Laser Guide Star Plans and Related Instrumentation for the WHT.

A.J. Longmore

[a] *Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ*

Abstract

The PPARC has funded a study to investigate the feasibility and scientific case for providing a Laser Guide Star facility for the WHT. Elements of the study include identification of key science drivers, site monitoring with measurements of returns from a laser excitation of the sodium layer, a straw-man engineering proposal for the laser launch system and development of models to predict the system performance and to assist in defining an error budget for the components. A view on the wavelength coverage is presented and some principal features of instrumentation that would complement an LGS facility are proposed.

Key words: Adaptive optics: Optical AO, IR AO; Adaptive Optics: Laser Guide stars

1 Introduction

Elsewhere in this volume Chris Benn has described the basic specification, design and expectations of the NAOMI (Nasmyth Adaptive Optics for Multi-purpose Instrumentation) AO facility for the WHT. The prime goal for NAOMI is good performance and reasonable sky cover at near-infrared (1.25 - 2.5μm) wavelengths. A natural extended goal for any telescope with an AO capability is to increase the sky coverage at infrared wavelengths to $\sim$100% and to obtain useful partial adaptive optics correction at as short a wavelength as possible. High sky coverage can be achieved by using laser guide stars. Extended short wavelength partial correction may be achievable through judicious choice of optimisation algorithms for the wavefront correction. This paper describes the PPARC Evaluation Programme to assess the potential for use of Laser Guide Stars (LGS) with the WHT. The results of some early LGS modelling are presented which outline implications for AO work on 4m-class telescopes compared to 8m class. Finally a very brief summary of possible constraints on the design of supporting instruments is given. This part of the paper was given to provide a background against which further discussion on the direction of a WHT instrumentation programme could take place.

2 Laser guide Star Basics

The main reasons for having an LGS system for use with NAOMI (and more generally) are to obtain very high sky cover at near-IR wavelengths and useful sky cover and AO performance at optical - red wavelengths. It is important to address which of these should be the prime drivers for the WHT system. Not only will this affect many of the laser technology decisions and NAOMI modifications required, it will also help to determine where priorities should be placed on new instrumentation to be fed by AO facilities. Such decisions will depend on the ultimate performance of ELECTRA [1] deformable mirror (DM) (Zadrozny et al. 1999), the closed loop bandwidth attained by the Real Time Control System (RTCS) and site parameters. The ELECTRA DM is unique in astronomy applications. It is comprised of 76 independent tip-tilt mirrors, closely mounted within a 10 x 10 grid pattern. Each segment is driven by three piezo-actuators which have strain-gauge compensation to eliminate hysteresis. This format has an excellent fitting error and offers extra optimisation options over a continuous facesheet mirror (see OTF conditioning). A period of use with the ELECTRA and NAOMI systems will be required before the extent to which this potential is realisable can be determined. Results from the long-term WHT site-monitoring JOSE programme [2] (Wilson et al. 1999) are encouraging with regard to laser beacon usage. Much of the turbulence is frequently low altitude, implying a large isoplanatic angle and small cone effect (the reduced corrective ability of an LGS system because of unsampled turbulence at high altitudes by a system focused at $\sim$ 80 km).

3 Optical Transfer Function (OTF) conditioning

Simulations based on standard Kolmogorov turbulence models tend to show that some significant gains can be made in partial correction at short wavelengths, for example by treating sub-areas of the wavefront independently and not trying to reconstruct a continuous wavefront (A. P. Doel, private communication 1998). Software algorithms could be developed to cut out longer baselines where not needed (for example to maximise the amount of optical light acquired within a 0".1 spectrograph slit). Other possibilities are to reduce

[1] http://aig-www.dur.ac.uk/electra
[2] http://www.ing.iac.es/Astronomy/development/hap/haphomepage.htm

noise propagation from unwanted baselines, reduce anisoplanatic decorrelation from unwanted baselines (giving a wider field for given required parameter) and to suppress the cone effect partially. This little studied area means there may be many options for tailoring point spread functions to meet specific observational requirements.

4 The PPARC LGS Study

4.1 Study Goals, components and participants

The study aims to provide the key site, modelling and design information which will be needed in determining what general level of system performance can be expected for a laser beacon system on the WHT. It will describe the key science drivers consistent with this level of performance. A straw-man proposal will be prepared for implementation of a system that should meet the modelled performance. It will provide a costing analysis including the major components and estimated total costs for such a system at a level sufficient to investigate how the science and the cost would be affected by making trade-offs in the base-line performance.

