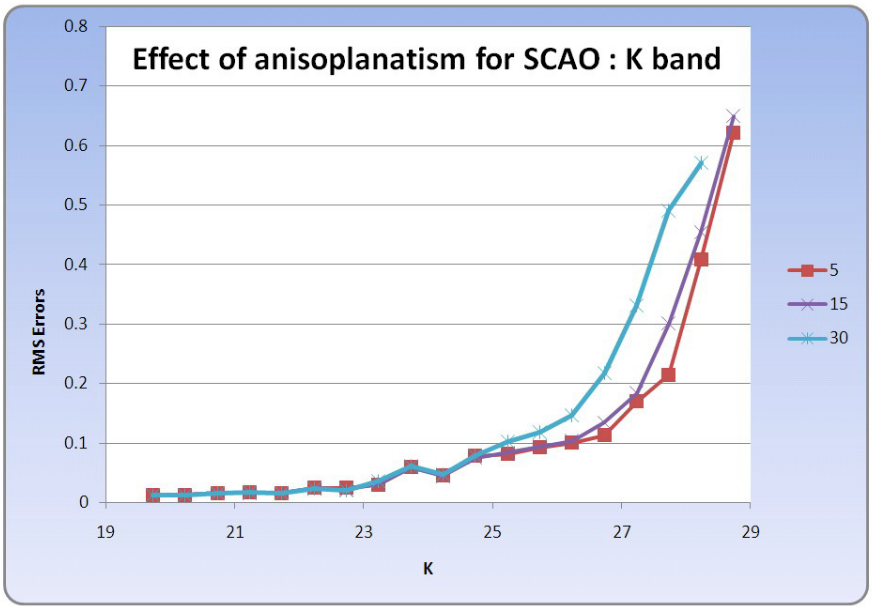

Figure 17: The effect of anisoplanatism on photometric accuracy in the Ks band. Different coloured lines show the effect of different levels of anisoplanatism for a target 5, 15 and 30 arcseconds off axis.

Perhaps the most obvious conclusion from Figures 15 and 16 is that, as one would expect, anisoplanatism has a stronger effect on photometry at shorter wavelengths. It is also clear from Figure 15 that the magnitude limit in the I-filter is brighter for SCAO than for MCAO (e.g. compared to Figure 9). However, this may be a function of the guide star brightness for SCAO, since one would expect better performance for brighter guide stars. In the absence of such bright stars, at shorter wavelengths it appears that SCAO could be particularly challenging for studies of faint resolved stellar populations. On the other hand, it can also be seen that for magnitudes I < 28, anisoplanatism has little effect on the photometric accuracy. Furthermore, Figure 16 shows that the effects are almost negligible for K: the magnitude limit is similar to that for MCAO (K=27.5), and anisoplanatism has very little effect over a field of view similar to that corrected by MCAO. As such, there is still a significant amount of interesting and useful work that can be done on resolved stellar populations with SCAO.

9 EFFECT OF CROWDING

Despite the vast improvement in resolution afforded by AO, crowding is still expected to have a strong effect due to speckles giving a complex shape of the extended PSF halo of the PSF. This is particularly true for MAORY PSFs. Because the extended component of the PSF is hard to model accurately, the poorly subtracted PSFs of brighter stars result in a high background with large fluctuations (which are greater than for a simple PSF where a larger fraction of the light is to be found in a simple Gaussian core). To measure the effect of different levels of crowding on photometric accuracy, we have performed simulations of MAORY/MICADO that are populated varying densities of stars. We use as an example the case of an old galaxy at 18 Mpc (see Figs. 7 and 8).

