GeMS: Gemini Mcao System, current status and commissioning plans

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ABSTRACT

The Gemini Multi-Conjugate Adaptive Optics project was launched in April 1999 to become the Gemini South AO facility in Chile. The system includes 5 laser guide stars, 3 natural guide stars and 3 deformable mirrors optically conjugated at 0, 4.5 and 9km to achieve near-uniform atmospheric compensation over a 1 arc minute square field of view.

Sub-contracted systems with vendors were started as early as October 2001 and were all delivered by July 2007, but for the 50W laser (due around September 2008). The in-house development began in January 2006, and is expected to be completed by the end of 2008 to continue with integration and testing (I&T) on the telescope. The on-sky commissioning phase is scheduled to start during the first half of 2009.

In this general overview, we will first describe the status of each subsystem with their major requirements, risk areas and achieved performance. Next we will present our plan to complete the project by reviewing the remaining steps through I&T and commissioning on the telescope, both during day-time and at night-time. Finally, we will summarize some management activities like schedules, resources and conclude with some lessons learned.

Keywords: Multi-conjugate adaptive optics, laser guide star

1. INTRODUCTION

The Gemini South (GS) MCAO project was reviewed in details by Ellerbroek et al[1] in 2003 where they presented an overview of the performance estimates, science applications, adaptive optics module, real time control system, laser, beam transfer optics and launch telescope, aircraft safety and laser traffic control. At the time, the project was expected to become an operational capability in the 2006-2009 timeframe. Table 1 describes the main chronological milestones of the project as of the time of this conference (June 2008). Most of the project was managed and executed by a small Gemini team (about 5 people) -mostly full time until 2004- and several consultants, and later on became more of a matrixed structure within Gemini. The GeMS acronym came up in 2007 to give a proper identity to the Gemini MCAO system, rather than use the generic name of the observational technique, nowadays common to many other projects.

The first part of this paper will review the systems subcontracted outside of Gemini. One of the early project difficulties was to find the right vendors for the various subsystems. The AO module was originally intended to be contracted as an integrated 'turn-key' module. Unfortunately, due to lack of bids and budget constraints, this scheme was not possible and Gemini finally redefined the procurement plan and ended up breaking out the AO module into many different subsystems, each of them being built by different specialized vendors, with Gemini assuming the role of interface management and keeping the responsibility for final integration. Due to their nature of being at the edge of the existing technology, a similar situation of finding few bidders happened with most sub-systems therefore shaping the final management strategies and driving the project schedule (this was particularly true for the laser, which took 2 years of negotiation starting in 2004). In addition, several areas like deformable mirrors and their electronics, real-time control

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Adaptive Optics Systems, edited by Norbert Hubin, Claire E. Max, Peter L. Wizinowich,
Proc. of SPIE Vol. 7015, 70150X, (2008)
0277-786X/08/$18 · doi: 10.1117/12.788958

systems and wavefront sensors and 50W laser required specific research and/or development programs executed by industrial companies and governmental laboratories, some initiated in the first few years of the project and financed through various grants and funding (see example[2] in this conference).

In the second section, we will review other areas of the project that are being done in-house, like the beam transfer optics -first defined as an in-house project for the Gemini North (GN) LGS system in 2004- and laser infrastructure. Decision was made to develop those internally for a variety of reasons including disappointing experiences with past vendors, budget constraints, complexity of integration with the telescope structure thus requiring lots of interfaces definition, and ultimately ease to handle installation on telescope by our crew at the best times for regular science operation (whereas a contractor is usually time-constrained).

Next we will describe the plans for integration and testing off and on the telescope, the main sequences of night-time commissioning and the roll-over to science operation. GeMS will be commissioned with GSAOI[3], a NIR imager with 85" square FOV and 20mas sampling delivered to Gemini South at the end of 2006. Flamingos-2[4], a NIR multi-object spectrograph with a 2x1'FOV (when used with GeMS), 90mas"/pixel sampling and resolutions from 1300 to 3000, will be the second instrument to take advantage of GeMS in late 2009.

Finally, we will detail some of the main characteristics of the project management aspects like resources and scheduling, by sharing some of the hard numbers, weaknesses and lessons learned for our organization, and recommendations to future similar projects.

Date	**Project phase**
April 1999	MCAO recommended as GS AO system
May-Sept 1999	MCAO feasibility study
Dec 1999 - May 2000	CoDR phase + review
June 2000 – May 2001	PDR phase + review
Oct 2001 – May 2004	CDR phase, RFP and external contract setup
2005	Contract monitoring (most internal resources went into GN Altair LGS integration and commissioning)
Dec 2005	GeMS internal project definition and effort launch
Jan 2006 – Oct 2006	In-house design phase
Oct 2006 – Aug 2007	Mix of on-going design, fabrication and I&T
Aug 2007	AO bench functionalities demonstrated
Sept 2007	Project status review by NSF
Oct 2007 – Dec 2008	Fabrication, I&T on telescope, some BTO redesign to simplify operations
Jan 2009	Scheduled LGSF first-light on sky
July-Sept 2009	Scheduled completion of science commissioning

Table 1: GeMS project chronological steps

2. REVIEW OF SUB-CONTRACTED SYSTEMS

A total of about US$12 millions was spent on external contracts including some R&D done in 2000-2002. All contracts were placed between 2001 and 2004, the latest being the 50W laser contracted out in September 2005. The overall average delay was 70% of expected contract duration, with only one system delivered on time, and several systems with delays over 100%. In this section, we focus on the major requirements, some risk areas and current performance.

2.1. 50W laser system

This system was contracted in September 2005 to Coherent Technologies Inc. (CTI), the same vendor who built the Gemini North laser, and that later became Lockheed Martin Coherent Technologies (LMCT). As of May 2008, the laser oscillators and amplifiers are being aligned on the final optical bench, factory acceptance testing is scheduled for mid-August, and delivery in Chile one month later. A full description of the 50W mode-locked solid state laser is reference 5 at this conference. The 50W laser requirements, technical risks, and current performance are summarized in Table 2 below.

