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# First performance of the GeMS + GMOS system – 1. Imaging

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## ABSTRACT

During the commissioning of the Gemini MCAO System (GeMS), we had the opportunity to obtain data with the Gemini Multi-Object Spectrograph (GMOS), the most utilized instrument at Gemini South Observatory, in 2012 March and May. Several globular clusters were observed in imaging mode that allowed us to study the performance of this new and untested combination. GMOS is a visible instrument, hence pushing MCAO towards the visible. We report here on the results with the GMOS instruments, derive photometric performance in term of full width at half-maximum (FWHM) and throughput. In most of the cases, we obtained an improvement factor of at least 2 against the natural seeing. This result also depends on the natural guide star constellation selected for the observations and we then study the impact of the guide star selection on the FWHM performance. We also derive a first astrometric analysis showing that the GeMS+GMOS system provide an absolute astrometric precision better than 8 mas and a relative astrometric precision lower than 50 mas.

**Key words:** instrumentation: adaptive optics – methods: observational – astrometry – globular clusters: general.

## 1 INTRODUCTION

Data from ground-based telescopes suffer from the effects of turbulence in the atmosphere. The first systems for sensing and correcting these atmospheric aberrations, known as adaptive optic (AO) system, were proposed in 1953 by Babcock (1953). AOs correct incoming light from distant celestial bodies, typically very dim, by using a relatively bright natural guide star (NGS) as a reference. With AO, the resolution of the images improves dramatically as long as the targets are close enough to a bright reference star. However, sufficiently bright stars are not available in all parts of the sky and typically less than 10 per cent of the sky can benefit from AO corrections. To extend the use of AO systems to the whole sky, artificial stars also called laser guide stars (LGS) have been developed (Foy & Labeyrie 1985). Using LGS does not come without its own drawbacks: due to the finite altitude of the LGS, some turbulence goes unseen by the WFS, limiting performance of the

AO system. Using multiple-LGS not only allows us to solve this so-called cone effect, but can also be used to increase the size of the corrected FoV. Because of back and forth laser propagation, tip-tilt modes stay undetermined, a significant detrimental effect for AO correction as tip tilt are the mode containing the most energy from atmospheric turbulence. (optional example phrase:) For example, in *K* band and good seeing conditions ( $r_0 = 60$  cm in *K*), the image motion (TT only) is roughly 0.2 arcsec rms, i.e 3.6 times the size of the perfect Airy Disk PSF. Rigaut and Gendron (1992) proposed to correct this issue by adding a second wavefront sensor guiding on NGS. This additional WFS can be as simple as a quadcell, allowing us to guide on very faint guide stars. In this scheme, sky coverage is almost complete as the presence of such faint stars is quite common even around Galactic poles. Different AO methods have been developed to allow observations over a wide field of view (FoV): Ground Layer Adaptive Optics (GLAO; Rigaut 2002; Tokovinin 2004), Multi-Object Adaptive Optics (MOAO; Hammer et al. 2004) and Multi-Conjugate Adaptive Optics (MCAO; Beckers 1988; Rigaut & Roy 2001). In GLAO, only the atmospheric turbulence close to the ground is corrected. This correction enhances the

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resolution over a wide field, as the light from every object in the sky pass through the same low layer of turbulence before reaching the telescope. However, the correction provided by a GLAO system is only partial, and usually does not reach the diffraction limit of the telescope. In order to further improve the performance over the full field, one need to add corrective elements (i.e. deformable mirrors) to compensate for the high altitudes turbulent layers. MCAO has first been demonstrated with the Multi-Conjugate Adaptive Optics Demonstrator (MAD; Marchetti et al. 2003), and now used in regular operation at Gemini-South, with the GeMS instrument (Neichel et al. 2014a; Rigaut et al. 2014).

GeMS is the dedicated AO facility at the Gemini South Telescope located in Cerro Pachón. It is the first instrument using a fixed five laser sodium guide stars (LGS) asterism, in addition of three NGS, to compensate the optical distortions induced by atmospheric turbulence over a 2 arcmin wide FoV (Rigaut et al. 2014). The compensation can be achieved using two deformable mirrors conjugated at the ground layer and at 9 km altitude. Over the full field, it can provide a uniform close to diffraction-limit point spread function (PSF) in the near-infrared bands (*J* to *K*), 5–10 times larger compared more classic Single Conjugated Adaptive Optic Systems (SCAO) or Laser Conjugated Adaptive Optic Systems (LGSAO; Neichel et al. 2014a). GeMS has been routinely in operation since mid-2013 in combination with the near-infrared Gemini South Adaptive Optics Imager (GSAOI; McGregor et al. 2004).

At this time, compensating enough the atmospheric turbulence in order to reach the diffraction limit in the visible bands still remains a challenging endeavor. This can now be accomplished over a very small FoV (10 arcsec maximum) around bright stars with the upcoming generation of Extreme AO system (Dekany et al. 2006; Dohlen et al. 2006; Macintosh et al. 2006; Esposito et al. 2010; Close et al. 2013; Jovanovic et al. 2015). The sky coverage for these instrument is logically extremely small. Over a wide FoV, different approaches have been taken such as reaching the diffraction-limit with a relatively small telescope and some post-processing (1.5-m RoboAO, Baranec et al. 2013, LAMP Law et al. 2009) or such as delivering a partial correction with larger telescopes. The Southern Astrophysical Research Telescope (SOAR) adaptive module (SAM) has been the first one in this category. Correcting for the ground layer turbulence only and using a UV Rayleigh LGS guide star and 2 NGS for tip tilt, it can deliver a PSF whose FWHM is down to 280 mas in *i* band over a square FoV of 3 arcmin (Tokovinin 2013).

During the commissioning of GeMS, concurrently to GSAOI, we also used GMOS (Hook et al. 2004) in its imaging mode to explore the performance of this MCAO system in the visible bands. We report with this publication the first performance in term of FWHM estimation, photometric and astrometric accuracies. In the first part, we are presenting the observations and the data reduction method. In the second part, we are explaining the FWHM performance for the GeMS+GMOS data sets. Then we estimated the throughput and the zero-point magnitudes obtained. We also examine the astrometric performance reached for these observations. Finally, we are discussing the possible science applications for such a unique system.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 GMOS: Gemini Multi-Object Spectrograph

GMOS is a spectro-imager working in the visible bands. It remains the most requested and used instrument at Gemini South Observatory with 72 per cent of the requested observing time in 2012. In its spectrograph mode, long-slit, multi-slit and one integral field unit (IFU) are available. The imaging mode covers a 5.5 arcmin  $\times$

**Table 1.** Table comparing the specificities of GMOS and GeMS+GMOS.

System	FoV	Pixel scale	Available broad filters
GMOS	5.5 arcsec $\times$ 5.5 arcsec	73 mas	<i>u</i> , <i>g</i> , <i>r</i> , <i>i</i> , CaT, <i>z</i>
GeMS+GMOS	2.5 arcsec $\times$ 2.5 arcsec	35.9 mas	<i>i</i> , CaT, <i>z</i>

5.5 arcmin FoV over three CCD chips with a pixel scale of 79 mas. The three CCD chips form a 6144  $\times$  4608 pixel array, with two gaps of about 37 pixels separating the detectors (Hook et al. 2004). In its imaging mode, GMOS-S has six standard broad-band filters: *u* band (336–385 nm), *g* band (398–552 nm), *r* band (562–698 nm), *i* band (706–850 nm), CaT band (780–933 nm) and *z* band ( $\geq 848$  nm). This paper focus on GMOS-S’s imaging capabilities.

### 2.2 GeMS: Gemini Multi-Conjugate AOs System

The Gemini Multi-Conjugate Adaptive Optics system, a.k.a. GeMS, is the first multi-LGS system offered to the astronomical community (Neichel et al. 2014a; Rigaut et al. 2014). GeMS introduces three main optical changes:

- (i) the throughput: the losses due to reflections have been evaluated to about 30
- (ii) the f-ratio: GeMS modifies the native telescope f-ratio of f/16 to f/33.2
- (iii) the FoV: GeMS FoV is a disc of 2 arcmin diameter.
- (iv) the current beam splitter (BS) cuts the visible light at 750–800 nm.

