

Relocate Gemini Multi-Conjugate Adaptive Optics System from Chile to Hawaii: A feasibility study

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ABSTRACT

The idea for moving the Gemini Multi-conjugate adaptive optics System (GeMS) from Gemini South (GS) in Chile to Gemini North (GN) in Hawaii has been proposed to revitalize the aging AO instrument at GN and to overcome a reduction of GeMS operation in the era of the LSST follow-up. To implement the system in the fastest way with enough operational and performance benefits, the GeMS subsystems should be moved in their current design allowing non-invasive modifications. For better system performance and stability, the relocation study proposes an upgrade of the LGS beam injector module and the BTO to combine two sodium lasers. The reconjugation of the high-altitude DM at 10.6 km can help to maintain the current level of AO performance. Relocating GeMS from Chile to Hawaii with the conservation of AO performance as a strict requirement is technically feasible in approximately 3 years taking into account the previous considerations.

Keywords: Multi-Conjugate Adaptive Optics System, GeMS, CANOPUS, Optics

1. INTRODUCTION

GeMS, the Gemini Multi-Conjugate Adaptive Optics (MCAO)^{1,2,3} System, is a world-class AO facility operating since 2012 at Gemini South Observatory in Chile to provide a near infrared diffraction-limited image quality at the science instrument. It consists of three subsystems working together by closed-loops, the Laser Guide Star (LGS)⁴, the Beam Transfer Optics (BTO) and the AO bench (CANOPUS). Since 2017, a new 22W SodiumStar laser (Toptica, GmbH) is operating at GS^{5,6} in place of the old LMCT (Lockheed Martin Coherent Technology) laser. It has been a unique opportunity to propagate two sodium lasers of different technology simultaneously on sky^{7,8,9,10}. After one year of operation, the GS LGS upgrade has made of GeMS a much more reliable system.

On the horizon of 2022, GS will play a dominant role for the observation of transient events with the development of the next generation of high and mid-resolution spectrographs^{11,12}. This will result in a reduction of operation for GeMS at the expense of the Large Synoptic Survey Telescope (LSST) follow-up. To overcome this situation and at the same time to revitalize the capabilities of an aging AO facility¹³ at GN, the idea for relocating GeMS with modifications and upgrades from Chile to Hawaii has been proposed. The scope of relocating GeMS is to provide significant improvements of the overall system performance, minimization of overheads and recurrent/known technical issues, and the solution of obsolescence with the conservation of AO performance as a strict requirement.

2. DESIGN CONSIDERATION

The fastest and easiest way to move GeMS to the North consists of disassembling and reassembling the subsystems (LGS, BTO, AO bench) in their current design allowing non-invasive modifications and upgrades. To exploit site's quality and instrument capabilities, we recommend to implement all of the following:

- For the LGS: LGS beam injection module redesign to use 2 Toptica lasers. Pro: Increase of twice the flux of photon to the LGS WFS.
- For the BTO: piezo-motors/mechanisms upgrade and polarization control improvement. Pro: Reduce loop instability.
- For the AO bench: Modernize CANOPUS, renew optics and re-conjugation of the DMs to the proper turbulence layer at GN. Pro: maintain the current level of AO performance.

2.1 LGS subsystem

Recently, a new 22W sodium laser has been commissioned at GN¹⁴ and so one extra laser will be available. To take advantage of it, the two GS and GN Toptica Lasers can be combined to provide one single laser beam of same characteristics with twice the power as illustrated in Figure 1. The upgrade of the GS/GN beam injector module⁷ is required to allow the injection of the two laser beams at the BTO.