Table 1 shows the major components of the study and the participating organisations / institutions. The remainder of this section outlines some concepts and features of the various components.

4.2 Science Case

The decision whether or not to invest further in an LGS system for the WHT must be driven by the scientific case. The study is funded to determine only key science drivers, not to provide a full scientific case. However, the study group recognises the importance of gaining a wide view of the potential science and of keeping potential users informed of the likely performance of an LGS AO system. It is therefore hoped that once most of the site monitoring and modelling has been completed an open science discussion meeting will be held before the study submits its final report.

4.3 Site Evaluation

It is almost certain that any laser guide star would be generated by firing a laser tuned to a wavelength within the Na doublet at ∼589nm. This light excites into emission Na atoms in a layer typically 80km high in the atmosphere. The key element of the site evaluation is to fire a laser to form a Na-line guide star. There are several benefits from doing an early site evaluation in this way. The Na layer is variable in strength, height and thickness, with both time and latitude. Thus knowing what photon return to expect helps determine the required laser launch power, which could be a significant cost driver. Height changes and zenith distance modify the focus at which the wavefront sensor (WFS) needs to operate. This impacts any modifications needed to the WFS design in order to implement LGS with NAOMI. The first goal of the monitoring programme is to fire a low power laser in September or October of 1999. It will be viewed first from the JKT at an angle such that the sodium layer thickness results in the guide star projecting a line across the sky a few tens of arcseconds across. Analysis of the intensity and structure of the line with time will give the required information on the Na layer. An additional advantage of this approach is that it will force local and wider safety issues to be addressed early. A fuller description of the site monitoring is given in a paper by Michaille et al. (these proceedings).

4.4 Modelling

The goal of the modelling is to provide high-fidelity performance prediction for a laser-equipped NAOMI system. Strehl ratio modelling will be used to verify the relevant components of the system error budgets. Detailed PSF prediction based on the site evaluation sodium abundance measurements and JOSE programme turbulence profiles will be used with instrumental models to support an end-to-end performance assessment of scientific potential.

4.5 NAOMI Modifications

Several modifications are likely to be necessary to the existing NAOMI design. A separate tip-tilt sensor will be required which can obtain tip-tilt signals from a natural guide star, while a wavefront sensor still monitors the laser guide star to derive higher order correction signals. Additional control facilities will be needed for the carriage motions of the WFS arm. Three stages move to maintain WFS focus, which will need to be derived separately as the laser guide star distance changes distance with zenith angle and the height of the sodium layer. Some extra calibration facilities may be needed.

Table 1
LGS Evaluation Study Components and Participants

Study Component	**Nature of work**	**Participants**
Scientific Case + cost benefit analysis	Astronomical case covering range of disciplines; comparison with costs	Durham/ATC
Site Evaluation	Na layer measurement/cumulative(UES) + SCIDAR	Imperial.College/Durham
WFS recording	LGS focus power spectrum calibration	Durham
NAOMI modifications	Opto-mechanical design; software evaluation	ATC/Durham
Modelling	Performance predictions based on site properties, laser power, design concept	Durham/IC/UCL
Systems Engineering	Overall design concept	Durham/IC/ATC
Monitoring laser technology	T&S for laser expert	IC
Other WHT/ING Engineering	Opto-mechanical and local infrastructure requirements and constraints	ING
Safety (environmental impact statement)	Monitor developments elsewhere, evaluate their implementation on WHT	ING/IC
Project Management	Agreeing work details, monitoring, co-ordination produce final integrated report	ATC

4.6 Systems engineering

In the final study, the requirements for the main components of the system will be described. An error budget will be derived for these components. In addition to the laser itself (see below) key elements will be the launch system, its mounting, handling of jitter, the location of the launch beam and the power requirement.

4.7 Laser Technology

This is still a fast-growing area, perhaps particularly so in the field of use for astronomy. Astronomy budgets generally demand turn-key operation and no laser-guide star system has yet genuinely achieved this goal. Apart from the well-known Starfire system [3] which has been used for astronomy, several other systems are in various stages of use or development. Of those listed in Table 2, the Lick/LLNL [4] (Olivier et al. 1996), MPIE [5] (Davies et al. 1999) and University of Illinois systems have all been fired successfully. Others are in various stages of design, construction or commissioning. At the time of writing it appears that a few groups are awaiting developments in key areas. A solid state laser would be the preferred option for a turn-key system, but stability of the medium is still problematic at the tens of watts output powers required.

