Smallsats as an enabler of innovation:

A Case Study of Satellite Quantum Key Distribution and Space Quantum Technologies

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Introduction

Access to space has rapidly improved in recent years due to increased launch opportunities through rideshares and dedicated small satellite (smallsat) launchers, as well as the emergence of CubeSats and other nanosatellite standards. A burgeoning market for CubeSat components and platform systems has developed in response to demand and it is now possible to build a small satellite from standard components and launch it within months via a launch broker. With even more commercial launch capability coming onstream, in particular micro launchers, it will become even easier for small groups and companies to deploy satellites and demonstrate in-orbit capability.

These possibilities were recognised in 2009 by a collaboration initiated between the University of Strathclyde and the Centre for Quantum Technologies (CQT), National University of Singapore [1]. CQT set up a space quantum technologies group (called SpooQy Lab), led by Dr Alexander Ling, working with Dr Daniel Oi, University of Strathclyde, to develop quantum entangled photon sources suitable for satellites. This capitalised on prior work and experience in quantum entanglement research at CQT for terrestrial quantum key distribution and fundamental physics.

The aim of the SpooQy Lab was to translate laboratory systems into rugged and miniaturised components able to function under the harsh conditions of launch and orbit and enable the development space quantum technologies. A key strategy was to use CubeSats to rapidly develop and test out devices and systems at a much faster tempo and lower cost than traditional space engineering programmes. The work initiated at CQT has inspired similar development and missions worldwide to develop CubeSat space quantum technologies. Here, we describe this work and some of the associated programmes that have stemmed from it.

Explainer Box: CubeSats

Nanosatellites are approximately 1-10kg with the most common type being CubeSats. CubeSats were developed as an educational tool in 1999 by Cal Poly and Stanford University to give engineering students hands-on experience in designing, building, and launching fully functional satellites. This was in contrast to traditional space engineering of large, expensive satellites whose development could be many years or decades in some cases. CubeSats were designed to be an inexpensive and quickly developed alternative suited to undergraduate engineering programmes.

Key to this is the CubeSat standard that defines important parameters such as the dimensions, mass, mechanical, and electrical interfaces. The CubeSat standard was originally built around a 1U (unit) cube of 10cm a side and 1kg. These can be combined to form larger form factor CubeSats, e.g. 2U, 3U, 6U being the more common sizes today, and the current standard (Rev.14 DRAFT) allows for CubeSats ranging from 1U all the way up

Figure 1: UKube-1 prepared for launch. This was UK's first official CubeSat, launched in 2014, and was built by Clyde Space Ltd in Glasgow. The 3U CubeSat, approximately 10cm x 10cm x 30cm and 3kg, carried 6 payloads.

to 12U (2x2x3 size) and 2kg per U (e.g. 24kg for a 12U). The availability of a standard has led to the development of a burgeoning market for CubeSat components and subsystems to support the increasing number of missions.

The first CubeSats were launched in 2003 and over the last few years the numbers have reached 100-200 per year with 2500 predicted to be launched in the next 6 years. Key to the rise in CubeSat missions is the availability of rideshare launches, whereby a launch vehicle will carry secondary or even tertiary satellite payloads into space in addition to the primary payload. Additionally, dedicated nanosatellite launches can carry upwards of 100 CubeSats and other smallsats into low Earth orbit on a single rocket. The cost to launch a CubeSat on either a rideshare or dedicated launch can range from free (e.g. if sponsored by a government programme) or USD150K for a 3U to USD600K for a 12U at commercial rates.

The capability of CubeSats have expanded massively with the development of miniaturised components such as X-band radios, star trackers, reaction wheels, with increased available power from large deployable solar arrays. This has allowed CubeSats to perform missions previously thought possible only on much larger satellite platforms such as Earth Observation, Astronomy, and Space Science. CubeSats have graduated from being a purely educational tool to a platform that can perform significant scientific and commercial missions. The company Planet, a spin-out of NASA Ames, is able to map the entire landmass of the Earth everyday using their fleet of “doves”, 3U CubeSats at a ground resolution of ~3-5m. Other CubeSats track ships and planes, whilst science missions have successfully observed exoplanets.

CubeSats are at the vanguard of the NewSpace revolution, aka Space 4.0, whereby the democratisation of space access, the emergence of a diversified and expanded scope of space actors including small enterprise and research groups, and a more agile approach to space systems development, have led to greater participation from many different sectors. The increasing commercialisation of space launch, for example the successes of SpaceX, has reduced in-orbit deployment costs dramatically and enabled the feasibility of “mega constellations”, some now being constructed. It has also led to the shift in the way that governments have approached national space programmes, with NASA and ESA seeing this as an opportunity to greatly encourage innovation in the space sector that has previously been characterised by engineering conservatism. CubeSats continue their role in inspiring the next generation of engineers and scientists to reach for space.