Putting large numbers of stars into an image is a very computationally intensive task, and so we have simplified the processes by determining the magnitude cut-off below which going deeper only adds to a uniform background. This cut-off has been determined by a trial where we take different cut-offs and see the effect on the fluctuations in the background level. We find that a cut-off 1.5 mag below the detection threshold will have no effect on the background fluctuations because the objects are too faint. To be completely sure we have applied the cut-off at 2 mag below the detection limit. The light from stars fainter than this limit is added to the images as part of a uniform background level which is effectively a sum of their flux. It is important to include this in the simulation since it gives the appropriate background level in a galaxy for a specific stellar population at a specific distance. The fluctuations due to marginally detected stars are also very important in determining photometric accuracy of the measurements as they determine the size and scale of fluctuations in the background upon which brighter stars have to be accurately photometered. The two effects of smooth background and fluctuations play important roles in determining the photometric accuracy with which it is possible to detect objects of all magnitudes.

Fainter stars are much more difficult to detect and photometer accurately in regions of high stellar density, and are often be retrieved with a magnitude that is too bright – a result of the bias that they are only detected when they happen to sit on top of a fluctuation. The brighter the population of stars in which one is interested, the deeper one can probe into regions with high surface brightness; and also the more accurate the photometry in all circumstances.

In Figure 18 we show the results of a simulation to study the effect of crowding (i.e. equivalently surface brightness) on stars of a given magnitude in an old galaxy. There are significant numbers of overlapping PSFs and so the crowding introduces large fluctuations in the background surface brightness, giving rise to large uncertainties in stellar magnitudes. We look in detail at how accurately the properties of different magnitude stars can be retrieved. The surface brightness in I band varies from 25 mag/arcsec^2 to 16 mag/arcsec^2. In terms of populated (detected) stars this corresponds to 40 (2000) pixels/star and 0.01(16) pixels/star respectively.

From Figure 18 it can be seen that bright stars (e.g. I=26.3) are almost unaffected by crowding right into the central regions of galaxies where the surface brightness is highest. This is because they are less affected by the background of fainter stars that create most of the crowding. At the other extreme, the faintest stars plotted here (I=29.3 and I=30.3) are anyway at or beyond the detection limit. But stars which are detected with a reasonable accuracy when isolated (I < 28) can also be probed well into the densest regions that might be expected in Elliptical and Spiral galaxies at the distance of Virgo. Thus we predict that the tip of the Red Giant Branch and evolved AGB stars should be observable at the distance of Virgo with 20% photometry at a surface brightness μ_I < 16mag/arcsec^2. However, it seems likely that detection of the Horizontal Branch stars in Virgo Elliptical galaxies will only be achievable in the lower surface brightness less crowded outer halo regions.