Laser requirements	**Values**
Total minimum power	50W (within EE99 of the beam)
Power short term stability	10% PV fluctuation over a 5 min period
Power long term stability	5% rms fluctuation over a 12 hour period
Nominal central wavelength and frequency stability	589.0 nm sodium D2 line +/-50 MHz
Beam diameter	5.0 mm ($1/e^2$ intensity point) +/-0.3 mm
Beam quality and beam quality stability	M^2<=1.4, beam quality stable within +/-10% (1s period)
Angular pointing stability	+/-0.4 mrad long term, 20 μrad rms when averaged at 10 Hz for 1 second every 30 min
Risks to Gemini and impact	**Solution**
Low power (less than 10W per beam): lower LGSWFS SNR	Work only when Na column density is high, or accept reduced performance with lower AO bandwidth)
Short term power stability (ms to tens of seconds): Rayleigh background variation and bias in spot centroids	Take calibrations more often (laser power with fast power-meter, background/dark at each observation)
Wavelength instability: reduces Na photon return if >200MHz	Improve stability of wavelength lock
Beam quality: reduces LGSWFS SNR	Optimize laser, use WFS centroid gain method to compensate for beam elongation
Performance (as of November 2007)	**Values**
Power	55W at output of non-linear crystal
Beam quality	M2= ~ 1.3 at 22W output power (no measurement at 50W)
Short term power stability	+/-5% at 22W output power (no measurement at 50W)

Table 2: Laser requirements, technical risks and current performance

2.2. Beam Transfer Optics (BTO) sub-systems

Gemini subcontracted several BTO sub-systems jointly for Gemini North and South: the Laser Launch Telescope (LLT) procured from EOST and delivered in February 2007, the BTO component controller software and the BTO diagnostic software, both procured from Observatory Sciences Ltd and delivered at the end of 2004. This software is aimed at moving the control mirrors in the BTO, provide telescope flexure compensation (through open-loop models), and also allow some laser beam pointing and profile diagnostic (or LLT image quality when looking at a natural guide star).

LLT requirements	**Values**
Clear aperture	450mm
Magnification	60x
Unvignetted FOV	+/-1.2’ on the sky
Low order aberrations (focus, astigmatism, coma, trefoil, spherical)	< 0.15 wave rms at 589nm
High order aberrations	< 0.06 wave rms at 589nm
Throughput	>97% at 589nm
Risks to Gemini and impact	**Solution**
Poor image quality: reduces the LGSWFS SNR as a poor laser M^2 would do	Improve alignment, or repolish mirror

Performance	**Values**
Wavefront error	Low order: 0.13w rms, high-order: 0.03w rms at 633nm
Wavefront error on sky	NGS EE50=1.09” with 0.7” seeing
Throughput	~ 94.5%: 0.1% per surface for lens (5 surfaces) and 95% for OAP with enhanced Al coating

Table 3: LLT requirements, technical risks and current performance

The LLT being located on the Gemini telescope axis (behind the secondary mirror), the software also features a slow closed loop mode to ensure centered propagation through the laser vane duct that crosses above the telescope primary mirror between the telescope top end ring and the secondary support structure, but this option is not being used at Gemini North where we exclusively use LUTs for the beam control. The LLT is an off-axis parabolic (OAP) mirror fed through a diverging lens, with a passive athermal focus mechanism. The LLT requirements, technical risks and current performance are detailed in the Table 3 above.

The opto-mechanical arrangement designed to support the mirror and keep it rigid to prevent pointing drifts was based on holding the glass through a ceramic central hub bonded to a cavity milled into the glass thickness. Unfortunately, the design and fabrication induced significant thermal stress at the bond line and originally (at Gemini North) caused severe wavefront error. To the contrary of Gemini North, the Gemini South OAP was not re-polished but just rebonded properly. Although a residual high-order defect remains in the surface figure, causing 5% LLT Strehl degradation, we have already verified the image quality on the sky (see Table 3). We are also currently exploring the possibility to recoat the OAP with a higher reflection coating at 589nm and modify the telescope tube design as to allow easy in-situ wash of the OAP since the mirror is exposed to the open air and gets dusty like the other telescope optics (10% reflectivity drop after 2 years of operation at Gemini North, despite doing monthly CO2 cleaning).

2.3. AO bench sub-systems

2.3.1. Summary of contractors

The AO bench, named Canopus to pair with the GN AO system called Altair, is a complex package that was divided amongst several contractors:

- **AO bench:** built by EOST (see reference 6) and delivered in November 2006, it includes the optical bench and supporting structure, 2 electronic thermal enclosures on each side of the bench, the various elements of the optical path (mounts, optics, electronics and controls), a calibration source for the Natural Guide Star (NGS) path and another for the Laser Guide Path (LGS).
- **Off-axis parabolas** (OAPs): 3 mirrors built by the Optical Science Center at University of Arizona and delivered in June 2005.
- **Deformable mirrors (DM)**: 3 mirrors built by Cilas, conjugated at 0, 4.5 and 9km of altitude, delivered in April 2006. There is a total of 917 actuators.
- **Deformable mirror electronics (DME)**: built by Cambridge Innovation and delivered in April 2006.
- **NGSWFS**: built by EOST and delivered in June 2007, it includes a 6-stage nest to position 3 probes around the field and feed 4 wavefront sensors: 3 fast tip-tilt sensors and 1 slow focus sensor (also sensing low-order non-common path aberrations)
- **LGSWFS**: built by tOSC (see reference 7) and delivered in July 2007, it includes two sets of active optics to compensate for LGS range versus telescope elevation (zoom corrector) and pupil size (magnification corrector), lenslet arrays (and associated optics like collimators and relay lenses) and 5 EEV39 CCDs.
- **Real Time Control (RTC)**: built by tOSC (see reference 8) and delivered in July 2007, this is the heart of GeMS, where all the information is processed to close 3 control loops: the AO (or high-order) loop through the 3 deformable mirrors, the loop fast Tip-Tilt loop, and the Tilt Anisoplanetism loop (plate scale) through DM0 and DM9. The only other loop, not directly controlled by the RTC, is the science path focus loop managed by the NGS focus sensor driving slowly the LGSWFS zoom corrector.

