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Small Photon-Entangling Quantum Systems (SPEQS) for LEO Satellites

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1 Introduction

In the past two decades, research into the foundations of quantum physics has led to various proposals for using quantum-based correlations, called entanglement, to enhance communication security [GRTZ02] or improve computational techniques [BEZ00]. By far, the most advanced demonstrations have been in quantum key distribution (QKD), where photon-pairs produced in a birefringent crystal can be used to distribute a string of correlated random numbers for one-time-pad cryptography. Much research has been done to ensure that this technique can be implemented securely [YDS10]. At the same time, research in this direction has been very fruitful for fundamental science as it has probed the distance limits to which quantum correlations can exist [Ursin07].

To date, however, the distance between communicating parties has been limited to about 140 km due to losses in optical fibers [MRTZLG04], as well as the need for line-of-sight in free-space optics [Ursin07]. For longer distance tests of quantum correlations, and in the interest of a wider network for QKD, we are proposing to place a source of quantum-entangled photon-pairs on a satellite in low earth orbit (LEO). Successful demonstration of this quantum light source will then be used to pave the way for more ambitious experiments where single photons from the satellite will be beamed to receiving stations on other satellites or on the earth.

For a cost effective demonstration, we are planning to use nano-satellites that follow the CubeSat standard [WERH11]. Though limitations on mass, volume and power constrain the capability of CubeSat systems, for proof-of-principle demonstrations the platform offers several advantages such as low cost and rapid development. These features are ideal for an iterated approach to the development of space-borne quantum technology. The initial experiment will demonstrate the ability to construct, launch, and operate a source of quantum entangled photon pairs in orbit. The space environment includes the forces and vibration of launch, vacuum, radiation, and thermal cycling which are considerable challenges to a laboratory experiment. Optical alignment, temperature control, and radiation damage are serious issues for any proposed quantum system in space and an incremental development will reduce the development risk.

In the following sections, we will briefly describe the quantum physics experiment we hope to achieve (Section 2), and provide a description of the proposed payload architecture (Section 3). We will end with a discussion of possible follow up experiments.

2 Small Photon-Entangling Quantum System (SPEQS)

The physics package that we have proposed is meant to be a complete optics experiment, consisting of a quantum-entangled photon pair source, single photon detectors and control micro-electronics. The form factor of these Small Photon-Entangling Quantum Systems (SPEQS) is designed to fit on a 1U CubeSat and must meet all the physical limitations (see Table 1). All sub-systems must undergo space qualification tests planned at the end of 2012. If successful, we may look forward to working with launch providers.

Mass	300 gm
Volume	300 milliliters
Power	1.5 W (continuous)
Data Return	< 1 MB per orbit

Table 1 SPEQS package physical limits

In order to verify that the entanglement source is operating correctly, we need to be able to establish the presence of non-local correlations in the measurement statistics on pairs of photons. This is carried out by comparing the observed correlations against a physical limit known as the Bell inequality. The Bell Inequality theorem constrains the allowed correlations under the assumption of local realism [Bell64]. Violating a Bell Inequality demonstrates that entanglement must be present and that the source is suitable for quantum key distribution.

The most convenient form of Bell inequalities are of the CHSH (Clauser-Horne-Shimony-Holt) type, where two parties, A and B, each obtain one-half of the photon pair. In our system, entanglement is carried by the polarization of the photons. The pairs of photons are emitted in

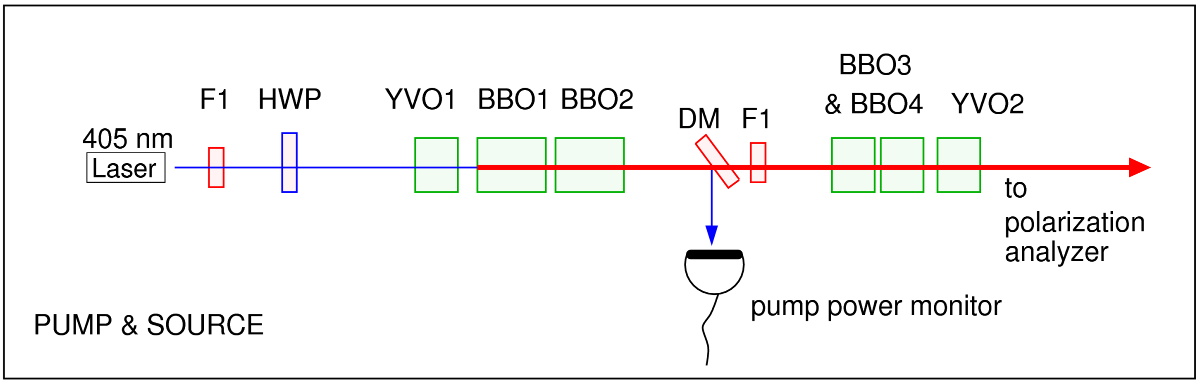

Fig. 1: Schematic for the optical setup, showing the number of bulk optical elements involved. The compact source of entangled photon pairs is built out of bulk elements such as a diode laser, spectral filters and birefringent crystals. The photon pairs are nondegenerate: one of the photons is centered on 760 nm and its twin is centered on 867 nm, obeying energy conservation.