Thus the approach for this WHT study is just to monitor progress in the laser technology and its application where possible. Some early experience will be gained from the site monitoring, but waiting to make a decision on the type of higher powered system should entail less technical and financial risk overall. The penalty will be a somewhat later implementation than the field leaders.

5 Study Timescales

The programme started in October 98. Na abundance measurements will be made Q3/99 - Q2/00. Performance modelling will start in earnest once some information from the laser returns is available, probably Q4/99 - Q2/00. Safety issues will need to be addressed throughout the programme, but particularly key issues must be addressed by Q3/99. Analysis of the models and preparation of a design concept will take place during Q1/00 - Q2/00, with the goal of producing a final report by July 2000.

[3] http://wwwsor.plk.af.mil/Mainpg/PAPABST.HTM
[4] http://ep.llnl.gov/urp/science/lgs_www/lgs_lick.html
[5] http://www.mpia-hd.mpg.de/MPIA/Projects/ALFA/index.html

Table 2
Summary of other LGS AO systems, at various stages of development

Telescope / Collaborators	**Type**
MPIE ALFA on Calar Alto telescope (AOA system)	Continuous wave; ∼5W
Lick, Keck; (system from LLNL)	Pulsed dye laser; 15 - 20W
Univ. of Chicago	Frequency-summed Nd:Yag 5 - 10W
Steward (6.5m)	Still evaluating technology ?
ESO VLT	Still evaluating technology ?
Univ. of Illinois	Rayleigh beacon
Gemini (S +)	Announcement of opportunity for proposal made mid-1999

6 LGS on 4m and 8m Telescopes

6.1 Potential of the 4m

Some possibilities for 'clever' OTF conditioning were mentioned in an earlier section. Even without such algorithms there are some areas where 4m class telescopes may compete with or even out-perform an 8m telescope when each is used with a laser guide star. A property of the cone effect is to reduce the effective diameter of the telescope, an effect characterised by a parameter d0. For turbulence occurring at several km altitude, d0 can be as small as 5m. Fig. 1 compares the peak signal from an ELECTRA- type deformable mirror on a 4m telescope with that from an 8m telescope using a 12 x 12 Shack- Hartmann WFS AO system with turbulence at ∼6km and 0".75 seeing. It shows that particularly at wavelengths shorter than 1 μm, 4m telescope may remain highly competitive for some observations. If the turbulence is

