SpooQy-1: the first nano-satellite to demonstrate quantum entanglement in space

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ABSTRACT

SpooQy-1 is a 3-unit nanosatellite that was launched into a Low Earth Orbit from the International Space Station on the 17th of June 2019. The spacecraft hosts a scientific payload capable of producing entangled photon-pairs and measuring their polarization in orthogonal bases to perform a Bell test. Since launch, SpooQy-1 has routinely demonstrated the generation and detection of polarization entangled photon-pairs in Space, something that has previously only been demonstrated by the 630kg Micius mission by the Chinese Academy of Sciences. The measured entanglement correlations can violate Bell's inequality with a CHSH parameter value of 2.60±0.06, over operating temperatures of 16 °C to 21.5 °C. These results demonstrate that quantum entanglement can be generated in space on highly resource-constrained platforms. A follow-on 12U mission, developed in partnership with RAL space, will build on this to demonstrate space-to-ground entanglement distribution, which is required for space-based nodes to support global quantum communication networks.

INTRODUCTION

SpooQy-1 was deployed into orbit from the International Space Station on the 19th of June 2019. It is a 3U CubeSat that features an entangled photon source and a single-photon analyzer/detection system to demonstrate the generation of quantum entanglement. Since launch, measurements of polarization entangled photons have been performed routinely and successfully with operations being conducted from Switzerland and Singapore ground stations [1]. SpooQy-1 was developed at the Centre for Quantum Technologies in Singapore, building on the heritage of compact, ruggedized correlated photon sources operated in extreme environments such as on high altitude balloons [2] and on board CQT's first CubeSat payload on board the 2U NUS Galassia-1 spacecraft [3].

The demonstration performed by SpooQy-1 is a core capability for future quantum network nodes that will be able to distribute entanglement to any two points on Earth. Local quantum communication links over free-space or fiber-optics are limited by link availability and high losses to a few hundred kilometers [4] as quantum signals are very weak (at the single photon level) and cannot be amplified. While quantum repeaters might be possible in the future and could reach further distances by teleportation of quantum states, any future quantum

internet is likely to include space-based quantum communication nodes [5].

An early application that can use shared entanglement as a resource is Quantum Key Distribution (QKD); a process in which an encryption key is generated between two nodes in a manner that would reveal eavesdropping attempts, thus providing strong guarantees about privacy and security [6]. Satellites can perform QKD to create cryptographically secure encryption keys with optical ground stations they pass over or transmit entangled photons to two ground stations simultaneously. The distributed keys can then be used for symmetric keying material to encrypt communications between the QKD key holders. Particularly useful are constellations of satellites that can perform quantum communications between any two points on Earth [7]. Recent advances in small satellite technology, especially in their pointing and tracking performance [8] and optical communication technologies [9], when combined with similarly miniaturized quantum light sources would enable deployment of such constellations.

MISSION OVERVIEW

The SpooQy-1 mission is to demonstrate quantum entangled photon sources on a CubeSat in space, through the violation of the CHSH (Clauser-Horne-Shimony-Holt) Bell's inequality [10]. This encompasses the following mission objectives:

- Demonstrate the generation of polarization-entangled photon-pairs in space.
- Demonstrate that the technologies used on its payload, the Small Photon Entanglement Quantum System 2, or SPEQS-2, particularly the new flexure stage design, isostatic mounting and thermal design, are performing as intended.
- Investigate aging of SPEQS-2 in space.

The development of entangled photon sources at CQT follows an iterative approach. Components used on SPEQS-2 that already had space heritage include electronics and optical components such as the laser, driving circuits for Liquid Crystal Polarization Rotators (LCPR), the Avalanche Photodiodes (APDs) as well as some mechanical mounting strategies. Furthermore, component level radiation tests were performed on the detectors and LCD polarization rotators [11]. The payload went through a functional model and engineering model iteration, and qualification models of both spacecraft and payload were qualified for an ISS-resupply rated launch and ISS-orbit thermal environments. The flight model was a complete copy of the qualification model satellite that underwent acceptance testing for workmanship level verification and ISS specific tests such as battery verification tests were carried out.

