The Rayleigh Technical Demonstrator: a novel concepts platform

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ABSTRACT

As part of a collaboration between Durham University and ESO, an experimental platform is presented whose purpose is for testing generic laser-based wavefront sensors (WFS) for adaptive optics. The Rayleigh Technical Demonstrator (RTD) has been designed to allow a laser launch and Rayleigh back-scatter collection by installing components solely on a Nasmyth platform of the William Herschel Telescope, La Palma. The aim is to provide a WFS testing port within the RTD, permitting new WFS concepts to be tested rapidly in conjunction. This means that the RTD only requires small modifications for each concept to be tested. The second goal is to permit near-contemporaneous comparison of WFS data with that from a tomographic WFS. Currently, the RTD is planned to trial with three “cone effect-free” WFS concepts as part of the CALDO project. Presented here is an overview of the RTD design with detailed information on novel components and design choices.

Keywords: Adaptive Optics, Laser Guide Star, Wavefront Sensing, Optical Design

1. INTRODUCTION

Designs of the next generation of optical and near-IR telescopes for astronomy (known collectively as ELTs) specify Adaptive Optics (AO) in order to achieve angular resolutions closer to their diffraction limit\textsuperscript{1} and to improve the throughput for instruments such as spectrometers.\textsuperscript{2} Although conventional (also called “classical”) AO implementations have used a star in the sky as a beacon for the AO wavefront sensors, an alternative approach, to increase sky coverage, is to mimic a star via back-scattering/stimulation using a focused laser beam. This mimicry permits the AO correction to be performed over much larger areas of the sky because the brightness requirement for guide stars is considerably reduced. The increase in coverage is typically one order of magnitude for the current generation of 8m telescopes.\textsuperscript{3} Also the brightness of the laser beacon is typically large when compared to stellar magnitudes and so the SNR of the wavefront measurements are large. Thus laser-based wavefront sensing has several advantages over the classical star-only approach.

There are further enhancements being developed for laser beacon AO and this has yielded a plethora of AO modes: Multi-conjugate AO, Ground-layer AO, and Laser-tomography AO to name but three. As classical laser beacon AO is only now becoming a common user facility at several telescopes,\textsuperscript{4,5} the need for a platform dedicated to AO development with laser beacons on a large telescope is manifest. This is one purpose of the Rayleigh Technical Demonstrator. The second is to investigate novel wavefront sensing concepts which do not measure the wavefront from a focussed spot beacon.

There are two major problems with using a laser beacon. The first is that whilst a star is at infinity and its wavefront samples a cylindrical part of the atmosphere, a laser beacon is created at altitude of (typically) 5–30\,km or 90\,km (the former via Rayleigh back-scatter and the latter via Sodium excitation near the mesopause). The wavefront from the laser beacon therefore samples a conical volume, leading to focal anisoplanatism. The second problem is of tip-tilt reciprocity which is a result of the same physical mechanism propagating the laser beam up as is utilised to recover the wavefront at the ground. It manifests itself as the mean linear phase within the cone (the “tilt”) being either cancelled or corrupted at the return of the laser light to the ground.

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The second purpose of the RTD is to therefore provide a platform for the experimental verification and analysis of novel concepts using lasers to measure a wavefront. They have been described in detail in other publications, and only a brief description is given here. They all share the goal of measuring the wavefront over a volume conjugate with that sampled by a wavefront from a star i.e. to reduce or eliminate the focal anisoplanatism. Common to the three ideas mentioned here is the avoidance of creating a beacon which provides spatially coherent light and instead differentiating between the upward and downward passages of the light. The other laser-beacon problem, namely tip-tilt reciprocity, is not explicitly meant to be solved by any of these concepts but is an area that can be investigated using the RTD.

This principal aim of this paper is to explain and outline the design of the RTD platform, and in particular of the design of various elements that are novel and of interest to the instrumentation community.

2. RTD CONCEPTUAL OVERVIEW

The Rayleigh Technical Demonstrator is designed to fit on the optical table of the Ground High-Resolution Imaging Laboratory (GHRIL), which is a Nasmyth platform of the William Herschel Telescope, Roque de Los Muchachos Observatory, La Palma. The WHT has a 4.2 m primary mirror and so is a large telescope for the purposes of AO development. A further advantage of this location is that the WHT is commissioning a Ground-Layer AO laser beacon system, GLAS, whose 514 nm laser is intended to be used for this experimental work. A 5W 532 nm laser is also available for use. A graphical overview of the bench design, showing the various sub-sections, is shown in figure 1.

