The *Laser Guide Star* TMR network of the European Union

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1 The *Laser Guide Star* network

There are still a lot of problems to address before the laser guide star is in regular operation at the largest telescopes to feed adaptive optics in the infrared as well as in the visible, whatever the gain in the variance of the phase error of the wavefronts. In particular in Europe several institutes are working about several of these problems, either from the point of view of theoretical studies, or from that of experiments, including experiments on the sky. These institutes have proposed to the European Union (EU) to fund the "Laser guide star for 8 meter class telescopes" network to work together in a coordinated way. The EU agreed to fund it, through its Training and Mobility for Researchers (TMR) programme.

Participating institutes are CRAL/Observatoire de Lyon (leading), European Southern Observatory (international organisation, Germany), Imperial College (UK), Instituto de Astrofisica de Canarias (Spain), Max-Planck-Institute für Extraterrestrische (Germany), Osservatorio Astrophysico de Arcetri (Italie), and National University of Ireland at Galway (NUI-G). Two institutes are associated partner and subcontractor: Laboratoire de Spectrométrie Physique (LSP) and Laboratoire d'Astrophysique de l'Observatoire de Grenoble, both in France.

The LGS network is a 4-year programme, which started in January 1997. The total funding is $\approx$ 1.6 million ECUS ($\approx$ 2 million US$). Most of this funding is devoted to salaries for postdocs and networking costs. 438 men.months (378 men.months for postdoc positions, and 60 men.months for PhD student grants) are funded and distributed among the seven partners. In addition, the participant institutes commit themselves to devote an effort of 531 men.months as a whole from their staff. Then the total manpower in the LGS networking amounts to almost a thousand men.months.

The planned tasks of the LGS network are divided into the following five workpackages.

Science trade-off: studying the science which is expected with a laser guide star at a very large telescope: which astrophysical programmes and LGS constraints.

Simulation code for AO-LGS system: providing a package of codes necessary to simulate the different steps or processes involved in the laser guide star concept. All the package modules will be cross-compatible. In particular the package will include all the modules necessary to run an end-to-end simulation.

Operational issues: addressing the problems related to operational issues, such as safety (staff, airplanes, satellites), light pollution (detectors, on-site telescopes), laser technologies, infrastructure requirements and operational costs, tuning of the point spread function, ...

Advanced wavefront sensing: improving the efficiency of the wavefront sensing: tilt measurement, as with the polychromatic guide star or with the perspective method, field widening as a benefit from the correction for the cone effect, and optimisation of the wavefront sensing (both hardware and algorithms)

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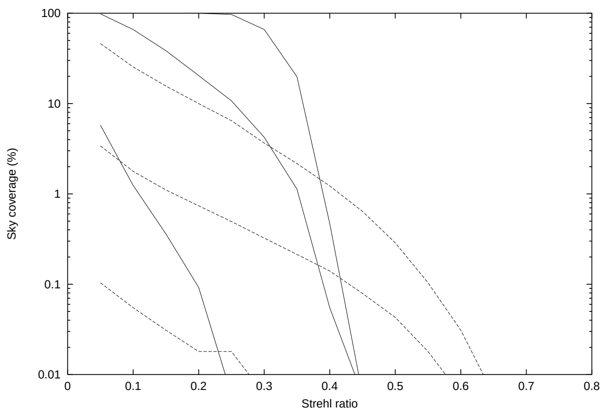

Figure 1: Sky coverage as a function of the Strehl ratio with a LGS (solid lines) and with a NGS (dashed lines), for galactic latitudes $b = 0$, 20, and 90^o from top to bottom. Optimistic seeing model; J band ($1.25\,\mu$ m).

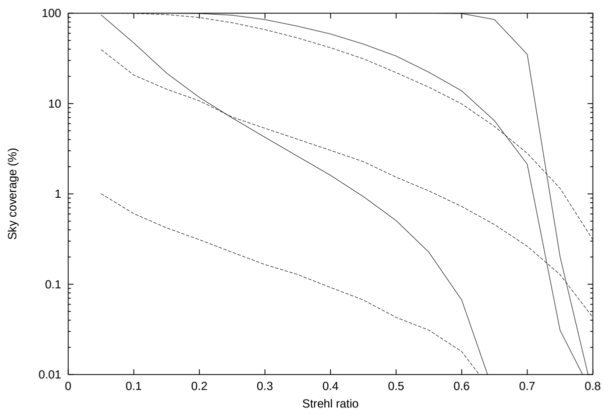

Figure 2: Same as Fig. 1 but for the K band ($2.2\,\mu$ m).

