UPGRADE OF THE ESO LASER GUIDE STAR FACILITY


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Abstract. The laser guide star facility (LGSF) is part of the fourth Unit Telescope (UT4), Yepun, at Paranal observatory. It provides a single centre-launched sodium beacon for the two adaptive optics instruments SINFONI and NACO located at Cassegrain and Nasmyth B, respectively. The original facility, which was installed in 2006, comprised a high-power sodium-resonant dye laser source, PARSEC, producing an output beam that was delivered via a 27 metre long single-mode photonic crystal optical fibre to a launch system located behind the telescope secondary mirror. This dye laser was recently replaced with a laser system based on solid-state Raman fibre laser technology known as PARLA. Apart from the laser source, the design of the rest of the LGSF remained essentially unchanged during the upgrade. Requirements for the new laser system include start-up times compatible with the flexible observing strategy of the Paranal telescopes and an output beam format compatible with the existing fibre-delivered launch system. The required optical power on sky (ie after the relay optical fibre) was between 6 and 7 Watts. Reported here are the main results of the design, integration and commissioning of the new laser system. Service mode observing using the LGSF restarted on February 20th 2013.

1 Introduction

The laser guide star facility (LGSF) is part of the fourth Unit Telescope, Yepun, at Paranal observatory [1]. Figure 1 shows a model of the 8 metre optical telescope with the main parts of the Laser Guide Star Facility highlighted in yellow. They are (1) a laser clean room under the Nasmyth B platform (2) Relay optical fibre (3) launch optics.

The laser clean room contains the bulk of the control electronics and the laser source. In the original facility, the laser source was a dye laser system (PARSEC) [2] specified to produce greater than 10 Watts average optical power in a single-frequency line centred of the sodium $D_2$ line. The free-space output from this laser was delivered to the input of the relay optical fibre via a benchtop beam relay system. The role of this beam relay is to format the beam spatially and spectrally, and to actively stabilise the beam position and direction in order to maintain the optical fibre coupling efficiency during operation.

A single-mode photonic crystal optical fibre of the index-guiding solid-core type transports the high power visible laser beam from the laser clean room to the launch optics behind the main telescope secondary mirror. This optical fibre has a length of 27.5m, a core mode field diameter of approximately 14 microns, and a numerical aperture of 0.041 measured at a wavelength of 592nm. Transmission losses, excluding input coupling, are approximately 10% in total.

The launch optics, mounted behind the secondary mirror of the main telescope, receive the visible beam output from the relay fibre and propagate a nearly collimated 50cm diameter beam onto the sky. They also provide beam expansion, focusing, and tip-tilt beam stabilization functionality.
Reported here are the main results of an upgrade of the Laser Guide Star Facility with a new prototype Raman optical fibre laser system. The new laser, PARLA, uses similar technology to prototype [3] and industrial laser systems developed in the frame of the ESO Adaptive Optics Facility (AOF) [4,5]. As a replacement system, it was specifically configured to be compatible with the requirements and interfaces of the existing facility. Included in the scope was an upgrade of the benchtop beam relay system prior to the relay optical fibre; the rest of the Laser Guide Star Facility remains essentially unchanged.

Fig. 2: Control Architecture of the Laser Guide Star Facility Showing Interfaces to Laser Sub-System
Figure 2 shows the control architecture of the Laser Guide Star Facility and the interfaces to the laser system. The location of the new laser system, PARLA, is highlighted in yellow. From the user side, the laser is controlled from a workstation over the telescope network. The laser also has a direct electronic interface to the LGSF safety system. Optically, the new laser system is required to deliver a beam formatted for efficient coupling and transport via the relay optical fibre while maintaining efficient excitation of the sodium $D_2$ transition. The laser frequency is also required to be tuned in and out of resonance with the sodium line for calibration purposes during the observing cycle.

