GEMINI
OBSERVATORY

MCAO Operational Concepts Definition Document

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Revision Control

03-22-01 BRENT

Removed references to Hokupa'a South throughout

Included comment on pulsed vs. CW laser issues.

Specified SALSA / laser shutter interface as using the GIS

Revised BTO description and figure 1 extensively

- New layout for pointing and centering mirrors
- Beam dump on telescope top end ring included in baseline
- Relay optics no longer have zoom capability
- LLT is fixed, not deployable
- Included LLT dust cover and BTO pre-alignment cameras
- Mentioned periscope optics

Revised AOM description and figure 2

- Included Diagnostic WFS
- Included more detail on source simulator requirements
- Removed NGS WFS reference source
- Made LGS WFS reference sources optional

Revised control loop block diagram

- Use of OIWFS for tip/tilt/focus adjustments
- Partitioned NGS/LGS control algorithm

Revised SALSA description

- Clarified that SALSA / laser shutter interface is through the GIS

Revised daytime calibration description

- Use of the diagnostic WFS
- LGS WFS reference sources listed as an option

Revised nighttime calibration description

- Control and use of BTO pointing and centering mirrors
- No LLT deployment
- No beam dump on the dome

Revised science operations description

- Included preparatory guide star observations
- Removed possible use of BTO beam dump shutter

Dithering and Nodding

- DM and tip/tilt loops to remain closed during small dithers, and frozen during large nods

Shutdown procedures

- Clarified that laser shutter is commanded via the GIS
- Removed telescope operator as a potential cloud sensor
- Eliminated potential use of beam dump shutter
- Speculated on satellite predictive avoidance

Described procedures for startup after shutdown

Included BTO commissioning tasks previously performed by Hokupa'a 85-South LGS

Clarified terminology in Strehl error budget (numbers still need to be updated)

04-04-01 BRENT

Updated Strehl error budget to be consistent with CoDR FPRD (still need new numbers for AOM error budgeting and new simulation results)

04-24-01 BRENT

Incorporated various clarifications as recommended by Richard Myers

04-27-01 BRENT

Included revised Strehl ratio budget.

Included revised BTO schematic.

04-30-01 Corinne

Revised MCAO CS description

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 obtained 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 that 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 version of the Altair (Mauna Kea) AO system. 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 LGS AO system, 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 a science integration as the telescope moves 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.
- Technology permitting, it would also be preferable to use a pulsed laser with a pulse repetition frequency (PRF) equal to the LGS wave front sensor (WFS) sampling rate. The latency in the AO control loop could be reduced by timing the laser pulse to return at the end of each WFS exposure. More importantly, WFS background noise due to Rayleigh backscatter could be eliminated or greatly reduced by range gating.
- 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 checks) or are integrated into the Gemini Interlock System (safety shutter open/close when the SALSA system is active). 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 will be five laser beams, one per laser guide star, traveling along the telescope structure. 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. Two arrays of 5 mirrors (the fast steering array and fixed mirror array in Fig. 1) reformat the 5 beams into an “x” shaped pattern for propagation into the sky.

Multiple pointing and centering mirrors actively maintain the beams alignment within the beam transfer optics and the location of the laser guide stars on the sky. The principal disturbances to be compensated by these mirrors include (i) displacement and modest tilting of the telescope top end at nonzero zenith angles and (ii) higher frequency errors due to atmospheric turbulence and telescope windshake. The pointing and centering arrays located on the telescope center section correct for disturbance number (i) to keep the laser beams properly aligned with respect to the telescope top end. The optical axis of the LLT will tilt along with the remainder of the top end, and an additional pair of pointing and centering mirrors located before the LLT entrance pupil is used to compensate by steering the beams and thereby maintain a fixed laser guide star pointing direction on the sky. Disturbance (ii) is compensated using the high bandwidth tip/tilt mirrors of the fast steering array.

All of these mirrors are controlled by the MCAO CS. The pointing and centering arrays are controlled at a modest control bandwidth using feedback from the near- and far-field diagnostic sensors located on the beam transfer optics optical bench attached to the LLT. The final pair of pointing and centering mirrors is driven from a lookup table as a function of the telescope pointing angle. The fast steering array is controlled at high bandwidth using feedback from the LGS wave front sensors in the adaptive optics module (AOM). The separate fast tip/tilt mirrors for each guide star enable the correction of differential beam jitter induced by tilt anisoplanatism. The fast tip/tilt mirrors are offloaded to the pointing and centering mirrors on the top end if they reach the limit of their dynamic range.

