Abstract. Two years after its first light in 2011, GeMS, the Gemini Multi conjugate adaptive optics System achieved the science verification process and started queue observations. From the Adaptive Optics (AO) point of view it is time to summarize the performance provided by the system after more than 6 months of science on very different observing conditions. We present a statistical study of the overall performance from the AO data recorded by the GeMS telemetry. In particular we study the seeing and LGS photon return performance dependency and conclude on the current limitations of the system.

1 Introduction

GeMS, the Gemini Multi conjugate adaptive optics System installed at GEMINI south (Cerro Pachon, Chile) started to deliver science since the beginning of 2013. It is now available for use by the extensive Gemini international community. GeMS is using the Multi Conjugate Adaptive Optics (MCAO) technique allowing to dramatically increase the corrected field of view (fov) compared to classical Single Conjugated Adaptive Optics (SCAO) systems [1]. It has been designed to feed two science instruments: GSAOI [2], a 4k×4k NIR imager covering 85”×85” with 0.02” pixel scale, and Flamingos-2 [3], a NIR multi-object spectrograph. Using GeMS in the visible is also possible on GMOS [6], with lower performances though.

GeMS is designed to use 3 deformable mirrors (DM) conjugated respectively at 0, 4.5 and 9km, 5 high orders wavefront Sensors (WFS) sensing the wavefront thanks to 5 Laser Guide Stars (LGS) Sodium type spread in a 1’ diameter field of view. GeMS also uses 3 additional Natural Guide Stars (NGS) WFS to sense the Tip-Tilt. Note that due to some actuators failures the 4.5km DM is not currently implemented on GeMS therefore the results presented in this paper only uses 0 et 9km conjugated DMs.

First science results are discussed in [4] and lessons learned are discussed in [5]. Paper’s goal is to focus on the AO performance during the 45 observed science programs and try to build a summary of the first 7 months of science observing time on GeMS/GSAOI. The panel is representative of the science AO fields ranging from opens clusters, globulars clusters, nebulæ’s fields, sparse fields and cosmological fields.

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2 Telemetry data summary

This paper presents the results computed from the GeMS’s telemetry data consisting on recordings of circular buffers (CB) of DMs voltages, LGS and NGS WFS slopes. For the AO analysis point of view, they constitute the core of the ”must to save” datasets. In addition, more than 50 states of the system are also saved and written in the CB headers files: loops status, centroiding gains values, flux per WFS (LGS and NGS), matrices loaded in the RTC, command law coefficients used to perform loops, motors bench positions, calibrations parameters...

The telemetry uses 3 process that needs to be started at the beginning of the night. The first process, is in charge of tracking the GSAOI status and starts the recordings of data (CB+status) when an exposure is detected. When GSAOI exposure ends, it saves CB data together with the status of the instrument to keep an history of the bench. This strategy allows to reduce significantly the number of data saved by the telemetry and avoids useless data (with loops opens, wrong gains, wrong calibrations, no image ect...).

A second process is in charge of computing the results each time it detects a new CB. After processing it computes in particular: a seeing estimate from the LGS WFS slopes, an error budget of the instrument (10 terms), displays of the PSDs of the main loops and a SR/fwhm map if also available. Finally results are displayed in a web page. The delay between the end of recording of the data and the display of the results in the telemetry web page is around 90s.

Finally a third process is used to process the incoming GSAOI images. The goal is to perform an automated fast detection of the stars in the 85x85” field of view and compute SR and fwhm for each of them. Average time of GSAOI processing is around 1mn including background removal, flat-fielding, removal of bad pixels, stars detection and SR/fwhm computing.

3 GeMS image quality: statistical study

3.1 Overall performance

We present in this section a summary of the GeMS delivered Image Quality (IQ) based on telemetry database (33 usefuls nights on 45 total observed since December 2012). In classical AO the image quality variation is almost only affected by the seeing fluctuations. GeMS/GSAOI image quality depends on many others parameters such as the NGS constellation geometry and distance, number of NGS used, brightness of the NGS, but also others related to MCAO like: LGS photons return, Cn2(h) (turbulence profiling), tomographic NCPA and other AO optimisations/calibrations to optimize the correction in the 85x85” fov. Note that the selected results presented in this paper were taken with 3 NGS constellations only.

Figures 1 and 2 respectively represents the SR and FWHM image quality delivered for a given fraction of the GeMS/GSAOI observed time (with GSAOI exposure time >10seconds) for K (red/plain line), H (green/dashed line) and J bands (blue/dotted line). They include all the filters used for scientific observations including narrow and broad bands filters. SR and FWHM values are average values on all the stars available on the entire fov (85x85”) respectively computed for 1073, 472 and 253 GSAOI scientific images in K, H and J bands. Figure 3 summarize the SR and FWHM GeMS IQ for 20, 50, 70 and 85% fractions of observed time for each band.