2 PARLA Laser System

2.1 System Design

The laser source is based on Raman fibre technology similar to systems that have been described elsewhere [3,5]. The main optical train is shown in figure 3. The laser system includes an electronics cabinet and a laser head which emits a free-space TEM$_{00}$ laser beam with a maximum output power of greater than 20 Watts. The laser linewidth is specified to be less than 20 MHz full width half maximum, and the centre frequency is tunable around the centre of the sodium $D_2$ transition at a nominal vacuum wavelength of 589.158 nm. Downstream from the laser head, a periscope, phase modulator, and a beam expander unit relay the optical beam to the existing beam stabilisation and optical fibre coupling system (BRS Input). The laser implements a local computer control system which is connected via a point to point ethernet link to a VME unit running the VW Works real-time operating system. This system allows for control and diagnostic functions of the laser from within the VLT Software.

2.2 Laser Format

The optimisation of the laser format for sodium guide star generation is being studied, see for example reference [6]. In this particular application, the photonic crystal relay fibre is an
important factor determining the optical power and laser format launched onto the sky. This optical fibre does not preserve the polarization state of the laser beam and Stimulated Brillouin Scattering (SBS), a nonlinear optical effect, limits the maximum power spectral density that it can transmit. For these reasons, the original single-frequency spectral line originating from the laser head was spectrally broadened in the free-space section. At the relay fibre input, the laser spectrum consists of multiple lines inside an overall intensity envelope. The individual lines are spaced by the 110 MHz and the intensity envelope has a width of approximately 440 MHz. The beam is linearly polarized, and a beam propagation factor $M^2$ of < 1.3 (goal < 1.15) at the relay fibre input was specified to achieve efficient single-mode optical fibre coupling. Techniques such as optical pumping of the sodium $D_{2a}$ line in the mesosphere, which require circular polarization, were not employed.

The phase modulator in the benchtop beam relay was used to increase the spectral width of the laser signal by applying a nearly sinusoidal phase modulation. The phase modulated laser field amplitude can be approximated by the relation:

$$E(t) = A \sum_{n=-\infty}^{\infty} J_n(\phi) \exp(i(\omega_0 + n\omega_{mod})t)$$  \hspace{1cm} (1)

where $J_n(\phi)$ is the $n^{th}$ order Bessel function, $\phi$ is the peak phase shift in radians, and $A$ is a constant. This implies that the modulated laser spectrum is split into a number of discrete lines separated by the modulation frequency $\omega_{mod}$. Figure 4 above shows simulated laser spectra for peak phase shifts of up to 3.76 rad together with the calculated overlap with the sodium $D_{2a}$ transition, modelled as a Gaussian lineshape with 1 GHz full width half maximum. The optimum phase shift is a trade-off between the total power transmitted through the fibre and the overlap between the broadened laser spectrum and the sodium $D_{2a}$ atomic transition which determines
the efficiency with which the laser light excites the sodium atoms in the mesosphere. The overlap decreases progressively from 100% at zero peak phase shift to 67% at a peak phase shift of 3.76 rad. A peak phase shift of approximately 2.6 rad was used in the installed system for a total power of 7 Watts exiting the relay fibre. The optical spectrum was measured with a scanning Fabry-Perot spectrum analyser on the installed laser system and it is shown in Figure 5. During lab tests it was also confirmed that the spectrum did not change significantly after propagation through the relay fibre and no significant signal was measured at longer wavelengths where one would expect to find the first Raman Stokes shift, if it were present.

2.3 Test Results

The laser system was subject to a number of tests at system and subsystem level before installation on the telescope. The measured output power from the laser head as a function of laser set point is shown in Figure 6. The output power varied linearly with set point, and a maximum output of 20.5 watts was measured during this test. Although this is a 20 watt class system, the final operating point of the laser source in the installed system is around 11 Watts to achieve the required 7 Watts launched power on sky.

Fig. 5: Measured optical spectrum of the beam prior to the delivery fibre. The x-axis is approximately linear in frequency measured in arbitrary units, and the y-axis is proportional to the optical intensity in arbitrary units.