### 2.3 Observations

During the commissioning of GeMS, we had the opportunity to obtain data with GMOS in 2012 March and May. GeMS change the native *f*/ratio of the telescope, from an f/16 beam to an f/33.2, hence, the imaging FoV of GMOS through GeMS is reduced to 2.5 arcsec  $\times$  2.5 arcsec, and with the pixel scale also reduced to 35.9 mas. Also, because GeMS as been designed to work in the NIR (see Section 4.2), only the reddest filter of GMOS can be used. These are the *i* band (706–850 nm partially), CaT band (780–933 nm) and *z* band ( $\geq 848$  nm). Table 1 summarized the differences when using GMOS and the system GeMS+GMOS.

We observed 15 targets including nine globular clusters with the GeMS+GMOS system during 2012 March and May. We will now focus on the globular clusters. They were selected as best choice targets as they contain numerous bright stars that can be used for the NGS constellation. The quantity of stars in globular clusters is also a great advantage to help for studying the different performance (FWHM, astrometry for example) of the system and its variability over the FoV. Table 2 summarized the observed targets and the observation characteristics. We will not present the whole performance analysis for every globular cluster. Instead, we chose to show only the most relevant results.

GeMS AO has not been designed for optical bands and therefore it will not reach the diffraction limit of the telescope under no less than exceptionally good seeing conditions. Performance in terms of PSFs FWHM are expected to vary both in absolute from excellent to quite poor but they also may lack of uniformity inside the GMOS field, a detrimental effect in most science cases. This lack of homogeneity is due non-corrected anisoplanatism.

The wind profiling method, described in Cortés et al. (2012), based on the estimation of the refractive index structure parameter  $C_n^2$  allows us to assess the dynamical turbulence structure, and to

**Table 2.** Table summarizing the observations obtained with GeMS+GMOS.

Targets	Dates	Filters	Exposure	Offset	Binning	Average FWHM (mas)
NGC 2849	2012-03-15	<i>z</i>	27 × 5 s	Yes	2 × 2	236.94
NGC 3201	2012-03-13	<i>z</i>	12 × 60 s	No	2 × 2	466.7
NGC 3244	2012-03-16	<i>i</i>	31 × 5 s	No	2 × 2	165.14
NGC 4590	2012-03-15	<i>i, z, CaT</i>	56 × 5 s	Yes	2 × 2	CaT:201.04, <i>i</i> :222.58, <i>z</i> :215.4
	2012-05-10	<i>i</i>	33 × 5 s	No	2 × 2	514.09
NGC 5139	2012-03-16	<i>i, z, CaT</i>	20 × 90 s	Yes	1 × 1	CaT:75.39, <i>i</i> :61.03, <i>z</i> :71.8
NGC 5286	2012-03-09	<i>z</i>	5 × 5 s	No	1 × 1	301.56
	2012-05-10	<i>i</i>	20 × 5 s	No	2 × 2	502.6
NGC 5408	2012-03-10	<i>z</i>	4 × 10 s	No	2 × 2	122.06
NGC 6369	2012-03-14	<i>z, i</i>	9 × 120 s	Yes	1 × 1	<i>i</i> :183.09, <i>z</i> :197.45
		<i>i</i>	2 × 240 s	Yes	1 × 1	183.09
NGC 6496	2012-05-09	<i>i</i>	25 × 5 s	No	2 × 2	567.22
	2012-05-10	<i>i</i>	6 × 5 s	No	2 × 2	552.86
	2012-05-10	<i>i</i>	4 × 15 s	No	2 × 2	782.62
	2012-05-10	<i>i</i>	24 × 15 s	Yes	2 × 2	574.4
	2012-05-10	<i>z, CaT</i>	21 × 10 s	Yes	2 × 2	CaT:746.72, <i>z</i> :660.56
CENTAURUS	2012-03-11	<i>z</i>	14 × 5 s	No	2 × 2	1191.88
	2012-03-12	<i>i, z, CaT</i>	13 × 60 s	No	2 × 2	CaT: 71.8, <i>i</i> : 66.77, <i>z</i> :72.87
		<i>z</i>	26 × 10 s	Yes	1 × 1	195.29
	2012-03-13	<i>z</i>	17 × 5 s	No	2 × 2	174.47
CIRCINUS	2012-03-14	<i>i, z</i>	6 × 120 s	Yes	1 × 1	<i>i</i> : 171.84, <i>z</i> : 137.83
	2012-03-12	<i>z</i>	12 × 15 s	No	2 × 2	466.7
		<i>z</i>	7 × 45 s	Yes	2 × 2	287.2
	2012-03-13	<i>z</i>	21 × 5 s	No	2 × 2	172.32
	2012-03-14	<i>z</i>	6 × 5 s	No	1 × 1	323.1
2012-03-16	<i>z</i>	4 × 5 s	No	2 × 2	192.42	
IC 4296	2012-03-15	<i>i</i>	4 × 600 s	Yes	2 × 2	177.34
		<i>i, z, CaT</i>	42 × 60 s	Yes	2 × 2	CaT: 152.21, <i>i</i> : 137.85, <i>z</i> : 160.11
M93	2012-03-11	<i>i, z</i>	5 × 5 s	No	2 × 2	<i>i</i> : 538.5, <i>z</i> : 646.2
ORION	2012-03-12	<i>i, z, CaT</i>	23 × 60 s	Yes	2 × 2	CaT: 269.25, <i>i</i> : 308.74, <i>z</i> : 265.66
	2012-03-15	<i>i</i>	14 × 5 s	Yes	1 × 1	251.3
SAGITTARIUS	2012-03-11	<i>z</i>	6 × 30 s	No	2 × 2	193.86
	2012-03-16	<i>z</i>	19 × 300 s	Yes	2 × 2	172.32

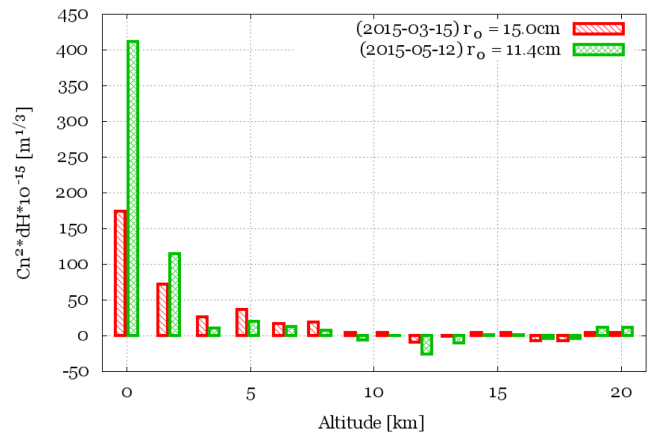
explain then the different performance obtained for these data sets. Fig. 1 presents the turbulence profiles obtained on sky on 2012 March 15 and 2012 May 10 for a pseudo open-loop (pseudo OL) measurements, represented in yellow. The seeing measured during these nights is  $r_0 = 11.4$  cm (seeing  $\sim 0.88$  arcsec) and  $r_0 = 14.8$  cm (seeing  $\sim 0.68$  arcsec), respectively. We remarked also the presence of a strong dome seeing component, which is part of the ground layer (altitude 0 km) turbulence. The better FWHM results obtained during 2012 March 15 than during the May 10 night (see Table 2) can be explained by the difference of  $r_0$  values. However the presence of stronger turbulences at higher atmospheric layers affects more the homogeneity of the AO performance during the first night than during the latter one.