For example: GeMS IQ20 in K band means that 20% of the observed time in K bands the average performance on the field was 26.4% of SR and 0.076” fwhm. The GeMS IQ is also useful to prepare and select scientific programs based on their required IQ and amount of time requested since we know the fraction of time we can perform at given resolution.
Fig. 1. Average of SR measured on the field for a given fraction of observed time. K, H and J bands are respectively represented in red/plain, green/dash and blue/dot lines.

Fig. 2. FWHM (") for a given fraction of total observed time. K, H and J bands are respectively represented in red/plain, green/dash and blue/dot lines.

Fig. 3. Summary of the Strehl Ratio and fwhm (average correction on the field) measured on GeMS/GSAOI as a fraction of the total observed time.

While IQ20 can be considered as "good observing conditions", IQ50 represents the average performance of the instrument (i.e. 1/2 chance to have better or worse IQ). We can thus consider that GeMS is currently capable of delivering in average 17.4%, 10.2% and 7.2% SR respectively for K, H and J Bands. Similarly, we have a typical FWHM of 0.094", 0.077" and 0.109" in K, H and J Bands.

We note that 90% of the time the FWHM in K band is less than 0.15" whatever the seeing conditions making us confident to deliver decent science data. On the other side SR>30% occurred only 10% of the time (or 3h on a total of total exposure of 30h). Compared to the original specifications the system was designed to deliver up to 60% SR in K band. The main reason is the photon return that is limiting our operating frequency and thus the corrected bandwidth. Secondly the loss of the third DM is also affecting the generalized fitting error particularly in the case where turbulence is located at 5km.

For these reasons we can consider that the current GeMS performance lies between GLAO and "real" MCAO performance. Upgrades are planned in the near future to improve performance ([4]). Note that the typical observed variability of the performance on the field is relatively constant at ±5% on SR units (i.e if a given GSAOI image has a SR average of 25%, maximum performance on the field is 30% and worse 20%).
3.2 Seeing LGS flux dependancies

In this section we present the average SR and FWHM as function of the estimated seeing. Figure 4 presents the SR versus the seeing for all the observed K Bands filters. Each point represent the average SR on the field for an individual GSAOI image and a total of 1073 images were processed. In order to increase the visibility of the plot we also display the same result as density maps. Figure 5 represents the 2D histogram of the probability to have an image with the given SR/seeing couple. One recognise the expected general behaviour where the SR increase as the seeing decrease. Darkest region reflects the functioning point of the system which occurs at a seeing of 0.6” and 17.4% (i.e reflecting the position of the IQ50 value as function of the seeing. Note that performing with a SR>17.4% is definitely possible for a given seeing condition but less probable than the average value. We also note a big disparity on the results. For instance with a given seeing of 0.6” the performance range from a SR less than 10% up to 40%. Figures 6 and 7 shows the FWHM resolution variation versus the seeing for all the K bands filters. Red plain line represents the theoretical diffraction limit at 2.2µm.

![Fig. 4. Strehl Ratio measured in average on the 2' field of view for each GSAOI scientific image (one point per image processed) versus the seeing in K Band.](image)

![Fig. 5. Density map of Figure 4. Darkest region reflects the functioning point of the instrument (most probable performance for a given seeing ex: SR=20% with 0.6” in K band).](image)

3.3 LGS Photon return variability

This section presents a summary of the photon return measured by the GeMS LGS WFS during the 6 months campaign of observations. An overview of the laser performance and a Beam Transfert Optics (BTO) description can be found in [7]. The LGS photon return is crucial for the AO system since it has been designed to operates as fast as 800Hz.

We estimate at 10ph/cm²/s/W the amount of minimum flux to keep at 800Hz a significantly low level of noise in the main LGS loop (i.e 35ph/frame/px on LGS WFS) [8]. Average flux
**Fig. 6.** FWHM (") measured in average on the 2’ field of view for each GSAOI scientific image (one point per image processed) versus the seeing in K Band.

**Fig. 7.** Density map of Figure 6. Darkest region reflects the functioning point of the instrument (most probable performance for a given seeing, ex: 0.074mas with 0.6” seeing). Red plain line illustrates the diffraction limit of the telescope in K band.

