MCAO Operational Concepts Definition Document

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Revision Control

1. Introduction

The Gemini-South multi-conjugate adaptive optics (MCAO) system will provide nearly uniform correction of atmospheric turbulence over an extended field-of-view significantly larger than is possible with a conventional adaptive optics system. Anisoplanatic wave front errors will be reduced by means of multiple deformable mirrors, which will be used to compensate for turbulence in three dimensions. A combination of 5 high-order laser guide star (LGS) wave front sensors and 3 tip/tilt natural guide star (NGS) wave front sensors are required to characterize the three-dimensional turbulence distribution and compute the commands to each mirror. The LGS wave front sensors will observe guide stars generated at a wavelength near 0.589 microns in the mesospheric sodium layer. The 3 NGS wave front sensors will be used to measure tip/tilt and tilt anisoplanatism, modes which are undetectable using laser guide stars due to the LGS tilt indeterminacy problem. Each NGS wave front sensor (WFS) will measure tip/tilt with a spectral passband of approximately 0.4 to 0.8 microns.

At the highest level, the MCAO system consists of the same basic subsystems as the LGS versions of the Altair (Mauna Kea) and Hokupa'a-85 (Cerro Pachon) AO systems. These subsystems are: Laser System (LS), Laser Room (LR), Beam Transfer Optics (BTO), Laser Launch Telescope (LLT), aircraft avoidance/safety systems (SALSA), the AO module (AOM), and the MCAO Control System (MCAO-CS). The top-level interfaces and operational requirements for these subsystems are largely analogous to the Altair and Hokupa'a CP LGS AO systems, although the use of multiple lasers, deformable mirrors, and sensors unavoidably leads to a number of new requirements. As just one example, the constellation of *5* laser guide stars projected by the LLT must remain fixed on the sky during an observation as the telescope rotates in azimuth and elevation.

Section 2 contains a description of each MCAO subsystem and summarizes their interfaces and operational requirements. Sections 3 through 5 then outline the steps involved in calibration and startup, science operations, and system shutdown in greater detail. Section 6 lists the characteristics of the system that must be calibrated during commissioning. Finally, section 7 summarizes an end-to-end Strehl ratio budget for the MCAO system.

2. System Overview

2.1. Laser System (LS) and Laser Room (LR)

The Laser System includes all components required to produce and maintain multiple laser beams at the sodium wavelength. The Laser System components are the laser head(s), laser enclosure(s), laser electronics, Laser System Control System (LS CS), cooling systems, and laser diagnostics.

- Technology permitting, it would be preferable that the laser system have a single laser head, which produces a beam whose total average power equals the sum of the individual laser beacon powers. Individual laser beacons are created by splitting the laser beam as many times as necessary, so that all beacons have the same average power. If no single laser head is capable of producing the required total laser power, there will be multiple laser heads housed by separate laser enclosures to produce the multiple beacons.

- The laser enclosure is the thermal enclosure that houses the laser head, and part or all of the laser electronics and diagnostics. It keeps the Laser System temperature constant at all times, whether the Laser System is operating or not. The thermal enclosure also prevents heat from being transferred into the air.

- The Laser System Control System (LS CS), which is not to be confused with the MCAO Control System (MCAO CS), is the hardware and software necessary to control and operate the Laser System. The LS CS is designed to be fully compatible with the MCAO CS and perform specific tasks as the MCAO CS demands, such as the LS prior-to-start internal safety check, LS automated start-up, LS automated shutdown, and LS emergency shutdown. Each global task corresponds to a sequence of actions specifically handled by the LS CS. The LS CS offers the possibility of either operating the laser remotely from the telescope Control Room, via the MCAO CS, or at the Laser System location, via direct low-level access to each action or sequence of actions.

- The LS cooling systems remove extra heat from the Laser System and transfers that heat to the Gemini telescope cooling system. The purpose is to prevent air turbulence from building up in the dome.

- During operation, the laser diagnostics provide real-time monitoring of the following Laser System parameters: laser output power, beam quality, beam divergence, beam pointing and centering, laser enclosure temperature, cooling fluids flow rates and temperature, and laser health status. These on-line diagnostics are also used during the Laser System start-up, along with other off-line diagnostics such as the polarization meter.

The Laser System also includes its own safety systems. These are either operated by the MCAO Control System via the Laser System Control System (prior-to-start laser safety check, safety shutter open/close when the SALSA system is active) or are integrated into the Gemini Interlock System (GIS). In case of an emergency due to the Laser System malfunctioning or to another cause, the GIS drops laser electrical power, which immediately switches off the laser light. Special attention is paid to prevent laser hazards by shielding all laser beams propagating at eye-level.

In the event that the Laser System produces a pulsed beam with a pulse repetition frequency (PRF) equal to the LGS wave front sensor (WFS) sampling rate, these two subsystems must be synchronized via the MCAO-CS or some other approach. The time lag between the laser pulse and the detection of photons at the WFS CCD will depend upon the telescope zenith angle and the current range distribution of the mesospheric sodium layer.

The Laser Room houses all or part of the Laser System and will be a temperature-controlled environment thermally isolated from the telescope enclosure. Depending on the Laser System location, the Laser Room will either be a separate room in the telescope pier, or it will simply coincide with the laser enclosure(s). All power supplies, cooling fluids and software connections are delivered to the Laser System through the Laser Room.

2.2. Beam Transfer Optics (BTO) and Laser Launch Telescope (LLT)

A system of optics and/or fiber optics will deliver the laser beams from the Laser Room to the Laser Launch Telescope (LLT). This Beam Transfer Optics (BTO) subsystem includes beam diagnostics, active beam alignment and steering, beam shaping, safety shutters, and polarization control. Fig. 1 is a schematic/cartoon of the basic components and functions of the BTO system.