The overall strategy is to carry out AO experiments using a shared launch capability, meaning that the laser light is launched into the atmosphere using the same telescope optics that are used to collect the returning light. The approach is thus similar to that previously used by the Durham group at the WHT and the UnISIS instrument.

The returning light is collected by the primary mirror and delivered to the Nasmyth platform, and so enters the RTD. It is initially multiplexed with the outgoing laser beam and then enters the Return Optics. These optics include a DM which is part of the ground conjugate AO component of the RTD (using a star for wavefront sensing). The DM-corrected light is then sent to a notch filter, centred about the laser line, which causes starlight to be sent to the AO arm of the RTD whilst the laser light is sent to the Concept Arm. The AO arm consists of the WFS for the ground conjugate AO system, a SLODAR WFS for turbulent layer profiling and a near-IR camera for imaging the PSF of the telescope (using the same star as used by the AO WFS).

The Concept Arm operates only with the back-scattered laser light, and its design is fixed to the point where the pupil is re-imaged. The remaining Concept Optics are specific to the AO experiment in-hand and it is intended that either a laser beacon WFS or one of the novel laser-based WFS concepts comprise these WFS-specific Concept Optics. By providing a re-imaged pupil with a FoV of 2 arc min as a standard interface,
in principle any AO WFS concept can be trialled using the RTD. The design as presented offers a laser-based WFS to be operated in open loop with a partially corrected wavefront or in closed loop by disabling the AO system WFS and driving the DM directly. Thus the measurement design aspect of a WFS within the RTD is well-defined.

The second major part of the main RTD optics is the Laser Launch Arm. This is currently designed to accept the output from the laser∗ and convert it to a format suitable for launch via the WHT primary mirror. After leaving the laser head, the collimated beam is translated to the beam height of the RTD and potentially resized. If necessary, the subsequent stage is to involve a beam shaper to convert the beam profile from the laser mode (typically TEM00, a Gaussian) to a “flat-top”/“top-hat”. The reasoning for this is explained later. Finally, the beam can be further modified depending on concept need and then re-formatted for coupling to the multiplexer and thence the telescope primary mirror for launch.

The final major part of the RTD is the Calibration Arm which allows internal alignment of the RTD optics by operating a “loopback” of the laser (via a tap on the Laser Launch Arm) and a white light source. These offer a pretense source which matches that expected by the AO or Concept Arms, and allows the RTD to be self-consistently aligned (internally) prior to operation on-sky.

3. LASER-BASED WFS CONCEPTS

As each AO experiment will utilise the Laser Launch Arm in an individual way, as well as use a different design for the WFS-specific Concept Optics, it is sensible to explain the method for each concept experiment and note the requirements made on the RTD design.

3.1. Sky Projected LAser Shack-Hartmann

The SPLASH concept is shown in figure 2, representing the upward and downward propagation of the laser. The concept operates by projecting a grid of spots onto the sky and then re-imaging this spot pattern using the whole telescope. Due to the difference in the turbulence sampled by the upward and downward paths, the displacement of each spot from its nominal zero is representative of the local tilt (relative to the global tilt) above the sub-aperture. The imaged spot pattern can therefore be treated exactly as the spot pattern from a Shack-Hartmann lenslet array. As emphasised previously, each spot is not a beacon but rather part of an intensity pattern whose distortion informs about the wavefront.

The RTD therefore needs to project a spot array onto the sky, which is to be achieved by creating a spot array at a conjugate altitude in the Laser Launch Arm. These spots will then naturally be re-imaged via the primary mirror onto the sky.

The Laser Launch Arm modification is achieved by placing a lenslet array adjacent with a Multiplexer Lens, after the beam has been reshaped into a “top-hat”. The lens is intended to reformat the collimated beam so that it is focused to where the telescope focus is present. The addition of lenslets causes the spot pattern to be formed prior to the focus, in a plane conjugated to the altitude of the spot pattern in the sky. At the focus of the lens, the defocused spot images overlap and then expand toward the primary mirror. The multiplexer should therefore be placed at this overlapping point.

∗GLAS laser is a Yb:YAG VersaDisk from ELS Elektronik Laser System GmbH
At the primary mirror, the chief ray from each lenslet is made parallel to all the others and the spots focus into the sky, as in figure 3.

