Retrieving tip-tilt information from Tomographic Laser Guide Star Adaptive Optics Systems

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ABSTRACT

Current Laser Guide Star (LGS) Adaptive Optics (AO) systems disregard all tip-tilt wavefront information received from the LGS Wavefront Sensors (WFS), as it is considered irretrievably entangled with the up-link turbulence that the laser encounters as it passes through the atmosphere to form a guide star. Consequently, they must still observe a Natural Guide Star (NGS) in order to correct for tip-tilt aberrations.

A method has recently been presented that use the tomographic capabilities of centre-launched, multi-LGS AO systems to predict the LGS uplink turbulence and hence allow correction with a reduced requirement on the NGS, or potentially no NGS requirement at all for some scientific applications. This method is summarised here, and its limitations discussed. Due to the increased separation of the laser beams at higher altitude, the method is more effective for correction of tip-tilt from high altitude turbulence, with performance approaching that of tomographic LGS AO with a tip-tilt NGS. The method is less successful for correcting tip-tilt contributions from low altitudes, though potential mitigation of this is considered.

We finally discuss the methods potential for ELT scale operation. Due to the large aperture size, and large LGS separation, it is expected that the method would be more effective for larger telescopes.

Keywords: Adaptive Optics, Laser Guide Stars, Tomography

1. INTRODUCTION

The use of Laser Guide Stars (LGSs) in Adaptive Optics (AO) has greatly increased the area of the sky available for correction, from ≈ 10% up to ≈ 85%.[1] In turn this has led to a vast increase in the number of astronomical science targets which can be observed using AO. The laser experiences turbulence whilst traveling upwards to form an artificial guide star, so its position will move in the sky. It is thought that this effect renders all 'tip-tilt' information gained from LGS Wave-Front Sensors (WFS) useless, as it is a function of LGS 'up-link' movement and the desired 'down-link' tip-tilt which have previously been considered to be entangled irretrievably. It has even been suggested that the tip-tilt the laser acquires on the up-link is the reciprocal of the global tip-tilt on the down-link path, hence little tip-tilt will be observed on the WFS at all. To correctly obtain the science path tip-tilt, a Natural Guide Star (NGS) must still be used. As a tip-tilt WFS requires relatively few photons and the anisoplanatic patch size is large for tip-tilt modes, the requirements on a NGS are much lessened.[2] Nonetheless, requiring a tip-tilt NGS still limits the sky-coverage of an LGS AO system.

Tomographic LGS configurations, such as Laser Tomographic AO (LTAO),[3] Multi-Object AO (MOAO)[4,5] and Multi-Conjugate AO (MCAO),[6,7] are coming online. These AO configurations use information from a number of LGSs, off-axis from the science target, to estimate the science path turbulence. Such systems overcome the so called cone-effect where the LGS samples a cone of turbulence in the science path rather than the full cylinder of turbulence seen by light from the science target.[8] They can also achieve a large corrected field of view in the case of MCAO, or a large 'field of regard' in the case of MOAO. Tomographic LGS systems still require a NGS to estimate tip-tilt modes, limiting their potential sky coverage. Suitable NGS are notoriously absent from much of the sky around the galactic poles, where many scientifically interesting targets exist.[1]

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Methods to obtain all correction information from LGSs alone have been proposed. Some require complex laser schemes and/or auxiliary beam viewing telescopes, such as those proposed by Ragazzoni[9] and Belen'kii.[10] More recently, Basden[11] has proposed an LGS assisted lucky imaging system, which could provide full sky AO coverage but entails discarding some science flux and would not be suitable for spectroscopy. Davies et al.[12] explored the potential usage of LGS AO with no tip-tilt signal, allowing 100% sky-coverage. It was found that for some applications, a dedicated NGS tip-tilt star was not required and a telescopes fast guiding system was adequate.

Recently a method has been proposed by Reeves et al.[13] to retrieve tip-tilt information from a number of LGSs in existing or currently proposed tomographic AO systems. It aims to improve AO performance across the whole sky with no tip-tilt NGS, potentially relaxing the requirement for, or for some applications eliminating the need for, a NGS. Here, we summarise the method and discuss its applicability to Extremely Large Telescopes (ELTs).