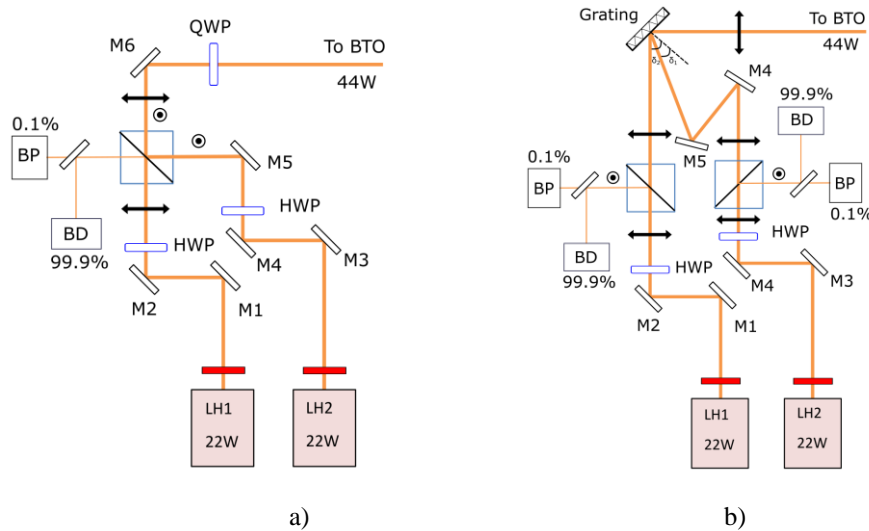


Figure 1: GN/GS beam injection module upgrade for beam combining. a) polarized cube beam splitter design for attenuation and injection; b) diffractive grating design for injection and CBS for attenuation. LH: laser Head. HWP: half Wave Plate. QWP: quarter Wave Plate. BP: beam Profiler and power meter. BD: beam Dump. M: motorized Fold mirror.

Figure 1, a) shows a polarized cube beam splitter can be used to combine and to attenuate two laser beams with linear polarization at the same time. This solution is the simplest and quickest to implement but it has the main drawback of providing two linear orthogonal polarization states of the output beam (see next section 2.2 about polarization issue). Figure 1, b) shows a diffractive grating can be used to combine the two beams with the same output polarization. The role of the polarized cube beam splitter is to attenuate and to send part of the laser light to the beam diagnostic system. In both cases, the combination of the two laser beams will produce a brighter guide star constellation resulting in a significant increase of the photon flux to the LGS wavefront sensors. This will make the system able to run at faster rates providing higher performance even during the low sodium season. Table 1 shows the pro. and cons. of the LGS upgrade.

LGS Beam injection module redesign to use 2 Toptica Lasers			
PRO	CONS	FTE	Non labour Cost
<ul style="list-style-type: none"> • Brighter guide stars, able to run at faster LGS rates, higher performance • Use of new parts will delay problems of obsolescence • Use lessons learned from current BTO / LGS to 	<ul style="list-style-type: none"> • Requires a new design for BIM to allow for the injection of two laser beams • A simple 3/2 split results in uneven guide star magnitudes. Possible 	0.5	<500K
			Order of the

optimize for Toptica laser <ul style="list-style-type: none"> GN BIM can be modified while GS BIM is in operations (no downtime for GS GeMS operations) Improve throughput Using two Toptica laser would open the possibility to choose for 2X3 LGS with a more efficient constellation 	to mix lasers together before BTO injection <ul style="list-style-type: none"> 2 lasers and configurable constellations may have unknown requirements A diffractive element affording 22W should be available, but need to be tested Tests at GS should require some time 	current BIM
		Operational Benefit
		HIGH
		Performance Benefit
		HIGH

Table 1: LGS subsystem upgrade, PRO and CONS.

2.2 BTO subsystem

The role of the BTO subsystem is to relay the laser beam to the laser launch telescope, to split the input beam into 5 beams of same intensity and to keep the constellation aligned on the wavefront sensors. It is composed of motorized mechanisms that have reached obsolescence and can potentially fail. It is the case of the Fast Steering Array (FSA) mechanism. The range of the piezo-motors does not keep always the constellation aligned on the LGS WFS specially when the photon flux is too low. The upgrade of these piezo-motors with a range up to 10 mrad (Nano MTA series, Mad-City labs, USA) will help to reduce the loop instability in bad seeing conditions.

Since the integration of the Toptica laser^{7,8} to the existing GS laser facility and the significant improvement of the system stability, they are still some issues that need to be fixed during relocation. As it can be seen on Figure 2, the LGS spots of the constellation on sky do not have always the same intensity resulting in unexpected behaviors of the BTO. Sometimes the faintest spot is lost forcing the laser operator to open the loop for re-alignment. Even when the seeing and conditions are good, the alignment can be an arduous task. Quantitatively, the intensity of the brightest (spot 4 on the FF) spot is two times the intensity of the faintest spot (spot 2 on the FF) on the LGS WFS.

