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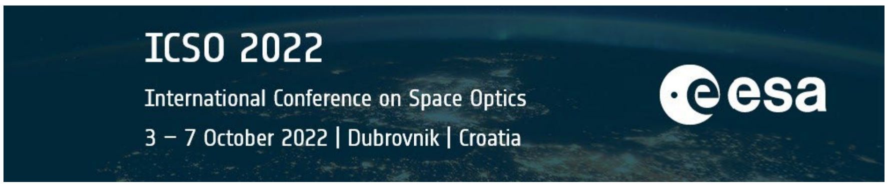

AO-enhanced Quantum Communications with the ANU Optical Ground Station

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AO-enhanced Quantum Communications with the ANU Optical Ground Station

Noelia Martinez[a], Sebastian Kish[b], Francis Bennet[a], Marcus Birch[a], Ping Koy Lam[b], Kate Ferguson[c]

[a]Australian National University, Research School of Astronomy and Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston Creek 2611, Australia;
[b]Australian National University, Research School of Physics, Acton, 2602, Australia;
[c]Australian National University Institute for Space, 121 Marcus Clarke, Canberra, 2602, Australia;

ABSTRACT

Satellites have the potential to support quantum communication over much longer distances than fibre optics networks and, as a result, there is a large amount of investment globally in quantum communication satellites. The Australian National University Optical Ground Station aims to provide ground services support for quantum communication satellites, and enhance the quantum link performance by the use of Adaptive Optics techniques.

Numerical simulations have been carried out to assess the advantage of correcting the atmospheric turbulence on quantum downlinks with Adaptive Optics. Fibre coupling efficiency of the communications light onto a single mode fibre has been chosen as the performance metric.

We pay special attention to the focusing optics and optimise them for the Single Mode Fibre coupling. We present the minimum requirements for an AO system to produce a significant improvement on the quantum link using off-the-shelf components. This paper gathers the main outcomes of the end-to-end numerical simulation and describes a potential pathway for future atmospheric corrected quantum communications.

Keywords: Adaptive Optics, quantum communications, ground receiver, fibre coupling

1. INTRODUCTION

Quantum key distribution (QKD) is the sharing of keys between two parties. Local data sent by a sender is encrypted using a key that is guaranteed by quantum mechanics to be securely shared only with the receiving party. Over the past 40 years, quantum communication had evolved from an application of quantum mechanics to a viable technology. Recently, discrete variable based QKD using polarization was demonstrated in a free-space satellite-to-ground channel up to a distance of 1200 km.[1] A quantum link was established from the low-Earth-orbit (LEO) Micius satellite to the Xinglong ground station. This exciting development is a major step towards realizing global scale secure quantum communications using low-orbit satellites.[2] With the continuing launch of optical enabled satellites for quantum communications, the ANU ground station aims to provide Adaptive Optics capability to enhance quantum link performances.

1.1 Adaptive Optics

Adaptive Optics systems measure and correct the atmospheric turbulence. Adaptive Optics (AO) are commonly used in ground-based telescopes to compensate for the light distortion caused by the atmosphere and to restore the spatial resolution in astronomical observations. Basically, an AO system consists of a wavefront sensor (WFS), which measures the aberrations in real-time by imaging a reference light source on the sky, and a deformable mirror (DM), which adapts its shape to the measured aberration and cancels out the undesired effect on the light.

Further author information: (Send correspondence to N.M.)
N.M.: E-mail: noelia.martinezrey@anu.edu.au

When applying Adaptive Optics to ground-to-space optical communications (classical and quantum), the signal originated at the satellite becomes the reference source for the turbulence sensing (in absence of a Laser Guide Star). Splitting the light between the communications receiver and the wavefront sensor implies an obvious reduction of bandwidth in the channel; therefore, the ideal scenario requires an additional light source at the satellite (i.e. a beacon) to retrieve the atmospheric turbulence information. Figure 1 shows the basic schematic of an AO system for quantum communications through the atmosphere.