In order to improve GeMS + GMOS performance, as Gemini is a queue-based telescope, we could use this information to know whether or not we are in conditions for observing with this system or not. Optimal conditions for GeMS+GMOS will be of course with the minimum high layer turbulence level, similar but slightly better than an equivalent GLAO system.

## 2.4 Data reduction

### 2.4.1 Data reduction method

To process the GeMS+GMOS data, we use the Gemini IRAF package.



**Figure 1.**  $C_n^2$  turbulence profiles. The bars represent the turbulence profiles obtained in pseudo-open loop profile. The dashed bars (red) are from 2012 March 15 and the checked bars (green) from 2012 May 10. For visibility purpose, the dashed bars were shifted by  $-0.25$  km and the checked bars by  $+0.25$  km. The negative value we can remark at an altitude of 12 km and above, can be either just noise or a bad estimation of the outer scale. Generally is the latter: the outer scale is used to deconvolve the raw profile using the autocorrelation of the slopes, which is a function of the outer scales. We kept the negative values as it gives us information on how reliable our results are.

At the end of each night, bias frames were taken for every GMOS configuration. Twilight flats were also obtained either at the beginning or at the end of the nights. We process the bias frames by overscan subtraction, trimming, and stacking to produce a master bias frame for each night. A very similar procedure was applied to the twilight frames to produce a master flat frame. The science frames are bias subtracted and flat-field corrected in the standard way.

As we obtained data for the redder part of the GMOS bandpass, most of the frames were contaminated by fringes. Fringe frames were obtained during 2012 March and May. The fringe correction and the sky subtraction were realized simultaneously using *girmfringe*<sub>IRAF</sub> task. Finally, the cleaned individual frames are reconstructed as single extension images using the *mosaic*<sub>IRAF</sub> task.

Some issues affect the stacking of these data.

(i) CANOPUS has a dynamic distortion which changes every night. It is therefore challenging to stack the data sets taken with offsets. This effect does not prevent us to stack the data set taken without offsets.

(ii) Due to the exceptional GeMS+GMOS combination, the WCS is not presented in the data headers. A WCS calibration with GeMS+GMOS has not been obtained.

#### 2.4.2 Astrometric calibration

A good World Coordinate System (WCS) calibration will depend on two main points : the availability of appropriate reference catalogues and the AO corrections.

The astrometric accuracy for the MCAO system and the instrument it feeds has already received much attention (Trippe et al. 2010; Meyer et al. 2011; Schoeck et al. 2013; Lu et al. 2014; Neichel et al. 2014b) as the PSF uniformity over a large field and the ability to actively control the plate scale can significantly reduce the largest astrometric errors encountered in previous AO systems. However this requires that the systemic residual distortions are well under control: the system should be carefully calibrated in the world coordinates system and the systematic errors should be kept low. During the early commissioning, priority was given to explore the AO performance and test functionality of different MCAO subsystems rather than to carefully calibrate the astrometric performance. For example, the plate scale control was not yet applied at this time. The targets used to assess performance were central part of globular clusters, i.e. very crowded fields, a perfect benchmark to check the PSF uniformity over the GeMS FoV. In this paper, we decided to focus on astrometric performance reached in single frames. We are lacking precise unconfused references stars to derive an accurate WCS as most of the catalogue can only offer a precision of about 1 arcsec (Lasker et al. 1990), i.e. about 27 times larger than the plate scale of GeMS+GMOS (0.0359 arcsec per pixel). Using the Mikulski Archive for Space Telescopes (MAST), we found images from the *Hubble Space Telescope* (HST) corresponding to the globular clusters observed with GeMS+GMOS. We first identified the brightest stars found in both frames and run the *ccmap*<sub>IRAF</sub> task to compute the plate solution from a list of matched pixel and celestial coordinate using a polynomial function of order 2. Once this first WCS approximation was registered in the header of the GeMS+GMOS, we used the SIMBAD data base (Wenger et al. 2000) to identify as much objects as possible in the field. We then run the *msctpeak*<sub>IRAF</sub> task, from the MSCRED package, with a function polynomial of order 4 with a sky projection combining the tangent plate projection and polynomials, called TNX WCS

projection. After running this task twice on the Z-band images of NGC6496, we obtained an acceptable WCS solution with a WCS rms of 50 mas (corresponding to 0.7–1 pixel approximately) in both direction. On the Z-band images of NGC3201, the best solution was achieved with a WCS rms of 90 mas (corresponding to 2–3 pixels approximately). In the case of NGC 5139, the best achieved solution in both direction is 65–76 mas in *I* band, 80–95 mas in CaT band and 76–90 mas in *Z* band.

## 3 FWHM PERFORMANCE

### 3.1 Measurement method

The PSF describes the two-dimensional distribution of light in the telescope focal plane for astronomical point sources. The PSF can be characterized by its FWHM or by the diameter enclosing a given percentage of the total brightness, thus describes the angular resolution achieved in an observation.

Images taken with AO should show a dramatic improvement gained through the use of AOs and the FWHM is the first measure that show the difference with and without AO.

The star detection and the FWHM values are obtained by running SExtractor (Bertin & Arnouts 1996) on the reduced individual images. The SExtractor parameters were optimized to allow the detection of faint punctual objects. We measured the FWHM for every processed single exposures for every target observed with the GeMS+GMOS system.

Fig. 2 shows two single 5 s exposure of a the globular cluster NGC4590 observed in the red, at *I* band ( $\lambda = 780$  nm), one with GMOS (left) and one with GeMS+GMOS (right), during the same night. Faint and crowded sources can now be identified. GeMS provided a factor of 2 of improvement in FWHM.

#### 3.1.1 FWHM maps

Figs 3–6 present the field images with the NGS Constellation and the studied area, for which the FWHM has been determined, and the FWHM maps for four different globular clusters observed in *i*- or *z* band.

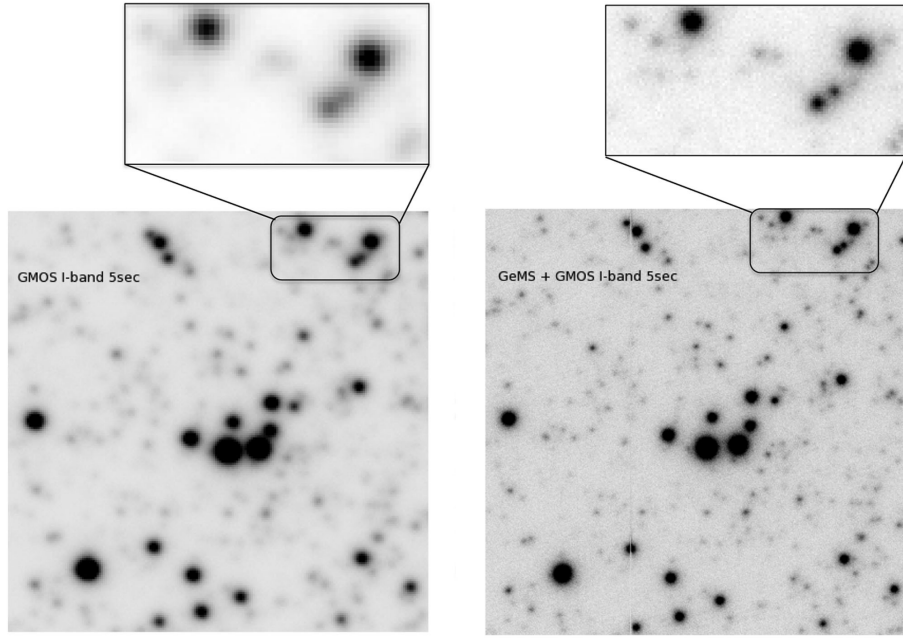
For the four globular clusters analysed here, the gain brought by GeMS over the natural seeing is a narrower FWHM by a factor 1.6–2.8. This observed difference, although the observations were taken at a similar natural seeing, can be explained by different reasons (by increasing order of importance:

(i) the NGS constellation is different: the three NGS are used to compensate for the tip tilt and tilt-anisoplanatism modes. Depending on their position over the field, and how they cover it, the correction will be more or less uniform.