Experimental feed-back: using of the feed-back expected from the experiments carried on by the participants, such as the measurements of the seeing vertical distribution (Vernin & Muũnoz-Tuñón 1995), and the LGS - adaptative optics experiment ALFA (Quirrenbach et al. 1997) and ELP-OA.

In the following I will review the current progress of these worpackages in our whole network.

2 Science trade-off

A detailed study has been done to determine the Strehl ratio and the sky coverage for different values for the wavelength λ , the D/r_0 value (where D is the telescope diameter and r_0 the Fried parameter), the galactic latitude and few other parameters. This study (Le Louarn et al. 1998a) relies on an analytical code using previous works (Sasiela 1994; Parenti & Sasiela 1994; Rousset 1993; Greenwood 1979).

In both the J and K bands (see Fig. 1,2), the sky coverage is satisfactorily in the galactic plane. An increase in the sky coverage at low Strehl ratio S in particular in the J band is provided with the LGS. But the cone effect (Tallon & Foy 1990) causes the LGS sky coverage to drop at $S \lesssim 0.4$ (Le Louarn et al. 1998b; Le Louarn, Hubin, & Foy 1997). At shorter wavelengths, the sky coverage is close to 0.

The same kind of study as also been done no longer statistically, but running crosscorrelations of catalogues of different types of objects of prime astrophysical interest, as quasars, active nuclei of galaxies, pre-main-sequence stars, and evolved long period variable stars (Table 1). It shows that even in the K band, the imaging capabilities of an adaptive optics device as NAOS at the VLT with $S = 0.2$ are marginal for quasars. In the J band, it si clear that in particular the cone effect prevents a wide use of the LGS. But in the K band, the benefit with the LGS is significant.

Strehl ratio The Strehl ratio has been modeled as a function of the magnitude of the natural guide star and of the natural reference for the tilt star, again in the case NAOS at the VLT. In the photon noise regime, the Strehl ratio is lower with a LGS, as already pointed out, because of the cone effect. At high magnitudes, the LGS Strehl is higher, because of the lack of photons in the case of the NGS. The LGS Strehl rapidly vanishes beyond magnitude 20 because the tilt correction has to rely on a NGS. It is worthwhile noting that the gain with the LGS is ≈ 4 magnitudes.

The programme of this Workpackage is almost completed.

Table 1: Number of objects in class given in Column 1 in the J and K bands for which a Strehl ratio $S \geq 0.2$ with an adaptive optics with (LGS) or without (NGS) a laser guide star, at an 8m telescope under medium seeing conditions. The subscript *min* means that stars are considered at the minimum of their light curve.

Class	K		J	
	NGS	LGS	NGS	LGS
QSO	21	2893	0	0
AGN	315	1393	68	0
PMS_{min}	127	624	14	0
VLP_{min}	1342	3148	371	0

3 Simulation code

The initial task of the simulation code workpackage has been to collect and evaluate the performances of existing software modules within the research network. In parallel, the network needs have been listed, from which a preliminary list of required software modules has been set-up. Also the standards of the software architecture have been chosen.

The purpose of the package is to allow the simulation of various processes involved in the laser guide star or laser guide stars formation and observation. It will allow also end-to-end models. Each of the elementary modules of the code can be addressed independently, through an instance; it can be initialized; it can neeed input data from other modules; it can produce output data either towards the user interface or to other modules. A project made of an ensemble of modules can have one or more instance(s) of the same module class, e.g.: multiple LGS (Fig 3).

The programme interface runs in IDL. It generates IDL source programmes and macro-applications (see for a schematic view Fig 4).

Achievements

End-to-end analytical code An end-to-end analytical code has been developed (Le Louarn et al. 1998a). The aim of this analytical code is to evaluate the performance of an adaptive optics system, equipped with a LGS. The performance are evaluated in terms of Strehl ratio and FWHM of the image. The code assumes a Shack-Hartmann type wavefront sensor and a piezo-stack deformable mirror. A separate tip-tilt correction loop is done on a natural guide star. It is assumed that the LGS is at a fixed altitude neglecting Sodium altitude variations.