Early development, including table-top demonstrations and component level testing, was performed in 2016 and engineering model development concluded in 2017. Engineering model vibration tests of the payload were performed in early 2018 and qualification tests of the spacecraft with payload were completed late 2018. Acceptance testing of the spacecraft was performed in January 2019 and the spacecraft was delivered to JAXA for launch to the ISS in February 2019.

Mission operations are conducted by CQT and SpeQtral, a spin-out company from CQT, using UHF/VHF ground stations in Singapore and Switzerland.

MISSION DESIGN

The payload followed a bottom-up development approach typical of scientific experiments, but there was a continuous tradeoff between performance and Size, Weight and Power (SWaP) of the payload. This led to a design, including mechanical interfaces, with a volume of about 2U. With no stringent attitude control requirements (measurements of the entangled photons are performed in-situ) this meant a 3U platform would be sufficient to host the payload and facilitate operations with 1U dedicated to spacecraft avionics, see Figure 1.

Figure 1 Overview of SpooQy-1 spacecraft and payload subsystems. The bottom two thirds contain the entangled photon source while the top third of the spacecraft contains the spacecraft subsystems.

Payload design

SPEQS-2 builds on the source launched on Galassia (SPEQS-CS [12]) with a different nonlinear crystal

arrangement, additional optical components and, as a result, more stringent alignment, and volume requirements. The electronics and software, including the laser driver, the polarization analyzer driver, and the Geiger-mode Avalanche Photodiode (GM-APD) control circuit are mostly inherited. The optical design is shown in Figure 2. The polarization entangled photon-pair source makes use of collinear, non-degenerate type-I Spontaneous Parametric Down Conversion (SPDC) to down-convert 405nm pump photons into polarization entangled photon-pairs. This type of SPDC has stringent requirements on the incident angle of the pump beam (<100 micro-radian deviation) but is not very sensitive to the temperature of the crystals. The nonlinear material used for SPDC are the two β-Barium Borate (BBO-1 and BBO-2) crystals. The photon-pair, comprising a signal and idler photon, is separated by a dichroic mirror and each photon is detected by an avalanche single photon detector. LCPRs allow rotation of the polarization of the idler or signal photons for characterization of the polarization correlations. For a full description see [1].

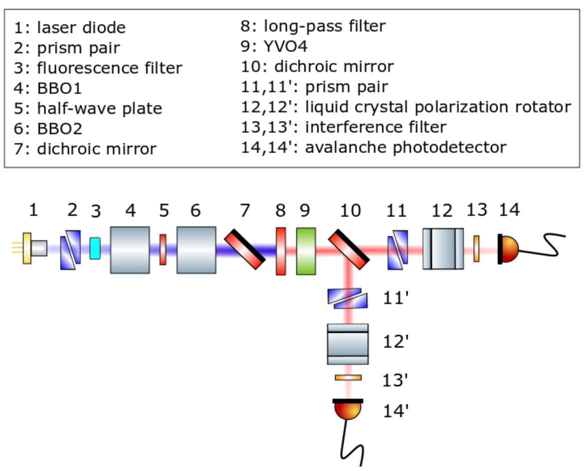

Figure 2 Optical design of SPEQS-2.

The operational temperature environment inside the spacecraft was expected to range from approximately 0 to 30°C. Furthermore, the payload had to withstand the vibrations experienced during launch. Active thermal alignment capabilities are not commonly used on-board CubeSats due to resource constraints [13] so the mechanical design of the payload incorporated passive thermal control approaches. This is reflected in both the mounting of individual components as well as the overall mechanical design and interface to the spacecraft bus, see Figure 3. For example, the alignment-critical nonlinear crystals are mounted on custom-designed titanium flexure stages that allow precise alignment while offering high stiffness. To prevent deformations from mismatched thermal coefficients, titanium was also chosen as the optical base material as well as for most of other optical elements that are directly mounted on this base. While the individual optical elements do not have as strict alignment requirements the total misalignment can still yield poor performance. To facilitate this the entire payload was decoupled thermally from the spacecraft bus using isostatic mounts, designed by UNSW Canberra, that use thin 0.4mm flexing members to buffer any relative expansion between payload and spacecraft and that also provide a very poor thermal conductivity path. Finally, the laser itself inside the payload produces heat during operations which is concentrated on one side of the payload, and thus would introduce thermal gradients that could lead to misalignments. To correct for this, and to have some level of active thermal control, a 2.5W heater was placed under the optical base that is able to even out the temperature distribution during operations. This heater proved extremely useful in attaining safe operating temperatures in orbit, despite initially only being intended for correcting thermal gradients. The thermal mounting strategy is further discussed in [13].

