Laser Guide Star upgrade of Altair at Gemini North

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ABSTRACT

Altair is the general-purpose Adaptive Optics bench installed on Gemini North that has operated successfully with Natural Guide Star (NGS) since 2003. The original design and fabrication included an additional WaveFront Sensor (WFS) to enable operation with Laser Guide Star (LGS). Altair has been recently upgraded and functional commissioning was performed between June and November 2005. The insertion of a dichroic beamsplitter in the NGS path allows to reflect the 589nm light to the LGS wavefront sensor and transmit the visible light of the NGS (or Tip-Tilt Guide star –TTGS-) to the tip-tilt-focus sensors. We will review the various modifications made for this dual operation, both in hardware and software, and describe the steps and results of the integration and testing phase on the sky.

Keywords: adaptive optics, natural guide star, laser guide star

1. INTRODUCTION

Altair is the Gemini North adaptive optics system. It is installed at the Cassegrain focus on the instrument support structure. It can be operated anytime by inserting a pickoff mirror into the main telescope beam path. During 2005, this observing mode (Altair + NIRI) was used about 12% of the time (approximately 100h). The AO module measures and corrects wavefront errors and sends out a f/16 beam (same focal ratio and focal plane position as the bare telescope) toward the Science Fold mirror that feeds the various instruments (currently only NIRI and NIFS can benefit from operation with AO). The optical design described previously[1] included a few special requirements like delivering a flat optical surface and, based on early site turbulence experiments, imaging the atmospheric layer 6.5km above the telescope onto the Deformable Mirror (DM). During Altair's commissioning, it was realized that this conjugation altitude was not optimum. A field lens is now inserted into the telescope focal plane to conjugate ground onto the DM, and this has produced significant improvement in the delivered isoplanatic patch[2].

In 2004, after we realized that the initial plans to use the On-Instrument WFS for focus and tip-tilt sensing were going to limit the performance in an unacceptable manner, an internal effort was launched within Gemini to upgrade the adaptive optics bench for LGS operation (see section 3). The first laser light onto the sky was obtained in March 2005 and technical commissioning of Altair LGS was performed between June and November. The major drawback during this campaign was the LGS size (1.5 to 1.8" FWHM at best) outside specifications, and the result of severe optical aberrations of the Laser Launch Telescope (LLT) off-axis parabola caused by thermal stress of the mirror mount. The consequences of this problem were mostly two-fold: (1) instability of the LGS spot size and shape on the sky and therefore residual centroid errors on the LGS wavefront sensor (WFS) not due to atmospheric turbulence, and (2) decrease of photon return forcing us to lower the LGS WFS sampling rate. The program was put on hold in November while the vendor was fixing the problem. Commissioning was resumed in February 2006 with a working LLT, and is now scheduled to be completed during April. System verification runs have been scheduled at the end of the semester. Altair LGS mode has been offered to the Gemini science community for the second semester of 2006.

In this paper, we will review the laser guide star facility, the opto-mechanical additions to the Altair bench, the software and controls upgrades and finally the early performances through the commissioning steps.

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2. LASER GUIDE STAR FACILITY

The laser guide star facility saw first light in March 2005. It has been described in full length previously[3]; we will only come back briefly on some of the general features and components. The laser is installed inside a thermally-regulated enclosure mounted on the side of the center section of the telescope.

- Laser system

The laser system is quite unique: a diode-pumped solid state 12W 589nm laser utilizing sum-frequency technology. It was designed and fabricated for Gemini by Coherent Technologies Inc. (now Lockheed Martin Coherent Technologies). The optical bench houses two laser oscillators (1064 and 1319nm) made of Nd:YAG rods double-end-pumped by fiber optic-coupled 806nm diode arrays ; a 1319nm double pass amplifier (used to increase the 1319nm output to acceptable levels for wavelength conversion) ; a 589nm sum frequency generator crystal ; a wavelength lock using acousto-optics modulators ; a diagnostic system, and a beam diagnostics section. Multiple sensors are located throughout the optical enclosure to monitor parameters such as pulse-width, bench and component temperatures, and dew points. The laser has a bandwidth of 500MHz and is tuned to the center of the sodium absorption line to +/-100MHz.

