# GeMS 2.0: are we there yet?

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## Abstract

The Gemini Multi Conjugated Adaptive Optics System GeMS is the only laser MCAO operational facility regularly used for queue-based science observations since 2013. GeMS delivers close to diffraction limit resolution in the infrared over a large 2 arc-minute field of view. Over the last two years GeMS has undergone a series of upgrades to improve both its performance and also its efficiency. On the technical side, we have integrated a new laser system in the laser guide star facility module. We are near the installation of the new Natural Guide Star wave front sensor, and a 3rd deformable mirror is on the way. While operationally GeMS is set to improve its availability and efficacy by moving operations down to our base facility and reducing the number of staff needed to operate the system. We will give updates of the each of these upgrades.

**Keywords:** AO, LGS

## 1. INTRODUCTION

The Gemini south telescope on Cerro Pachón Chile has an AO systems known as the Gemini Multi-Conjugate Adaptive Optics System (GeMS). This is a multi-conjugate system with three deformable mirrors conjugated to 9, 4.5 and 0 km respectively, five laser guide star wave front sensors, three natural guide star wave front sensors, and one additional truth sensor for tracking sodium layer variations. GeMS provides a uniform AO correction over a 2' field of view with K-band performance of up to 40% Strehl. The system was commissioned in 2011 and has been in operations since 2012. The system was designed as a facility capable of providing the AO corrected beam to all instruments mounted on the Gemini telescope. In practice it has only been used with the GSAOI IR imager (McGregor et al. 2004)[1], but it is planned for future commissioning with the FLAMINGOS-2 IR imager and spectrograph (Eikenberry et al. 2004)[2] and the GMOS-S optical imager and spectrograph (Hook et al 2004)[3]. For a full review of GeMS design and commissioning see Rigaut et al. (2014)[4] and Neichel et al. (2014)[5]. In Sivo el al. (2017)[6] we proposed a set of upgrades to GeMS to get to GeMS 2.0. Below we go over the status of the upgrades as well as provide an overview of GeMS performance.

## 2. NEXT GENERATION SODIUM LASER

The GeMS systems until recently was using a second generation SFG laser system built by LMCT. This was a 50W sodium laser operating at 589nm that was prorogated through a free space beam transfer system where it was split into five beams. The laser beams are launched from a laser launch telescope that sits behind the Gemini secondary mirror used to form a 1x1 arcminute constellation of five laser guide stars on sky. (d'Orgeville 2012)[7]. In 2017 the laser system at Gemini south was upgraded to a modern Raman fiber laser produced by Toptica photonics known as the SodiumStar 20/2 (Enderline et al. 2014)[8]. This new generation of sodium laser is 22W but much more efficient at exiting sodium and produces a smaller guide star to the old more powerful LMCT laser (Marin et al 2018)[9].

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In 2014 the internal effort began to upgrade the laser system as the LMCT laser was poor in performance and had large overheads associated with its maintenance and functionality (See figure 1).