When the light returns from the spot pattern back-scatter, the entire pupil is used for imaging each spot. The chief rays from each spot are no longer parallel, and do not overlap at the telescope focus. Together with the wide FoV required to re-image the spot pattern from altitudes of a several kilometres, these qualities permit the use of a Spatial Multiplexer—which allows incoming light to be differentiated from that outgoing by allowing only some (incoming) angles and image planes to be reflected pass whilst (outgoing) light can pass through. Further details of a Spatial Multiplexer design are given below.

As the passage through the Return Optics will have a limited FoV (2 arc min), this will limit the minimum altitude of the spots (to approximately 7 km). The Concept Optics are relatively simple and need only focus the light from the spot pattern altitude onto a detector.

3.2. Projected Pupil-Plane Pattern

The PPPP concept is designed to take advantage of Fresnel diffraction of a collimated beam passing through turbulence. The conceptual outline of PPPP is shown in figure 4. The result of propagation is that the wavefront aberrations are transformed into intensity changes through propagation. These changes and the wavefront are related by the Intensity Transport Equation, so the physical principles utilised are very similar to those exploited by Curvature Sensing. The primary difference is that the signal is created by back-scatter from two layers in the sky that are on the same side of the pupil whereas a Curvature Sensing device uses defocused images from planes conjugated to opposite sides of the pupil.

The RTD is therefore meant to output a collimated beam and then collect back-scatter from specific heights. The laser launch is therefore as for the SPLASH launch but without the lenslets i.e. a Multiplexer Lens is the sole optic needed to re-format the collimated laser light and, together with the primary mirror, acts as an Galilean (afocal) telescope. This effectively means that the laser is focused at the telescope infinity focus, whereas the back-scattered light will be from a specific height and so again a spatial multiplexer can be used.

As with the SPLASH needs, the FoV limitations restrict the minimum altitude from which the wavefront sensing signal can be recovered but the Concept Optics are simply those needed to re-image light from altitude onto a detector, as for SPLASH. In principle, the wavefront sensing signal can be determined from the back-scatter at one altitude and this would simplify the Concept Optics design considerably (in fact, become identical to that for SPLASH). However,
the current design for the RTD will incorporate a variable curvature mirror to change the height at which the back-scatter is imaged (although no attempt will be made to track the laser light as it travels through the atmosphere.) The intended rate of change is between 2 altitudes (typically ∼ 5 km height) within ∼ 5 ms.

Although the actual light back-scattered from a single height (in reality, a cylindrical “slice”) will have a fixed size on the detector, that from other altitudes will have different image sizes. The solution to this is to either have image-scale invariant optics or to use object-telecentric optics; the former is more complex but also does not require a reduction in throughput. Image-scale invariance is achieved naturally by using the variable curvature mirror solution, thus conferring an advantage in using a deformable mirror.

3.3. ESO Laser Layer Advanced Sensing (ELLAS)
The ELLAS concept differs from the previous ideas in that an attempt is made to simulate light coming from a distant source, so having (relatively) high spatial coherence. It is essentially the use of shearing interferometer as a WFS but instead of sensing using a beacon, the back-scattered light comes from a volume that has the same width as the telescope primary. It is shown diagrammatically in figure 5. To obtain sufficient spatial coherence, the back-scattered light is spatially filtered to restrict the FoV to a few arc sec’s. This then implies that the interferogram is produced from light which has come vertically down, or nearly so, onto the telescope aperture—a situation reminiscent of the passage of star-light. The remaining Concept Optics are then similar to conventional phase-shifting shearing interferometers, already used with a laser beacon as an astronomical wavefront sensor.

The laser launch is therefore identical to PPPP in requiring a collimated beam to be emitted from the primary aperture of the telescope. As the FoV of the back-scattered light is very small, this permits the multiplexer to be either Temporal or Spatial (again, explained in detail below). The advantage of limited FoV also considerably eases the requirements in the Concept Optics, which permits reducing the beam size post re-imaged pupil. The Shearing Interferometer Package thus can be made both optically stable and convenient for insertion/removal.

3.4. TOMography using Beacons Off-Axis and Inference
The TOMBOI idea is different from the above concepts in that it does use a series of laser beacons, in order to provide a source of wavefronts. It is designed to permit investigation of tomographic wavefront reconstruction for Laser-tomography AO using One-Sided Curvature Sensing of several off-axis laser beacons, as in figure 6.

