Validating an entangled photon light source in space with the SpooQy-1 CubeSat

Xueliang Bai[1], Robert Bedington[1], Karthik Ilangovan[1], Hong Nhung Nguyen[1], Rakhitha Chandrasekara[1], Alexander Lohrmann[1], Aitor Villar[1], Md. Tanvirul Islam[1], Alexander Ling[1,2]
Centre For Quantum Technologies, National University of Singapore[1]
S15-02, 3 Science Drive 2, 117543, Singapore; +65 65166758
cqtbx@nus.edu.sg

NUS Department of Physics, National University of Singapore[2]
S12-02, 2 Science Drive 3, 117551, Singapore

ABSTRACT

Quantum Key Distribution (QKD) is a technology that can distribute private encryption keys between two parties with strong security assurances underpinned by quantum mechanics. Entanglement-based QKD is one of the strongest forms of QKD. Performing QKD using satellites can overcome the range constraints of ground-based QKD systems imposed by atmospheric losses or attenuation in optical fibers. In 2017, satellite-based QKD has been demonstrated by the Chinese Academy of Sciences' 630kg Micius satellite. Independently in Singapore we are developing similar, but greatly more compact QKD technologies targeted at CubeSats. Our first on-orbit demonstration of a simple quantum light source was in 2016 on board the Galassia 2U CubeSat. Next on the pad, our SpooQy-1 CubeSat is a 3U GomSpace platform built at CQT that aims to validate the space-worthiness of our next generation entangled photon light source and demonstrate a radio beacon of quantum random numbers. In future missions our miniaturized entangled photon light sources can be combined with high precision Pointing, Acquisition and Tracking System (PATS) and optical communication links to enable a global QKD network with small satellites.

INTRODUCTION

The main objective of SpooQySat, the SpooQy-1 CubeSat, is to demonstrate in-orbit a space-compatible quantum light source to increase the Technology Readiness Level (TRL) of future global Quantum key distribution (QKD) networks. QKD[1] is a family of techniques used to generate private random encryption keys and share them between only two parties. Basic features of quantum mechanics are exploited in order to measure the privacy of the key during the sharing process with the effect that the absence of an eavesdropper can be verified, and keys that have potentially been intercepted can be discarded. Once a key is distributed securely, it can be used as a symmetric key to encrypt and decrypt messages. These messages can be shared publicly as they are provably secure against future hacks from advanced computers, provided the keys were based on genuinely random processes and provided they remain private. QKD schemes based on quantum entanglement can make strong guarantees with respect to such privacy and randomness.

Essentially, QKD requires the exchange of individual photons and so very low-loss optical links need to be established. Optical fibers are limited to about 100km before losses become overwhelming[2] and free-space optics in atmosphere have similar limitations[3]. Performing QKD in space is attractive because atmospheric losses are much less at altitudes higher than 20km above the Earth's surface, enabling much longer distance optical links. Space-based QKD has been studied by various groups around the world.[4,5] It is only recently that significant progress has been demonstrated in space. In 2017, the 630kg Chinese Micius satellite successfully demonstrated quantum key distribution experiments between itself and ground observatories.[6,7]

Our approach at the Centre for Quantum Technologies (CQT) is to develop similar, but highly-miniaturized, QKD technologies for CubeSats. Our current focus is a quantum light source called the Small Photon Entangling Quantum System (SPEQS). It is designed with the Size, Weight and Power (SWaP) constraints of a CubeSat platform in mind, providing a fast and cost-effective way to iterate the technology to maturity. The end goal is to produce a SPEQS device that would be sufficiently powerful to enable a QKD link between satellites, or between a satellite and an optical ground station, when it is paired with the relevant free-space link technologies.[8] The first device in this series is SPEQS-CS, which is a device for producing pairs of polarization correlated photons. Once validated in a balloon test, a SPEQS-CS device was integrated in the GomX-2 satellite for ISS launch in 2014. This satellite did not make it to orbit due to a rocket explosion, but it was recovered from the wreckage and both the satellite and the SPEQS payload were found to be completely operational.[9] Another SPEQS-CS device was integrated into the Galassia CubeSat, a satellite designed by National University of Singapore (NUS) engineering students in 2015.[10] This unit has been successfully deployed and demonstrated in space and is still operational.[11]

