Correction of photometric scintillation noise via tomographic wavefront sensing: simulation and on-sky demonstration

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ABSTRACT

Atmospheric scintillation noise severely limits the precision of time-resolved photometry for ground-based observations of bright stars. We describe developments of a method to correct this noise, for large and extremely large telescopes, via tomographic wavefront sensing. Wavefront sensor data for multiple reference stars is used to produce a 3D model of the instantaneous aberrations induced by atmospheric turbulence above the telescope. If the altitudes and relative strengths of the turbulent layers are known, then the phase aberrations of the wavefront at each height can be determined using tomography. This 3D model can then be used to calculate the propagation of the wavefront to ground level, and hence to estimate and correct the intensity fluctuations due to scintillation for a given target in the field of view. Potentially, this technique can be applied to the wavefront sensors of existing tomographic AO systems, with the scintillation correction applied and optimised in post processing. The method has been tested extensively in simulations. For example, for tomography using the 4 laser guide star asterism of the VLT, our simulations suggest that the RMS photometric noise for bright stars (which will be limited by scintillation) could be reduced by a factor of four in typical conditions. The method has also been tested in an on-sky demonstration, using the Orion Trapezium asterism as the reference stars for tomographic wavefront sensing on the Isaac Newton Telescope in La Palma.

Keywords: Seeing, Scintillation, Tomography, Adaptive Optics Methods

1. INTRODUCTION

The effects of the Earth's atmosphere severely limits high-precision ground-based photometry of astronomical sources. The effects of this optical turbulence are two-fold. Firstly, it deforms incoming wavefronts by slowing the sections that pass through regions with a higher refractive index, distorting and broadening the point spread function (PSF), thereby limiting the angular resolution. Secondly, as the light from a source passes through the Earth's atmosphere, regions of high altitude optical turbulence produce spatial intensity fluctuations known as scintillation. These spatial fluctuations, or 'flying shadow patterns', change over time both as the turbulence moves with the wind and as the turbulence evolves,[1] inducing intensity variations in the range of $\sim 0.1 - 1.0\%$[2] averaged over exposures of a few seconds for time-resolved photometry. Thus, scintillation noise significantly limits the capability of observing astronomical sources with intrinsic intensity variations such as exoplanet transits and stellar seismology.[3]

Whilst Adaptive Optics (AO) techniques have been developed to significantly improve image resolution, correcting scintillation noise is a different challenge. Since scintillation is produced by high altitude optical turbulence, it is only correlated over a very small range of angles and hence it cannot be corrected using differential photometry. A number of scintillation correction techniques have been proposed. These include the use of a ferroelectric liquid-crystal spatial light modulator to control the transmittance of a telescope pupil,[4] using the achromatic nature of scintillation,[5] differencing signals from binary stars[6] and conjugate plane photometry.[7] However, as of yet, no such instrumentation for scintillation correction is in common use.

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A scintillation correction technique for large telescopes that uses tomography was proposed by James Osborn in 2016.[2] To correct the scintillation noise, the Wavefront Sensor (WFS) data from several guide stars located near to the astronomical target is combined using a tomographic algorithm to produce an estimate for the instantaneous phase aberrations above the telescope. The estimated intensity fluctuations at the ground are calculated from the Fresnel propagation of the aberrated wavefront. This estimated scintillation pattern can then be used to normalise the measured photometric data. A key benefit to this method is that the model can be used to correct the scintillation noise in any direction within the field of view (FOV) as well as at any wavelength, meaning all objects within the field can be corrected simultaneously.

As such, an ideal application for this scintillation correction technique would be the ground based observations of multi-spectral transit photometry of exoplanets. From measurements of the absorption and emission lines during an exoplanet transit at different wavelengths, the molecules in the planet's atmosphere can be determined. These measurements help to develop our understanding of atmospheric processes including atmospheric chemistry, the greenhouse effect, the physics of clouds and winds.