2.3.2. Main requirements and high-risk areas

AO requirements	**Values**		
Deformable mirrors: active actuators/slave actuators/pitch	DM0: 240 / 53 / 10mm ; DM4.5: 324 / 92 / 5mm ; DM9: 120 / 88 / 5mm		
LGS signal level at WFS	80-125 PDE/cm^2/s or 250-390 PDE/subaperture@800Hz		
WFS read time + processing latency	< 1.25ms		
0dB closed loop bandwidth	70Hz		
Number of WFS	LGS = 5	NGS = 3 (TT)	NGS = 1 (focus)
WFS order	16x16	1x1 (quadcell)	2x2

WFS pixel size on sky	1.5”	0.75”	0.05”
WFS read noise	4e$^-$	none	8e$^-$
AO bench transmittance to WFS	0.59 (1-2.5µm)	0.46-0.67 (0.5-0.7µm)	0.11-0.17 (0.5-0.7µm)
WFS detector QE	0.95 peak	0.6 peak	0.72
WFS sampling rate	800Hz	800Hz	~0.1Hz
High risks and impact	**Solutions**		
Pupil misregistration caused by bench flexures: lower Strehl and may cause loop instabilities	Strengthen mounts, WFS mechanisms to compensate misregistration		
NGSWFS throughput (not in specifications): reduces sky coverage	Step-by-step throughput measurement and new coating/fiber alignment		
Aging DM rest shape: actuator saturation in medium to bad seeing, loop instability	Repolish DM		
LGSWFS pixel edge diffusion: degrades the quadcell transfer function and reduces SNR	Change CCD controller, upgrade CCDs and microlens arrays		
Vibrations due to telescope M2 system or cryo-coolers from other instruments: lower Strehl (image widening)	Strengthen mounts, improve M2 control, improve cryo-cooler damping, implement TT predictor		

Table 4: AO system main requirements and risks

As reference, we obtain the following results with the GN LGS AO system[9]: a/ LGSWFS: about 400 counts at 500 Hz with 10W laser power in low Na abundance season ; b/ Focus sensor: 11250 counts with 17.5 R magnitude guide star in a 50s exposure time ; 3/ TT sensor (4 channels): 10 counts/channel from the sky and 34 counts/channel from the TT star with 17R source in dark time running at 10ms exposure time.

3. REVIEW OF IN-HOUSE DEVELOPMENT

3.1. Laser infrastructure

This work package (see reference 10) consists of the telescope modification to house a 3.6x1.1m laser optical bench on the telescope elevation (‘Nasmyth’) platform. A large extension is being built to the existing platform in order to fit a Laser Service Enclosure (LSE), a clean room environment for the Laser Bench (LB), large enough to allow work by 3 people. Separate support structures are built for the LB and the LSE, and are both attached rigidly to the telescope mount.

Infrastructure requirements	Values
Laser support structure natural frequency	> 8Hz
Clean room environment	Class 10,000
LSE ambient air temperature	0 to 20C, regulation to 0.4C of setpoint

Table 5: LSE main requirements, risks and achieved performance

The overall infrastructure is a 10-ton addition to the telescope. This represents only 2.5% of the total weight of the telescope but could nonetheless contribute to some mount control issues because of the variation of the moment of inertia. An analytical model showed that the telescope mount control loop would require some re-tuning (in particular the velocity loop) if the moment of inertia is changing by more than 10%. A real-life test was performed with a dummy load attached to the telescope mount and did not uncover any further issue.

As of April 2008, the laser infrastructure is 81% complete in design and fabrication.

3.2. Beam Transfer Optics (BTO)

The Gemini South BTO (see reference 11) was originally designed to be a copy of the Gemini North version upgraded for 5 beams all along the path. In order to keep the LGS geometry projected to the sky constant with respect to the LGSWFS (mounted on the AO bench at the Cassegrain rotator), a rotating mirror (‘K-mirror’) is required just prior to the LLT. Some new design and complexity was also introduced due to the new location of the 50W-laser on a Nasmyth-like platform. The main functions of the GS BTO are:

- Conduct the Laser from the LSE to the LLT using motorized and non-motorized fold mirror arrays

- Correct constellation rotation due to field rotation
- Correct vibration introduced on the Laser Bench using the Laser Bench Beam Stabilization (LBBS)
- Correct uplink atmospheric jitter using the Fast Steering Array (FSA)
- Provide information about the beam quality and propagation through the laser vane duct with the Diagnostic System

  As of April 2008, the BTO is 85% complete in design and fabrication.

3.2.1. Main requirements and high-risk areas

BTO requirements	**Values**
LGS constellation	1 beam on axis, 4 beams off-axis on a 1’ square pattern
1-axis blind positioning on the sky	1” PV
1-axis pointing accuracy at 800Hz on the sky	0.05” rms
Laser polarization to the sky	circular
Throughput	> 75%
Risks to Gemini and impact	**Solution**
No significant risk	GN BTO performs to specifications
Performance	**Values**
Throughput	85% at GN
Blind positioning on-sky	1” is 2.5deg rotation of actuator screw (Newport mount)

Table 6: BTO main requirements, risks and achieved performance

3.2.2. GS BTO features

Early 2008, after the laser vendor confirmed they could produce one single beam with the required 50W power, we decided to simplify the BTO and produce the splitting into 5 separate beams at the top-end ring of the telescope rather than on the laser bench. This simplification yields improved throughput, less optical surfaces to align and maintain, fewer controls, no de-rotating mirror on the elevation axis, no alignment shutters. A block diagram of the BTO is shown in Figure 1.

The sky-pointing accuracy is achieved by a 2-layer control. Since the laser is mounted on a structure supported from the telescope mount and immersed in a dynamic environment (mount vibrations, wind load on LSE, A/C inside LSE), we have designed a simple Laser Bench Beam Stabilization (LBBS) system made of a fast piezo-actuated mirror (truss pointing mirror) and a Position Sensing Device (PSD) working in closed loop. The main purpose of the mirrors and controls in the truss area is to relay the laser beam in a completely enclosed path to the LLT through a thin and long laser vane duct. In order to accomplish this, we control centering and pointing through the vane with an elevation Look-Up Table (LUT) to compensate telescope flexures, and a fast steering mirror to compensate for beam jitter in the BTO, maintaining the 5 beams centered on FSA, which in turn stabilizes the beams on the sky by compensating the up-link atmospheric seeing.