All BTO optics will be coated so that laser light losses are minimized at the sodium wavelength, with high reflectivity coating on mirrors and AR coatings on lenses and beam splitter cubes. There are either one or multiple laser beams traveling along the telescope structure. Multiple beams are the baseline case. In this case, the BTO deliver all laser beams stacked in a line to reduce scattering from behind the secondary vanes into the field-of-view of the telescope. An array of 5 mirrors (M3 in Fig. 1) reformats the 5 beams into an "x" shaped pattern for propagation into the sky. Multiple pointing and centering loops actively maintain the beam(s) alignment (M3, M6, and additional mirrors along the path to the Laser System). These loops are controlled by the MCAO CS, and are low bandwidth to compensate for slow beam drifts due to thermal noise and telescope flexures. The final pointing element in the BTO is an array of fast tip-tilt mirrors controlled by the Adaptive Optics Instrument (AOM) via reflective memory to correct for the laser beacons' seeing-induced jitter on their way up to the sodium layer (M2). The separate mirrors for each beam enable the correction of differential beam jitter induced by tilt anisoplanatism.

Also part of the BTO:

- A laser shutter is located at the LS/BTO interface. Optionally, a second shutter located at the BTO/LLT interface (actually a flip mirror to divert the beam to a cooled dump on the telescope head ring) would make it possible to propagate the laser beam(s) to the top of the telescope for LS and BTO calibrations without launching the beams to the sky. Without this second shutter, the telescope and beams must be aimed at a larger (0.5 meter diameter) dump mounted on the interior of the dome while aligning the BTO.

- Two or more lens assemblies re-image the laser output plane onto the final surface before the laser beams are launched to the sky. These relays prevent diffractive effects, which could introduce nonuniformities in the profile of the outgoing beams. Under control by the MCAO CS, these assemblies may optionally act as a zoom lens to optimize the laser beam diameter on the LLT primary mirror with respect to the current seeing conditions.

- Circular polarization is maintained at the end of the BTO/LLT subsystems by means of a rotating quarter wave plate located near the Laser System output. This maximizes the photon return from the sodium layer.

- Average laser beam power, and also near- and far-field beam parameters, are monitored before the laser beacons are launched to the sky. Those measurements are either inputs to the active control loops or are used as on-line diagnostics. All measurements will be displayed by the MCAO CS.

- De-rotation optics prevent the beacon constellation from rotating on the sky while the telescope is tracking, to maintain the beacon constellation fixed in the LGS WFS focal plane. The orientation of these optics determines the influence matrix between tip/tilt adjustments at the M2 array and the motion of the guide stars on the sky.

- A beam splitter and corner cube combination located in front of the BTO diagnostics enables the use of light from a natural star as a calibration source for the BTO optical axis and subsequently for the laser beam(s) alignment.

Once the beam has been propagated to the top-end of the telescope, the Laser Launch Telescope will resize the beam for propagation to the sky. The LLT, located behind the Gemini telescope secondary mirror, must not obscure the secondary central hole when the MCAO system is not used. To this effect, the LLT primary mirror deploys and retracts over the secondary central hole each time the MCAO system is used. The motion of the LLT primary mirror is controlled by the MCAO CS. This is the only active feature of the LLT , since no focus adjustment on the sky is needed.

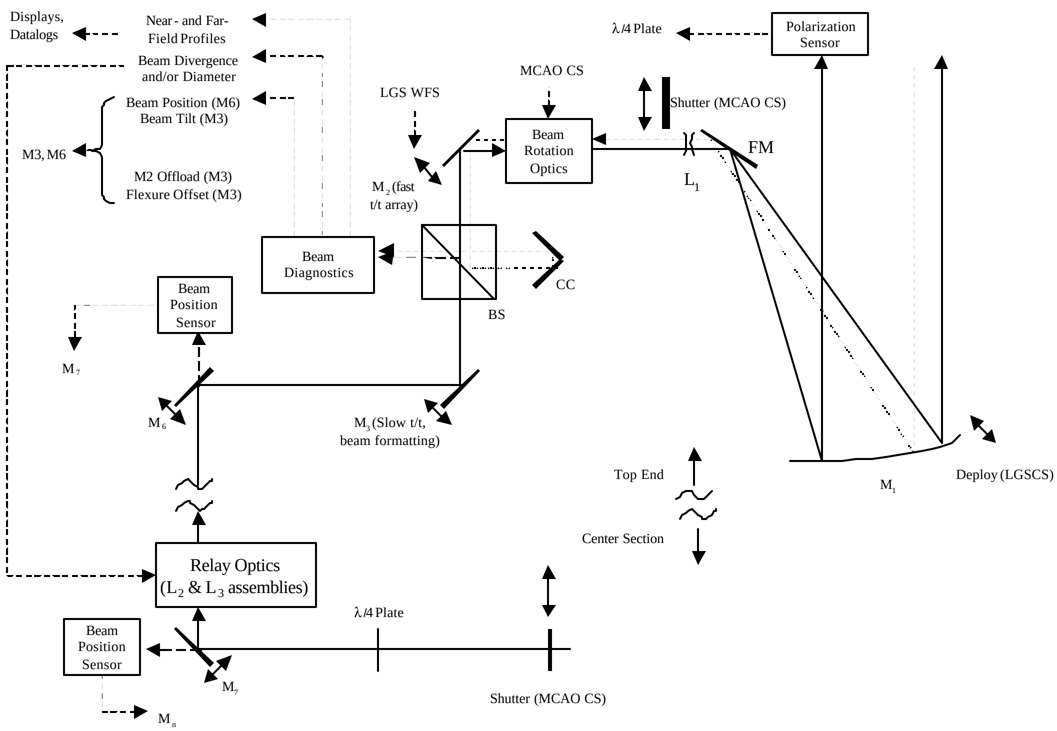

Figure 1: Beam Transfer Optics (BTO) Schematic. See Section 2.2 for a Discussion.

