ELT LGS-AO: Optimizing the LGS Return Flux

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Abstract. For the ELTs the use of AO with multiple sodium Laser Guide Stars will be routine. We think it is important to study the LGS generation in order to optimize the LGS-AO systems. It is in this context that we are working on the understanding and optimization of the laser parameters. In this paper we report on a part of our LGS return flux studies, aimed at identifying the optimal laser formats for CW and pulsed lasers. We have done recently numerical simulations on the LGS return flux for different laser formats, solving the Bloch equations for the interaction of the mesospheric sodium atoms with the laser radiation. The simulations have been used for the design of the future ESO LGS facilities. However the simulations need to be validated. We report on the ESO Wendelstein transportable 20W LGS unit, recently built and commissioned to make systematic field studies on the LGS. The first experimental results on the LGS return flux obtained during the commissioning are reported.

1. Introduction

At ESO our laser group is working on the understanding and optimization of the laser parameters for maximum LGS return flux. We have done recently numerical simulations on the LGS return flux for different laser formats, solving the Bloch equations for the interaction of the mesospheric sodium atoms with the laser radiation [1,2]. Also other authors have simulated the LGS return flux [3]. The simulations need to be validated with field-tests.

Taking advantage of the internal laser developments, we have designed, built and tested the transportable 'Wendelstein' Laser Guide Star Unit (WLGSU), in collaboration with industry. The WLGSU has been commissioned in 2011. It has the objective to make at different astronomical observatories field experiments on a number of LGS-AO aspects, as well as to field-test the new fibre lasers developed originally at ESO labs [5, 6] and lately with industry.

The WLGSU commissioning has been done at the public Allgäuer Volkssternwarte Ottobeuren (AVSO) in Bayern, Germany. With it we have started to test the LGS return flux vs laser optical parameters. The first return flux experimental results obtained during the Commissioning at AVSO are reported in this paper, which was presented as a conference poster.

2. Scientific Rationale on LGS Return Flux

From the simulation work it is evident that the LGS return flux (RF) depends measurably on the spectral, temporal, and polarization properties of the laser beam generating it. We have built the WLGSU laser in a way that it is possible to vary fundamental parameters such as linewidth, D2b re-pumping, temporal format. Our LGS return flux simulation results are used as basis for the determination of the laser parameters of the ESO future LGS facilities. It is of strategic importance to validate the simulations experimentally in the next years and to determine the optimal laser emission parameters. The main areas to be looked upon with field tests on LGS return flux are:

2.1. LGS Return Flux vs ALT-AZ and Polarization

The LGS return flux depends on the beam optical polarization state as well as on the angle θ(**B,S**) between the laser photons propagation vector **S** (Pointing vector) and the local geomagnetic field vector **B**.
Optical pumping of the sodium atom to the most efficient transition is obtained via circular polarization of the laser beam, but it is hampered by the Larmor precession.

The contours in Figure 1 show the sodium atom return for power densities similar to the ones of the experiment, as a function of polarization ellipticity (abscissa, χ) and field vectors angle (ordinate, θ). The latter changes when pointing the LGS at different ALT-AZ coordinates.

The return flux vs ALT-AZ and laser polarization has to be measured via well calibrated aperture photometry, by mapping the sky and alternating quickly different polarization states.

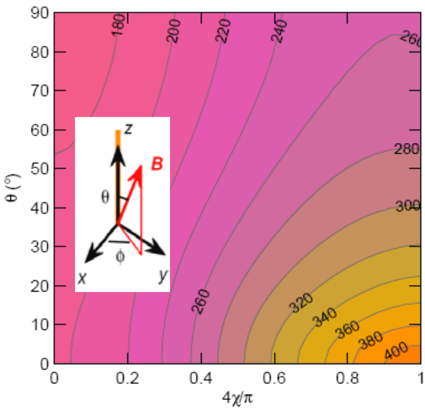


Figure 1: contour plot of ψ, the sodium atom return flux per solid angle, with units ph/s/sr/(W/m^2) vs the Poincare Sphere angle χ in abscissa (0= linearly polarized, π/4=circularly polarized) and the field vector angle θ(**B,S**) in ordinate, for the case of magnetic azimuth Φ=90° and I=46W/m^2 (see [1] for details)

As it depends also non-linearly on the LGS power density at the mesosphere, the measurement has to be repeated for different laser powers.

