Abstract. The use of tomographic adaptive optics is fundamental to fulfilling scientific goals for many proposed instruments at major observatories. Tomographic AO uses knowledge of the atmospheric $C_n^2$ profile and to date, the majority of the profiles used to design and simulate these systems have come from external turbulence profilers. The $C_n^2$ profile resolution required for accurate predictions of ELT instrumentation exceeds that of existing instrumentation and here we define the requirements on these profilers for ELT support. However, tomographic AO systems can also measure $C_n^2$ profiles and we highlight several cases where external profilers can provide critical functionality to support on-sky operations.

1. Introduction

The next generation of facility-class Adaptive Optics (AO) systems will make use of tomographic wavefront sensing techniques to provide correction over wider fields of view or improve the performance of laser guide star AO systems [1]. Through the use of multiple Wavefront Sensors (WFSs) these tomographic systems are capable of mapping the full volume of turbulence above the telescope and thus determining a full $C_n^2$ profile (see e.g. Vidal 2010 [2] and references therein). Profiles defined using WFSs that are part of the AO system are generally called internal profiles as opposed to an external profile derived from a profiling instrument mounted on an auxiliary telescope.

Common with many types of existing turbulence profilers the vertical resolution and maximum altitude of the $C_n^2$ profile is dependent on telescope diameter and the angular separation of sources being observed. Tomographic AO system performance is $C_n^2$ profile dependent and the sensitivity of the AO system to changes in the profile is also defined by the WFS configuration. The tomographic configuration of next generation of wide-field AO systems on Extremely Large Telescopes (ELTs) defines a profile sensitivity that exceeds the capabilities of existing external profilers. However, the internal profile measured using the AO system WFSs will be sensitive enough to determine a $C_n^2$ profile at sufficient resolution to for example, analyse AO correction [3] or use as an input to PSF reconstruction algorithms [4]. At first sight this makes the role of the external profiler redundant once a tomographic AO system is operational.

Recent on-sky tests of tomographic AO systems [5] have provided insight into how external profilers could be used in the era of facility-class tomographic systems. In this paper I aim to identify both requirements and potential roles of external profiling systems as facility support
instruments. I also argue that external profiling, whilst not essential for AO operation, may provide significant operational advantages and improve observing efficiency. First I introduce the various types of tomographic AO system that will be in use in the future, then describe their sensitivities and how profiling could be used with these systems. Finally I present several uses for external profilers that would support tomographic AO system operations.

2. Tomographic AO

There are several ‘flavours’ of tomographic adaptive optics system which cover a range of performance levels, sky coverage and corrected fields of view. In general there is a trade-off between the fidelity of correction and the corrected field of view, but all tomographic AO systems rely on the use of multiple wavefront sensors. These wavefront sensors have to date been typically of Shack-Hartmann (SH) type, therefore most tomographic AO systems therefore resemble multi-baseline SLODAR [6] systems.

The sensitivity of tomographic AO performance to changes in $C_n^2$ is defined primarily by the separation of the guide stars (natural or laser) in use, and the diameter of the WFS sensing elements (subapertures in the case of a SH-WFS) although it is complicated by the number of independent baselines between guide stars within the asterism. The impact of a given layer changing altitude on AO performance is then also dependent upon the strength of that layer. Simulations of E-ELT AO systems have shown that for the most demanding cases, the $C_n^2$ profile vertical resolution must approach 100-200 m [7]. At this resolution, the AO system may start to become sensitive to changes in the thickness of the turbulent layer also, particularly for Ground Layer AO (GLAO) [8].

Tomographic AO systems can be separated into those that provide ‘fixed’ and ‘floating’ tomographic correction. A ‘floating’ tomographic system in general uses a single Deformable Mirror (DM) that is optically conjugated to the telescope pupil. The shape the DM should assume is calculated by first defining a number of virtual layers within the atmosphere at which the incoming wavefront will be reconstructed. The DM is then mathematically projected through these virtual layers to find an optimal DM shape that will provide the correction along the desired line of sight to the target object [2]. This is one reconstruction approach that can be adopted for both Laser-Tomographic and Multi-Object AO, although several others exist. As the $C_n^2$ profile changes the altitude of the virtual layers can be adjusted within the reconstructor and AO performance remains optimised for the observed turbulence profile.

For ‘fixed’ tomographic systems (such as Multi-Conjugate AO or GLAO), the DM(s) are optically conjugated to one or several fixed altitudes within the atmosphere. This configuration means that if the strongest turbulent layers in the atmosphere do not match the conjugated altitude of the DM(s), AO system performance can be degraded [9]. It should be noted however that both GLAO and MCAO systems can also make some use of floating tomographic control techniques to optimise performance (see e.g. [10] and references therein).

The number of reconstructed layers in the atmosphere is dependent on the number of subapertures within the WFSs. For a low-order system such as CANARY on a 4.2m telescope, 3-4 reconstructed layers are required [3]. Simulations of ELT-scale AO systems have shown that AO performance is even more sensitive to the number of layers within the atmosphere [11]. To optimise performance, these $N$ layers should be continually adjusted within the reconstructor to track the strongest $N$ layers in the atmosphere. However, weaker layers within the atmosphere can also have a large impact on performance, particularly for wide-field observations. Simulations of E-ELT AO have shown that the altitude of the strongest 40 layers should be known up to altitudes of 20-30 km.
3. Profiling requirements

Irrespective of the system architecture, it is clear that knowledge of the profile is critical to operate a tomographic AO system on-sky. As stated in Section 1 however, the internal WFSs can achieve sufficient resolution to satisfy these requirements. Initially where knowledge is required before the internal WFSs will be available is during the instrument design phase. This is particularly true for MCAO where the conjugate altitude of the DMs must be fixed. To allow estimates of the number of nights an instrument could be used or to optimise the system design for robustness, requires not only a median profile but example profiles over an extended time period. Representative profiles of night-to-night profile variation would be useful over the course of at least a year to fully describe the expected AO system performance.