- Beam Transfer Optics (BTO)

A set of 4 mirrors and 3 lenses relay the laser beam from the laser bench exit window to the top end ring of the telescope following the truss structure. A dedicated hollow rectangular tube was installed behind one of the secondary mirror vane and is used to transport the laser beam to the launch area located on the telescope axis behind M2.

- BTO Optical Bench

The beam enters an optical bench where a small fraction is extracted toward a diagnostics system, whereas most of the power goes through a fast steering mirror (to compensate atmospheric jitter) and a set of slow steering mirrors (for pointing in the sky and centering onto the launch mirror).

- Laser Launch Telescope

This is a reflective off-axis design which includes a beam expander from 5 to 300mm (gaussian diameter at $1/e^2$ intensity points) and a parabola that propagates a circularly polarized collimated beam to the sky.

3. OPTO-MECHANICAL LAYOUT OF ALTAIR LGS MODE

The beam entering Altair is first collimated by an off-axis parabola onto the DM (177 actuators) which in turns reflects the light toward the Tip-Tilt mirror (TTM) and then the science beamsplitter that transmits the infrared light toward the science fold and the instruments, and reflects the visible light into the WFS paths. The common path between NGS and LGS mode is made of three additional mirror: first, an off-axis parabola, in a classical arrangement to form a F/30 focus at the entrance of the WFS ; second, the selection of the guide star within the field of view is performed by two flat motorized gimbal mirrors. All the optics described so far are located on the main 'horizontal' bench at the exception of the gimbal #2 which is located on a vertical bench attached to the main one. There, the guide star light goes through different paths depending on the operation mode:

- NGS mode: light goes through a field stop in the focal plane and through a set of collimating optics onto the ADC right before the 12x12 lenslet array and CCD (0.55"/pix).
- LGS mode: this mode is actually dual in the sense that it uses simultaneously the 589nm LGS light for the closed-loop on the DM, and also light from a TTGS for the TT mirror closed-loop and control of the slow focus drifts.

The LGS WFS path components were already designed and installed when Altair was initially delivered. They share space with the NGS path components on the Altair benches[3] with the NGS path components. Altair uses a calibration source for each mode: the LGS source is a 600µm fiber core (equivalent to a 1" LGS). Because the LGS is formed in the mesospheric sodium layer at altitudes varying between 85 and 120km (when pointing at zenith), it focuses after the NGS (about 180mm at F/16), which is also taken into account by the location of the source. Both modes were actually aligned for the acceptance of Altair: at the time, the split between the two modes was made by a pinhole mirror located in the NGS focal plane letting the NGS light go through a small hole in the center (also acting as field stop), and reflecting the out-of-focus LGS light. The only path that was not implemented was the TTF NGS needed for LGS operation. Due to space constraints and the need to leave the NGS path unchanged and in operation in the telescope, the original upgrade scheme contemplated the addition of all the new components as bolt-on type assemblies in the unused back of the vertical bench. All the opto-mechanical upgrades were installed on Altair during a few days only with very little impact for the NGS path and operation.

The LGS WFS path is reflected off a dichroic beamsplitter (see further) to an optical train leading to the WFS:

- A set of two flat mirrors (called roof mirrors) and a first singlet collimating lens mounted on a zooming motorized translation stage in order to bring the LGS ranging in distance from 85 to 200km always in focus at the input focal plane of the LGS WFS.
- Two lenses, driven according to an open loop model, move along the optical axis to compensate for (1) mis-registration DM/WFS and (2) spherical aberration, consequent to the large defocus of the LGS after passing through the main telescope.
- At the WFS focal plane, just before the entrance of the last collimator, we have installed a 3.2" field stop. This is vital in filtering the Rayleigh background.
- The LGS WFS uses a 12x12 lenslet array and an EEV39 CCD like the NGS WFS. We use a quadcell arrangement in each sub-aperture. The initial configuration used unbinned pixels of 0.92", with a guard pixel -on each side- around each quadcells. Because the spot size is slightly larger than initially specified, and to accommodate worse seeing conditions, we have implemented a binned mode, using 2x2 binning, which gives 1.84"/pixel (3.68"/sub-aperture). In this last mode, there is no guard band. Note that in binning mode, the sub-aperture field of view is effectively limited by the physical field stop (see above). The current readout noise is approximately $12e^-$, and is still a sensitivity-limiting factor, even though readout noise is less an effect in LGS mode than in NGS mode, as the fatter LGS spot necessarily requires to have more photons (SNR on the spot centroid is proportional to the spot FWHM divided by the square root of the number of photo-detected events. As for most AO path alignment, both the image must be aligned in the field stop and the pupil imaged on the lenslet.

