Free-space quantum communication link with adaptive optics

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ABSTRACT

The Australian National University have been developing a quantum communication instrument with adaptive optics (AO) to achieve free-space Quantum Key Distribution (QKD). With organisations such as SpaceX and OneWeb planning on launching constellations of satellites for high-speed global communication, this provides an opportunity for innovative and disruptive technologies to be adopted for such endeavours. There is a need for secure, high-bandwidth communications for both civilian and defence use, to support the growth of ever-connected technologies and missions.

The ultimate goal of this research is the development of ultra-secure global communications networks enabled by quantum encryption and quantum key distribution. A key capability in such a global network is ground-to-satellite and satellite-to-satellite quantum communications requiring robust quantum-enabled ground-stations and satellite capability. We have combined expertise in AO, optical telescopes, and astronomical instrumentation from the ANU Research School of Astronomy and Astrophysics, with expertise in quantum technologies and free-space laser links at the ANU Department of Quantum Science, to develop an optical ground station to support quantum communication.

We utilise continuous-variable QKD, a technology which does not rely on detecting single photons and hence uses a much less complex detection system, and is also compatible with existing communication technologies such as fibre optics and free space links. This enables existing classical communication networks can be converted into a continuous-variable QKD system. Continuous-variable QKD system can be multiplexed, where multiple quantum channels can be simultaneously used with the same transmit and receive technologies, resulting in much higher data transfer rate. AO compensates the effects of atmospheric distortion to maximise the quality of the optical link, thereby reducing atmospheric turbulence induced loss and noise at the receiver. An AO system measures the distorted wavefront caused by atmospheric turbulence with a wavefront sensor, and corrects these distortions with a device such as a deformable mirror. This restores the optical quality of the optical system, and allows the quantum state to be transmitted and detected after transmission through a turbulent atmosphere.

INTRODUCTION

Free space optical communications have the potential to offer license free and secure high-bandwidth data transmission. The low beam divergence of a laser inherently aids in securing a data transmission, but the addition of Quantum Key Distribution (QKD) enables ultimate security. Transmission through free-space introduces challenges due to atmospheric turbulence distorting the wavefront of the transmitted laser beam. These

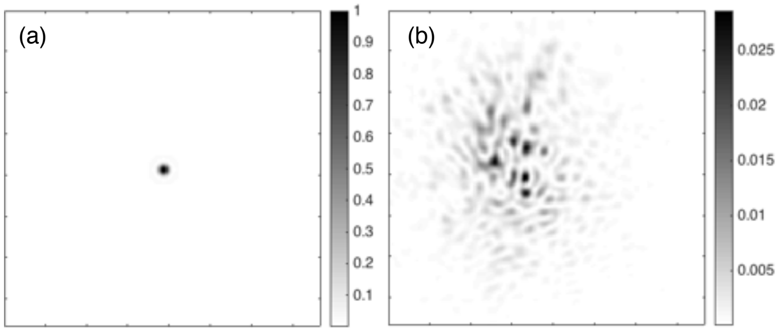

Figure 1: The point spread function (a) is the perfect image which can be produced by an imaging system. Atmospheric turbulence distorts and spreads the light from the image (b), resulting in a much lower amplitude. These images were produced in simulation.

distortions not only reduce the available data rate, but also reduce the performance of any QKD system.

ADAPTIVE OPTICS

When an image of a distant object is formed on a detector, the size and shape of the image are determined by the imaging system and the incident wavefront. A perfectly flat wavefront from a point source will produce the point spread function of the optical system (Fig. 1(a)), which is the best image that a particular optical system can produce. Refractive index variations caused by turbulent layers in the atmosphere distort optical wavefronts, reducing the quality of the image formed and often producing a speckle pattern (Fig. 1(b)) consisting of random intensity fluctuations in an image (also known as scintillation). The resolution of a diffraction limited telescope is λ/D, which defines the amount of diffraction from the telescope aperture diameter D. When transmitting through a turbulent atmosphere the resolution will be reduced to the characteristic physical size of the turbulent cell, known as the Fried parameter (r_0). Any optical signal transmitted from this telescope will diverge as λ/r_0. Typical values for r_0 for astronomical observing (looking up) are in the range 5-10 cm for a relatively poor site, and 12-18 cm for a relatively good site. r_0 can be as small as several millimetres if a telescope is pointing horizontally, as the optical signal propagates constantly through the ground layer of turbulence[**?**].

