Laser Guide Star Facility for the ESO VLT

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1. Introduction

ESO has been studying the possibility of introducing a Laser Guide Star Facility (LGSF) for the VLT to serve the adaptive optics (AO) instruments foreseen on the UT3 telescope of the Paranal Observatory: NAOS-CONICA and SINFONI.

Although full project funding, according to the ESO Long Range plan, will only start in 2001, we have performed a comprehensive feasibility study, with some innovative developments, especially on the possible injection of the laser light through a single-mode fibre (see the following article). The LGSF concept is the basis of this article.

The LGSF is foreseen as an add-on to the VLT telescope, able to create an artificial guide star in the mesospheric sodium layer, at 90 km average altitude. The LGSF would be used as a slave system to the AO systems, to produce an artificial reference star for the wavefront sensor, close to the observed object, whenever necessary. Figure 1 illustrates how the baseline LGSF concept would be implemented on the VLT.

The activities reported here have been carried out at ESO, with the enthusiastic scientific collaboration of the Max-Planck-Institut für Extraterrestrische Physik (MPE) in Garching,. MPE has built the Calar Alto Laser for the ALFA system (Davies et al, 1999).

The definition of the LGSF is at the conceptual design stage, with a solid baseline solution explored in detail and two open options: the final choice for the laser, and the use of a fibre relay for the laser beam instead of a mirror system. The final choices will be made during the LGSF Conceptual Design Review.

This article gives an overview of the conceptual design we are currently working on.

2. Project Rationale

The most important limitation of current NGS-AO systems, is the scarcity of a good reference star for the wavefront sensor (WFS) to exploit the full potential gain of the adaptive optics loop. The NGS should be bright enough to overcome both sensor read-out and photon noise. If it lies outside of a small field, optimum correction cannot be achieved, due to anisoplanetism effects.

To minimise the former, wavefront sensors with a high quantum efficiency and very low read noise are required. Thus photon noise is the only unavoidable contributor to the WFS noise. Even so, with Natural Guide Stars (NGS) the performance in the K-band of a medium-sized AO system drops significantly when $m_V \geq 15$. Figure 2 shows the expected K-band Strehl performance for a 60-element curvature system with the VLT as a function of NGS magnitude and its angular distance from the science target. Note that Strehl curves depend by the seeing at 6th power. Our analytical computations are for 0.66" seeing at 0.5 μm, 6 msec τ_o, and 0.4 Strehl contribution from field anisoplanatism at 20" elongation, in K-band.

The analytical simulations allow a parametric exploration of the AO performance. Although this is less accurate than a full numerical simulation, the results are according to our estimates accurate to within 10-15%, and serve well the purpose of this discussion. The effect of anisoplanatism on AO systems is very evident in Figure 2. For example, a 10th magnitude NGS which is 25 arcseconds away from the science target

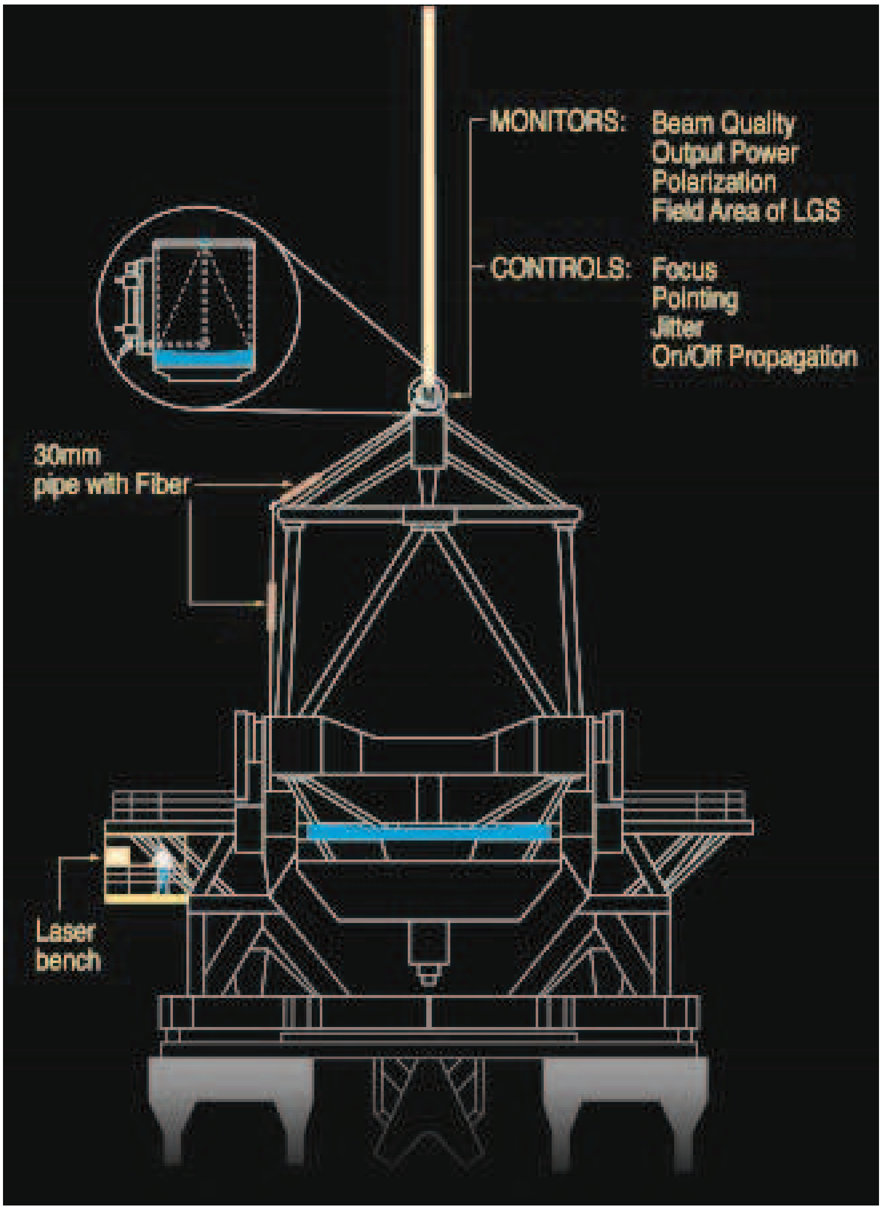

Figure 1: Layout of the LGSF. The laser and its controls are mounted under the Nasmyth platform, in a well-insulated laser room. The laser beam is relayed to the 50-cm-diameter launch telescope located behind the UT secondary mirror.