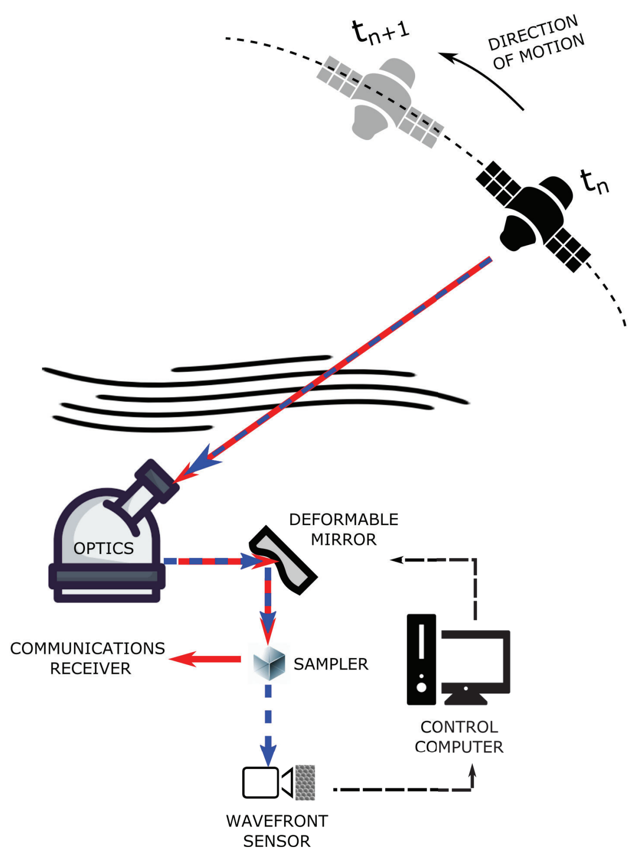


Figure 1. Basic configuration of an Adaptive Optics system for a space-to-ground communications link; the red arrow represents the quantum channel and the blue arrow represents the beacon.

1.2 The Australian National University Ground Station

The Australian National University (ANU) is currently building an optical ground station for bidirectional laser communications (classical and quantum).[3] The ANU Ground Station will be located at Mount Stromlo Observatory, Canberra. It will be a two level building with the 0.7m Ritchey–Chrétien telescope by PlaneWave Instruments (RC700) and Adaptive Optics capability for space to ground optical communications (Figure 2). It will have the capacity to host numerous instruments including the lunar communications receiver for the Artemis program and equipment for the reception of quantum encryption.

The ANU Ground Station will be integrated within the new Australasian Optical Ground Station Network (AOGSN),[4] an initiative by Australia and New Zealand to create a Free Space Optical network that will provide ground coverage and site diversity for optical communications with satellites in Low Earth Orbit and Geostationary Orbit.

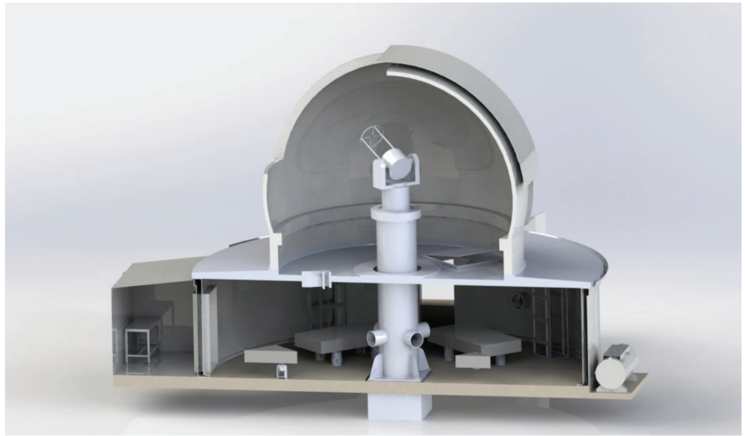


Figure 2. CAD render of the Australian National University Ground Station showing the PlaneWave RC700 telescope, the Coudé clean room, and additional server room to the left of the laboratory space.[3]

2. SYSTEM MODELLING

End-to-end numerical simulations have been performed using the Object-Oriented Matlab Adaptive Optics (OOMAO) Toolbox[5] as the modelling tool. OOMAO is an end-to-end open source simulation tool that models the behaviour of a complete Adaptive Optics system as well as the propagation of the light through the atmosphere.

The simulation framework models the communications downlink coming from a satellite on a 500-km Sun-Synchronous orbit; it included the propagation through the atmosphere of three signals: a quantum channel (wavelength 850 nm), a classical optical link (wavelength 1550 nm), and a beacon (wavelength 1550 nm). This work focuses on the quantum channel.

The ANU Ground Station (diameter 0.7 m) was modelled as the ground receiver; additionally two different optical receivers were analysed too (diameters 0.4 m and 0.8 m). The central obscuration of the ground receiver plays a fundamental role in the maximum achievable coupling efficiency; the ANU Ground Station (central obstruction 25%) was specifically designed to minimise losses due to the central obscuration and hence, will show better performance compared to optical receivers with obstruction ratios of 32% and 40%.