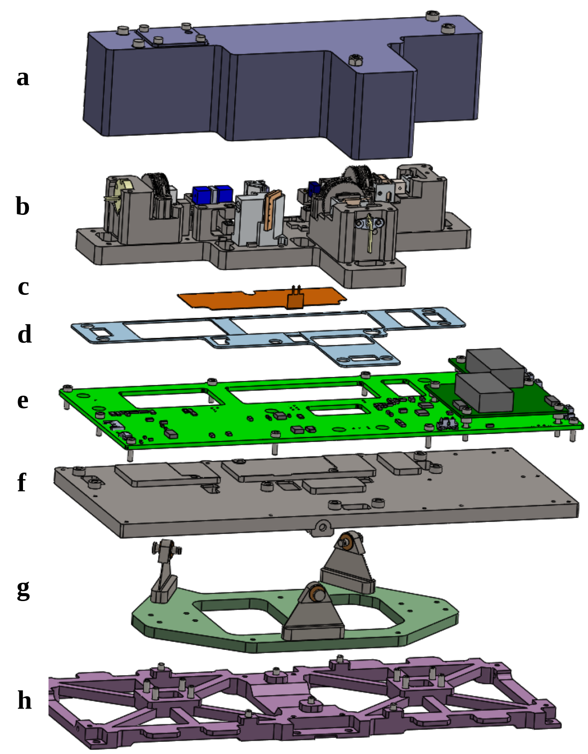

Figure 3 SPEQS-2 exploded view. a: Free-floating light-tight aluminium cover with air escape vent. b: Optical unit base with opto-electronics components mounted inside. c: Sheet heater. d: Viton sheet. e: Electronics board with daughter board. f: Payload structure. g: Isostatic mount. h: Bus structure interface.

Beneath the optical base and the sheet heater is a Viton sheet to reduce direct thermal contact to the payload electronics. These consist of control circuits for the opto-

electronic components including the laser and detectors, voltage amplifier stages for the detectors, a micro-controller, and electronic interfaces to the spacecraft. When turned on and commanded by the spacecraft, the micro-controller runs the desired demonstration: setting the laser currents, LCPR values, detector control circuit voltages, experiment time etc. It saves the data into its own memory at the end of each demonstration and transmits this to the spacecraft. The spacecraft bus provides power, an initialization command and receives data. The communication interface is a serial interface.

The payload occupies 2U in volume of the satellite and weighs approximately 0.9kg. Mechanically it interfaces via a custom frame component to the ISIS CubeSat structure and electrically it uses pico-lock connectors and a custom interface board for the cabling that connects to the on-board computer.

Spacecraft design

The design philosophy for the spacecraft bus was to primarily use Commercial-Off-The-Shelf products (COTS). Ultimately, the GomX-3 platform (from GomSpace ApS) was selected as a basis for SpooQy-1 rather than choosing an optimized set of individual subsystems from different manufacturers. This meant a proven, reliable satellite bus could be used which reduced the necessary verification and validation efforts and lowered technical risk. To some extent the capabilities of the SpooQy-1 subsystems were then driven by what was available for the GomX platform. An overview of the spacecraft and its subsystems is shown in Figure 4.