Phase screen generation and propagation code A phase screen generation code is developed. Its is based on FFT and low spatial frequency compensation and geometrical propagation. Another one relies on a fractal method. Also an upgraded three dimensional propagation code using Fresnel propagation is developed.

Wavefront sensor codes Three codes to simulate wavefront sensors have been upgraded and added in the network package; two of them correspond to the Shack-Hartmann and curvature sensors; the third one is for the global wavefront reconstruction (Cannon 1995).

The β release of the core of the simulation package will be distributed among the network partners this fall.

4 Operational issues

The tasks in this workpackage include various operational issues that have to be solved in order to operate a laser guide star AO system in an efficient and safe way.

Safety During 1997 ALIENS (Aircraft Light Imaging Emergency Notification System) has been installed and optimized for operation with the ALFA LGS-AO system. ALIENS detects aircraft by comparing successive frames taken from a visual CCD camera and applying image processing techniques to identify planes and suppress the detection of other moving objects.

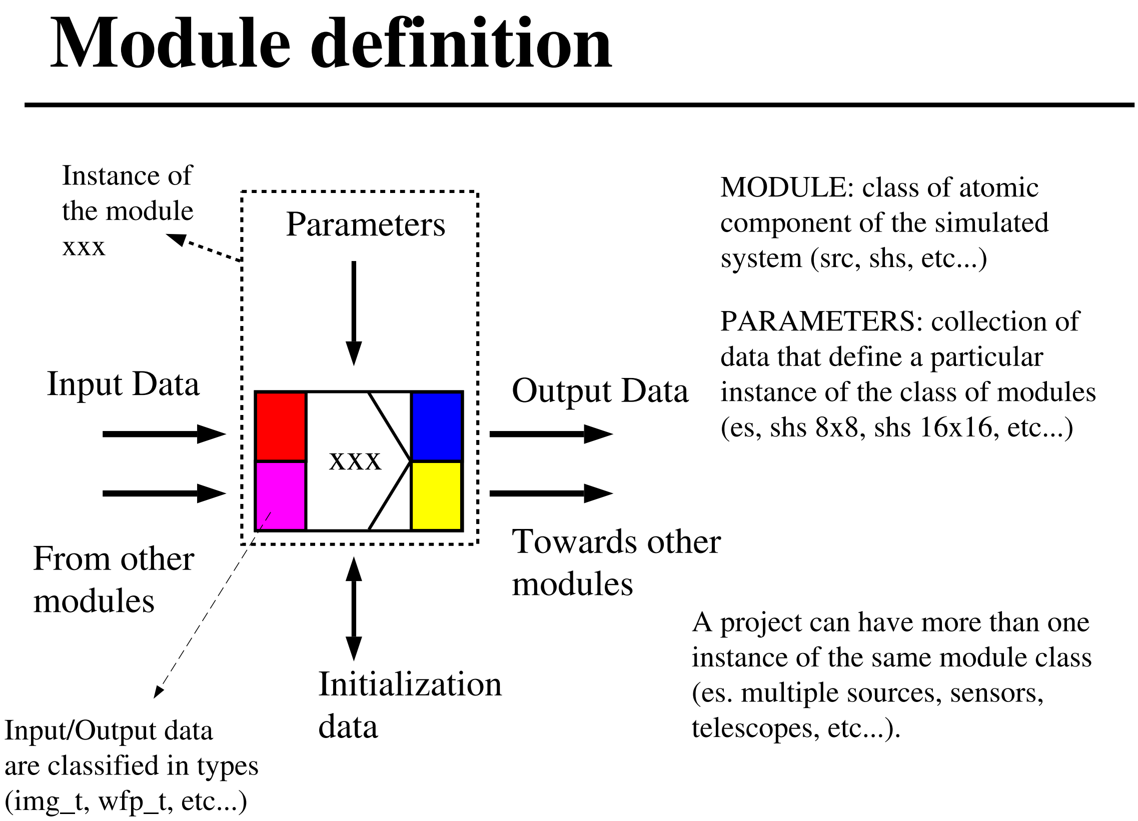

Figure 3: Scheme of the module interfaces in the Simulation Package interface (Esposito, private communication).