the state, $|\Psi\rangle=\frac{1}{\sqrt{2}}(|HH\rangle+|VV\rangle)$. If both photons were to be measured along the same polarization angle, they would always get the same result, i.e if A and B both measured along the H-V directions, then if A obtained H, then B would obtain H and vice versa. These perfectly correlated results are not sufficient to establish entanglement and choices of measurement directions which differ between the two sides are required. The most convenient set of measurement directions are that A can randomly choose to measure in the A_1 ={H,V} directions or the A_2 = { $+45^{\circ}$, -45° } directions, and that B also independently and randomly chooses to measure in the B_1 ={ $22.5^{\circ}, 112.5^{\circ}$ } directions or the B_2 ={ $-22.5^{\circ}, 67.5^{\circ}$ } directions.

Hence, the four possible joint measurements $A_j B_k$ on a pair of photons are $A_1B_1, A_1B_2, A_2B_1,$ or A_2B_2 each occurring equally at random. Each party assign to the results the values +1 and -1 respectively and then they combine their data to calculate the average value of the product of the two results for each joint measurement choice which will lie between ± 1 . Under the assumptions of local realism, it is simple to show that $S=|\langle A_1B_1\rangle+\langle A_1B_2\rangle+\langle A_2B_1\rangle-\langle A_2B_2\rangle|<2$ and that any violation must be due to the presence of quantum entanglement [CHSH69]. A perfect state violates this bound with $S=2\sqrt{2}\approx 2.828$. Additionally, the degree of violation is a measure of the secrecy that can be extracted from such a state [Ekert91].

In the first experiment, we need to validate our source is functioning in space before we attempt to send entanglement to a remote party. This is achieved by onboard polarization analysers which are placed at the output of the entanglement source, and we hope to demonstrate that the source of photon-pairs produces correlations that violate the CHSH bound.

3 SPEQS

3.1 Optical Sub-system

The workhorse technique for generating polarization-entangled photon pairs is using Spontaneous Parametric Down Conversion (SPDC) in which a laser is used to pump birefringent crystals. Some of the pump photons are split into a pair of photons. One very useful feature of SPDC is the production of correlated photon-pairs that can be used as heralded sources of single photons. Heralded single photons have many applications by themselves (e.g. detector calibration, and some QKD protocols). However, by further careful arrangement of the crystals, SPDC process can be made to emit photon pairs whose polarization correlations can be described very well by a quantum mechanical state that can violate the CHSH bound.

Traditional laboratory experiments with SPDC involve large frame lasers and bulky optical equipment, which are hard to align and suffer large drift with variation in temperature and pressure. To overcome this problem, we have designed a compact and monolithic source that is only 8 cm long (see Fig. 1).

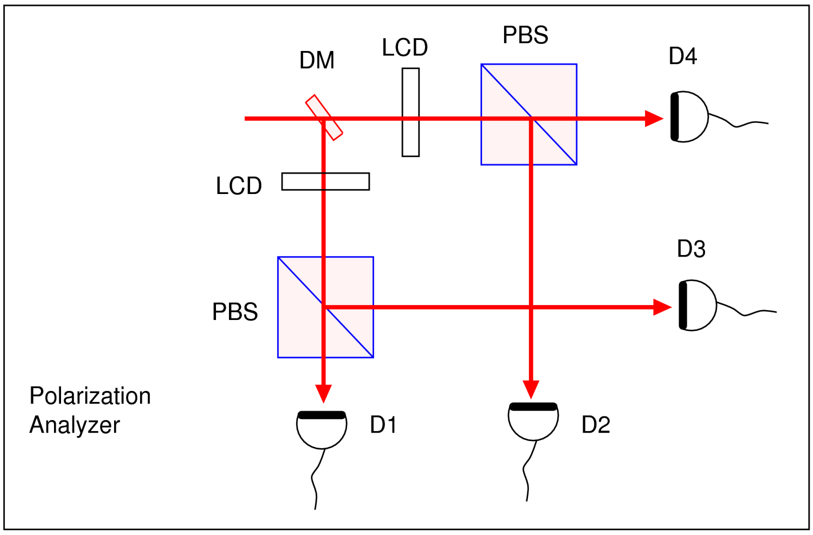

Fig 2: The detector layout. The photon pairs are centered on 760 nm and 867 nm; they are split by a dichroic mirror (DM). Using liquid crystal devices (LCD) and polarizing beam splitters (PBS) enables an extra pair of detectors for redundancy.