2.2. LGS Return Flux vs Linewidth

The optimal laser linewidth is allowing efficient optical pumping of the sodium atoms of a given velocity class, avoiding however the saturation by the laser flux. Hence in general with more peak power more velocity classes have to be excited, and the laser linewidth enlarged. Figure 2 shows the efficiency s_{ce} as a function of the laser line fwhm, for 20W peak power lasers pointed in the worst direction ($\theta = \pi/2$). The s_{ce} is the photon flux on the ground corrected for its dependence on sodium centroid height, abundance, airmass, atmospheric transmission and launched laser power [1, 4].

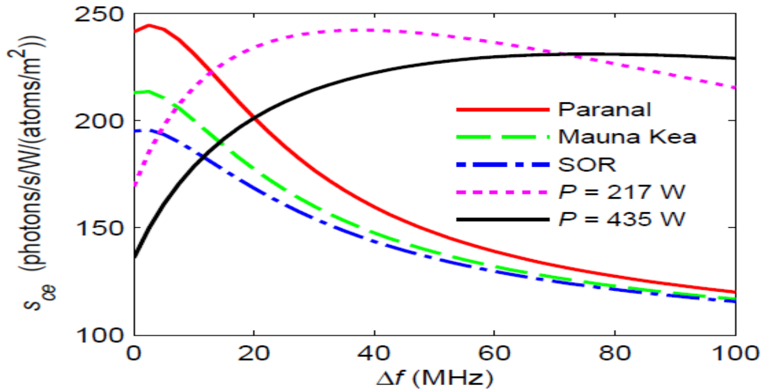


Figure 2: Beam efficiency s_{ce} as a function of laser line FWHM (abscissa) for P=20W laser at Paranal (solid red curve, standard conditions), Mauna Kea (dashed green), and SOR(dash-dotted blue), depending on the local geomagnetic-field strengths (P=20W, θ = π/2). Dotted magenta (solid black): CW laser at Paranal with powers of P = 217 W (P = 435 W), possibly representative of microseconds long pulses peak powers. (see [1] for more details)

2.3. Return Flux vs D2b re-pumping

Experiments have to be done to validate the gain in LGS return flux to be obtained with sodium ‘re-pumping’, i.e. with photons able to rescue electrons which have landed on the ground state F=1 and bring them to the F=2 level for the D_{2a} transitions. This is obtained by adding photons emitted 1.713GHz toward the blue (D_{2b}) of the main laser line emission. The experiment has to vary the laser power and the percentage of the power emitted on the D_{2b} sodium line to assess the optimal re-pumping for a given laser configuration.

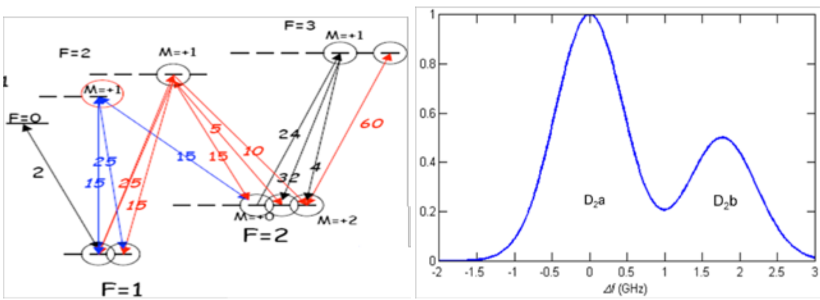


Figure 3: D_{2b} repumping is used to re-inject electrons which have landed in the sodium orbital energy hyperfine ground state F=1 (corresponding to the D_{2b} line) into the F=2 level, corresponding to the more effective transitions of the D_{2a} line