Fig. 6: Output Power Characteristic of the Laser Source
Figures 7 and 8 show the results of a test of the complete system including a relay optical fibre of the same type installed in the final system. The duration of the test was approximately 12 hours, and the system parameters were recorded with a sampling interval of 2 seconds. Figure 7 shows the optical power at the input and output of the relay optical fibre measured during the test. The output power was measured with a bolometer, and the fibre input power was measured using a calibrated pick-off mirror before the relay fibre. During this test, the direction and lateral position of the laser beam at the input to the relay optical fibre were actively stabilised using an automated closed loop system, as is the case in the telescope. The average power at the input to the relay fibre was 8.86 watts, the output power was 7.16 watts and the average optical fibre throughput was 80.8%. The optical fibre throughput includes both the transmission losses of the relay optical fibre (approximately 10%) and the input coupling losses, implying an input coupling efficiency of around 90%. The beam quality of the laser beam at the input of the relay optical fibre was measured with a Phasics SID4 wavefront sensing camera. Using an aperture mask set at 5% intensity, the rms wavefront error was measured to be 8.2 nm excluding tilt and focus terms. During this test, the amplitude of the phase modulation was set to generate four spectral lines similar to the spectrum shown in Figure 5.

![Graph showing measured optical power into and out of delivery fibre during test.](image)

**Fig. 7:** Measured optical power into and out of delivery fibre during test

The infrared laser wavelength was also measured and logged during the test. Figure 8 shows the measured frequency error, in units of MHz, from the nominal set point during the test. The deviation is within a few MHz, which is compliant both with the required value of 50 MHz and the goal of 20 MHz.

![Graph showing optical frequency error of the laser measured during test.](image)

**Fig. 8:** Optical frequency error of the laser measured during test
In addition to the selected optical characteristics reported above, the laser system was subject to a comprehensive set of performance and functional tests including the control system and interface to the VLT Control Software.

Fig. 9: VLT UT4 telescope at Paranal, during the LGSF commissioning, February 14th 2013. Photo courtesy of G. Hudepohl, ESO.

3 Commissioning and Science Verification

The laser was installed on the telescope at the start of 2013, and commissioning took place in February 2013. The commissioning process included stand-alone tests of the Laser Guide Star Facility with the new laser system and commissioning and science verification with the complete observing system and the two adaptive optics instruments, SINFONI and NACO. Figure 9 shows a photograph of UT4 taken during the commissioning in February 2013.

3.1 LGSF Commissioning

The LGSF was recommissioned first as a stand-alone system before the start of observations and science verification tests with the instruments. To verify the correct output wavelength, the centre frequency of the laser system was scanned in steps of 250 MHz and 100 MHz around the nominal centre of the sodium $D_2$ transition and the relative return flux (brightness) of the laser guide star was measured using the UT4 guider camera. The guider output is in analogue to digital units (ADU) which are nominally linear with the flux. Figure 10 shows a plot of return flux versus laser wavelength taken during on-sky calibration. The measured lineshape is a convolution of the broadened laser spectrum and the sodium $D_2$ transition. The main peak
corresponds to the $D_{2a}$ transition and the broad shoulder in the high frequency side corresponds to the sodium $D_{2b}$ transition. The laser was tuned to the peak of the $D_{2a}$ determined on sky in the final configuration.

![Graph showing flux of the laser guide star measured on the telescope guider as a function of centre frequency of the laser taken during on-sky calibration. The vertical scale is in analogue to digital units (ADU) of the guider which is nominally linear with flux.]

**Fig. 10:** Flux of the laser guide star measured on the telescope guider as a function of centre frequency of the laser taken during on-sky calibration. The vertical scale is in analogue to digital units (ADU) of the guider which is nominally linear with flux.

The angular size subtended by the laser guide star was measured using the telescope guide camera at different altitudes and is listed in Table 1. Images of a natural star were taken before each LGS measurement and used to infer the seeing. The exposure time for the LGS images was approximately 2 seconds. This exposure duration averages the majority of the seeing effect, but formally is too short to qualify as a true long-exposure measurement of the spot size.