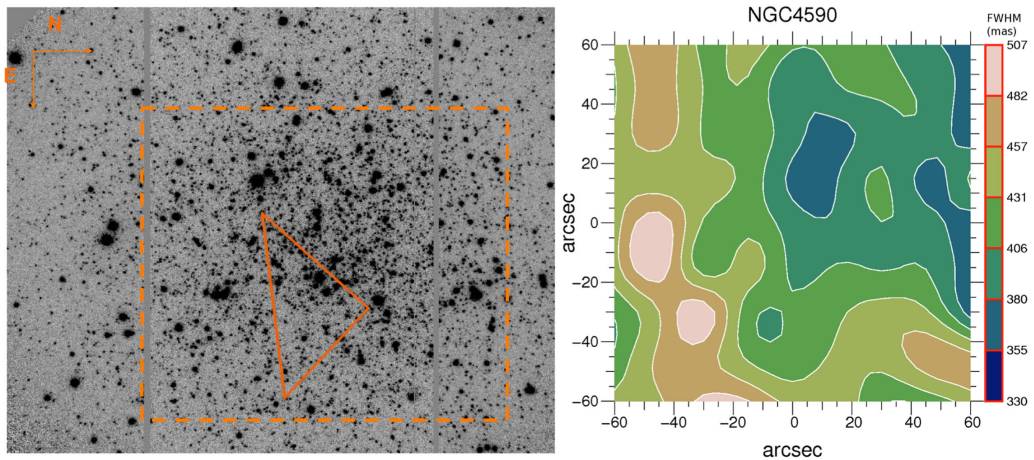
(ii) the laser photon return: if GeMS receives less laser photons, the loops are running at a slower frequency and the overall performance will decrease. This could be due to varying sodium density Neichel et al. (2013), airmass or laser power.

(iii) the turbulence profile: depending where the principal layers are located, GeMS can more or less correct them.

As an illustrative example, we took a look in particular at NGC4590. This globular cluster was observed on 2012-03-15UT at an elevation of 73° and an airmass of 1.043, and on 2012-05-10 UT at an elevation of 75° and an airmass of 1.035. The NGS constellation was the same for both observation. In this case, the factor of 2 of difference in FWHM performance (see Table 2) can come from



**Figure 2.** Visual comparison of the image quality on a section of NGC4590 taken in  $I$  band for 5 s exposure. Left: taken with GMOS. Its average FWHM is 0.7 arcsec. Right: taken with GeMS+GMOS. Its average FWHM is 0.35 arcsec.



**Figure 3.** Left: field image of NGC 4590 with the N-E orientation, in  $I$  band. The NGS constellation and the studied area marked. Right: FWHM map.

either the turbulence profile either the laser return. It is known that in March there is statistically less sodium than in May. From table 2 of Neichel et al. (2013), the average sodium return in 2012 March was  $6.5 \text{ photons s}^{-1} \text{ cm}^{-2} \text{ W}^{-1}$  versus  $13 \text{ photons s}^{-1} \text{ cm}^{-2} \text{ W}^{-1}$  in 2012 May. Looking at the  $C_n^2$  profile for these two nights (see Fig. 1), the March night has  $1.74 C_n^2 \cdot \text{dH} \cdot 10^{13} \text{ m}^{1/3}$  at 0km while the May night has  $4.11 C_n^2 \cdot \text{dH} \cdot 10^{13} \text{ m}^{1/3}$  at the same altitude. There is also a factor of 2 of  $C_n^2$  turbulence at 1.69 km with  $0.72 C_n^2 \cdot \text{dH} \cdot 10^{13} \text{ m}^{1/3}$  for 2012 March versus  $1.15 C_n^2 \cdot \text{dH} \cdot 10^{13} \text{ m}^{1/3}$  for 2012 May. It seems then that the most influential factors for the FWHM performance while observing these data sets were the level of ground layer turbulence and the photon return from the LGS.

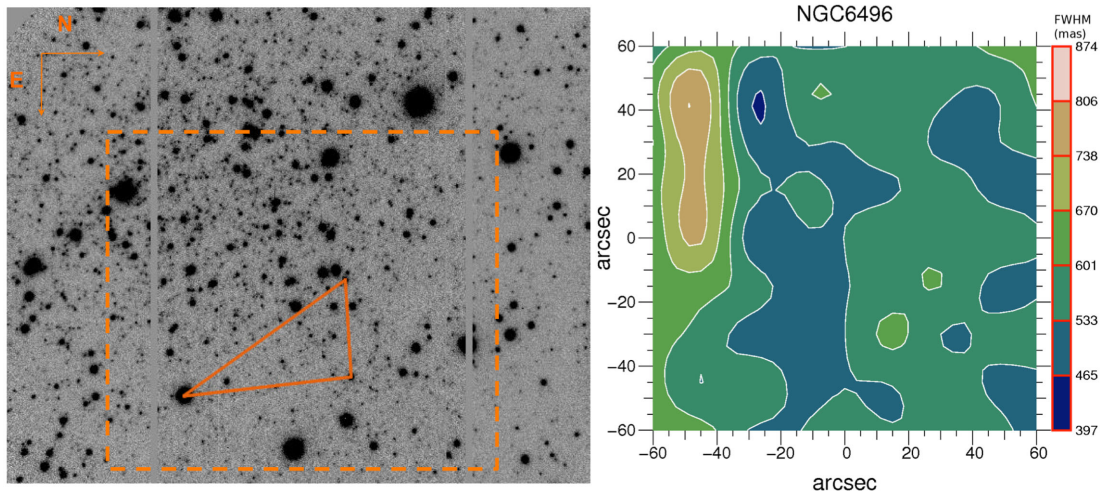
### 3.1.2 Improvement FWHM – seeing

The Differential Image Motion Monitor (DIMM) is located at 1.5 m above the ground on Cerro Pachón and delivers an estimate of

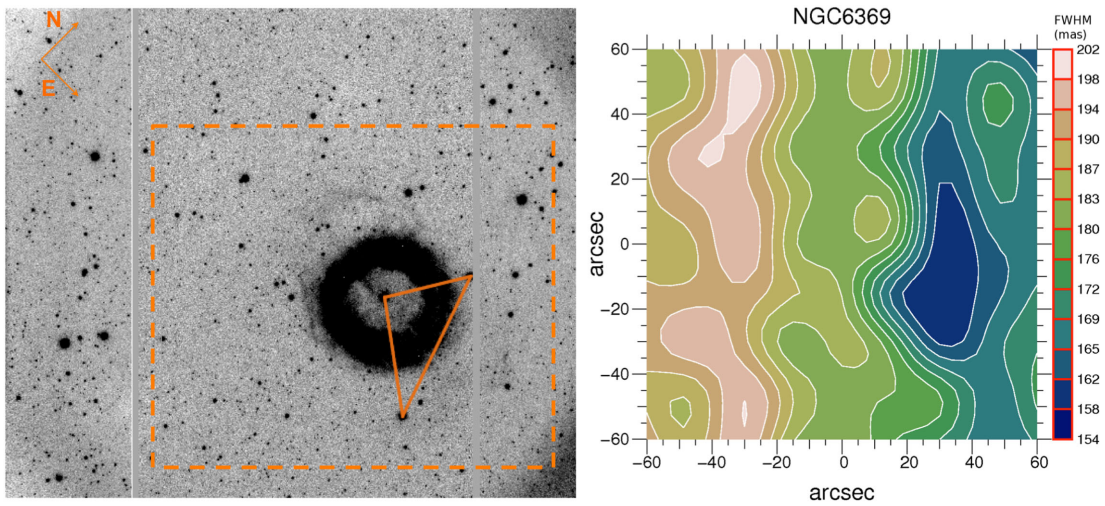
the seeing in the total atmosphere, normalized at 500 nm. It is accompanied by a Multi-Aperture Scintillation Sensor (MASS) permitting one to measure the seeing in the free atmosphere above  $\sim 0.5$  km. The ground layer seeing produced in the first 0.5 km above the observatory can be evaluated by subtracting the turbulence integrals measured with the DIMM and MASS (Tokovinin & Kornilov 2007). The FWHM PSF of a GLAO system is therefore expected to be close to the free atmosphere seeing but never better as it cannot correct for free atmosphere turbulence.