2. CORRELATION OF TIP-TILT BETWEEN TELESCOPE AND BEAM-LAUNCH APERTURES

If the global tip-tilt across the telescope aperture is identical to that over the beam launch telescope, any tip-tilt encountered by the LGS up-link path will have an equal but opposite effect on the return path. Consequently no tip-tilt will be observed on the LGS WFS and the tip-tilt component of the science path can not be determined by that WFS. This is referred to as tip-tilt 'reciprocity' and is certainly the case if the laser is launched from the full aperture of the telescope. All current facility LGS AO systems use a separate Laser beam Launch Telescope (LLT). On these telescopes and those planned for the future, $D_{LLT} << 0.1D$, where D_{LLT} denotes the diameter of the LLT and D is the size of the telescope aperture. Determination of LGS up-link tip-tilt can only be possible if the up-link and down-link tip-tilt components are uncorrelated or it will not be fully observed by the WFS. The covariance between two concentric Zernike modes of different radii in Kolmogorov turbulence is shown in Equation (1),[2]

$$\mathrm{C} = 0.0145786 e^{\frac{1}{2} i\pi(n-p)} \sqrt{(n+1)(p+1)} \left(\frac{R}{\mathrm{r}_0}\right)^{5/3} \times \int_0^\infty dk \frac{J_{n+1}(2\pi k) J_{p+1}(2\pi\gamma k)}{\gamma k^{14/3}}, \tag{1}$$

where γ represents the fractional size relationship between the two apertures, n and p are the radial orders of the two Zernike polynomials, R is the radius of the telescope, J_{n+1} and J_{p+1} are Bessel functions of the first kind, k is the wavenumber of the light and r_0 is the atmospheric Fried parameter.[14]

The covariance between concentric tip-tilt modes of different radii are plotted in Figure 1 (where $n, p = 1$). A plot of the correlation of tip-tilt modes in ten thousand simulated random Kolmogorov phase screens is also plotted. It is evident that the correlation of tip-tilt modes between small and large apertures in the regime where $D_{LLT}/D < 0.1$ is less than 0.1. This result means that tip-tilt modes will not be reciprocal and will be visible on an LGS WFS. Observed tip-tilt will be some function of the turbulence encountered by the laser as it propagates up to form an artificial guide star and the global tip-tilt across the telescope aperture as it propagates back.

3. TOMOGRAPHIC LGS TIP-TILT DETERMINATION

In this section, the geometric method of uplink tip-tilt determination derived in Reeves et al.[13] and the required extension to the Learn and Apply algorithm for tomographic AO algorithm is summarised.

3.1 Geometric method of retrieving down-link turbulence induced slopes

As demonstrated in the previous section, the measurement from a LGS WFS is a function of the atmospheric turbulence the laser propagates through on the way up to form a guide star and the turbulence the return light propagates through as it travels back down to the telescope. For AO correction of an astronomical science target the two components must be separated and only the latter is required. If using a Shack-Hartmann or Pyramid WFS, WFS measurements will be in the form of slopes representing the gradients of the measured phase within any given sub-aperture. The use of such a gradient measuring WFS is assumed in the following derivations. We

