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Nanobob: A Cubesat Mission Concept For Quantum Communication Experiments In An Uplink Configuration

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ABSTRACT

We present a ground-to-space quantum key distribution (QKD) mission concept and the accompanying feasibility study for the development of the low earth orbit CubeSat payload. The quantum information is carried by single photons with the binary codes represented by polarization states of the photons. Distribution of entangled photons between the ground and the satellite can be used to certify the quantum nature of the link: a guarantee that no eavesdropping can take place. The versatile space segment is compatible with a multiple of QKD protocols, as well as quantum physics experiments.

Keywords: nanosatellite, CubeSat, uplink, QKD, entanglement, cryptography, quantum, network

1. INTRODUCTION

Quantum Key Distribution (QKD), that is, the quantum secure exchange of a secret key between two parties usually identified as Alice and Bob, provides a level of communication security that cannot be obtained by classical cryptographic means, including those based on numerical algorithms. The quantum information can be coded into the polarization state of a single photon. In a properly designed experiment, an eavesdropping attempt by a third party (commonly called “Eve” in the language of cryptography), would necessarily lead to detectable errors, since the no-cloning theorem states that an arbitrary unknown quantum state cannot be copied perfectly [1]. Given our ever-growing reliance on secure data communication, the intrinsic security of quantum communication largely outweighs the disadvantages of additional complexity and cost. QKD has already been demonstrated to be a practical way to distribute secret keys between two parties in a number of fiber networks (see, e.g., [2] and references therein). However, fiber losses limit the maximum distance between two parties to a few hundred kilometers, as the no-cloning theorem prohibits the use of simple optical amplifiers. Much progress has been made in the development of quantum repeaters using entanglement swapping over subsections of the overall distance, but this remains a technologically extremely challenging solution [3]. Free-space links on Earth are ultimately limited to about the same distance of ~200 km by Earth’s curvature. For the foreseeable future therefore, exchanging secret keys on a global scale requires the use of trusted relay nodes. Satellites are the best option to limit the number of trusted nodes by using a scheme first proposed in

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The CSUG NanoBob Team is composed of the following engineers, students, and educators who all contributed at different stages to the current study: Yves Gilot (STMicroelectronics), Juana Rodrigo (Rolls Royce), Thierry Sequies (UGA), Vincent Borne (UGA), Jean-Yves Burlet (UGA), Alexis Christidis (UGA), Jesus Segura (UGA), Benoit Boulanger (UGA), Veronique Boutou (UGA), Mylene Bouzat (Air Liquide), Mathieu Chabanol (UGA), Laurent Fesquet (UGA), Hassen Fourati (UGA), Michel Moulin, Jean-Michel Niot (Air Liquide), Rodrigo Possamai Bastos (UGA), Bogdan Robu (UGA), Etienne Rolland (UGA), and Sylvain Toru (UGA).

[4] and recently demonstrated between Chinese and Austrian optical ground stations (OGSs) using the Micius satellite as a trusted relay [5]. In principle a single satellite suffices to bridge global distances. In this scheme, the satellite exchanges different secure keys with different OGSs. Performing bitwise XOR operations on the key, the different OGSs can exchange secure keys between them, with the satellite acting as a trusted node (see Fig. 1).

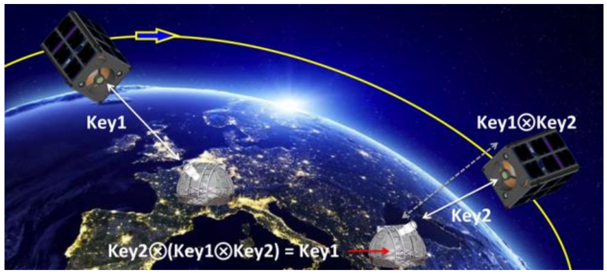

Figure 1. Global QKD using a trusted node satellite.