In September 2021 this method was tested on-sky for the first time using the Orion Trapezium cluster as the reference stars for the tomographic wavefront sensing on the Isaac Newton Telescope in La Palma. In this paper we describe the on-sky experiment used to implement this method and present promising preliminary on-sky results. We also present results from a simulation of the 4 Laser Guide Star Facility (4LGSF) on the Very Large Telescope (VLT) which is an ideal basis for this method.

2. METHOD

A scintillation correction method for large and extremely large telescopes using a tomographic algorithm has been proposed. Full details of this method can be found in James Osborn's paper,[2] but a brief synopsis is given below.

Spatial-temporal intensity fluctuations, known as scintillation, are produced by the propagation of light through high altitude optical turbulence in the atmosphere. Hence, if the high altitude phase aberrations can be measured, then an estimate for the observed spatial intensity fluctuations can be produced numerically. This estimate can then be used to normalise the measured photometry and correct the intensity variations.

If the altitudes and relative strengths of the turbulence profile above the telescope is known, then the WFS data from multiple guide stars can be used to produce a 3D model of the phase aberrations above the telescope. This 3D model is produced using a tomographic algorithm that projects the WFS measurements onto each turbulent layer and uses the overlap in the WFS measurements from the reference stars on each layer to determine the low-order phase aberrations at each altitude in the Zernike basis. Only low orders can be measured as the sampling of the wavefront aberrations are limited by the spatial sampling of the WFS. Hence, only the low frequency intensity variations can be corrected.

The ground layer is fully sampled by all the stars. At higher altitudes there is less overlap between the WFS measurements, as seen in figure 1, and hence there is less information for these high layers. Turbulent layers above the altitude at which the WFS measurements no longer overlap will not be sampled and will add noise to the system. As such, this method is ideal for large telescopes, where the higher layers are better sampled. For small telescopes, the stars must be very close together to fully sample all the layers and therefore the sky coverage is very low for Natural Guide Stars (NGS).

A significant benefit to this method is that it can be easily applied to any existing tomographic Adaptive Optics (AO) system, so long as the turbulence profile is known. Another key benefit is that it can be applied entirely in post-processing so long as the WFS data are recorded. In addition, all stars in the field can be corrected simultaneously at any wavelength. It should be noted however, this method is only beneficial for scintillation limited stars where the scintillation noise is larger than the shot noise of the star signal.

3. EXPERIMENT

An on-sky demonstration of the method outlined in section 2 was designed and performed in September 2021, on the Isaac Newton Telescope (INT) in La Palma. This low cost, proof of concept experiment was designed

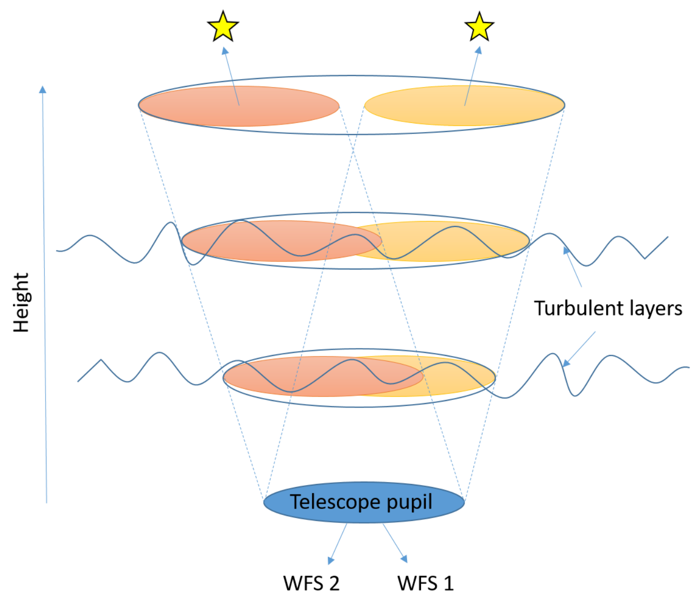

Figure 1. A schematic showing the basis of atmospheric tomography. The phase aberrations at each turbulent layer is determined from the overlap in the WFS data from several guide stars.

with a single WFS and a SCIDAR turbulence profiler attached to the INT. The photometry was also measured from the WFS images.