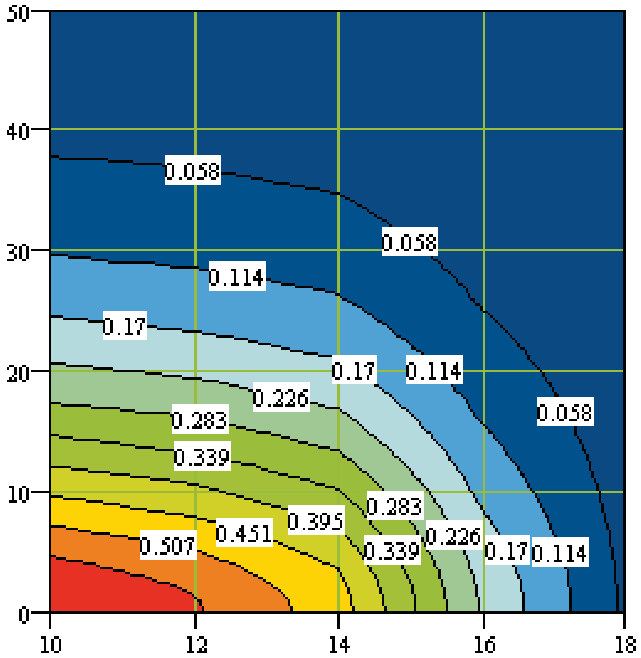

Figure 2: K-band iso-Strehl curves, computed for a 60-element curvature system, vs NGS magnitude (x-axis) and elongation between science object and NGS (y-axis, arcsec).

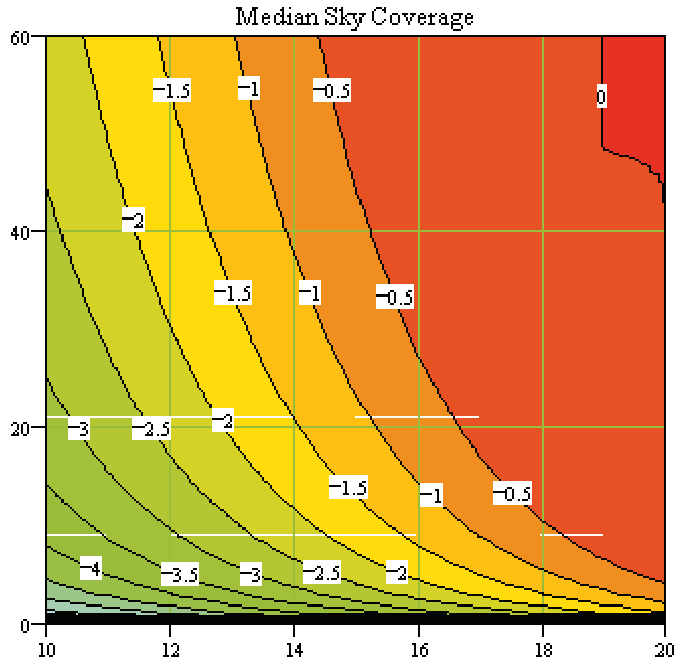

Figure 3: Logarithmic iso-probability curves for NGS. V-band NGS magnitude on the horizontal axis, NGS elongation from the science object in arcsec, on the vertical axis.

gives the same Strehl ratio as a 17th magnitude NGS on-axis.

The scientific justification of the LGSF comes from sky-coverage considerations. Put in simple terms, we need the answer to the question: 'what fraction of the sky can be observed with AO, and how many of my objects can be observed?' (Le Louarn et al., 1998, Di Serego Alighieri et al., 1994) The requirement of a relatively bright NGS, at short distance from the science object, limits the use of AO systems. The higher the Strehl Ratio required the greater the limitation. Figure 3 shows the median sky coverage iso-probability curves for a NGS plotted on a logarithmic scale.

Using a LGS, the reference signal for the AO wavefront sensor can be made equivalent to that of a NGS of $m_V \cong 9.5$ with seeing-limited diameter. It is rather like providing the telescope with a headlight, enabling the AO system to find a reference star wherever the telescope points. This opens the possibility of observing many more extragalactic targets than with a NGS-AO system. Two problems still prevent us reaching complete (100%) sky coverage: (a) the 'focus anisoplanatism' or cone effect (Tyler, 1994), and (b) the intrinsic indetermination of the image motion (tip-tilt) signal. The cone effect, for an 8-m telescope in the Near Infra-Red (NIR), and one single LGS, gives an unavoidable but tolerable reduction of the Strehl performance.

The tilt problem can be overcome by using a natural star in the field in addition to the LGS. The image blur is corrected using the LGS, the image motion (tip-tilt) using a NGS. The NGS for tip-tilt can, however, be much fainter and typically 2.5 times further away than a high-order NGS reference.

The ultimate sky coverage and AO performance depends largely on the tip-tilt sensor and is one of the reasons why ESO has put considerable effort to develop a high-performance tip-tilt correction subsystem, the so-called STRAP system. We will report on the STRAP system in a next issue of *The Messenger*.