The atmospheric turbulence the downlink will experience, is defined by the Fried parameter (r0). A Fried parameter of 5 cm at 550 nm has been selected as the most turbulent scenario at Mount Stromlo Observatory, Canberra, where the ANU Ground Station will be located.

Only night-time scenarios have been simulated.

The simulation framework is summarised in Table 1.

The coupling efficiency to a Single Mode Fibre has been selected as performance metrics; the coupling efficiency is defined as a the ratio of the average power coupled into the fibre and the average power available at the focal plane, as described in.[6]

3. COUPLING OPTICS OPTIMISATION

Based on previous research works, the maximum achievable coupling efficiency varies with the relative aperture D/f of the coupling optics,[7].[8] Figure 3 shows the effect of the coupling optics in the coupling efficiency. Optimum values of D/f have been selected for all the simulated cases: $D/f \approx 0.11 - 0.12$ for the 850 nm beam, and $D/f \approx 0.21 - 0.22$ for the 1550 nm beam, with the range varying depending on the central obscuration of the ground receiver.

The optimum coupling optics have been designed based on the ratio aperture/focal length as well as the type of focusing optics (plano-convex lens, doublet lens, aspheric lens) in Table 2. The wavefront maps of each lens have been extracted from Zemax OpticStudio and implemented in OOMAO.

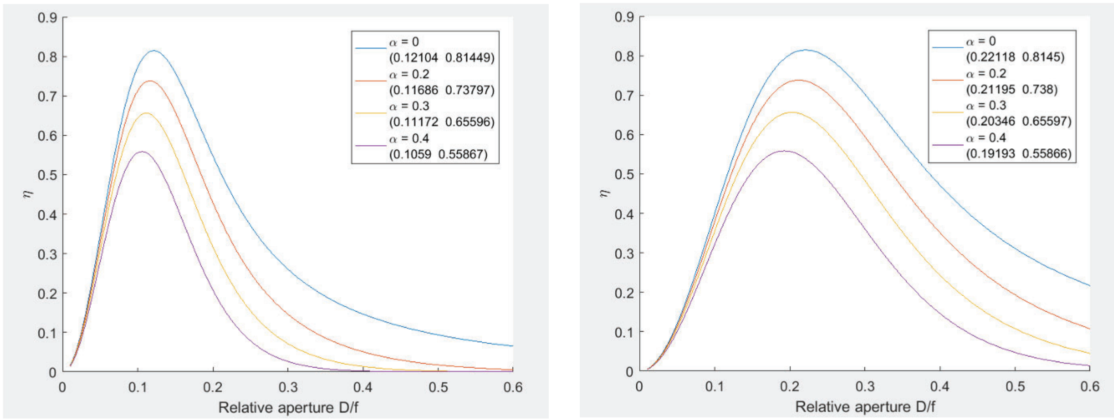
Table 1. Simulation Framework

ATMOSPHERE	
Atmospheric layers	3 layers at 0 m, 4000 m, and 10000 m
Fried parameter (r0)	5 cm @ 550 nm
Average wind speed	21 m/s
Sky background	220 cps
RECEIVER	
ANU Ground Station	
Aperture	0.7 m
Central obscuration	25%
Focal length	8.4 m
Optical losses	-0.61 dB
SMF mode field radius	5 μm
Ground Station A	
Aperture	40 cm
Central obscuration	32.5%
Focal length	0.280 m
Optical losses	-1.8 dB
SMF mode field radius	5 μm
Ground Station B	
Aperture	80 cm
Central obscuration	40%
Focal length	0.480 m
Optical losses	-1.8 dB
SMF mode field radius	5 μm
TRANSMITTER	
Orbit	500 km Sun-Synch
Elevation angle	Zenith
CLASSICAL SIGNAL	
Wavelength	1550 nm
Laser power	1 W
QUANTUM SIGNAL	
Wavelength	850 nm
Laser power	90 pW
BEACON	
Wavelength	1550 nm
Laser power	1 W

Table 2. Focusing lenses under study

Lens Type	**Focal Length [mm]**	**Diameter [mm]**
Plano Convex	100	25
Doublet	100	25
Aspheric	102	25.4

Figure 4 presents an example of how the focusing lens affects the coupling efficiency for a classical communications downlink at 1550 nm, with the aspheric lens outperforming with respect to the other optical elements (best focusing capability and smallest wavefront error). No atmospheric correction was applied in this case.



