GeMS, the path toward AO facility

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ABSTRACT

GeMS, the Gemini South MCAO System, has now been in regular operation since mid-2013 with the imager instrument GSAOI. We review the performance obtained during this past year as well as some of its current limitations. While in operation, GeMS is still evolving to push them back and is currently in the path of receiving two major upgrades which will allow new exciting science cases: a new natural guide star wavefront sensor called NGS2 and a replacement of the current 50W laser. We are also actively moving along the path of further deeper integration with the future AO-fed instruments, we present our first preliminary results of astrometric and spectrometric calibrations with diverse Gemini instruments using an internal calibration source. We finally report our efforts to make GeMS a more robust instrument with the integration of a vibration rejection feature and a more user-friendly AO system as well with advanced gain optimization automatization.

Keywords: MCAO instrument, pathfinder, Laser, Wavefront Sensors

1. INTRODUCTION TO GEMS

The Gemini Multi Conjugate adaptive optics System (GeMS) has been in regular science operation for the past two years at the Gemini South Telescope located at Cerro Pachón in Chile. GeMS is the first and only MCAO system based on a sodium Laser Guide Stars (LGS) asterism. The system design and its commissioning have been extensively described in two reference papers.[1,2] As a brief reminder, the laser guide stars are arranged as the five pips on a dice with a corresponding Shack-Hartmann wavefront sensors for each guide star, the so-called "star-oriented" mode. The external stars are located 42.4 arcseconds away from the central laser guide star. The laser bench, its electronics and cooling systems are enclosed at the side of the telescope into a 8x2 meter container shaped clean room. The laser bench is nominally able to produce a single beam of 50 W at the 589 nm wavelength. This laser beam is then propagated along the telescope structure, split and dynamically aligned

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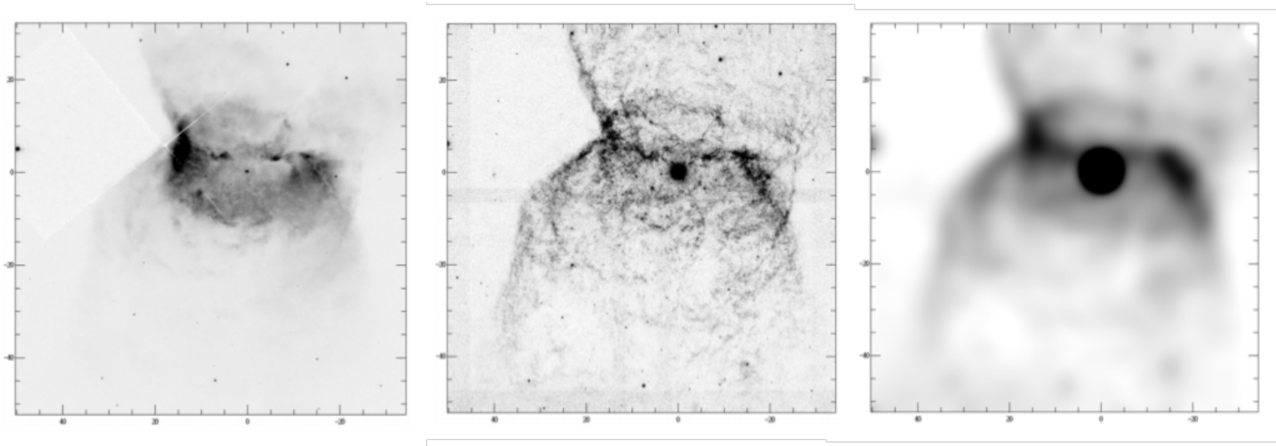

Figure 1. Left: HST WFPC2 image in the [N II] band display a smooth aspect. Center: The GeMS/GSAOI displays a similar resolution in H_2 narrow band where filaments are clearly visible. Right: The GeMS/GSAOI image convolved by a 2 arcseconds kernel to display the effect of a strong atmospheric turbulence, the filaments become invisible and the central region is smeared by the central binary star. (Credits: Manchado et al. 2015)