2.3. *Adaptive Optics Module (AOM)*

2.3.1. Components and Functions

Fig. 2 is a schematic/cartoon of the adaptive optics module, which includes all of the mirrors, sensors, and diagnostics needed to compensate the science beam and deliver it to the science instrument. These components include those usually thought of as the principal elements of the real-time MCAO control loop, namely 3 deformable mirrors, a tip/tilt mirror, 5 higher-order LGS wave front sensors, and 3 tip/tilt NGS wave front sensors. The other components illustrated in Fig. 2 are necessary to initially calibrate and control the drift of these basic elements, including:

- The On-Instrument Wave Front Sensor (OIWFS) used to measure and compensate for tip/tilt/focus errors between the AOM and the science instrument, both for calibration and in real time. The Gemini High Resolution Wave Front Sensor (HRWFS) can also be used for calibration of higher-order non-common path aberrations while viewing a bright star or a simulated guide star. The HRWFS does not calibrate for optical aberrations in the instrument proper, and the feasibility of calibrating for these errors beyond focus is not yet clear. The HRWFS is also limited to on-axis wave front measurements. Neither of these sensors is included in the MCAO system, and their measurements will be provided to the MCAO system via either reflective memory or the TCS.
- Reference sources to illuminate the LGS wave front sensors with known plane wave fronts to calibrate for imperfections in lenslet arrays. If these sources are adjustable in translation they may be used to measure the tilt transfer function of each WFS for an ideal point source, which in turn can be used to focus the Hartmann spots on the WFS detector array. The illumination level and translation adjustments for these sources are controlled by the MCAO-CS, as are the associated flip mirrors and/or beamsplitters.
- Simulated natural- and laser guide stars located at the intermediate image plane near the entrance of the AOM. These simulated guide stars are used for (i) daytime verification of optical alignment between the OIWFS and the AOM, (ii) measurement of DM influence functions and DM-to-WFS alignment, (iii) daytime tests of the MCAO control loop. Note that both visible and IR NGS sources will be necessary for (i) and (iii). The deployment and illumination level for these sources is controlled by the MCAO-CS. The simulated LGS and the NGS sources should be usable simultaneously to perform operations with the LGS wave front sensor while measuring performance at the science instrument. The LGS sources must be matched to the narrow spectral passband of the LGS WFS. The NGS sources should be white light sources (pinholes or monomode fibers) and must be unresolved at 1 micron (e.g. 8 microns diameter sources).
- Retractable and adjustable atmospheric dispersion correctors (ADC's) in the science path and the NGS wave front sensing path. These are controlled by the MCAO-CS.
- An optional higher-order NGS WFS with the capability to patrol at least a significant fraction of the AO field. This sensor is intended for diagnostic measurements using the simulated guide stars and bright natural guide stars, not for closing a real-time control loop. These diagnostics include (i) measuring wave front quality at off-axis field points, and (ii) validation of algorithms for determining the biases and gain variations in the LGS wave front sensors that are induced by fluctuations of the sodium layer. Item (ii) is part of commissioning for the MCAO system as described further below.

Various alignment degrees-of-freedom are required for each WFS in the MCAO system. Each tip/tilt NGS WFS must patrol a significant fraction of the 1 arc minute radius field to acquire and track guide stars, with a range of 120 arc seconds and a relative accuracy of 1-3 milli arc seconds. A common scan mirror for all three probes may be the best approach to implementing line-of-sight dithers (see Section 4.2). The LGS wave front sensors require a common focus adjustment over a range from 90 to 200 km to account for variations in the distance to the sodium layer, as determined by the distribution of the layer and the telescope zenith angle. The line-of-sight of the 5 LGS wave front sensors need not be adjustable, since the nominal laser guide star constellation is fixed with respect to WFS coordinates. The final tilt mirror array in the beam transfer optics will maintain the pointing of the laser guide star pattern to account for flexure between the AOM and the LLT, and also turbulence-induced jitter for each of the 5 upward LGS propagation paths. Finally, the optional higher-order NGS WFS would require both line-of-sight and pupil adjustments in order to patrol the field.

Certain additional alignment degrees-of-freedom may or may not be required, depending upon the passive alignment stability of the AOM. These may include the alignment between the WFS lenslet arrays and detectors (translation and focus), and the pupil imaging between the lenslet arrays and the deformable mirror conjugate to h=0. These degrees of freedom should require only very occasional adjustment at most. For the LGS WFS, static tip/tilt alignment may require a separate set of adjustments for each simulated guide star source.

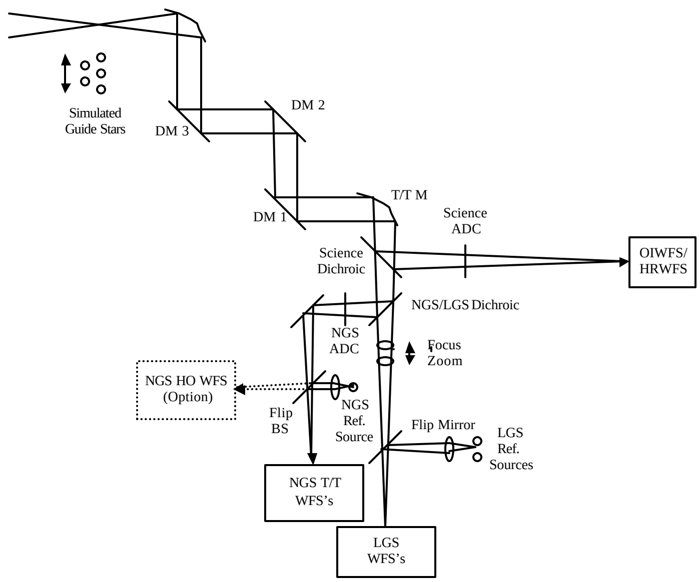

Figure 2: **Adaptive Optics Instrument (AOM) Schematic. See Section 2.3 for a discussion.**

2.3.2. Real-Time Control Loops

Fig. 3 is a block diagram of the real-time adaptive optics and alignment control loops that will be active during science observations. This is intended as a conceptual block diagram, not as a signal processing implementation (focus and tip/tilt measurements, for example, are not directly output from the LGS WFS). The primary function of the MCAO system is atmospheric turbulence compensation, which is accomplished via adjusting the figure and tilt of the tip/tilt and deformable mirrors on the basis of LGS and NGS WFS measurements. The remaining calibration and offloading functions illustrated in Fig. 2 are analogous to those found in Altair, with some extensions necessary because of the multiple wave front sensors and deformable mirrors:

- The focus measurements from the LGS WFS are unreliable at low temporal frequencies because of (i) flexure between the science instrument and the AOM and (ii) random fluctuations in the mean range to the sodium layer. The OIWFS is not subject to these error sources. Focus measurements from the OIWFS and the LGS WFS are "blended" in a low pass/high pass fashion before the tomographic wave front reconstruction algorithm.
- The DC component of the LGS WFS focus measurement is nulled by adjusting the focus of the LGS WFS.
- The average tip/tilt measurement from the NGS WFS's is unreliable at low temporal frequencies because of flexure. The tip/tilt from the OIWFS and the average tip/tilt from the NGS WFS's are also blended before the tomographic wave front reconstruction algorithm.
- The DC components of the differential NGS tip/tilt measurements are unreliable due to uncertainty in the exact separations between the guide stars. Differential tip/tilt measurements are high pass filtered before the tomographic wave front reconstruction algorithm. (Without this filtering, the figures of the DM's would be adjusted to yield apparent guide star separations equal to the *a priori* estimate of the separations, which could alter the plate scale at the science instrument.)
- The DC component of the NGS tip/tilt measurements are nulled by adjusting the locations of the NGS guide probes.
- Tip/tilt commands are offloaded from the tip/tilt mirror (TTM) to the secondary mirror (M2). This reduces the mis-registration between the DM and each wave front sensor which is induced by adjustments to the TTM.
- Focus and possibly other low-order modes are offloaded from DM 1 to the telescope control system. The bandwidth of this offload is very low, since the purpose is to correct residual telescope misalignments and mirror figure errors.
- DM actuator commands are fed back to null DC piston, tip/tilt, and waffle on each mirror. The DC components of three combinations of quadratic modes are likewise nulled. Buildup of these modes would introduce plate scale distortions, which cannot be detected by the tip/tilt NGS WFS's without precise *a priori* knowledge of the separations between the guide stars. The required tolerance on nulling the DC component of these modes is about 25 nanometers peak-to-valley for 10 parts per million change in plate scale. (The modes must still be corrected at bandwidths above about 0.1 Hz to compensate for tilt anisoplanatism).
- Tilt measurements from the LGS WFS are input to the beam transfer optics tip/tilt loop to keep the guide stars centered in the WFS field-of-view (Strictly speaking, the tilt command sent to mirror array M_2 in the beam transfer optics should also anticipate telescope tip/tilt errors which will be corrected by the TTM, but the magnitude of these errors (0.01—0.03 arc seconds RMS) are small enough to be negligible relative to the linear dynamic range of the LGS WFS).
- Finally, the MCAO-CS drives atmospheric dispersion correctors in the science and NGS wave front sensing paths as a function of telescope azimuth and elevation (not shown).

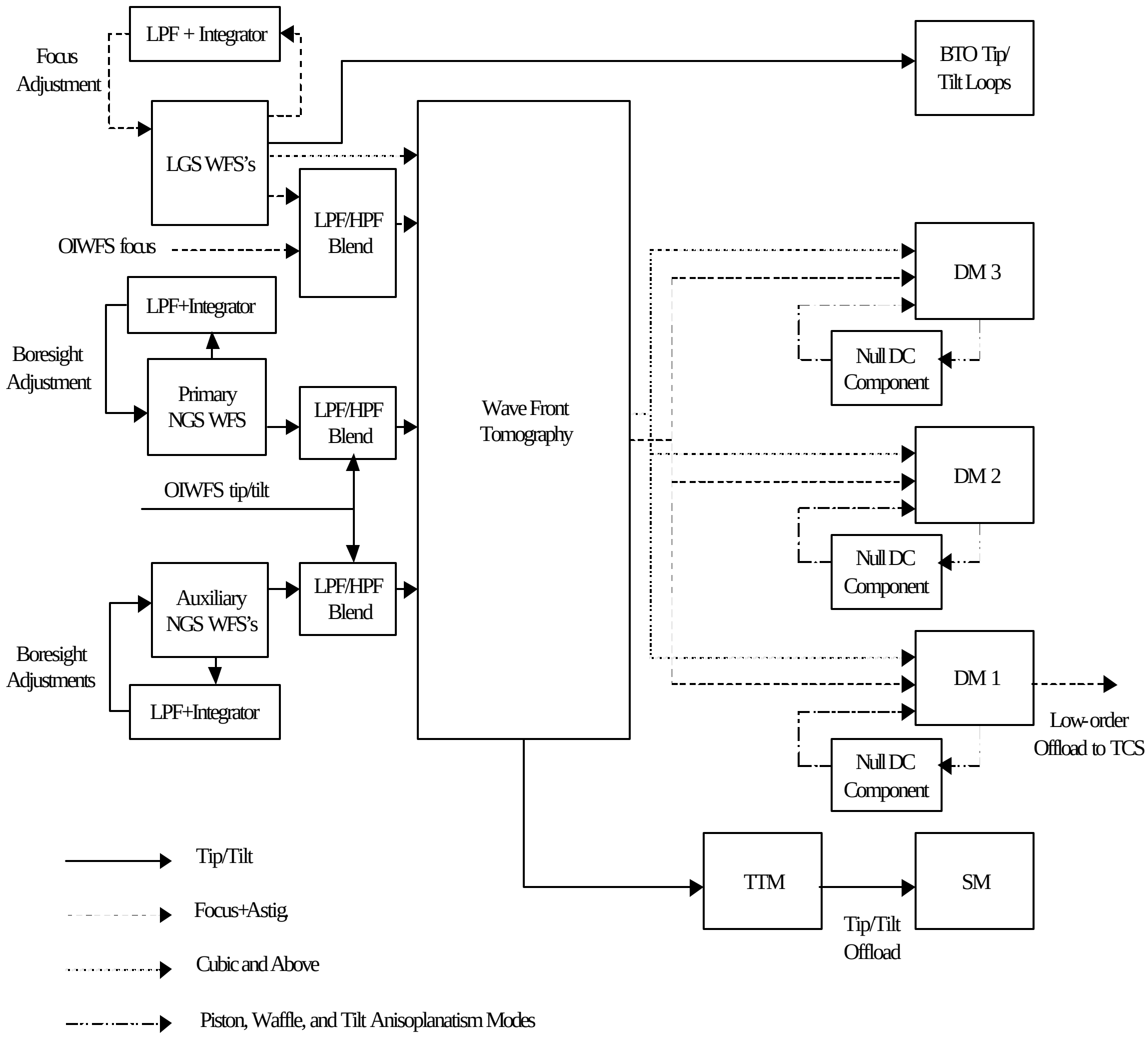

Figure 3: MCAO Control Function Schematic.