SPEQS-1

The first stage was to develop the “small photon entangled quantum source 1” (SPEQS-1) as a proof of concept. This device consisted of a 405nm blue laser diode pumping a set of nonlinear crystals to produces pairs of correlated photon pairs. The polarisation of the photon pairs were then analysed in the same device to test the performance of the down conversion process. Previously, such experiments in the lab would typically take up an optical table and require manual adjustment and a controlled environment. The challenge was to reduce the form factor to ~100mm x 100mm x 30mm with a power consumption of a few watts and being able to withstand the extreme conditions of launch and in space.

Figure 2: SPEQS-1 correlated photon pair source. The quantum payload is 10cm x 10cm x 3cm in size with a mass of 300g. It produces pairs of photons that possess the property of quantum entanglement that can be used for secure communication.

Balloon Tests

Figure 3: High altitude balloon test of SPEQS. Two campaigns were carried out to test the operation of the first prototypes of the quantum source in field conditions. The balloons reached altitudes of over 35km before bursting and the payloads safely returning to Earth by parachute.

As a precursor to the launch campaign, SPEQS prototypes were tested on high altitude balloons with collaborators in Germany and Switzerland in 2012-13. This demonstrated the autonomous operation of the device and the ability to perform under extreme environmental conditions. The balloon tests reached altitudes of 35km or greater with extreme low temperatures and pressures. The payloads also had to survive the loads associated with the rupture of the balloons and uncontrolled descent back to Earth.

Figure 4: CRS-3 Launch Failure 28th October 2014. The Antares resupply mission to the International Space Station was carrying the GomX-2 CubeSat and the SPEQS-1 payload. Photo: NASA

GomX-2

The first launch of SPEQS-1 was as a hosted payload on the GomX-2 2U CubeSat operated by GomSpace A/S on top of an Antares 130 rocket on 28th October 2014. The CubeSat was to be ferried as cargo as part of the commercial resupply services 3 (CRS-3) mission to the International Space Station (ISS) from which it would be put into an independent orbit via a CubeSat deployer. Unfortunately, shortly after take-off, the first stage failed and the craft was engulfed in a massive fireball as it fell back to Earth. Remarkably, the cargo was retrieved and returned intact. GomX-2 was still operable and the SPEQS-1 payload performed with no observable change due to its unintended environmental test [2].

Galassia

Figure 5: PSLV-C29 Launch of Galassia, 16th December 2015. Photo: ISRO

Despite the setback from the destruction of the CRS-3 mission, the CQT team was able to quickly build another flight model of the experiment. Fortunately, NUS Engineering had been building its own 3kg 2U CubeSat called Galassia and was able to accommodate SPEQS-1 as a payload at short notice. This was aided by the standardised form factor (PC104) used for SPEQS-1 and Galassia so that they could be integrated very easily. This is in contrast with more bespoke satellites where the payload is often customised specifically for the satellite bus on which it will fly, hence making it more difficult to be compatible with a different satellite.

Just over a year after the failure of our first attempt, on 16th December 2015 Galassia was launched on the Indian PSLV-CA rocket into a near equatorial 500km altitude orbit along with 5 other small satellites. SPEQS-1 was able to operate successfully in orbit and its performance was characterised over the next year proving the design concept of the photon pair source [3]. The experience gained in building and operating this first successful mission was employed in the planning for more ambitious missions to follow [4,5].

CQuCoM

Encouraged by the success of the SPEQS-1 and Galassia, Strathclyde and CQT gathered a 6-nation consortium to propose in 2015 a CubeSat mission to perform space to ground quantum communication[6]. The CubeSat Quantum Communications Mission (CQuCoM), led by Daniel Oi, would be conducted by researchers and companies from the UK, Singapore, Germany, Austria, Italy, and the Netherlands and was bid into the Horizon 2020 Further and Emerging Technologies programme. Though unsuccessful in obtaining funding, the proposal has spawned several research proposals by members of the original consortium, including QUARC (UK), Nanobob & Q3Sat (Austria-France), and QUBE (Germany) that would also exploit the possibilities of CubeSats for space quantum communications.