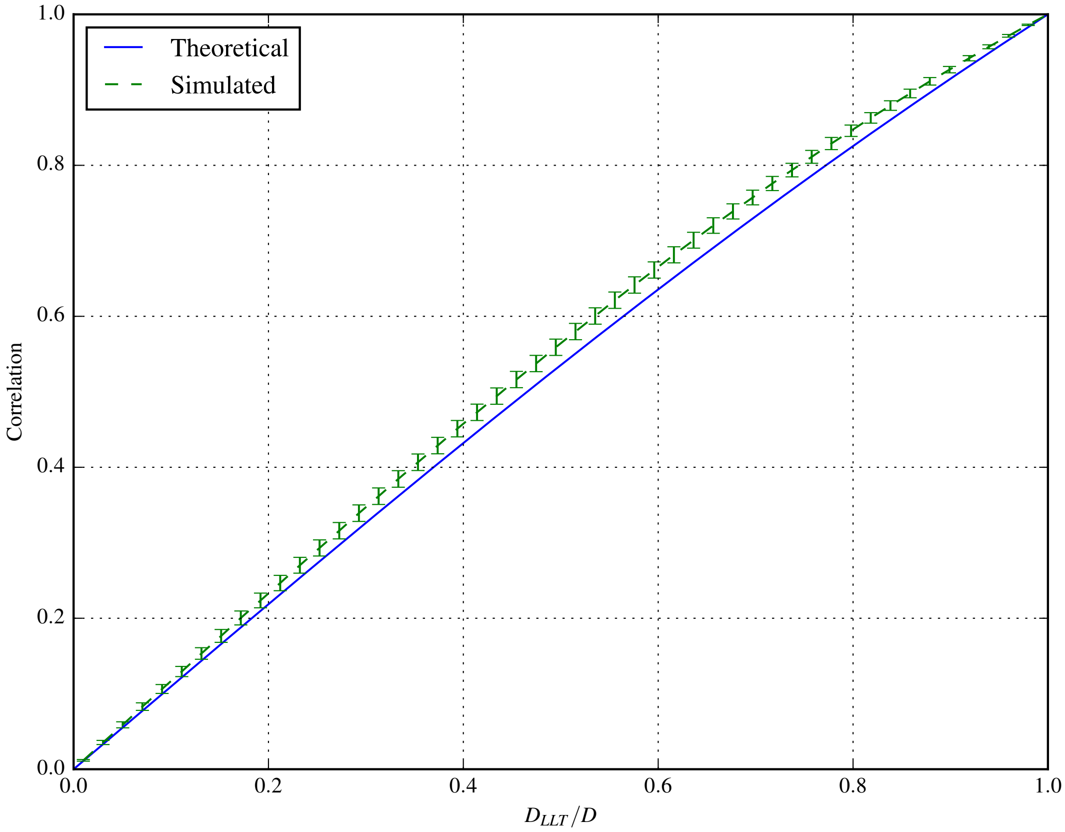

Figure 1. Theoretical and simulated correlation of phase perturbations in Kolmogorov turbulence between concentric tip-tilt modes as a function LLT diameter, D_{LLT}, as a fraction of the telescope diameter, D.

can express slopes measured by an LGS WFS as the sum of the laser up-link induced slopes and the down-link turbulence induced slopes,

$$\tilde{\mathbf{s}} = \tilde{\mathbf{s}}_{\mathbf{l}} + \tilde{\mathbf{s}}_{\mathbf{t}}, \tag{2}$$

where $\tilde{\mathbf{s}}$ is a vector representing the slopes measured on a WFS, $\tilde{\mathbf{s}}_{\mathbf{l}}$ is a vector representing the slopes caused by LGS up-link turbulence and $\tilde{\mathbf{s}}_{\mathbf{t}}$ is a vector representing the slopes caused by down-link turbulence. For AO correction of a natural astronomical science target we must obtain $\tilde{\mathbf{s}}_{\mathbf{t}}$. Note that LGS up-link turbulence results exclusively in tip-tilt modes being observed on the WFS and no higher order modes, so $\tilde{\mathbf{s}}_{\mathbf{l}}$ will be homogeneous in the x and y directions. For an AO system with a single LGS and no external reference, determining $\tilde{\mathbf{s}}_{\mathbf{t}}$ is not possible as there is not enough information to determine $\tilde{\mathbf{s}}_{\mathbf{l}}$. In a tomographic system, there is more information about the turbulence sampled by the LGSs on the up-link, and $\tilde{\mathbf{s}}_{\mathbf{t}}$ can be computed.

For the remainder of this section we consider a trivial 2-dimensional, tomographic, two LGS AO geometry, where both LGSs are centre-launched. The following approach can be scaled to many centre launched LGSs, though the mathematics quickly becomes cumbersome with more than three. The LGSs are labeled LGS α and LGS β and the observing WFSs as WFS α and WFS β. Slopes measured on WFSs are denoted as $\tilde{\mathbf{s}}_{\alpha}$ and $\tilde{\mathbf{s}}_{\beta}$ respectively. This geometry is illustrated in Figure 2.