According to the extended Huygens-Fresnel principle[1], turbulence will also cause the image intensity to vary with time. Particularly dark periods ($\sim$30dB) are known as 'deep fades' which can last for up to several milliseconds, and at a data-rate of GHz the signal packet loss can be significant. Digital communication techniques such as forward error correction can mitigate the effect of a deep fade, however the addition of adaptive optics would provide far superior performance. Not only does the image intensity vary with time, but turbulence will cause the location of the image will move on the millisecond time scale. The combination of image motion, intensity variation, and non-diffraction limited image size combine to significantly reduce the signal to noise ratio of and optical signal propagated in free space.

Adaptive optics (AO) is the technique of measuring and correcting wavefront distortions to restore image quality by flattening the distorted wavefront. This removes image motion, intensity fluctuations, and restores near-diffraction limited imaging performance. Fig. 2 shows a schematic of a closed-loop AO system. A wavefront sensor (such as a Shack-Hartmann wavefront sensor) is used to measure wavefront distortion. An active optical elements such as a deformable mirror (DM) is used to correct distorted wavefronts by physically distorting the reflective face sheet using mechanical actuators.

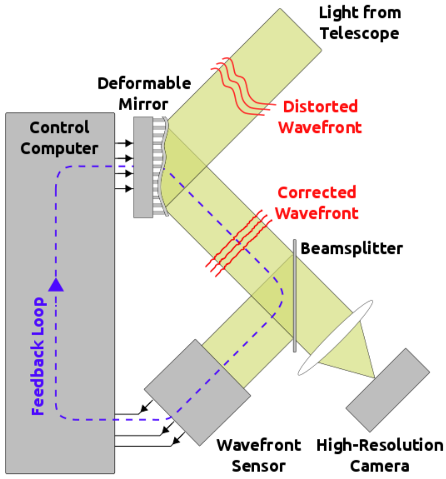

Figure 2: A closed-loop AO system restores near diffraction limited imaging by measuring atmospheric turbulence with a wavefront sensor, and corrects the resulting wavefront distortions with a deformable mirror.

A closed-loop control system between the wavefront sensor and DM is used to provide good correction for atmospheric turbulence, and can result in near diffraction-limited images.

Adaptive optics for astronomical telescopes is used for large aperture telescopes (4-10 m), where the atmospheric turbulence limits the resolution. AO is used to restore near diffraction limited imaging to these telescopes, enabling images equivalent to or better than space-based telescopes such as the Hubble Space Telescope. Atmospheric turbulence is generated by layers of wind and thermal variation, and can be modelled as discrete turbulent layers above a telescope. These layers are in motion, which causes the turbulence above a telescope to continuously vary. A typical AO system for an astronomical telescope will track stellar objects at up to 15 arcseconds per second (equivalent to 180 degrees over 12 hours), which is slow enough to consider the stellar object stationary and the turbulence moving in front of the telescope. Tracking rates while following orbiting objects are much higher, and can be up to 2 degrees per second. The telescope therefore crosses much more turbulence in a given time period in this situation, so the AO system must operate at a higher rate (at least 1.5 kHz) than for astronomical observations (which typically run at 500-800 Hz).

An AO system corrects for atmospheric turbulence by measuring it. This measurement requires a reference source, or guide star, with which to measure the distorted wavefront. A guide star for astronomical applications is typically a bright star near an object of interest. The star light then passes through a patch of the atmosphere where the wavefront becomes distorted by turbulence. Light from this star is collected by the telescope and directed into the wavefront sensor, where the wavefront distortions are measured. The guide star can be any source bright enough and close enough to the object that is to be corrected by the AO system. For an optical communications system the signal itself, or a seperate signal can be sent as the guide star. The maximum separation between the two signals will depend on the exact turbulent characteristics of the site, but the two must typically be within 20 μ rad.

The performance of an AO system is measured as the Strehl ratio. The Strehl ratio is defined as the ratio between the peak intensity of the collected image, and of the diffraction limited image produced by the optical system. A Strehl ratio of 100% is a perfect image, atmospheric turbulence typically results in a Strehl ratio of less than 5%. An AO system can provide a Strehl ratio from 10% to 85%, depending on the exact requirements of the system. A Strehl ratio of 25% and above is considered as good performance by an AO system. Below a Strehl of around 10% an image will contain a significant amount of speckles, where the light is not contained within a single core.