The average FWHM presented in Fig. 7 was obtained from GeMS+GMOS images taken in  $i$  band ( $\lambda_c = 780$  nm). To compare the FWHM to the seeings, we corrected the DIMM and the MASS seeing values from a factor of 0.915, following the equation 5 from Tokovinin (2002).

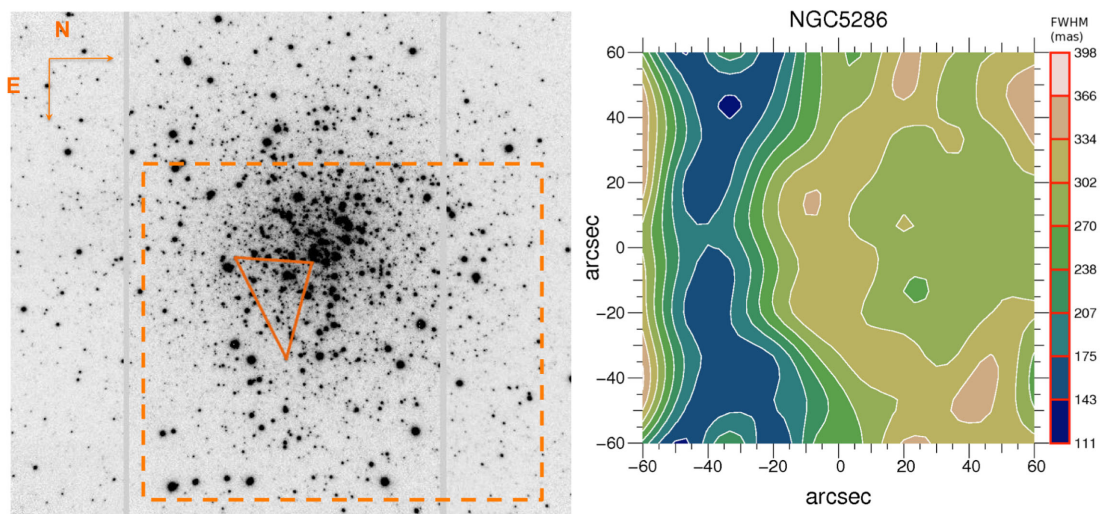
Fig. 7 shows the evolution of total and free-atmosphere seeings measured by the DIMM and MASS site monitor at Cerro Tololo on



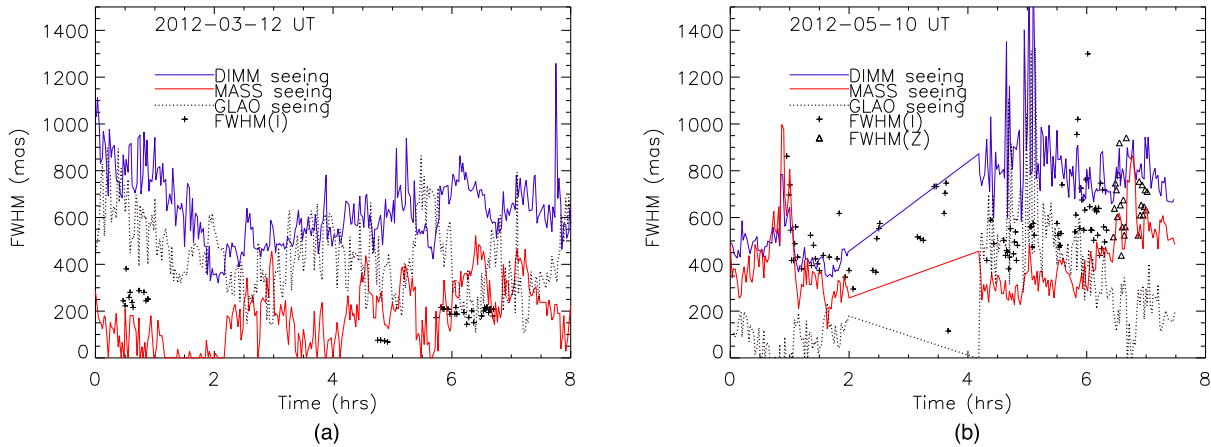
**Figure 4.** Left: field image of NGC 6496 with the N-E orientation, in I band. The NGS constellation and the studied area marked. Right: FWHM map.



**Figure 5.** Left: field image of NGC 6369 with the N-E orientation, in Z band. The NGS constellation and the studied area marked. Right: FWHM map.



**Figure 6.** Left: field image of NGC 5286 with the N-E orientation, in Z band. The NGS constellation and the studied area marked. Right: FWHM map.



**Figure 7.** Atmospheric conditions on two of the GeMS+GMOS nights. The blue lines show the total (DIMM) seeing, the red lines the free-atmosphere seeing (MASS) and the black dotted lines the GLAO seeing. The crosses are the FWHM of  $i$ -band GeMS+GMOS images, the diamonds the FWHM of  $z$ -band GeMS+GMOS images. The errors on the FWHM is  $\pm 20$  mas. Left: during this 2012 March night, we obtained better performance than a GLAO system will provide us. Right: during this May night, FWHM performance equivalent to the ones expected by a GLAO system were obtained between 4 h and 6 h, although the GeMS+GMOS FWHM performance were very variable.

two nights. These measurements are a good approximation of the atmospheric conditions at Cerro Pachón as these two telescope sites are separated by 14 km and have a 300 m altitude difference. This figure also allows us to visualize the improvement factor between natural seeing, GLAO seeing and the average FWHM for these two different observing nights, as an example for the two observing periods with GeMS+GMOS.

We can see in Fig. 7a., for the 2012-03-12 UT night, the FWHM values are below or equal to the GLAO seeing values. We are obtaining better if not equal performance than a GLAO system. The MCAO and the two Deformable Mirrors (DMs) have been correcting better than one DM could have done alone. However, Fig. 7b, for the 2012-05-10 UT night, the FWHM results are mostly located between the DIMM and MASS data and during the third quarter of the night, these results are equivalent to the GLAO seeing values. We were able to obtain correction similar to the ones expected by a GLAO system. The main turbulence factor was then coming from another turbulence layer or GeMS performance were not optimal.

### 3.1.3 NGS constellation comparison

During the night of 2012-05-10 UT, NGC6496 was observed using different GeMS configurations such two different NGS constellations.

Depending on the constellation geometry and guide star magnitude, the expected performance will be different. Best constellation are the ones that cover most of the field, and the more distant stars are, the lower the plate scale error will be. Generally, at the first order, we want to maximize the area of the triangle delimited by the three stars. However, this has to be mitigated by the noise propagation, i.e. the magnitudes of the stars. One difference between both observations is the quality of the NGS constellation : looking at the top panel of Fig. 8 and at the  $r$ -mag given for the NGSs in Table 3, it seems that the top left image has an NGS constellation which constitutes a better equilateral triangle with brighter NGSs and widely spread in the field. This implies bigger and more homogeneous FWHM zones as seen in the bottom left FWHM map (see Fig. 8).

The NGS constellation for the top right image is limited to one part of the field and has fainter NGS  $r$ -magnitudes, which explains the more drastic separation of FWHM values in the bottom right map (see Fig. 8).