3. The WLGSU

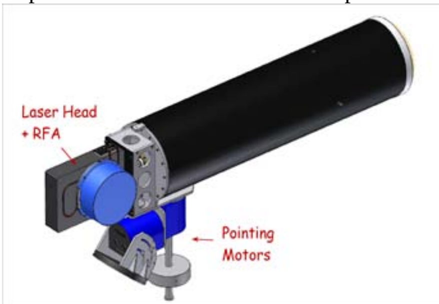
The WLGSU has been built integrating components reused from ESO proprietary fiber laser development prototypes. The Raman Fiber Amplifier, Laser Head and launch telescope subsystems have been built and assembled in collaboration with industry. The design of the laser and of the launch telescope follows for the most part the AOF/4LGSF Laser Guide Star Units design concept, although in an experimental, transportable, somewhat less engineered version, but with extended functionalities. With the WLGSU we have therefore built an experimental system which also verifies some of the 4LGSF LGSU design solutions such as the laser architecture, components and the launch telescope optics. The two electronic cabinets and interlocks have been designed and built by ESO. Extensive tests in the labs have been performed to validate performance, including a 200 hours long-term test and climatic chamber tests. The companies involved to produce the WLGSU subsystems are IPG Corp., MPBC Inc., Toptica AG, Astelco GmbH, Sill Optics.

3.1. WLGSU Main Requirements and Specifications

- The WLGSU has to project >18W CW at 589nm on a 300mm gaussian beam, with a beam quality better than 100nm rms across the full aperture.
- The WLGSU has to remain within the specifications under the operating conditions of gravity and environment loads.
- Temperatures in the range 0-15C and humidities in the range 5-90% are considered operational.
- The launch telescope has to be able to point anywhere on the sky with ALT $\geq$ 20 deg with a pointing accuracy <15 arcsec and a tracking precision <5 arcsec
- The laser output polarization state may be changed remotely, with a range in ellipticity from 0 to 1, in steps of 0.05.
- The Polarization Extinction Ratio shall be $\geq$ 97%, defined as ratio of the desired polarization vs intensity, averaged across the output 300mm laser beam and weigthed by the Gaussian intensity level.
- The Laser linewidth is <5MHz, with the possibility to broaden it up to 25 MHz via remote control.
- It shall be possible to generate and vary the laser emission intensiity on the sodium D_{2b} line, at 1.713GHz from the main D_{2a} emission line, on the same laser beam and with the two lines of same line shape. The D_{2b} emission is remotely controlled and can be up to 30% of the total intensity.
- It shall be possible to operate the laser also in long-pulse mode, with amplitude modulation frequencies between 1 and 700 kHz.
- The WLGSU can be remotely controlled via Ethernet. It uses liquid coooling/heating for the electronic cabinets and for the laser, with a heat exchanger double circuit output set at two different temperatures. The set temperatures are 16±1°C and 18±1°C.
- The WLGSU deployment time is <2 days.

3.2. WLGSU Design, Integration and Verification

The 37kg laser head and the Raman Fiber Amplifier are contained in a volume of 500x350x300 mm^3. The laser head is attached directly to the carbon fiber structure of the 44kg refractive Launch Telescope, which is mounted on an Astelco NTM-500 mount with stepper motors and precision encoders. The NTM-500 is used in ALT-AZ configuration and was installed on a Pier at AVSO. Alternatively it can be installed on a solid transportable tripod. The Sill Optics beam expander unit allows to focus the LGS at the mesosphere. The large output lens L2 on the launch telescope is 380mm in diameter and weighs 22kg.



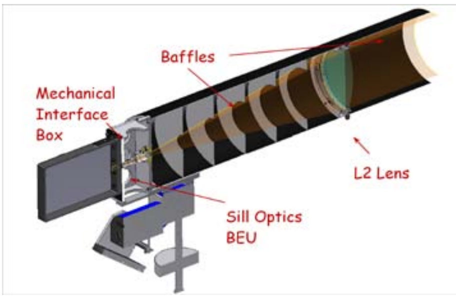
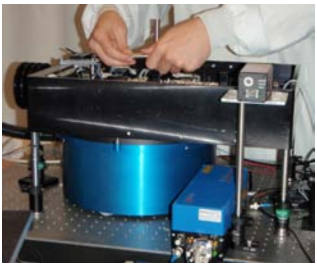


Figure 4: Layout of the Wendelstein Laser Guide Star Unit, hosting the 20W laser head and the launch telescope. The telescope tube and interface is in carbon fiber, with a coefficient of thermal expansion chosen to athermalize the lens system focus. The overall weight of the launch telescope + laser head is <85kg. The launch telescope and the pointing motors NTM-500 are from Astelco Gmbh.