Adaptive optics can be used to produce a near diffraction limited beam for horizontal laser communications as well as vertical. The AO wavefront sensor measures the wavefront distortion caused by the atmosphere on a suitable guide star, and provides control feedback to the DM. The laser is reflected off the DM and is imparted with a distorted wavefront such that the optical signal achieves a corrected (flat) wavefront as it reaches its target. A signal propagated horizontally has a more limited range than vertical propagation, due to curvature of the Earth, stronger turbulence, and scattering and absorption by the atmosphere. This limited range means that smaller aperture telescopes can be used, because the angular size of the emitter or target will be relatively large. For example, a telescope with a 50 mm aperture has a diffraction limit of 31μ rad for a wavelength of 1550 nm. This means that after 10 km a diffraction limited beam would be about 31 cm in diameter, which does not require a large telescope to collect a strong signal-to-noise ratio optical signal. To achieve a similar beam size to a satellite in Low Earth Orbit at 500 km, a telescope of diameter 2.6 m would be required.

High bandwidth laser communication was recently demonstrated with the Lunar Laser Communications Demonstration (LLCD)[4]. This system consists of four 40 cm ground based receiving telescopes with superconducting single photon detectors for the uplink laser, and a 10 cm telescope for the downlink laser. The uplink laser has a power of 40 W, and the downlink laser has a power of 0.5 W. The demonstrated downlink communication speed was 622 Mbps over a distance of 384,000 km. This system did not contain adaptive optics, and required immense optical power projected from the ground. The ground based detectors were superconducting photon-counting detectors in order to receive the signal sent by the much lower power laser of the satellite. The use of adaptive optics can reduce the cost and complexity of future ground-to-space laser communication systems by relaxing the power requirements on the communication lasers while achieving a low error rate due to the improved wavefront[3].

QKD OVER FREE-SPACE WITH ADAPTIVE OPTICS

We have designed and build a demonstrator AO system to achieve AO corrected laser communications over a horizontal path. This system is designed to enable us to implement and experiment with combining an AO system with CV-QKD. We plan to use the coherent state with homodyne detection protocol that is commonly used with fibre demonstrations of CV-QKD [5].

QKD is one solution to the key distribution problem. In this problem Alice needs to secretly share an encryption key remotely over a public channel with Bob. Bob can then use that key to send an encrypted message to Alice. By encoding this key in a series of quantum states Alice and Bob can use quantum information to quantify the amount of information that might have leaked to the eavesdropper Eve.

The protocol chosen for this paper is part of a family of Gaussian protocols named as it uses Gaussian quantum states and measurement [7]. The protocol states with Alice generating two sets of random numbers distributed according to a Gaussian distribution of zero mean and some variance V. Alices random numbers will form the basis for the final shared key. Bob will also generate a series of numbers randomly chosen as 0 or 1 the same length as Alice's random numbers. These numbers will determine if Bob measures phase or amplitude of the received light. Alice will then modulate her random numbers onto the sidebands of a laser to create coherent quantum states with one series modulated into phase and the other amplitude. These states are then sent to Bob through a public channel. Bob will use a homodyne detector to measure the phase or amplitude of the received light depending on his random numbers.

Once all of Alices states have been measured by Bob they will sift through the data to determine which numbers Alice should discard. Alice and Bob now share a correlated set of data and need to collectively determine how much information was lost to Eve. Due to quantum mechanics and the no cloning theorem any influence from Eve will appear as noise on Bob's measurements. To deterime the influence of Eve, Alice and Bob can reveal a portion of their data. An upper bound on the information shared between Alice and Eve can then be found. Using the estimated shared information between Alice and Bob a lower bound on the key rate is given by, $KR >= I(A : B) - \chi(A : E)$. With Eves optimal attack on the protocol these quantities can be found using the parameter, V and the channel transmission, T, and noise relative to the output, σ^2 [6]. To optimise the protocol Alice can tune V [8].