Also part of the BTO:

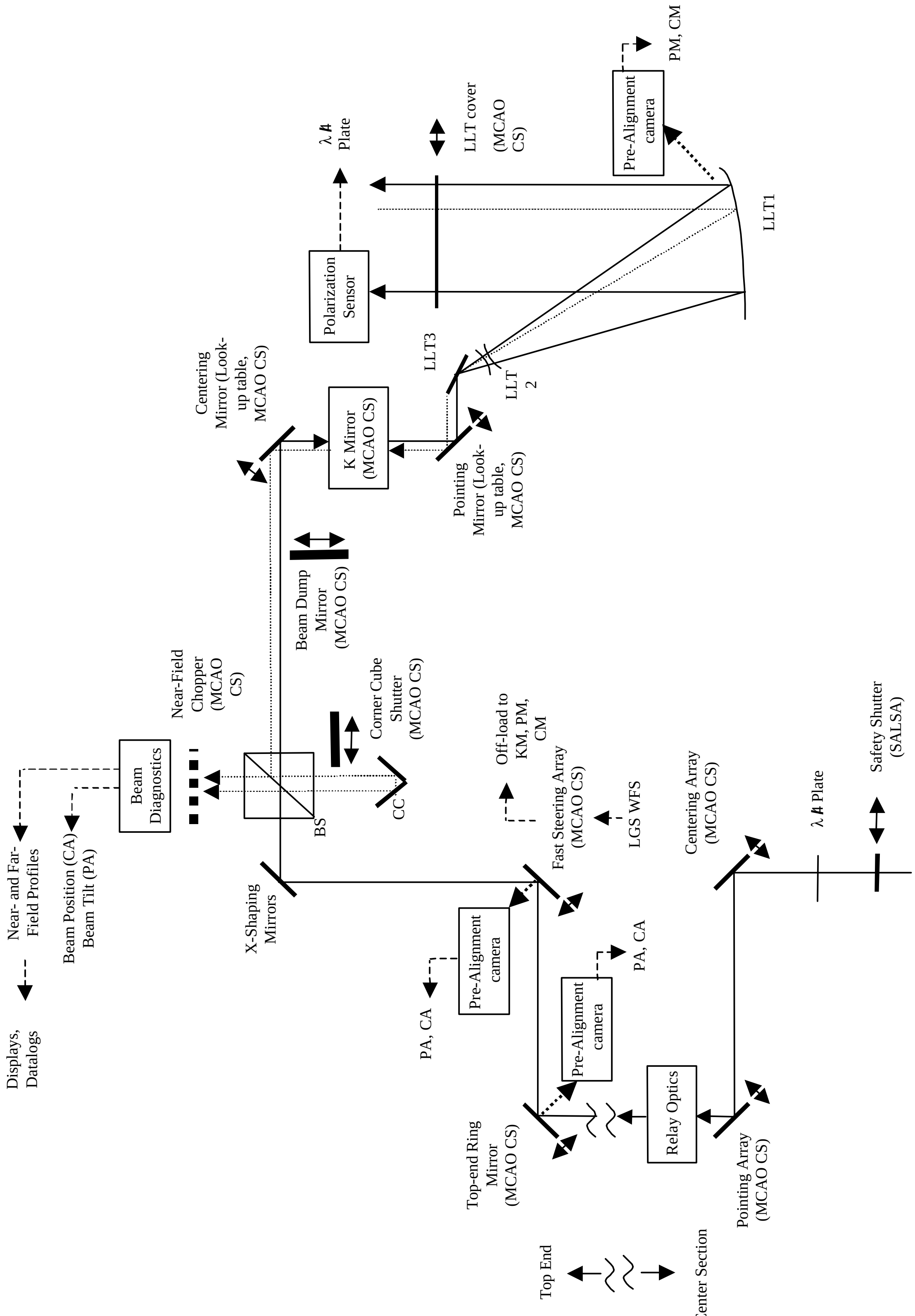
- A laser shutter is located at the LS/BTO interface. A second shutter located at the BTO/LLT interface (actually a flip mirror to divert the beam to a cooled dump on the telescope top ring) makes it possible to propagate the laser beams to the top of the telescope for LS and BTO calibrations without launching the beams to the sky.