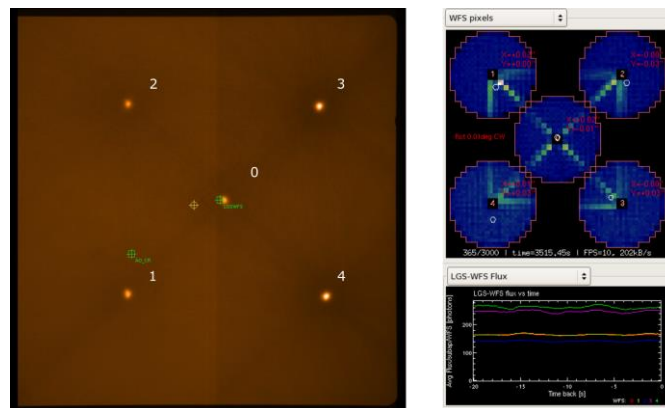


Figure 2: Left: Image of the LGS constellation taken by the Far Field camera (FF) during a regular AO run in 2018. Right: Image of the wave front sensors with AO loops closed (top) and the corresponding flux (bottom). Each color for each spot. Spots of the constellation are numbered from 0 to 4, being spot 2 the faintest and spot 4 the brightest.

The intensity of each spot of the constellation depends on the BTO optics and the polarization state of the beam at the TRA and on-sky. Figure 3 plots the beam power with the telescope elevation at Zenith (left) and at horizon (right) as a function of the input polarization (E-pol).

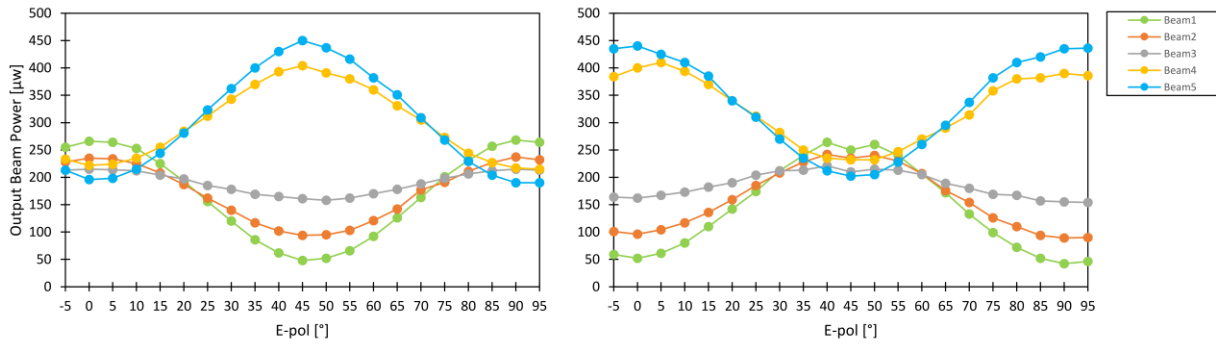


Figure 3: LGS beam power as a function of E-pol. Left: Telescope at Zenith. Right: Telescope at Horizon. Each color for each LGS beam. Measurements were performed with a He-Ne laser that mimics the Toptica laser beam characteristics. The beam was propagated to the BTO at low power.

As it can be readily seen, the E-pol angle provides a range of $\pm 10^\circ$ where the input beam is divided in 5 beams of same intensity. An offset of the E-Pol out of this range can explain the difference in intensity between the faintest and the brightest spot of the LGS constellation.

In a minor circumstance, the second main cause of a change of intensity can be related to the output polarization state of the beams on-sky. It is known that in the best case¹⁵, only 1 beam is circularly polarized while the others are elliptical. This is mainly due to the B-pol that is common to the 5 beams and so polarization is optimized only for one LGS star. In order to solve this problem, an optical system to control the individual polarization is proposed on Figure 4. The system consists of 5 wave plates mounted on a compact rotating stage (DT-34 Miniature Rotation Stage, PI) one for each beam. Because of space constraints and to make the BTO upgrade non-invasive, a good location is between the FSA and the XSA as illustrated.