The small aperture size of the INT significantly limited the sky coverage of this method as it required bright, scintillation limited stars to be within a very small area of sky. A simulation was designed to find candidate asterisms for testing this method. The best target was found to be the Orion Trapezium Cluster - a popular target amongst AO tomography demonstrations.[8] The target star, the star for which the correction will be applied, was selected as Orionis C, the brightest star in the cluster with a 5.13 magnitude in the V band. Orionis A and Orionis D were then used in addition to Orionis C to perform the tomography which have V band magnitudes of 6.5 and 6.3 respectively.

To perform the tomography, an estimate for the turbulence profile above the telescope is required. A SCIDAR instrument,[9] which uses the cross correlation of the scintillation patterns measured from two stars to measure the profiles, was used to measure the turbulent layer heights and relative strengths.

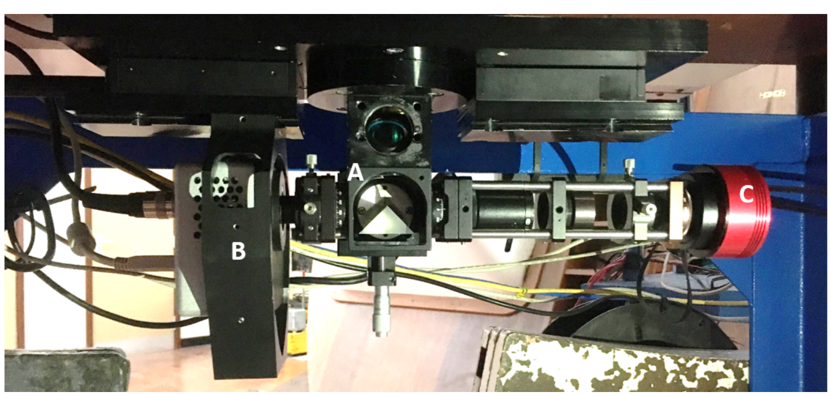

Figure 2. A photograph of the instruments attached to the INT. Label A shows the prism that is used to move from one instrument to the other, label B shows the SCIDAR instrument and label C shows the WFS optics - comprising of a collimating lens and lenslet array - and the detector.

Both the SCIDAR and WFS optics were attached to the INT and a reflecting prism was used to switch between the two instruments. Figure 2 shows a photograph of the two instruments attached to the INT.

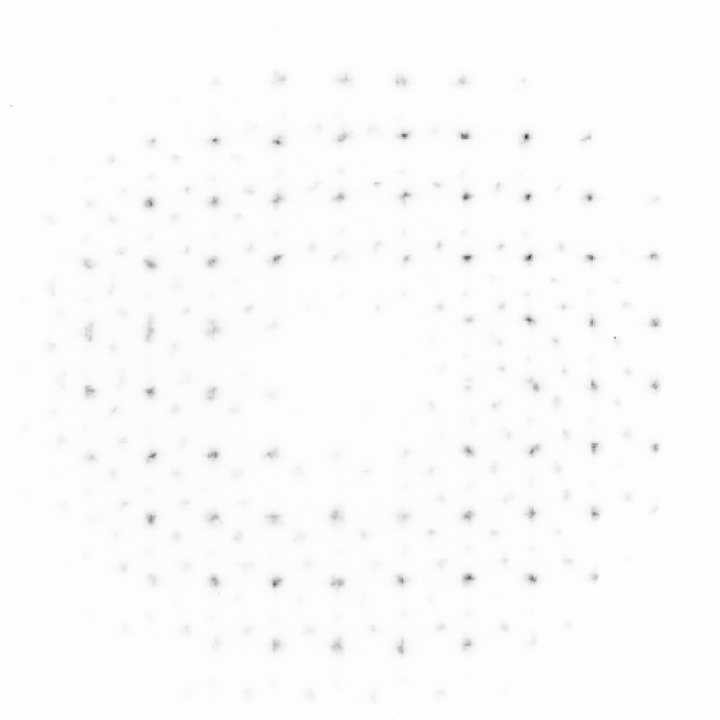

Figure 3. An example 0.1s exposure WFS frame of the Orion Trapezium Cluster. The frame has been inverted such that the stars can be easily seen.