To switch between the NGS and the LGS mode (figure 1), a motorized translation U-shaped stage mounted on the back side of the vertical bench (figure 2) inserts the following components:

- A dichroic beamplitter located about 25mm past the NGS focus. By moving in, this dichroic pushes the NGS field stop out (remember the LGS beam focal plane is approximately 340mm downstream from the NGS focal plane, at F/30). The dichroic reflects the 589nm LGS light toward the LGS WFS and transmits the rest of visible NGS light to the TTF sensors. Ideally this dichroic should have a very narrow bandpass -a few nm- to avoid pollution of the NGS light onto the LGS WFS (if the NGS used is close to the LGS in the field). It proved difficult to find vendors capable to produce such a coating where the narrow bandpass is reflected (it is easier to transmit). Our dichroic has 98% reflectance at 589nm with a 40nm FWHM bandwidth, and transmittance above 90% across 400-900nm. We ended up adding a 589/1nm Rugate notch filter with 82% transmission at the entrance of the WFS to reduce the visible light pollution. With this configuration, we determined that a second magnitude TTF NGS would be needed to cause leaks on the LGS WFS (which is way brighter that the typical ninth magnitude brightest NGS we plan to use in science operation).
- A silica singlet field lens right after the dichroic, in the TTGS path: the beam diameter is only 1.5mm so the surfaces must be kept very clean. This lens reimages the pupil onto the Field Scanning Mirror (FSM). The dichroic and field lens are both mounted on a single bracket that, when retracted, also passively brings in the new NGS field stop attached to a rotary mechanism.
- A flat mirror is next and forms the first reflection of a periscope that reflects the light through the bench to the back side.

There a second periscope mirror reflects light to a doublet SF5/BK7 collimating lens and then to the TTF NGS ADC. The ADC is a pair of rotating prisms where the glasses (CaF2and LLF6) used in each prism are cemented with Sylguard silicone to avoid thermal stress. Next is the doublet BK7/SF5 camera lens that creates a f/32 beam to the FSM, then focusing onto the TT sensor.

Theoretically, the Field Scanning Mirror requires a very high angular motion accuracy because it drives the pointing accuracy of the beam into the science instrument: in the case of a spectrograph, one typically needs to center an object in 65mas slit to better than 1/10th of the slit size. This scales to 0.30 arcsec for the mirror accuracy (mirror space) over a range of +/-1°. In practice this is very difficult to achieve so we decided to relax this specification and compensate with the Real Time computer, using electronic/software offsets. The other important specifications of this device are stability (should not move once in position by more than 0.1arcsec/mn) and backlash lower than 0.3 arcsec (again in mirror space). We procured a commercial mirror platform with a +/-1° range and 3 arcsec accuracy (equivalent to 25" range and 20mas accuracy on the sky). FSM is the first element at one end of a 1.2m long cavity (attached to the vertical bench) that holds the TTF sensors.

In order to avoid pollution of LGS light (V-magnitude equivalent of about 9) through the main dichroic -about 1.5% of 589nm light is transmitted- onto the TT sensor when we use a faint TTF NGS, light reflected by FSM goes through a custom 589nm rejection filter that has a 2nm FWHM bandwidth and an optical density of 7 at 589nm (this filter was originally designed as a neutral density for the 12W laser beam in our diagnostics cameras systems of the beam transfer optics). The light is split between Tip-Tilt and Focus cameras by a custom 80/20 beamsplitter (over 400-900nm) where most of the light goes in reflection to the photon-demanding fast TT sensor.