This source consists of a laser diode, and all the necessary optical crystals for generating polarization-entangled photon pairs. We are now working on integrating the source with the single photon detector setup - our proposed layout is shown in Fig. 2. Standard practice is to pass the separate photons from a pair through polarizing filters. By observing the rate of coincidences as the filters are rotated, the quality of the quantum state (and hence the presence of quantum entanglement) can be measured. Typically, these polarizing filters are mounted on mechanized rotation stages - however, this is not practical in a CubeSat as it can cause the nano-satellite to spin. An inertial-free polarization rotation device (based on liquid crystals) was built, and when operated in conjunction with polarizing beam splitters, the results are similar to using rotating polarizing filters (Fig. 3).

3.2 Electronics Sub-system

One of the big challenges in the electronics sub-system is the control circuit for operating the single photon detectors. Geiger mode Silicon based single photon detectors are convenient due to their small form factor.

One disadvantage of these detectors is that they require an operating voltage of about 150V and this voltage is highly dependent on the temperature of the diode junction. If the operating

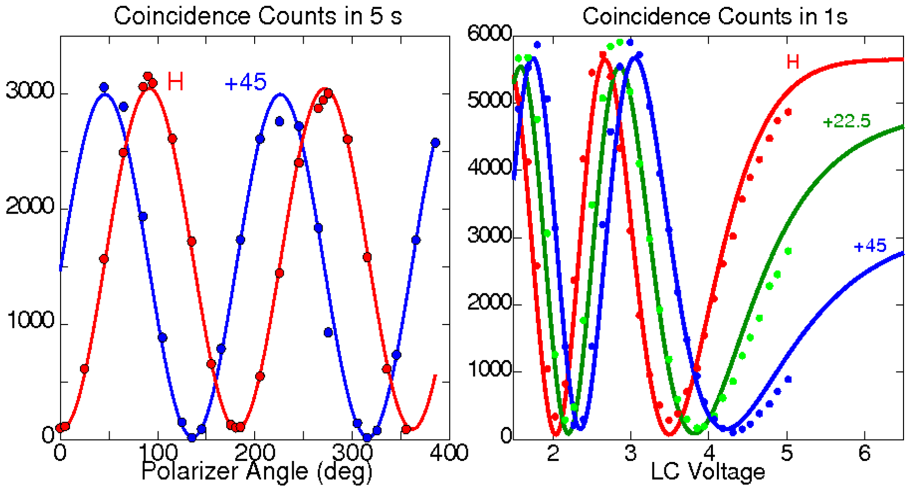

Fig. 3: Measured high resolution curves illustrating polarization correlations from the SPEQS package. The figure on the left is obtained by rotating linear polarizers. The figure on the right is obtained by using polarization rotators based on liquid crystal (LC) technology. The correlations needed to demonstrate a violation of Bell's Inequality can be obtained from these curves.

voltage is not tuned to the temperature, the analog pulses generated by the diode can be too low (leading to under counting of events), or too high (leading to electrical damage). Commercial modules come with a thermoelectric cooler to stabilize the detector temperature but this option is not viable with CubeSats due to the power constraints. To bypass this problem, we have designed a software-based window comparator that senses the average peak height emitted by the detectors (see Fig. 4.). We have implemented this design with a custom passive quenching circuit around each detector, and successfully demonstrated that the window comparator will successfully operate single photon detectors over a wide range of temperatures [SL11].

4 Steps towards space qualification

An engineering model for the SPEQS micro-electronics has been built and demonstrated to meet the physical limitations of the 1U CubeSat, including the 1.5 W limit for power consumption. The engineering model has also been exposed to individual tests in the thermal-vaccum and vibration environment.

In a recent test, the SPEQS package was tested at high altitude, using a micro-balloon. In this test, a fully powered SPEQS package was attached to a 1.6 kg weather balloon, equipped with GPS transceivers and radio beacons for tracking. The balloon had an ascent velocity of approximately 6 ms^{-1} while carrying a payload of 2 kg. This balloon was launched from the town of Konstanz in southern Germany, and reached an altitude of 37.5 km, before the balloon burst. During the descent, the payload deployed a parachute, and the package descended at approximately 6 ms^{-1}.The entire flight lasted for about 3 hrs 25 min, and landed approximately 75 km from the launch site.

