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Quantum physics with CubeSats: in-orbit observation of photon pair correlations on board the Galassia spacecraft

Rakhitha Chandrasekara, Zhongkan Tang, Yue Chuan Tan, Cliff Cheng and Alexander Ling. Centre for Quantum Technologies, National University of Singapore.
Luo Sha and Goh Cher Hiang, Department of Electrical and Computer Engineering, National University of Singapore.
Daniel K.L. Oi, SUPA Department of Physics, University of Strathclyde;
Block S15, 3 Science Drive 2, Singapore 117543. +65 6516 6897, rakhitha@u.nus.edu

ABSTRACT

Secured global quantum communication networks sharing a private encryption key can be established with entangled photon sources onboard satellites in Earth orbit. Even though optical transceivers for ground-to-space communication exist, no space capable source of entangled photons has been demonstrated. A faster and cost-effective way to reach the orbit is by means of CubeSats. This demands significant miniaturisation work on the photon source to fit within the size, weight and power restrictions of CubeSats. The first milestone in our programme is to deploy a source of correlated photon pairs in space as a pathfinder experiment to demonstrate and validate the technology readiness level of critical optical components required to build entangled sources. The first attempt was unsuccessful when the launch vehicle (CRS Orb-3) failed shortly after take-off, although our payload was successfully recovered intact and found to be fully operational. We are pleased to report that the second attempt with a newly built payload, has been successful and the first milestone has been accomplished. The source was launched on board the Galassia CubeSat (PSLV C29) to an orbit of approximately 550 km and 15^0 inclination. We observed in-orbit generation of high quality photon pair correlations (with a contrast of 97 ± 2%). This performance is compatible with the baseline data collected prior to launch and shows no degradation after spending 140 days in orbit. The performance of the subsystems and the in orbit correlation generation will be presented with the base line data. We will also present plans for future missions.

INTRODUCTION

A symmetric one time key shared between two authorized parties allows a provably secure communication in the presence of an eavesdropper. Quantum Key Distribution (QKD) is a method of distributing such keys using quantum signals with its security relies on the basic postulates of quantum mechanics. In particular, entanglement-based QKD is a powerful technique which relies on entangled particles[1]. It also requires a less number of trusted components to implement[2].

Photons based entanglement generation and detection techniques are mature enough for practical QKD implementations.The state of the art QKD demonstrations with photons are limited to distances around 300 km with optical fiber (using weak laser pulses)[3] and around 144 km in free space (using entangled photons)[4].The distance limitations are mainly due to intrinsic fiber losses and line of sight problems in free space, thus hindering the process of realizing a global QKD network.

A number of proposals have been made by researchers on achieving global QKD networks. The most feasible solutions rely on satellite to ground quantum communication links where satellites host either quantum light sources or detectors[5,6,7].A satellite hosting a quantum light source can be benefitted from the low optical losses associated with the down link compared to an uplink[8].

A quantum source or a detector onboard a satellite can be acted as a trusted relay between two ground stations. As the satellite is in contact with one ground station a symmetric key can be established between the two parties. When it is in contact with a second ground station another symmetric key (different) can be established. At this point the satellite has got both keys and the second key can be used to transmit the first key securely to the second ground station. Thus the two ground stations can share a symmetric key.In addition to that hosting quantum light sources in satellites also enables tests of fundamental quantum physics experiments where relativistic effects play a key role[9].

Cubesats are a faster and cost effective way to reach the Earth orbit with science experiments[10]. In particular, we propose that Cubesats can effectively host compact and robust sources of entangled photon pairs [11,12].

We are working on a series of iterative Cubesat missions with an increased scope for each stage, towards a demonstration of a space to ground QKD link. The scope of the first mission is limited to a simple technology readiness demonstration of an entangled photon source onboard a Cubesat. Such a working entanglement source will lead to a sufficiently high brightness and entanglement quality photon pair source demonstration on board a nano satellite. The level of brightness and entanglement quality shall be sufficient to establish a practically useful encryption key with a ground station in subsequent Cubesat missions.