Light pollution The TRIFFID camera of NUI-G was used in September 1997, coincident with the ALFA laser as a preliminary experiment to measure light pollution by phase-sensitive detection of multiply-scattered light. The preliminary experiments were successful, but limited in scope on the small telescope (Delplancke et al. 1998). A larger telescope will be used to make measurements far away from the direction of the direct Rayleigh-scattered beam.

Laser type and configuration Studies for dedicated laser components have been done at LSP (Grenoble), in particular on CuHBr lasers (Coutance, Naylor, & Pique 1995; Coutance & Pique 1998), and on modeless lasers to allow pulsed dye lasers to match the Doppler profile of the D_2 sodium line. Other possibilities for the oscillators based on non-linear crystals have been studied. The goal is to obtain relatively low costs components.

5 Advanced wavefront sensing

The first generation laser guide star (LGS) systems on 8-m telescopes will be systems with a single LGS, and a natural guide star (NGS) for tilt sensing. Using a single star means that one is limited by the cone effect. In Section 2 it is one clearly shown that one needs a solution to the cone effect, in order to go to shorter wavelengths, and a solution to the tilt determination problem to increase the sky coverage.

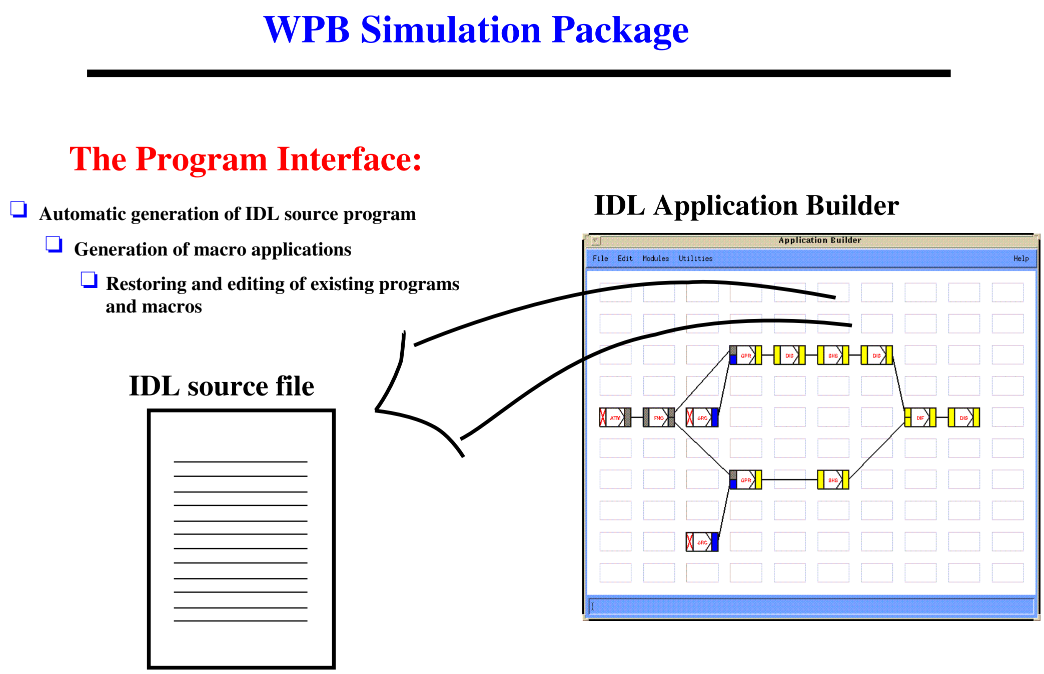

Figure 4: Scheme of the Simulation Package interface (Esposito, private communication).

The Field Methods proposed to correct for the cone effect provide as a byproduct a field of view significantly larger than the isoplanatic patch. This is crucial for many astrophysical applications. In particular CRAL has proposed to map the 3-dimensional phase disturbances in the direction of the observed objects. A laboratory experiment has been setup at CRAL to simulate the light propagation through a 2-layer turbulent atmosphere, and then to check that one is able to restore the phase screens properties. The first data of this experiment are being processed.