The next generation of SPEQS is an enlarged and upgraded version that can produce polarization entangled photon-pairs. The SpooQySat mission has the goal of demonstrating SPEQS producing and detecting entangled photons in-orbit, (i.e. photons will not be beamed outside of the spacecraft). Currently, we are qualification testing the satellite (engineering model shown in Figure 1). With the help of the Singapore Space and Technology Association (SSTA), SpooQySat will be launched via Japan Aerospace Exploration Agency (JAXA) and will be deployed from the International Space Station (ISS) sometime in 2019, with a 6-month expected life time before atmospheric re-entry.

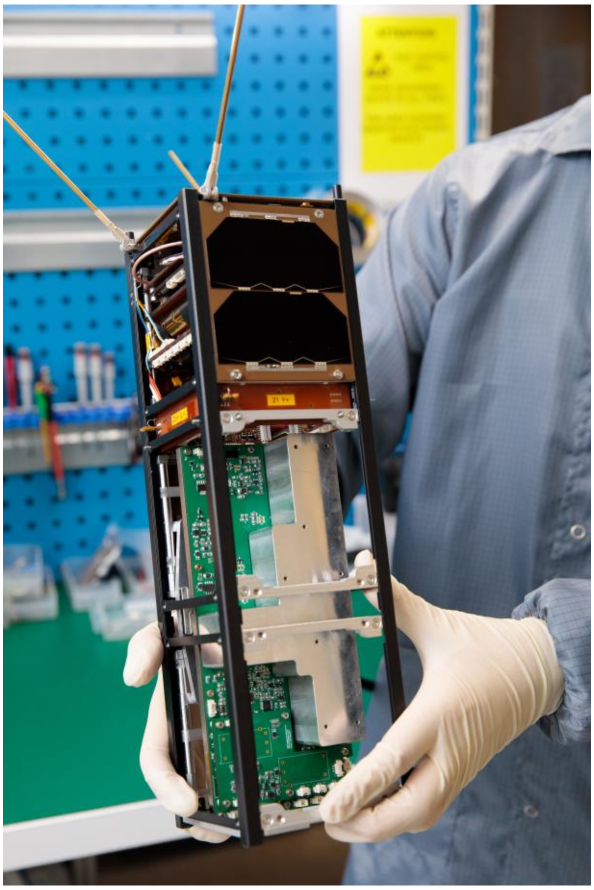

Figure 1: Partially integrated engineering model of SpooQySat. Removed solar panels reveal structural model SPEQS payload.

SPOOQYSAT MISSION OBJECTIVE

The exclusive payload on SpooQySat is our entangled photon light source (SPEQS). In the Galassia mission, we validated the performance of the electronics and optical components on the SPEQS-CS including verifying that the laser source, the polarization analyzer driver circuit and the Geiger-mode Avalanche Photodiode (GM-APD) control circuit work properly in the space environment. Carrying such heritage, the main objective for the SpooQySat satellite is to develop quantum entangled photon sources to demonstrate, on a CubeSat in space, violation of the CHSH (Clauser-Horne-Shimony-Holt) Bell's inequality[12]. This main statement for SpooQySat encompasses the following mission objectives:

- Demonstrate the generation of polarization-entangled photon pairs in space.
- Demonstrate that the technologies used on SPEQS, including the new flexure stage design, mounting and thermal design, are working as intended.
- Investigate aging of the SPEQS device.

In addition, since SPEQS can be used as a quantum random number generator, a secondary mission objective is to use SpooQySat as a random number beacon, periodically broadcasting quantum random numbers via UHF amateur frequency for use in demonstrating beacon based cryptographic schemes.

SATELLITE DESIGN OVERVIEW

The satellite bus is mainly designed using commercial-off-the-shelf (COTS) products. In 2015 we considered many of the CubeSat subsystem suppliers then available in the market with flight heritage, robustness, size and performance in mind. Ultimately, rather than designing an optimized selection of subsystems built around our payload, we selected the 3U GomX CubeSat platform (from GomSpace ApS). The baseline design for the SpooQySat satellite is GomX-3[13], with modifications to accommodate the SPEQS payload, and unrequired subsystems removed (such as fine pointing ADCS and camera). Using a single-supplier satellite platform allows us to integrate a proven, reliable satellite bus with a shorter development cycle and lower risks. This means that to some extent the SpooQySat subsystems are driven by the capabilities of the GomSpace hardware than our top-down definition of a space mission, i.e. the SPEQS device and it's mounting structure is designed to accommodate the SWaP requirements of a 3U GomX CubeSat platform. The layout of the SpooQySat satellite is illustrated in Figure 2.