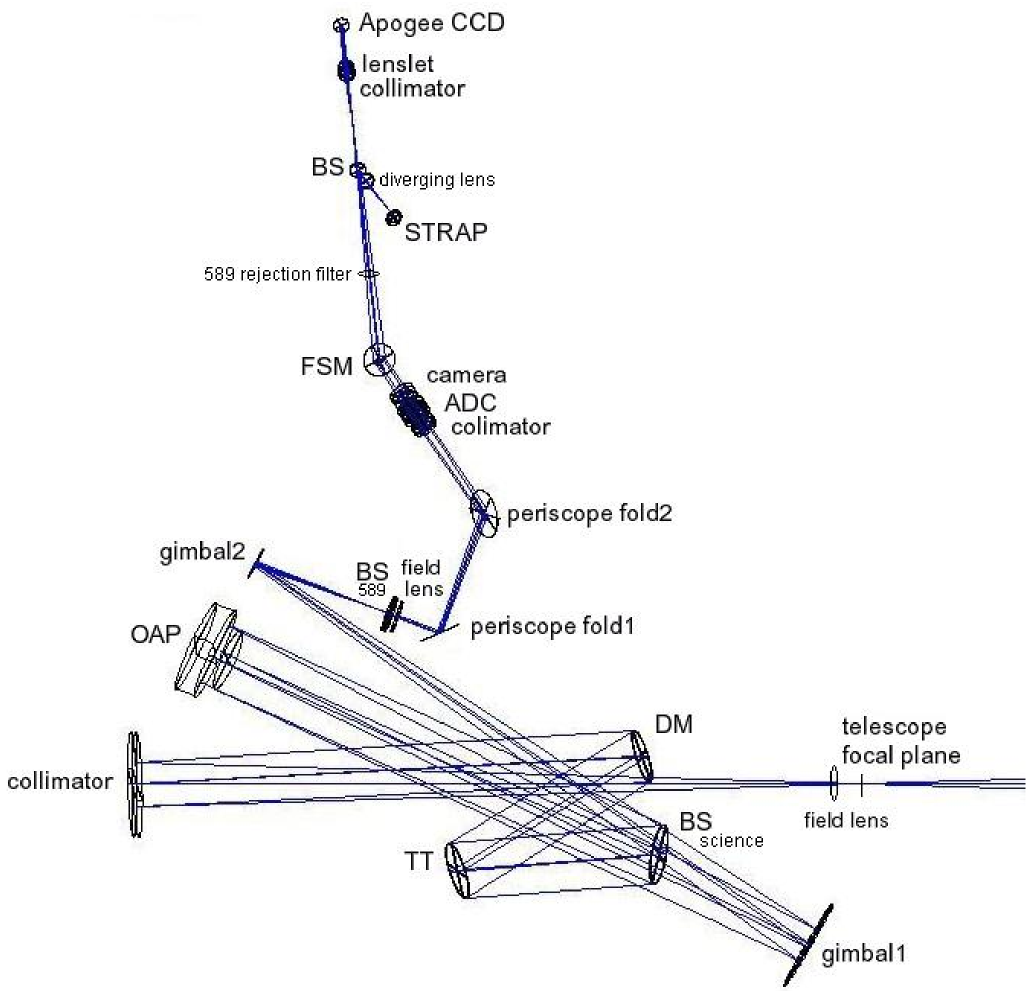

Figure 1: optical layout of Altair LGS TTF path (LGS WFS path reflected off BS_{589} is not shown)

The focus path has a field stop, a singlet collimator and a 4x4 lenslet (from Advanced Microoptics Systems) array imaging the Hartmann pattern onto an Apogee Alta E57+ CCD camera (3.3"/sub-aperture). This device measures focus and low order aberrations (astigmatism, coma).

The Tip-Tilt focus path simply images light onto a Strap[4] camera made of a 2x2 lenslet array coupled onto a APD quad cell. Alignment is quite critical and our non-telecentric f/32 beam -faster than the f/40 recommended value by the vendor- is prone to form a blind area in the center of the quad cell (besides the fact that a very small area is masked by the glue cementing the 4 lenses of the lenslet array) causing the tip-tilt detection to not be perfectly stable and fast converging. The recommended FWHM star size on the array is about 1/3 of the lenslet array diameter of 5.4mm. We solved that problem by introducing a diverging lens to increase the f/ratio onto Strap to f/77.