- 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.
- One or more relay lenses re-image the laser output plane onto the laser launch telescope primary mirror. These relays prevent diffractive effects, which could introduce non-uniformities in the profile of the outgoing beams.
- Average laser beam power, and also near- and far-field beam parameters, are monitored by diagnostic sensors before the laser beacons are launched to the sky. These measurements are used as inputs to the active control loops and are available as on-line diagnostics. All measurements are displayed by the MCAO CS.
- A beam splitter and corner cube combination located in front of these BTO diagnostics enables the use of light from a natural star as a calibration source for the BTO/LLT optical axis and subsequently for alignment of the laser beams.
- A K-mirror prevents the beacon constellation from rotating on the sky while the telescope is tracking, to maintain a fixed beacon constellation in the LGS WFS focal plane. Note that the orientation of the K-mirror determines the influence matrix between tip/tilt adjustments at the fast steering array and the motion of the guide stars on the sky.
- Pre-alignment video cameras view the scattered light from the beams on several mirror surfaces to simplify initial acquisition of the beams by the BTO diagnostic sensors.

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 optics are protected while not in use by a deployable cover.

The LLT, located behind the Gemini telescope secondary mirror, must not obscure the light path through the secondary central hole. A deployable LLT has been rejected as being too difficult to implement. Instead, a “periscope’’ (not illustrated) consisting of two powered mirrors is located behind the LLT primary mirror, and is used to divert the light path through the hole around the LLT with no significant increase in emissivity. This allows long-wave IR instruments to be used with the LLT still in place.

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



2.3. *Adaptive Optics Module (AOM)*

2.3.1. Components and Functions

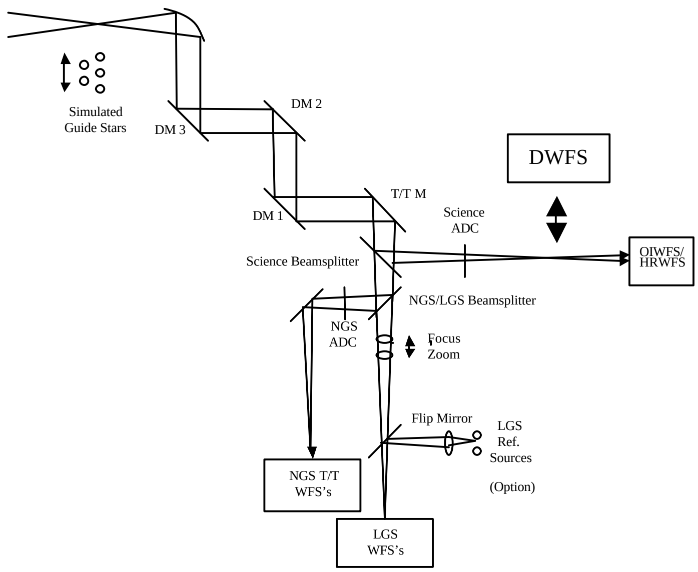
Fig. 2 is a schematic/cartoon of the adaptive optics module, which includes all of the mirrors, sensors, and diagnostics needed to compensate the science beam and deliver it to the science instrument. These components include those usually thought of as the principal elements of the real-time MCAO control loop, namely 3 deformable mirrors, a tip/tilt mirror, 5 higher-order LGS wave front sensors, and 3 tip/tilt NGS wave front sensors. Most of the remaining 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 OIWFS may be substituted for one of the three NGS tip/tilt WFS for some observations. This sensor is not part of the MCAO system, and its measurements will be provided to the MCAO system via either reflective memory or the TCS.
- Simulated natural- and laser guide stars located at the telescope 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, DM-to-WFS alignment, and non-common path wave front errors, and (iii) daytime tests of the MCAO control loop. 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. They must subtend approximately 1 arc second each, and be adjustable over a range corresponding to 90-200 km on the sky. Two different types of NGS sources are required. This first set will be used with the NGS tip/tilt sensors, and must subtend approximately 0.3 arc seconds and have a spectral passband of 0.40 to 0.80 microns. The second set will be used with the diagnostic wave front sensor (see below) and with science instruments. These must be unresolved point sources at a wavelength of 1 micron and must have a spectral passband of 0.85 to 2.2 microns. The NGS and LGS sources are deployed in and out the beampath as two complete sets, but do not need to be individually adjustable in translation.
- A diagnostic WFS (DWFS) located in the science path with the capability to patrol the AO field. This sensor is used for diagnostic measurements using the second class of simulated NGS, not for closing a real-time control loop. These diagnostics include (i) measuring science path wave front quality, and (ii) measuring DM actuator influence functions (including any variations due to temperature and flexure-induced misalignments) and determining nominal actuator commands to minimize the science path wave front errors.
- Atmospheric dispersion correctors (ADC's) in the science path and the NGS wave front sensing path. These are controlled by the MCAO-CS.