(a) (b)

Figure 3. Effect of the coupling optics in the achievable fibre coupling efficiency (η) into a 5 μm (w_0) SMF with a 0.7 m receiver station and a range of central obscuration ratios (α). No atmospheric turbulence has been considered for this analysis. (a) Wavelength of the incoming signal 850 nm; (b) Wavelength of the incoming signal 1550 nm.

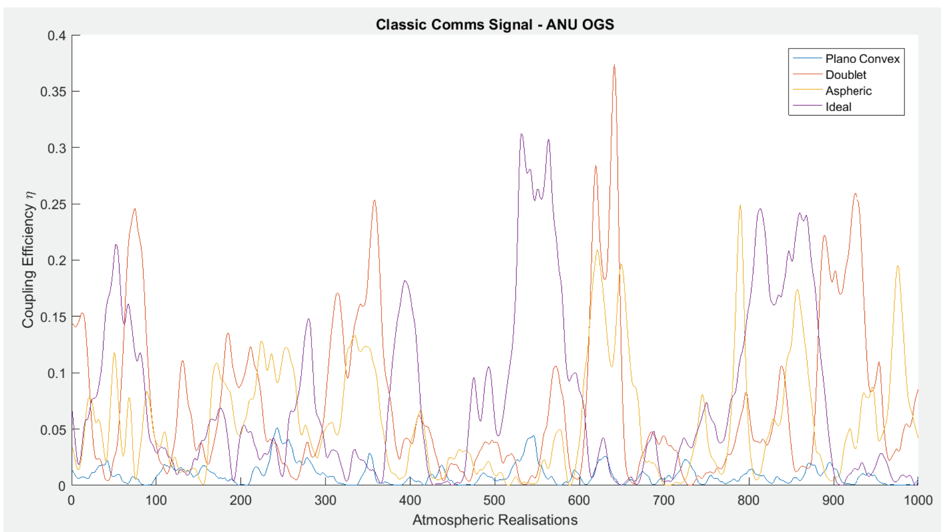


Figure 4. Effect of the coupling optics in the achievable coupling efficiency of a classical communications signal (wavelength 1550 nm) received by the ANU ground station under strong turbulence conditions (r0 = 5 cm) without atmospheric correction.

4. OPTIMISED ADAPTIVE OPTICS

The effect of correcting for the atmospheric turbulence using Adaptive Optics was first studied assuming the most suitable dimensioning of the Adaptive Optics system optimised for the turbulence strength and each diameter of the receiver station. 50% of the beacon light (received on the ground) has been assumed to be available for the wavefront sensing.

Three configurations in the AO correction have been considered: (1) 10x10 Shack-Hartmann wavefront sensor (WFS) and a Deformable Mirror (DM) of 121 actuators; (2) 14x14 Shack-Hartmann WFS and a DM of 225 actuators; and (3) 20x20 Shack-Hartmann WFS and a DM of 441 actuators.

The use of Adaptive Optics with separate correction of low order modes of the atmospheric turbulence (tip-tilt) and high order modes of the atmospheric turbulence was also analysed.

Figure 5 shows examples of how an 850-nm incoming beam would look like at the focus plane of the receiver telescope under strong turbulence conditions of r0 = 5 cm without atmospheric correction and with partial or total correction.