As the first step, we are building polarization entangled photon sources called Small Photon Entangling Quantum System (SPEQS) which strictly follow Cubesat's SWaP requirements. In this paper we report two SPEQS integrated Cubesat missions with one failed attempt due to a rocket launch failure[13] (GomX-2 by GomSpaceAPS in 2014) and a successful in-orbit SPEQS operation with the Galassia Cubesat (Department of Electrical and Computer engineering, NUS in 2015)[14].

SMALL PHOTON ENTANGLING QUANTUM SYSTEM (SPEQS) OVERVIEW

Single Photon Source

The SPEQS single photon source is based on Spontaneous Parametric Down Conversion (SPDC) process which is a well established technology for generating single photons[15]. In SPDC process a single pump photon interact with a non linear crystal (ex: Beta Barium Borate) down converts into a pair of daughter photons (with low probability) while obeying energy and momentum conservation. These daughter photons carry classical correlations in energy, time and polarization. By carefully arranging crystals we can put the two daughter photons into a superposition state to achieve the polarization entanglement[16]. In SPEQS we have adopted collinear Type I SPDC for its compact geometry.

As a pathfinder mission we have first built a correlated source (classical correlations in polarization) and Figure 1 shows the photon source and the single photon detection subsystem[14]. We use Beta Barium Borate (BBO) as the non linear crystal which requires less stringent thermal stabilization.

Electronics Subsystems

The SPEQS electronics design is reported in detail previously[17,18] and an overview of each subsystem is given here.

A semiconductor laser diode (LD) is used to provide pump photons at 405 nm to interact with the non linear crystals. The optical power of the laser diode (at a fixed current) fluctuates with temperature. A pin photodiode (PD) is used in a negative feedback loop to lock the optical power into a desired value.

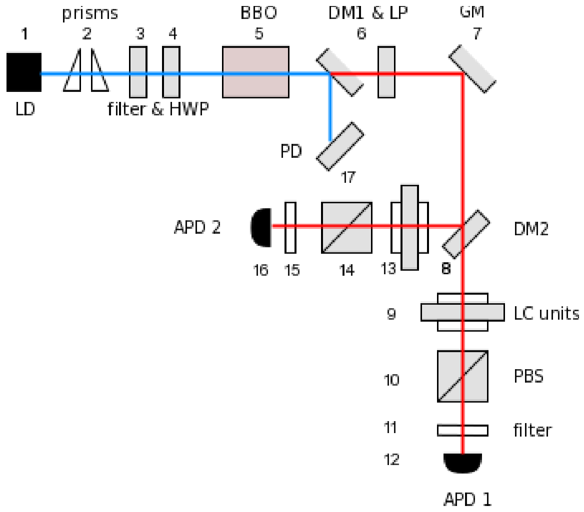

Figure 1: The schematic of the polarization correlated photon pair source integrated with the Galassia Cubesat[14]. The components labelled from 1 to 6 generate correlated photons with a Beta Barium Borate (BBO) crystal in non degenerate, Type-I collinear geometry. A Dichroic Mirror (DM) separates the daughter photons based on the wavelength. A polarization analyzer combined with a single photon detector register photons at an intended polarization setting.

In SPEQS a polarization rotator (LC unit) together with a polarization beam splitter (PBS) acts as a polarization analyzer. The LC unit is an electrically controllable optical rotator (non inertial) based on nematic liquid crystal technology. An AC square wave with a varying amplitude is required to drive the LC unit.

An Avalanche Photo Diode configured in geiger mode (GM-APD) is used to detect single photons. The photon detection efficiency of a fixed bias GM-APD is affected by the temperature and active temperature stabilization techniques have been ruled out due to Cubesat's power constraints.A software based temperature compensation technique has been implemented to maintain the GM-APD detection efficiency[19]. This technique has also increased the linearity of the detector significantly compared to a fixed bias passively quenched GM-APD[19].

A successful detection of a daughter photon by a GM-APD enables a digital signal to a coincidence detection unit (AND gate) for correlation measurements. The coincidence window is maintained at ~4.2 ns to suppress accidental coincidences. An overlap of two such GM-APD signals in time domain is registered as a correlated event.