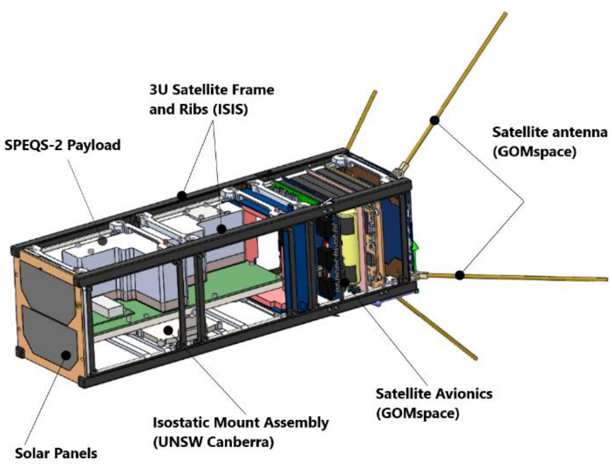

Figure 4 SpooQy-1 sub-systems

The SpooQy-1 avionics 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 64MB flash storage is used as the on-board computer (OBC)
- a coarse ADCS system (on-board the OBC) with 3 magnetorquers for 3-axis detumbling
- an electrical power management system (EPS) with a 38 Whr (4 lithium-ion 18650 cells, 7.7 Whr maximum depth of discharge) battery pack. The 3.3 V power bus supplies the subsystems including the OBC, ADCS (onboard the OBC) and the communication system, while 5V (max. 2 A) is supplied to the SPEQS-2 payload. The peak system power consumption is rated at 3.85 W and the peak payload (SPEQS-1) power consumption is rated at 2.5 W.
- 10 pairs of space qualified triple junction solar cells can provide on average 4.5Whr energy gain each (ISS) orbit.

Ground segment

The ground segment provides telemetry and telecommand functions as well the ability to download experiment data. The Singapore ground station is located on top of an eighteen-storey building on the NUS campus. An additional UHF ground station was built in Switzerland to provide redundancy and additional data download opportunities. GOMspace AS100 UHF ground stations were used for both stations (see Figure 5). 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 counterpart to the NanoCom AX100 radio on board SpooQy-1, designed specifically as an integrated component to request/respond via the CSP (CubeSat Space Protocol (see http://www.libcsp.org) during operation. The ground segment and NanoComAX100 radio support download rates up to 19.2kb/s.

Figure 5: (a) Singapore UHF ground station (b) Switzerland UHF ground station

VERIFICATION AND VALIDATION

Apart from bottom-up development, such as component level tests, table-top demonstrations and functional/engineering model tests, the SpooQy-1 mission followed a general top-down verification and validation approach. Both qualification and acceptance tests were performed involving thermal bakeout, thermal-vacuum and random vibration tests. The qualification and acceptance test levels are summarized in Table 1.

Table 1 Testing levels.

Test	Qualification	Acceptance
Random vibration	7.1g RMS	7.1g RMS
Thermal vacuum bakeout	72 hours at 40°C	72 hours at 40°C
Thermal vacuum cycle	8 cycles from -10 to 40 °C	2 cycles from -5 to 35°C

The test levels followed the requirement stated in the interface control document (ICD) from the Japan Aerospace Exploration Agency (JAXA). Sine sweep tests performed before and after both QT and AT showed that the first eigenfrequencies for all 3 axes were above the required level (100Hz) and no structural damage had occurred. Functional testing prior to and after each test showed that both the spacecraft and the payload passed each test successfully. Figure 6 shows the vibration test setup for the Qualification Model (QM) of the payload.

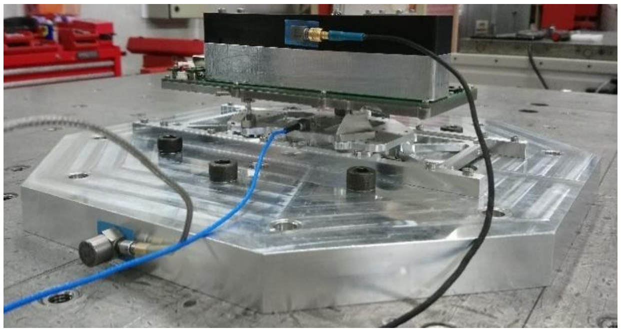

Figure 6 Random vibration test performed for the Qualification Model of the payload at ST engineering.

Thermal vacuum test ranges were determined following guidelines from the European Cooperation for Space Standardization (ECSS). The internal temperature range of SpooQy-1 was predicted to range from 0°C to 30°C. Accordingly, including a margin, the test range for the qualification and acceptance tests were set at -10 to 40°C and -5 to 35°C, respectively. Figure 7 shows the test setup for the thermal vacuum test performed on the Flight Model. The thermal bakeout test was required by the test facility to protect the main thermal vacuum chamber.