A 10x10 WFS was used to ensure enough spatial sampling and a high signal-to-noise ratio (SNR) for each subaperture. The number of Zernike modes that could be reconstructed was limited to the number of subapertures used, however, the low order focal modes contribute the most scintillation noise and thus sufficient correction can still be achieved with only the low order modes.

A ZWO ASI 1600MM camera was used as the detector for the WFS frames. The CMOS camera's large format and fast readout meant that it can encompass all the star spots and a short exposure, high frame rate, could be used with low read-out noise. In addition, the camera can be used to perform reasonably good photometry. The WFS optics comprised of a collimating lens, V band filter and a lenslet array.

In simulation we find that the technique works well using exposure times much longer than typical AO correction. This is because both the wavefront measurements and intensity fluctuations average in the same way. Averaging the wavefront measurement doesn't bias the reconstructed intensities so low order correction can still be achieved. As such, WFS data packets were collected with 50 frames per packet with an exposure time of 0.1s.

An example WFS frame is given in figure 3. As can be seen, the field is very crowded with four stars per subaperture. Great care was taken for the centroiding and photometry to avoid contamination with the use of windowing, thresholding and masking.

4. DATA REDUCTION

There are multiple steps to performing the data reduction which are outlined below. Each step was optimised in turn. The tomographic algorithm used in this research is a Multi-Conjugate AO (MCAO) algorithm which uses the Zernike basis for the WFS measurements. The algorithm is based on a minimum-mean-square-error estimator that minimizes the mean residual phase variance in the FOV of interest.[10] A model approach is used, which assumes all the turbulence is located on the discrete layers input in the reconstruction matrix.

- The spots for each of the three stars of interest are measured from the WFS data. A window of 18x18 pixels is used around each star and a Centre of Gravity algorithm is used to measure the spot centroids.
- The WFS data is also used to perform the aperture photometry on the target star. A 2nd order curve fit is used to correct any systematic trends in the photometry.
- The measured centroids for each star are converted to Zernike modes using a Zernike decomposition matrix.
- The SCIDAR data is used to estimate the turbulence profile. The median turbulence profile is used and an optimal grouping method[11] is used to compress the profile to five layers.
- The tomographic reconstruction matrix is produced using the estimated turbulence profile and the star separations, and is applied to the WFS data to get the reconstructed phase at each altitude.
- The reconstructed phase aberrations are used to estimate the scintillation pattern for each exposure resulting from the Fresnel propagation of the aberrated wavefront.
- The estimated intensity fluctuations are used to normalise the measured intensity of the target star.

5. RESULTS

5.1 On-sky

The performance of the tomographic reconstruction was measured via the Pearson r correlation coefficient between the the measured intensity and the tomographically reconstructed intensity. In addition, the factor by which the scintillation index was corrected was also used.

In this section the results for one of the best performing data packets are presented. The light curve was temporally binned to filter out some of the higher frequency variance, resulting in an effective exposure time of 0.2s. This packet has a measured SNR of 217 and a measured scintillation rms noise of 4.6×10^{-3}. For a 5.13 magnitude star in the V band, the expected shot rms noise for a 0.2s exposure time on the INT is 1.6×10^{-4}. Hence, we can be confident that the observation is scintillation limited.

The measured light curves from the aperture photometry were corrected for any long timescale systematic trends. Usual differential aperture photometry could not be used as the comparison star is fainter than the target and thus the calibration induces random intensity fluctuations to the target light curve. Thus, a third order polynomial curve fit was instead used to correct any systematic noise.

