Reshaping and polishing the GeMS MCAO system

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ABSTRACT

GeMS, the Gemini South MCAO System, has now been in operation for 3 years with the near infrared imager GSAOI. We first review the performance obtained by the system, the science cases and the current operational model. In the very near future, GeMS will undergo a profound metamorphosis, as we will integrate a new NGS wavefront sensor, replace the current 50W laser with a more robust one and prepare for a new operational model where operations will shift from the mountain to the base facility. Along this major evolution, we are also presenting several improvements on the loop control, calibrations and automatization of this complex system. We discuss here the progress of the different upgrades and what we expect in terms of performance improvements and operational efficiency.

Keywords: adaptive optics, multi-conjugate adaptive optics, laser guide stars, tip-tilt sensing

1. INTRODUCTION

The Gemini Multi-conjugate Adaptive Optics System (GeMS),[1,2] an AO facility instrument installed on the Gemini South telescope at the top of Cerro Pachon (Chile), delivers a uniform, close to diffraction-limited images in the near infrared bands (from 0.95 μm to 2.5 μm) over a field of view of 120″. GeMS is the first multi-conjugate adaptive optics system based on sodium laser guide stars (LGS) and the only one currently in operation. It uses five laser guide stars, distributed on a 60″ square asterism, with an extra star at the center. Light gathered from LGSs allows 5 16x16 sub-apertures Shack-Hartmann wavefront sensors to measure the optical wavefront distorted by atmospheric turbulence. Measurements can be then used to pilot two deformable mirrors (DM) to compensate for it. The DMs are conjugated to layers of turbulence located at 0 km and 9 km (known as DM0 and DM9 respectively). As tip-tilt remain undetermined from LGS measurements, the tip-tilt and plate scales modes (high altitude quadratic modes) are measured by a second set of wavefront sensors with light from natural guide stars (NGS) present in the field. Measurements from 3 NGS are necessary for compensation of tip-tilt and plate scale modes over the full field of view. One of the NGS probes diverts 30% of its light to a Slow Focus Sensor (SFS). The SFS compensates for the slow altitude drift of the sodium layer in the mesosphere. The AO bench itself, called Canopus, is physically installed at the Cassegrain focus of the Gemini South Telescope.

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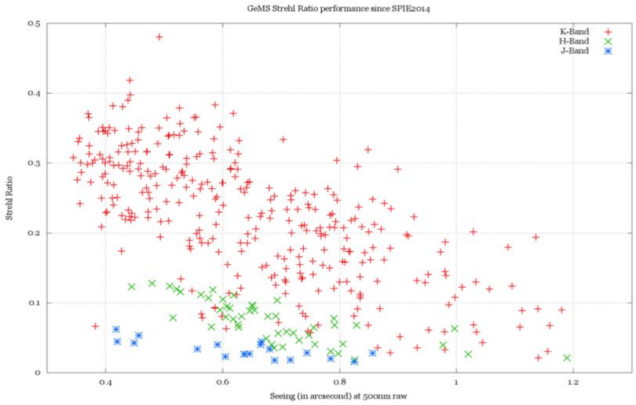

Figure 1. Sample of GeMS performance over the 2014-2015 year in terms of Strehl ratio in fonction of the seeing. Narrow-band images have been accounted as the broad band images (Brγ is accounted as K-band, for example). In red, performance in K-band, green in H-band and blue in J-band.

For the past 3 years, GeMS has been combined with the 85” by 85” GSAOI near infrared imager.[3] GSAOI consists of 4 2048×2048 pixels Hawaii-2RG and is equipped with a comprehensive set of wide and narrow band filters. In the future, GeMS could also routinely provide its AO-corrected beam to others instruments such as the near infrared spectro-imager Flamingos-2[4] or the visible spectro-imager GMOS.[5] Flamingos-2 has a capacity for multi-object spectroscopy (MOS) while GMOS can routinely deliver MOS and Integral Field Unit (IFU) science in the visible bands.

2. OPERATION AND SCIENCE EXAMPLES

Performance of GeMS in good atmospheric seeing has been steady over the 2 last years and can reach about 40% Strehl in K-band over the field of view included inside the triangle made by the 3 NGS. Maintaining performance has been more challenging in the case of medium to bad seeing, mostly due to the lower-than-expected laser power (see next section for further details). A full overview of the performance in the period 2014-2015 is offered in Figure 2.

