FIRST PERFORMANCE OF THE GeMS + GMOS SYSTEM.

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Abstract. During the commissioning of the Gemini Multi-Conjugated Adaptive Optics (MCAO) System (GeMS), we had the opportunity to obtain data with the Gemini Multi-Object Spectrograph (GMOS) in March and May 2012. Several globular clusters were observed that allow us to study the performance of this unexpected combination. GMOS is a visible camera, hence pushing MCAO toward the visible. We report here on the early results with the GMOS instrument, derive performance in term of full-width half-maximum (FWHM) and improvement against natural seeing, and derive a first photometric and astrometric analysis.

1 Introduction

1.1 GMOS: Gemini Multi-Object Spectrograph

GMOS is a spectro-imager working in the visible.

In its spectrograph mode, long-slit, multi-slit and one IFU are available. The imaging mode covers a 5.5' x 5.5' field of view (FoV) over three CCD chips with a pixel scale of 79 mas. The three CCD chips form a 6144 x 4608 pixel array, with two gaps of about 37 pixels separating the detectors [1]. In its imaging mode, GMOS-S has six standard broad band filters: u-band (336-385nm), g-band (398-552nm), r-band (562-698nm), i-band (706-850nm), CaT-band (780-933nm) and z-band (≥848nm). The present paper focus on GMOS-S’s imaging capabilities.

1.2 GeMS: Gemini Multi-Conjugate Adaptive Optics System

The Gemini Multi-Conjugate Adaptive Optics system, a.k.a. GeMS, is the first multi-laser guide stars system offered to the astronomical community. It uses five sodium laser guide stars, four at each corner of a 60” square and one in the centre to form an X-shaped constellation, in conjunction with three natural guide stars [2]. GeMS has been designed to deliver an almost diffraction limited image quality in the Near Infrared (NIR), over a field of 2 arcmin across. It started commissioning in 2011, and is now open through the regular queue process at Gemini.

1.3 GeMS+GMOS system

During the commissioning of the Gemini MCAO System (GeMS), we had the opportunity to obtain data with the Gemini Multi-Object Spectrograph (GMOS) in March and May 2012.

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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’x2.5’, and the pixel scale is 35.9mas. Also, because GeMS as been designed to work in the NIR (see Section 3.2), only the reddest filter of GMOS can be used. These are the i-band (706-850nm), CaT-band (780-933nm) and z-band (≥848nm). Table 1 summarized the differences when using GMOS and the system GeMS+GMOS.

We observed 14 globular clusters with the GeMS+GMOS system during March and May 2012. In order to better understand its scientific capabilities and to provide more thorough documentation for future users of this system, we aim to create image quality maps based on FWHM measurements and to determine the throughput of the GeMS+GMOS system by comparing it to the known throughput of GMOS alone.

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

<table>
<thead>
<tr>
<th>System</th>
<th>Field of View</th>
<th>Pixel Scale</th>
<th>Available Broad Band Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMOS</td>
<td>5.5’ x 5.5’</td>
<td>79 mas</td>
<td>u, g, r, i, CaT, z</td>
</tr>
<tr>
<td>GeMS+GMOS</td>
<td>2.5’ x 2.5’</td>
<td>35.9 mas</td>
<td>i, CaT, z</td>
</tr>
</tbody>
</table>

2 FWHM Performance

The star detection and the FWHM values are obtained by running SExtractor [3] on the reduced images. Figures 1, 2, 3, 4, and Table 2 present the field images with the Natural Guide Star (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.

**Table 2.** Table presenting the average FWHM and natural seeing obtained for four globular clusters with their observing band and the exposure time used.

<table>
<thead>
<tr>
<th>NGC</th>
<th>Observed Band</th>
<th>Exp. Time</th>
<th>Natural Seeing</th>
<th>Average FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4590</td>
<td>i-band</td>
<td>5 sec</td>
<td>0.8”-1.1”</td>
<td>382.6 mas</td>
</tr>
<tr>
<td>NGC 6496</td>
<td>i-band</td>
<td>5 sec</td>
<td>0.8”-1.1”</td>
<td>635.5 mas</td>
</tr>
<tr>
<td>NGC 6369</td>
<td>z-band</td>
<td>120 sec</td>
<td>0.5”</td>
<td>179 mas</td>
</tr>
<tr>
<td>NGC 5286</td>
<td>z-band</td>
<td>5 sec</td>
<td>0.7”</td>
<td>335.6 mas</td>
</tr>
</tbody>
</table>

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 to 2.8. From Table 2, we can also observed that for a same natural seeing range, the FWHM performance for NGC4590 and NGC6496 are almost a factor two apart. This difference can be explained by different reasons:

– 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. See Vidal et al. from this conference for a more detailed analysis of the impact of the NGS constellation.

– the laser return: if we have less laser photons, the loops are processing slower and the overall performance will decrease.
– the turbulence profile: depending where the principal layers are located, we can more or less correct them.

Fig. 1. Left: Field image of NGC 4590 with the N-E orientation (North Right - East Down), the NGS constellation and the studied area marked by a solid and a dashed orange line, respectively. Right: FWHM map.