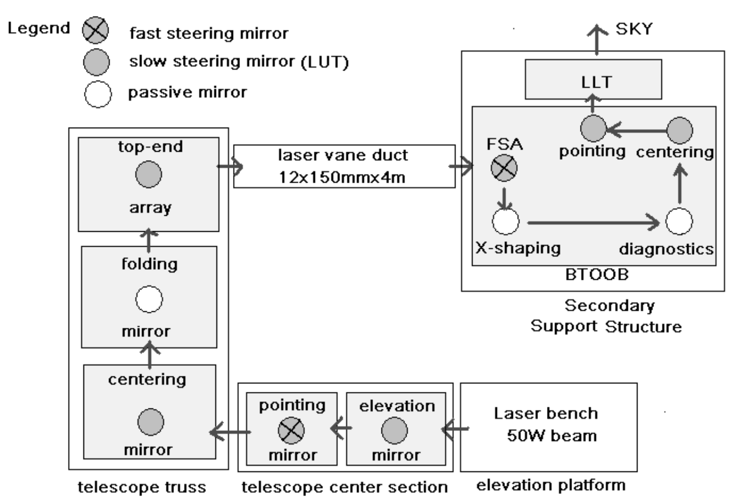


Figure 1:BTO block diagram showing active/passive elements

3.3. AO bench integration

As of April 2008, Canopus is 54% complete in lab I&T. When the AO bench was delivered to Chile, we started the internal integration of the various sub-systems made by different vendors according to the following sequence:

- AO bench: installation of all the main optics in their mounts (dummy flat mirrors in lieu of the DMs) and realignment of the 3 ‘bare’ (i.e. no detectors) paths -NGS,LGS,Science- using a phase shifting interferometer mounted in the diagnostic output and working in double path. We adjusted to verify that the wavefront error in the 3 paths was still meeting specifications as demonstrated at the factory acceptance (respectively 50/50/60nm rms for the Science(no ADC)/NGS(with ADC)/LGS paths). Two important optical specifications verified and met at factory acceptance were: 5% PV science path Strehl ratio field variation (spec. is 5%) and 17μrad Science-LGS wavefront slope error (spec. is <40μrad).
- Start of a variety of troubleshooting, repairs and upgrades to several components and aspects of the bench that was accepted out of specifications due to extended delays faced by the vendor. In particular: thermal insulation management in the electronics enclosures, reliability of servo and 2-position mechanisms, NGSWFS probes (fiber optics attachment and travel limit switches), etc…
- Deformable Mirrors and Electronics: integration and static test with an interferometer to verify data obtained at the successful factory acceptance (but now obtained with the definitive electronics). Although we are not equipped as well as the vendor was to repeat the tests, we were able to confirm the overall good behavior and in particular important specifications like maximum stroke (+/-4μm), differential stroke (>2μm), influence function (<25% coupling).
- NGSWFS: installation and alignment with NGS white light calibration sources ; we measured a 132 nm PV focus error that will need to be compensated by a focus model, after final characterization versus the atmospheric dispersion corrector position (not tested yet). Test of Tip-Tilt guide star Avalanche Photo-Diode (APD) detectors.
- LGSWFS and RTC: installation and alignment of hardware on optical bench and in electronics enclosures. Connections to external systems the RTC reads information from (like NGSWFS APDs). Acquisition of 5 LGS LED calibration sources, optimization of pupil registration, wavefront errors.
- DM and DME: installation one at a time, connectivity test with RTC
- Canopus and RTC functionalities (see Figure 2):
  - close AO loop on DM0, then integrate DM4.5 and close loop with 2 mirrors and finally repeat with the 3 mirrors. Tomography effects become evident when poking off-axis actuators on the various mirrors.
  - Close the loop with the Tip-Tilt mirror and the 3 NGSs.
  - Close the Tilt Anisoplanetism loop with the DM0 and DM9 and the 3NGSs.
  - Inject low-order Kolmogorov turbulence on the DM control commands and verify basic behavior of the system
  - Assess stability of the RTC and various subsystems in closed loop
- Diagnostic WFS (DWFS): designed and built by Gemini, it is made of a direct imager (SBIG camera) and a SHWFS (Miniwavescope from AOA) mounted on an exchanging stage (to do either wavefront sensing or PSF evaluations) and movable in X-Y to analyze the whole 2’ FOV. This laboratory test output path is folded on top of the Canopus structure on a temporary optical bench and simulates the science focal plane.
- Calibrations at zenith and ambient temperature: TT mirror motion, WFS plate scale, nominal LGS centroid gains with quadcell transfer functions, measurement of WaveFront Error (WFE) in science path (using the DWFS)
- Flexure: Canopus is mounted on a 1-axis rotary frame simulating one component of telescope elevation. Characterization of wavefront and pupil registration at various bench gravity angles. Next verification and optimization of performance at various angle by also adjusting the LGS source Z-position (and therefore the LGSWFS zoom corrector)
- Dynamic analysis: a hot-air turbulence box (‘turbulator’, see reference 12) designed and built by Gemini is inserted in the optical path in front of DM0 and provides high-order Kolmogorov turbulence that can be combined with the low spatial order generated with the DM to form a realistic atmospheric profile.