**Fig. 8.** Strehl ratio measured in K Band as function of the main loop frequency (Hz).

**Fig. 9.** Example of LGS flux variability along a night of observation. In blue and red are represented the photon return on the LGS WFS measured respectively the 1st of February and 25th of May. We observed a factor ≈4 between summer and winter conditions and also a strong variability along the night (factor 2).
measured in summer (Dec-Feb) is 3.8ph/cm²/s/W and 8.1ph/cm²/s/W for June. The immediate consequence is that we are forced to set a typical loop frequency around 250Hz in summer and 500Hz in winter thus affecting the bandwidth of the instrument and lowering dramatically its performance. Figure 8 shows the SR VS the LGS loop frequency dependancy. Unsurprisingly the faster we run the better the SR is. It also explains why it is difficult for GeMS to perform a good performance in summer despite good seeing conditions. Hopefully in winter a higher photon return tends to balance for the bad seeing conditions. Figure 9 illustrates the high variability of the photon return between a typical summer and winter night (1st February 2013 and 25 May 2013).

3.4 Selected science case study

3.4.1 Orion Bullets

Images made on the Orion SV program can be considered as the standard performance provided by GeMS. We observed this program in January/February 2013 (see also [4] for science details). Figure 10 represents the SR measured in average on the images (K Short filter) as a function of the seeing. Red points represents the performance on the selected Orion program images superimposed on the overall SR VS seeing performance distribution of GeMS (gray tones density). We recognise the “natural” tendency where the SR increased from 10% to 30% when the seeing improved from 1” to 0.55”. Location of the points are centered on the trend of the overall SR dependency explaining why we consider this program as a good example of the GeMS classical performance. Figure 11 shows the SR VS flux measured on the LGS WFS (in ph/sec/pixel). Another clear dependency is also visible on the LGS flux since when it increased from 10000 to 16000 ph/sec/px, performance improved from 10% to 30%. This is the general trend we observed on any program. An overview of the LGS facility and how we plan to improve the photon return is detailed in [7]. In conclusion that program took advantage of both improvements in seeing and LGS photon return.

3.4.2 RCW41

The program called RCW41 was observed under 2 different nights (29th of January and 1st of February 2013) under similar conditions and approximatively at the same hour (i.e similar zenithal angle). We measured during the first night an average of SR≈32% while we had a very significant drop of performance with a SR≈16% during the second one. Figure 12 shows the entire data set (red circles points) and their location on the SR VS Seeing graph. One clearly see the difference of regimes between the 2 nights. During night #1 we achieved SR between 20% and 37% for seeing ranging from 1.2” to 0.7” while during the night #2 we had SR between 7% and 20% for similar seeing conditions. The performance achieved during night #1 is particularly good compared to the GeMS average behaviour (points are well above the darkest part of the density plot, i.e the overall averaged performance) while on the night #2 it is back to regular performance (SR≈15% with seeing at 0.7”).

It also is important to consider that for both nights we spanned similar LGS photon return (Figure 13) leading to the same LGS frame rate (250Hz). Loops settings were also very similar in both cases (loops gain, leaks...).

Finally looking at SR VS LGS rms residual error plot we see that the SR improvement comes essentially on the low high orders rms residuals (measured on the LGS WFS). The LGS
Fig. 10. Density map of SR Vs Seeing. Red points are the performance for the selected GSAOI image on the Orion bullets science program only.

Fig. 11. Density map of SR Vs Flux measured on LGS WFS (ph/s/px) Red points are the performance for the selected GSAOI image on the Orion bullets science program only.

Fig. 12. SR Vs seeing distribution for the RCW41 program observed on night#1 (29/01/2013) and night #2 (01/02/2013).

residual error is composed of the sum of the noise, bandwidth and the generalised fitting error terms. Noise level was measured at the same level on both nights (same LGS photon return) and the average windspeed was also similar (same bandwidth error). In conclusion we think we encountered on the night #1 a good Cn2(h) profile that matched particularly well with the deformable mirrors conjugated at 0 and 9km. Most of the time (ex: night #2) the high orders rms errors are higher. Of course it can be a combination of the noise and BW terms but in average we think the contribution of the Cn2(h) is significant and we pay the price on the performance by missing the DM at 4.5km. Further analysis are planned on the Cn2(h) measurement, the BW
and noise terms to help to quantify precisely the dependency of the generalised (tomography) part on the residual error.

4 Conclusion

We presented a statistical performance approach of GeMS/GSAOI over its first 6 months of science operations. The typical performance of the instrument is currently SR\(\approx18\%\), 10\% and 4\% respectively in K, H and J bands and average FWHM resolution on the 85x85" field of view were measured at 94, 77 and 109 mas. We identified that the current performance is mainly limited by the missing 4.5km conjugated deformable mirror (increasing the tomography error) and the LGS photon return (reducing the typical operating frequency at 250Hz in summer and 500Hz in winter). Upgrades are planned to restore the 3DM configuration and improve the LGS photon return.

References

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