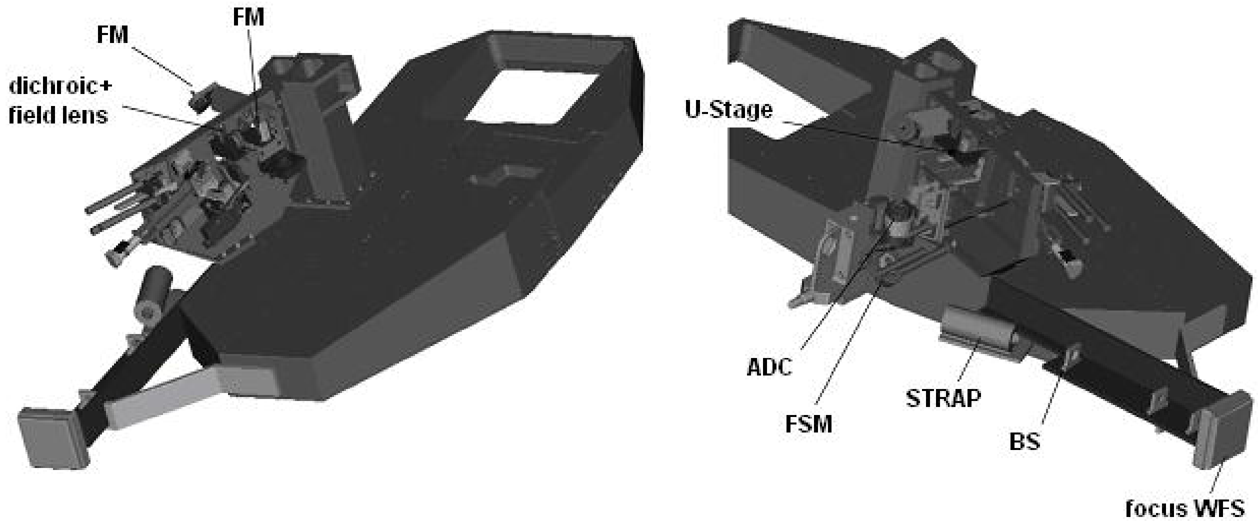

Figure 2: view of both sides of the vertical bench housing the LGS TTF opto-mechanics upgrades (courtesy HIA)

4. SOFTWARE AND CONTROLS

The LGS upgrade of Altair also required adding electronics interfaces and software control to the new hardware. This was done in day-time and did not cause down-time for the instrument:

- Moving mechanisms: 6 actuators (two for FSM, tow for ADC, one for U-stage) run through an OMS58 controller. The FSM actuators are from the Newport CMA serie: they dissipate 1.2W in idle mode and 3.8W under typical load.
- Strap camera: High Voltage power supply, VME interface board, iris control (and glycol cooling)
- Apogee camera: linked to a Linux computer by a fiber optics link (camera also glycol-cooled)

As for most Gemini systems, software is split between low-level component control ('go to', encoder reading, datuming, direct troubleshooting, etc..) and high-level (Telescope Control System) through and EPICs database communication layer. Some of the new functions are:

- Selection of LGS mode: U-stage deployment, gimbal assemblies remain fixed
- Modification to LGS zoom assembly, allowing it to use the focus information form the slow focus WFS and adjust accordingly: this is needed to track the changing height of the sodium layer
- NGS TTF ADC assembly reacts to changes in the Cassegrain Rotator and zenith angle
- Field Scanning Mirror centers beam onto Strap and slow focus WFS

A general control block diagram is presented in figure 3. The heart of the adaptive optics system is the Real Time Controller (RTC) that performs the following main functions (three closed loops):

- **TT loop**: receive centroid values from Strap at up to 1kHz, calculate NGS atmospheric jitter and applies corrections to the Tip-Tilt Mirror, which offloads at 200Hz to the telescope M2 (which in turn offloads to the telescope mount as in regular operation). This loop is independent from the DM loop, and runs at 1kHZ as long as we get a minimum of 20 photons/channel on STRAP APDs (below this number, the integration time is increased)
- **High-order loop**: read pixel values from LGS WFS at up to 1kHz, compute centroids, send commands to the Deformable Mirror (depending on the laser power, sodium layer intensity and noise on the LGS WFS, the loop is sometimes closed at slower speed like 500 or 200Hz: we try to get 150 to 200 ADU/sub-aperture as minimum number), and the DM offloads at 0.1Hz to the telescope M1 through the Telescope Control System (only astigmatism and trefoil, coma is offloaded to M2)