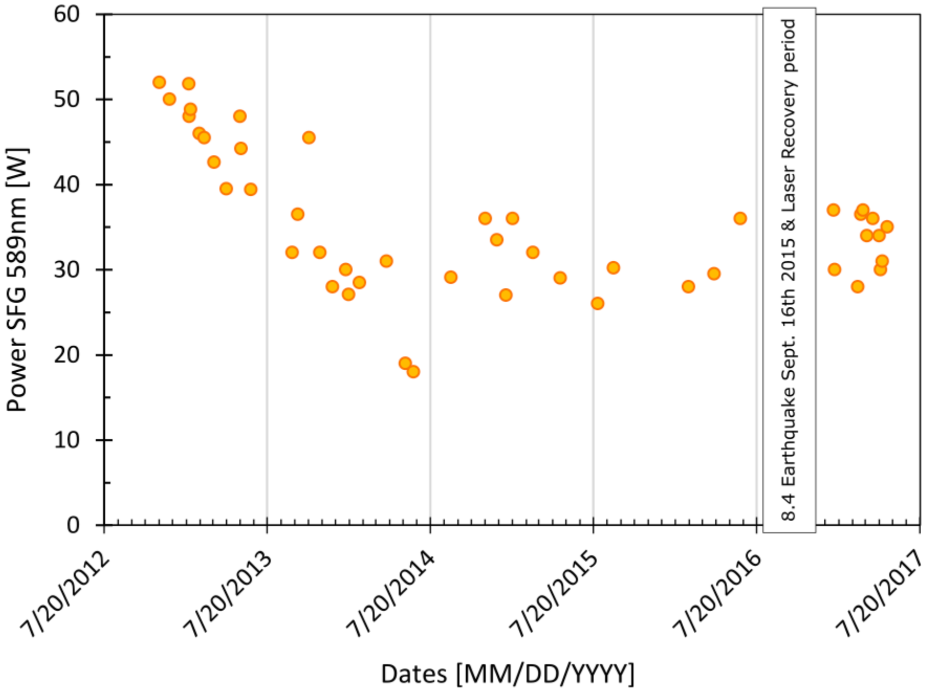

*Figure 1: The LMCT laser saw first light in January of 2011 and since then had a steady decree in power. Figure from Sivo et al. (2018)[10]*

After a competitive process we selected the 20W Toptica Sodium Star laser based on RFA technology as our new laser system. The main requirements of this new laser were to maintain the photon return from the sodium layer obtained by the LMCT laser while decreasing the time dedicated to maintenance and downtime. The second key requirement was that the ability to use the LMCT laser would not be removed until the Toptica laser had been proven as a viable replacement after its commissioning run. Figure 2 and 3 below show the installation of the new laser system that allowed us to keep operational the old systems as well. For a full description see Chirre el al. (2018)[11].

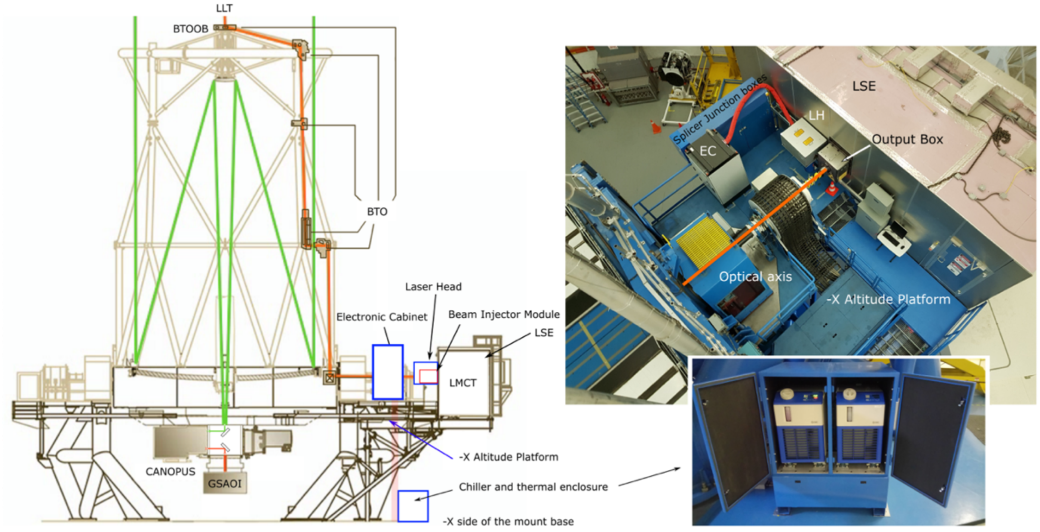

*Figure 2: The Gemini south BTO on the left and the new setup with the two lasers on the right. The LSE houses the LMCT laser, while the Toptica laser is the EC and the LH. The output box houses the BIM. Figure from Marin et al. (2018)[9]*