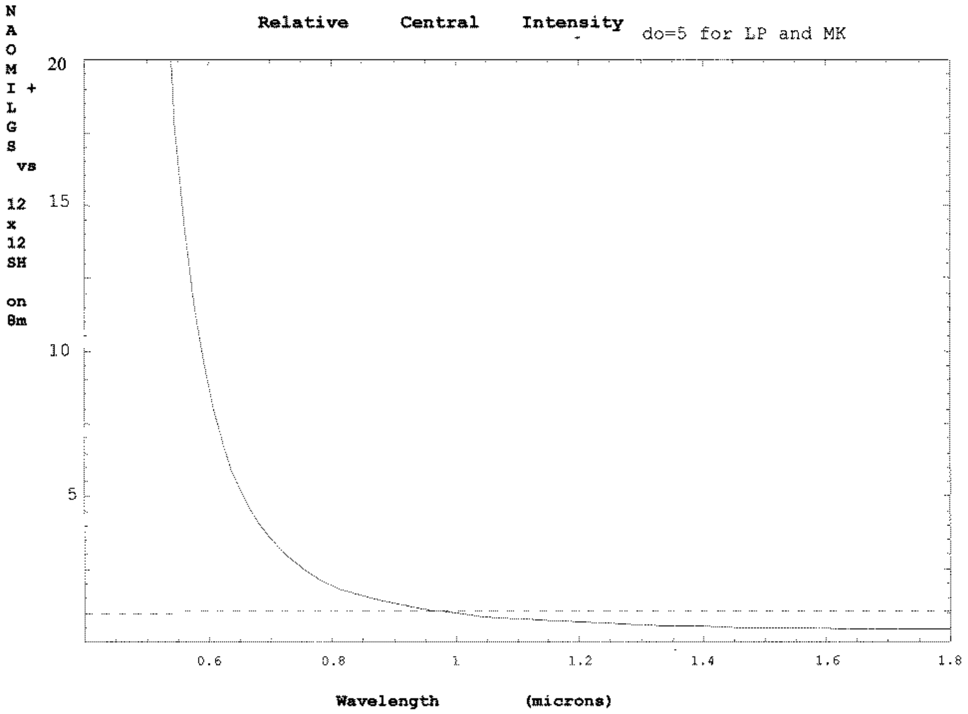

Fig. 1. Comparison of the peak signal from an ELECTRA- type deformable mirror on a 4m telescope with that from an 8m telescope using a 12 x 12 Shack- Hartmann WFS AO system with turbulence at ~6km and 0".75 seeing.

significantly lower for the 4m it may win at wavelengths as long as 1.4 μm. Another area of potential advantage for spectroscopy, that also favours the 4m if the cone effect dominates, arises if one relaxes the 'jitter' (tip-tilt) error budget to allow a nominally diffraction-limited core image to move around. Sky cover using a laser guide star would be enhanced significantly at short wavelengths if the distance over which a natural guide is usable for tip-tilt correction could be increased. Such an increase would automatically follow from a relaxed tip-tilt error budget. In-slit energies in the I-band of $> 40\%$ inside 0.1" might be achievable over almost the whole sky, for example.

6.2 Instrumentation

This section mostly flies some kites with regard to ideas for the general direction of instrument development on the WHT if it acquires an LGS system. The guide-line used is that the 4m must do worthwhile science in an 8m telescope era. Further considerations are that NGS AO performance is strongly dependent on seeing; offset guide stars at largish angles may or may not give good correction on a given night. PSFs will not be repeatable over a range of time scales, so this must be unimportant for the instrument or compensated for or calibrated. What does the above mean for planning an instrumentation programme now? Firstly, we still don't know accurately what performance to expect. We can give best case and conservative estimates for some useful parameters, especially relative to an 8m, but the results will still be site dependent. Using Fig. 1 as a guide, a key issue will be to find a sensible choice for the upper end of the wavelength range where returns become unfavourable compared to those from an 8m. Pragmatically one might choose at least to provide a capability on a 4m telescope up to the point where a given observation takes no longer than four times as long as on an 8m. This would lead to a firm conclusion not to compete at thermal (say two micron window or longer) wavelengths, with a softer conclusion to start competing seriously somewhere below 1.4 to 1.2 microns. 'Clever' OTF conditioning could extend the short wavelength limit to $\sim$0.5 microns – the CFHT AO Bonnette facility has already indicated that worthwhile correction can be obtained in the R band. The next choice is between common-user, multi-purpose instruments or special purpose / modular instruments. At this point it must be remembered that not only is short wavelength AO extremely seeing dependent, but also performance and isoplanatic angle both decrease very rapidly with decreasing wavelength. Thus a wide field (say > 60" ?) imaging or multi-object spectrometer might have limited applicability below 1 micron unless results from conjugating the DM to the height of the dominant turbulent layer are particularly favourable. Similarly it will not be possible to optimise the quality of the input images to cross-dispersed high resolution or wide wavelength range intermediate resolution spectrometers simultaneously for all wavelengths. A system which puts 50% of the light from a point source at 1 micron through a 0.1" slit, for example, may only deliver 20% at 0.6 microns. What does this leave? The pros and cons of a few options are listed below without further discussion.

- Integral field units with choice of input angular scales giving high spectral resolution across a relatively narrow bandwidth.
- Multiple IFUs, but still over a small field. For any IFU or image slicing system the treatment of sampling at the diffraction limit and how this varies with wavelength will need careful consideration.
- Simultaneous multi-channel imaging and imaging polarimetry, at neighbouring wavelengths. Experience in this area shows that substantial post-processing is still required to extract the best information from the data.
- Fabry-Perot imaging spectroscopy.
- Coronagraph. This has been a popular option for consideration with AO systems, but again optimum performance across a wide range of wavelengths is a challenge.

In all the above a major consideration should be throughput. One advantage of giving up on the multi- purpose single instrument is the potential to build modular or separate instruments tailored to some specific science goal. Plug-and-play detector systems for specific wavelength ranges combined with modular very high throughput special-purpose spectroscopic facilities could in many experiments compete with the sensitivity of an 8m telescope having 'just' a good common-user spectrometer.

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