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 beam transfer optics will control the pointing of the laser guide star pattern to account for flexure between the AOM and the LLT, and also correct for turbulence-induced jitter along each of the 5 upward LGS propagation paths. Finally, the diagnostic WFS will require line-of-sight adjustments 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 LGS 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. If these degrees of freedom are necessary, they would be controlled using WFS measurements from reference sources located immediately before the LGS WFS.

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 (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) trends and random fluctuations in the mean range to the sodium layer. The OIWFS is not subject to these error sources, and a long-term bias in the OIWFS focus measurement indicates that the LGS focusing optics must be adjusted to bring the two sensors into agreement. The OIWFS focus measurement is therefore used as the error signal for a low bandwidth control loop that controls the position of the LGS focusing optics.
- Similarly, the average tip/tilt measurement from the three NGS WFS's is unreliable at low temporal frequencies because of flexure. The OIWFS tip/tilt measurement is used as the error signal for a low bandwidth control loop that adjusts the aimpoint for the MCAO tip/tilt control loop. For small tip/tilt biases, this adjustment may be implemented in the control law. For larger errors it may be necessary to actually adjust the positions of the NGS WFS's.
- Tip/tilt commands are offloaded from the tip/tilt mirror (TTM) to the telescope secondary mirror (M2). This reduces the mis-registration between the DM and each wave front sensor that is induced by adjustments to the TTM.

- Focus and possibly other low-order modes are offloaded from the DM's to the telescope control system for correction via M2 and the telescope primary mirror (M1). 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, waffle, and other uncontrolled modes on each mirror. This process may not be necessary if the temporal filter for the AO control loop is not a type I servo (i.e., does not have infinite DC gain).
- 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 the BTO fast steering array should also anticipate telescope tip/tilt errors that 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).