Figure 4 shows the measured normalised intensity plotted against the tomographically reconstructed normalised intensity. The Pearson r correlation coefficient measured between the two is 0.82 - a strong positive correlation. Hence, the tomographically reconstructed intensity has successfully estimated the intensity fluctuations. However, as can be seen there is a systematic error in the scaling of the reconstructed intensity such that a smaller peak to peak variation is measured. There are many possible sources for this systematic scaling, including systematic noise in the measured photometry or the estimation for the turbulent layer heights and strengths used in the tomographic reconstruction being inaccurate.

Figure 5 shows the measured normalised intensity and the tomographically reconstructed normalised intensity. The strong correlation between the measured and reconstructed intensities can clearly be seen. Normalising the measured photometry of this data packet reduced the scintillation index by a factor of 3.12, meaning a reduction in the scintillation rms by a factor of 1.77. Hence, the noise has been reduced by $\sim 43\%$.

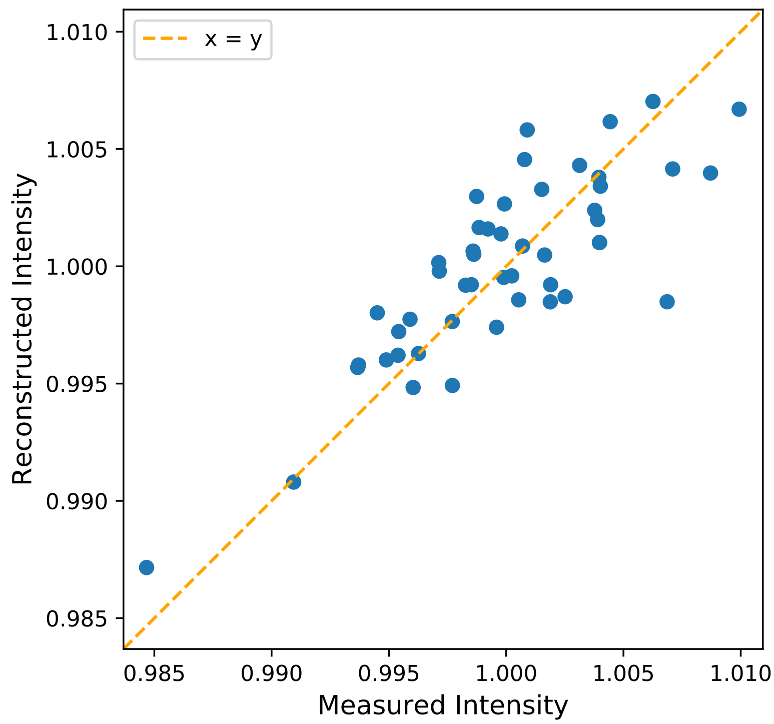

Figure 4. A plot of the measured normalised intensity against the tomographically reconstructed normalised intensity. A strong correlation between the two is measured with a correlation coefficient of 0.82.

5.2 Simulation

This proof of concept experiment has demonstrated that correction of scintillation induced intensity fluctuations via tomographic reconstruction is possible in practice. However, the set-up has a number of limitations which are likely to reduce the effectiveness of the correction such as performing the photometry with the WFS images. We expect a much higher degree of correction would be obtained using a full tomographic wavefront system employing laser beacons with a separate imaging detector dedicated for photometry.

As such, a simulation for an optimal set-up was produced. The simulation used a Monte Carlo phasescreen representation of the atmosphere and Fresnel propagation to produce intensity fluctuation patterns. A WFS that includes the random measurement errors due to shot noise, but otherwise perfectly measures the atmospheric Zernike terms, was simulated. The tomographic reconstruction algorithm was produced assuming perfect knowledge of the turbulent layer altitudes and relative strengths.