The SPEQS performance is evaluated based on the maximum rate of observed coincident detections (brightness),and the relative polarization contrast (visibility) between the two down converted photons.

All the electronics sub systems are controlled by a Cypress CY8C3666 Programmable-System-On-Chip (PSoC3) micro-controller. The PSoC3 is an 8-bit, 8051 architecture bundled together with reconfigurable analog and digital blocks which can be combined together to automate the SPEQS experiment.

SPACE HERITAGE OF SPEQS

The successful near-space demonstration[20] of SPEQS device has proved its robustness and technology readiness level for space based missions. We have successfully integrated SPEQS devices with GomX-2 and Galassia Cubesats while in-orbit data is available from the latter mission.

GomX-2 Satellite Integration

The first SPEQS integration was with the GomX-2, a 2U Cubesat developed by the GomSpaceAPS in 2014. The satellite was scheduled to launch from International Space Station (ISS)[21] into a polar orbit.

The mission was unsuccessful due to an unfortunate rocket launch failure and later GomX-2 was recovered from the crash site. The satellite was found to be operational and the SPEQS device continued to produce high quality correlations after the explosion[22].

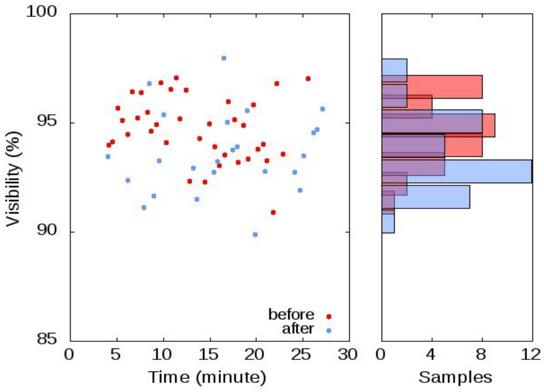

Figure 2: The visibility of the SPEQS device before and after the explosion[22].The baseline visibility was 95 ±1% and the recovered package produced a visibility of 94 ±2%. The histogram on right shows the visibility distribution over 30 minutes experimental time.

The brightness of the SPEQS device after the explosion has not deviated significantly from the baseline (see Figure 3 top). Meantime, the response of the LC unit has shown some slight degradation after the explosion.

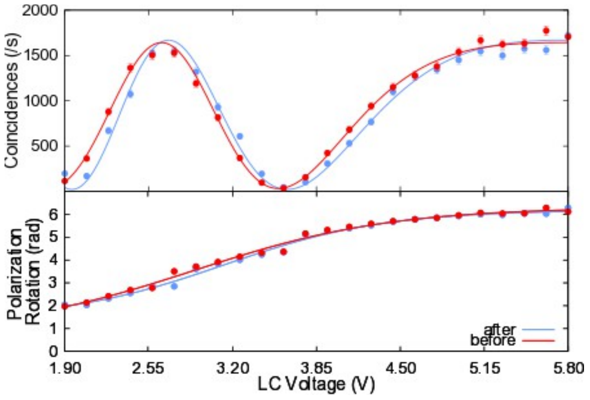

Figure 3: The brightness of the SPEQS device[22] remain unchanged before and after the explosion (top figure). The LC unit shows a reduced ability to perform polarization rotation.

The post explosion performance of the SPEQS device proved the robustness of the assembling techniques used for the photon source alignment and the reliability of electronics to survive on harsh environments.

Galassia Satellite Integration

The subsequent SPEQS integration was with the Galassia, a 2U Cubesat built by the department of ECE, NUS[23]. The satellite was successfully launched into an equatorial orbit (550 km, 15^0) using PSLV C29 rocket in December 2015.

The integrated SPEQS flight model has been subjected to a series of vibration tests followed by a thermal vacuum test.

Vibration test

The vibration test procedure adhered to a combination of qualification test values with acceptance level times (see Table 1).

A separate sinusoidal and random vibration tests have been carried out on each axis. At the end of the full vibration test a baseline has been established to compare the SPEQS performance against the pre vibration test.The SPEQS device showed no degradation of visibility and the brightness under those vibration conditions.