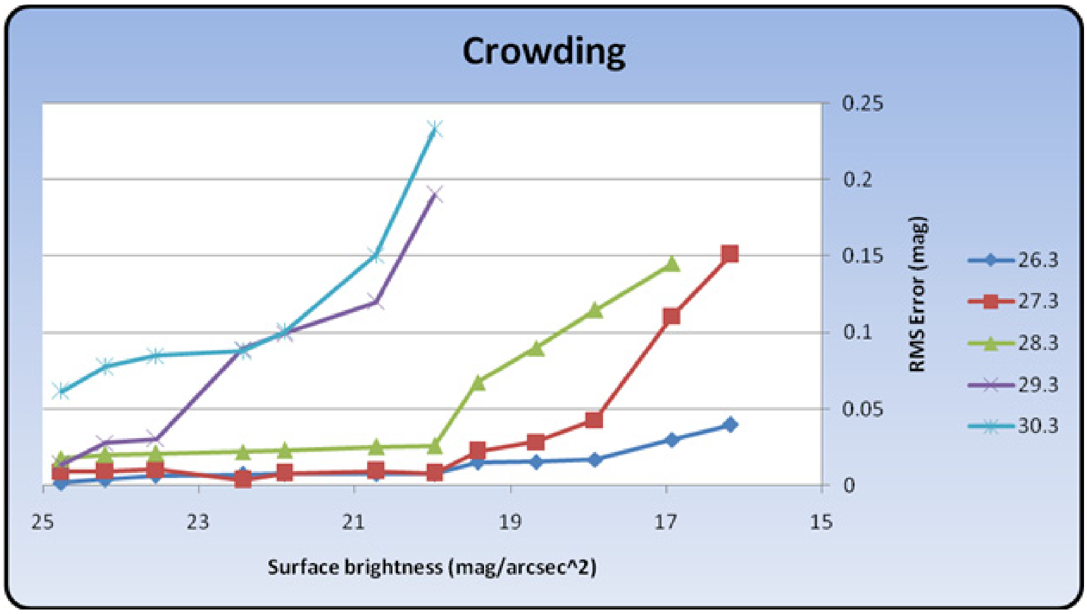

Figure 18: The effect of crowding for observations in the I-filter for stars of different magnitudes (given to the right) at different surface brightness levels for a galaxy at 18 Mpc (m-M = 31.3). The number of stars detected ranges from 500 (for 25 mag/arcsec^2) to 60 000 (16 mag/arcsec^2). The stars retrieved go from I=30.3 (light blue) to I=26.3 (dark blue).

10 POSSIBLE IMPROVEMENTS

In this section we make an initial assessment of the improvements (beyond the status reported here) in photometry and CMD analysis that one might expect. These will be investigated in detail using simulations during the next project phases.

10.1 Optimization of K-band Sensitivity

The K-band sensitivity is strongly limited by 2 effects: (i) the K-band filter adopted is that currently used in HAWK-I, which has only 80-85% transmission, (ii) the thermal background from the telescope and AO system. In this section we assess how much improvement one might expect if these two conditions are optimized. Specifically, we adopt a filter transmission of 98%. This has been achieved for GROND, using an advanced filter design developed by the Laser Zentrum Hannover; developing similar high throughput filters suitable for MICADO is part of an on-going development project (see Section 4.5 of the Opto-Mechanical Design, RD5). We have also investigated the impact of observing on a cold night so that the thermal background from the telescope and AO system is negligible. The impact on the K-band sensitivity is shown in Figure 19 one gains about 0.45mags in depth for the same integration time.

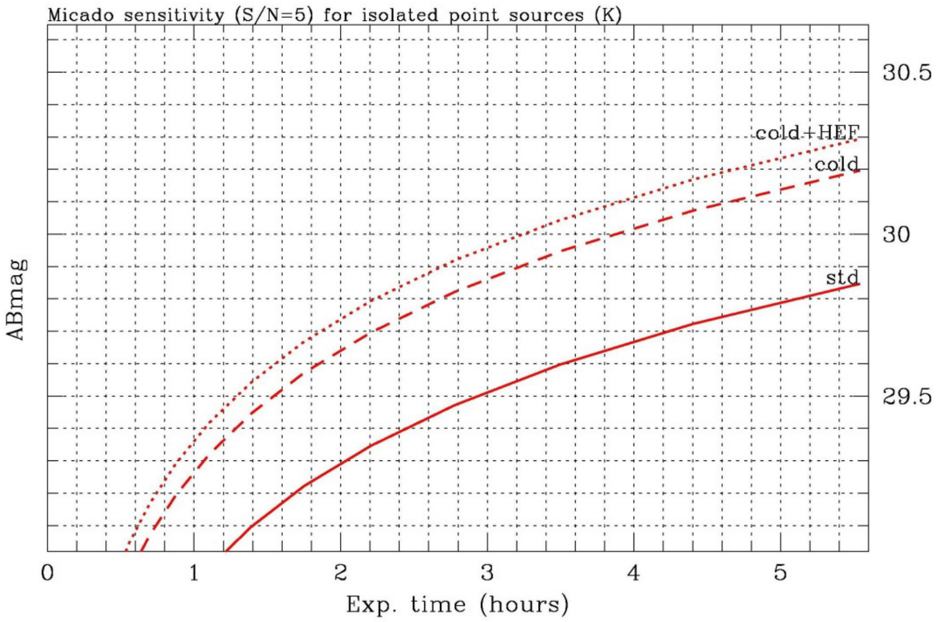

Figure 19: calculation of improvement in K-band sensitivity if observations are done on a cold night (i.e. negligible thermal background from telescope & AO system) and the K-band filter transmission is improved ('cold+HEF').