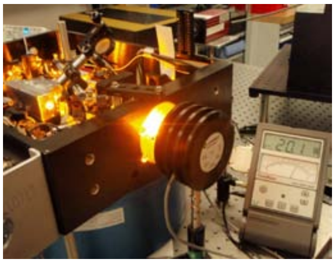
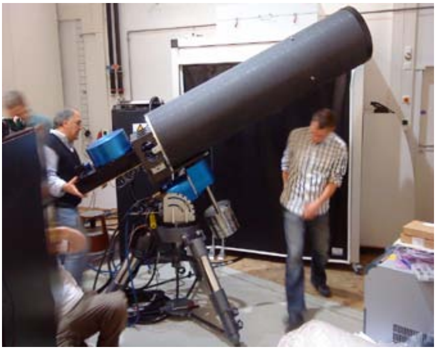


Figure 5: the laser head (left) has been integrated and tested together with the company Toptica Photonics. The Raman Fiber Amplifier is the blue cylinder attached below the laser head. The 20W power emission is shown in the right picture, taken after the exit window, with the laser head open.

During the design phase, Finite Element Analysis models of the Laser Head and of the Launch telescope were produced and optimized. Athermal optimization of the opto-mechanics has been achieved. As shown in the figures of this section, first the laser head and then the laser head on the launch telescope were assembled and their performance verified with quite a number of laboratory tests. The thermal and performance behavior of the fiber Raman amplifier and of the laser head have been investigated via long-term tests (>200 hours at full laser power).



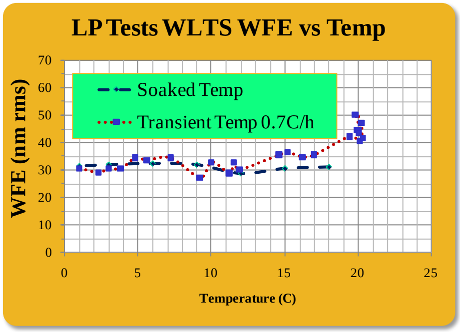


Figure 6 left: the transportable WLGSU installed on a tripod. The Launch Telescope System has been tested in the climatic chamber for soaked air temperatures and transients. Right: the rms wavefront error of the launch telescope has been tested at different temperatures, showing a a good athermalized system and the fulfilment of the specifications (70nm rms)

4. WLGSU commissioning at AVSO

Figure 7: the first light of the WLGSU at AVSO, Bavaria

The WLGSU was installed for commissioning at one of the AVSO domes and had the first light on the night of June 23rd 2011. A 60cm receiver telescope equipped with an SBIG ST-10 CCD and standard Johnson filters was in the second AVSO dome, at 13m distance from the launch telescope. The receiver telescope is used to do photometry.

The summer of 2011 in Bavaria has given very few truly clear nights; nonetheless we could test the WLGSU, calibrate it, observe and derive the first results on return flux in the North-South meridian. We had obtained permission from the German aviation authorities to propagate the laser beam from 23:30 to 5:00, above ALT=45°.

The WLGSU performed rather well, besides the thermal cycles with temperatures in the dome between 7 and 37 °C. We fine tuned during commissioning the pointing and focusing as well as the observing procedures and the data reduction SW. With the receiver telescope, images containing reference photometric stars next to the LGS were obtained, for different laser configurations and pointing directions in the available pointing range.

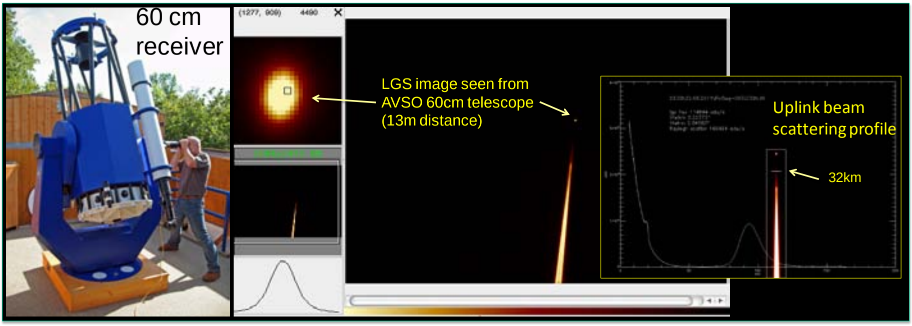


Figure 8: Using the SBIG camera on the AVSO 60cm receiver telescope (left) we acquired sky images containing the LGS, the uplink beam and calibrator stars for the photometry.