We are still pursuing the goal of streamlining and automatizing operations of GeMS in order to reduce the Gemini operation night staff required to operate it. Moreover, we are involved in the general Gemini telescope process to migrate operation from the telescope control room to our La Serena base facility. To this effect, a Transponder-based Aircraft Detection (TBAD) unit,[6] directly shutting down the laser propagation when the laser beam is close from a plane, has been recently put into commissioning phase. In conjunction with VITRO (VIsualizador de TRansito Oceanico), a software providing commercial plane positions from the Chilean civil aviation DGAC, Gemini night operation staff can now decide when to safely propagate or stop the propagation of the laser beams without the help of three external spotters. We expect to operate GeMS from La Serena in 2017.

Science programs with GeMS-GSAOI are tackling a diversity of astrophysical cases. The GeMS-GSAOI wide field with a high spatial resolution has been helping several teams to reach unprecedented depth in ground-based photometric study of crowded stellar population.[7,8] It also helped to push the study of stellar population and formation in very different environment than our own galaxy, uncovering several hundreds of Young Stellar Objects candidates in the Large Magellanic Cloud.[9] It can also be used to deliver high resolution and high SNR to diffuse extended gaseous regions such as planetary nebulae[10] or Herbig-Haro jets[11] (see Figure 2).

Finally, during the commissioning of GeMS, the GMOS instrument was used in its imaging mode. As expected, the performance was slightly better than an equivalent GLAO system in the visible, *i.e.*, improving the FWHM by a factor of about 2 compared to the seeing in median atmospheric conditions but not reaching the diffraction limit of the telescope. The gain in light concentration due to better resolution overcomes the lesser throughput due to the additional Canopus optics. Results have been compiled and are the subject of a dedicated publication.[12]

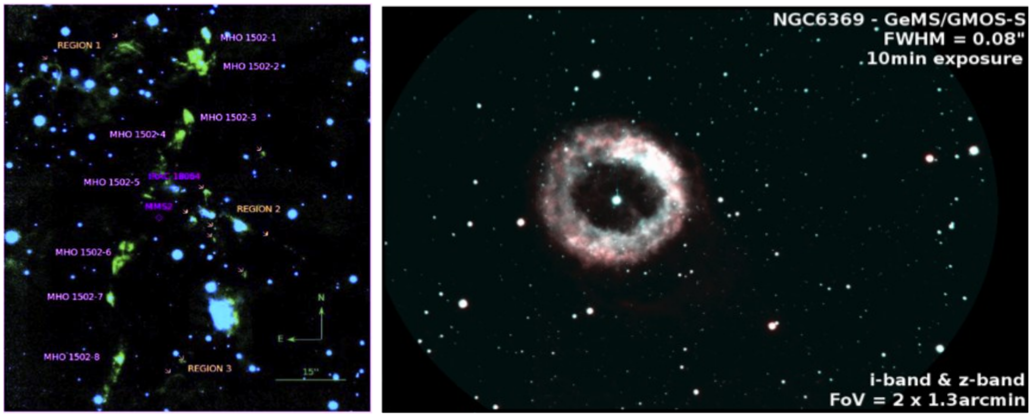

Figure 2. Left:GeMS-GSAOI image of MHO 1502 such as mapped by Ferrero *et al.*. Right: A GeMS and GMOS NGC6369 planetary nebula. This image with a FWHM of 0.08 in i- and z-band was taken in excellent seeing condition.

3. A NEW LASER SYSTEM

The laser system is one of the very key components for the GeMS instrument. The current laser, a 50W sodium laser system delivered by Lockheed Martin Coherent Technologies (LMCT) in March 2010, has seen its first light on-sky in January 2011.[13] Two infrared laser lines are independently amplified multiple times before being mixed inside a sum frequency generation birefringent crystal to produce a laser line centered the D2a sodium resonance. This complex system is located in a container-like box mounted on a side telescope platform providing a controlled environment. Since its first light, a very significant amount of engineering efforts has been devoted into the laser maintenance and its preparation before GeMS-GSAOI runs, with varying degrees of success in terms of laser power (from 25 to 35W over the last 2 years) and stability over a run. In September 2015, a 8.3 magnitude earthquake hit northern Chile. As a result, GeMS laser suffered from major misalignment and could only be recovered in February 2016 after massive troubleshooting operations on the laser bench. The laser power has very been recently improved to 37W with an M^2 of 1.2.