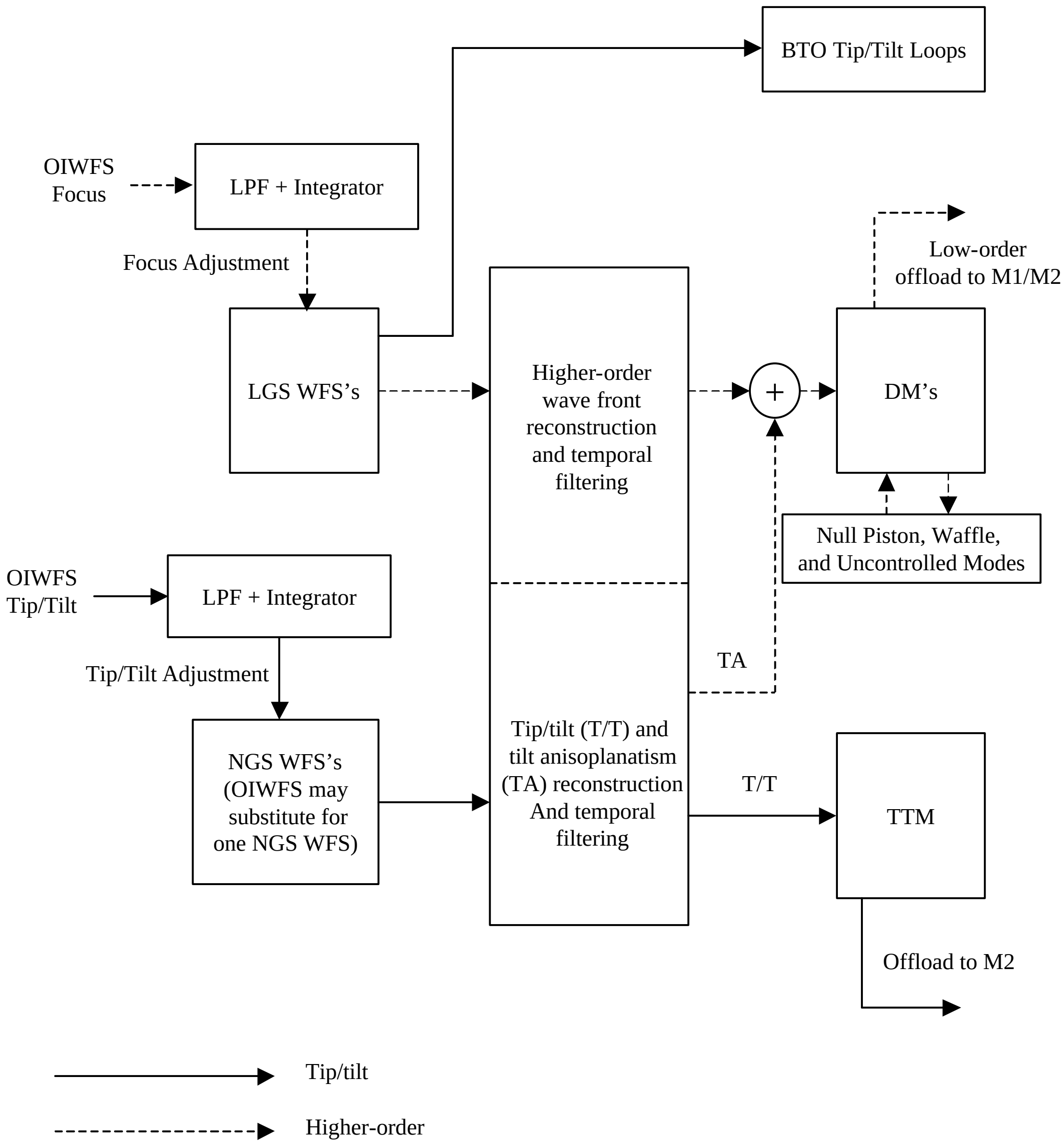


Figure 3: **MCAO Control Function Schematic.**

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 for the control of the LS, the BTO, the LLT, the SALSA, and the AOM. The MCAO Control System will interface the other systems of the telescope as the OCS (Observatory Control System), the TCS (Telescope Control System), the SCS (Secondary Control System), the A&G (Acquisition and Guidance) …as described in the following figure.

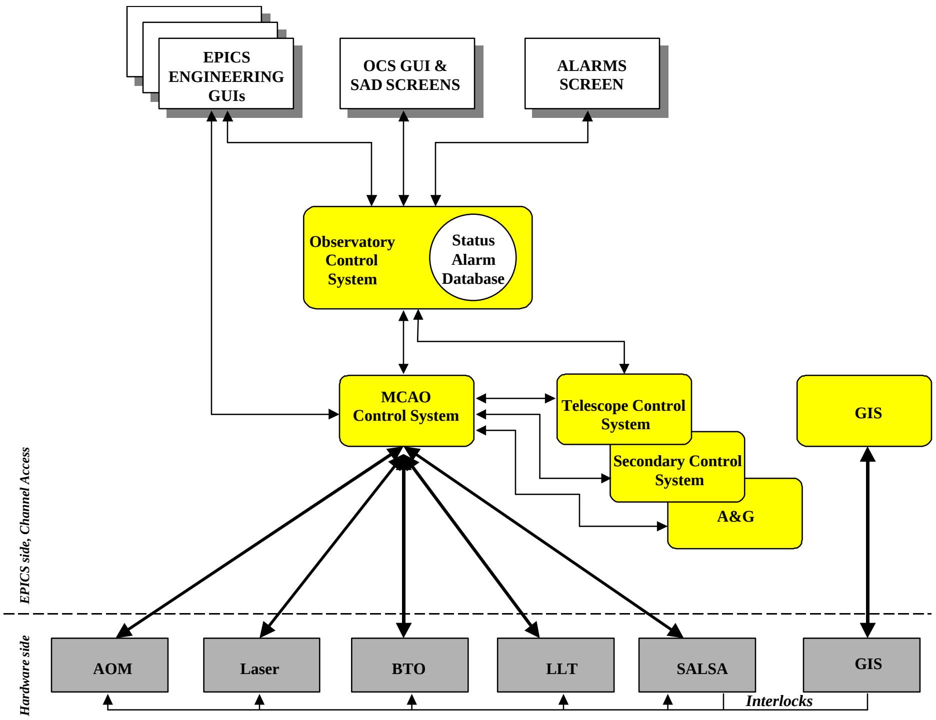


Figure 4: Relative position of the MCAO CS in the Gemini Observatory

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 in six independent sub-systems:

- The AOM Controller which manages all of the opto-mechanical assemblies of the AOM except the DM, TTM and the readout of the WFS.
- The BTO/LLT Controller which manages all of the opto-mechanical assemblies of the BTO and LLT.
- The Laser Controller.
- The SALSA Controller.
- The AOM DWFS Controller which manages the readout of the AOM DWFS.
- The Real Time Controller which performs the real time wavefront reconstruction. The two main real time features handled by for RTC 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 a single standard PowerPC CPU.
    - The LGS control, which will require a lot of CPU power (2.3Gflops), and will be implemented on multi-CPU boards (based on PowerPC processors).

A simplified block diagram of the NGS and LGS controls is given in the following Fig. 5. The NGS process will consist of two main tasks: computing the TTM commands and the tip/tilt anisoplantism modes for the DMs.

- The NGS process: in closed loop, the tip/tilt measurements from the 3 NGS and/or the OIWFS tip/tilt measurements are computed and used as input signals to compute the control of the TTM(1). These tip/tilt measurements are also used to compute the tip/tilt anisoplatism modes for the DMs (2); the output actuator commands are then summed into the LGS loop.

The LGS process will consist on computing the commands of the DMs:

- The LGS 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 (3). The output vector is added to the NGS one (2) and sent to the DMs. From these commands, the commands of the un-illuminated actuators are computed (4).

The parameters of these two processes will be optimized in real time with a number of optimization and background processes :

- The LGS and NGS WFS gains used to compute the slopes measurements from the pixels measurements are optimized according the seeing at slower rate that the NGS and LGS processes.
- The NGS control matrixes used to compute the TTM actuator controls and the anisoplantism modes of the DMs are optimized using the modal optimization
- The NGS probe arm positions are adjusted in some modesto reduce the NGS slope errors at a very slow rate.
- The TTM and DM commands are offload to the M2 and M1 of the telescope
- The LGS control matrix is updated according to the telescope elevation at a very slow rate
- The BTO Fast Steering Array is adjusted in real time from the LGS slopes measurements at the same rate as the LGS process
- The AOM pupil alignment mirrors are adjusted in real time from the LGS slopes measurements at a very slow rate

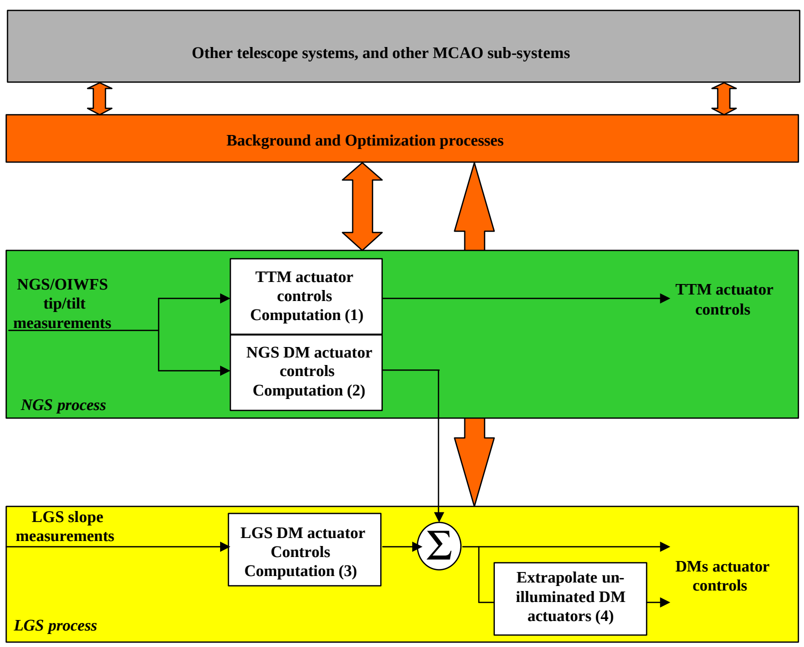


Figure 5: Real-time wave front control block diagram

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.

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 camera, and any radar feeds from local air traffic control agencies. Whenever a potential conflict arises in one of these systems, SALSA will close the laser shutter via the GIS and 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

3.1.1.1 Measure the bias and read noise levels in each WFS CCD.

3.1.1.2 (Option—only if local reference sources are included in the LGS WFS design) Insert the reference source flip mirrors, 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.