As shown in Figure 8 to the right, besides the LGS photometry the uplink beam scattering profile was derived via our automatic recognition SW, in order to deduce the high altitude scattering. The high altitude scattering is used by Lidar experimentalists to derive online the atmospheric throughput. We are considering if this method may be used to derive the sodium abundance from the observed LGS brightness at low laser power. The observations which we could do were scans of laser polarization and re-pumping for different Zenith distances of the LGS on the North-South meridian.

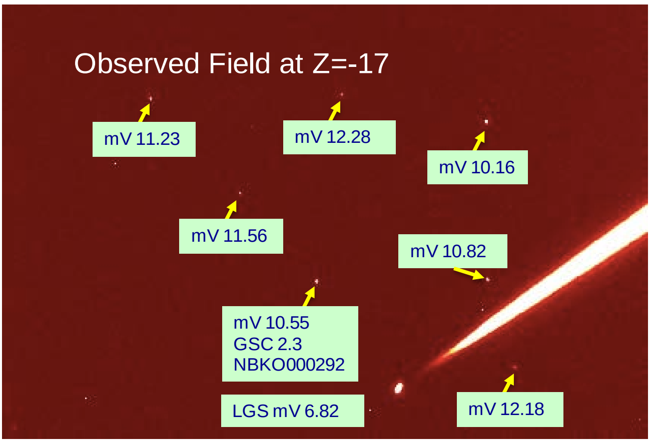


Figure 9: typical 5sec exposure CCD image of the LGS, the uplink beam and the magnitude calibration stars, obtained during the commissioning runs at AVSO. The colour table is saturated to show the stars of faintest magnitude detected. The LGS V-magnitude in this frame was m_V=6.82, with the laser emitting circularly polarized light and the D_{2b} line. The field of view is 10.56’ x 7.11’

We have obtained during the WLGSU commissioning at AVSO a total of 5 nights of photometric data. We could well calibrate the LGS photometry but not measure the sodium abundance; however, based on published sodium abundance statistical data, we have simulated the expected LGS return flux and compared it with the observations. One such result is shown in Figure 10, for a scan in LGS pointing Zenith angle while alternating linear and circular polarization of the laser light. The average seeing was 1.6". Judging from the plot it seems that during the night the sodium abundance has increased progressively during the 3 hours of observation. The statistical data basis is too small to draw final conclusions on whether there is very good agreement between simulations and experiment, as far as absolute return flux is concerned. Nevertheless we have achieved and exceeded at AVSO the return flux specification for the E-ELT baseline (12 Mph/s/m^2 at Zenith on the ground).

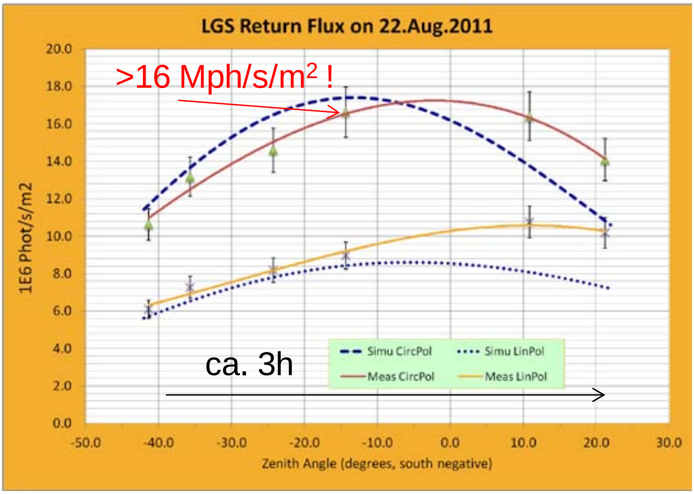


Figure 10: LGS return flux measured for circular and linear polarizations (triangles and crosses) compared with the simulations (dashed, dotted lines), as a function of the Zenith position on the principal meridian.

The commissioning of the WLGSU at AVSO in Bavaria was successful. We demonstrated at AVSO good field performance of the WLGSU and got first scientific data. We need now to obtain much more statistical data in Paranal and at other observatories in order to properly validate the sodium interaction models and the LGS return flux simulations for different laser emission parameters and pointing coordinates.

5. References

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