The K-band iso-Strehl contours for a LGS-AO 60-element curvature sensing system are shown in Figure 4. The NGS magnitude and elongation axis refer to the tip-tilt reference star. The LGS is assumed to be pointed close to the science target. Compared to Figure 2, the gain in sky coverage is very evident even though the cone effect limits the maximum achievable Strehl. There is an even larger gain if one looks at the encircled energy improvement for a spectrograph (Le Louarn et al., 1998, Bonaccini, 1996).

Figure 5 combines the information contained in Figures 2 and 4, and shows the overall sky coverage (combining NGS magnitude and elongation) achieved with a given Strehl ratio, for NGS-AO and LGS-AO systems. The simulated system corrects 80 Karhunen-Loewe modes[1]. Using a LGS-AO,

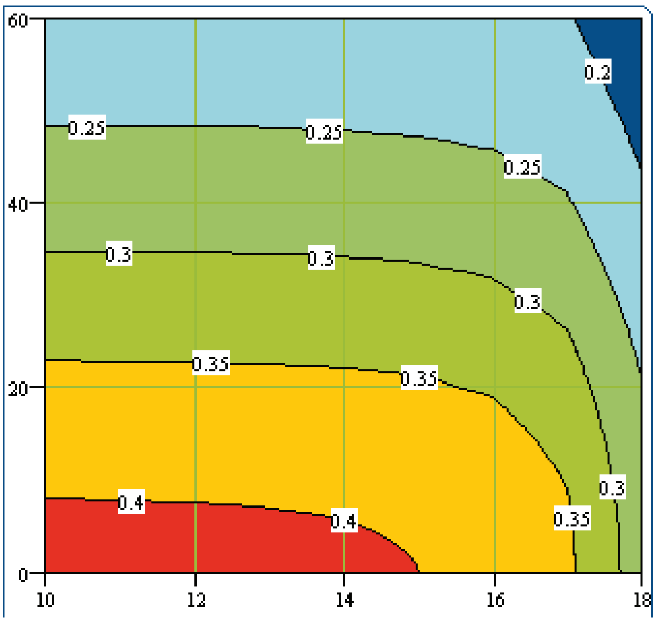

Figure 4: K-band iso-Strehl curves, for a 60-element curvature sensing AO system with a LGS, using a tip-tilt natural guide star. The NGS V-magnitude and elongation (arcsec) from the science target are the horizontal and vertical axes respectively. This plot should be compared with Figure 2.

[1]Karhunen-Loewe modes: they are an orto-normal basis for the expansion of the wavefront. They are often used in AO systems, as the modes are also statistically independent (see e.g. Adaptive Optics in Astronomy, p. 31, F. Roddier ed., Cambridge Press University 1999).

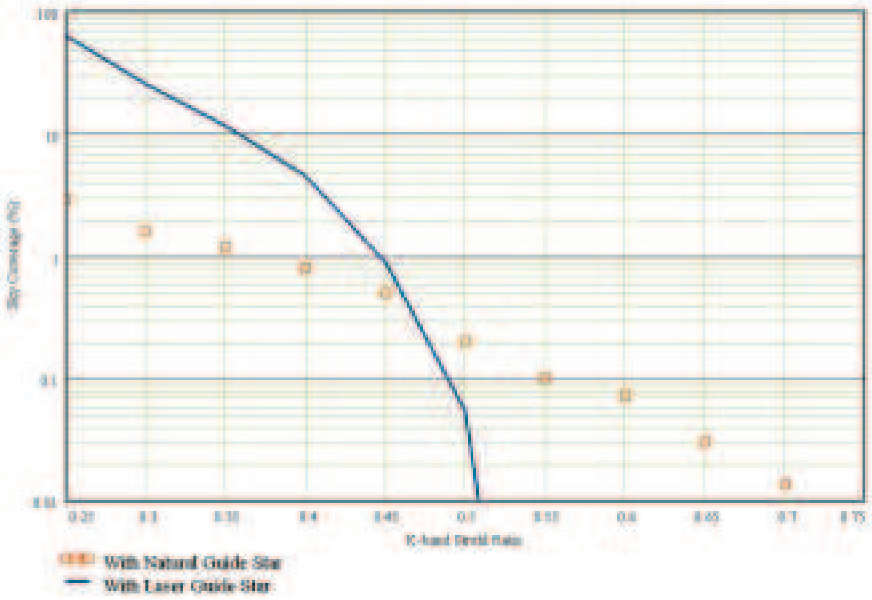

Figure 5: Sky coverage of an AO system correcting 80 Karhunen-Loewe modes, as a function of the K-band Strehl Ratio. The model atmosphere is as described in the article. NGS and LGS curves are plotted. The assumed single sodium LGS has a m_V = 10 and 1 arcsec FHWM. The saturation of the LGS curve at SR = 0.52 is due to the cone effect: Irrespective of how good the tip-tilt reference signal is, higher Strehl ratios are not possible.

the maximum K-band Strehl obtainable is 0.52 in our example, and this is seen in the saturation of the LGS-AO sky coverage curve. The sky coverage for a Strehl Ratio < 0.45 in K-band is always larger than NGS-AO in this configuration.

The LGS-AO system foreseen for the VLT will not reach Strehl ratios much greater than 40% in K-band, due to the cone effect. Note that the PSF core achieves the resolution of the diffraction limit (0.057″ in K-band), therefore the spatial information can be recovered. The images may be further boosted using post-processing techniques such as deconvolution if necessary (Conan et al. 1998, Christou et al., 1999). Figure 6 shows the long-exposure Modulation Transfer Function (MTF) for the uncorrected seeing, for the LGS-AO and for the 'perfect' telescope. The LGS-AO system allows the attenuation of all the spatial frequencies transmitted by the telescope to be restored by post-facto deconvolution.