The 4LGSF on the VLT was chosen as an ideal basis for this technique. The VLT was simulated with the four LGS in a square around a scintillation limited target star with a 45" separation as shown in figure 6 and it is assumed the observation is near zenith. A one second exposure time and a 16×16 WFS was used for each guide star. The simulation included the laser reference beacon's cone effect, tip-tilt indetermination and the spot elongation.

Eighteen turbulence profiles measured in Paranal,[12] each simulated with five layers, were used in simulation to test this experimental set-up. Figure 8 shows an example of the measured normalised intensity, reconstructed intensity and corrected intensity that were simulated and figure 7 shows the measured normalised intensity plotted against the tomographically reconstructed normalised intensity. The measured correlation between the measured and reconstructed intensity is 0.98 which results in a reduction in the scintillation rms noise by a factor of 5. It was found that on average the scintillation rms noise was reduced by a factor of four.

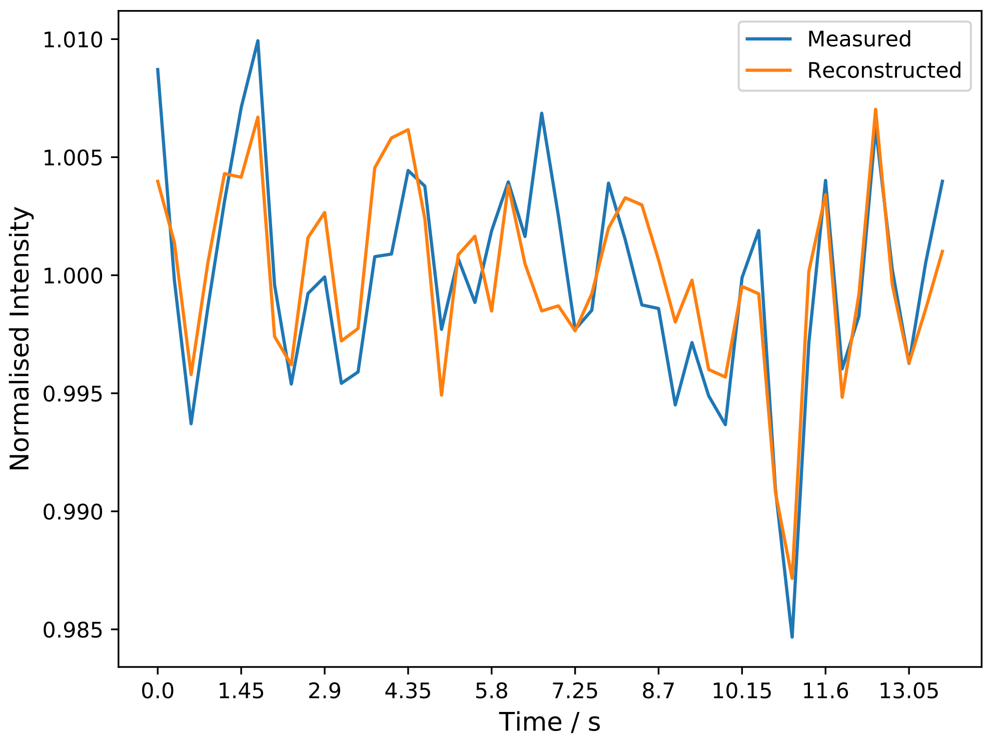

Figure 5. A plot of the measured normalised intensity and the tomographically reconstructed normalised intensity.

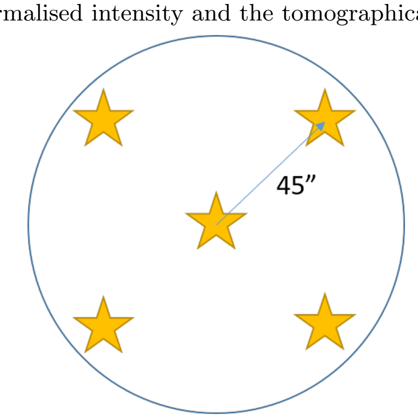

Figure 6. A schematic showing the asterism used in simulation. Four laser guide stars surround a scintillation limited target star.