WFS β observes the area of turbulence which causes the up-link tilt on WFS α, hence we postulate that there is a transform $\hat{\mathbf{T}}_{\alpha\beta}$ which relates the down-link turbulence induced slopes, $\tilde{\mathbf{s}}_{\beta\mathbf{t}}$, to up-link induced tip-tilt measured on WFS α, $\tilde{\mathbf{s}}_{\alpha\mathbf{l}}$,

$$\tilde{\mathbf{s}}_{\alpha\mathbf{l}} = \hat{\mathbf{T}}_{\alpha\beta}\tilde{\mathbf{s}}_{\beta\mathbf{t}}. \tag{3}$$

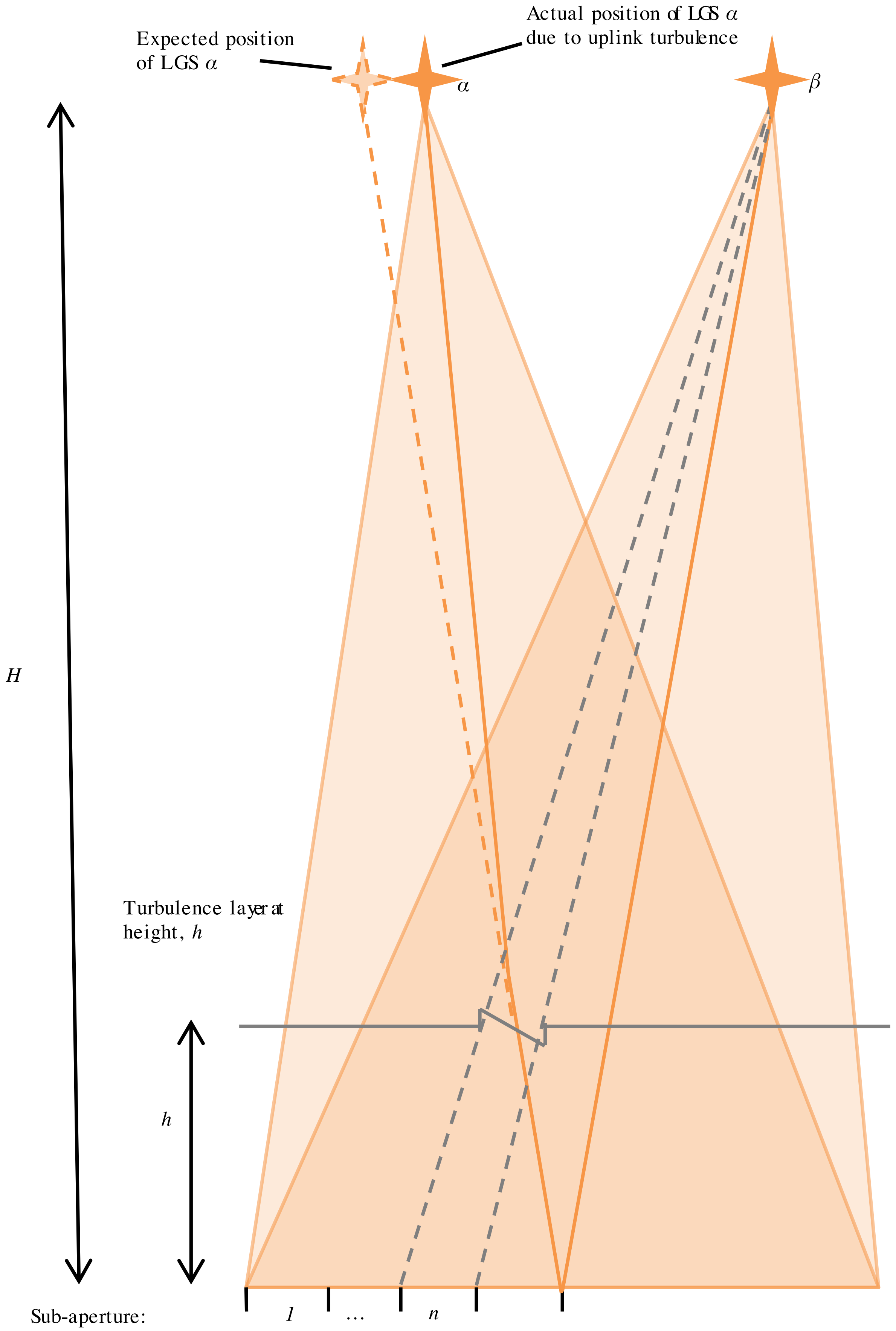

Figure 2. The geometry of the LGS system under consideration. One turbulent layer is shown, which features only a tilt at the point that LGS α overlaps with the field of view of sub-aperture n on WFS β.

We initially consider the simple situation illustrated in Figure 2, where a single turbulent layer at a height h, which features only a tilt in the section where LGS α overlaps with the field of view (FOV) of sub-aperture n on the WFS observing LGS α. In this case it is clear that such a transform, $\hat{\mathbf{T}}_{\alpha\beta}$, exists and can be trivially computed as WFS β is unaffected by up-link turbulence so $\tilde{\mathbf{s}}_{\beta\mathbf{l}} = 0$, hence $\tilde{\mathbf{s}}_{\alpha\mathbf{l}} = \hat{\mathbf{T}}_{\alpha\beta}\tilde{\mathbf{s}}_{\beta}$. In general however $\tilde{\mathbf{s}}_{\beta\mathbf{t}}$ will not be known, as LGS β will also experience up-link tip-tilt. For this general case,

$$\begin{aligned} \hat{\mathbf{T}}_{\alpha\beta}\tilde{\mathbf{s}}_{\beta} &= \hat{\mathbf{T}}_{\alpha\beta}(\tilde{\mathbf{s}}_{\beta\mathbf{t}} + \tilde{\mathbf{s}}_{\beta\mathbf{l}}) \\ \hat{\mathbf{T}}_{\alpha\beta}\tilde{\mathbf{s}}_{\beta} &= \tilde{\mathbf{s}}_{\alpha\mathbf{l}} + \hat{\mathbf{T}}_{\alpha\beta}\tilde{\mathbf{s}}_{\beta\mathbf{l}} \end{aligned} \tag{4}$$