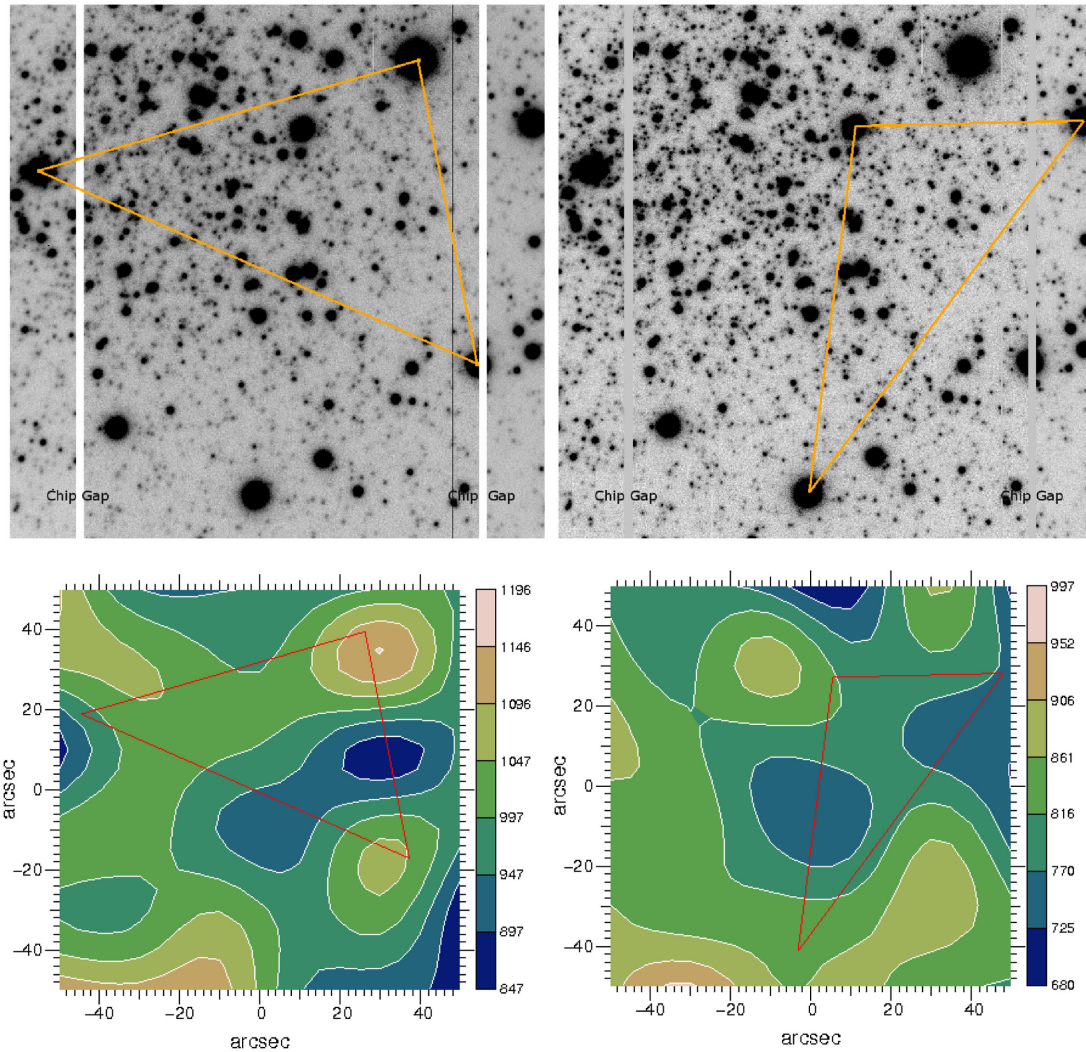
Although the magnitude of the NGSs are different (see Table 3), they are all in the range of NGS  $r$ -magnitude accepted for GeMS, i.e.  $R < 15$  mag. The Fig. 8 shows that the GeMS system performed in equivalent way for both observations and our limiting factor appears to be the natural seeing. This is indeed not surprising as we already know that the GeMS system is underdimensioned for the visible wavelength range, i.e. it has an insufficient number of actuators and a too low loop frequency to be able to have an optimized correction with visible wavelengths. The GeMS+GMOS visible performance are therefore very dependent on the natural seeing and the atmosphere.

The GeMS LGS loop is currently limited by the combination of its laser power and format and is, in average, running at 300–400 Hz. To compensate for the atmospheric turbulence distortions, the actual DM0 is using 240 actuators and DM9 is using 120 actuators. To perform as well in the red bands ( $r$  and  $i$ ), any AO system would need at least twice the loop frequency (from 1 to 1.5 kHz) and twice the current number of actuators. Moreover, an MCAO system based on LGS guide stars would require about 9–10 times more LGS spots on the sky and as many corresponding WFS. The laser power required to sustain this type of operation is about 25–30 times more than what the actual GeMS Lockheed Martin Coherent Technologies (LMCT) laser can deliver.

## 4 THROUGHPUT AND ZERO-POINTS ESTIMATION

### 4.1 Method

We expect the GeMS throughput to be lower than GMOS simply due to the added number of mirrors in the MCAO system, each of which absorbs some of the transmitted light. What we aim to estimate is by how much the throughput deteriorates due to GeMS. We determined the difference of flux transmission between GMOS



**Figure 8.** Comparison of FWHM performance obtained with different NGS constellation. Top: *I*-band 15 s individual observations of NGC 6496 using two different NGS constellations represented by the orange lines. Bottom: FWHM map corresponding of the above images. The FWHM unit is milli-arcseconds.

**Table 3.** Table summarizing the observations, the NGS magnitudes and the observing conditions for one particular target: NGC6496.

Images	Dates	Filter	Exp. time	Aver. FWHM	CWFS1 <i>R</i> -mag	CWFS2 <i>R</i> - <i>R</i> -mag	CWFS3 <i>R</i> -mag	Airmass	$r_0$	MASS seeing
Image 1	2012-05-10 UT	<i>i</i> band	15s	$860 \pm 168$ mas	12.7	11.1	13.3	1.05	10	0.36 arcsec
Image 2	2012-05-10 UT	<i>i</i> band	15s	$691 \pm 133$ mas	14.8	12.7	13.9	1.1	12	0.2 arcsec

and the GeMS+GMOS (G+G) system using the following equation (equation 1):

$$(G + G) \text{ Throughput} = \frac{(G + G) \text{ Flux}}{\text{GMOS Flux}} \times \frac{\text{GMOS Exp. Time}}{(G + G) \text{ Exp. Time}} \quad (1)$$

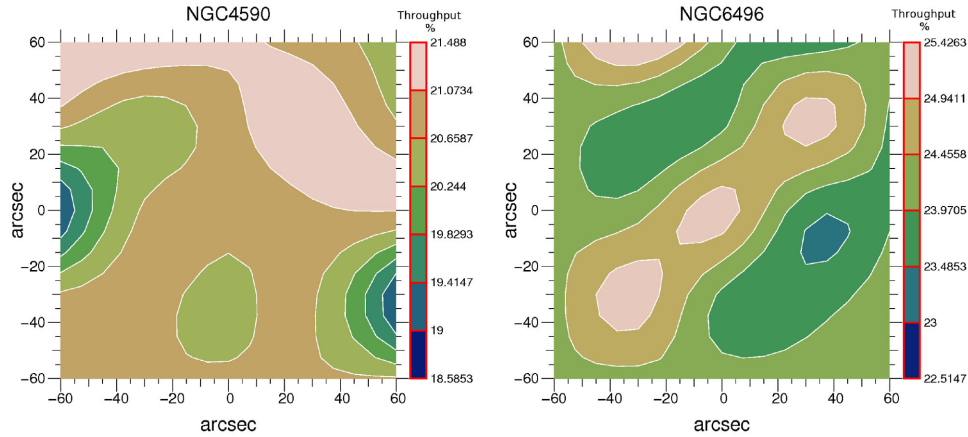
To obtain an absolute value of this throughput difference, we only created maps for data that we have equivalent GMOS images in gain, filter and binning. Such data exist only in the *i* band.