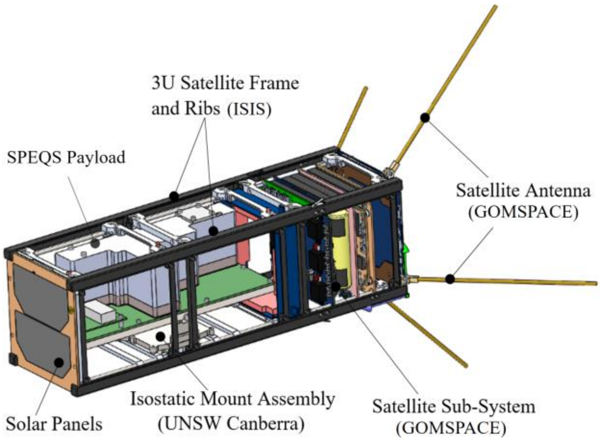

Figure 2: SpooQySat layout with interstage panels, side solar panels, harnesses removed[19]

SPOOQYSAT BUS DESIGN

SpooQySat Subsystems

The SpooQySat subsystems chosen include a half-duplex UHF transceiver combined with deployable canted turnstile UHF antennas used for both uplink and downlink; a 32-bit AVR controller with a 64MB flash storage used as the on-board controller (OBC) for housekeeping and data handling; an attitude determination system (onboard the OBC) with 3 magnetorquers for 3-axis detumbling; and a 38 Whr (4 lithium-ion 18650 cells, 7.7 Whr maximum depth of discharge) battery pack with the electrical power management system (EPS). The 3.3 V power bus will supply subsystems including the OBC, ADCS (onboard the OBC) and the communication system, while the 5V (max. 2 A) is supplied to the SPEQS payload. For the SpooQySat mission, the peak system power consumption is rated at 3.85 W and the peak payload (SPEQS) power consumption is rated at 2.5 W and the duration for each experiment is approximately 35mins. 10 pairs of space qualified triple junction solar cells can provide on average 4.5Whr energy gain each (ISS) orbit.

The elementary satellite bus components are detailed in Table 1. The majority of the satellite bus subsystems, including the OBC, radio and the EPS, are arranged to form the avionics stack residing at the -Z end (as shown in Figure 2) of the satellite and self-contained within a 1U volume.

Table 1: Elementary satellite bus components[20]

Subsystems/Functional components	Component Description
On-board controller with coarse ADCS (OBC)	Nanomind A3200
Mother board	Nanodock-DMC3
Half duplex UHF transceiver	NanoCom AX100
Deployable canted turnstile UHF antennas	NanoCom ANT430
Antenna release	Interstage Panels
Electrical power system (EPS)	NanoPower P31us
Battery pack	NanoPower BPX
Battery	Battery (Lithium Ion 18650 cell)
Solar panels with integrated Magnetotorquers	NanoPower P110 Series
Solar Cells (integrated onto above)	AzurSpace 3G-28 space qualified solar cells
Sensor Bus System	GomSpace Satellite Sensor Bus (GSSB)
Flight Preparation Panel (FPP)	NanoUtil FPP Top
Interstage Cover	Blank interstage panel to provide cover between solar panels.
Payload Interface Board	Customized interface board that connects the payload and the avionics stack

UHF GROUND STATION

All photon pairs produced in SpooQySat will only be detected in-situ within the SPEQS units, so no optical ground station is needed - only UHF ground stations will be used. The Singapore ground station is located on top of an eighteen-storage building in the NUS campus. A secondary UHF ground station is established in Switzerland to provide a backup system and to provide additional data download opportunities. The ground stations are built using GomSpace UHF Ground Station and have identical setups (see Figure 3). Both ground stations are equipped with a twinned Yagi antenna with a tracking mount. The rotor is controlled by a Linux based server computer (NanoCom MS100). The ground station radio (NanoCom GS100) is the ground counterpart (with a 25W power amplifier) for the NanoCom AX100 radio on board SpooQySat, designed specifically as an integrated component to request/respond via the CubeSat Space Protocol (CSP)[15] during operation.