Axis	Sine sweep	Random
X axis	4.5 g	6.7 g rms
Y axis	4.5 g	6.7 g rms
Z axis	4.5 g	6.7 g rms
Frequency	5 – 100 Hz	20 – 2000 Hz

Table 1: The sine and random vibration test profiles were a combination of qualification level test values with acceptance level test times. The performance (visibility and brightness) of the SPEQS device at the end remain unchanged.

Thermal vacuum test

After the vibration tests a thermal vacuum test has been conducted to check the satellite's functionality at the simulated orbital environment.Prior to the thermal vacuum test the satellite was baked at 45^{0}C for 72 hours for outgassing purposes.

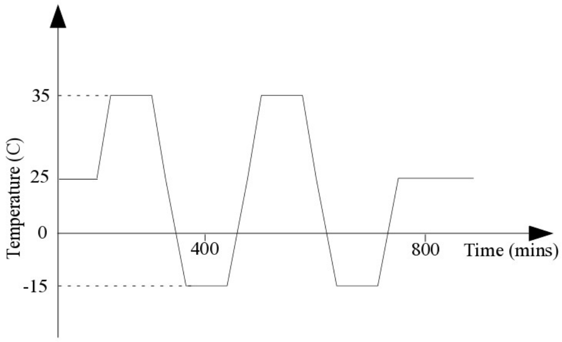

Figure 4: The thermal vacuum test consisted of two thermal cycles and in each cycle the temperature varied between -15^{0}C and 35^0 C with a dwell time of 1 hour on each plateau. The vacuum pressure was maintained at 10^{-5} Torr.

The post thermal vacuum SPEQS performance concluded its flight model acceptance.

SPEQS In-orbit Performance with the Galassia

A baseline has been established at 23 ^{0}C prior to the rocket launch. The first opportunity to turn on SPEQS was taken place after 36 days of satellite's in orbit operations. The SPEQS device was turned on at 12 ^{0}C (based on the OBC temperature reading),temperature ascending phase in sun light. Prior to the scientific experiment, a heating mode (2.5W) has brought the temperature of the optical unit close to the target operating temperature (18 ^{0}C). Figure 5 shows the temperature profile[14] of the optical unit in space along with the baseline at 23 ^{0}C.

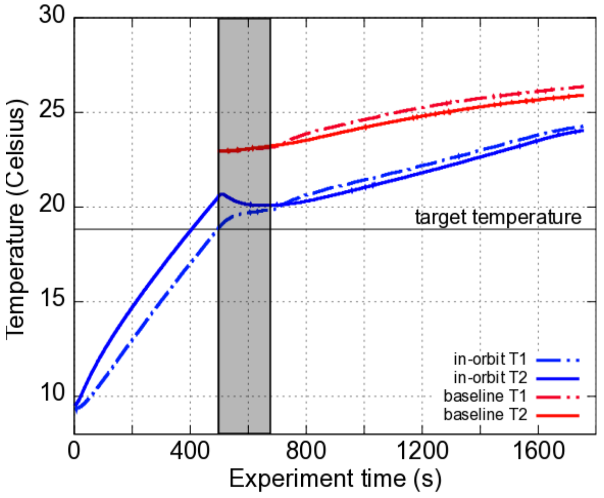

Figure 5: The SPEQS device has two thermistors which are attached near the laser diode (T1) and GM-APDs (T2). Upon activation (at t = 0) a 2.5W heater brought the temperature of the optical unit close to the target operating temperature (18 ^{0}C) with in 8.3 minutes. Then the system stabilizes and monitors the GM-APD's dark counts for 3 minutes (grey area) prior to the scientific experiment.

Space Radiation and Detector Background Noise

After the heating mode the experiment monitors GM-APD's background counts and stabilizes the temperature compensation feedback loop (see the concept of operations in ref. 17) within next 3 minutes. An increase in background counts has been observed (see Figure 6) and the amount of increase (approximately 40000 cps) was larger than the predicted figures for such an orbit based on radiation simulations[24].