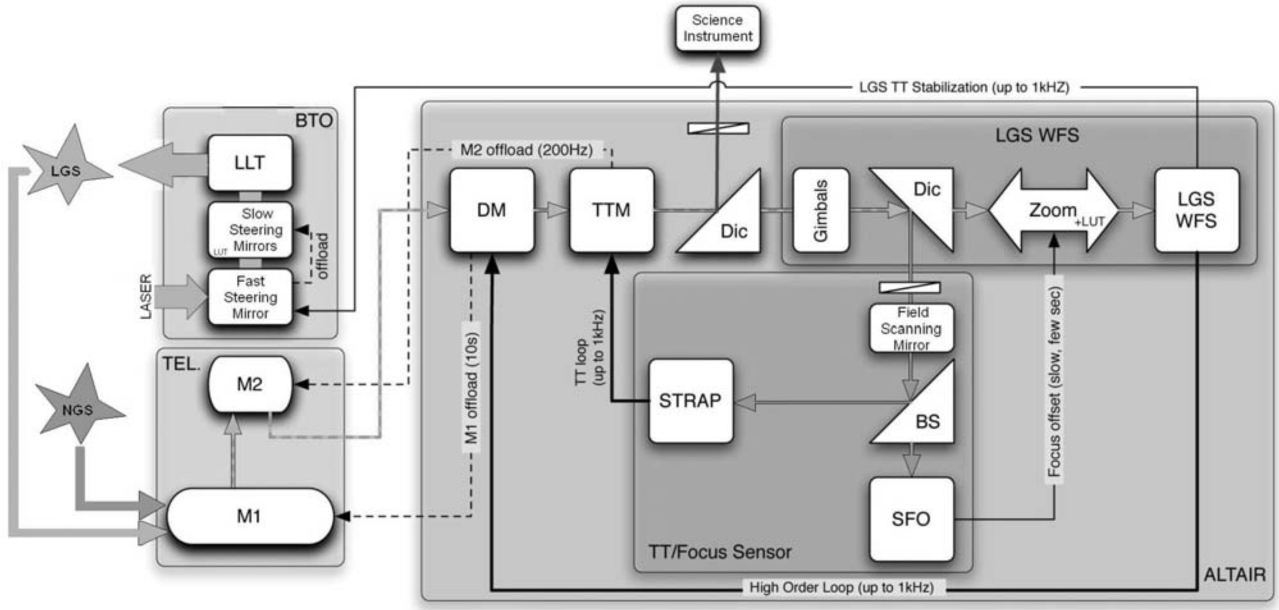

Figure 3: control block diagram of Altair LGS mode

- **Focus loop**: a 0.1Hz slow focus correction sent to the zoom roof mirror that maintains both NGS and LGS in focus by adjusting for sodium layer distance variation beyond the elevation correction done in 20Hz follow mode through the TCS by a Look Up Table (LUT). When the sodium layer moves up and down, the LGS focus correction is applied on the DM that also introduces a defocus in the NGS path (and science path), which the true focus sensor detects: it then sends a demand to move the LGS zoom, and the DM will refocus both path simultaneously
- Calculate the LGS atmospheric jitter and send Tip-Tilt corrections at up to 1kHz to the Fast Steering Mirror in the beam transfer optics of the laser: the LGS motion on the sky is only partially corrected by the main NGS TT so there is a residual motion of the LGS in the sub-apertures of the lenslet (these are used as quad-cells, which have a relatively small linear range, and the motion limits the accuracy of wavefront estimation)
- Send a sinusoidal dither signal (at 1/6th of the high-order loop sampling frequency) to the BTO FSM in order to measure the centroid gains with a lock-in detection technique: because of the finite distance of the LGS, the thickness of the sodium layer and the off-axis viewing of the outer sub-apertures, the gain of each centroid is variable and must be measured in real-time.
- Cleanup of invisible modes and actuator extrapolations

Finally, because it is not located in a pupil plane, the laser Fast Steering Mirror moves the beam on the Laser Launch Telescope mirror so it is also offloaded to the Slow Steering Mirrors (centering and pointing mirrors) in order to avoid drifts and vignetting in the LLT.

Depending on the science program needs, the TCS is in charge of centering the laser position in the science field of view through the laser slow steering mirrors, setting the Altair gimbals to center the LGS on the WFS, and finally setting the NGS on the TTF sensors through the Field Scanning Mirror. When dithering the object on the science detector through telescope mount offsets, an equivalent opposite dithering must be applied to the laser slow steering mirrors to maintain the LGS stationary on the WFS. The field of view for both the LGS and NGS is 1 arcmin.