In parallel, we looked for potential laser replacements with similar performance in terms of photon return but increased robustness and ease of use, in order to decrease the engineering workload and provide more sustainable long term operation for GeMS. Based upon favorable conclusions from an internal study, the Gemini board endorsed the procurement of a new laser. The procurement phase was done through a public request for quotes. The review committee opted for a Toptica SodiumStar laser. The laser will be assembled before the end of 2016 and received and tested by Gemini staff over the course of 2017. Gemini also intends to replace the current Gemini North laser with such a Toptica laser in the coming years.

The Beam Transfer Optics (BTO) system transferring the laser beam between the telescope side platform and the Laser Launch Telescope placed behind the secondary mirror will be modified *a minima* to accept the beams from one or the other laser. The BTO will continue to split the laser beam into 5 beams to form the asterism of 5 Laser Guide Stars (LGS). The Toptica laser will also be mounted on the telescope side platform but outside of the controlled environment box (see figure 3). We currently intend to keep the current LMCT as a backup unit. In a longer term, depending on our on-sky results of photon return in the low sodium concentration season (i.e. summer),[14] this scheme allows us to keep open the option of co-adding both laser beams for improved AO performance.

4. A NEW NGS WFS: NGS2

We are also addressing another shortcoming of the current GeMS instrument by preparing an upgrade for the Natural Guide Star Wavefront Sensor (NGS WFS). The current WFS can acquire up to 3 NGS with 3 mechanical probes moving over a technical field of view of 120 arcseconds to deliver measurements of tip-tilt and plate scales modes. Each probe is essentially a quad-cell APD fed through an optical fiber after the incoming beam being split by a tiny pyramid. Due to alignment and design issues complicated by the compactness of the probes, the

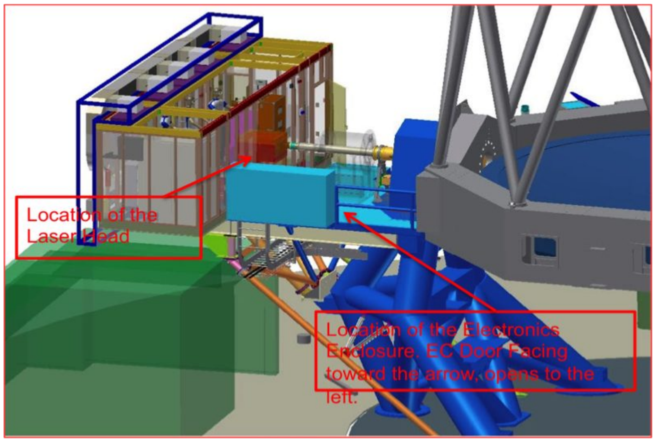

Figure 3. Scheme of the telescope laser side plateform. The telescope structure lies on the right. The LMCT laser is currently contained in the container-like box on the left. The new laser will be installed in the intermediate open space and connected to the beam transfer optics in a similar manner as the current one.

throughput is vastly below the original specification (the best estimate of the throughput gives a low 4%). For regular science programs, GeMS requires three stars of magnitude 15.5 or brighter in the R-Band. Moreover, the probes have a limited field of view of 1.4" and do not possess auxiliary wide field acquisition cameras; the NGS acquisition process can be slow as optical distortion prevents us to forecast probe positions to the arcsecond level compared to the star position on sky.

Both concerns can be addressed simultaneously with large benefits using more recent technology. The NGS2 project, replacing the current NGSWFS, has been proposed by an ANU group led by Francois Rigaut, funded by several Australian institutions and the Gemini Observatory (See Rigaut *et al.*, this conference for further details). The project is based upon the acquisition of the full technical field of view of 120" by a single focal plane EMCCD camera. Three small regions of interest can be then defined around the NGS and read up to 800 Hz. Centroid measurements will serve to deliver tip-tilt and plate scale modes. The system is simpler and more robust than the current NGS WFS: it is based on classic sized optics, there are no moving parts except a focus stage to compensate for eventual drifts and finally the software associated with NGS2 will incorporate a model to compensate for previously calibrated high distortion.

We expect the new NGS2 to deliver precise tip-tilt and plate scale modes measurements at least down to magnitude 17 with a goal for 18. This will dramatically increase the GeMS sky coverage (see Figure 4), allowing GeMS to observe more extra-galactic science fields. The acquisition procedure will also be accelerated and simplified as the operator will be able to check the entire field of view and eventually correct the position of the region of interest in front of the NGS.