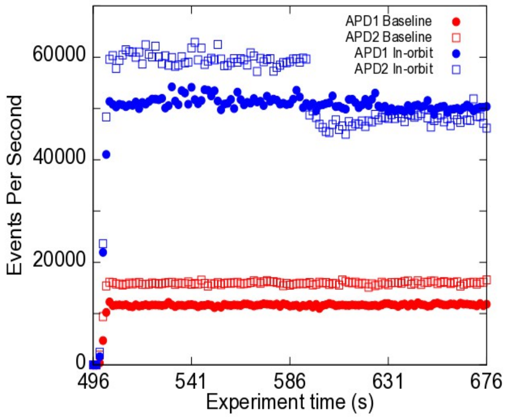

Figure 6: The dark counts profiles of the two GM-APDs in orbit and on Earth[14]. The baseline dark counts of the two GM-APD's were ~12000 and ~16000 cps which were then increased to ~50000 and ~60000 cps respectively, after exposing to space radiation for 36 days.

A second experiment conducted in eclipse confirmed that the increase in dark counts was due to space radiation.

Single Photon Detection Performance

The SPEQS utilizes a software based temperature compensation technique to maintain the GM-APD detection efficiency[19]. The bottom-to-top count ratio (BTR)[19] for a given GM-APD is an indirect measurement of the photon detection efficiency. Figure 7 shows the BTR maintenance of GM-APD1 in orbit (for two separate experiments) along with the baseline while performing the scientific experiment.

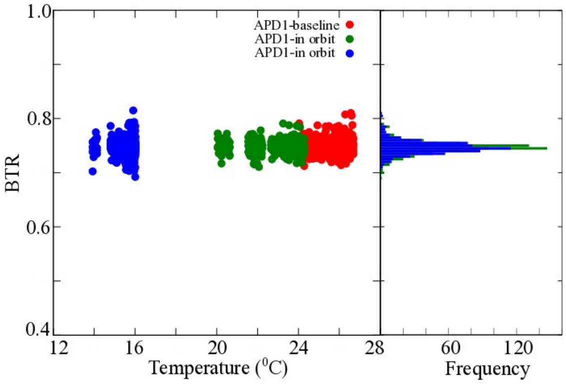

Figure 7: GM-APD1 bottom to top count ratio (BTR) maintenance with the temperature.The baseline data (in red) was collected prior to the launch (from 23-27 ^{0}C) . The green and blue data points correspond to two separate experiments in orbit. The target BTR was 0.75 and the SPEQS device maintained the BTR at 0.75 ± 0.04 for the whole temperature range. The figure on right shows the BTR distribution for the three experiments.

Laser Diode performance

After the dark count mode it turns on the laser diode and stabilizes the optical power. The optical power was maintained at 10mW throughout the experiment.

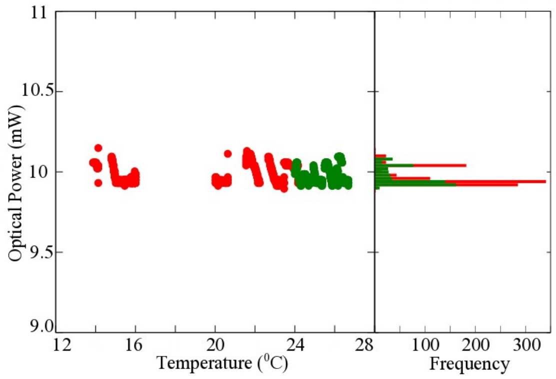

Figure 8: Performance of the Laser diode's feedback system with temperature. Red data points correspond to the two separate in orbit experiments (12.5 – 16 ^{0}C and 19 – 25 ^{0}C). The green data points correspond to the baseline on Earth (23 – 27 ^{0}C). The average locked optical power was 9.975 mW ± 0.051mW for the whole temperature range. The distribution of locked power is plotted on right.

The subsystem level performance of the SPEQS device was comparable with the baseline and confirmed the intended operation of optical and electronics components under space conditions.

Single Photon Source Performance

The comparable performance of SPEQS's subsystems can be used to assess the optical source robustness in terms of the assembling techniques.