The Best Use of Photons The adaptive optics group of OAA is developing a new kind of wavefront sensor: the Pyramid Sensor (Ragazzoni 1996). The sensor is a modified version of the Foucault test. It presents several interesting characteristics: i) it has a linear relationship between the measured signals and the wavefront derivatives; ii)) it has the possibility of easily changing the sensor sensitivity or the ratio between the measured signal and the wavefront perturbations respectively; iii)) it has the capability to easily change the pupil sampling acting on the pupil reimaging optics.

6 Experimental feed-back

European teeams are working about several experiments, which deliver important feed-back for the other work-packages and valuable information for the design of 8 m class adaptive optics and laser guide star systems.

Seeing vertical distribution This task has been successfully completed, in particular due to a joint observing run at the Calar-Alto Observatory. Fig 5 and Fig 6 show examples of $C_n^2(h)$ profiles got at the 2.2 m telescope by the Imperial College team simultaneously with ALFA observations at the 3.5 m telescope. These profiles have been obtained respectively with a SCIDAR and with a generalized SCIDAR (Dainty and Rigal, private communication).

The SCIDAR measurements show an important contribution to the seeing strength from high altitude layers. Such a situation with an 8 m telescope would markedly decrease the maximum Strehl ratio because of the cone effect. The generalized SCIDAR shows the importance of the boundary layer, or/and of the dome seeing.

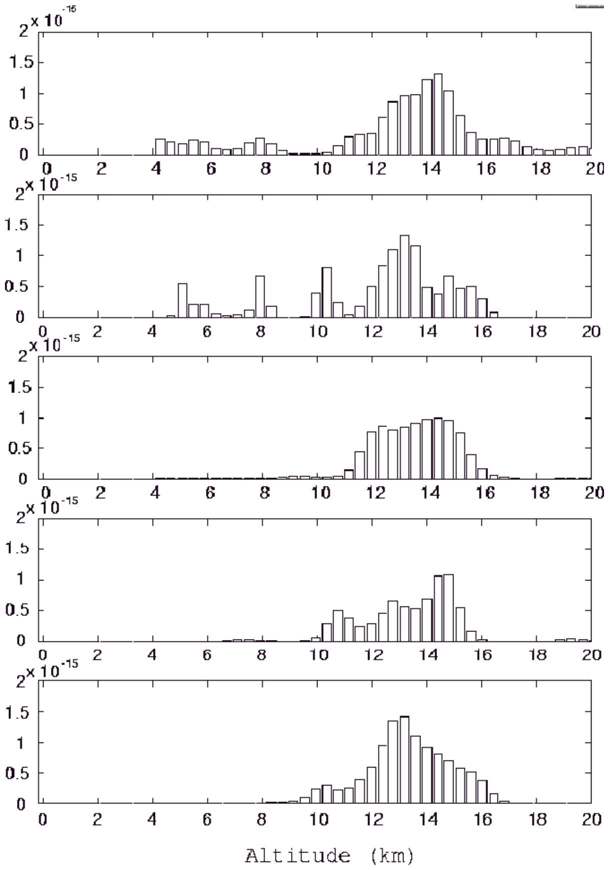

Figure 5: $C_n^2(h)$ profiles (in $m^{1/3}$ unit) observed at the 2.2 m Calar-Alto telescope with the Imperial College SCIDAR, simultaneously with ALFA LGS-AO observations at the 3.5 m telescope.