5. TECHNICAL COMMISSIONING

A total of five observing runs (June, July, August, September, November) for technical commissioning allowed to bring up most of the subsystems and functionalities. Overall, we spent 17 nights with the following efficiency:

- Total observed: 92.7h (61%) so equivalent to 10 full nights approximately
- Total fault loss: 26.5h (17,5%) split between all systems (laser, telescope, instrument)
- Total weather loss: 32.5h (21.5%)

By then we had achieved the following milestones:

- Open-loop models of Beam Transfer Optics
- Close high-order loop with Altair DM on LGS (and offload to M1)
- Close Tip-Tilt BTO Fast Steering Mirror (FSM) loop to stabilize LGS on the sky
- Close Altair Tip-Tilt mirror loop on NGS with Strap
- Close NGS slow focus (SFO) loop to LGS path

As explained earlier, the main limitation left over for performance optimization was the large LGS spot size. Commissioning activities were resumed mid April (after two months of delay due to weather), and 8 additional nights were required to get the instrument fully ready for science verification programs (that included LLT re-commissioning, tuning of loop parameters, flexure look-up tables, miscellaneous calibrations and image quality optimization with calibration of non-common path aberrations). We have refined acquisition methods to the point that the acquisition time is now below 10mn. We will now detail some of the conclusions and early performance results at the time of submission of this paper (end April 2006).

LGS

The spot size obtained under 0.75" seeing is about 13 pixels FWHM on the Acquisition Camera (0.12"/pixel), which is considering the geometric elongation (or blur) when imaging through a 8-m aperture. The core spot (i.e. the true spot size in the sky, as viewed from ground if there was no turbulence) is estimated to be about 0.9". The central LGS sub-apertures will see spots of 1.2" in similar –worse than median- conditions.

The LGS WFS can be operated in non-binning -'small pixel'- mode (2x2 pixels forming a quad-cell of 0.92" side) or binning -'large pixel'- mode (4x4 pixels forming a quad-cell of 1.84" side): the flux obtained is 188 and 277 ADU/2ms/sub-aperturewith respectively under good 0.4" seeing (estimated by Altair).

Centroid gains

Through the dithering technique, the centroid gains are measured for each sub-aperture. The filtering gets only the "physical" component. We do that by projecting to and from a basis of 3 possible spatial vector of possible centroid gain variation: x=cte, y=cte and a radial mode. The first two represent what is constant over the pupil: seeing, beam size. The last one represents the geometrical elongation due to the finite thickness of the Na layer.

At the difference of Altair NGS mode (where the main TT mirror dithers), the dithering mode for LGS is made with the BTO Fast Steering Mirror that does not affect at all the science path. This method conceived by F.Rigaut is unique so far. The tests consisted in varying the amount of dithering sent to the FSM and look at how this affects the determination of the centroid gains (from the centroid gain, and particularly the third mode, we can get an estimate of the radial variation of the centroid gains, something proportional to the Na layer thickness).

The conclusion is that the centroid gain and Na layer thickness estimation does not depend on the dithering amplitude for the smallest dithering amplitude of 0.02. However, we adopted a default value of 0.15 because the estimation looks less noisy (and LGS TT signal still looks normal).

STRAP

The characteristics of the sensor were measured by moving the 10µm calibration source using the TTM.

- The field of view is 1.14 arcsec, slightly squarish.
- The dip (central hole in the sensitivity map due to the microlenses array) is about 45% of the peak sensitivity. Besides the central feature, there is no oddity in the sensitivity map.
- The four APDs are fairly well balanced: their relative sensitivity is (0.905, 0.912, 0.884, 1)

- The dark current (iris closed) in "high flux" mode (temp -9C) is [190, 383, 1796, 169] counts/s/APD for APD #1,2,3,4 respectively, whereas its is [68, 112, 362, 39] in low flux mode (temp=-29C). In observing mode, we have managed to close the loop in a stable way at 100Hz in low level mode with a R=18.2 magnitude (at 200Hz on a R=16 magnitude NGS).