## 4.2 Results and discussion

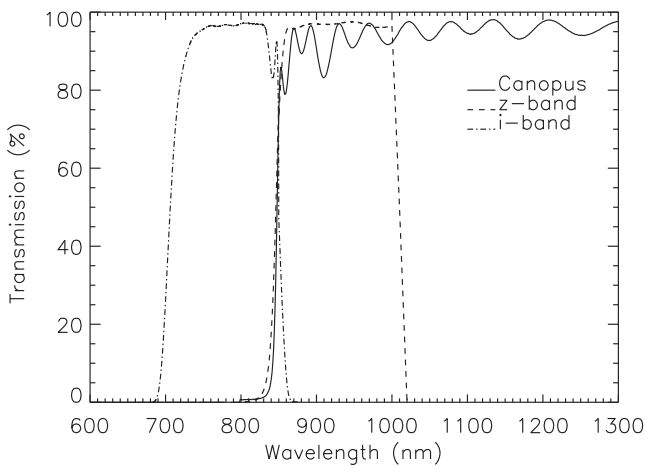
Fig. 9 shows the throughput difference in percentage for two globular clusters. Remarkably, for each individual frame, the GeMS

throughput varies by less than 4.7 per cent across the examined portion of the CCD chips.

The low throughput observed in *i* band can be explained by the wavelength cutoff of the BS used in the AO bench. This BS cuts at 850 nm, all the light with a lower wavelength being sent into the Wave-Front sensors of the AO bench, only the wavelength larger than 850 nm are directed towards the science instruments. If GMOS would be used with GeMS for science operations, one option to improve the throughput would be to change the BS with one having a cutoff at 600 nm (see Fig. 10). This would allow us to observe in the GMOS *r*-band filter. We could not afford shorter wavelengths, as the laser sodium light (at 589 nm) has to be seen by the AO Wave Front sensors. Note that changing the BS for a shorter wavelength cut will affect the limiting magnitude of the NGSs, needed for the



**Figure 9.** Throughput difference map in percentage for two globular clusters: NGC4590 (left) and NGC6496 (right).



**Figure 10.** The solid line shows the Canopus transmission according to wavelength for the setup used in this work. It is evident that the BS cut-off point occurs within the  $i$  band's 706–850 nm range. This explains why the  $i$  band throughput determined above is so much lower than we might expect from the GMOS throughput.

tip-tilt correction. We estimated that going for a 600 nm BS would decrease the limiting magnitude by 1. This will also impact the sky coverage. Another possibility will be to use a BS sending only the laser light ( $\lambda = 589$  nm) to the wavefront sensor and the rest to GMOS. In that case, the tip-tilt sensing would be done with a peripheral WFS on the telescope guiding system. This solution would open observations with all the GMOS filters, however it would introduce more anisoplanatism in the images. Such a system is being implemented at Gemini North for the Altair AO system: the current Altair science dichroic will be replaced by a sodium notch filter, passing only the 589 nm wavelength light from the LGS to the AO system (Trujillo et al. 2013). The rest of the spectrum from 400 nm to the GMOS red cutoff at 1.1 microns is intended as science capable light. Tip/tilt correction will be performed close to the science target with the GMOS on-instrument wavefront sensor or with the peripheral wavefront sensor. An image quality improvement of roughly a factor of 2 is expected in this mode over seeing limited observations.

During the 2012 May 2012 observing run, we also obtained GeMS+GMOS data for a photometric standard field (Smith et al. 2007) in  $i$  and  $z$  band. Its exposure time is 12.5 s at an airmass

of 1.39. The same field was observed in 2012 June with GMOS in the same filters with an exposure time of 4.5 s at an airmass of 1.16. Three stars, isolated from others field stars and from each other, were selected in this field and we measured their FWHM and flux. We used the *FLUXAUTO* from *SEXTRACTOR*. In both  $i$  and  $z$  bands, we gain in sensitivity in the GeMS+GMOS data, with an improvement factor of 1.2 in  $i$  band and 1.5 in  $z$  band. In term of flux, as most of the  $i$ -band wavelength range is cut to feed the AO bench, we lose a factor of 2.9 on these three well-isolated stars by using GeMS. However, in  $z$  band, we gain a 1.5 factor by using GeMS on these same stars. The use of GeMS with GMOS is therefore useful not only for crowded fields but also for single well isolated stars.

### 4.3 Zero-point magnitude

We also used the Smith et al. (2007) photometric fields observed with GeMS+GMOS to estimate the magnitude zeropoint in the observed bands :  $i$  band, CaT band and  $z$  band, when observed. These fields were acquired in open-loop which causes a diminution of the light transmission. The photometric calibration was done on 10 stars and we extrapolated the value for the CaT filter.

We obtained the following AB zero-point magnitude values :  $\text{mag}_{\text{ZP}}(i \text{ band}) = 29.00 \pm 0.15$ ,  $\text{mag}_{\text{ZP}}(\text{CaTband}) = 28.85 \pm 0.20$ ,  $\text{mag}_{\text{ZP}}(z \text{ band}) = 28.75 \pm 0.15$ .

## 5 ASTROMETRIC PERFORMANCE

Astrometry deals with the measurement of the positions of objects on the sky, with ultrahigh precision and as a function of time. Based on the globular cluster data, we estimated a first astrometric performance of GeMS+GMOS.

### 5.1 Distortion correction

For a set of non-dithered images, it is expected that there will be no systematic distortions between images since the distortion map (if any) will remain in the same. As such, the presence of systematic distortions in images taken with GeMS would suggest the AO system introduced these distortions. The distortion factors which may affect our data set are

- (i) the  $(x, y)$  image offsets (in undithered images),
- (ii) the image rotation,
- (iii) the astigmatism at  $0^\circ$  and  $45^\circ$ ,

- (iv) the focus,
- (v) and the higher order distortions.

The distortions were measured in the images by using first- and second-order Zernike polynomials.

To ensure the distortion correction algorithm performed adequately, a number of simulated images with various distortions were created and processed. The simulated images were created with a single type of distortion as well as a combination of all forms. The results from the simulated images showed the algorithm was sufficient, successfully removing all simulated distortion patterns.

For our undithered data set on the target NGC3201, we have an average displacement of 23.49 mas before distortion correction. After correcting for the first-order distortions, we obtained an average displacement of 15.08 mas.

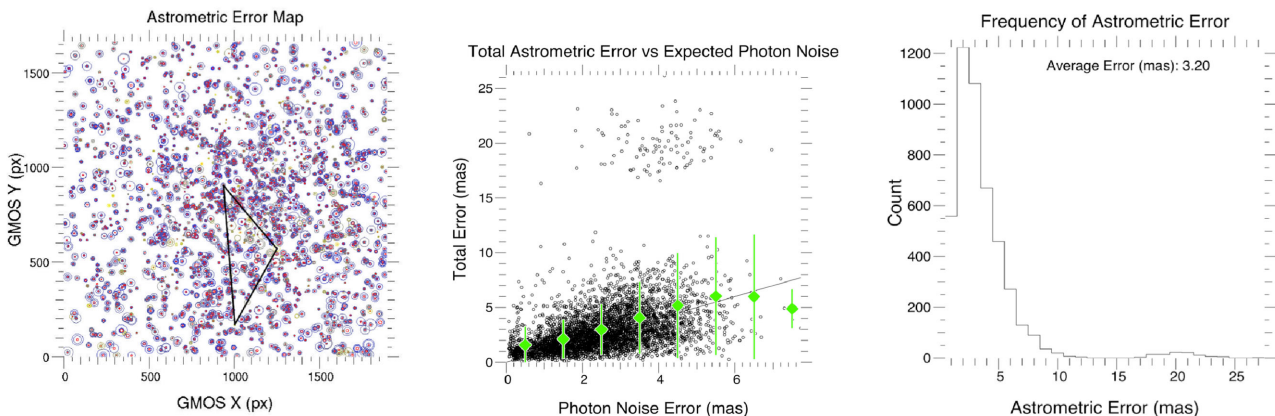
## 5.2 Astrometry error

The average astrometric error for our different targets was determined only for the undithered data sets and are presented in Table 4.