into five circularly polarized 10W beams using a Beam Transfer Optics (BTO) system. It is finally projected on sky through a Laser Launch Telescope (LLT) mounted on top of the telescope Secondary Mirror structure.[3] Canopus, the MCAO bench, is mounted on a port of the Gemini Instrument Support Structure (ISS) located at the Cassegrain focus of the telescope. The AO fold of the ISS feeds to Canopus a f/16 beam. Two deformable mirrors (DM), conjugated at an altitude of 0 km and 9 km, and closely followed by a Tip-Tilt mirror, are then able to perform the correction of the beam wavefront corrugated by the atmospheric turbulence located around these altitudes. The beam is then split into a visible beam and an infrared beam by a 800 nm dichroic beamsplitter. The infrared beam is reduced by two off-axis parabolae to a f/33.2 ratio and feed to the Gemini instruments through the ISS by a Science Fold Mirror. Meanwhile, the visible light is then split anew using a notch beamsplitter. The laser light at 589 nm is reflected to the five Shack-Hartmann LGS WFSs while the rest of the visible light is used to select on up to three natural guide stars (NGSs) available in the Canopus 2 arcminutes field of view. The light from these NGSs is used by three quadcell APD WFSs mounted on opto-mechanical probes to measure global Tip-tilt and Tip-tilt anisoplanatism. Currently, only the GSAOI[4,5] instrument is commissioned in AO-mode. GSAOI is an near infrared imager covering a square "wide" field of view of 85 by 85 arcseconds sampled at 20 milliarcseconds per pixel, allowing to sample telescope diffraction PSF of the Gemini 8 meter telescope. However GeMS can potentially feed the other instruments, namely Flamingos-2[6] and GMOS.[7]

2. SCIENCE HIGHLIGHTS

The main interest for the GeMS/GSAOI pair lies in the wider Field of View (FoV) available with a quasi uniform PSF in using an MCAO instrument rather than a more classic LGS AO system. This was brilliantly demonstrated with the "Orion Bullets"[8] , a combination of three full GSAOI fields covering no less than 3 arcminutes by 3.9 of the Orion Nebula. Using images taken back in 2007 by ALTAIR,[9] the Gemini North AO facility, one could clearly see the improvement on resolution but also, more importantly for the science team, measure the kinematics of these outflows triggered by the dynamical decay of a non-hierarchical system (Gemini press release: http://www.gemini.edu/node/12343).

In the case of NGC2346[10] , GeMS provided the resolution and FoV to image both the central region of this planetary nebula and its clumpy H_2 filaments (see figure 2). GeMS/GSAOI images display a similar, and sometimes higher, resolution to the ones delivered by the Hubble Space Telescope (HST) instruments. GeMS/GSAOI can therefore advantageously be used for its filters in the K-band, unavailable in HST, in conjunction with previous HST images at shorter wavelengths (Gemini press release: http://www.gemini.edu/node/12388).

To image fully the Liller 1 globular cluster[11] , GeMS was able to deliver correction down to 75 milliarcseconds full width half maximum (FWHM) for the entire set of GSAOI images, close to the diffraction limit in K-