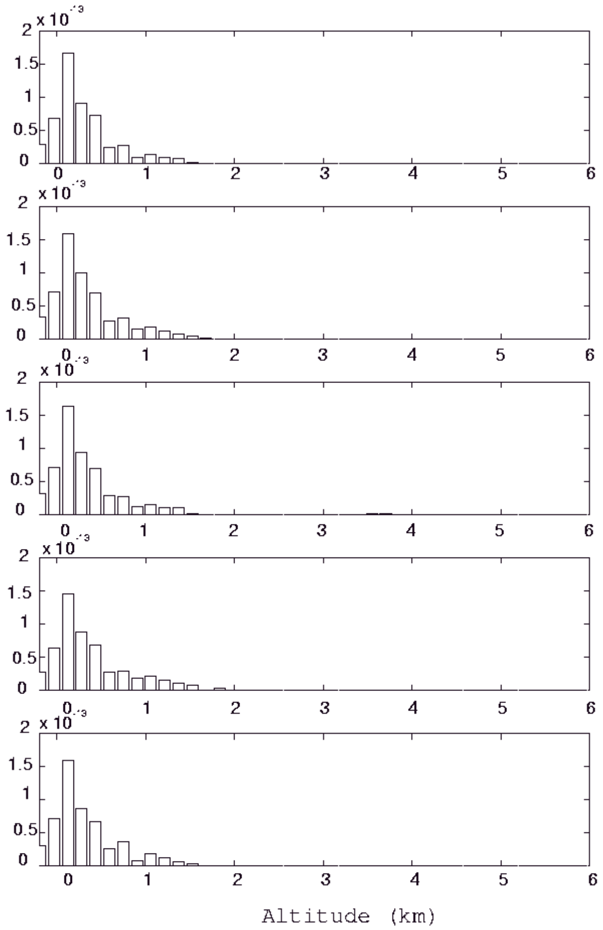

Figure 6: Same as Fig. 5 but with the Imperial College generalized SCIDAR.

The goal of such measurements is to contribute to a quantitative description of the image quality (Strehl ratio and FWHM) obtained with ALFA.

Polychromatic artificial star The CRAL has processed the data got with the AVLIS laser (LLNL) to check the feasibility of the polychromatic LGS. Important results are:

- the emission from the $4P_{3/2}$ level of mesospheric sodium atoms is first observed; it is strong enough to measure the tilt with ~50 W average power;
- it increases with the peak power in spite of saturation, possibly due to the resonant two-photon coherent absorption.

Adaptive Optics + LGS

ALFA The performance of ALFA have been improved during 1997 (Quirrenbach et al. 1997), fixing software bugs in the AO software and improving the algorithms for low light levels and slower integration times. New detectors for wavefront sensors and tip/tilt sensor further push the light level required for stable operation towards even lower levels.

The laser guide star system of ALFA is now fully operational (Davies et al. 1998). Significant improvements in image resolution have been achieved using the laser for high order correction. ALFA will be offered to visiting astronomers in 1998 on a 'shared risk basis' and several participating teams (IC, , MPE, NUI-G and OAA) have agreed to submit a joint proposal.

ELP-OA The CRAL and several French institutes have set up the programme ELP-OA aiming at coupling an AO with a polychromatic LGS (Foy et al. 1995) at a telescope. Currently the functional analysis of this programme is completed.

Vertical distribution of sodium

The NUI-G TRIFFID camera was extensively modified to be used with the Calar Alto 1.2 m telescope, producing Na-D images of the elongated plume of the MPIE Na laser from the 3.5 m telescope, with a vertical resolution ≤ 500 m, and time resolution limited only by photon statistics. Experiments during a seven day run in September 1997 (see an example of the profile in Fig. 7) showed gross changes in the Na-layer vertical distribution — of considerable significance for laser guide star adaptive optics (O'Sullivan et al. 1998). Better temporal resolution will be possible with the larger (2.2 m) telescope at Calar Alto. It is proposed to repeat the experiment with the larger telescope in May/June 1998.
The purpose of these measurements of the sodium column density is in particular to determine its value as input in end-to-end models of the LGS.

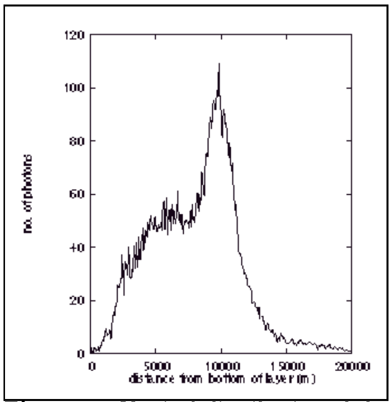

Figure 7: Vertical distribution of the relative density of sodium atoms in the mesosphere at Calar Alto during an ALFA run (O'Sullivan et al. 1998).

7 conclusion

The European contract for the LGS network will end on December 2000. The network plans to organize a workshop that fall. The goal will be to give an in-depth view of the work done during our 4-year contract, and to compare it with the progress elsewhere in the word.

acknowledgements

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