6. DISCUSSION

An experiment test a scintillation correction using a tomographic wavefront sensing has been implemented on-sky. Preliminary results are encouraging with a strong correlation measured between the measured and reconstructed intensities.

This on-sky experiment was far from the ideal. The small aperture size of the INT was a big limitation in terms of the instrumentation as the sky coverage was very limited to get sufficient sampling of the high altitude turbulent layers. In an optimum set-up, a large telescope ($\sim$ 8m or larger) would be used along with laser guide stars such that greater sampling of the turbulent layers can be achieved. In addition, simultaneous turbulence profiling would be performed and a separate dedicated camera would be used to perform the photometry.

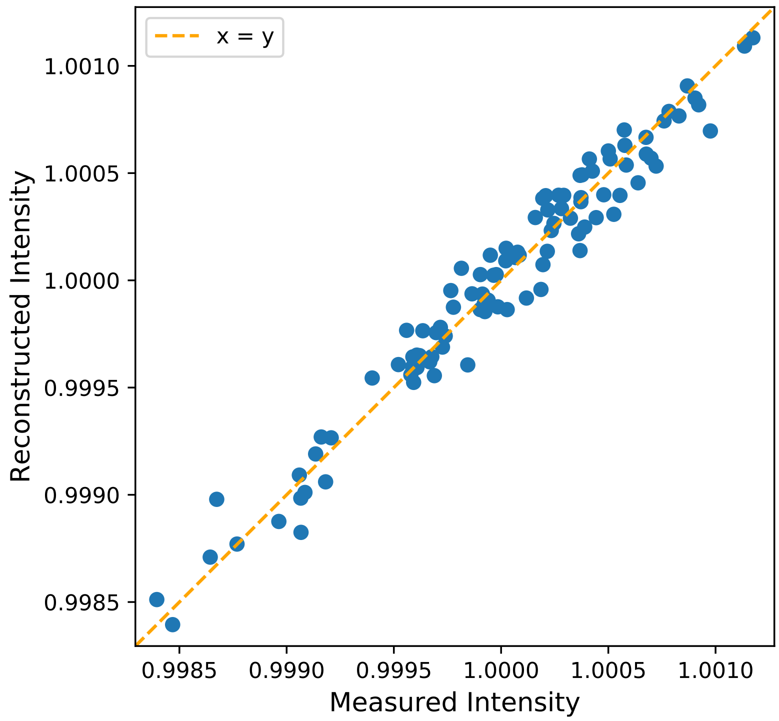

Figure 7. A plot of the measured normalised intensity against the tomographically reconstructed normalised intensity for one of the VLT simulations. A strong correlation between the two is measured with a correlation coefficient of 0.98.

Switching between the WFS optics and SCIDAR instruments took several minutes. This ~ 10 minute delay is not optimal. Whilst it is unlikely the profile has changed significantly in that time period, the relative heights and strengths of the turbulence profiles can change over very short time periods.[13] Without simultaneous turbulence profiling, any sudden changes in the profile cannot be applied to the reconstructor. Thus, ideally, a separate turbulence profiler should be used simultaneously with the WFS measurements to ensure accurate profiles are used.

In addition, the necessity of using the WFS data to perform the photometry is sub-optimal for multiple reasons. The crowded subapertures severely limits the aperture size that can be used and the ability to measure a reasonable estimate for the sky background. The diffraction of the WFS spots also leads to light loss and summing over all the subapertures results in more read-out noise. Ideally, the photometry would be done using a separate detector.

Given these limitations, the fact that a strong correlation has been measured between the measured intensity and the tomographically reconstructed intensity, demonstrates the viability of this method. Whilst the correction measured on-sky is relatively small, it is expected that with a more optimum set-up, a much larger correction in the rms would be measured. Simulations of the VLT suggest a correction in the scintillation rms noise by a factor of four can be achieved.