and

$$\hat{\mathbf{T}}_{\beta\alpha}\tilde{\mathbf{s}}_{\alpha} = \tilde{\mathbf{s}}_{\beta\mathbf{l}} + \hat{\mathbf{T}}_{\beta\alpha}\tilde{\mathbf{s}}_{\alpha\mathbf{l}}. \tag{5}$$

By combining Equations (4) and (5), expressions for $s_{\beta l}$ and $s_{\alpha l}$ can be obtained,

$$\tilde{\mathbf{s}}_{\beta\mathbf{l}} = (\hat{\mathbf{T}}_{\alpha\beta} - \hat{\mathbf{T}}_{\beta\alpha}^{-1})^{-1}(\hat{\mathbf{T}}_{\alpha\beta}\tilde{\mathbf{s}}_{\beta} - \tilde{\mathbf{s}}_{\alpha}) \tag{6}$$

and

$$\tilde{\mathbf{s}}_{\alpha\mathbf{l}} = (\hat{\mathbf{T}}_{\beta\alpha} - \hat{\mathbf{T}}_{\alpha\beta}^{-1})^{-1}(\hat{\mathbf{T}}_{\beta\alpha}\tilde{\mathbf{s}}_{\alpha} - \tilde{\mathbf{s}}_{\beta}). \tag{7}$$

$\tilde{\mathbf{s}}_{\alpha}$ and $\tilde{\mathbf{s}}_{\beta}$ are the WFS measurements and the $\hat{\mathbf{T}}$ transforms can be obtained by considering the geometry of the system i.e., where sub-apertures from a WFS observe the up-link path of the other laser(s). It is now possible to calculate the turbulence induced slopes, as $\tilde{\mathbf{s}}_{\mathbf{t}} = \tilde{\mathbf{s}} - \tilde{\mathbf{s}}_{\mathbf{l}}$. These are the slopes which would have been measured from a guide star with no up-link tip-tilt effects, and can be used to perform the AO reconstruction without the requirement of an NGS for tip-tilt measurement. The above analysis can be performed for more complex LGS AO systems with many LGSs in other geometries.