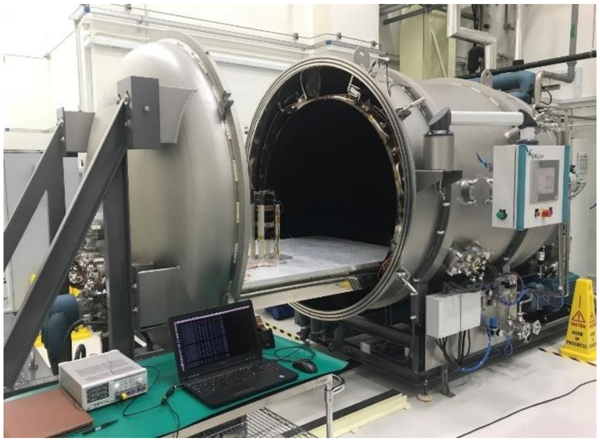

Figure 7 Thermal vacuum test performed for SpooQy-1 Flight Model at ST engineering.

In addition to environmental tests and spacecraft/payload level functional tests there was a battery of tests required to be able to launch the spacecraft via the International Space Station. These included battery verification tests (full charge and discharge cycles) before and after every test, JSSOD deployer fit checks, sharp edge inspection tests (in case the spacecraft had to be handled by an astronaut) and further verification tests that applied at the sub-system level and could be complied with because of GOMspace's ISS launch heritage. If not properly accounted for these tests can lead to delays that impact booking of testing facilities etc.

LAUNCH & OPERATIONS

SpooQy-1 was launched to the ISS as part of the Cygnus NG-11 resupply mission on an Antares 230 rocket. It was deployed into an orbit with an inclination of 51.6° at 408km altitude on the 17th of June 2019. A picture of the deployment taken by an ISS astronaut is shown in Figure 8. Housekeeping data was received from the spacecraft within a couple of hours after launch and full command was established within a few days. The thermal environment in the orbit has a seasonal variation associated with its position with respect to the Sun and the Earth. The current orbit environment was characterized by monitoring the temperature in the payload as well as the dark counts in the single photon detectors. This information is used to set the conditions

for the experiments (laser current, heater power, heater time, experiment duration etc.).

The quantum entanglement experiment is generally run on SpooQy-1 during the parts of the orbit when the temperature environment of the payload supports operations (15°C -28°C) and a demonstration takes about 10 minutes to run. The payload is typically commanded to operate until the next pass with cycles of heating and running demonstrations, depending on beta angle conditions. When continuously in sunlight (high beta angle) the temperature seen by the payload is not usually favourable. During the approx. 10 minute ground station passes entanglement demonstration and housekeeping data are downloaded and new commands are uploaded. There are on average 5-6 useful passes per day.

RESULTS

Within a few weeks after launch the first successful violation of Bell's inequality was achieved. The main performance metric is the entanglement quality which is represented by the Clauser-Horne-Shimony-Holt (CHSH) test. The CHSH parameter has a quantum mechanical maximum of $2\sqrt{2}$~2.82, any value >2 represents a violation of the local-realistic assumptions of "classical" physics. The maximum violation achieved in orbit for SpooQy-1 was 2.60 ± 0.06 (for details see [1]). Successful experiments can be run routinely given suitable thermal conditions. This mission has demonstrated that quantum entanglement technology can be deployed on board resource constrained satellites in novel operating environments. This creates a pathway for applications such as quantum key distribution from CubeSats and is a major building block towards future space-based quantum network nodes. CQT's next mission, in collaboration with RAL Space, is planned to launch in Q3 2022 and will demonstrate space-to-ground entanglement distribution and quantum key distribution using an optical terminal and satellite bus built by the RAL Space team in the UK. SpooQy-1 has already demonstrated a range of technologies required for this mission and the development of the next-generation, entangled photon-pair source is on-going.

Acknowledgements

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Figure 8 SpooQy-1 deployed from the ISS on the 17th of June 2019. Photo credit: NASA