2. THE NANOBOB INFRASTRUCTURE

NanoBob will demonstrate optical quantum communication in free space between an OGS and a nanosatellite in an uplink configuration. By placing the entangled photon source (“Alice”) on the ground the space segment contains the “Bob” detection system only, and therefore consumes less power, becomes smaller and less complex, thus increasing its reliability. The space segment payload is also versatile: the receiver is compatible with multiple QKD protocols and other quantum physics experiments, such as for the investigation of entanglement decoherence in a gravitational potential (see [6]). To the best of our knowledge, NanoBob, having completed its Mission Definition Review following CNES/ESA guidelines [7], is so far the most advanced European project focusing on the use of entangled photons and a CubeSat platform [8]. It demonstrates the feasibility of miniaturizing the Bob receiver module, promising to significantly lower the development time and cost of future quantum space missions, and opens the way to using a constellation of relatively cheap satellites to achieve global coverage and low latency. NanoBob distinguishes itself by the use of a CubeSat receiver terminal that will be capable of executing most polarization-based single photon bi-partite protocols; most notably BB84 [8] and its more secure decoy-state variant [10], as well as the E91 protocol based on the Einstein-Podolsky-Rosen *gedanken experiment* [11]. Other secure quantum communication tasks such as secure password authentication can be performed using the NanoBob payload and bit-commitment protocols [12]. In order to enlarge the number of end-users that can use the same OGS, we envisage a synchronized quantum network in order to extend the geographical reach of the OGSs at the metropolitan scale. Quantum networks promise combining secure data exchanges via fiber and free-space optical quantum communication channels with efficient data computing nodes. Despite some encouraging results, a major obstacle towards the realization of operational quantum networks is represented by the lack of a universal synchronization protocol allowing the different remote building blocks to work together. We will address this synchronization issue by exploiting a universal, all-optical, and plug-and-play strategical approach that has been recently demonstrated [13]. The extreme simplicity of this solution renders its implementation feasible with current technologies, paving the way towards a universal, plug & play quantum fiber network synchronized to a free-space ground-to-satellite link.

3. FEASIBILITY STUDY

Here we report on the outcome of the aforementioned feasibility study. The NanoBob CubeSat will be launched in a Sun Synchronous Orbit (SSO) at a height of 550 km and a local hour of 22h30, in order to achieve a minimum time in orbit of 3 years and a de-orbit in less than 10 years while enabling the satellite to have a maximum of encounters with different OGSs in a variety of locations. We envisage using the ESA OGS at Tenerife as the primary OGSs, with secondary OGSs that include the MeO at the Observatoire de la Cote d’Azur and a new portable OGS developed at the IQOQI. For this, these OGSs will be equipped with a state-of-the-art entangled photon pair source and associated detection equipment, as well as beacon lasers for pointing and tracking, and classical communication.

Table 1. Results of a SWaP (Size, Weight (Mass), and Power) analysis, including contingency.

Item	Size (ml)	Mass (g)	Peak Power (mW)	TRL	Margin	Size Margin	Mass Margin	Power Margin
Payload	**5 045**	**2 680**	**14 500**			**1160**	**819**	**6850**
Quantum Optical Module (808 nm)	125	200	4 000	4	50%	63	100	2000
Beacon Receiver Module (1530 nm)	145	360	6 000	3	50%	73	180	3000
LCO-QKD	4 050	830	0	4	20%	810	166	0
Beacon Transmitter Module (1565 nm)	200	350	1 500	2	50%	100	175	750
Retro-reflector	125	340	0	7	20%	25	68	0
Detector cooling	100	300	0	2	20%	20	60	0
Time Tagging Module	100	100	2 000	2	50%	50	50	1000
Beacon Signal Processing	100	100	500	7	10%	10	10	50
Data storage	100	100	500	7	10%	10	10	50
Platform	**5 425**	**5 148**	**12 060**			**403**	**443**	**617**
OBC	110	94	500	9	5%	6	5	25
ADCS	750	1 225	2 470	9	5%	38	61	124
GPS	35	24	1 200	9	5%	2	1	60
UHF/VHF module	110	75	4 000	9	5%	6	4	200
S-Band module	130	62	3 800	9	5%	7	3	190
Antennas	110	128	0	9	5%	6	6	0
PMU & batteries	680	840	90	9	20%	136	168	18
Mechanical structure	3 000	2 000	0	9	5%	150	100	0
Detector radiators	200	400	0	5	20%	40	80	0
Solar panels	300	300	0	9	5%	15	15	0
TOTAL PAYLOAD & PLATFORM	**10 470**	**7 828**	**26 560**			**1563**	**1262**	**7467**

A Size, Weight (mass) and Power (SWaP) analysis, including a conservative contingency, yields an estimated volume of 12 L, mass of 9 kg, and peak power consumption of 34 W. This is well within the limits imposed by the 12U CubeSat standard form factor [14].

In a typical encounter between satellite and one OGS the satellite will adapt its attitude just before arriving above the horizon, aiming its receiver telescope towards the OGS. During this pre-acquisition flight segment, pointing of the satellite relies on satellite ephemeris and star tracker data. A second control loop will be implemented using the beacon laser signals to fine-tune the attitude, both about the two axes perpendicular to the line of sight (using the quadrant signal) and about the line of sight (using the linear polarization of the beacon laser; alternatively, the polarization direction of the quantum channel is adjusted in the OGS using ephemeris data of the satellite). Once the satellite and OGS telescope are tracking each other, the exchange of a quantum key can commence.