2.4. MCAO Control System (MCAO-CS)

The MCAO Control System controls the alignment, operation, and diagnostics of the MCAO system. It will be responsible of the control of the LS, the BTO, the LLT, the SALSA, and the AOM. This control system will interface these subsystems with the Telescope Control System (TCS) and Observatory Control System (OCS). It will exist alongside a number of other control systems.

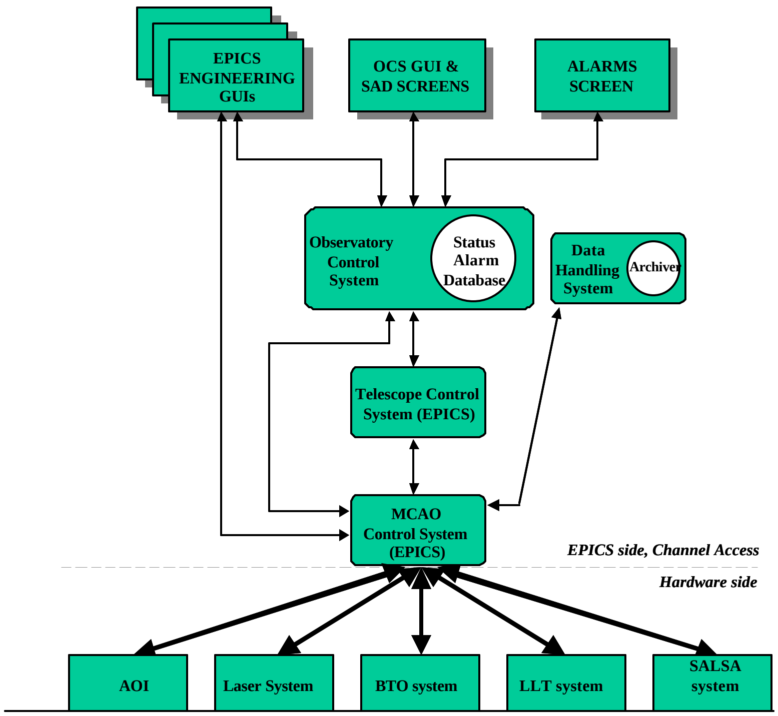

Figure 4: Relative position of the MCAO CS in the Gemini Observatory

Due to its high level complexity in terms of real time performance and number of hardware interfaces to control, the MCAO CS will be split between at least two EPICS/ VxWorks based VME crates:

- One dedicated for the control of the LS, the BTO, the LLT and the SALSA subsystems ; and
- One dedicated for the AOM. The two main real time features handled by for AOM will be:
  - The NGS control (i.e., computing the contribution to DM and TTM commands from NGS tip/tilt measurements). This will be implemented on standard CPUs.
  - The LGS control, which will require a lot of CPU power (4Gflops), and will be implemented on specialized CPU boards (based on DSP or PowerPC processors).

A block diagram of the NGS and LGS controls is given in the following Fig. 5. The NGS control will consist on two main tasks: the real-time process itself and the optimization process.

- The real time process: in closed loop, the tip/tilt measurements from the 3 NGS are computed and used as input signals to compute the control of the TTM. It corresponds to a simple 6 by 2 matrix multiplication (1). A temporal filter is applied to the output vector and the resulting commands are sent to the TTM (2). These tip/tilt measurements are also used to compute the tip/tilt anisoplatism modes for the DMs (3). This is also done through a simple matrix multiplication and the output actuator commands are then summed into the LGS loop.

- The optimization process (4): From real time measurements (slopes and actuator controls), the signal to noise ratio and the temporal behavior of the tip/tilt and tip/tilt anisoplanatism modes is determined. Optimized gains for these modes and then a new optimized control matrix needed by the real time process (1) are recomputed. The modal basis itself will vary between observations, depending upon the distribution and brightness of the three NGS. This optimization process is run in real time but at a slower rate than the TTM closed loop process.

The LGS control will consist also on two main tasks: the real time process itself and the optimization process:

- The real time process: in closed loop, the slope measurements from the 5 LGS are computed (using dedicated bias and gain compensation algorithms). These slope measurements are then used as input signals to compute the control of the 3 DMs. This is done through a simple matrix multiplication (5). The output vector is added to the NGS one (3) and sent through a temporal filter to the DMs (6).
- The matrix determination: the control matrix needed by the previous process (5) will be recomputed as a function of telescope elevation, and fed into the LGS closed loop (7). This computation is necessary because the DM-to-WFS influence matrix varies with the range of the LGS, which will vary with elevation angle.

Safety systems external to the laser subsystem, such as those controlling beam propagation to the LLT and the sky, will be controlled by a set of interlocks via the Gemini Interlock System (GIS). These interlocks will be active whenever the LGS-CS is on.