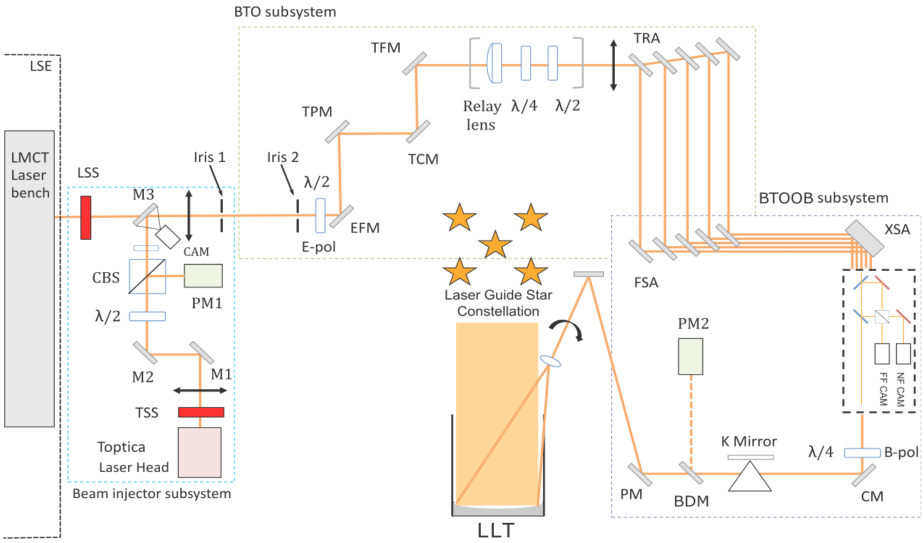

*Figure 3: Block diagram of BTO with both laser systems shown. Figure from Chirre e. al. (2018)*[11]

The sodium return of the new laser system was a key requirement and was shown in Marin et al. (2018)[9], to be comparable to the previous LMCT system and much more efficient. In addition, the Toptica laser was found to have a 15% smaller spot size than the LMCT laser using the same beam transfer optics and launch telescope. Figure 4 below shows a direct comparison between the LMCT and Toptica lasers on the same night.

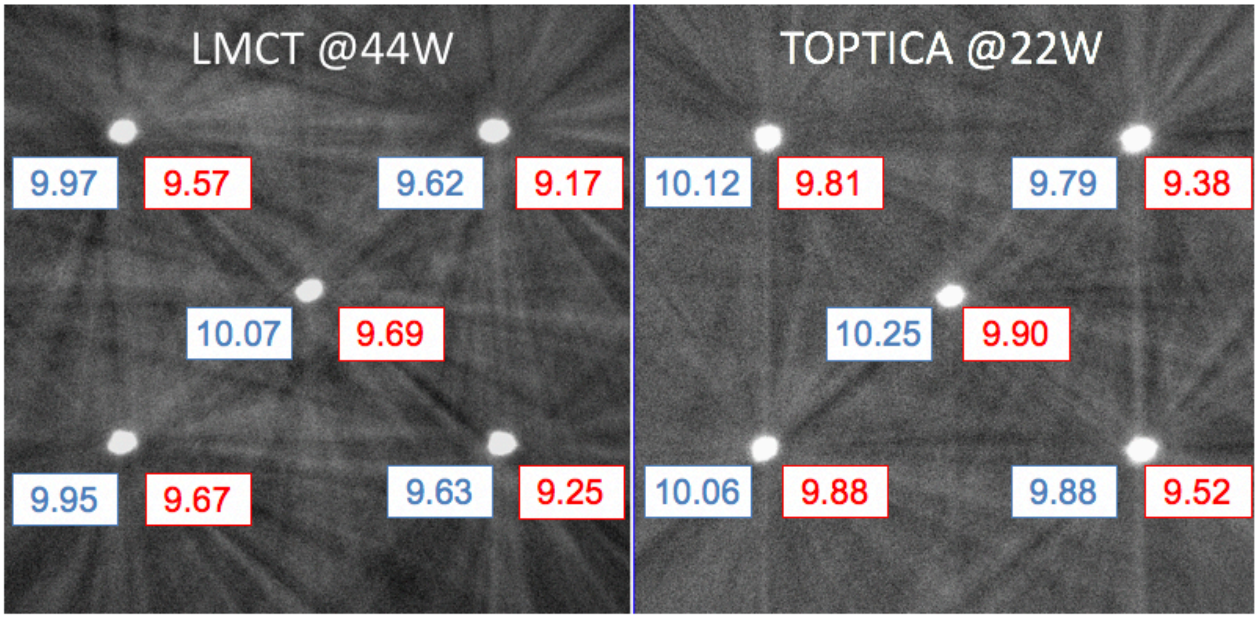

*Figure 4: Stacked images of the LGS spots as seen by the telescope acquisition camera. Each is a stacked set of 10 0.1s exposures and have had the scatter subtracted. The boxes in blue correspond to V-band magnitude while the red to the r-band magnitude, with the LMCT laser on the left and the Toptica on the right*

The main goals of the laser upgraded project have been achieved in that we have as much return as with the old LMCT laser, but more importantly we have much better reliability. Since the installation and commissioning of the Toptica laser there has been no degradation of performance and there has been no down time related to the laser itself. The laser system has gone from being one of the least reliable subsystems of GeMS, to being one of the most robust subsystems of GeMS.