During the flight, the SPEQS package was fully operational, and we were recording data such as temperature, laser power and single photon detector dark counts. The optical source was not aligned to the detectors, although it had been calibrated in the laboratory for correlated photons and a record of the wavelength spectrum (and hence the relative alignment of crystal to laser diode), had been kept.

The SPEQS package was inspected upon retrieval, and no damage was observed based on visual and electronic inspection. The SPEQS package was also optically tested in the laboratory and the results compared against pre-flight data – the optical wavelength spectrum

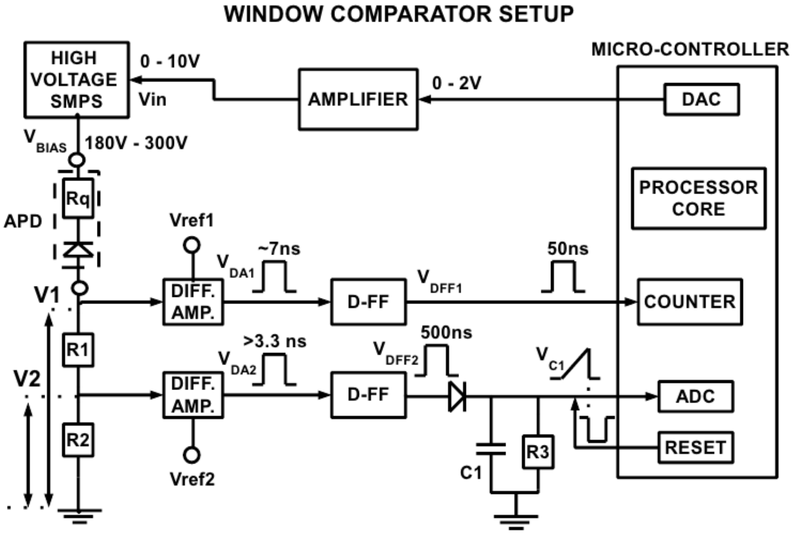

Fig. 4: Window Comparator circuit to ensure that the analog pulse height generated by single photon detectors lies in the optimal range. The number of pulses leaving the bottom discriminator is estimated by the voltage level in the capacitor C1. CLD - constant level discriminators, D-FF - flip-flops used for pulse stretching. The Digital-to-Analog (DAC) controller is built into the micro-controller.

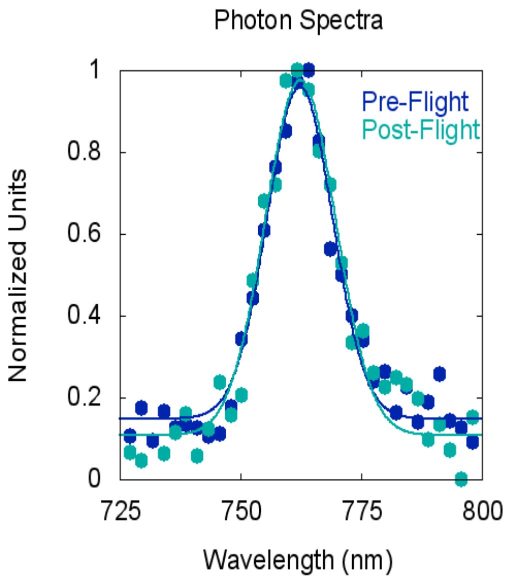

Fig. 5: Photon spectra for signal photons. The spectra overlap well (instrumentation error is approximately 0.5 nm) and is taken as evidence that the optical alignment did not shift during flight.

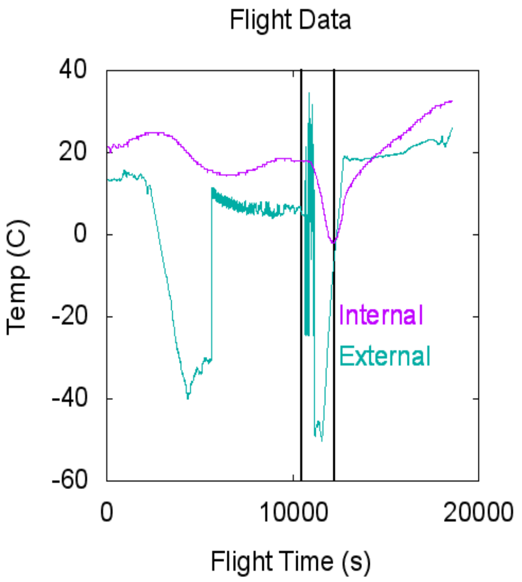

Fig 6: Temperature readings experienced by the balloon payload. The SPEQS test package experienced the internal temperature. The balloon burst at approximately 10500s after launch, and landed at approximately 12270s. The rate of ascent slowed down once the balloon entered the stratosphere.

before and after the flight were indistinguishable. This balloon flight has validated the design choices used in the construction of the SPEQS package.