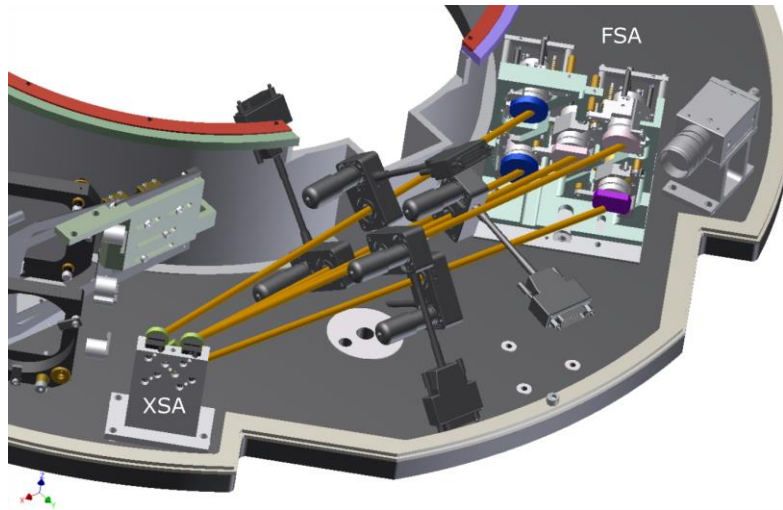


Figure 4: Optical subsystem to control the beam polarization of each LGS. The 5 beams are shown in orange between the FSA and the XSA. The wave plate mechanisms are the black elements placed between the FSA and the XSA mirrors.

By adjusting the individual polarization and taking a set of buffers the laser operator can adjust the photon flux on the LGS WFS with the purpose to minimize the difference in flux between the brightest and the faintest spots. Table 2 shows the pro. and cons. of the BTO upgrade.

BTO Upgrade			
<p>PRO</p> <ul style="list-style-type: none"> • No need to redesign optical layout • Can be done in a way that improves AO loop stability • FSA Piezo-motors upgrade • Add non-invasive individual polarization control • Can be done at GS prior to moving and fully tested • Fix problem with obsolescence 	<p>CONS</p> <ul style="list-style-type: none"> • No optimization for Toptica Laser • Constellation remains fixed • B-pol change to array of 5 individual polarizers not feasible in the current setup but can be removed 	<p>FTE</p> <p>0.3</p>	<p>Non labour Cost</p> <p><800K</p> <p>Order of the current BIM</p>
		Operational Benefit	
		LOW	
		Performance Benefit	
		NEUTRAL	

Table 2: BTO subsystem upgrade, PRO and CONS.

2.3 AO bench

The AO bench at GS has two deformable mirrors to correct for atmospheric turbulence above Cerro Pachón. DMs are optically conjugated to the telescope secondary and the turbulence layer at 9 km. A position for a DM at 4.5km is available but not in use. On Mauna Kea (at GN), the high-altitude turbulence layer is between 12 km and 16 km, while there is no need to correct turbulence at the intermediate altitude layer. To maintain the performance of GeMs for the North, the DMs should be re-conjugated to the proper atmospheric turbulence layer in the least invasive intervention. This task consists of moving the deformable mirrors in the collimated beam (between OAP1 and OAP2), preserving the current off-axis optical relay design and the rest of the optical train unchanged. Figure 5 shows the science path of the AO bench in its current design in blue at GS and after re-conjugation of the DMs in green for GN.

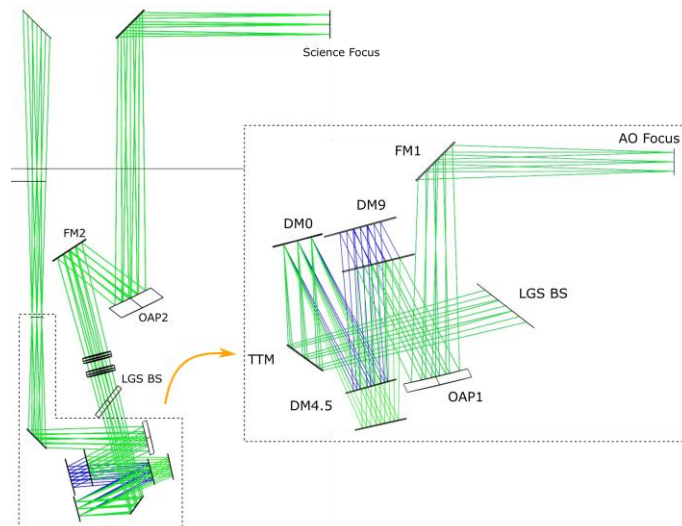


Figure 5: Science path optical layout of the AO bench with DMs re-conjugation. GS design is in blue and GN in green.