Gemini staff are responsible for the overall supervision of the project, the integration and commissioning phase on the telescope and the replacement of the current SFS measurements by measurements by one of the telescope peripheral wavefront sensors. Completion of the project is expected over the course of 2017.

5. ASTROMETRIC CALIBRATION

Although astrometry was not a formal part of the original science cases envisaged for GeMS, it can become a staple of the GeMS-GSAOI science due to its unprecedented ratio between diffraction-limited resolution and a large field of view. The astrometric precision is currently limited by some still undetermined dynamic systematic effects to about 0.4 to 0.5 milliarcsecond rms after calibration of high-order distortions in post-processing.[15] This performance can currently only be achieved if a sufficient number of natural sources are present in each GSAOI quadrant. Calibrating and understanding the sources of distortions requires an accurate reference target that can be inserted in the Canopus bench at any time. We will be very soon upgrading the Canopus focal plane calibration source to this effect. The current Canopus calibration source is made of 10 usable sources (*i.e.* fake stars) which are created through a combination 10 μm pinholes fed by optical fibers. They are used for various

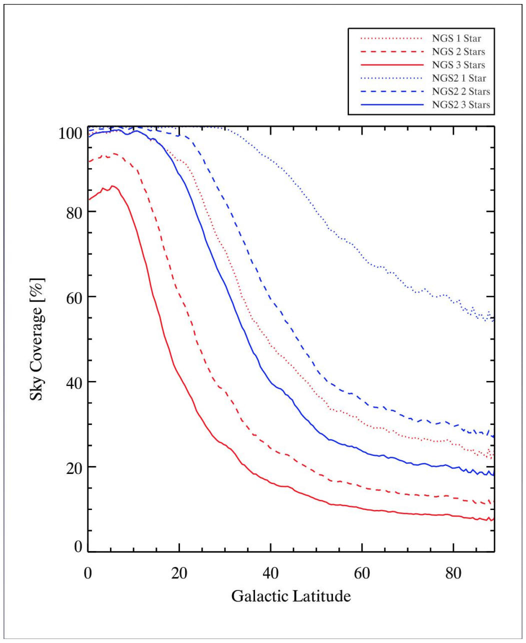

Figure 4. Sky coverage of the NGSWFS in function of the galactic latitude. In red curves for the current NGSWFS and expected for NGS2 with a limiting magnitude of 17. Acquisition with less than 3 NGS is feasible with a small decrease in uniformity of the performance over the field of view.

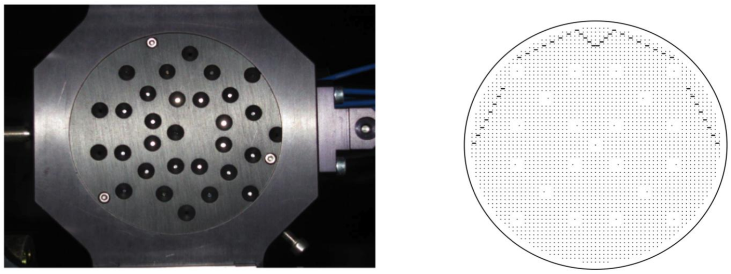

Figure 5. On the left, a picture of the actual NGS focal plane calibration source. About 10 sources are actually used for calibration. On the right, the design of the photomask. Each black dots represents a 10μm clear pinhole over a chrome covered quartz plate. Slits are present outside the GSAOI field of view.