10.2 Efficacy of the I-H Colour Baseline

The results in Section 7 convincingly show that photometry over the long I-K colour baseline is strongly limited by the K-band sensitivity. In this section, we briefly assess whether the I-H baseline is sufficient to separate different stellar populations. The clear positive conclusion is demonstrated by Figure 20 and Figure 21. Given that the calculated sensitivity in the H-band is about a magnitude deeper than that in the K-band, and that the shorter baseline is still sufficient for useful scientific interpretation of the CMDs, we expect to achieve significantly better results using I/I-H rather than I/I-K. This will be addressed using simulations as part of the on-going photometry study, in order to better understand the trade-off between sensitivity, colour baseline, PSF shape and their respective impact on CMD analysis and scientific pay-off.

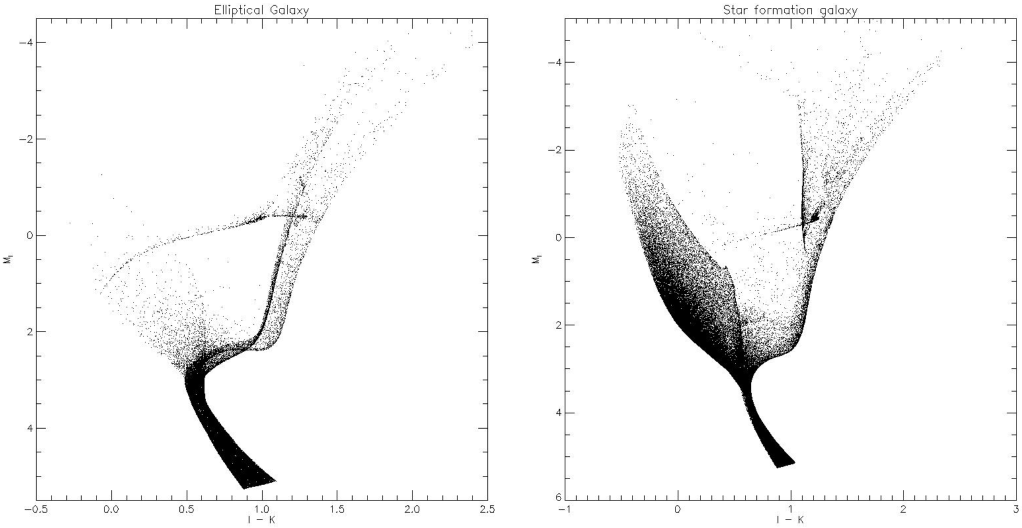

Figure 20: synthetic I/I-K CMDs for elliptical (left) and star forming (right) galaxies. These are plotted on an absolute magnitude scale (that can be adjusted to Virgo or Cen A by applying a distance modulus of 31.3 or 27.4 respectively). These are the input CMDs that have been used for the simulations presented in this document, and show that different branches are well separated.