The formations of the beacons, within the cylinder which is sampled by a wavefront from a star, can be created by the same optics as used for SPLASH (indeed, it can be identical although perhaps simplified to reduce experimental complexity). The arrangement of lenslets prior to the Multiplexer Lens would not need be contiguous in this case, which would lead to a loss of throughput unless the collimated beam were re-formatted to channel light only to where the lenslets were placed. The back-scattered light would be collected and separated via a spatial multiplexer and then a specific altitude would be imaged by the Concept Optics. The altitude would be chosen so that the defocused beacon images are fully separated on the detector, allowing each to be processed individually. Thus the design requirements for TOMBOI are very similar to that for SPLASH except for simplified lenslet layout and ability to change the imaging altitude.

4. DESIGN FEATURES
As the RTD is designed to be a flexible platform for laser-based AO experimentation, several of the components intended for use are either novel or benefit from explanation.
Figure 5. Outline of the ELLAS wavefront sensing scheme. A large ‘spot’ is created to produce many scatterers, overcoming the focal anisoplanatism. To increase spatial coherence, a pinhole is employed prior to a shearing interferometer.

Figure 6. Outline of the TOMBOI wavefront sensing scheme. The beacons, created in an analogous manner to those for SPLASH, are used as sources for One-Sided Curvature Sensor arrangement.
4.1. Beam Reshaping

All of the concepts described above either require (PPPP, ELLAS) or benefit (SPLASH, TOMBOI) from the output intensity from the laser having a constant and circularly symmetric profile. As an example, PPPP makes the assumption that a plane-parallel constant-intensity beam is propagated up from the telescope aperture. Ideally, in fact, the output profile is a scaled version of the telescope aperture (primary mirror aperture less shadow of secondary mirror). As the actual beam from the laser will be a fundamental TEM mode—a Gaussian profile—a beam reshaper is required to re-format the beam shape. An investigation was carried out into suitable methods and there are effectively two solutions available: converting into a “top-hat” or into an arbitrary shape.

There are a plethora of techniques which reshape a Gaussian into a top-hat, which is also called a “flat-top” or (equivalently for this purpose) a “super Gaussian”. The devices that preserve spatial coherence can broadly be divided into refractive and diffractive methods and this leads to an important difference: the refractive methods are afocal whilst the diffractive operate at a focus. For the purposes of the RTD, the need for afocal shaping implies a refractive solution, and for this project a commercial re-shaper was purchased†. However, in principle diffractive solutions offer higher throughput and could be developed to work with Fresnel diffraction rather than Fraunhofer, thus made afocal more easily. An advantage of diffractive techniques would be an increase in throughput via the ability to reshape the beam to match the telescope aperture, as mentioned above.

4.2. Multiplexing

The benefits of a shared laser launch choice are many, but the design then imposes other constraints. In particular, a problem is how to distinguish between outgoing light and the back-scattered light that is collected by the same telescope optics. To preserve throughput and reduce the constraints on the novel concept designs, the need to multiplex between incoming and outgoing light was carefully studied. Two approaches were deemed possible: temporal multiplexing where the “time of flight” of the outgoing light (from a pulsed laser) can be used to choose back-scattered light from suitable altitudes, and spatial multiplexing where the focused altitude of the outgoing laser light differs from the altitude(s) that the back-scattering occurs at.

Temporal multiplexing is a technique already used at the UniSIS\textsuperscript{10} LGS AO facility on Mt Wilson. It is essentially an optic which is transmissive for the duration of the laser pulse but reflective when the back-scattered light has returned (or vice-versa). This requirement implies fast switching between the states (typically 1 kHz) and has been achieved via a spinning optic with alternating clear and reflective parts, see figure 7. A consequence of the approach is a limited FoV—\(\sim 2\) arc sec—as the reflective components are small to reduce the size of the overall optic. Whilst acceptable for the ELLAS concept, for SPLASH and PPPP the typical image field (assuming a 4 m wide area at 10 km) is 1.4 arc min.

Spatial Multiplexing is designed to offer a solution for large FoV back-scatter collection. The current concept is a Pinhole Mirror which is a flat mirror with a pinhole in the centre, oriented at 45° to the surface. The idea is that at the infinity focus of the telescope, laser light that leaves the telescope collimated is naturally focused and can pass through the pinhole, as in figure 8. Put alternately, the outgoing laser light direction covers a very narrow range of angles (principally, perpendicular to the primary mirror vertex). Back-scattered light from a finite altitude will instead come from a wide range of angles and so the image on the mirror will cover a much larger area than the pinhole: using a 4 m wide area at 10 km with the specifications of the WHT telescope, the image is \(\sim 20\) mm versus a typical pinhole size of \(\sim 0.2\) mm.