In general there will be more than one discrete turbulent layer in the atmosphere, hence the measurement of a particular element in $\tilde{s}_{\beta t}$ which overlaps with LGS α will not just represent the turbulence at height h, but will be the sum of measurements from all turbulent layers. This represents some noise in the measurement of $\tilde{s}_{\alpha l}$. The noise is mitigated by increasing the number of LGSs, such that other layers from non-overlapping heights average to zero, leaving only the common measurement of the slope at the point LGS α overlaps with the layer at altitude h.

The transforms that relate downlink slope measurements to uplink slope measurements, $\hat{\mathbf{T}}_{\alpha\beta}$, can be shown to be of the form

$$\hat{\mathbf{T}}_{\alpha\beta} = \frac{\lambda}{2\pi}\begin{pmatrix} \frac{H-h_1}{H} & \frac{H-h_2}{H} & \cdots & \frac{H-h_N}{H} \\ \frac{H-h_1}{H} & \frac{H-h_2}{H} & \cdots & \frac{H-h_N}{H} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{H-h_1}{H} & \frac{H-h_2}{H} & \cdots & \frac{H-h_N}{H} \end{pmatrix}, \tag{8}$$

where λ is the wavelength of the light and H is the altitude of the LGS. h_n denotes the centre of the vertical height 'bin' resolvable by the sub-aperture n. By considering the system geometry, including the launch angle of LGS α and β, θ_α and θ_β respectively, h_n can be expressed as

$$h_n = \frac{H(\frac{D}{2} - (n+0.5)d)}{\frac{D}{2} - (n+0.5)d + H(\theta_\alpha + \theta_\beta)}, \tag{9}$$

where D is the diameter of the telescope pupil, d is the sub-aperture diameter and n is the sub-aperture index.

For the centre launched case, the slopes due to down-link turbulence, $\mathbf{s}_{\mathbf{t}}$, cannot be determined for a turbulent layer at the ground. For a layer at this height, $\tilde{\mathbf{s}}_{\alpha\mathbf{t}} = \tilde{\mathbf{s}}_{\beta\mathbf{t}}$, $\tilde{\mathbf{s}}_{\alpha\mathbf{l}} = \tilde{\mathbf{s}}_{\beta\mathbf{l}}$, $\tilde{\mathbf{s}}_{\alpha} = \tilde{\mathbf{s}}_{\beta}$, and there is no-longer more than one independent equation from which to determine $\tilde{\mathbf{s}}_{\alpha\mathbf{l}}$ and $\tilde{\mathbf{s}}_{\beta\mathbf{l}}$. An AO system which launches the LGSs from different points within the telescope aperture could potentially overcome this limitation as $\tilde{\mathbf{s}}_{\alpha\mathbf{l}} \neq \tilde{\mathbf{s}}_{\beta\mathbf{l}}$, so they again be determined. A system with LGSs launched from outside the telescope aperture (side launched) is unlikely to be suitable for this method of LGS up-link tip-tilt correction as a LGS's launch path is not observed by other LGS WFSs. It is possible that outer WFS sub-apertures could be used as they may correlate strongly with the launch path turbulence, though this is outside the scope of this work.

3.2 Learn and Apply Approach

The geometric approach described in the previous sections to estimate and recover LGS tip-tilt modes is not optimal. It requires knowledge of the turbulence $\mathrm{C_n^2}$ vertical profile and that the calibration of the LGS WFSs and pointing of the LGSs is perfect. It would also not take into account our understanding of atmospheric turbulence statistics to improve correction. As correlation between adjacent sub-apertures can be significant,[2] information from sub-apertures around those which view the up-link path of another LGS can be used to improve estimation of its up-link tip-tilt.