# 3. SECOND GENERATION NATURAL GUIDE STAR WFS

The next upgrade to the GeMS system is a replacement of the current Natural Guide Star Wave-Front Sensor (NGSWFS) used from tip/tilt correction in the optical at up to 800Hz. The current system has proven very difficult to use in operations and very poor in performance. The requirement for GeMS was a limiting magnitude of 18, but the current NGSWFS has such poor optical throughput that the limiting magnitude is only 15.5 in r-band. This results in a sky coverage of only about 5% at the galactic pole rather than the designed 30% at the pole. This greatly limits the amount of science targets that GeMS can achieve. The second issue with the current NGSWFS is that is based on three probes that patrol the f/16 technical field of the NGSWFS focal plane in the GeMS AO bench called CANOPUS. This field suffers from optical distortions introduced by the GeMS off-axis parabolas that cannot be easily modeled with the current NGSWFS. In practice what this means is that it is difficult to acquire the natural guide stars on the probe arms and more critically during offset sequences the natural guide stars will often not land in front of the probe arms requiring a time-consuming spiral search to recover. For these reasons it was decided to upgrade the NGSWFS.

With the Australian National University (ANU) we have been working on a new focal plane WFS for GeMS based on a single EMCCD placed in the focal plan with multiple Regions of Interest (mROI). The new NGSWFS is known as NGS2 (Rigaut et al, 2016)[12]. In addition to this the Slow Focus Sensor (SFS) that was part of the old NGSWFS and used for tracking the slow change in mean sodium altitude will be replaced by the facility Peripherical Wave Front Sensor 1 (PWFS1) as detailed in Marin et al. (2017)[13]. Figure 5 below gives the simulated sky coverage of the new NGSWFS which should reach a limiting magnitude of 18+ in r-band.