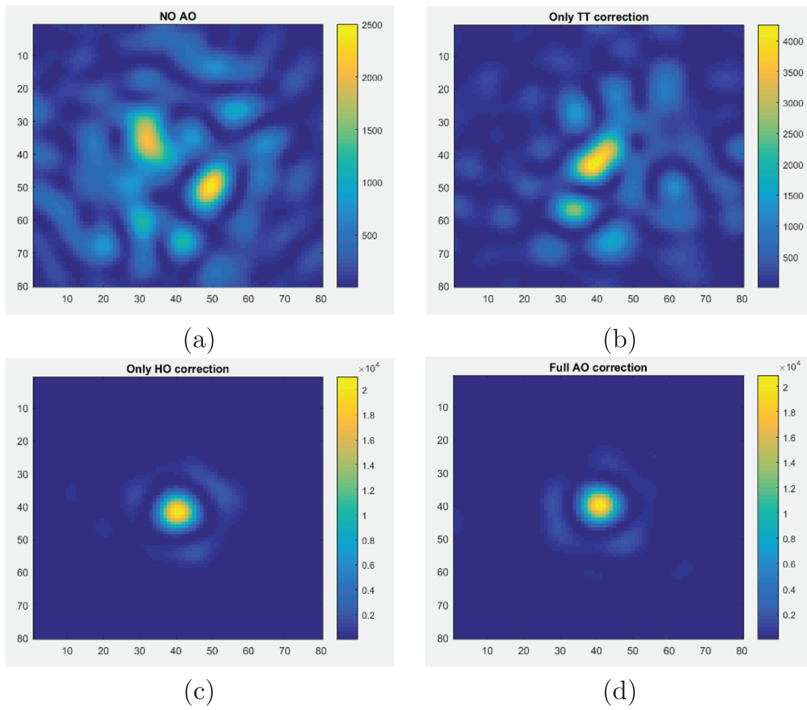


Figure 5. Short exposure images of a 850-nm beam at the receiver focus plane with (a) No AO; (b) Only TT correction; (c) Only High Order correction; (d) Full AO. Atmospheric conditions r0 = 5 cm.

4.1 Simulation Results

This section summarises the outcome of the numerical simulations assuming the most optimised AO system. Figure 6 shows the coupling efficiency without (first 1000 iterations) and with Adaptive Optics (last 1000 iterations) to compensate for the atmospheric turbulence in the quantum link. Each iteration corresponds to the average of 1000 independent atmospheric realisations. Receiving the communications signal with the ANU OGS results in the best fibre coupling efficiency compared to the 80 cm and the 40 cm receivers; coupling efficiencies using a 40 cm receiver are slightly worse, but better to the 80 cm receiver due to smaller apertures being less affected by the atmospheric turbulence.

The fibre coupling efficiency improved from $\approx 2\%$ (no AO in the strongest turbulence) to $\approx 45\%$ after applying AO to the quantum link received by the ANU Ground Station.

When analysing the performance of using Adaptive Optics with two deformable mirrors, one for tip-tilt (low order aberrations of the atmosphere) and another one for higher order aberrations, results (Figure 7) show that even though tip-tilt modes are dominant in the atmospheric turbulence, the spread in the incoming beam due to the high order modes has a significant effect on the coupling efficiency.

5. LOW COST ADAPTIVE OPTICS FOR QUANTUM CHANNELS

A low cost AO system was dimensioned for the atmospheric correction on the quantum downlink. The performance was tested using end-to-end numerical simulations and the modelling framework described in previous sections.