Figure 9 shows the in orbit photon pair generation compared to the baseline established on Earth[14]. The visibility was maintained at 97 ±2% for both in orbit and baseline. The brightness of the source has been increased due to a different operating temperature range.

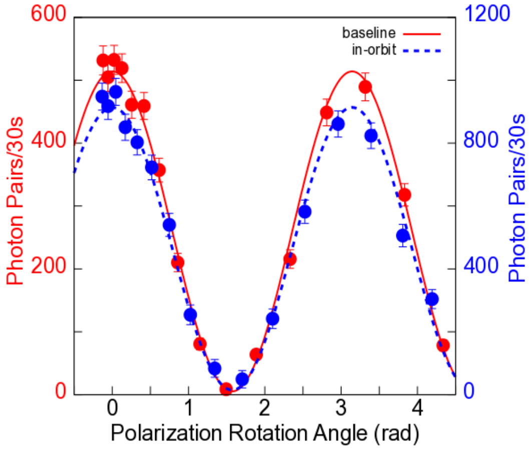

Figure 9: The polarization correlations after subtracting background in orbit (in blue) and on Earth (in red) at 30s integration time for each polarization setting[14].This data have been used to check the performance of the polarization rotator using Malu's law (lines). The visibility is 97 ±2% in both cases and is sufficient for polarization measurements with entangled photon pairs.

This in orbit correlated measurements have proved that the critical optical components required to build an entangled photon source can survive a rocket launch and space conditions.

SPEQS ROADMAP

SpooQy missions

SpooQySats are CubeSats being assembled at Centre for Quantum Technologies. They are dedicated to host SPEQS payloads for in-situ testing for TRL raising purposes. SpooQy-1 will be the first such nano satellite in a series of iterative missions into LEO.

With the successful operation of a correlated photon source on board the Galassia nano satellite, we are currently upgrading SPEQS devices to validate an entangled photon source. SpooQy-1 will be hosting polarization entanglement based SPEQS devices in 2017 [25].

SPEQS 2

SPEQS 2[26] will be the successor of SPEQS entanglement based photon sources. It will generate and detect entangled photons on board a nano satellite with sufficiently high brightness (~1 Mcps coincidences) with visibility (99%) which can violate a Bell's inequality. Such high brightness and visibility photon sources will facilitate a space to ground entanglement based QKD demonstration with nano satellites operating in LEO.

DISCUSSION

A significant miniaturization work have been done on a lab based single photon source to fit into a Cubesat while following the SWaP requirements.The quantum payload (SPEQS) is fully autonomous and can be integrated with a Cubesat to demonstrate the technology readiness level of critical optical components required to build entangled photon sources for space based QKD networks.

The first SPEQS integration was with the GomX-2 nano satellite which was an unsuccessful mission due to a rocket launch failure. Later the satellite was recovered from the crash site and found out that the SPEQS was intact and fully operational.It continued to produce high quality correlations and the performance was comparable with the baseline obtained prior to launch.

The next SPEQS integration was with the Galassia nano satellite which was successfully launched into an equatorial orbit. The SPEQS device survived a series of environmental tests followed by a rocket launch. An elevated level of background counts has been observed at its first operation (after 36 days from launch) and a subsequent background count check in eclipse confirmed the impact of space radiation on Si based avalanche photo diodes. In spite of the increase in dark counts, it continued to produce high quality polarization correlations (visibility of 97 ± 2%) even after spending 140 days on orbit.This level of performance is comparable with the baseline data established prior to the rocket launch.

This successful demonstration of a working correlated photon source in space has led to upgraded SPEQS devices to carry entangled photons. The SpooQy-1 nano satellite will host such an upgraded SPEQS device in 2017.

The successor of upgraded SPEQS devices will lead to a demonstration of sufficiently high brightness (~1 Mcps correlations) and high visibility (~ 99%) entangled sources (SPEQS2) onboard a nano satellite. Such a high level of brightness is required to overcome a satellite's downlink optical losses while generating a useful key.The high entanglement visibility allows violation of a Bell's inequality and such a source will facilitate a space to ground QKD demonstration with entangled photon sources hosting on nano satellites.

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