Learn and Apply (LA) is a method used in tomographic AO systems, such as MOAO and LTAO, for open-loop tomographic reconstruction which accounts for atmospheric turbulence statistics and the calibration of an AO system.[15] Instead of using a purely geometrical approach for LGS up-link tip-tilt determination, LA can be modified to implicitly account for up-link tip-tilt.

If there is a linear relationship between off-axis WFS measurements, $\tilde{\mathbf{s}}_{\mathbf{off}}$, and WFS measurements on-axis to the direction of a science target, $\tilde{\mathbf{s}}_{\mathbf{on}}$, one can write

$$\tilde{\mathbf{s}}_{\mathbf{on}} = \hat{\mathbf{W}}.\tilde{\mathbf{s}}_{\mathbf{off}} \tag{10}$$

where $\hat{\mathbf{W}}$ is the tomographic reconstructor. If $\hat{\mathbf{W}}$ can be obtained, it can be used to calculate pseudo WFS measurements in the direction of a potential science target, which can then be used to calculate DM commands to provide correction in that direction. Vidal et al. show that that in this case, a generalised tomographic reconstructor for a given turbulence profile can be expressed as

$$\hat{\mathbf{W}} = \hat{\mathbf{C}}_{\mathbf{OnOff}} \times \hat{\mathbf{C}}_{\mathbf{OffOff}}^{-1}, \tag{11}$$

where $\hat{\mathbf{C}}_{\mathbf{OnOff}}$ and $\hat{\mathbf{C}}_{\mathbf{OffOff}}$ are the covariance matrices between on-axis and off-axis slopes, and off-axis and off-axis slopes respectively. These matrices can be created analytically, by recording large open loop data sets from the AO system or some combination of these two approaches, where a fitting of analytical covariance matrices to raw ones is performed in a 'learn' step. This latter approach is the most likely for on-sky AO systems as it incorporates the systems calibration into the reconstructor. Once both covariance matrices have been computed, the reconstructor, $\hat{\mathbf{W}}$, can be formed and 'applied' to off-axis slopes to give an estimation of on-axis slopes. The LA algorithm has been tested successfully both in the laboratory and on-sky by the CANARY MOAO demonstrator.[5]

We propose that the LA algorithm is also applicable for LGS tip-tilt determination, as it was demonstrated in Section 3.1 that the required science direction slopes are a linear function of the off-axis LGS measurements. The advantages of using LA are many fold. Recording some raw data in a 'learn' step accounts for system alignment and LGS pointing. The mathematics shown in Section 3.1 does not have to be repeated for higher numbers of LGS, which quickly becomes cumbersome. The turbulence profile does not have to be externally measured to a very high vertical resolution as it is determined in the 'learn' step. Finally and perhaps most importantly, the use of covariance matrices implicitly includes information about LGS up-link from sub-apertures near to those identified as geometrically observing a LGS beam.

To use LA, the LA algorithm must be altered to account for the fact that the tip-tilt signal from LGS WFSs is no longer removed. The analytical form of slope covariance matrices in this case must be derived. We consider the covariance between two WFS separated slope measurements with the definition given in Equation (2),

$$\begin{aligned}\langle s_\alpha s_\beta \rangle &= \langle (s_{\alpha t} + s_{\alpha l})(s_{\beta t} + s_{\beta l}) \rangle \\ &= \langle s_{\alpha t} s_{\beta t} \rangle + \langle s_{\alpha t} s_{\beta l} \rangle + \langle s_{\alpha l} s_{\beta t} \rangle + \langle s_{\alpha l} s_{\beta l} \rangle.\end{aligned} \tag{12}$$

Of these terms, the first is only a result of down-link turbulence and is the same as the covariance matrix which would be required in conventional Learn and Apply. This term can be calculated in a form similar to that which Vidal et al.[15] use to obtain the covariance matrices between separated NGS WFS measurements with some modification to account for the cone effect associated with LGSs.