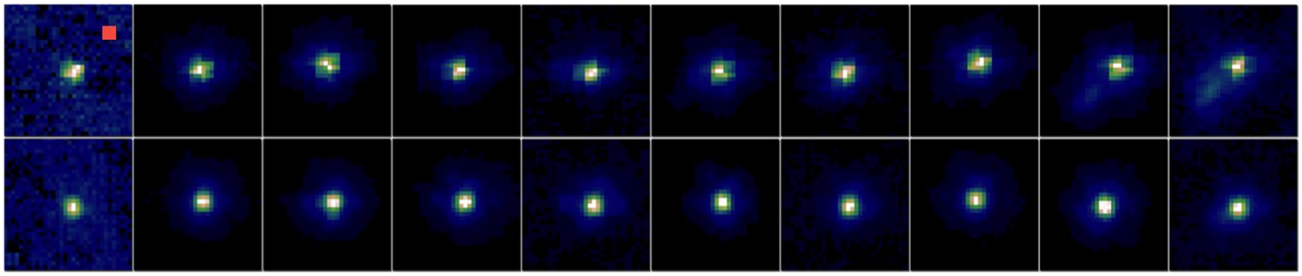

Figure 6. Imagelets around PSF in the Flamingos 2 during the NCPA process. A red box has been added to represent the size of the real Flamingos 2 pixel before applying the super resolution process. 2 last imagelets are the ones further away from the center of the field and their PSFs are more aberrated. On the top are represented imagelets before the NCPA process, on the bottom are the ones after NCPA process.

AO calibrations (NGS WFS and GSAOI tomographic Non Common Path Aberration (NCPA)). The position of each pinhole is only known within the limits of about 100 μm. We will replace it with a custom design quartz photomask covered in chrome with sub-micron precision on the position and size of clear pinholes and multiply their number so they cover the entire Canopus field of view with a pitch slightly inferior to 2 arcseconds (see figure 5). Additional empty space has been cleared around 19 pinholes in order to continue the current AO calibrations. Additional thin slits have been added; they are located outside the field of view of GSAOI but inside the MOS area of the Flamingos-2 instrument. We intend to provide some spectral calibration of the Flamingos-2 instrument in combination with GeMS using the same mask (see next section for further details).

On a longer term, for science targets in sparse fields, a diffractive pupil mask,[16] carefully creating diffraction spikes in the image is forecasted. In sparser fields, the astrometry is particularly interesting for brown dwarfs and possibly for exoplanets detection through astrometric measurements.

6. AO FACILITY: PREPARING FOR FLAMINGOS2

In order to prepare for a GeMS-Flamingos-2 pairing, several calibrations need to be taken care of. Flamingos-2 is currently in operation in seeing-limited mode where its plate scale is about 180 milliarcseconds per pixel. In its AO-mode, due to the change of f-ratio introduced by Canopus, the plate scale is expected to change to about 90 milliarcsecond which is severely under-sampling the diffraction-limited PSF in the near-infrared domain. One the very necessary calibrations, if the complete optical quality including the AO- and science-instrument is not exquisite, remains the NCPA process. In the case of GeMS, the NCPA calibration needs to be done with tomography, correcting as much as possible optical misalignment in the full field of view using the combination of DM0 and DM9. In the case of the critically sampled GSAOI, the tomographic process is achieved through OPRA,[17] a yorick module achieving NCPA calibration through the Phase Diversity principle[18,19] in the Fourier domain. The OPRA code has been extensively customized over the years for the GeMS-GSAOI NCPA process, in order to accelerate its operation and improve results.

Due to Flamingos-2 being severely under-sampled and the current tomographic NCPA OPRA module based per definition (due to the use of the Fourier domain information) on well-sampled images, we wrote an additional module to achieve super-resolution on the phase diversity defocused images in the Flamingos-2 plane. Super resolution images can be easily achieved in the case of a NCPA calibration using a well calibrated Tip-Tilt Mirror in open loop to dither by a sub-pixel distance between consecutive low resolution images. In our case, we choose to acquire 16 consecutive low resolution Flamingos-2 images in a regular grid of 4 by 4 with a pitch of 22.5 milliarcseconds and reconstruct the final image by interlacing the low resolution ones[*]. Samples of the super resolution images, acquired in H-Band filter, can be seen in Figure 6. Estimating the Strehl ratio in a super resolution image remains a risky endeavor but we tentatively give an estimate of about 7% in average. One can clearly see PSF of different shapes, with some large extensions when PSFS are afar of the center of the field (the last ones in figure 6).

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[*] this algorithm is an extremely simplified version of the drizzle algorithm, routinely used with Hubble Space Telescope images.