3.1.1.3 Set the figure of each DM using previously calibrated actuator commands, cycling the mirror if necessary to avoid hysteresis effects (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 NGS sources. Adjust the TTM and focus on DM 1 to null the tip/tilt/focus measurements from the OIWFS. Insert the DWFS, and measure wave front quality across the field.

3.1.1.4 Insert and turn on the simulated LGS sources. Measure and store the gradients sensed by each LGS WFS for the calibrated DM actuator commands. Repeat at several LGS ranges.

3.1.1.5 Close the tip/tilt and higher-order AO control loops to verify stability.

3.1.2. Periodic Maintenance

3.1.2.1 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, with actuators on all three DM's adjusted to yield to best fit to multiple DWFS measurements across the entire field of view.

3.1.2.2 Measure WFS-to-DM alignment using the waffle poke test.

3.1.2.3 Measure the DM-to-WFS and TTM-to-WFS interaction matrices and compute reconstruction matrices.

3.1.3. Major Maintenance

3.1.3.1 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.

3.1.3.2 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. 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, and eventually should be fully automated as an observing script. The sequence starts with the laser running and all laser shutters closed.

1. Open the laser shutter at the LS/BTO interface. Close each beam pointing and centering loop through the BTO in sequence, using images from the pre-alignment cameras as necessary. Verify beam pointing, centering, quality, and power for each beam using the diagnostic sensors. Open the pointing and centering loops, and close the laser shutter at the LS/BTO interface. These operations may be performed at the end of the day.
2. Open the LLT dust cover.
3. Slew the telescope to a reference star. The active optics peripheral wave front sensors (PWFS) guide stars are acquired and the telescope's tracking and active optics are enabled. The SALSA and internal laser safety systems are operating.
4. Initiate MCAO CS control of the BTO centering mirror (CM), pointing mirror (PM), and derotation K-mirror (KM). These elements are positioned using a lookup table with the telescope pointing angle as input.
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. Switch telescope tip/tilt control from the PWFS to 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 near- and far-field diagnostic sensors. Adjust PM and CM so that the star images are correctly centered. Move the corner cube shutter in Fig. 1 to the closed position.
8. Open the laser shutter at the LS/BTO interface. Close each beam centering and pointing loop through the BTO in sequence. Verify beam pointing, centering, quality, and power for each beam, and polarization at the diagnostic sensor.
9. Zoom the LGS WFS to focus at the nominal range for the current elevation angle.

10. Open the laser beam dump shutter in the beam transfer optics to propagate the laser to the sky, and verify that signal is detected from each guide star at the LGS WFS.
11. If desired, proceed to steps 4—5 and 9—12 of the science operation sequence in section 4.2 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. Preparatory Observations

Observe the science field with the acquisition camera to determine the precise locations and magnitudes of the guide stars for the MCAO NGS WFS and the OIWFS. This information will be used to compute the MCAO control algorithm and position the NGS WFS probe arms.

4.2. Target Acquisition and Closing the Loop

These operations should take a maximum of 2 minutes, and should eventually be automated as part of the observing script.

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 OIWFS guide star, and switch to tracking using the OIWFS, the MCAO TTM, and M2.
4. Deploy the tip/tilt NGS wave front sensors in the AOM and acquire the tip/tilt guide stars.
5. Adjust the NGS WFS locations to center the guide stars on each sensor. This compensates for flexure and any residual uncertainty in the positions of the 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.
9. Switch to tracking using the MCAO NGS WFS. Close the DM control loop using the MCAO wave front sensors. Whether this is done in one or several stages will be determined during commissioning.
10. Close the supervisory control loops for LGS WFS focus and NGS WFS boresight using the OIWFS tip/tilt/focus measurements as input.
11. Perform the science instrument integration. AO performance can be monitored using the output displayed by several of the supervisory loops (estimated PSF's, open- and closed-loop turbulence statistics, LGS signal level…)
12. 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.

4.3. Dithering and Nodding

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

(a) "Dithering" and "nodding" 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 arc seconds. Dithering is typically used as a method to suppress effects of bad pixels. A typical dither is a few arc seconds.