The second and third terms describe the relationship between the observed down-link turbulence and the tip and tilt observed by another WFSs due to the patch of turbulence that the lasers pass through on their up-link paths. They can be calculated again by considering the separation of each sub-aperture on the down-link with the launch path for each laser. As they are formed by a large tip or tilt from one WFS correlating with measurements from a single, or small number of, sub-aperture(s) from another WFS, it is expected that they will appear as a matrix of vertical and horizontal stripes.

The final term is the covariance between the up-link induced tip-tilt measurements. This value is dependent upon the separation between the two laser paths at an altitude layer and as it is a result of only tip and tilt, it is constant for each pair of WFSs. Assuming a centre launched case, this term will be large for low altitude layers, where the up-link laser paths overlap and small at high layers where the laser paths are separated. As it is constant, this value reduces the contrast of the the covariance matrices and so effectively make them less useful. Hence, it is again expected that this approach will work well at higher layers where this term is small, but less well for low layers where it will dominate.

Reeves et al.[13] show simulation results using a LA approach which verify the method, though also show that it does not perform well for correcting tip-tilt contributions from ground layer turbulence. It is proposed that ground layer tip-tilt may be corrected using far off-axis NGS. These can be dimmer than NGS used for GLAO, as they need only correct for tip-tilt and further off-axis than tip-tilt NGS used in tomographic LGS AO as they need only correct for ground layer turbulence. Thus gains significant gains in sky-coverage are likely.

4. APPLICABILITY FOR CURRENT TELESCOPES AND EXTREMELY LARGE TELESCOPES

For some existing and planned LGS AO system designs, only a change to the AO reconstructor is required to implement LGS uplink tip-tilt determination, with no additional hardware. It will only work effectively for centre launched, multi-LGS schemes, such as that at the William Herschel Telescope (WHT),[16] the Gemini South observatory,[17] the Large Binocular Telescope (LBT)[18] and the proposed Thirty Metre Telescope (TMT).[19] As the method uses the differential motion between LGSs to sense tip-tilt, it is important that drift of each LGS beam is minimal. This is not a problem for the LGS system at the WHT, as multiple LGSs are created by splitting a single laser beam into four. For other systems where each beam is created from an independant laser, the laser pointing must be kept constant.

Other multi-LGS systems are side-launched, such as the AO Facility (AOF) at the Very Large Telescope (VLT),[20] the planned Giant Magellan Telescope (GMT)[21] and the planned European Extremely Large Telescope (E-ELT).[22] As the downlink path of each LGS does not observe the uplink path of another, it is unlikely that LGS tip-tilt determination can be performed on these LGS AO systems. Due to the potentially high covariance between the phase gradient at the edge of the telescope pupil and the LGS launch path, some information may be retrieved. We are currently investigating the extent of this, and what performance gains could be achieved.

It is shown in Equation (12) that the performance of LGS uplink tip-tilt determination is dependant upon the seperation of the uplink laser beams. The method works more effectively for high altitude turbulence because the beams are further apart. For ELTs, larger LGS asterism diameters are required to sample the large pupil area, hence the beams will separate more quickly. This is expected to allow the method to correct for lower altitude tip-tilt aberrations than for current telescope generation aperture sizes.

5. CONCLUSIONS

In this paper, we have introduced and summarised a technique which determines the uplink tip-tilt of LGS in centre-launched, multi-LGS AO systems. Such a method has the potential of increasing LGS AO corrected sky-coverage when introduced into a Learn and Apply type tomographic reconstructor. Though ground layer tip-tilt contributions are not well corrected, tip-tilt from high altitudes is. We propose that ground layer tip-tilt is corrected by off-axis tip-tilt NGS, which still allows an increase in sky-coverage over conventional LGS tomographic AO.

The applicability of the method is reviewed for current and future telescopes, including the future ELTs. Observatories which feature centre-launched LGS systems may be able implement tip-tilt determination with little or no modifications to hardware. For observatories where lasers are launched from the edge of the telescope aperture it is unlikely that it will perform well, though we are currently working to characterise its performance.

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