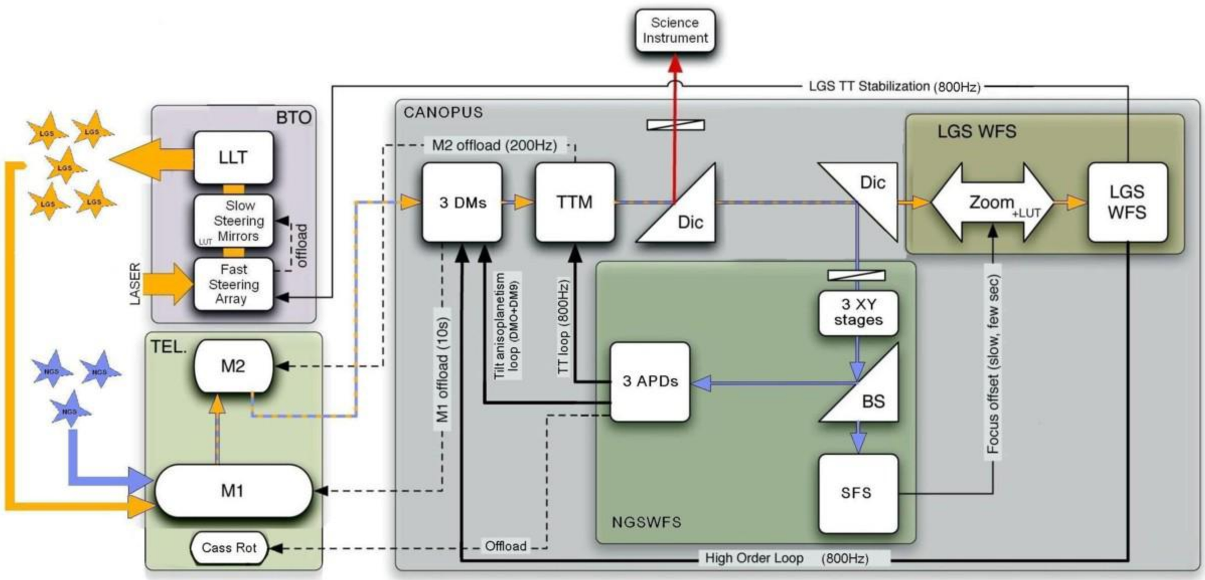


Figure 2: Canopus system block diagram showing control loops

4. COMPLETION OF I&T IN LABORATORY AND ON THE TELESCOPE

In this section, we review the main steps planned to complete Integration and Testing of all GeMS sub-systems both in the laboratory and on the telescope. We highlight the possible risk areas and review the error budget and the main contributors.

4.1. Laser Guide Star Facility I&T

The Laser Guide Star Facility (LGSF) is the system made of the laser, BTO LLT, safety systems and infrastructure supporting laser propagation. The following chronological steps will be followed prior to readiness for first-light:

- Test of services and control of LSE (humidity, temperature, particles counts): this will be done at ground level in the dome and simulate conditions on the telescope
- Construction of Laser Bench and Laser Service Enclosure support structures: pre-assembly on observing floor then successive setup on telescope mount. It is expected the large LSE structure installation will last two days and require one night of shutdown. Telescope mount performance will be assessed after each structure is installed.
- Installation of BTO 'optical' boxes on telescope truss and alignment of optical train with He-Ne alignment laser on elevation axis. Determination of elevation LUT for the various active mirrors.
- Installation of LBBS and commissioning of closed loop control.
- Final alignment of BTO Optical Bench, including the rotating K-mirror, then re-installation of LLT and BTOOB on Secondary Support Structure (laser vane duct is already installed).
- Installation of LSE on support structure and telescope mount performance assessment (this is the heaviest part, about 5 tons).
- Post-delivery acceptance of laser at Cerro Pachon: this will be a quasi repeat of the tests performed at the factory to verify that the system was not affected by shipment. The GN laser performance did not suffer from shipping so we don't anticipate major delays in this activity.
- Installation of laser bench and laser electronics inside LSE, then commissioning of laser using all final services (glycol, air, power, network, etc…)
- Laser Interlock System (LIS): testing of all safety features (in particular laser safety shutter located inside BTO) when laser power is on. This step is essential and complex since there are many systems (hardware, computers,…) connected to LIS and scattered throughout the summit facility.

- Propagation of laser in low power mode into BTO up to diagnostics cameras in BTOOB and to the dome, then testing beam stability with LBBS
- Confirm readiness milestone for propagation to the sky

4.2. Canopus I&T

We will install Canopus on the telescope only when we have resolved all the engineering tests and interfaces we can perform in the laboratory. Those activities includes:

- Investigate the abnormally high Pixel Edge Diffusion (PED), or pixel crosstalk, measured with the LGSWFS EEV39 CCDs (AIMO version -Advanced Inversion Mode Operation-). tOSC has measured 25% and we have confirmed this amplitude by measuring the WFS quadcell transfer functions. The first troubleshooting tests will consist in tuning the bias voltages and clocking of the SDSU detector controller.
- Characterization of overall bench alignment and performance at lower temperature: we can run the instrumentation laboratory air conditioning to the lower set point and achieve a 12deg difference with ambient. Look-Up Tables might be needed to compensate for thermal effects.
- Characterization of overall bench (in particular the NGSWFS) alignment and performance at various elevations from zenith to 60deg: confirm we have all the degree of freedom required and can compensate for flexures with LUTs.
- Characterize and calibrate the 2 ADCs (visible and IR) motion (neutral point, induced wavefront error).
- Re-measure the NGSWFS throughput and eventually devise an upgrade path: the transmission through probe 1-2-3 (pickoff optic to output of fiber) is currently respectively 70-59-66% of the specification and this loss reduces sky coverage by ~10%. We believe the injection into the fiber is causing most of the loss.
- Characterize NGSWFS X-Y stage positioning accuracy to meet the operational requirements for guide star acquisition: a) absolute positioning accuracy < +/- 0.25” (150 µm) over its full patrol range ; b) resolution for differential movements < +/-0.02” (12 µm) ; c) differential positioning accuracy < +/- 0.001” (0.625 µm) for a common adjustment of up to 2 arc seconds (1.25 mm). The chosen stage offers a resolution of 1.0 µm, an accuracy of +/-2.0 µm per 25mm of travel (i.e. +/-0.16 µm over 2mm travel) and a repeatability of +/-2.0 µm.
- Continue dynamic characterization with turbulator and DM disturbances.
- Vibration testing: we know the typical power spectrum of the telescope instrument support structure environment (dominated by the cryo-coolers from the various other instruments) and are considering the purchase of a commercial shaker to perform testing in the lab.
- Experiment with different high-level control algorithm (see reference 13), in particular an optimal reconstructor for 3DMs
- Transportation of Canopus to the summit, verification of basic performance after shipment.
- Installation of Canopus on 2-axis flexure rig to measure and implement flexure models required on telescope (a new dummy science camera will be used).
- Coupling of Canopus and GSAOI in the summit lab (boresight with a pointing-centering pair of mirrors): verification of main GSAOI functionalities, first assessment of image quality in the IR and Non-Common Path Aberrations (NCPA) files, first troubleshooting of GSAOI On-Detector Guide Window operation).
- High-level operational software: this is a significant effort (at least about 1 FTE) and considers features like instrument configurations (Canopus LGS and NGS geometry, GSAOI on-detector guide window), Observing Tool (new items for targets, Canopus, GSAOI), sequence executor, Instrument Status Display, Telescope Control Console (sends target and guide stars coordinates, control integrations of GSAOI and Flamingo-2 WFS, etc…).
- Confirm readiness milestone for installation on telescope of Canopus and GSAOI.