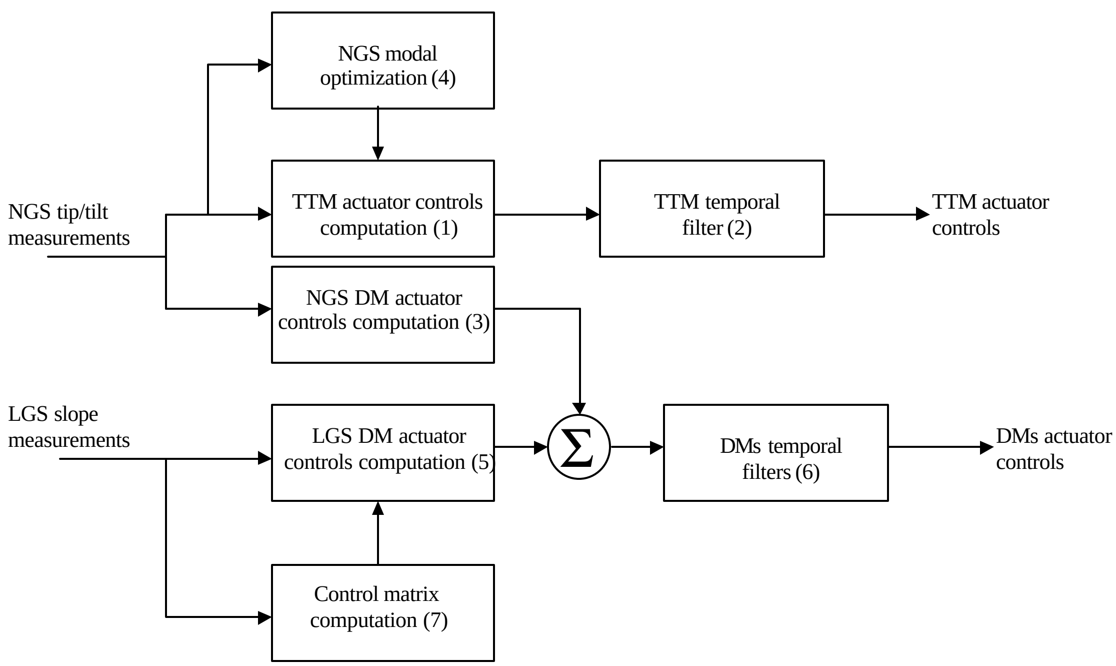

Figure 5: Real-time wave front control block diagram

2.5. Safe Aircraft Localization and Satellite Acquisition system (SALSA)

This is a somewhat simplified version of the same system to be used with the Altair LGS AO system at Gemini-North, and presently encompasses all the subsystems that monitor the area of sky around the projected laser beam for aircraft. The main components of SALSA are the bore-sighted aircraft camera, the all-sky aircraft cameras, and any radar feeds from local air traffic control agencies. Whenever a potential conflict arises in one of these systems, SALSA will send a halt command to the MCAO-Control System. The MCAO-CS should then attempt a Level-1 Halt procedure (see section 5.1). No user intervention should be required; whenever the laser system is propagated, the SALSA system is active. A display of the currently monitored fields, any object detected, and any object classified as aircraft and its time to intercept will be displayed to the observer in the control room.

There will be an equivalent of the Mauna Kea Laser Traffic Control System at Cerro Pachon. Any laser propagated into the sky must be coordinated with other telescopes on Cerro Pachon and possibly Cerro Tololo. The system must prevent any propagated laser beam from crossing the line-of-sight of another telescope that is observing at 589nm. Most likely this coordination will only be necessary for telescopes on Pachon but this is to be confirmed.

At this time it is not clear which agencies must be notified to avoid illuminating satellites. For several existing LGS AO systems, satellite predictive avoidance for unwaived lasers is managed by the laser clearing house at USAF Space Command. The times, locations, and targets for proposed propagations must be submitted several days in advance, and how this procedure might be modified to support queue-based observing is not clear.

3. Calibration and Startup

3.1. Daytime AOM Calibrations

The frequency of these calibrations varies. Tentative frequencies are indicated for each calibration. We have sorted the calibrations in three categories: daily, periodic maintenance that can be carried out without opening the AOM, and major maintenance, which can take place once a year or so and could necessitate opening the AOM. As a goal, all daily calibrations will be automated and carried out by a single calibration command. These calibrations should not take more than 30 minutes.

3.1.1. Daily Calibrations

- Measure the bias and read noise levels in each WFS CCD.
- Insert the reference source flip mirrors and beamsplitters, turn on the reference sources, and center them in the fields-of-view of the higher-order wave front sensors. Measure and store the reference gradients sensed by each WFS for a known flat wave front at the WFS. Measure WFS gains and tilt transfer functions by scanning the reference sources.
- Set each DM figure using previously calibrated actuator commands (These commands do not necessarily flatten the mirrors, but should produce a corrected wave front at the science instrument). Center the TTM. Insert the simulated guide star sources. Adjust the TTM and focus on DM 1 to null the tip/tilt/focus measurements from the OIWFS. Measure on-axis wave quality using the HRWFS, and wave front quality across the field using the (optional) diagnostic HO WFS.
- Acquire and center the simulated guide stars on the LGS wave front sensors. Measure and store the gradients sensed by each LGS WFS for the calibrated DM actuator commands.
- Close the tip/tilt and higher-order AO control loops to verify stability.

3.1.2. Periodic Maintenance

- Adjust the deformable mirror calibration as required if the wave front measurements in step 3 of daily maintenance are out of tolerance. This requires a tomographic wave front reconstuction algorithm.

- Measure WFS-to-DM alignment using the waffle poke test.
- Measure the DM-to-WFS and TTM-to-WFS interaction matrices and compute a reconstruction matrix.

3.1.3. Major Maintenance

- Adjust alignment between the lenslet arrays and WFS detectors if measured tip/tilt gains and transfer functions measurements in step 2 of daily maintenance are out of tolerance.
- Adjust WFS-to-DM alignment if the results of the waffle poke test in item 2 of periodic maintenance are out of tolerance.

3.2. Laser Startup

The startup procedure for the Laser System is dependent upon the type of laser to be used, however the operation of the LS components should be transparent to the end user. Whatever the Laser System, functions such as power optimization, wavelength control, and thermal control including the cooling systems, will be automated. Although Laser System start-up will be implemented by the MCAO CS as a single action, each individual step of the sequence will also be accessible via the Laser System Control System for debugging and engineering purposes.

3.3. Nighttime Calibration

The primary purpose of the nighttime calibration sequence is to establish a common boresight reference between the Beam Transfer Optics and the OIWFS. This is necessary because deployment of the LLT primary mirror will not be entirely repeatable. AO loop performance may also be characterized on a known reference field if desired. This operation should not take more than 5 minutes once the telescope is on the object. The sequence starts with all laser shutters closed and the LLT primary mirror retracted.