Fig. 2. Left: Field image of NGC 6496 with the N-E orientation (North Right - East Down), the NGS constellation and the studied area marked by a solid and a dashed orange line, respectively. Right: FWHM map.

3 Photometric Performance

3.1 Method

We expect the GeMS throughput to be lower than the GMOS throughput 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 and the GeMS+GMOS system using the following equation (Eq. 1):

\[
\text{(GeMS + GMOS) Throughput} = \frac{(\text{GeMS + GMOS}) \text{ Flux}}{\text{GMOS Flux}} \times \frac{\text{GMOS Exp.Time}}{(\text{GeMS + GMOS}) \text{ Exp.Time}}
\]  

(1)
Fig. 3. Left : Field image of NGC 6369 with the N-E orientation (North Right - East Down), the NGS constellation and the studied area marked by a solid and a dashed orange line, respectively. Right : FWHM map.

Fig. 4. Left : Field image of NGC 5286 with the N-E orientation (North Right - East Down), the NGS constellation and the studied area marked by a solid and a dashed orange line, respectively. Right : FWHM map.

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

3.2 Results

Figure 5 shows the throughput difference in percentage for two globular clusters. Overall, we find that the throughput through GeMS is 25% of the native GMOS one, for the i-band filter. In z-band, the throughput appears to be 10-20% less when going through GeMS, compared to GMOS going straight to the sky. The low throughput observed in i-band can be explained by the wavelength cutoff of the Beam Splitter (BS) used in the AO bench. This beam splitter cuts at 850nm, all the light with a lower wavelength being sent into the Wave-Front sensors of the AO bench, only the wavelength larger than 850nm are directed toward the science instruments. If GMOS would be used with GeMS for science operations, one option to improve the throughput would be to change the beam splitter with one having a cutoff at 600nm (see Figure 6). This would allow to observe in the GMOS r-band filter. We could not afford shorter wavelengths, as the laser sodium light (at 589nm) has to be seen by the AO Wave Front sensors. Not that
changing the BS for a shorter wavelength cut will affect the limiting magnitude of the Natural Guide Stars, needed for the tip-tilt correction. We estimated that going for a 600nm BS would decrease the limiting magnitude by 1. This will also impact the sky coverage. Another possibility will be to use a beam splitter 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 (see Trujillo et al. this conference for more details).

4 Astrometric Performance

Based on the globular cluster data, we estimated a first astrometric performance of GeMS + GMOS. There are two different astrometries to take in account: the absolute astrometry and the relative astrometry.

4.1 Absolute astrometry

We are presenting here the case of NGC 4590 for which we have 31 individual images taken during the same night with the same configuration (exposure time, filter and binning). After founding the star position in each individual frame with SExtractor, we create a Master Reference Frame (MRF) from the average star position. We compare then the difference in position from all the individual images to the MRF. The results are shown in different ways: the astrometric error map (Figure 7 left), the comparison of the total astrometric error to the expected photon noise (Figure 7 center), and the frequency of the astrometric error (Figure 7 right). The photon noise is estimated following the Equation 2, where $N_{\text{photon}}$ is the number of photons of one object. For NGC4590, the average astrometric error is 3.20 mas.

$$\sigma_{\text{photon}} = \frac{\text{FWHM}}{\sqrt{N_{\text{photon}}}}$$ (2)
Fig. 6. The blue line shows the Canopus transmission according to wavelength for the setup used in this work. It is evident that the beam-splitter cut-off point occurs within the i-band’s 706-850nm range. This explains why the i-band throughput determined above is so much lower than we might expect from the GMOS throughput.

Fig. 7. Left : Absolute astrometric error map. Each circle is centered 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.

4.2 Relative astrometry

To measure the relative astrometry, we select one image from NGC4590, used for the absolute astrometry, and compare the distance from a central bright unsaturated star to the brightest (unsaturated) star in various regions of the sky. In the presented case, NGC4590, we chose nine different regions around the central star. From the left panel of Figure 8, we show that we obtain a consistent precision for star to star distances lower than 50”. From the right panel of Figure 8, we remark that some regions are being better corrected from others. The best corrected
regions are the ones located around the natural guide star constellation. This demonstrates the importance of the NGS constellation choice.

![Error on separation (4 images)](image)

Fig. 8. Left : Astrometric error versus the expected photon noise. Right : Histogram showing the frequency of the astrometric error.

5 Discussion - 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. A CCD upgrade for GMOS-South is scheduled during the 2014A semester, which will increase its performances for the wavelength range [600-1050]nm. We are then expecting better performances of GeMS+GMOS. The GeMS+GMOS combination is also very interesting when used in Long-Slit and Multi-Object Spectroscopy mode. The gain in spatial resolution will not only allow us to use smaller slit size but it will also allow us to reduce the exposure time for a requested SNR, comparing to GMOS without AO. Thanks to GMOS versatility, we can envisage the use of GeMS with the IFU mode (5”x7”), which will compete with the Narrow Field Mode (7.5”x7.5”) of the system VLT/MUSE- GALACSI. The complete sets of data and results obtained with the GeMS+GMOS combination and precise details on the analysis are presented in Hibon et al. 2013 (in preparation).

References