We are detailing here the case of NGC 4590 for which we have in our hands 31 individual images taken during the same night with the same configuration (exposure time, filter and binning). After finding the star position in each individual frame with `SEXTRACTOR`, we create a Master Reference Frame (MRF) from the average star position. We compared then the difference in position from all the individual images to the MRF. The results are shown in different ways: the comparison of the total astrometric error to the expected photon noise (Fig. 11 centre), and the frequency of the astrometric error (Fig. 11 right). The photon noise is estimated following the equation (2), which gives the error in the position of the centre of the stars purely based on photon noise. For NGC4590, the average astrometric error is 3.20 mas.

**Table 4.** Table summarizing the absolute astrometric error measured in one of the undithered data set for our targets. The number of undithered frames used for the astrometric calculation is also included in the table.

Targets	NGC 2849	NGC 3201	NGC 3244	NGC 4590	NGC 5286	NGC 5408	NGC 6496	CENTAURUS	CIRCINUS	M93	SAGITTARIUS
Abs. astro. error (mas)	2.47	4.73	2.80	3.20	4.4	7.38	5.39	5.51	5.66	5.15	5.28
Nber. undith. images	12	12	17	31	11	4	6	17	21	5	6



**Figure 11.** Left: absolute astrometric error map. Each circle is centred on a star. Yellow circles are a high flux stars, blue circles are the low flux star. The red circles represent the estimated photon noise. Center: astrometric error versus the expected photon noise. Right: histogram showing the frequency of the astrometric error.

The same method was applied to each globular cluster : an MRF was created for each of them. The number of undithered images is different for each target. Table 4 summarizes the astrometric performance expected for undithered images. This performance varies between 2.4 and 7.4 mas, which is quite encouraging. We can also observe in Table 4 that there is no trend between the astrometric precision obtained and the numbers of undithered images used for the calculation. As seen from Fig. 11 (centre), most of the error do follow the photon noise trend, hence no systematic errors seem to be present, at least for undithered data.

$$\sigma_{\text{photon}} \propto \frac{\text{FWHM}}{\sqrt{N_{\text{photon}}}} \quad (2)$$

## 6 DISCUSSION AND CONCLUSION

### 6.1 Expected performance

During 2014, a CCD upgrade has occurred for GMOS-S. The EEV CCDs have been removed and Hamamatsu CCDs have been installed and commissioned. These new CCDs are more sensitive in the red part of the visible spectrum : in *i* band, the CCD Quantum Efficiency (QE) improved from 65 to 90 per cent, which corresponds to a 1.38 factor improvement. In *z* band, the CCD QE improved from 30 to 85 per cent, corresponding to a 2.83 factor improvement. With the arrival of the new CCDs, we also installed a Y-band filter with a central wavelength of  $\lambda_c = 1010$  nm and covering the wavelength range [970–1070]. This same range is covered by the filter Z of the instrument GSAOI used exclusively with GeMS. The better red sensitivity of the Hamamatsu CCDs and this new near-infrared filter in GMOS allows us to envisage the continuation of the use of the GeMS+GMOS system at least for imaging data.

We expect to upgrade in 2015 the GeMS natural guide Wave-Front Sensor to a more sensitive version and more robust version

called NGS2. The main benefit will be a large increase (50 per cent sky coverage up to  $40^\circ$  from galactic plane with three guide stars, 50 per cent sky coverage at to galactic pole with one guide star) in the GeMS sky coverage, as GeMS will be able to guide on stars as faint as  $r$ -mag = 17. In 2016, GeMS will also receive a new laser: the goal is primarily to increase laser operation robustness in order to integrate GeMS in the regular Gemini queue system. A possible additional benefit might be an increase in laser photon return leading to improved AO performance. Gemini North is currently upgrading its AO facility ALTAIR to support GMOS in the visible bands with a new dichroic, we are considering how to replicate this effort for GeMS.

## 6.2 Science cases with GeMS+GMOS

Two of the advantages of AO science in the visible are the availability of better science detectors in the visible, with lower dark current and lower read noise than the ones used in infrared, and the fact that the visible sky is much darker than the  $K$ -band sky. The combination of the visible instrument GMOS with the MCAO system GeMS is a unique opportunity and could have then an important scientific impact, as a pathfinder for future extremely large telescope instrumentation.

Due to the correction of the crowding noise, the first and obvious application of such a system is open/globular clusters. We will be able to better resolve stellar populations and obtain deeper magnitude limit from ground-based telescope. This will help with cluster classifications (Gerashchenko 2013), age (West et al. 2004; Bridges et al. 2006), metallicity (Vanderbeke et al. 2014), distance and reddening determination (Bonatto, Campos & Kepler 2013).

Nebulae, and more specifically planetary nebulae (Zijlstra & Weinberger 2002; Villaver, García-Segura & Manchado 2003), would also take advantage of this observing system in order to characterize their weak surrounding emissions and improve our understanding or their association with star formation.

Galaxies and the study of their morphology (Baillard et al. 2006; Kuminski et al. 2014; Dieleman, Willett & Dambre 2015), their disc formation, their relation with the intergalactic medium (IGM), and the link between the evolution of the IGM and star formation, for examples, would too (Scannapieco et al. 2006; Oppenheimer & Davé 2009; Wiersma et al. 2010).

Moreover, faint targets, such as distant galaxies and gravitational arcs (Ellis et al. 2001; Glassman, Larkin & Lafrenière 2002; Hu et al. 2002; Messias et al. 2014) are also an important area to explore with visible MCAO. A large FoV with a great AO correction, and therefore a great improvement in resolution, is a great combination for studying the distant universe.

## 6.3 Conclusion

We have in our hands the first MCAO visible data.

The astrometric and photometric performance level reached is very encouraging to deepen the study and develop the science capability of such a system.

The FWHM performance varies from 60 mas to 700 mas depending on the seeing, the atmospheric conditions, and the AO performance. But overall, it is an improvement over the natural seeing by a factor of 2–3. In terms of throughput, the AO correction allows us to improve the sensitivity by a factor at least 1.5, the AB zero-point magnitude found are  $\text{mag}_{\text{ZP}}(i \text{ band}) = 29.00 \pm 0.15$ ,  $\text{mag}_{\text{ZP}}(\text{CaTband}) = 28.85 \pm 0.20$ ,  $\text{mag}_{\text{ZP}}(z \text{ band}) = 28.75 \pm 0.15$ . Finally, the astrometric performance, in terms of residual

star jitter, gives an avg error of 3.2 mas, for typical exposures of 5 s, and it scales as expected with the photon noise, which means that no systematic error are detected, at least in the data studied in this paper. Thanks to the availability of *HST* images for the GeMS+GMOS observed globular clusters, we are able to reach an astrometric calibration with a precision around 100 mas. A CCD upgrade for GMOS-South has increased its performance for the wavelength range [600–1050] nm. We are then expecting better performance of GeMS+GMOS. The GeMS+GMOS combination is also very interesting when used in Long-Slit, Multi-Object and Integral Field Spectroscopy modes. The gain in spatial resolution will not only allow us to use smaller slit size but since the exposure time to reach a given signal-to-noise ratio scales roughly as the square of the image quality, the use of such a system represent a substantial efficiency improvement, comparing to GMOS without AO. Spectroscopic performance will be presented in a future paper. Thanks to GMOS versatility, we can envisage the use of GeMS with the IFU mode (5 arcsec  $\times$  7 arcsec), which can be used in a similar fashion as with the Narrow Field Mode (7.5 arcsec  $\times$  7.5 arcsec) of the system VLT/MUSE- GALACSI (Ströbele et al. 2012).

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