4.3. Image quality error budget

The error budget[14] was established in 2001 for PDR and is reproduced in Table 7. This is the average performance over a 1” square field at zenith with bright NGS and median site seeing (0.7” FWHM). The original resulting Strehl ratio was 22, 42 and 61% respectively at J, H and K bands. Some recent sub-system errors have been identified and are being quantified (highlighted as *): LGSWFS PED, LLT turbulence and IQ, M2 edge mask, laser M^2. The PED alone contributes to a 2.3x reduction in SNR but recent modeling shows that the photon return is still a factor of 10 above the worst case threshold in low Na abundance season. During integration and optimization, we focus on and correct only error terms contributing to more than 5% relative Strehl reduction (since the last few percent can typically take considerable efforts).

1	**total AO system error**	**199**
	atmospheric compensation	183
	anisoplanetism over 1' square field	133
	fitting error due to finite spatial resolution of DM and WFS	109
	WFS measurement noise	32
	LLT parabola polishing errors*	TBD
	LLT tube turbulence*	TBD
	laser M^2=1.4*	TBD
	Pixel Edge Diffusion*	TBD
	read noise*	TBD
	others?*	TBD
	finite temporal bandwidth of control system (servo lag)	26
	diffraction, quadrant detector SH sensor, 3D LGS	48
	residual windshake	34
	implementation error	69
	uncorrectable mirror fabrication errors	43
	non-common path errors	46
	uncalibrated flexure/thermal variations	41
	WFS centroid gain estimation error	21
	DM to WFs misregistration	24
	LGS focus variability	12
	component non-linearities (hysteresis, discritization)	10
2	**total uncorrectable errors in telescope**	**116**
	primary mirror figure	60
	secondary mirror figure	60
	secondary mirror masked edge*	TBD
	alignment	20
	self-induced seeing	50
	AO fold mirror	30
	science fold mirror	50
3	**total uncorrectable errors in instrument**	**65**
	flexure relative to OIWFS	25
	high-order IQ effects	60
4	**total**	**239**

Table 7: GeMS image quality error budget

5. COMMISSIONING PLAN

GeMS commissioning plan has been written based on the experience gained at Gemini North by essentially the same team of people, some with significant experience with AO systems. All MCAO-specific tests (multiple guide stars and loops) are obviously integrated into the sequence. We have a total of 128h of testing and anticipate a total of 16 nights (8h/night). Based on an estimated 60% observing efficiency that we achieved at GN (time lost to fault and weather were respectively 17 and 21%), we therefore expect to complete the commissioning plan in about 25 nights or about 5 months (5 runs of 5 nights each), and then move into the science demonstration campaign. In order to meet this rather aggressive schedule, a flexible night scheduling will be essential in case some complex fault is discovered and requires some extended day-time activity to be repaired. Three weeks between runs is also a reasonable amount of time for people to rest and work on general troubleshooting, high and low level software fixes and upgrades, data analysis, etc… We are gathering a large and well trained laser team to have the LGSF operating at its best (our goal is less than 10% laser down time on average during first the 6 months of operation). Lots of monitoring will be in place through circular buffers and through the Gemini Engineering Archive system that logs hundreds of signals versus time throughout the telescope systems.

Besides the risks highlighted in section 2 and 3 in sub-system description, the main technical issues we could encounter are:

- Potential issue for dithering with the BTO FSA (200Hz sinusoidal signal sent by RTC and used as a lock-in detection technique to measure the LGSWFS centroid gains) due to the lack of a local position sensor on the piezo platforms that were procured. This will require a careful cross calibration similar to what was done at GN.
- Canopus Non Common Path Aberrations (NCPA) that can only be compensated for optics conjugated within the 0 to 9km range. Low and high order defects on optics located outside that range (like OAP3 or science ADC) can not be compensated and we will need to integrate GeMS with GSAOI to measure the full impact on performance.

Table 8 below lists the sequential steps to be followed during night-time commissioning (there are many others tests and calibration steps to be done during day-time).

STEP	DURATION
LGSF technical commissioning	
first night-time propagation at zenith: find spots on AcqCam	1 h
check spot spacing on sky and optimize	4.5 h
check spot focus and shape (collimate)	4 h
KM to PM/CM alignment compensation model	2 h
PM/CM flexure model and absolute position	4.5 h
laser power, spot photometry, fratricide effect	3 h
calibrate absolute position angle of LGS constellation on sky	0.5 h
Canopus technical commissioning	
acquire laser spots on WFS	1 h
measure fratricide effects on WFS	3 h
close HO loop	1 h
close BTO FSA loop	3 h
test offload to M1	2 h
check high-order stability	2 h
close NGS loop	2 h
test offloading to M2	2 h
test modal gain optimization	3 h
establish photometric model	3 h
re-check modal gain optimization at faint end	3 h
check FSA dithering for centroid gain estimation	8 h
LGS zoom calibration vs elevation	2 h
close SFS loop	3 h
photometric calibration of SFS	3 h
test acquisition procedure	8 h
check IQ in GSAOI	2 h
test r0 measurements	2 h
test high-level software tool (MYST, SPYDR)	4 h

GeMS-GSAOI science commissioning	
optical throughput	2 h
performance (Strehl) optimization	9 h
Performance (astrometry) evaluation in different modes	3 h
Performance (Strehl) evaluation in different modes	9 h
limiting magnitude guide stars	6 h
limiting separation for NGSWFS	6h
stability test	4h
test guiding close binaries	3 h
test guiding extended objects	1 h
test non-sidereal tracking	1 h
integration into queue: SeqExec test	8h

Table 8: GeMS commissioning steps

One of the main focus of the commissioning phase is to verify that the top-level requirements are being met in the various categories like science (overall performance and optics) and operation. In Table 9, we reproduce only 6 of the 19 science related items defined in the Functional and Performance Requirements Documents (the others are: wavelength coverage, emissivity, flat fielding, seeing limit, transferred FOV, ability to dither, zenith angle, F/ratio, atmospheric dispersion corrector, atmospheric diagnostics data, number of NGS, ghost images, scattered light). GeMS operational model (see reference 15) and technique for aircraft detection/avoidance (see reference 16) are also presented at this conference.