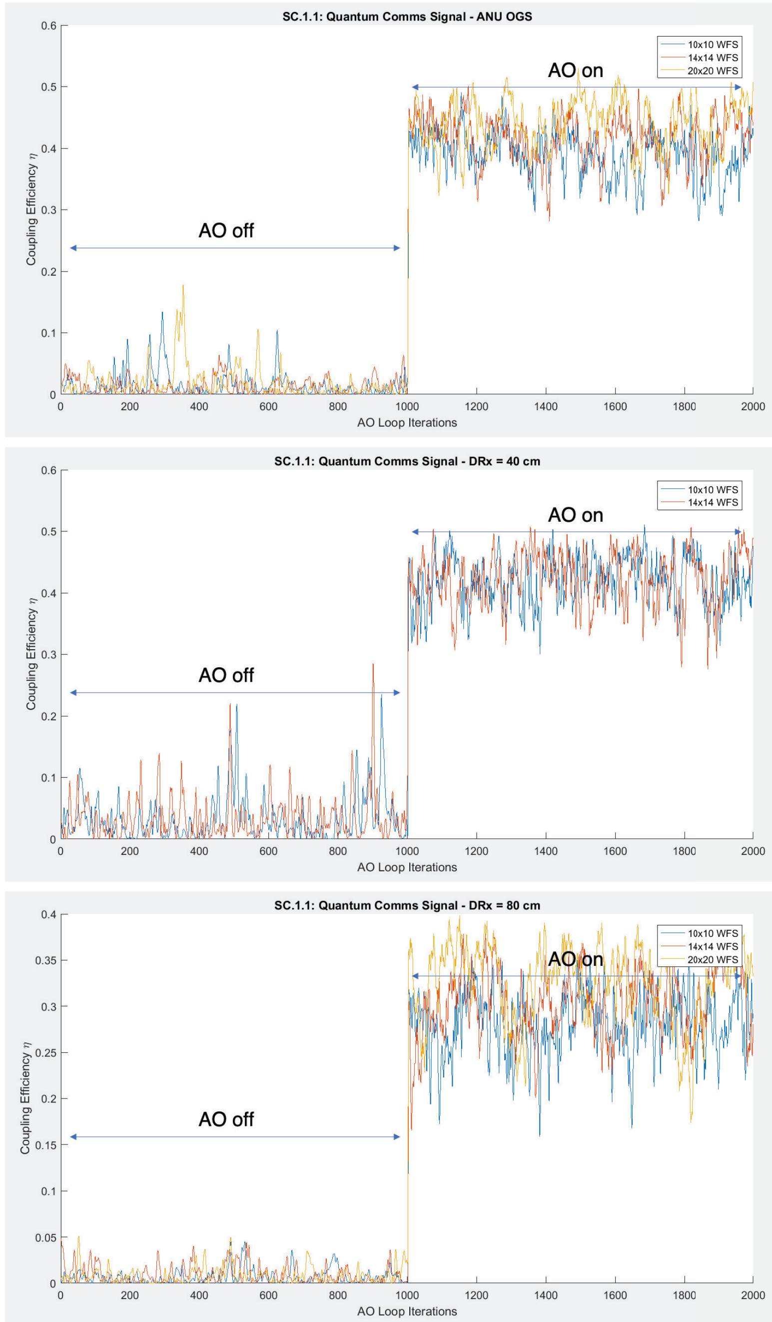
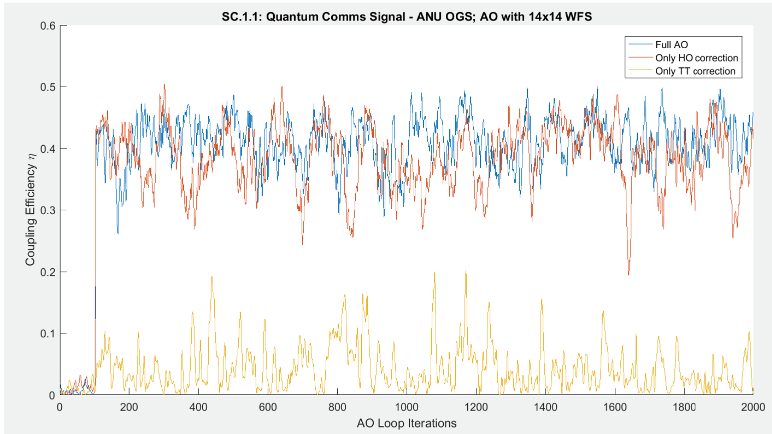


Figure 6. Adaptive Optics effect: the fibre coupling efficiency improves in the second 1000 iterations after turning the AO system on. The wavelength of the incoming light is 850 nm; Atmospheric turbulence r0 = 5 cm.

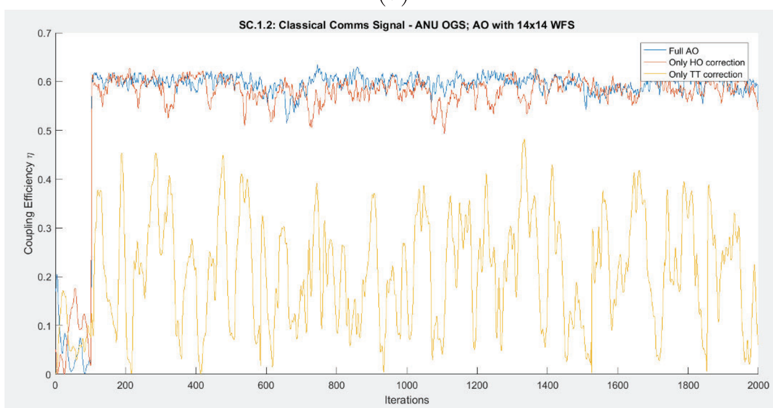
5.1 Dimensioning

One of the most expensive elements in the AO system is the Deformable Mirror; the strength of the turbulence determines the number of actuators and stroke required to compensate for a specific atmospheric turbulence. We have chosen the two cheapest DMs in the market: the Thorlabs DM with 50 actuators, and the ALPAO DM with 69 actuators.

The atmospheric turbulence requires a specific absolute stroke and inter-actuator stroke in the Deformable



(a)



(b)

Figure 7. Effect of partial (only tip-tilt TT correction) and full Adaptive Optics correction (high order modes + TT) on a (a) Quantum link; (b) Classical link, received by the ANU OGS under strong turbulence conditions (r0 = 5 cm).