1. Deploy the LLT primary mirror.
2. Slew the telescope to aim at the beam dump mounted on the dome.
3. Open the laser shutter at the LS/BTO interface. Close each beam pointing and centering loop through the BTO in sequence. Verify beam pointing, centering, quality, power, and polarization at the beam diagnostic sensor, and also the orientation of the LGS constellation. Open the pointing and centering loops, and close the laser shutter at the LS/BTO interface.
4. Slew the telescope to a reference star. The PWFS sources are acquired and the telescope's tracking and active optics are enabled. The SALSA and internal laser safety systems are operating.
5. Deploy the AO fold and science fold mirrors, and command the deformable mirrors to their nominal figures.
6. Acquire the reference star with the OIWFS and track using the TTM and M2.
7. Because of the corner cube in Fig. 1, the reference star is now imaged or sensed by the BTO beam diagnostic sensor. The time-averaged far-field image location becomes the boresight reference for the diagnostic sensor, accounting for flexure of the top end and the variability in LLT deployment.
8. Open the laser shutter at the LS/BTO interface. Close each beam centering and pointing loop through the BTO in sequence, using the references obtained in step seven above for the M3/M6 loop. Verify beam pointing, centering, quality, power, and polarization at the beam diagnostic sensor, and also the orientation of the LGS constellation.
9. Zoom the LGS WFS to focus at the nominal range for the current elevation angle, and verify that signal is detected from each guide star on the LGS WFS.
10. If desired, proceed to steps 4—5 and 9—12 of the science operation sequence in section 4.1 to characterize the performance of the AO loop on a known reference field. Otherwise, shutter the laser, open the OIWFS track loop, and proceed to the first observation.

4. Science Operations

4.1. Target Acquisition and Closing the Loop

These operations should take a maximum of 2 minutes.

1. Slew the telescope to the science field. The PWFS sources are acquired and the telescope's tracking and active optics are enabled. The laser is shuttered at the LS/BTO interface. The BTO pointing, centering, orientation, and polarization control elements are set to their nominal (calibrated) values for the current zenith angle. The SALSA and internal laser safety systems are operating.
2. Deploy the AO fold and science fold mirrors, and command the deformable mirrors to their nominal figures (if not already there).
3. Acquire the primary tip/tilt NGS with the OIWFS and track using the TTM and M2.
4. Deploy the tip/tilt NGS wave front sensors in the AOM to acquire the primary and auxiliary tip/tilt guide stars.
5. Close the NGS WFS alignment loops to center the guide stars on each sensor. This compensates for flexure and any uncertainty in the positions of the auxiliary guide stars. This will require several seconds to one minute to average out turbulence effects.
6. Zoom the LGS WFS to focus at the nominal range of the sodium layer for this elevation angle.
7. Open the laser shutter at the BTO/LS interface. Close each beam pointing and centering loop through the BTO in sequence. Verify beam pointing, centering, quality, power, and polarization at the beam diagnostic sensor, and also the orientation of the LGS constellation. Verify that signal is detected on the LGS WFS.
8. Close the high bandwidth BTO tip/tilt loops to center the LGS spots on the LGS WFS. Close the LGS WFS focus loop to focus the sensor at the measured range of the sodium layer.
9. Close the TTM and DM control loops using the MCAO wave front sensors. Whether this is done in one or several stages will be determined during commissioning.
10. Perform the science instrument integration.
11. Open the DM control loops and return to tracking using only the OIWFS. Open the BTO control loops, and shutter the laser at the LS/BTO interface. Open the OIWFS track loop and proceed to the next observation.

If present, the optional shutter at the BTO/LLT interface would be used instead of the shutter at the LS/BTO interface. In this case there would be no requirement to open and close the BTO control loops between science fields.

4.2. Dithering and Chopping

Nodding and dithering observations must be supported by the MCAO system. Chopping will not be supported. The definitions of these operations are as follows:

(a) "Nodding" and "Dithering" involve adjustments to telescope pointing on a timescale of a few seconds to a few minutes. Nodding is typically used to obtain a reference background and/or flat field information away from the field of interest. A typical nod is 10 to 100 arcseconds. Dithering is typically used as a method to suppress effects of bad pixels. A typical dither is a few arcseconds.

(b) "Chopping" is a technique historically used at mid-IR wavelengths to suppress sky background noise. The Gemini implementation is to tilt the secondary at frequencies in the range of 3-10 Hz so that the detector samples two patches of sky.

The locations of the laser guide stars must remain fixed in the frame of the LGS WFS for both Dithering and Nodding, since the LGS wave front sensors have a fixed bore-sight and do not patrol the field as in Altair. The relative locations of the natural- and laser guide stars are therefore different at the two ends of the dither, and two different reconstruction matrices will be required. The DM control loops must be frozen between the two ends of the dither, but the tip/tilt loop should remain closed on the OIWFS.

During a bore-sighted Dither or Nod, the TCS offsets the telescope and commands the OIWFS and MCAO TT NGS WFS to maintain a fixed RA-Dec pointing. The LGS propagation directions and the bore-sight of the LGS WFS follow the dither of the main telescope. The LGS beam pointing loops remain closed during the dither.

5. Shutdown Procedures

5.1. Aircraft and Safety Halts

1. Aircraft approaching beam: Under normal operating conditions, the MCAO-CS will first freeze the higher-order AO and BTO control loops, and then shutter the laser at the LS/BTO interface after it receives an “acknowledge” signal or a specified interval has passed. This is a critical task and the specified time will be short, perhaps 0.01 to 0.1 seconds.
2. Clouds approaching beam: Laser propagation must be halted as above for clouds sufficiently dense to interfere with aircraft detection. Possible cloud sensors include the full-sky camera and the telescope operator.
3. Loss of signal at the LGS WFS: The AO control algorithm must monitor the signal level at the LGS WFS to detect large pointing errors or other failures in the beam transfer optics. In this event, the MCAO-CS must freeze the higher-order AO and BTO control loops, and shutter the laser at the LS/BTO interface.
4. Loss of signal at a BTO sensor: Freeze the higher-order AO loop, shutter the laser at the LS/BTO interface, and center all BTO tip/tilt mirrors.
5. Safety alarm from LS diagnostics or telescope operator: Power down laser, shutter the laser at the LS/BTO interface, center all BTO tip/tilt mirrors, and freeze the higher-order AO loop. The last resort HALT command

An alarm must sound to inform the telescope operator in all of these cases. Predictive avoidance of satellites must be resolved as part of scheduling and not in real time. If the optional shutter at the BTO/LLT interface is included in the system, this shutter would be used for events 1—3 above, and there would be no need to freeze the BTO control loops.