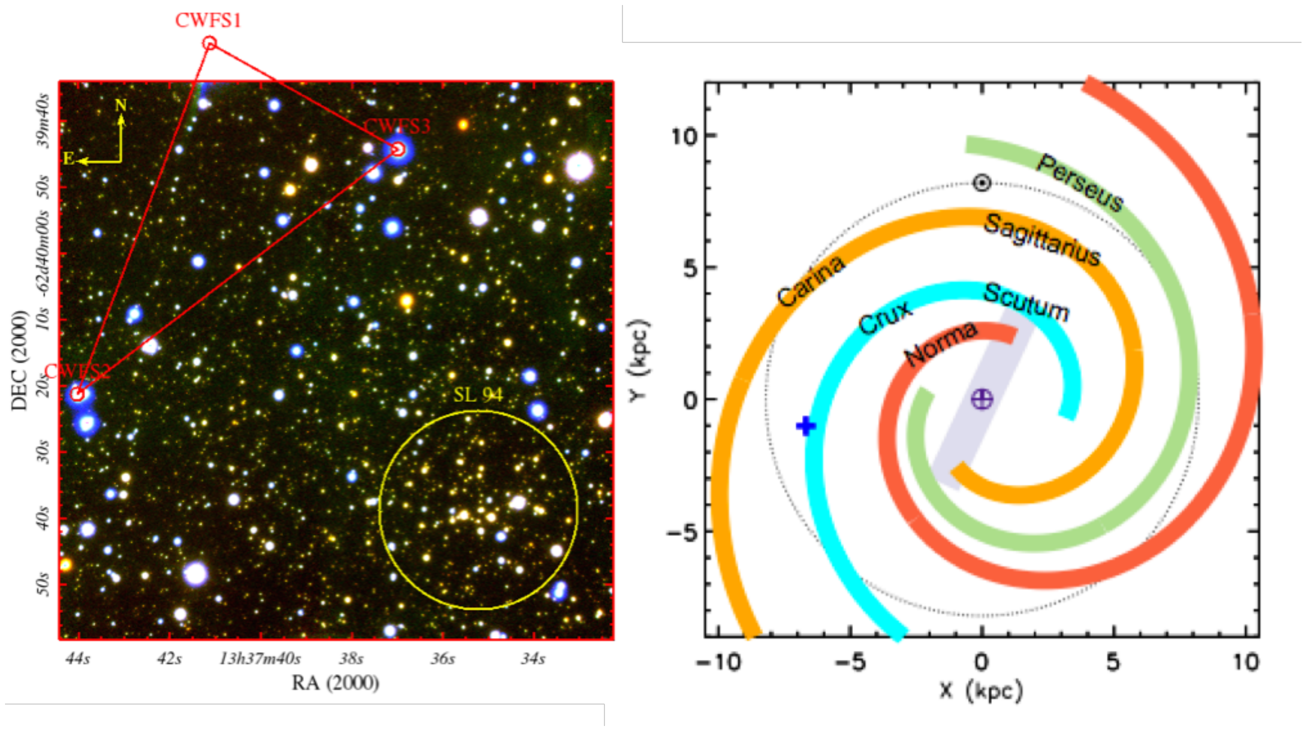

Figure 2. Left: The open cluster La Serena 94 taken by GSAOI with 3 guide stars labeled CWFS. Right: The blue crux represents the estimated location of La Serena 94 in the Crux arm of the Milky Way. The position of the Sun is represented with a dotted circle. (Credits: Santos et al. 2015)

band. This performance allowed the science team to delve into the inner region of this globular cluster and image more than 65 000 stars, down below the main sequence turn-off level. This gives the science team an unprecedented view of this very crowded environment, prone to stellar collisions (Gemini press release: http://www.gemini.edu/node/12379).

For La Serena 94[12] , the main driver for the use of GeMS/GSAOI was the extended sky coverage, i.e. the ability to observe an evolved open cluster without the elongation and loss of Strehl Ratio due to anisoplanatism present in a classic LGS AO system. This region is indeed deeply embedded inside the galactic plane with a massive extinction ratio in the visible, with no close bright enough star to guide in the direct vicinity of the cluster. Three guide stars are however available further away from the cluster. The Adaptive Optics provides a way to image the fainter main sequence stars in a field where Red Super Giants are packed in the center and may contaminate a seeing-limited image. It allowed to study the physical properties of this evolved open cluster which lies deep in the Crux arm of our Milky way.

3. OPERATING GEMS

3.1 Performance

The performance of the GeMS MCAO instrument reached through the commissioning and early science verification periods is extensively described in a reference paper.[2] The performance remains dependent on many variable conditions: the seeing amplitude (r_0) and speed (τ_0), the C_n^2 turbulence profile, the sodium concentration in the mesosphere, the magnitude of the NGS guide stars and the shape of their asterism. However, once we select GSAOI science frames (with more than 30 seconds exposure) and based on three natural guide stars, as it has been done previously during the science verification phase, we have been able to maintain very similar performance since then (see figure 3). However we met several operational hurdles since the official start of GeMS operation mid-2013. One of them was an elongation of the PSF, especially in the corners of the GSAOI detectors. This was progressively troubleshooted during the first semester of 2014 and definitely fixed in a winter