Techniques to reduce or remove the LGS cone-effect are being studied at various institutes, for example by using multiple guide stars (Fried and Belsher, 1994), or with a hybrid system where the low orders are corrected with the NGS, the remaining high orders with the LGS. These will be necessary for visible AO compensation on future extremely large aperture telescopes.

3. Project Status

ESO's Scientific Technical Committee has confirmed the scientific relevance of the LGSF, and asked to prepare a proposal for equipping with it the VLT Unit Telescope hosting AO systems. A baseline solution has been studied in detail during 1998, for the subsystems of the laser, the beam relay and the launch telescope. The preliminary design activities were frozen in February 1999, except for the studies on a single-mode fibre relay. This was to allow the feasibility of the fibre relay system to be thoroughly investigated before proceeding further.

The past months have been spent on the development of a prototype single-mode fibre relay system, from the laser output to the launch telescope. The fibre-optics industry has been involved in order to have access to state-of-the-art fibre production technologies. We have used a 532 nm, 5W Continuous Wave (CW), *Verdi** laser from Coherent GmbH, to do the laboratory experiments and studies. The results of our studies and tests so far indicate that the fibre relay solution, although not as easy as it seems, is feasible and also very attractive. We plan to conclude this development with working fibre relays in June 2000, and resume LGSF detailed design activities in the summer 2000. Assuming that funding is forthcoming as planned, one could envisage commissioning of the LGSF on the VLT by the end of 2003.

A brief explanation of the baseline LGSF design is given below and represents the present conceptual design around which we are working. It is likely to be modified somewhat during the preliminary and final design phases.

4. High Level Operational and Functional Requirements

The LGSF is seen by the AO instruments as a telescope server facility. It is therefore compliant with the VLT requirements/standards and integrated hardware and software with the telescope environment. The AO systems (NAOS and MACAO) on UT3 will be able to send basic commands and receive the diagnostic status.

The LGSF will never take independent initiatives except for safety reasons, such as air-traffic alerts from the dedicated monitoring camera. In this case, it notifies to the clients that it is going to shut down the beam propagation before doing it.

Concerning light pollution from the LGS, work is in progress to determine it quantitatively (Delplancke et al., 1998). The monochromatic laser beam scattering does not disturb the IR instruments. The operational scheme proposed is to create an area-of-avoidance around the laser beam: the LGSF monitors the pointing of the other Paranal telescopes, and creates an alert status

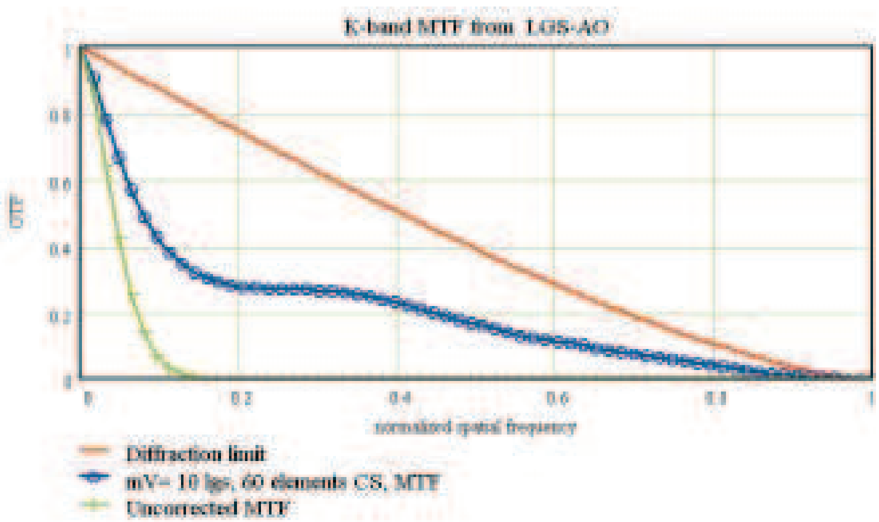

Figure 6: MTF in K-band, for the VLT with uncorrected seeing, LGS-AO correction, and the perfect telescope

*The *Verdi* is an all-solid-state diode pumped Nd:YVO4 laser, recently produced by Coherent.

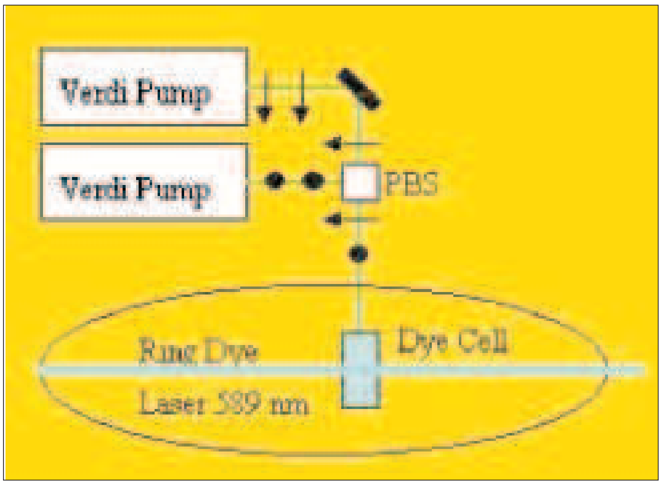

Figure 7: Baseline laser conceptual scheme. Two solid-state pump lasers are combined in a single beam, 20W at 532 nm, pumping a ring-dye resonator laser, using Rodhamine 6G as dye and servo-tuned to 589 nm.

when another telescope is pointing close to the cone-of-avoidance. The actions to take in this case are still to be decided.