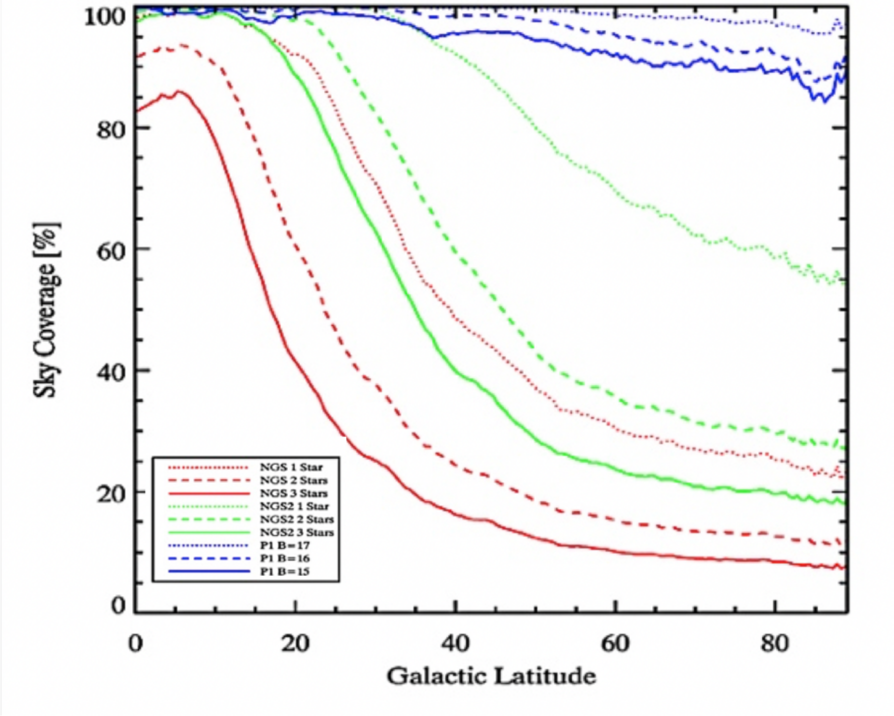

*Figure 5: Sky coverage of the current NGS and the new NGS2*

In addition to the added sky coverage of the new NGS2 system, the simplicity of its operation will allow for lower overheads than what is currently offered. With the view of the entire focal plane it will also be possible to compute a distortion model in the NGSWFS focal plan and the previous issues with losing guide stars on off-sets should disappear. The NGS2 system is set to be installed in the AO bench in July of 2019 with on-sky commissioning is set for October of 2019.

## 4. ASTROMETRIC CALIBRATIONS

A strong science case for GeMS has been that of astronomy, though it was not one of the initial science cases and therefore not a requirement during the development. While there have been many successful astrometry program that use GeMS, due to design limitation and the constant removal and reinstallation of the science camera, GeMS suffers from static and dynamical optical distortions (Parri and Fiorenrino, 2019)[14] limiting the astrometric performance to 0.4 to 0.5 mas rms after calibration and post-processing (Nichel et al, 2014)[15]. In 2016 we decide to change the internal Natural Guide Star (NGS) calibration source to a pinhole mask that has a series of evenly spaced pinholes that can be used for measuring the optical distortion. The mask as shown in figure 6 was installed and first used for Non-Common Path Aberrations (NCPA) (Garrel et al. 2016)[16].

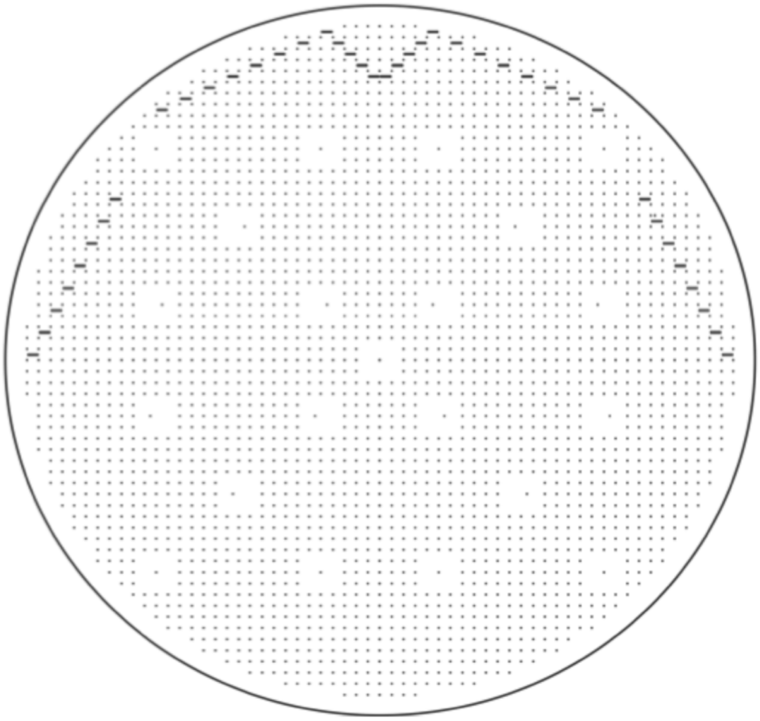

*Figure 6: A diagram of the astrometric mask. The isolated pinholes are for NCPA calibrations, and the slits are for spectral calibrations*

Riechert et al. 2018[17] used the astrometric mask to characterized the distortion in the GSAOI field of view. They found that the results from using the mask are similar to what can be found using on-sky data. The mask also allowed them to derive relationships of the measured distortion on GSAOI with the telescope elevation (of 0.15 mas per 10 degrees) and cassegrain rotator angle (0.3 mas per 45 degrees). This shows that the mask is very useful. and that for astrometric accuracy of better than 200 μas, there is a need for several calibration images during a single observing block. We are still working on an operations model for how to take astrometric mask data during observing blocks, but expect to offer it for programs that request it.