Re-conjugating DM9 to the turbulence layer between 12km and 16km is not feasible in the current optical design. The optical plane conjugated to the high-altitude layer is not accessible in the collimated beam and DM9 should be moved before OAP1. This solution is too invasive and requires a complete re-alignment/re-arrangement of the optics on the bench that is not compatible with a fast implementation of GeMS to the North. An accessible optical plane in the collimated beam is conjugated to 10.6 km where vignetting of light does not present an issue. Furthermore, to keep the telescope pupil plane on DM0, the intermediate DM (DM4.5) will be moved to an optical plane conjugated to 5.58 km. Figure 6 shows the opto-mechanical model of the AO bench at left and after re-conjugation at right. Because of space constraints and the closeness of the NGS subsystem, the repositioning of DM4.5 at 5.58 km can be problematic. As there is no need to correct turbulence at this altitude on Mauna Kea, DM4.5 can be replaced by a fold flat mirror.

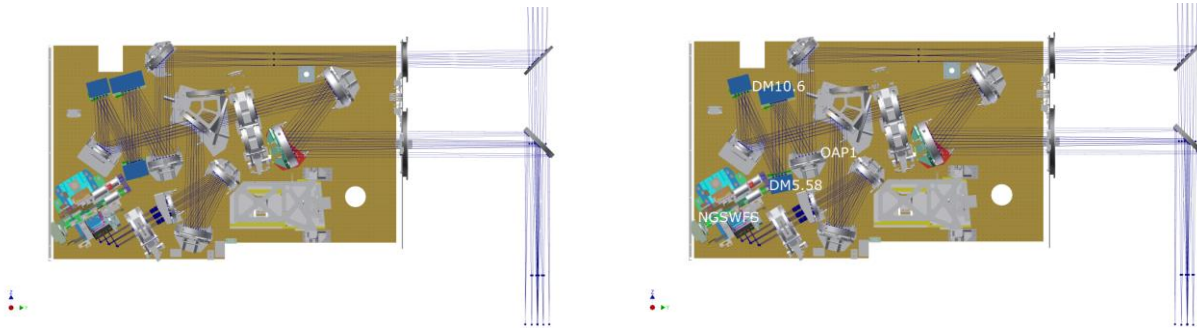


Figure 6: Opto-mechanical model of the AO bench. Left: GS model, 2018 upgrade. Right: DM Re-conjugation for GN.

Several AO bench subsystem upgrades can be considered during GeMS relocation. This is the case of the science beam splitter to open new science capabilities in the NIR and/or the VIS and the Cal. Source to allow for spectral calibration and improvements of distortion and NCPA mapping. The use of new parts should help to mitigate obsolescence problems for most components and the optical components can be renewed to increase throughput.

AO bench Re-conjugation and upgrade				
PRO	CONS	FTE	Non labour Cost	
<ul style="list-style-type: none"> Keep level of AO performance for GN Possible to install turbulence simulator for troubleshooting Improved NCPA mapping Improved distortion mapping Potentially can be done at GS prior to moving though not fully tested Fix problem with obsolescence Renew optics Upgrades 	<ul style="list-style-type: none"> Very sensitive alignment Redesign LGSWFS assembly for configurable constellation BS mounting highly sensitive to temperature. Mount will need to be redesign Spare parts may not be available 	2	<800K	
		Operational Benefit		HIGH
		Performance Benefit		HIGH

Table 3: AO bench subsystem upgrade, PRO and CONS.

2.4 AO simulation

Simulations were run using the latest version of YAO to model the peculiarities of the GeMS system. Typical atmospheric turbulence profiles for Cerro Pachón and Mauna Kea were used. Since we are only interested in comparing the performance between different turbulence profiles, only the K-band Strehl ratio was reported. Three values are reported: The Strehl on-axis, which is the maximum Strehl, the average across the field, and the variation in Strehl.

Simulations were run with the zenith angle set to 0° and 45° . The simulation results, tabulated in Table 4, show that the performance on Mauna Kea should be comparable to that on Cerro Pachón.