The LGSF is required to produce a m_V = 9.5 equivalent artificial reference star with a FWHM of 1.5″ (seeing limited as goal). For median Paranal seeing, down to 60 degrees zenith distance, a 6.5W CW Sodium laser will serve the purpose. For worse seeing conditions, or in the presence of thin cirrus clouds, a laser power in the range of 10W would be preferable.

The LGS has to be independently pointed within 20″ from the defined optical axis of the VLT, with a relative pointing accuracy of 0.3″. Automatic focussing of the LGS on the sodium layer will be performed, up to zenith angles of 60 degrees.

The safety measures of the LGSF will comply with the Paranal observatory strict safety regulations, Chilean law, and the FAA regulations as applicable in Chile.

5. LGSF Baseline Design Solution

The baseline solution study has divided the LGSF into three different subsystems: (a) the laser room, including the laser and its servo-controls, (b) the beam relay and (c) the launch telescope with its diagnostics. We report here briefly on (a) and (c). A companion article in this issue describes the prototype fibre beam relay subsystem in detail. We will report in future issues of *The Messenger* design details on subsystems (a) and (c).

We propose to use a relatively low-consumption laser (4KW), and to build a thermally stabilised laser room under the Nasmyth platform of UT3. The laser choice takes into account commercial availability, support, stability and servicing issues, so as to minimise the LGSF operation and overhead costs.

The baseline solution for the relay of the 20-mm-diameter laser beam from the laser room to the launch telescope could in principle use flat mirrors in a shielded light-path. The laser beam would be hidden behind one of the secondary mirror (M2) support spiders when crossing above the primary mirror. The mirror relay system was investigated in detail. It is cumbersome and difficult to implement in practice. Turbulence effects in the relay path as well as dust contamination and thermal effects on the optics, can degrade the LGS quality considerably. Air tightness, several servo-controls and also frequent maintenance would be necessary.

The alternative solution for the laser relay we propose uses a 30 m long, single-mode optical fibre. This is an innovative solution and not easy, given the power densities involved: one Watt of injected power in a 5.5 micron core fibre corresponds to a power density of 4 MW/cm^2. We have found a viable solution to this problem. It will deliver a diffraction-limited beam at the launch telescope input, with >70% throughput. The use of a single-mode fibre would result in savings in laser power, money and manpower.

A 50-cm diameter laser launch telescope is located behind M2. The aperture is dictated by the optimisation of the LGS beam diameter for the best Paranal seeing conditions. The projected beam diameter will be adjusted to the actual seeing conditions. The telescope is a polychromatic reflective design, which allows the LGS to be positioned within a 1-arcminute field on the sky, with a visible monitoring camera. Figure 1 shows a schematic diagram of the foreseen setup.

The level of automatism to be built into the LGSF is large, in order to allow routine and reliable operation at the VLT. This increases the initial cost and complexity of the facility, but we believe it will prove highly beneficial later, during operation. A number of servo-systems and automatic computations are planned, based on dedicated hardware/software.

6. Baseline Laser and Laser Options

Only a complex micro-macro pulse modulation scheme would allow slightly greater flux returns from the mesospheric sodium than a CW laser (Milonni and Fugate 1997). Considering that CW lasers are intrinsically more stable and simpler, that coatings for CW lasers

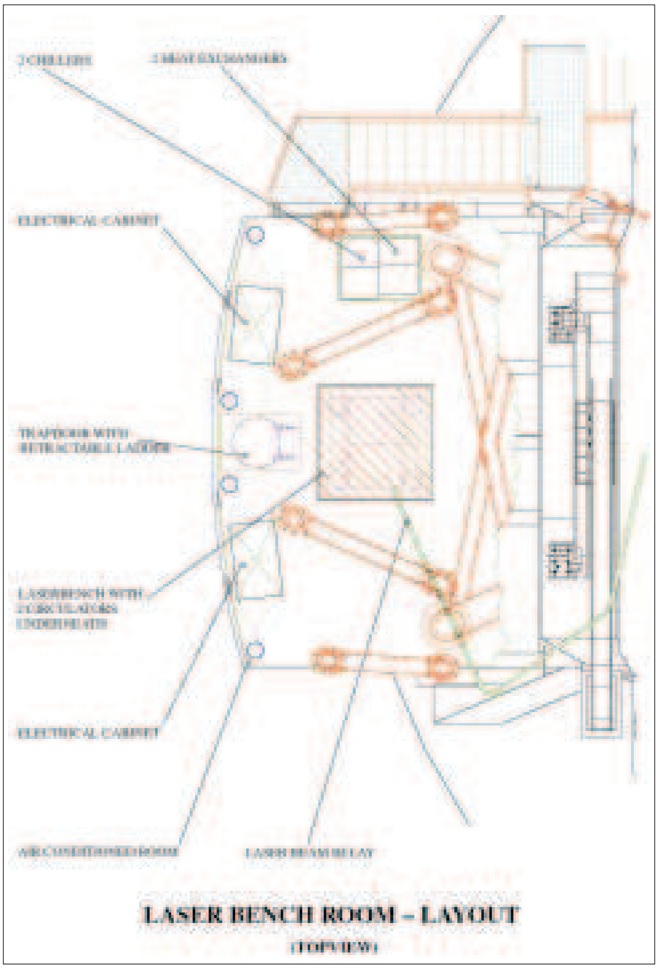

Figure 8: Layout of the laser room designed, with the laser optical table and the necessary accessories. The room is thermally isolated and conditioned.

are less demanding, and that CW lasers safety issues are easier to handle than for pulsed lasers, we are concentrating on CW lasers solutions.

The baseline laser is a modified version of a commercial product from Coherent, made of two 10W Nd-YV0$_4$ CW Verdi diode laser pumps at 532 nm, combined into the Coherent jet-streamed ring dye resonator model 899-21, using Rhodamine 6G as dye. The general advantages of solid state lasers as compared to ion-lasers for pumping, are the much higher conversion efficiency and greater compactness.