5.2. Standby Mode

Due to weather and other reasons, there may be occasions when the use of the MCAO system is interrupted for up to several hours during the course of a night. To whatever extent is practical, the MCAO Laser System and AOM shall be placed in a standby mode to maximize the life of the LS and minimize the stray light and heat dissipated into the dome. The procedures to enter and exit standby mode will be implemented by the MCAO CS as single actions, and will be transparent to the end user. Each individual step of the sequences will also be accessible for debugging and engineering purposes.

5.3. Nightly Shutdown

The shutdown procedure for the Laser System is dependent upon the type of laser to be used, however the operation of the LS components should be transparent to the end user and the Laser System shutdown will be automated. Although the Laser System shutdown will be implemented by the MCAO CS as a single action, each individual step of the sequence will also be accessible via the Laser System Control System for debugging and engineering purposes.

6. Commissioning Procedures

Various functions of the MCAO system will require calibration and check-out in a commissioning phase at the Gemini-South telescope. These are primarily related to the adaptive optics instrument, since the SALSA safety system and most features of the BTO and LLT systems will have been implemented during commissioning of the Hokupa’a-85 LGS AO system. In roughly increasing order of complexity, the principal AOM system parameters and functions to be calibrated and tested include:

- Calibration of the DMs offsets and gains versus temperature.
- Calibration of the DM influence functions.

- Calibration of the end-to-end system loop transfer functions. These first three items are repetitions of tests that will first be performed during system integration.
- Calibration of uncommon path wave-front aberrations in the adaptive optics instrument package using the HRWFS, simulated guide star sources, and the optional higher-order NGS WFS illustrated in Fig. 2.
- Control of the NGS WFS path and science path atmospheric dispersion correctors based upon telescope pointing.
- Acquisition of guide stars in the fields-of-view of the MCAO NGS WFS's.
- Closed-loop control of the LLT fast steering mirror using tip/tilt measurements from the LGS WFS.
- Adjusting focus for the LGS WFS based upon telescope zenith angle.
- Testing algorithms for estimating the variations in LGS WFS gains and biases in real time. This step also requires the optional NGS WFS, but it may be redundant after experience with Altair.
- Testing algorithms for automatically optimizing AO control algorithm parameters, such as control loop bandwidth, in real time. New, untested algorithms may be necessary because the MCAO system employs multiple guide stars of different magnitudes.
- Testing algorithms for estimating point spread functions from time series of WFS measurements and DM actuator commands. Once again, new algorithms may be necessary due to the use of multiple guide stars and the desire to estimate residual variations in the PSF across an extended field-of-view.

Beyond those functions required for Hokupa'a-85, there are also several new features of the BTO system that are associated with the use of multiple laser guide stars. These are:

- Proper operation of the pointing and centering loops with multiple laser beams.
- Diagnostic beam quality measurements with multiple laser beams.
- Controlling the orientation of the LGS pattern on the sky.

MCAO Strehl Ratio Budget

The following table is patterned after the format found in the MK-LGS OCDD. Although all wave front errors are added in quadrature, the phase variances associated with atmospheric turbulence compensation under section 3.0 have been reverse-engineered to sum to values obtained by more detailed modeling. This budget should be considered preliminary. Quantities denoted TBR (to be reviewed) have been lifted direction from the MK-LGS OCDD and require further analysis for the Gemini-South MCAO system. The remaining AO contributions in section 3.0 are based upon worst-case performance at the corner of a square 68 arc second field, and will be updated to reflect mean performance over a square 1 arc minute field.

MCAO Field-Averaged Bright NGS Error Budget Spreadsheet			
Errors expressed in terms of RMS OPD in nanometers RMS errors added in quadrature. Strehl = exp[-(RMS phase)^2]	Zenith	30 degrees	45 degrees
1.0 Telescope Limitations	116.19	120.39	129.71
Strehl at 1.65 microns	0.82	0.81	0.78
Tip/Tilt Image Smear Effects	0.00	0.00	0.00
Servo Loop Performance Higher-Order Wave Front Errors			
Primary Mirror	60.00	65.00	75.00
Secondary Mirror	60.00	63.00	70.00
Alignment	20.00	20.00	20.00
Self-Induced Seeing	50.00	50.00	50.00
AO Fold Mirror	30.00	30.00	30.00
Science Fold Mirror	50.00	50.00	50.00
2.0 Instrument Limitations	123.56	123.56	123.56
Strehl at 1.65 microns	0.80	0.80	0.80
Tilt/Image Smear Effects			
Flexure relative to OIWFS	25.00	25.00	25.00
Higher-Order Image Quality Effects (TBR)	121.00	121.00	121.00
3.0 MCAO System	226.05	252.40	303.58
Strehl at 1.65 microns	0.48	0.40	0.26
Atmospheric Compensation			
Fitting Error	111.00	115.00	132.00
Anisoplanatism	138.00	169.00	219.00
LGS Noise and Servo Lag	94.00	105.00	126.00
NGS Noise and Servo Lag (Bright Stars)	10.00	10.00	10.00
Wind Shake (TBR)	34.00	34.00	34.00
Implementation Errors			
Non-Common Path Errors (TBR)	79.00	79.00	79.00
System Calibration Errors (TBR)	30.00	30.00	30.00
LGS Calibration Errors (TBR)	50.00	50.00	50.00
Total RMS OPD	282.60	305.73	352.49
Strehl Ratio at 0.85 microns	0.01	0.01	0.00
Strehl Ratio at 1.25 microns	0.13	0.09	0.04
Strehl Ratio at 1.65 microns	0.31	0.26	0.17
Strehl Ratio at 2.20 microns	0.52	0.47	0.36