5 Future Work

The next step after demonstrating successful operation of an entangled source will be to transmit entanglement between spacecraft, effectively separating the two measurement locations. Two main ways of achieving this are through tethers or free-space transmission.

A tether can be used to maintain the relative separation and orientation of two spacecraft with respect with each other. It can also transmit power, communications, and also entanglement via an optical fibre. A 2U CubeSat could be launched with one 1U cube containing the source and one detector, and the other 1U cube containing the second detector. The two units would separate in orbit but would remain connected through a tether. This would be reeled out in order increase the separation. A gravity gradient will naturally orient the two satellites so that one is vertically separated above the other with a small tension in the tether. Measurement results from both satellites can be then combined in order to validate the operation of the source and that the entanglement was preserved during transmission. Maintenance of the polarization of the photons as they traverse the fibre would be a challenge, though active means of tracking the drift are available.

Connecting separate CubeSats using tethers tens or hundreds of metres long may be possible but to reach much longer separations free space optical transmission will be required. One satellite would contain the source, one detector, and a transmission telescope, the other collection optics and a second detector. The simplest orbital geometry would be to have the two satellites in the same orbital track but longitudinally displaced. The two CubeSats could be launched as one unit which then separates in orbit. Microthrusters would then controllably increase the distance between the two satellites. Onboard attitude determination and control systems (ADCS) would allow the satellites to point towards each other. Sun sensors and star trackers determine the attitude of the satellites. Reaction wheels in conjunction with magnetorquers can control the rotation of the satellites. Miniaturised systems have been developed for CubeSat applications.

Even though the ADCS would be able to point the two satellites towards each other, it is likely that some sort of fine beam steering will be needed in the transmitter, e.g. a microtranslation stage within the beam forming system. The requirements for the receiver should be less stringent if we allow a greater acceptance angle, though it is still preferable to limit this to reduce stray light entering the system. Narrow band filters can also help in this regard. Precise pointing could be achieved by using a guide laser from the receiver to the transmitter which if pulsed can also act as a trigger for gating the detectors.

A major constraint upon the transmitter is the limited aperture available in a CubeSat envelope, of the order of 5cm radius. For a wavelength of 800nm, this gives a diffraction limited beam divergence half angle of ≈ 5 microradians. At large distances, the effective beam spot will be larger than the collector and transmission efficiency will suffer. Assuming perfect collection over the receiving aperture, the loss at 300km would be at least 60dB, at 1000km it would be 120dB. This will reduce the quantum bit rate, though high brightness entanglement sources could be used to compensate. Deployable optics would allow for a larger effective aperture though the added mechanical complexity and mass would have to be factored into a system design analysis. Using a 6U CubeSat transmitter would allow an effective aperture of 10cm radius with a consequently greater range.

Synchronisation of the two remote detectors is an issue but this has been addressed in previous ground based experiments [HLK09]. GPS timing can be used to synchronise local clocks which can then be used to time-stamp detection events. With two detectors in proximity, the coincident detection events can be directly compared and only a running count is needed to be stored.

Relative orientation of the two satellites would also have to determined and factored into the polarization measurement axes. It is possible to encode entanglement into other degrees of freedom, such as time-bin [BGTZ99], or orbital angular momentum [DLBPA11], though detection is not as simple.

Ultimately, a full space-based QKD system would involve sending entangled pairs of photons to ground stations. It is not likely that this will be achievable on the CubeSat platform. The satellite would need to separately track the two ground targets with large aperture optics. At low altitudes, the traverse velocity would be high, at higher altitudes the optics will be need to be larger in order to reduce diffraction. Atmospheric absorption, scattering, and turbulence will all impact on beam quality. Some sort of adaptive optics may be required to reduce beam wander. The two line-of-sight beam paths effectively squares the loss rate compared to a single path so the effect of having large emitting (reduce beam divergence) and receiving aperture (increase collection area) becomes paramount in delivering viable quantum bit rates. For these reasons, it is probable that much larger satellite platforms will be required to support these capabilities. However, CubeSat experiments are a relatively inexpensive and rapid means of developing the core technologies before ramping up to a full scale demonstrator.

Acknowledgments

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