[†] Newport Refractive Beam Shaper GBS-UV-H with custom visible coatings.
However, the Pinhole Mirror has one disadvantage which is the pinhole effectively restricts the FoV to be off-axis by more than $\sim 1$ arc sec. This in turn prevents on-axis imaging and forces the NGS AO to work with off-axis guide-stars. Of the three concepts proposed that require a spatial multiplexer—SPLASH, PPPP, and TOMBOI—all may operate by the Multiplexer Lens focus being confocal with a negative telescope focus (for the RTD, $-250$ km). This places the pinhole before the telescope focus itself and in a position where the image from an object at infinity (such as a star) can be approximated using geometric optics. For the case of no atmospheric aberrations, the image would be a copy of the telescope aperture so by placing the pinhole in the shadow of the secondary obscuration, the on-axis light reflects from around the pinhole whilst the laser light passes through, see figure 9.

The defocused pinhole mirror solution does restrict the FoV by allowing on-axis beams, and a small FoV of approximately $\sim 0.4$ arc sec, and then beams whose images on the mirror do not intercept the pinhole. Using the WHT as an example, the minimum off-axis angle permissible is then $\sim 3.5$ arc sec. The FoV limitations for an object in both mirror cases can be summarised: imaging is possible on-axis and more than $\sim 4$ arc sec distant, for the defocused mirror, or imaging is possible more than $\sim 1$ arc sec from the axis for the focused mirror.

An omission in the discussion so far of the defocused mirror is the effects of phase aberrations on the image of the on-axis object. Note that it is assumed a geometric copy of the telescope aperture. In reality, the image of a star at the $-250$ km focus (a defocused image) will be distorted and the ‘shadow’ of the secondary mirror will not match the pinhole aperture. The result will be vignetting of the re-imaged pupil, which will therefore show complex amplitude distortions. Quantification of this error was analysed via numerical simulation and results are shown in figure 10 for an instance of phase aberrations present at the telescope aperture. In summary, it is shown that despite the pinhole causing intensity variations (scintillation), the phase is not adversely disturbed. This is confirmed by a Shack-Hartmann WFS simulation. It was carried out for both the original pupil (pre-pinhole) and the re-imaged pupil (post-pinhole), the optical configuration of the WHT, the pinhole confocal at $-250$ km, and $D/r_0 = 20$. A scatter plot showing the comparison of tilts from corresponding sub-apertures is shown in figure 11; the correspondence is excellent and confirms that post-pinhole pupil is suitable for wavefront sensing. Furthermore, comparisons of the Strehl ratio from the pupil/re-imaged pupil, 0.013/0.012, reveal that the PSF is not overly affected either. Regarding the RTD, these results indicate that the pinhole mirror effects on the on-axis PSF is acceptable for imaging and the NGS AO WFS—note that the off-axis PSF is unaffected.

4.3. Metal Optics

To reduce costs and allow maximum flexibility in the optical design of the RTD, fabrication of metal optics in-house was chosen. These optics are milled from aluminium, using an Ultra High-Precision Optics Milling Machine. Currently, work is in progress to determine if the machined surface has an acceptable small-scale and large-scale roughness, contributing to light scattering and wavefront aberrations respectively. Further manufacturing steps to take before use may include over-coating with Nickel, remachining, polishing and over-coating once more but with Silver, in order to maximise throughput.

\[^{1}\text{Nanotech 350FG}\]
Figure 10. Simulation of a pinhole placed at $-250 \text{ km}$ focus of the WHT and showing the effects on the amplitude and phase of light from an object at infinity. The scintillation is evident in the amplitude plots but barely distinguishable in the phase plots.
5. FUTURE PLANS AND CONCLUSIONS

- Designed flexible platform for shared laser launch AO experiments.
- Have four novel AO concepts to trial, with outlined design requirements.
- Explained novel methods and components: beam reshaping and spatial multiplexing.
- Currently components being purchased and parts being made in-house.
- Immediate timetable is to test purchased and made components and begin assembly in Durham to perform design tests.

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