In addition the wavelength of frequency-doubled light from Nd-doped laser crystals is around the maximum of the absorption spectrum of Rh6G, whereas the light of argon-ion lasers is clearly off the absorption peak.

This laser configuration delivers > 6.5W of CW power on a 20 MHz FWHM TEM$_{00}$* line, or a LGS with $m_V \cong 9$ after beam conditioning. A similar ring-dye laser has proven to be robust and stable during the past years at Calar Alto.

The laser line is broadened to 500 MHz, to avoid both the saturation of mesospheric sodium atoms and non linear effects in the fibre.

We have the capability of doubling this power in the future, by adding two such laser systems on the same optical table. This scenario would produce 13W CW of sodium laser power, and would use two independent single-mode fibres to relay the beams to the launch telescope. The orthogonally polarised beams at the fibre output would be combined in the launch telescope.

For safety and operational stability reasons, the laser bench would be installed in an isolated room underneath the Nasmyth platform. This room also contains the dye solution chiller, the pump laser heat-exchanger, two electronics cabinets and workspace for maintenance work (Fig. 8).

The dimensions of the laser room allow convenient access to the optical table. The room is temperature stabilised and supplied with filtered air to avoid contamination of the optics. In order not to impact on the telescope seeing the laser room is thermally insulated, with the outer walls at the same temperature as the air in the telescope enclosure.

Vibration, air turbulence, temperature variations and dust contamination directly influence the line width as well as the power and beam-pointing stability of a jet-streamed dye laser. The dye-laser oscillator therefore is installed in a fixed spatial position on a rigid optical table that de-couples the laser head from vibrations, e.g. when the telescope is moving.

Figure 8 shows the layout of the laser room together with the accessory devices. The laser optical table size is chosen so as to allow a later addition of a second 6.5W laser. The room is thermally isolated and conditioned.

The total mass of the laser bench equipment is estimated to be 1.3 metric tons. We estimate the entire laser room to weight not more than 4 tons. An analysis of the static and dynamic impact of the laser room mounted under the Nasmyth platform on UT3 has been done and found to be negligible. The power, communication and cooling budgets have indicated that one VLT Service Connection Point (SCP) will be sufficient for the laser room.

*TEM$_{00}$ is the fundamental Transversal Electromagnetic Mode of the resonator.

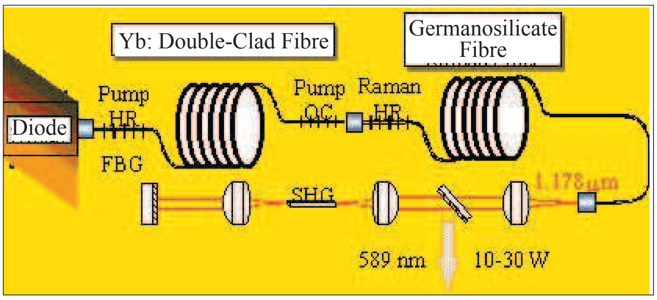

Figure 9: Fibre laser layout. The pump laser is a diode-pumped double-clad Yb-doped fibre that outputs 1.1137 µm. The Raman is a high-delta germanosilicate single-mode fibre, which is directly coupled to the pump fibre. Feedback for both the pump and Raman fibres are provided by FBGs. The second harmonic of the 1.178 µm first Stokes is generated within the fibre Raman laser cavity, and is ejected by a dichroic mirror. (Courtesy J. Murray, LiteCycles Inc.)

7. Alternative Laser Choices

Two alternative laser choices are currently being monitored.

One solution, in which the fibre itself is the laser, is being studied by Litecycles Inc. (Murray et al., 1998). This is still in the feasibility phase and it has