(a) (b)

Figure 3: (a) Singapore UHF ground station on the roof top. (b) Switzerland UHF ground station[20]

ENTANGLED PHOTON SOURCE PAYLOAD

SPEQS Design Overview

The entangled photon source on-board SpooQySat inherits a lot of its design from the source (SPEQS-CS) on the Galassia mission with an increased number of optical components and higher requirements in alignment precision and stability. This drives the requirements for the optical structure to be larger to accommodate the additional (and larger) components. The finalized payload design occupies 2U in volume (see Figure 2) of the satellite and weighs approximately 0.9kg.

SPEQS Design and Assembly

The optical designs of SPEQS payloads has been discussed in our previous works.[8,16] While several designs have been tested and some built as functional models, the optical layout used in the SpooQySat engineering, qualification and flight model devices is shown in Figure 5 below. The optical path is designed to be straight from the pump source to the detectors, omitting the fold mirror found in the SPEQS-CS designs so reducing reflection losses. The achromatic half wave plate (component 5 in the figure) allows for a brighter, stabler and more compact design than those previously considered[21].

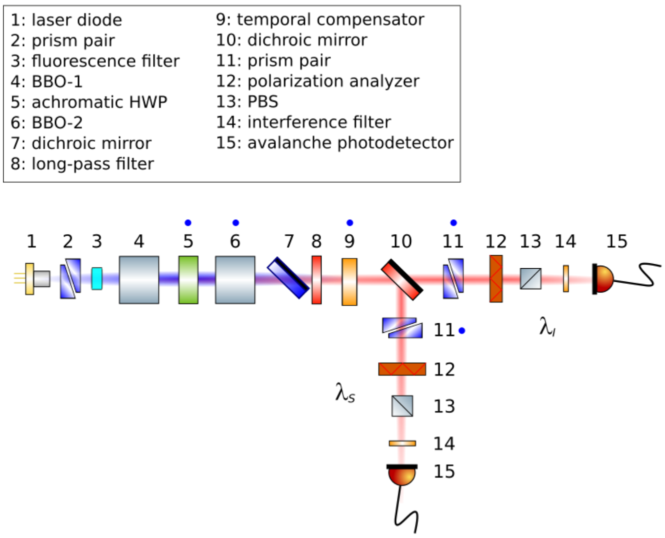

Figure 4: SPEQS optical layout. (The blue dots are additional components comparing to SPEQS CS)

The optical unit and the baseplate are in contact with each other to minimize the thermal gradient. During operation, the laser diode at one end of the unit is a significant heat source and can cause a temperature gradient. A heater is designed to fit into a 0.4mm deep cut-out in the middle section of the baseplate, which is used to minimize the temperature gradient and maintain the thermal and thermoelastic stability of the optical unit. A Viton seal is designed as to insulate the optical unit from printed circuit board (PCB). The enclosure is made from black anodized aluminum. The construction material for both the optical unit and the baseplate are titanium (specifically, Ti-6AL-4V, grade 5) for thermal expansion compatibility.

Close attention has been paid to thermal expansion and mechanical creep of the satellite structure, which may result in deformation of the titanium optical bench structure. An isostatic mount for the payload has been designed by our collaborators in the University of New South Wales (UNSW) Canberra, Australia. The mounting structure consists of three stainless-steel (SS301) blade-like mounts. Each of these mounts has two-degree of freedom to isolate the thermo-elastic extension of the satellite structure as well as providing thermal isolation. The baseplate is mounted on top of the isostatic mount, which mounts to a specially designed side panel that replaces a section of the ISIS CubeSat chassis:

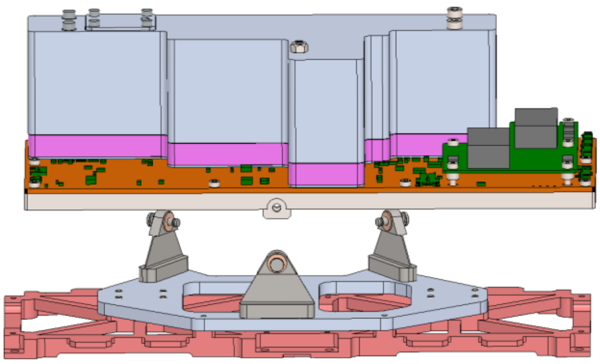

Figure 5: SPEQS payload shown floating to reveal the UNSW Canberra designed isostatic mount beneath.