Site	DM9 altitude	Zenith angle	Strehl max.	Strehl avg.	Strehl rms.
CP	9 km	0	0.648	0.506	0.083
MK	9 km	0	0.643	0.490	0.080
MK	10.6 km	0	0.656	0.483	0.088
CP	9 km	45	0.454	0.279	0.072
MK	9 km	45	0.411	0.270	0.053
MK	10.6 km	45	0.410	0.271	0.054

Table 4: K-band Strehl ratio comparing the MCAO performance of Cerro Pachon and Mauna Kea.

Increasing the conjugation altitude of DM9 by a modest amount does not provide any significant benefits. It is also compared the performance of the two sites when correction is applied with only a single DM, which we called ground-layer adaptive optics (GLAO).

Site	DM9 altitude	Zenith angle	Strehl max.	Strehl avg.	Strehl rms.
CP	9 km	0	0.499	0.352	0.066
MK	9 km	0	0.510	0.356	0.068
CP	9 km	45	0.291	0.157	0.051
MK	9 km	45	0.273	0.185	0.036

Table 5: K-band Strehl ratio comparing the GLAO performance of CP and MK.

The simulation results, tabulated in Table 5, show that the GLAO performance at Mauna Kea is comparable but slightly better than, at CP. It is also shown that adding another DM conjugate to 4.5 km is useful for the CP turbulence profile but not as beneficial at Mauna Kea. Therefore, the performance with the existing GeMS system is almost identical on both sites CP and MK and re-conjugating the high-altitude DM at 10.6 km does not improve the performance of GeMS on Mauna Kea but can help to maintain the current level of performance.

2.5 AO bench status in 2019

The AO bench is closed with covers and it is not positively pressurized, therefore the optical elements are exposed to ambient conditions. The most critical factors are temperature and exposure to dust, causing degradation on the optical surfaces and their coating. The optics are blown out before each run and a contact cleaning is performed once a year. These two types of cleaning are not enough to maintain the optics within requirements with a direct effect on the instrument throughput. Figure 7 shows the instrument throughput of the LGS path at left and the science path at right measured in 2018 (blue) before optical replacement and compared to the data taken in 2012 (red). It can be seen a significant decrease of throughput in the visible, and the near infrared wavelength range.

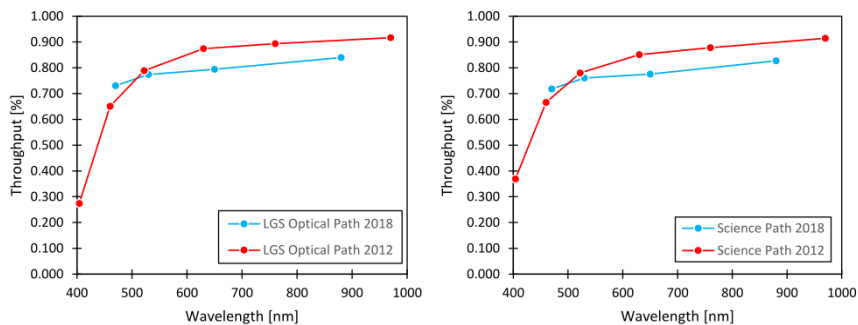


Figure 7: Instrument throughput measured in 2012 (red line) and 2018 (blue line). Left: Laser Guide Star optical path. Right: Science path. Data taken in 2012 were measured with the IRIS reflectometer while data taken in 2018 were obtained

with the CT-7 reflectometer. After calibration, we measured a difference of 0.1% in reflectivity between the two instruments.