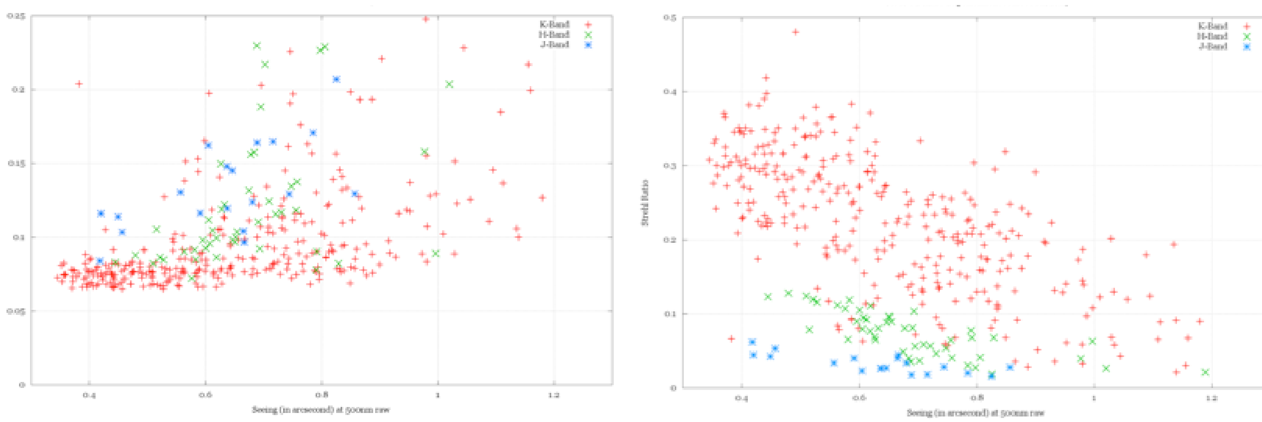

Figure 3. Left: Performance over the last year in terms of FWHM in function of the seeing for J, H and K domains. Right: Performance in term of Strehl Ratio in function of the seeing for the same 3 domains. All images taken in narrow bands have been assimilated into the wide band they are part of.

shutdown mid-2014. It was due to an improper saving procedure of the parameters driving the offload to the primary mirror and more importantly to a poor re-alignment of the five field stops in the LGS WFS, leading to vignetted beams. One other issue troubleshooted this past year was a telescope strong vibration at 37Hz especially when the telescope was pointed at low elevation. The biggest hurdle still remains the availability, power and beam quality of the GeMS 50 W laser (see next section about limitations).

In good seeing and favorable C_n^2, GeMS is still able to reach up to 40% of Strehl Ratio in K-Band, a performance very similar to other single AO sodium LGS systems. The typical performance is located around 20% of Strehl ratio in K-band corresponding to a 70 to 80 milliarcseconds FWHM over the full GSAOI field. Finally we remind here in table 1 the lowest performance for science images we manage to follow for a given seeing condition.

3.2 Operation model

GeMS is a complex instrument necessitating many subsystems to act in unison. During the commissioning and science verification phases, a large crew of engineers were available on-site or remotely to help troubleshooting frequent faults. The operational night model is currently stabilized at seven staff members, including three aircraft spotters, with minimal assistance from on-call engineers. In 2016, Gemini North will be remotely operated from the base facility in Hilo, Gemini South is expected to follow in 2017. In this new model, the three airplane spotters duties will be replaced by a combination of two aircraft detection systems (VITRO and TBAD[13]). In the long term, we will pursue our goal to automatize the procedures driving the AO system to reduce the night staff to two persons, similar to a regular non-AO night.

3.3 Limitations

The current limitations of the GeMS instrument are now well known and understood. The opto-mechanical probes of the NGS WFS are currently not in specification regarding their throughput, due to design and alignment difficulties. The limiting magnitude for the guiding has been measured to be a 15.5 magnitude in R-band. This greatly affects the sky coverage and the number of science targets GeMS can currently offer to the potentially interested Gemini user community.

Table 1. Lowest performance in FWHM in function of the atmospheric seeing in the queue mode.

Natural Seeing @550nm	FWHM (J)	FWHM (H)	FWHM (K)	Gemini IQ constrain (zenith)
<0.45”	0.08”	0.07”	0.06”	20%-ile
0.45” - 0.80”	0.13”	0.10”	0.09”	70%-ile
0.80” - 1.00”	0.15”	0.13”	0.12”	85%-ile

A second well-known limitation is the operation of the 50W laser in a variable environment. Several important technical issues concerning the cooling, the fine alignment and the monitoring of this very complex and environmentally sensitive system have been troubleshooted but in the meantime, several GeMS/GSAOI runs had to be canceled due to the unavailability of the laser on time. We have been operating several runs this past year with a power ranging from 23 to 35 W with a degraded beam quality. In these difficult conditions, the adaptive optics performance is limited by the number of photons available for the LGS WFS system. We maintain a 140 to 160 photons per subaperture per frame for adequate loop stability and performance: in the low sodium summer season this requirement translates into a 100 to 200 Hz AO loop frequency, while in late autumn high sodium season GeMS can sustain an AO loop frequency ranging from 300 to 700 Hz. As the system was designed to run at 800Hz, the servolag and noise errors are understandably a major factor in the complete AO error budget.