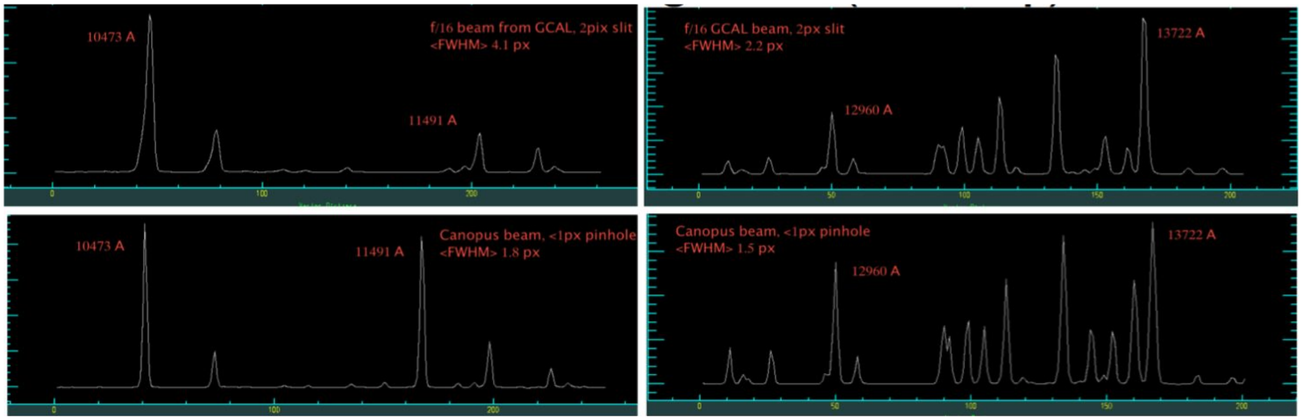

Figure 7. On top, Flamingos2 spectrum with the J-H grism of a calibration source in the f/16 mode through a 2 pixel slit. On the bottom. Only edges of the bands are represented. On the bottom Flamingos2 spectrum with the same grism but through Canopus with a f/32 beam. The slit is about 1 pixel in this case.

The super resolution images are then used as inputs for the OPRA phase diversity module. We limited the reconstruction to half the modes we routinely use in the case of GSAOI images, i.e. 60 DM0 modes and 39 DM9 modes, in order to ensure the convergence of the OPRA iterative process. Results through 2 iterations of the full OPRA process can be seen in the Figure 6. In this case, the Strehl Ratio is estimated to be around 25% and PSFs have now a more common shape all over the field of view. The Full Width Half Max is estimated to 90 milliarcsecond. It means a Flamingos-2 180 milliarcsecond slit would contain an already good fraction (70 to 80%) of the encircled energy. We will continue to improve the NCPA process as our goal is to be able to achieve science with 90 milliarseconds slits for Flamingos-2 in its AO-fed MOS mode.

We also briefly checked the quality of the Flamingos-2 spectrum using one of the Canopus pinhole sources in the focal plane fed by a hand-held spectral calibration source (model: HG1 from Ocean Optics) through an optical fiber. As can be seen in Figure 6 , results are very encouraging for the J-H band. Spectrum were taken in a classic setting, i.e. a slit 2 pixel wide fed by f/16 beam issued from the Gemini Calibration Unit. In this setup, at the edges of the spectral band some skewness in the line profile can be seen. By comparison, Canopus provides to Flamingos-2 an f/32 beam, a spectrum taken without NCPA optimization provides a less skewed and narrower line response. In the future, the Canopus focal plane calibration source will have the option to be fed by a permanently installed spectral calibration source. More systematic calibrations will be then achieved.

7. CONCLUSION

While maintaining GeMS in operation, we are preparing it to be extensively reshaped over the course of the next few years. The new laser will improve the reliability of GeMS and its AO performance while decreasing the engineering workload. The new NGS WFS, NSG2, will open exciting new science cases to the Gemini community due to the larger sky coverage while decreasing our current observing overheads. We will also start to operate the GeMS system remotely next year as a part of the general Gemini Telescope new operation scheme.

We are also making significant progress in polishing several aspects of the GeMS calibrations: the new Canopus focal plane calibration unit will allow to better track the drifts of optical distortions and help our users in their post-processing endeavor. New calibrations such as NCPA and spectral lines resolution are underway to prepare the GeMS to Flamingos-2 pairing. The same tools will be used for GMOS pairing. Finally we will also refine the tip-tilt control law to include a vibration compensation scheme based on a LQG control law (See Sivo *et al.*, this conference for further details).

GeMS is an already unique and complex AO facility tackling efficiently science cases requiring both high spatial resolution and wide field of view. Reshaping its last few challenging sub-systems and polishing its calibration to a new level will bring a new intense luster to this MCAO system.

8. ACKNOWLEDGMENTS

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