<table>
<thead>
<tr>
<th>Zenith (deg)</th>
<th>NGS Size (arcsec)</th>
<th>LGS Size (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.4</td>
<td>0.55</td>
<td>1.16</td>
</tr>
<tr>
<td>19.4</td>
<td>0.68</td>
<td>1.28</td>
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<tr>
<td>24.6</td>
<td>0.66</td>
<td>1.34</td>
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<td>36.2</td>
<td>0.92</td>
<td>1.59</td>
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<td>41.7</td>
<td>0.88</td>
<td>1.79</td>
</tr>
<tr>
<td>54.9</td>
<td>0.90</td>
<td>1.62</td>
</tr>
</tbody>
</table>

The return flux and apparent magnitude of the laser guide star were not measured photometrically. However, the counts from the SINFONI wavefront sensor, based on photon-counting avalanche photodiodes, were accessible. The wavefront sensor counts and the system performance during the science verification were the two metrics used to verify that the return flux was sufficient to meet the operational requirements. Measurements of the apparent laser guide star magnitude were made using SINFONI at different altitudes and at different times during the commissioning period. Typically the flux measured on the wavefront sensor equated to around 6.
million counts per second. The optical power launched onto the sky was between 6 and 7 watts during these tests. This level of photon return was found to be sufficient to achieve good closed loop adaptive optics performance during science verification. However, further measurements are needed before a definitive comparison can be made between the measured and theoretical return flux for this system. The principal uncertainty is the sodium abundance which has been shown to vary by a factor of four seasonally [7] and by a factor of up to 2 during a single night. Frequent measurements taken at different times of the year are therefore needed before firm conclusions can be drawn.

3.2 Science Verification

The observing targets selected for science verification are given below in table 2. These were repeats of existing and already published observations.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Object Name</th>
<th>Description</th>
<th>Existing OB Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACO</td>
<td>NGC3621</td>
<td>Bulgeless Galaxy with NC</td>
<td>083.B-0279(B)</td>
</tr>
<tr>
<td>NACO</td>
<td>Centaurus A</td>
<td>AGN with central black hole</td>
<td>280.C-5005</td>
</tr>
<tr>
<td>NACO</td>
<td>NGC 5139</td>
<td>Omega Centauri</td>
<td>60.A-9800(J)</td>
</tr>
<tr>
<td>SINFONI</td>
<td>Haumea (TNO136108)</td>
<td>Solar system, trans-Neptunian object</td>
<td>087.C-0167(A)</td>
</tr>
<tr>
<td>SINFONI</td>
<td>NGC3621</td>
<td>Bulgeless Galaxy with NC</td>
<td>083.B-0279(B)</td>
</tr>
</tbody>
</table>

The observations selected for NACO were successfully executed during the commissioning nights. Observations were mainly made with the 7x7 wavefront sensor and the adaptive optics loop remained closed without problems down to an altitude of 30 degrees during standard operation tests. The instrument was operated in a number of different configurations: tip-tilt correction only, high order correction only, and with full correction. On the night of 17th February with full correction, Strehl ratios in the range 15.6 – 37% were measured in seeing ranging from 0.76” to 0.99” recorded by the observatory differential image motion monitor. Figure 11 shows an image of the cluster in Omega Centauri taken during commissioning.

The observations of Haumea and NGC3621 with SINFONI were also completed successfully. SINFONI was able to work stably in closed loop with the laser during standard operation tests. When observing the trans-Neptunian object Humea, it was possible to observe up to the twilight limit without problem. For the last two nights of the planned commissioning period the system was handed back to science operations for service observing.

4 Conclusion

The laser guide star facility (LGSF) at ESO Paranal observatory has been upgraded with a prototype laser source based on Raman fibre laser technology. This is the first time that this type of laser has been operated as part of a major astronomical observing facility. The system was installed and successfully commissioned together with the adaptive optics instruments SINFONI and NACO in February 2013, and it is currently in science operation.
Fig. 11: Ks band NACO image of the cluster in Omega Centauri. Field of view 37”x37”, seeing 0.75” $\tau_0 = 3.7$ms, DIT 4sec. The stars fwhm is between 0.094” and 0.11”, tilt rms 0.012”, full correction.

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References

4. R. Arsenault et al., The Messenger 123, (2006), 6-10