The last GeMS limitation is the number of DMs currently active. GeMS was designed with three DMs in mind but the DM conjugated at 4.5km had to be permanently displaced. It replaces the one at 0 kilometer due to several hardware issues, leading the system from 684 active actuators to 360. Currently the mid altitude turbulence is left uncorrected leading to a stronger variability of the correction performance depending of the C_n^2 profile.

4. MAJOR UPGRADES AND FUTURE IMPROVEMENTS

Several projects have been developed to tackle the limitations described in the previous section. Priorities were defined to progressively upgrade the hardware and improve both the performance and the instrument ease-of-use with minimal downtime. They are, per degree of maturity:

- An upgrade of the NGS WFS by an Australian National University team led by Francois Rigaut called NGS2. NGS2 will be based on a Nüvü EMCCD camera able to directly acquire the full Canopus FoV. Three configurable Regions of Interest (RoI) will be defined around NGSs in order to read the detector up to an 800Hz frequency rate with minimal delays. The Tip-Tilt will be measured in focal plane through centroids measurements. The project has successfully passed reviews and is currently being assembled. We forecast to both reduce the overheads required for the acquisition of the NGS and increase the sensitivity of the system to a limiting magnitude of 17 (Goal: magnitude 18). In figure 4 are shown the improvement in terms of sky coverage. The integration and tests of this new system are planned for mid-2016.
- A replacement of the current laser by a more robust alternative with a similar or greater photon return. An internal feasibility study in the first semester of 2015 evaluated if the laser could be replaced with more recent laser models. The results of this study and the current laser issues have led the Gemini Board to take the decision to acquire a new laser in late May 2015. A call for proposals has been issued in September 2015. The new laser will be probably integrated into the telescope system over the year 2017 and the current laser kept as a spare.
- A reintegration of the missing DM at 4.5 km altitude. We are currently contracting external manufacturers to produce a new DM0 and the associated electronics during 2016. We will keep this system as a spare and delay its integration until the previous upgrades are successfully commissioned.

In parallel of these major initiatives, we are also implementing several fast-tracked improvements in the next semesters:

- The RTC software will be modified to perform a Linear Quadratic Gaussian (LQG) control on the Tip-Tilt loop in regular operation. The evaluation of the performance improvement, due to the active vibrations compensation, has already been done using real on-sky data in replay mode and results were very encouraging [Leboulleux et al, Juvénal et al, this conference]. This work, led in collaboration with the french Institut d'Optique and ONERA, will also lead to the automatization of the optimization for the Tip-Tilt loop. We are expecting the LQG first results on-sky during the first semester of 2016 with the current NGS WFS still in place.

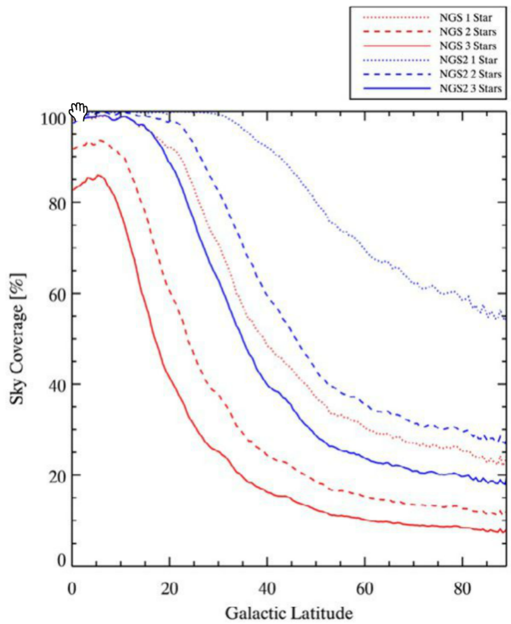

Figure 4. Simulations of sky coverage given a number of stars in the 2 arcminutes Canopus FoV relative to the galactic latitude. The red lines covers the current case where the NGS WFS is limited at 15.5 magnitude. The blue lines covers the new NGS2 WFS case with a limiting magnitude of 17. The drawback effect of missing natural guide stars, anisokinetism, is less detrimental for image quality than its equivalent in a single LGS WFS case (anisoplanatism).