Specification	Value	Comments/Values		
Strehl ratio at H	54%	Average over 1’, median conditions, bright NGS, zenith, excludes telescope and instrument aberrations		
PSF uniformity at H	4%	Over central 1’		
PSF estimation	2% accurate	Over 1’, saved with instrument data		
Astrometry stability over 100”	3mas/100”	On top of calibrated distortion		
Sky coverage	10%	Galactic pole with Strehl loss < 50%		
Throughput	0.70	Of telescope throughput without AO		
		Science path (K)	LGS path	NGS path
	Canopus	0.76	0.78	0.72
	Gsaoi/wfs	0.50	0.84	0.59
	Detector	0.70	0.87	0.60
	Total	0.27	0.57	0.25

Table 9: Top-level GeMS science requirements

6. REVIEW OF PROJECT MANAGEMENT

6.1. Resource summary

Some 40 engineering division staff (7 at Gemini North and 33 at Gemini South) and 3 science staff have been involved with GeMS (or will have been after final integration and commissioning) since the end of 2005. All the data presented here runs from January 2006 until April 2008 (not until completion). Figure 3 represents the variation of engineering FTE used over time (we have spent around 8 FTE each year), and the histogram of hours per person, which shows that 80% of the FTEs are provided by 12 staff who dedicate an average of 47% of their time to the project (ranges from 17 to 97%).

Table 10 presents FTE collected with the timecards. The numbers are biased (and probably under-estimated by 15%) by two facts: overtime by exempt staff is not accounted for and, unfortunately, people do not fill their time card accurately (this would require a closer monthly control). Note that the software effort appears artificially low because a lot of the high-level software is done by the AO science staff (not included in the analysis, but at least another ½ FTE of software).

The estimates entered in our project management software are also inaccurate (over-estimated in this case by about 50% compared to timecards), which is a consequence of the difficulty to produce detailed enough planning. Based on all the information to-date, we expect to spend another 6-8 FTE to complete GeMS.

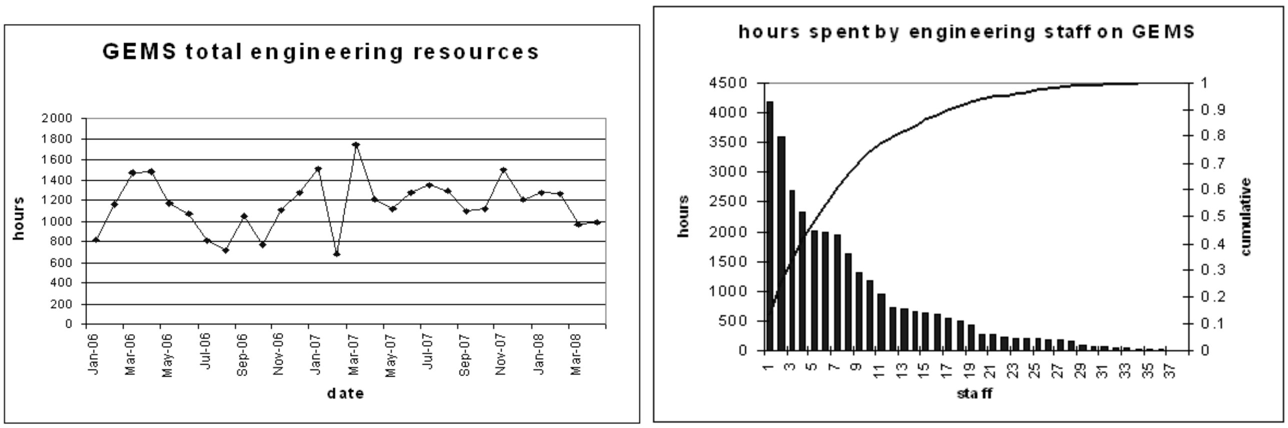


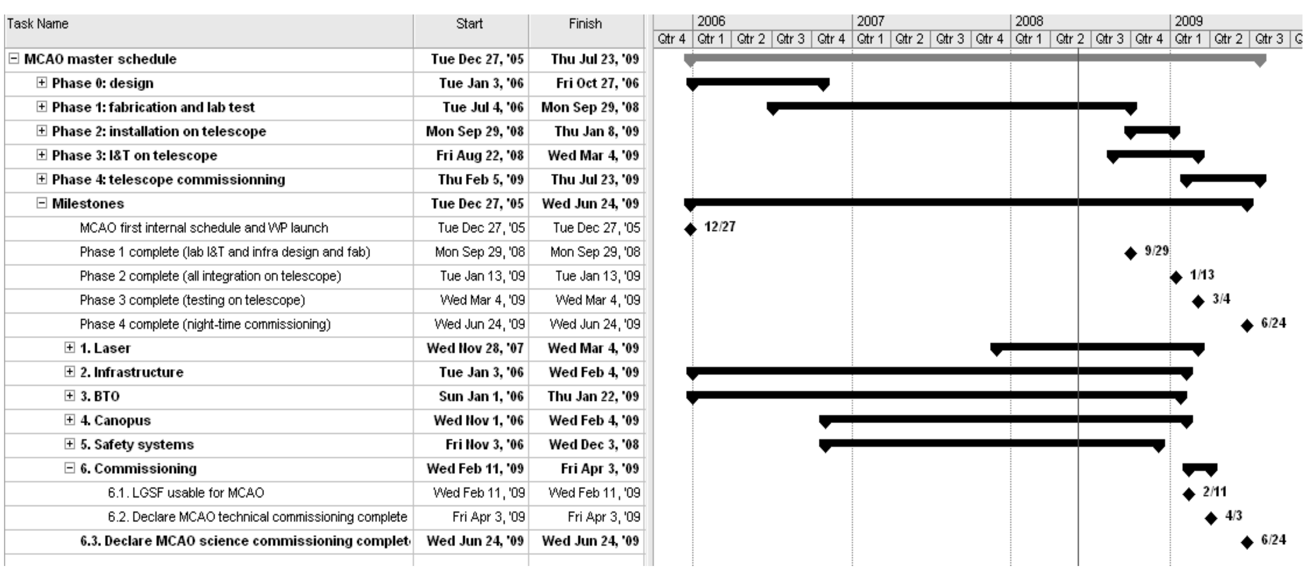
Figure 3: GeMS resources over time and histogram