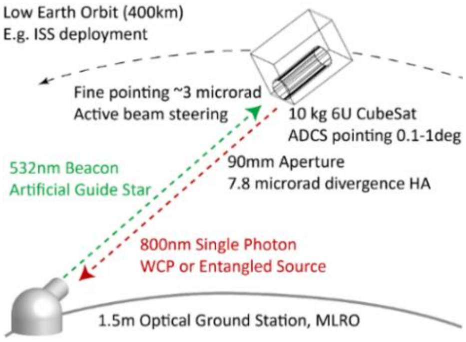

Figure 6: Initial CQuCoM Concept. This mission proposal established the feasibility of using CubeSats for space quantum communications.

SpooQy-1

Development at CQT did not stop at the successful operation of SPEQS-1 on Galassia. SPEQS-1 had demonstrated proof-of-principle of the generation of correlated photon pairs in a miniaturised space source but we had not yet shown polarisation entanglement. This would require a larger payload and a dedicated 2.6kg 3U CubeSat to house the SPEQS-2 source. Building on the lessons learned from previous missions and field tests, a compact and robust polarisation entangled photon pair source was successfully carried on the SpooQy-1 CubeSat that was launched to the International Space Station on 18th April 2019 and deployed into orbit on 17th June 2019 [7]. It soon showed that quantum entanglement could be generated and measured with a nanosatellite, much smaller than the Chinese Micius satellite (650kg) launched in 2016.

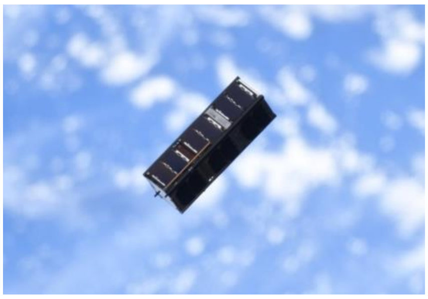

Figure 7: SpooQy-1 after deployment from the ISS 17th June 2019. The SPEQS-2 payload successfully demonstrated the generation of entangled photons in space on a nanosatellite with a mass of 2.6kg, far smaller than the Micius satellite (650kg) previously. Photo: NASA

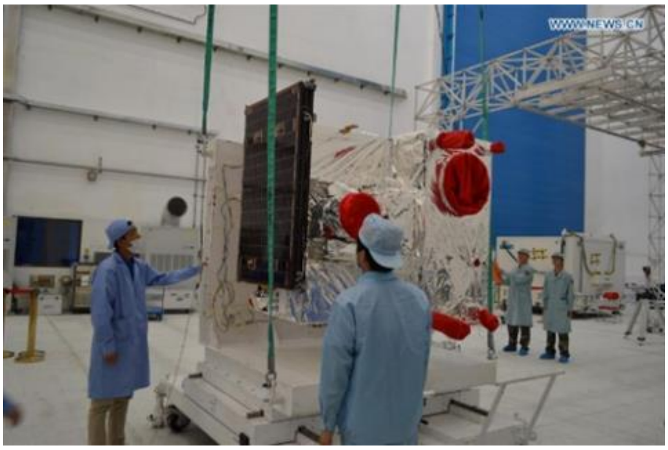

Figure 8: Micius Satellite being prepared for launch. The QUESS mission launched Micius in 2016 and successfully demonstrated a series of pioneering space quantum communication experiments. Micius has a mass of 650kg and is estimated to have cost USD100M in addition to the launch. Photo: Chinese Academy of Sciences

After the initial demonstration of the SPEQS-2 source, SpooQy-1 continues its scientific mission to study the long-term performance of the device and its components. We are gathering valuable information on the radiation tolerance of the single photon detectors used to measure the entanglement which we can compare with models and simulations.

Centre for Quantum Technologies

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SpeQtre

SpooQy-1 demonstrated that entangled photons could be generated on a nanosatellite but now the next step is to transmit one of the photons in each entangled pair to an optical ground station, thus distributing entanglement between Space and Earth. The Micius satellite has demonstrated the transmission of entanglement from space but is a much larger and costlier satellite. In 2018, CQT and Strathclyde embarked on concept study with RALSpace for a nanosatellite that could perform satellite QKD with a ground receiver. A spin-out company from CQT, SpeQtral Pte Ltd, is managing the Singapore engineering efforts.

The challenge is to increase the rate at which entangled photons can be produced by the source and to send them accurately from the rapidly moving CubeSat in low Earth orbit to a telescope on the ground, overcoming the high diffraction loss due to the long range and restricted size of the transmitter and receiver.