Slow FOcus sensor (SFO)

Measured pixel scale is 41.8 mas/pixel in non-binning mode, hence 167.2 mas/pixels in binning 4x4 (spots are too big to work at any finer sampling). The field of view per sub-aperture is approximately 3.22 arscec.

The flexure measured has an amplitude of 0.87 arcsec in X and 0.885 arcsec in Y. This is surprisingly large but we are able to cope with it, given it is about 1/5 of the sub-aperture field of view.

One main concern for exploitation and performance of Altair LGS mode is actually related to SFO sensitivity. R=16 magnitude star was easily achieved in 15sec exposures, and magnitude 17 in 30sec. However, we might have to go to 120sec for R=18, which will hamper the observations. One solution would be to have a very good LUT for the zoom mechanism, and rely on the fact that the Na layer altitude does not change too quickly. In this case, we would not need to wait for 120sec and more (needs a gain, thus reaction time has to be 2-3 iterations) to take the first science images, but would rely on the focus made on the previous object.

The Apogee camera has good performance of dark current (-35C is a good point to operate): it was measured to be within 7.5 and 8 ADU/s for exposure time between 10 and 120sec. Darks show some pattern indicative of some parasitic light in or close to the optical path. This subtracts well and does not add much noise, but it may be a contributor to the STRAP background.

The focus sensor (4x4 Shack-Hartmann) also measures astigmatism and coma, One central issue people using LGS AO have dealt with is the static stability of wavefront corrections. This is mostly due to the nature of the LGS and the type of aberrations encountered (variability of laser M^2, cone effect, geometric distortion of spots) compared to a standard NGS. Other observatories are using truth sensors that are low temporal frequency but have higher spatial sampling to measure high order aberrations. These truth sensors estimate the static compensated wavefront error and feed it back to the LGS WFS reference slopes. Because Altair's laser produces a very stable beam quality and the RTC uses a fancy centroid gain estimator, we believe our low-order truth sensor (astigmatism, coma) will be sufficient (to be verified on the sky very soon).

Telescope performance

The LGS mode commissioning also had some positive feedback on the overall telescope performance: we discovered a 83Hz resonance in the Altair TT mirror power spectrum (figure 4), which indicates that LGS is jittering in the sky. This was diagnosed as being induced by M2 XY positionner follow-mode. Since this effect is not seen in NGS mode, we concluded that the M2 XY stage motion creates a vibration (because of rough ramping of the stepper motors) that excites some other optical component located on the Secondary Support Structure, most likely one of the optics of BTTOB or LLT. This problem has been solved, at least temporarily, by disabling the XY follow-mode since coma can be corrected easily by the DM.

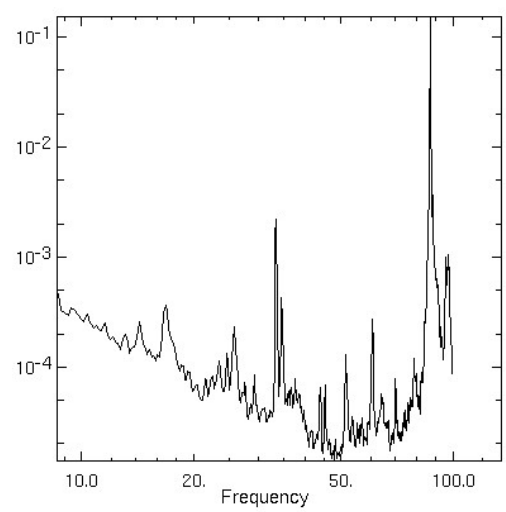

Figure4: Altair TT mirror power spectrum evidencing the LGS jitter at 83Hz

6. CONCLUSION

Altair LGS mode is now fully implemented. After LGS first light in March 2005, technical commissioning was started in June and is nearly completed as of April 2006. The equivalent of 18 full nights (without time loss) were required to complete the task list. The commissioning was spread over such a long period due to a 4-month interruption to repolish the LLT off-axis parabola that was out of specification, and also uncooperative weather for nearly 2 months in spring 2006. Although non-common path aberration still have to be modeled to optimize the delivered image quality, we have already achieved 73mas FWHM images in K, which is very encouraging. The overall readiness and usability of the instrument has been brought to an efficient level for science operation, including training of the telescope operators and laser operation. LGS AO science is expected to ramp up in the second semester of 2006 and certainly be in full swing in 2007.

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