Work groups	**El.Eng.**	**El.Tec.**	**Me.Eng.**	**Me.Dra.**	**Me.Tec.**	**So.Eng.**	**Op.Eng.**	**Total**
Reported	2.7 (15%)	2.0 (11%)	2.2(12%)	6.2 (34%)	1.0 (5%)	2.0 (11%)	1.3 (7%)	18.1 (100%)
Work area	**Infrastructure**	**BTO**	**Canopus**	**Proj.Man.**	**Others**			**Total**
Reported	4.4 (24%)	8.5 (47%)	3.6 (20%)	0.9 (5%)	0.7 (4%)			18.1 (100%)

Table 10: Resources in FTE per work area (1 FTE = 1700h)

6.2. Schedule summary

GeMS was split into successive phases. The observatory priorities for 2008 include completion of phase 1 and 2 (up to installation of all hardware on telescope). The timeline was originally built with Microsoft Project and later imported into Project Insight. The milestone calendar per I&T package is linked directly into the main detailed task list.



Graph 4: GeMS schedule, phases and milestones

6.3. Management practices and lessons

6.3.1 Project planning and constraints

The Gemini engineering staff main function is to operate the Gemini North and South telescopes and their instrumentation. Historically, since the end of telescope commissioning, there have been only few opportunities where substantial projects have been conducted internally. GeMS is probably the first major endeavor involving tens of staff over many years and is running in parallel with operations since we do not have a dedicated development team. Managers have suffered from lack of solid training in project management skills and methodologies (first of 'lesson learned'). Various management tools have been implemented and are currently being reformed (since end of 2008), in particular the way we prioritize and define resource/schedule for projects through a web-based project management software called *Project Insight*. The difficulties with project management start in the definitions and estimates of tasks through the Work Breakdown Structure process, which needs to be done as much in depth as possible involving all levels of staff members. Tasks execution should not start until reasonable definition is achieved ('lesson learned'). The WBS process is difficult and requires both brainstorming and a lot of coaching to staff. With GeMS, the drafting-related processes have been an area where we have most failed in making good estimates, and should be given more attention (based on typical pace of 1 drawing per day for a basic part).

Amongst the three typical constraints of project management, we have frozen mainly the scope (GeMS's performance), allowed some flexibility into cost (until planning resources and supplies was detailed enough), and used the time as our main variable due to the lower level of priority allocated to development versus telescope operations.

6.3.2. Project tracking

Beyond the overall project communication through regular meetings, both technical or more general depending on the audience and the frequency, it is important to track progress and obtain feedback from upper management. This activity can become time-consuming and frustrating if done without proper habits, methodologies or tools. A well-established Microsoft-based project allows good tracking, both at low or high level depending on the time spent, and can be complemented with detailed information from employees timecards to verify the estimates ('lesson learned'). Detecting schedule drift is an area where a 6-sigma approach to project management quality can be useful to unearth and correct root issues (following the DMAIC methodology -Define-Measure-Analyze-Implement-Control-). Overall, project tracking and progress reviews allow to maintain momentum in activities and keep people focused and motivated over long period of time (years).

6.3.3. More lessons learned

There are several areas of importance in a matrixed resource environment (like Gemini) and we will give some examples. It is essential to understand and quantify staff allocation across projects to prevent conflicts and delays. A server- or web-based interface tool accessed by all can simplify this coordination. Beyond people, space and shared facilities (like clean room) also require proper coordination. Building accountability into people is another challenging area that make it possible to meet deadlines. Specialized engineering skills (FEA was an example in our group), when not duplicated within a team, must be identified and scheduled with care to prevent them to become critical path (resource 'bottle neck') or suffer a work burnout. Continuous system engineering is also required to ensure that technical communication, documentation and quality is maintained between disciplines and project phases: requirements, interfaces, configurations and compliance matrices are some of the key areas to monitor.

Because GeMS involves several modifications to the telescope, we have also spread them in time as much as possible to prevent shutdown of science operations and significant cost increase spent in overtime hours if all integration is concentrated prior to a deadline. In general, definition and weighting of management risks should be done early on and revised constantly to guide the project.

7. CONCLUSION

GeMS, the Gemini MCAO system, will have taken about 45 FTE and 10 years to complete. This is the first such AO system of its kind to be built on a large telescope and its operation will pave the way for future Extremely Large Telescopes (ELTs). Since the last public review[1] in 2003, the project has gone through many milestones although at an apparent slow pace due to the complexity and challenges for the Observatory staff to do both in-house project development and operate the two Gemini telescopes night after night. The next 12 months are obviously crucial since we will go through installation on telescope and full commissioning. No major technological risks remains but there are several areas where sub-system optimization is on-going to meet all the scientific performance requirements. The similarities with the GN LGS system, the technical issues uncovered during that first commissioning (2005-2006) and the operational experience gained by our staff have and will continue to contribute to our success.

ACKNOWLEDGMENTS

We want to thank the various contractors who have worked sometimes passionately for this unique project, Brent Ellerbroek for his continued support, the NSF review members (September 2007) for their guidance, Louis Hlousek for introducing new ideas with BTO, all the GS technicians (C.Aguilar, G.Alarcon, V.Alvarez, C.Araya, H.Diaz, C.Figueroa, H.Figueroa, L.Godoy, A.Gutierrez, P.Pjeda, E.Tapia) for their dedication, and the other various areas of our organization for their support (administration, information system, etc…).

The Gemini Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

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