(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 NGS locations will move with respect to the frame of the MCAO TT NGS and the OIWFS, however, and the probe arm positions for these sensors must be adjusted. The relative locations of the natural- and laser guide stars are consequently different at the two ends of the dither, and two different sets of NGS reconstruction coefficients will be required. The BTO control loops must be remain closed between the two ends of the dither or nod. For small dithers, the DM and tip/tilt loops must also remain closed. For large nods, these loops should be frozen until the natural guide stars are reacquired (which should be automatic).

5. Shutdown Procedures

5.1. Aircraft and Safety Halts

1. Aircraft approaching beam: Using the GIS, the SALSA safety system will command the LS/BTO laser shutter to close after a short delay (0.01-0.1 seconds), allowing the MCAO-CS time to freeze the higher-order AO and BTO control loops.
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.
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 will shutter the laser at the LS/BTO interface (via the GIS), and freeze the higher-order AO and BTO control loops.
4. Loss of signal at a BTO sensor: The MCAO-CS will shutter the laser at the LS/BTO interface (via the GIS), freeze the higher-order AO loop, and center all BTO tip/tilt mirrors.
5. Apparent shutter failure, or a safety alarm from LS diagnostics or telescope operator: Power down laser (via the GIS), 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. There is a possibility that predictive avoidance of satellites may be resolved as in item 1 above if the proper interfaces can be established with the laser clearing house. For cases 1 and 2 above, observations would resume as described in section 4.2 after the aircraft or clouds had passed. For cases 3 and 4, the BTO system will need to be realigned as described in section 3.3. Case 5 will require step-by-step initialization and diagnosis of the laser as described in section 3.2

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. In roughly increasing order of complexity, the principal AOM system parameters and functions to be calibrated and tested include:

- Calibration of the DM 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 DWFS, OIWFS, and the simulated guide star sources.
- 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 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. 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.

The principal commissioning tests for the SALSA, BTO, LS, and LLT subsystems include:

- Verifying the interface between SALSA and the laser safety shutter.
- Operation of the BTO pointing and centering loops with a single laser beam.
- Diagnostic beam quality measurements with a single laser beam.
- Aligning the BTO/LLT optical axis to the Gemini telescope.
- 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. All results describe average performance over a square 1 arc minute field, computed for slightly above-average turbulence conditions (r_0 = 0.166 at 0.5 microns, not r_0 = 0.166 at the correct reference wavelength of 0.55 microns).

This budget summarizes MCAO performance estimates as of April 27, 2001. Quantities denoted TBR (to be reviewed) require further analysis for the Gemini-South MCAO system.

MCAO Field-Averaged Error Budget (Bright NGS)	Zenith	30 degrees	45degrees
1.0 Telescope Limitations	116	120	130
Strehl at 1.65 microns	**0.822**	**0.810**	**0.784**
Primary Mirror	60	65	75
Secondary Mirror	60	63	70
Alignment	20	20	20
Self-Induced Seeing	50	50	50
AO Fold Mirror	30	30	30
Science Fold Mirror	50	50	50
2.0 Instrument Limitations	65	65	65
Strehl at 1.65 microns	**0.941**	**0.941**	**0.941**
Flexure relative to OIWFS	25	25	25
Higher-Order Image Quality Effects (TBR)	60	60	60
3.0 MCAO System	199	238	290
Strehl at 1.65 microns	**0.563**	**0.440**	**0.295**
Atmospheric Compensation			
Fitting Error	109	117	130
Anisoplanatism	133	169	222
Servo Lag	26	30	35
WFS Noise	32	37	43
Diffraction and Three-Dimensional LGS	48	55	65
Wind Shake (TBR)	34	34	34
Implementation Errors			
Uncorrectable Errors	43	43	43
Non-Common Path Errors			
Uncalibrated Flexure/Thermal Variations	41	68	80
WFS Centroid Gain Estimation Error	21	23	25
DM/WFS misregistration	24	24	24
LGS Focus	12	12	11
Component Nonlinearities (TBR)	10	10	10
Total RMS OPD	239	274	324
Strehl Ratio at 0.85 microns	**0.044**	**0.016**	**0.003**
Strehl Ratio at 1.25 microns	**0.235**	**0.149**	**0.070**
Strehl Ratio at 1.65 microns	**0.436**	**0.336**	**0.217**
Strehl Ratio at 2.20 microns	**0.627**	**0.541**	**0.424**

Table 1: Image quality error budget for bright natural guide stars