To finish the protocol Bob uses error correction to match his measurements to Alice's original random numbers in a step known as direct reconcillation. The final step is for both Alice and Bob to use a hashing function for privacy amplification to negate Eves mutual information. The range of the protocol can be extended further by Alice instead correcting her string to match Bob's measurements. This is known as reverse reconcillation and this changes the lower bound on the key rate to $KR >= I(A : B) - \chi(B : E)$.

The advantage of CV-QKD over its more common Disecrete Variable (DV) QKD couterparts is that is brings higher bandwidths. This increased bandwidth comes from the use of optical sidebands to deterministically create quantum states and high bandwidth measurements from homodyne detection. The disadvantage is that it is not as robust against noise and generally doesn't acheive the same transmission distances that DV-QKD does.

A key requirement of CV-QKD is to have a low-loss system with a stable link. Using AO for free-space propagation stabilises the optical signal on a detector, and maximises the received signal by returning near-diffraction limited performance to the optical system and stablising the channel transmission and noise.

SYSTEM DESIGN

Our AO system is designed as a closed loop system with a Shack-Hartmann wavefront sensor, and high-speed, long stroke deformable mirror (DM). The system is designed for horizontal propagation over a distance of several hundred meters, to approximately 12 km. The optical system is a single transmit/receive system, with signals separated either with a beamsplitter or fibre optic re-circulator. Fig. 3 shows the optical layout of the system: a laser originates from the AO system and is reflect off the DM to pre-distort the wavefront, and transmitted through the telescope. A corner-cube retroreflector is used to reflect the laser signal back into the AO system, where it is again corrected and fed into a receiver. An LED is used as a beacon with wavelength 590 nm, as this is close to the peak quantum efficiency of the wavefront sensing camera. Relay optics are used to transform the beam for wavefront sensing and conjugate the wavefront sensing plane with the DM. The AO loop runs at a closed loop rate of 2 kHz, with 69 actuators in a square 7×7 grid providing correction. The Shack-Hartmann wavefront sensor has 6×6 subapertures. The transmit/receive telescope aperture is 30 mm, making the system capable of correcting r_0 down to 4.2 mm. A 2" mirror is used as the input into the system, and is conjugated to the DM. This mirror can be replaced with a steering gimbal mirror to assist with automated acquisition and tracking in future iterations of the system. Dichroic mirrors are used to split the communication signal at 1550 nm, from the wavefront sensing guide star signal at 590 nm. An acquisition camera allows us to view the scene and manually acquire the retroreflector.

The AO system was tested in the lab using artificial turbulence produced with hot air flow. With a loop rate of 2 kHz the closed loop bandwidth achieved is 125 Hz.

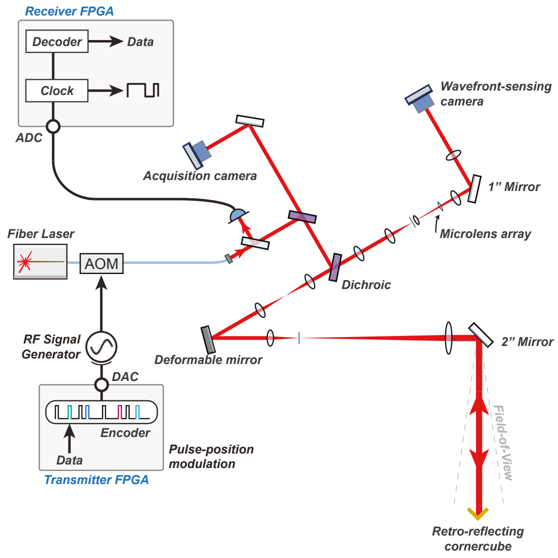

Figure 3: The AO system optical layout.

The system will be redesigned to make it more compact such that it can fit on a 40 cm portable telescope for testing with high-altitude platforms such as weather balloons and high-altitude aircraft. This will allow us to experiment with near-space conditions and prototype QKD payloads, without the expense of going to space. The portable system will also be able to receive signals from a variety of sources, such as from satellites in Low Earth Orbit, and in Geosynchronous orbit.

CONCLUSION

The ANU have developed a CV-QKD compatible AO system demonstrator for horizontal application. Lab testing resulted in a closed loop bandwidth of 125 Hz. We are working towards demonstrating the system horizontally over several hundred meters to several kilometres. The CV-QKD protocol is compatible with common off the shelf hardware such as modulators and fibre splitters, allowing this system to interface with existing communications technologies already in use today.

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