## 5. THIRD DEFORMABLE MIRROR

GeMS as designed is a three deformable mirror system with DMs conjugated to 9, 4.5 and 0 KM. During the initial commissioning of GeMS one of the DMs began to fail. This was the DM conjugated to 0 KM, as at the time it was not feasible to get a new DM, so the decision was taken to move the functional DM at 4.5KM to 0KM and replace the 4.5KM DM with a flat mirror. This left GeMS as a two DM system rather than the designed three DM system. This has affected the performance of GeMS especially on nights with high turbulence at 4.5 KM. Simulations were done in YAO using a typical turbulence profile for Cerro Pachon and an $r_0$ of 0.166 m at 500nm. The loop is run at 500 Hz with a simple integral controller, with loop gains of 0.4 for tip-tilt and 0.35 for the DM. The DM has a leak factor of 0.02 to avoid the accumulation of poorly sensed modes. The simulation show a 10% boost in SR with the addition of the 3rd DM.

There is currently a project to procure a new Xinetics DM with custom control electronics to use as a replacement for the current DM at 0 KM and to move the DM at 0 KM back to 4.5 KM. We expect to get this DM in house by the end of the year with integration into the system at a later time.

## 6. OPERATIONS IMPROVEMENTS

GeMS is currently run in block schedules of 1-3 seven-night blocks per observing semester. The reasons for this are due to the high maintenance needed to keep the system running and the large number of resources needed for night time operations. Marin et al (2014)[18] provides an overview of the various maintenance tasks needed to run GeMS and the nighttime staffing model. Since then GeMS operations have been simplified by the reliability of the Toptica laser, and the night time staff has been reduced due to the use of Transponder Based Aircraft Detection (TBAD). However, there is still the need for 4 night time staff members instead of the standard two person night crew used at Gemini and GeMS is still run on site instead of from the base facility. The larger night crew and the need to be run from the summit makes GeMS less flexible than other instruments and leads to the block scheduling approach which can have a dramatic impact on completion rates if one of the blocks gets affected by poor weather.

To get GeMS in line with standard Gemini operations and increase its use and efficiency the observatory is undergoing internal projects to both bring GeMS operations to the base facility and to reduce the number of night time staff. Moving GeMS to the base facility is well advanced and we expect to run GeMS from the base facility in 2020.

The current staffing model includes the standard Gemini two-person night crew, plus one AO Operator and one Laser/BTO operator. The need for these extra staff members is due both to hardware and software limitations that will need to be corrected before they can be removed from nighttime operations. Removal of the Laser/BTO operator requires the installation of new hardware and software to correct for design issues in the BTO. The main issue is keeping the laser guide stars well aligned on the Laser Guide Star Wave-Front Sensors LGSWFS. The Gemini free space BTO as shown in figures 2 and 3 above transmits the laser beam(s) from the gravity invariant platform to the back the Gemini secondary mirror where the Laser Launch Telescope (LLT) is located. All the elements of the BTO are motorized in order to account for flexure as the telescope moves in elevation. Once the laser beam is split into 5 a series of mirror arrays are used for fast steering and shaping of the constellation, then a series of larger mirrors perform macro control on the constellation for large pointing errors and rotation. We have proposed increasing the dynamical range of the fast steering mirrors and are also making improvements to the control software to increase the stablitly of this system. With these improvements we hope to remove the need for a dedicated Lasers/BTO operator.

## 7. NEW RTC

The other extra role at night time is the AO Operator. The need for a dedicated AO operator is due to the GeMS Real-Time Controller (RTC) needing an expert user. As part of a new project funded by the National Science Foundation (NSF), GEMMA (Gemini in the Era of Multi-Messenger Astronomy), (Sivo et al, 2019)[19]. A new multi-instrument RTC is being developed by Gemini. This new RTC will be used in GeMS and in new systems down the road and will remove the need for a dedicated AO operator.

## 8. PERFORMANCE

As we continue to upgrade the GeMS system we keep track of the performance on sky. Figure 7 below shows our performance overall and since the Toptica upgrade. GeMS continues to work at up to 40% SR in K band with ~70 mas resolution in the best conditions. We expect our new upgrades to maintain or improve on that performance while increasing our efficiency.