Thermal Compensation Circuit

Another engineering challenge for SpooQySat is how to compensate the rapid change of the thermal environment in low earth orbit (LEO) when active thermal stabilisation (e.g. thermoelectric cooler based thermal control) is not practical due to the SWaP constraints. From the Galassia mission, we have identified a temperature dependent response of the Liquid Crystal Polarization Rotator (LCPR) - an electrically controllable non-inertial polarization rotator used as part of the photon polarization detector. Such temperature dependent response is compensated by a novel, low power capacitance tracking based control system for the LCPR operating in the temperature range of 10-30 degrees Celsius.[17]

Random Number Generation

A by-product of the quantum entanglement experiment is we can use the detected photons to generate quantum random numbers. On board SpooQySat, we have developed a special experiment profile that can generate and publicly broadcast the numbers to amateur UHF ground stations using periodic beacons. On the ground side, we have developed a Quantum-Safe key expansion algorithm using a randomness beacon and a 256 bits HMAC as a pseudorandom function. This algorithm allows mobile devices that have limited or no QKD capacity, but access to such a public randomness beacon, to carry out high volume secure communication. The algorithm will be discussed in detail in a paper in preparation.[18]

SPEQS/OBC SOFTWARE INTERFACE DESIGN

The SPEQS payload has its dedicated controller to operate the desired experiment and can save the experiment data into its own memory before transferring it to the OBC. The satellite bus only needs to provide power, an initialization command, and then receive the data after the experiment is completed. Once SPEQS is switched on, it acts as an autonomic system until the end of the experiment to prevent unintended interruption during the science experiment.

The SPEQS device is designed to communicate with the OBC via a serial connection. 16 experiment profiles are designed for the mission with different purposes. Once SPEQS is turned on by the OBC, it will direct its internal program with the desired experiment profile based on the configuration bits embedded in the initiation command from the OBC. Each experiment lasts approximately 35mins, generating 1024 kbits of scientific data along with the error handling data at the completion of a single experiment. This data is framed before sending to the OBC. The OBC will send a status frame to SPEQS after the data transfer is finished to acknowledge receipt and then switch off SPEQS.

SCIENCE PHASE CONCEPT OF OPERATIONS

In ISS orbit (400km) with an estimated field of view (FOV) of 140 degrees, the average number of passes per day is 1.7 with a 4-minute downlink time window each pass. In practice, we round this down to 1 useful orbit per day for nominal operation, due to the likelihood of satellite passes happening at times when there are no operators at the ground stations. At this stage, we are only planning 1 experiment per day, although the on-board resources potentially allow more. If the first few experiments can be successfully downloaded, we can consider increasing the duty-cycle of the payload operation.

The scientific payload can be initiated when the ground operation team is confident that the satellite performs nominally after the in-orbit commissioning. The payload operation for SpooQySat is irrespective of the satellite's attitude inclination, altitude etc. However, the performance of the payload is related to the environmental temperature. Therefore, the ground operators shall analyze the housekeeping data for the previous passes and plan the payload operation at the appropriate orbital time.

CONCLUSION AND OUTLOOK

SpooQySat is a precursor to future QKD networks using miniaturised entangled photon light sources. In future missions our light source can be combined with high precision Pointing, Acquisition and Tracking System (PATS) and optical communication links to enable QKD with small satellites.[8] Towards such a global QKD network we have been performing design studies for various missions.

Together with a European consortium we have proposed the CQuCom 6U space-to-ground CubeSat QKD mission.[22] Additionally, with the team at UNSW Canberra, we performed a preliminary study on an inter-satellite QKD demonstration in LEO using two 6U CubeSats. The two satellites would be launched as a single 12U CubeSat. After the launch, each CubeSat will be separated and manoeuvred to their operational orientations. Once a relative velocity of ~10cm/s is achieved between two satellites, inter-satellite QKD demonstrations would be conducted. Pointing errors of less than 5 micro-radians rms between the platforms would need to be achieved.