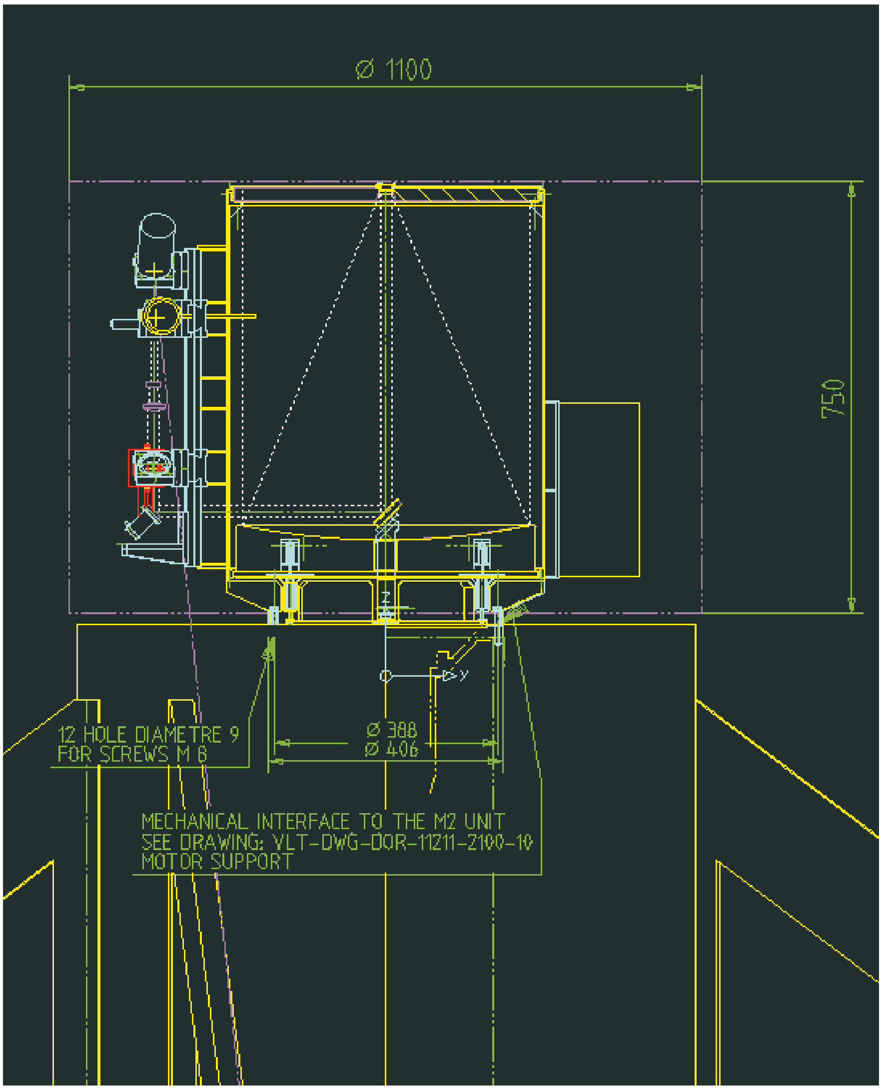

Figure 10: The launch telescope is a 25X beam expander. It is mounted behind the M2 unit, together with its accessory beam monitors: power, alignment, polarization meters, and beam pointing/focussing servos. Two cameras are present, one to monitor the LGS in the field, and one for air-traffic surveillance.

recently attracted the interest of the Gemini AO project as well. The concept is shown in Figure 9.

Two 100W CW laser diode-bar arrays are used, efficiently coupled in a double-clad Yb-doped fibre which outputs >50% of the input power at 1.1137 μm from the single-mode fibre core. The Yb-doped fibre is fusion-spliced with a single-mode germanosilicate fibre 1 km long. The Stimulated Raman Scattering (SRS) effect in this long fibre is used to stretch the wavelength and tune it to 1.178 μm, i.e. twice the 0.589 μm of the D_2 sodium line, by the use of fibre Bragg gratings (FBG) written on the fibre and servo-tuned by piezos. The fibre output beam is focused on a second harmonic generation crystal (SHG) for intracavity doubling, which will convert the 1.178 μm photons to 0.589 μm. The longitudinal mode spacing of such a long fibre Raman laser is 100 kHz, giving a truly broad-band excitation of the mesospheric sodium. The goal for the line FWHM is ≤ 2 GHz, and the CW output power should be in excess of 10W CW, with a goal of 30W. However, an unpolarised sodium 2 GHz laser line would return about half the flux of a 20 MHz FWHM line. A 10W broad-band laser would therefore be equivalent to 5W of 'narrow-band' power. Perceived risks of this technology are the larger than expected linewidth, excessive non-linearity (Stimulated Brillouin Scattering) losses and a lower than expected efficiency of the intracavity SHG crystal. We are taking advantage of our models of the non-linear effects, developed for the fiber relay studies, to further investigate this laser design.

The great advantages of this solution are that the single-mode fibre output plus frequency doubling crystal give a high beam quality, the long fibre length (1 km!) allows the laser source to be placed far away from the telescope, in a VME-rack sized box. If this laser would be commercially available, it would be the ideal solution.

The second laser choice under investigation is a recent development at MPE in Garching. It is a two-stage laser with a seeded dye-laser amplifier which would deliver at least 10 W CW with 500 MHz line width. This laser would give an equivalent LGS magnitude $m_V = 8$.

8. Launch Telescope

The input interface to the launch telescope (LT) is a collimated beam 20-mm in diameter. The output is a diffraction limited spot at 90 km altitude with the possibility to focus it between 70 and 200 km. The LT optical quality specification is to have a Strehl ratio >0.95 within 10 arcsec of field radius, and with 80% encircled energy diameter of 0.7" within 1 arcminute field radius. This is required to ease the alignment tolerances and to have a CCD monitoring camera looking at the surrounding sky field (notching out the LGS). The launch telescope is thus a 25X beam expander. We have explored a reflective solution based on a two-parabolic-mirror stigmatic design and verified the feasibility of its opto-mechanical tolerances. Lightweight mirrors can be used; the total weight of the LT and its structure is estimated to be 80 kg.

A wedged, anti-reflection coated exit window provides shielding from turbulence and dust, and a 10^{-3} laser flux return, to monitor the exit beam quality and power. We will also monitor the beam polarisation state and its frequency spectrum. The volume from the fibre end to the exit window is airtight.

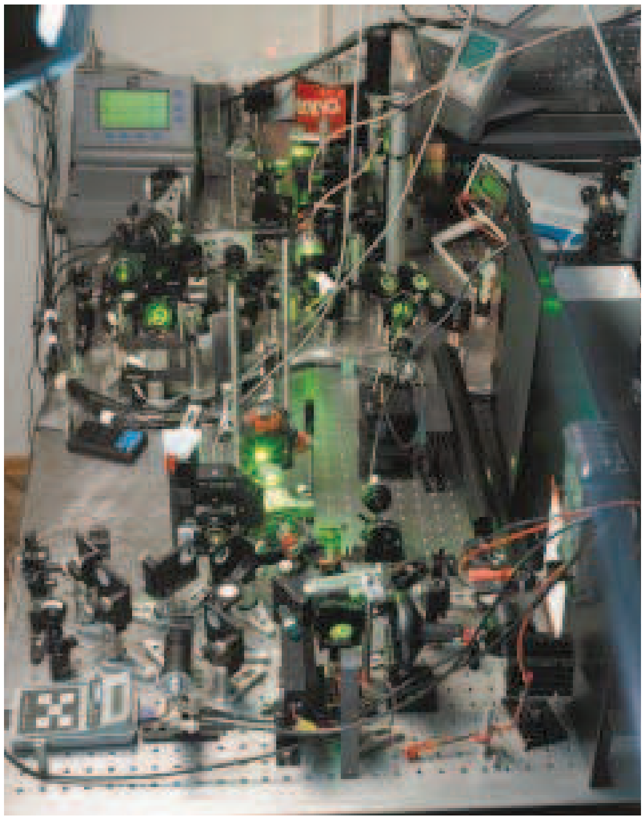

Figure 11: View of the laboratory setup where the fibre experiments have been carried out. The setup allows the measurement of the spectrum, power and propagation properties of the laser beam. The injection, fibre output and SBS return beams can also be characterised.