Mirror (DM). Analytical and numerical analysis of the required stroke for an atmospheric turbulence of r0 = 5cm have been performed in order to conclude whether the two low-cost DMs (Thorlabs and ALPAO) fulfil the stroke requirements.

The required total stroke and absolute inter-actuator stroke were calculated based on analytical expressions and Monte Carlo simulations.

The mechanical stroke required by the atmospheric aberrations was estimated based on the reflected wavefront phase excursion. The expression which accounts for the DM reflected wavefront phase excursion (ϕ_0) that copes with 99% of the possible cases comes from the outcome of solving for ϕ_0 in Eq. 1.

$$P(-\phi_0 \leq \phi \leq +\phi_0) = \int_{-\phi_0}^{+\phi_0} f_\phi(\phi; D; r_0)dx = erf(\frac{\phi_0}{\sqrt{2}\sigma_\phi}) = 0.99 \tag{1}$$

Whose solution is $\phi_0 = 2.576\sigma_\phi$. The dependence on D and r_0 is included in $\phi_\sigma^2 = \Delta_1$. Δ_1 is described in[9] (see Eq. 2), and gathers the analytical expressions for the residual wavefront phase variance upon correcting the first J Zernike polynomials. For this case, the DM is assumed to correct for all the modes (low order and high order) and therefore, the first term is selected; in case of having a separate TT DM, the selected term would be Δ_3.

$$\Delta_1 = 1.0299\Big(\frac{D}{r_0}\Big)^{(5/3)} \tag{2}$$

The total WF phase excursion over the entire optical aperture is therefore $2\phi_\sigma$; Eq. 3 translates it into total optical path difference in the reflected wavefront (OPD^{WF}).

$$OPD^{WF} = 0.832\lambda\Big(\frac{D}{r_0}\Big)^{(5/6)} \tag{3}$$

The same expression applies to derive the constraint on the absolute inter-actuator optical path difference in the reflected wavefront; the pupil diameter D is replaced by d, the inter-actuator distance: $d \simeq D/(n_{act} - 1)$ with n_{act} being the number of actuators along the pupil diameter (Eq. 4).

$$OPD^{WF}_{IntAct} = 0.832\lambda\Big(\frac{d}{r_0}\Big)^{(5/6)} \tag{4}$$

The analytical stroke for a deformable mirror in the ANU OGS Adaptive Optics system (for a 1550 nm signal) is required to be 11.63 μm; likewise, the inter-actuator stroke is required to be 2.30 μm in a 8x8 DM and 2.61 μm in a 7x7 DM.

The required stroke was also calculated using the numerical simulation tool OOMAO. The simulation generated 10000 completely independent realisations of the atmosphere and computed the maximum difference of the wavefront on the ANU OGS pupil at the approximate locations where the projection of the DM actuators would be. The geometry of the simulation is shown in Figure 8.

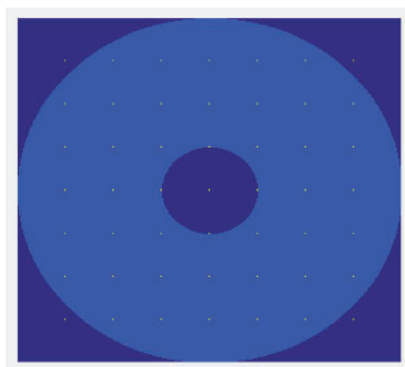


Figure 8. Arrangement of locations over the ANU OGS entrance pupil where the wavefront OPD values are measured. These locations correspond roughly to the actuators projection on the ANU OGS entrance pupil if a 8x8 DM were located at the pupil plane.

For each independent realisation of the simulated wavefront, only the values of the wavefront at the actuators locations were considered. The maximum value minus the minimum one was computed to obtain the wavefront stroke of this particular realisation. This results on a total of 10000 independent total stroke values from which it was derived the probability density function.

The histogram for the total stroke i shown in Figure 9. The Probability Density Function was fitted using a log-normal distribution showing very good agreement with the analytical results.

Based on the results showed above, only the ALPAO DM69 would fulfil the absolute stroke and inter-actuator stroke requirements for a r0 = 5 cm.

The proposed low cost AO system for the quantum downlink will consist of an ALPAO DM69 and a 8x8 Shack-Hartmann WFS with the FirstLight C-Red One detector.