Acknowledgments

We are extremely grateful to the team at UNSW Canberra led by Russell Boyce and including Douglas Griffin, Simon Barraclough, Jai Vennik and Paul Van Staden who worked on the isostatic mount design and analysis and to Denis Naughton and Avind Ramana who worked on the intersatellite QKD project.

The SpooQySat satellite and the SPEQS programme are fully funded by the National Research Foundation, Prime Minister's Office, Singapore (under the Research Centres of Excellence programme and through Award No. NRF-CRP12-2013-02) and by the Singapore Ministry of Education.

References

1. Gisin, N., Ribordy, G., Tittel, W. & Zbinden, H. Quantum Cryptography. (2001). Rev. Mod. Phys.74.145

2. Korzh, B. *et al.* Provably secure and practical quantum key distribution over 307 km of optical fibre. *Nat. Photonics* **9,** 163–168 (2015).

3. Ursin, R. *et al.* Entanglement-based quantum communication over 144 km. *Nat. Phys.* **3,** 481–486 (2007).

4. Bedington, R., Arrazola, J. M. & Ling, A. Progress in satellite quantum key distribution. *npj Quantum Inf.* 1–12 (2017).

5. Oi, D. K. *et al.* CubeSat quantum communications mission. *EPJ Quantum Technol.* **4,** 6 (2017).

6. Liao, S. *et al.* Satellite-to-ground quantum key distribution. *arXiv:1707.00542 [quant-ph]* (2017).

7. Yin, J. *et al.* Satellite-to-Ground Entanglement-Based Quantum Key Distribution. *Phys. Rev. Lett.* **119,** 200501 (2017).

8. Bedington, R. *et al.* Nanosatellite experiments to enable future space-based QKD missions. *EPJ Quantum Technol.* **3,** 12 (2016).

9. Tang, Z. *et al.* The photon pair source that survived a rocket explosion. *Sci. Rep.* **6,** 25603 (2016).

10. Sha, L., Koenraad, M., Seng, S. W., Hiang, G. C. & Ling, A. Galassia system and mission. *Small Satell. Conf.* SSC14-XI-2 (2014).

11. Tang, Z. *et al.* Generation and analysis of correlated pairs of photons on board a nanosatellite. 1–7 (2016). *Phys Rev Applied.*5.054022

12. Bell, J. S. On the Einstein Podolsky Rosen paradox. *Physics* **1,** 195–200 (1964).

13. Gerhardt, D. *et al.* GOMX-3 : Mission Results from the Inaugural ESA In-Orbit Demonstration CubeSat. *Small Sat Conf.* SSC16-III-04 (2016).

14. Japan Aerospace Exploration Agency. JEM Payload Accommodation Handbook Small Satellite Deployment Interface Control Document. **8,** 1–101 (2015).

15. AAUSAT3; GomSpace. CubeSat Space Protocol.

16. Chandrasekara, C. M. R. B. Demonstrating Miniaturised, Entangled Photon pair Sources On Board Nano Satellites to Enable Future QKD Missions. in *Proceedings of IAC*, 25–29 (2017).

17. Rakhitha Chandrasekara, Kadir Durak, Alexander Ling. Tracking capacitance of liquid crystal devices to improve polarization rotation accuracy *Optics Express*. **25,** 20363–20368 (2017).

18. Islam, T., Wildfeuer, C. & Ling, A. Proposal for quantum-safe shared randomness expansion. (2017).

19. Grieve J. *et al.* SpooQySats: CubeSats to demonstrate quantum key distribution technologies, *Acta Astronautica* AA6923, 2018 (in press)

20. Bai, X. *et al*. SpooQy-1, a CubeSat to demonstrate an entangled photon light source, *Advances in the Astronautical Sciences*, vol. 163, No. 2, Rome, Italy, (2017)

21. Lohrmann, A. Villar, A. Ling, A. Generating entangled photon pairs in a parallel crystal geometry, *ArXiv:1805.11809v1*, (2018)