The replacement of the three-fold flat mirrors of the science path is the first step of the long-term plan to replace the optics which do not meet specifications that includes the off-axis parabolas and the tip-tilt mirror. The surface mapping done during the last shutdown maintenance (July, 2017) showed that the fold flat mirror 3 has several scratches, some water marks and evidences of an aging coating compared with a previous reference (2012). While the reflectivity measurements have shown that the coating does not meet the specifications ($\geq 98\%$ on average between 500 – 2500nm) by 2% at 500 nm and between 0.1 and 1% for the others wavelengths, the main factor to replace the mirror is the current cosmetic status. After replacement, the reflectivity data has showed a major improvement of 5.8% and 8% for 365 and 404 nm respectively, while for 460 nm the reflectivity improved by 1.1%. The main concern is the low reflectivity value at 522 nm. The other wavelengths (630, 760 and 970 nm) are within the specifications. A gain between 2.5% and 3.9%, and between 1.5% and 2.8% were measured on the LGS WFS with CBs at 200Hz and 800Hz respectively after replacement. A similar procedure will be applied in the current year in order to change the fold flat mirror 1 and fold flat mirror 2 in the science path. An increase of reflectivity of 2% in the visible and 1% in the NIR is expected for each new optics with a gain of 2% on average for the LGS flux.

2.6 FTE and Cost estimations

This includes all of estimations with the addition of the recommended Modifications/Upgrades Design, Review, Acceptances, Assembly, Integration and Tests. The estimation varies depending on the final Modifications/Upgrades to be executed. Some of them make sense only if done together (i.e. LGSWFS Detector Upgrade requires the RTC Upgrade too, but not the other way around). Some other Modifications/Upgrades could be only partially executed providing enough Operational and Performance benefits. Taking that into account, the following Table 6 provides a (non-strict) range for the total estimated FTEs and Non Labour Cost.

Action	FTEs	Non Labour Cost
LGS Beam injector redesign to use 2 Toptica Laser	• TOT: 5.0	• <500K
Cal. Sources Upgrade	• TOT: 0.5	• ~100K
LGSWFS Detector upgrade	• TOT: 6.0	• ~200K
RTC upgrade	• TOT: 2.0	• ~1.0M
Science Beam Splitter Upgrade	• TOT: 0.7	• ~100K
Modernize CANOPUS control	• TOT: 6.0	• ~500K
Renew CANOPUS optics	• TOT: 1.0	• <200K
Laser pointing camera	• TOT: 0.5	• ~50K
BTO and LLT disassembling and reassembling, including calibrations	• At GS: 1.00 • At GN: 2.00 • TOT: 3.0	• Cost for shipping • GeMs team travel
BTO piezo-motors upgrade	• TOT: 1.0	• <600K
BTO polarization control	• TOT: 1.0	• <100K
CANOPUS optical bench to be dismantled and remounted, including reconjugation	• At GS: 1.00 • At GN: 3.20 • TOT: 4.20	• Cost for shipping • GeMs team travel
GSAOI dismounting, packing and shipping at GS, unpacking and installation at GN	• At GS: 0.3 • At GN: 0.35 • TOT: 0.65	• Cost for shipping • GeMs team travel
SW Engineering training at GN	• TOT: 1.0	• Travels
LGS operator training at GN	• TOT: 0.25	• Travels
Knowledge transfer at GN	• TOT: 0.25	• Staff temporary relocation
Test and debugging at GN off sky	• TOT: 3.00	• GeMs team travels
Commissioning, test and debugging at GN	• TOT: 3.00	• GeMs team travels
Documentation	• TOT: 2.00	• 0
	FTEs Total	NON LABOUR COST TOTAL

	between ~34.00 and ~40.00 in ~3 yr	~5.0 M
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Table 6: Total estimated length and non labour cost of the relocation project.

3. SUMMARY

The GeMS relocation project studies the feasibility of moving the MCAO facility from Chile to Hawaii in the era of the LSST follow-up. It has been shown that a complete move the GeMS subsystems in their current design with modifications and upgrades is the fastest and easiest way for relocating GeMS to the North. The upgrade of the LGS beam injector module will benefit to the system performance by increasing the flux of photon to the LGS WFS. The upgrade of the BTO will benefit to the loop stability by a better balancing of the intensity of each spot of the constellation. The AO bench re-conjugation to the high-altitude turbulence layer at GN is not feasible in the least invasive intervention but simulation has shown that re-conjugating the high-altitude DM to 10.6 km helps to maintain the actual level of AO performance. By moving the DM4.5 to 5.58km, the telescope pupil plane is maintained at the same location and the rest of the optics is unchanged. For space constraints, DM at the intermediate layer can be replaced by a fold mirror. In conclusion, relocating GeMS with modifications and upgrades to the North with the conservation of AO performance as a strict requirement is technically possible and can be performed in approximately 3 years for a non labour cost of 5.0 M.

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