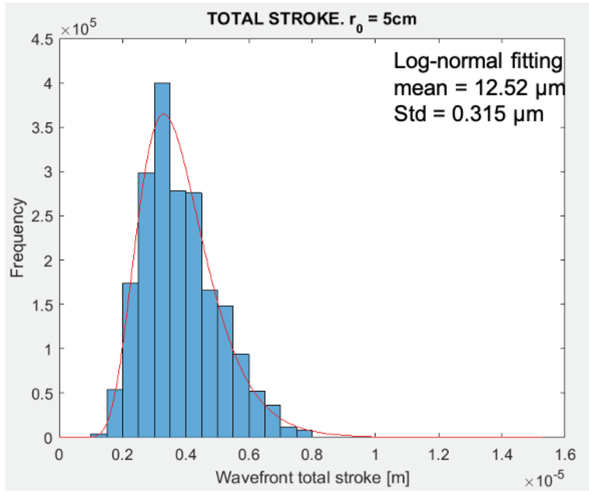


Figure 9. Histogram and corresponding Log-normal fitting for total wavefront stroke values.

5.2 Simulation results

Once the low cost Adaptive Optics system was dimensioned, the performance was tested on the quantum communications channel with the AO system operating at 1 KHz and 2 KHz. The detector noise was also taken into account.

Figure 10 shows that low cost AO can achieve a fibre coupling efficiency of 33%-43% in the quantum signal with the ANU Ground Station, demonstrating the clear advantages of Adaptive Optics in quantum communications even with the a system design that just fulfils the requirements to the very minimum.

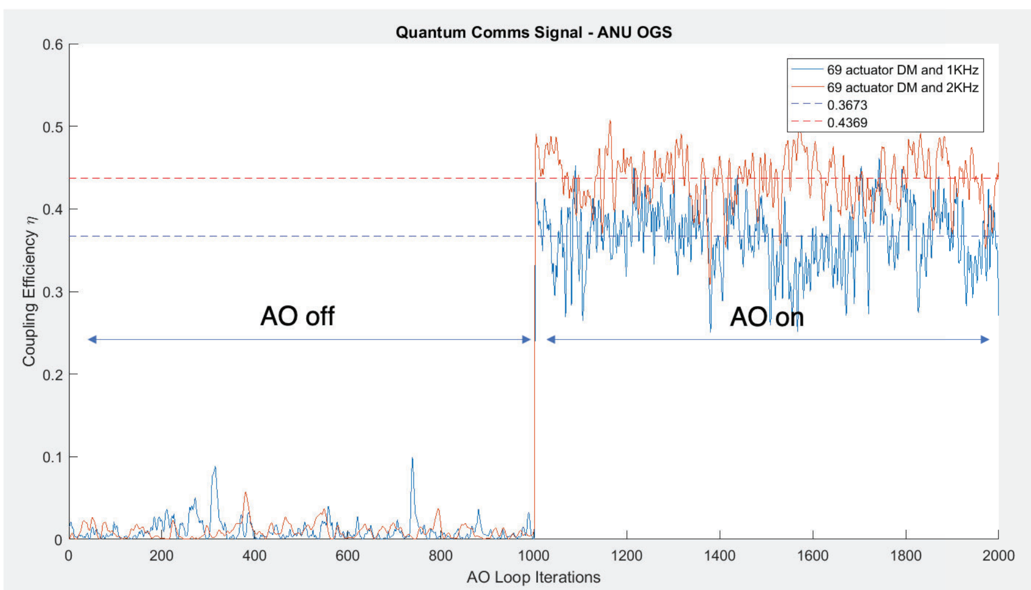


Figure 10. Low cost AO for a quantum downlink received at the ANU OGS. Strong atmospheric conditions (r0 = 5cm). First 1000 iterations correspond to open loop operation and second 1000 iterations correspond to close loop operation of the AO system.

6. CONCLUSION

Both quantum and classical downlinks are deeply affected by the atmospheric turbulence; in the case of quantum communications, due to a photon-starved scenario, the effects of the atmosphere on the achievable coupling efficiency of the incoming signal into a single mode fibre are critical. Adaptive Optics correction in the quantum link showed improvements in the coupling efficiency from $\approx 2\%$ (no correction) to $\approx 45\%$ (with atmospheric correction).

Even low cost Adaptive Optics have been proven to have clear advantages for the coupling efficiency into Single Mode Fibre for the quantum downlink; an AO system with a 8x8 Shack-Hartmann wavefront sensor and the ALPAO 69 actuator deformable mirror operating at 2 KHz would achieve coupling efficiencies of $> 40\%$ on the quantum channel using the ANU OGS as ground receiver.

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