- We already started this effort in 2015 but we will continue to automatize several optimisation procedures actually performed manually by the AO operator. This effort will be led in collaboration with the Flat Wavefronts company. The goal is to progressively reduce the current direct involvement of the AO operator in night runs to a remote on-call model.
- We are planning to design and install extra remote controlled calibrations masks, both in focal plane and pupil plane. These two masks will serve to better characterize the GeMS optical field distortions on a regular basis, as the systematic errors on a multi-epoch basis are still a limiting factor of the astrometric precision.[14] The pupil mask will be especially useful for astrometric science cases in sparse fields. This work is led in collaboration with the Lawrence Livermore National Laboratory.[15]

Finally, we are also pursuing the integration of GeMS with different instruments. 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 results will be published soon in an upcoming paper [Hibon et al. *in prep*]. We had the opportunity to test the spectral resolution of the infrared spectrograph Flamingos-2 with an internal spectral calibration (model Mercury Argon HG-1 from Ocean Optics) installed at the focal plane of the GeMS Canopus bench. The reduced f-ratio of the Canopus-feed beam further optimise the optical quality of the Flamingos-2 instrument. This can be seen with the reduced FWHM of spectral lines at the extrema of the J-H band. In the AO mode where the individual sources are expected to be smaller than 2 pixels, the spectral resolution is constant all over the J-H band. Further tests are now pending to provide multiple spectral sources all over the Flamingos-2 FoV for its MOS mode and determine a way to optimise the NCPA for this very undersampled instrument (90 milliarcseconds plate scale in the AO mode).

5. CONCLUSION

After a successful commissioning and a comprehensive science verification phase, GeMS has now been in operation since mid-2013 and delivered high quality science associated to the infrared imager GSAOI. We have been able

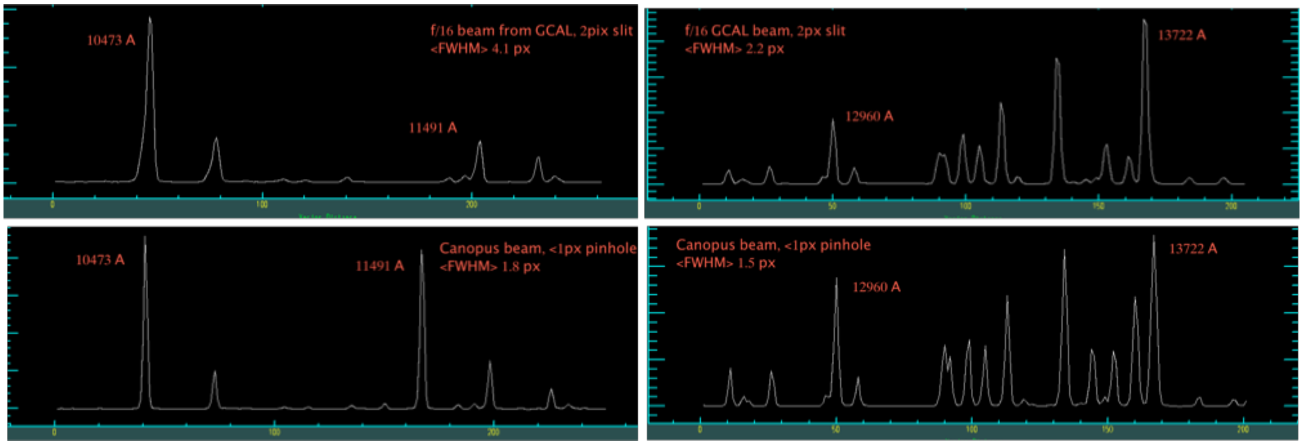

Figure 5. Spectral calibrations taken with an internal calibration source at the J-H band (left: extreme blue of JH grism; right: central to red part of the JH grism). Upper band: Spectral lines taken by the GCAL argon calibration source in seeing limited mode. The FWHM is not fully gaussian and slightly tailed to the blue, reducing the spectral resolution. Lower band: Spectral lines taken in AO mode with a smaller pinhole size and through Canopus which delivers a f-ratio of f/33.2. The spectral resolution is improved and more constant all over the spectral coverage.

to maintain the core AO performance in spite of several important operational hurdles. We remain committed to develop GeMS to improve both its reliability and performance. In the near future, GeMS will transit through several fundamental hardware upgrades (NGS2, laser, DM0...) and software enhancements (vibration control, automatic calibrations and optimisations...). Finally, we will pursue the integration with spectral instruments until we can offer these new AO modes to the Gemini community.

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