The space available behind the UT3 secondary mirror is limited and we are forced to expand the beam by a factor 25 within 600 mm of design space. The current design is shown in Figure 10. It delivers a very good performance with a central obscuration of 0.7% in area for a 2-arcminute-diameter field (see Table 1). However it has tight tolerances and requires an athermalised design: its feasibility has been checked. We will also have to introduce alignment diagnostics. The pointing has to be remotely controlled within a minimum range of 1 arcmin radius. Fast steering is also necessary to compensate the LGS jitter induced by the atmosphere on the upward-going 50 cm beam which differs from the downward path toward the collecting 8-m telescope. The expected rms jitter is 0.34 arcsec for the median Paranal atmosphere and therefore a fast steering range of ± 2-arcsec is specified. The steering signal is provided by the AO high order WFS that is looking at the LGS. The bandwidth of the steering device has to be better than 200Hz at –3dB.

The pointing and steering would be done at the level of the fibre output. The range of fibre motion is ± 0.79 μm for slow pointing with 0.1 μm precision, and ± 12 μm for fast steering. Commercial devices are available which meet these specifications together with their control electronics.

We plan to enclose the launch telescope and its liquid-cooled electronics in an aerodynamic wind-shield, behind M2 unit. The static and dynamic impact on M2 structural stability have been studied and shown to be negligible.

Conclusion

The conceptual design of the LGSF has been completed and the main interfaces with UT3 as well as the environmental and structural impacts have been assessed. Further optimisation will be carried out in the next phases. Laser beam relay system designs using both conventional optics and monomode fibre have been explored. This latter solution has many advantages

Table 1: Launch Telescope Design – Optical Performance

	Design Requirements / Value Achieved	
Field	10 arcsec radius	1 arcmin radius
Strehl Ratio at 589 nm	>0.95 / 0.99	-- / 0.975
80% Encircled energy diam. (")	-- / 0.45	0.7 / 0.5

and we now feel confident that this solution can be adopted.

We have however to finish the tests of the final fibre-relay modules in the laboratory. A burn-in test is being discussed with MPE, to be performed with the 4.5W CW sodium laser at Calar Alto. After these tests have been satisfactorily completed, the detailed design activities for the LGSF can be resumed by the second half of next year, pending approval by the ESO management.

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VLT Laser Guide Star Facility Subsystems Design

Part I: Fibre Relay Module

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The advantages of the LGSF fibre relay approach are twofold: (1) we avoid the cumbersome optomechanical relay, and (2) transfer a diffraction limited beam. The opto-mechanical relay system would require a sealed tube for the laser beam optical path to avoid turbulence and dust contamination, with air-tight sliding joints at the elevation axis, two servo-controlled steering mirrors to keep the optical alignment and several safety interlocks if the beam has lost alignment. Point (2) is very important, as much effort needs to be spent to ensure a good beam quality. Assuming the LGS is an extended object, the adaptive optics wavefront sensor error is proportional to the area of the LGS divided by its flux. As it is both costly and difficult to increase the laser power, all possible efforts have to be taken to minimise the LGS spot size, i.e. the laser beam quality. Some laser relay systems in other LGS projects are even considering incorporating active or low order adaptive optics in the laser beam relay optical path, to ensure a good outgoing beam quality.

Incidentally, injection of high laser power in a single-mode fibre is very useful in long distance fibre communication systems to save repeaters. In fact, much work has been done and literature is available on the subject (Tsubokawa et al., 1986; Cotter, 1982). However the successful injection of several watts of continuous wave (CW) visible laser power has not been demonstrated for long fibres. As we are concerned with a fibre length of 30 m for the VLT LGSF system, we have been able to achieve this in the laboratory and have also learned a few tricks in the process. A fibre relay (Figure 1) provides a very flexible solution and significantly simplifies the integration. It would also be readily applicable to multiple LGS systems needed for future high-order AO systems on large telescopes.

The potential causes of power losses in the fibre are:

1. Coupling losses from the laser beam to the fibre core. These include Fresnel reflections and laser to waveguide mode mismatches..

2. Extinction losses in the bulk material. In a 30 m long low-loss, pure fused silica fibre, the bulk losses from scattering and absorption are expected to be about 8%.

3. Scattering at the fibre core-cladding interfaces.

4. Mode conversion from low-loss trapped modes to high-loss cladding modes.

5. Stimulated Raman Scattering (SRS).

6. Stimulated Brillouin Scattering (SBS).

7. Four-wave mixing between forward and backward Stokes modes.

Points 1 and 6 are the most important causes of losses in our case.

The basic requirements of our fibre relay system (Fig. 1) are:

(i) stable throughput above 70 % over 30 m for 589-nm CW laser light in the multi-Watt regime

(ii) diffraction limited output for the smallest possible LGS spot size

(iii) polarisation preserving.

The latter allows the output of several fibres to be combined, and to circularly polarise the light for the optical pumping of the mesospheric sodium atoms. In order to achieve these requirements, three fundamental problems have to be solved:

1. Efficient coupling of a free-space laser beam into a small-frame optical fi-