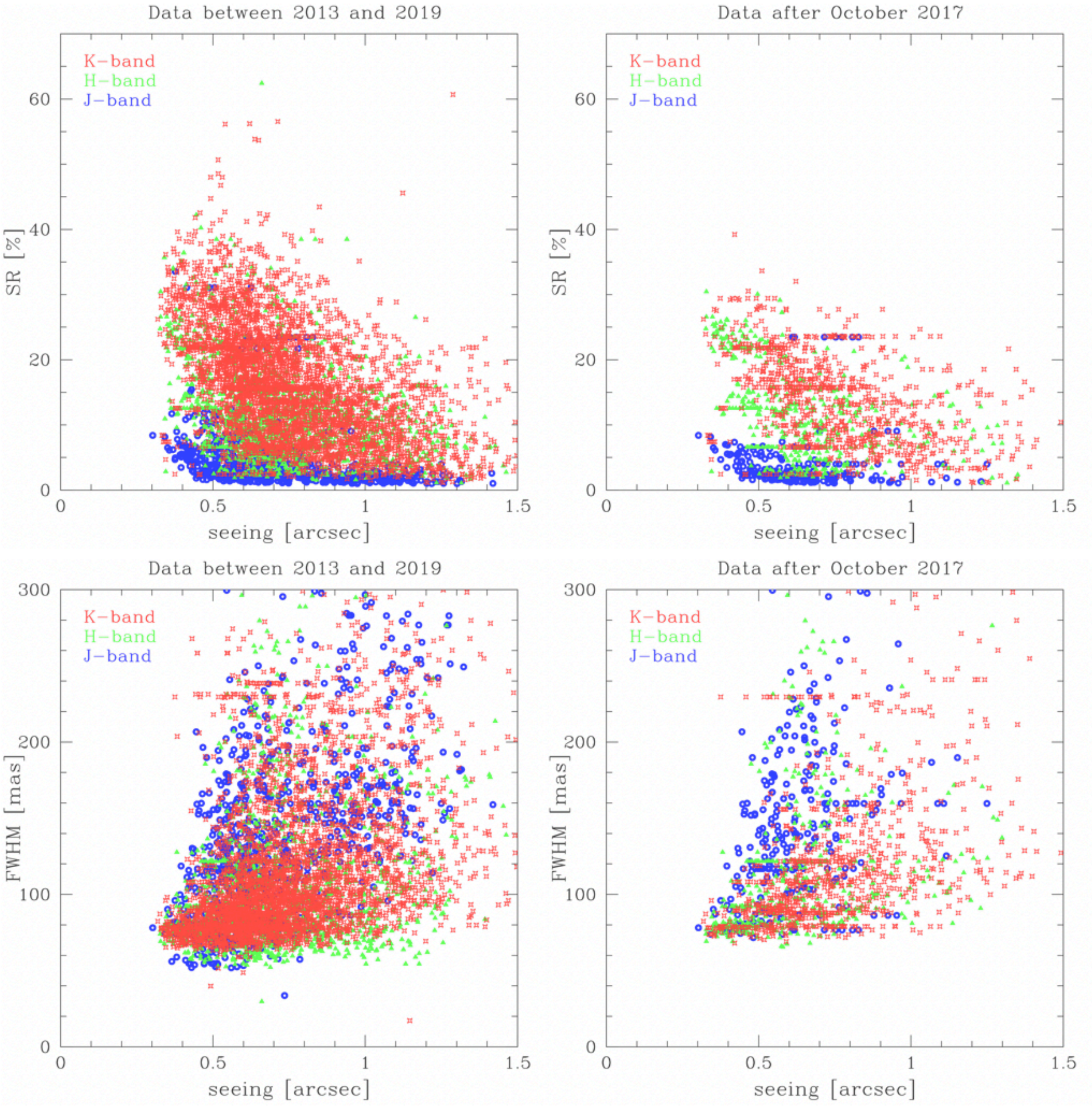

*Figure 7: GeMS performance, overall on left and post Toptica upgrade on right*

## 9. CONCLUSIONS

GeMS 2.0 is a comprehensive plan of upgrades to the system that focuses on improvements to efficacy allowing for more use of the GeMS system. The proposed upgrades are ongoing with the laser upgraded completed and the NGSWFS upgrade near completion as well. When we achieve GeMS 2.0 we will have an efficient fully queue operated MCAO system capable of being used any night.

## 10. ACKNOWLEDGMENTS

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