The latest large and extremely large telescopes will all be equipped with tomographic AO systems. For example, the 4LGSF on the VLT or the Multi-conjugate Adaptive Optics RelaY (MAORY)[14] and the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI)[15] for the Extremely Large Telescope (ELT). Such systems would be ideal for this scintillation correction technique. With AO in open loop, the instrumentation could be setup to apply the scintillation correction in real time, or it can be applied entirely in post-processing using the WFS and turbulence profile data.

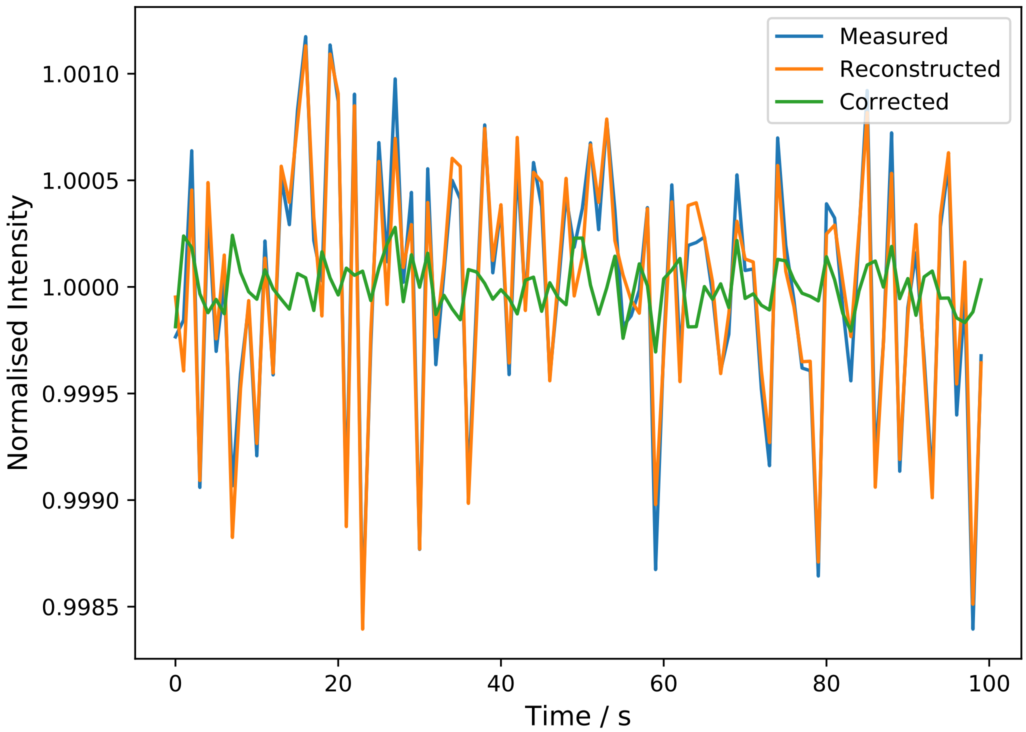

Figure 8. An example simulated light curve for the VLT. The measured normalised intensity, reconstructed intensity and corrected intensity are plotted for 100s of data.

7. CONCLUSION

In conclusion, atmospheric scintillation noise produced by high altitude optical turbulence significantly limits high-precision ground-based astronomical observations. A scintillation correction technique using tomographic wavefront sensing has been successfully demonstrated on-sky.

An experiment observing the Orion Trapezium cluster on the Isaac Newton Telescope was performed using a single wavefront sensor and a SCIDAR instrument. Results show a strong positive correlation between the measured intensity and tomographically reconstructed intensity. The on-sky experimental set-up has a number of limitations and it is expected that much higher performance can be achieved with a laser tomography facility.

Tomographic AO systems will be required for the next generation of large telescopes and hence will be ideal for this scintillation correction technique. Simulations of the 4LGSF on the VLT suggest a reduction in the scintillation rms noise by a factor of four can be achieved.

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