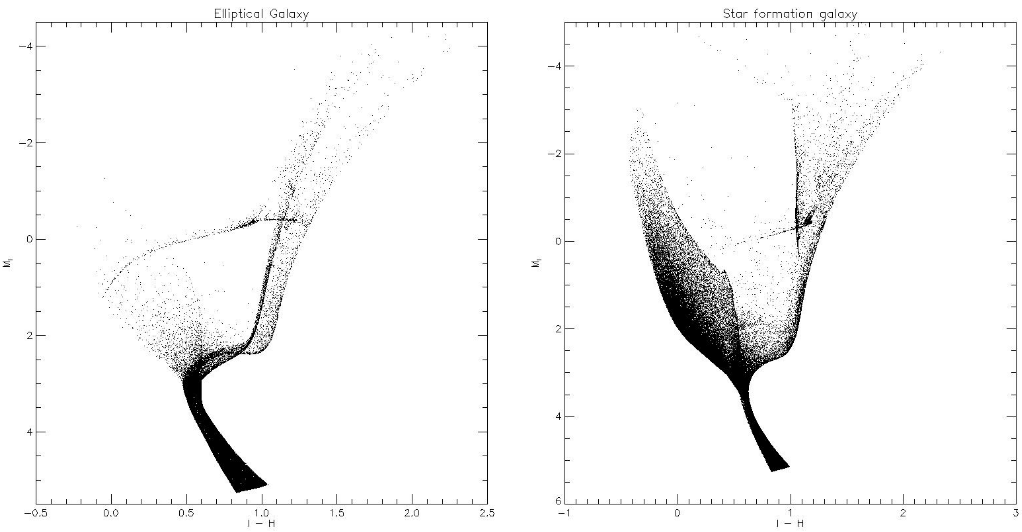

Figure 21: synthetic I/I-H CMDs corresponding exactly to those in Figure 20. The key issue here is that even with the shorter colour baseline, the different branches are still well separated. Thus the I-H colour is sufficient for useful scientific interpretation of the stellar populations in a galaxy.

11 SUMMARY AND CONCLUSIONS

This study has addressed the basic issues involved in carrying out accurate photometry in crowded stellar fields using MICADO. The conclusions are:

(i) Standard, publically available, photometry packages such as STARFINDER and DAOPHOT/Allstar do a good job in most circumstances despite the unusually complex shape of the MAORY PSF. The CMDs that are measured from the simulated images look very promising and are sufficiently well defined to pick out detailed stellar evolution phases and thus determine the ages of the stars.

(ii) Improvement of the PSF model is likely to yield gains in 2 areas: (a) photometric fidelity for stars at the faint limit, and (b) more accurate subtraction of bright stars, so as to reduce the noise from the residuals in their wings, and hence recover some of the lost sensitivity due to the severe crowding effects in the centres of galaxies at the distance of Virgo.

(iii) In Virgo galaxies, it should be straight forward (if time consuming) to make a basic distinction between predominantly young and predominantly old stellar populations on the basis of their CMDs even using the tools and techniques currently available.

(iv) Detecting the Horizontal Branch (i.e. the oldest stars) in Virgo galaxies, or the oldest Main Sequence turnoffs at the distance of Sculptor group, remains on the edge of possibility in these present simulations for any other filter than I. **Any increase in strehl (or encircled energy) that is possible helps this aim significantly.**

(v) With a SCAO system, good photometry can be obtained over at least half the full MICADO field of view in I and virtually the whole field of view in Ks-filter. While this is sufficient to obtain a detailed look at distant stellar populations, MCAO has a clear advantage to map resolved stellar populations at the limits of distance and depth in crowded and/or distant galaxies.

(vi) In Virgo Ellipticals, it should be possible to perform accurate photometry on the brighter stellar populations (tip of the Red Giant Branch and beyond). The limits on this are the crowding imposed by the very densely packed stellar populations in the centres of galaxies.

(vii) The performance for resolved stellar photometry and CMD analysis (at all distances) may be significantly improved by either optimising K-band conditions (thermal background, filter transmission, etc) or by using H-band instead.

While this study has addressed a number of important question about whether it is realistic to study resolved stellar populations out to the Virgo cluster (and to which the answer is 'yes', but with some constraints), there is clearly room for further work. This will be pursued during the next Preparatory Phase of MICADO. In particular, the next set of simulations needs to address 2 main issues:

(i) What can realistically be achieved with deeper (5-10 hr) exposures at different distances (1, 2, and 3 R_{eff}) – and hence crowding regimes – from the centres of Virgo galaxies;

(ii) H-band sensitivity, and whether I-H colour provides sufficient baseline for discriminating different stellar populations;

(iii) More accurate methods of PSF reconstruction to improve photometric accuracy and depth in very crowded stellar fields.

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