Measurements of the variability of the layer altitude at shorter timescales is also required. Adjustment of the reconstructed layers and subsequent recalculation of the tomographic reconstructor can carry a significant computational overhead. However, all that is required is the altitude of the layers and not an absolute measure of their strength.

It should be noted that telescope observations have shown that there is always a significant ground/boundary layer component and therefore a reconstruction layer is always conjugated to the telescope pupil. Although the ground layer is often the dominant layer within the atmosphere, it does not affect the performance of the tomography because it is common to all WFS signals. Whilst a measure of atmospheric strength in terms of seeing or \( r_0 \) is required to estimate overall system performance, individual high layer strengths need not be calibrated absolutely.

In addition to \( C_n^2 \) profiles, wind velocity profiles can also be used with some reconstructors that can make use of the temporal statistics of the atmosphere. Whilst these techniques have not been implemented to date within any facility class AO systems, initial on-sky tests have shown they provide a significant improvement in performance particularly in the presence of high wind speeds or telescope vibrations (e.g. [12], [13]). Limits on the required accuracy of the wind velocity profile have not been fully calculated at this stage.

4. External profilers for operational support

There are many situations where an external profiler supporting tomographic AO systems could very rapidly return any initial investment required for its installation. For major facilities such as the E-ELT this statement holds true even if only a few minutes were saved per observation/target due to the high cost of observing time. Here I present several possible ways in which an profiler could assist with tomographic AO operations:

- **Queue scheduling** Tomographic AO systems with multiple WFSs and DMs are complex to setup for observation. Whilst existing tomographic AO systems have not in general been developed to facility-class level, it could take 2-3 hours to prepare an instrument for observations. An early indication of the high-altitude profile (remembering that the ground layer is not required), either through profile forecasting or direct measurement near sunset would help to ensure that the optimal tomographic instrument is used for the predicted tomographic conditions.

- **Reconstructor pre-computation** If an internally measured profile is used to build the reconstructor, then the target must be acquired and an on-sky dataset recorded before the computation of the reconstructor can begin. As already stated in section 3, there can be a significant overhead in the calculation of the tomographic reconstructor. Building the reconstructor from externally measured profiles whilst (e.g. the telescope is slewing) could save significant amounts of time.

- **AO Performance optimisation** The variability of the atmospheric turbulence profile is such that it is highly unlikely that the system will have been exposed to a wide range of...
Figure 1. Sketch of E-ELT (not to scale) optical layout showing conjugate altitudes of each mirror in main optical train and observed conjugate layers caused by passage of two idealised layers passing through the telescope structure at different heights.

Tomographic configurations during the instrument commissioning phase. Due to this, much of the initial performance optimisation tasks will have to be performed off-line using recorded WFS measurements taken during science observations. An unbiased measurement of profile at high vertical resolution will be required as inputs for developing both simulations and PSF reconstruction algorithms.

- **Instrument comparisons** Each AO instrument will use its own WFSs, correction elements and real-time control optimisations. The only unbiased atmospheric profile reference between instruments would therefore be an external profiler. Not only will this be crucial during commissioning, but also to allow performance optimisations developed for one AO instrument to be applied to another.

- **Automation** For existing tomographic AO systems, the reconstructor is currently crafted by hand through fitting of the number of layers, layer altitudes and wide range of other parameters (such as misalignments due to flexure etc.) that can affect AO performance. The number of degrees of freedom required can result in a reconstructor fit which can contain errors that are not always obvious even to the trained observer, let alone an automated system. The use of an external profiler as an automated check of the internally measured profile could provide a robust check and form a critical part of the on-sky operating procedure.

- **Targeted line of sight profiling** An external profiler need not point along the line of sight of main science target after initial acquisition. Profiling along alternate lines of sight, such as that of the next science target, or ‘upwind’ from the current target would once again provide an estimate of how the profile could change in the coming minutes. This could potentially provide early-warning of upcoming profile variations to allow reconstructor optimisation before AO performance becomes degraded.
- **Dome-seeing and structure-induced turbulence** One aspect of ELT design that could be of particular importance is the impact of dome-seeing, or structure-induced turbulence [14]. For example, due to the optical design of the E-ELT, a single turbulent layer flowing through the telescope could be observed at several conjugate altitudes up to ±3.5 km from the telescope pupil (see Fig. 1) Turbulence caused by wind-flow through the telescope structure and localised heat sources could also contribute to the observed profile. In this manner, the ground layer could appear to the internal profile as conjugated layers. An external profiler would not be observe these layers, providing a potentially important diagnostic tool to improve telescope performance.

5. Conclusions
In this paper I have addressed the requirements that future tomographic AO systems will place on external profilers, based primarily on on-sky experience gained using CANARY and the external turbulence profilers supporting the CANARY project. I have summarised requirements on the required vertical resolution of turbulence profiles required for instrument design based on simulations of several E-ELT AO systems where a 100-200 m vertical resolution profile up to 20 km in altitude is required for the most demanding wide-field AO instruments for the E-ELT. The absolute strength of the individual layers is not required, but at least the strongest 11 layers must be identified. More layers are required in the measured profile to fully characterise AO performance. The strength of the ground layer is not required although its thickness can be used to estimate/characterise GLAO performance.

Whilst noting that tomographic AO systems are in general self-calibrating with respect to the turbulence profile, I have identified several cases in which external profilers could be used to support tomographic AO observations that hold the potential to improve observational efficiency and AO performance. These applications of external profilers in this manner will become more critical for E-ELT operations, where observing time is at a premium.

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