QUARC/ROKS

Based on the worked performed in the CQuCoM proposal, a UK effort in Satellite QKD was initiated in 2016, obtaining funding from the UK Space Agency National Space Technology Programme to work with Bristol University to develop key subsystems of a CubeSat quantum communication payload. This Quantum Research CubeSat (QUARC) project would establish UK capability in satellite quantum key distribution (QKD) technologies [8]. QUARC combined Bristol experience in short range QKD with the knowledge from CQuCoM and collaboration with CQT. The initial QUARC funding was followed up by support from the UK National Quantum Technology Programme and the Quantum Communications Hub.

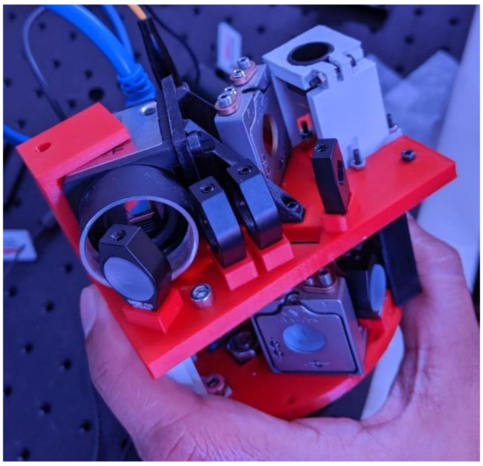

Figure 9: Early prototype of QKD payload. QUARC developed miniaturised pointing systems required for sending single photons thousands of km from space to ground.

The company Craft Prospect Ltd, a space start-up established in 2017 based in Glasgow, saw the potential for CubeSats to deliver commercially viable satellite QKD services. Craft Prospect has since been a working to commercialise the technology, developed by QUARC, as part of the Responsive Operations for Key Services (ROKS) mission. Strathclyde, Bristol, and other partners are working with Craft Prospect to deliver a fully functional nanosatellite QKD system for launch in 2022. A ROKS derived payload is also planned for launch on the Canadian microsat QKD mission QEYSSat as part of a joint UK-Canada collaboration.

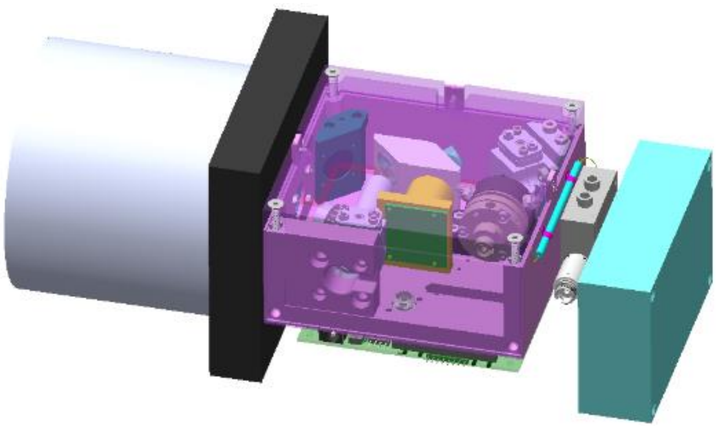

Figure 10: ROKS Payload Design. The technology developed in QUARC is being engineered for flight in the ROKS mission by Craft Prospect Ltd.

QT Hub Mission

The QUARC research will be combined with the CubeSat platform developed in SpeQtre for a mission by the Quantum Communications Hub led by York University. This will demonstrate UK quantum technologies to perform satellite to ground QKD and is due to launch after SpeQtre and will take advantage of flight heritage gained from the UK-Singapore mission. The Quantum Communications Hub mission partners include the University of Strathclyde, University of Bristol, Heriot-Watt University, University of York, and RAL Space.

Conclusion

Traditional space mission development has a high cost of entry and long development times that is unsuitable for most research groups and activities. Small satellite missions and NewSpace development approaches provide an alternative path that allows for a faster and iterative development cycle at a much lower cost [9]. This promotes more novel missions and technologies as risks can be spread out and managed in a sequential manner over several launches instead of a single large mission. CubeSats are ideal platforms to gain experience, knowledge, and national capability at a fraction of the cost of traditional space programmes. With the expanding capabilities of small satellite systems, mission scope and science aims of CubeSats have become increasingly ambitious. The knowledge and experience acquired from CubeSat missions are being applied to larger missions and in the development of advanced quantum technologies such as quantum memories that may be a key enabler of a future global quantum internet [10,11]. The smallsat efforts of Singapore, UK, and other countries indicate that CubeSats can be leveraged to catalyse and accelerate these areas, widening access to space, and catalysing innovation.

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