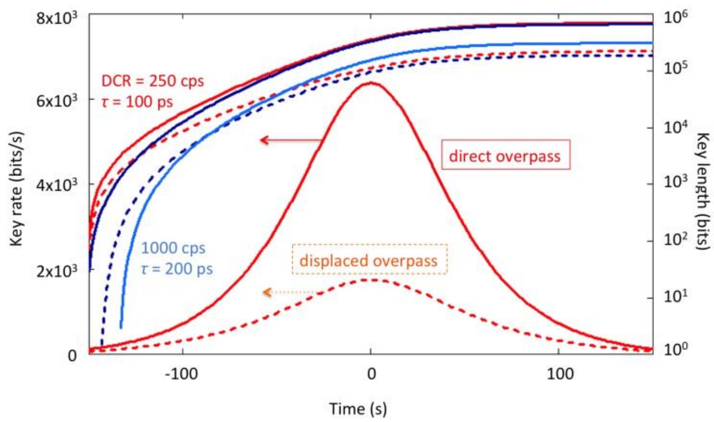

Figure 2. Secure key production during one overpass. The bell curves show the secure key rate (left axis), while the secure key length is given on the right y-axis, both for two scenarios: The solid curves are for a direct overpass, the dashed curves for a pass at a horizontal distance of 500 km. t=0 s corresponds to the distance of closest approach. The red curves correspond to a dark count rate per detector of 250 cps, the dark blue curves are for 1000 cps. In all cases the coincidence time window (normally dominated by detector jitter) equals 100 ps, except for the light blue curve, which gives the secure key length in a worst case secenario of dark counts equal to 1000 cps and a coincidence time window equal to 200 ps. For the simulation we assumed that the source generates $3 \cdot 10^8$ pairs/s, a conservative estimate of the new source performance. The link attenuations was calculated for atmospheric conditions characterized by r_0 = 20 cm, typical of the ESA OGS in Tenerife. All other conditions are as in [8].

During the next roughly three minutes the satellite detects and times the arrival of single photons that are collected by its telescope and analyzes their polarization state. The satellite opens an authenticated public communication channel (either optical or RF, with the same or another ground station) and sends the photon arrival times and the basis in which each photon was detected to the ground station. The latter then proceeds with clock synchronization by performing a cross-correlation operation on the time series of photon detection times, comparing it to its own time series of photon detection events [15]. This procedure reduces the coincidence time window to roughly hundred picoseconds, ultimately limited by detector jitter. A small coincidence time window reduces accidental coincidences due to detector dark counts and residual background counts. Finally, the ground station and satellite carry out the basis reconciliation, error correction, and privacy amplification steps to produce the quantum secure key shared by the OGS and the satellite. Figure 2 shows the results of a simulation of the rate at which such a key can be constructed for two different ground track scenarios and different assumptions as to the detector dark count rate and coincidence time window. The secure key rate is such that per encounter keys can be constructed with a length exceeding 100 kbits.

4. SATELLITE SUBSYSTEMS

Where possible standard or commercial-of-the-shelf components will be used to build the 12U CubeSat (Fig. 3). This is true for the satellite platform (bus), on-board computer, and power and telemetry systems.

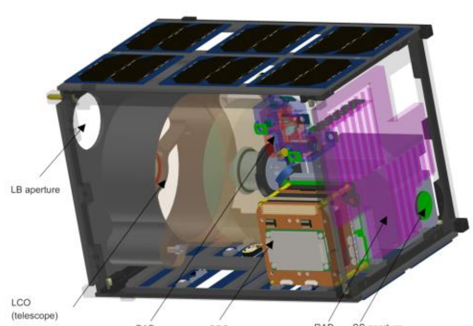

Figure 3. Schematic view of the main components of the light collection optics (LCO), polarization analysis and detection module (PAD), star tracker (SS), on-board computer (OBC), solar panels and the radiator (RAD) for passive detector cooling. Notably, the laser beacon (LB) with its telescope and the battery packs are not shown to provide an unobstructed view of the remainder.

A number of critical subsystems will be developed in-house or by partners. Of these we mention:

4.1 Optical Module

The optical module consists of a telescope with high light gathering power followed by the quantum channel polarization analyzer and a separate unit dedicated to detecting the ground-to-satellite beacon laser. It is complimented with a small diameter telescope that focuses the satellite beacon laser, as well as two corner cubes that retro-reflect the OGS beacon laser; part of the two-way laser beacon system discussed in section 4.4. The main telescope maximizes the number of photons captured from the photon stream directed towards the satellite by the OGS and is polarization neutral: the spread in polarization of beams taking different paths through the telescope is less than 1°. A Cassegrain telescope was designed with an opening aperture of 150 mm diameter and an overall length of just 125 mm with a Field Of View (FOV) of the quantum channel's detectors (100-µm diameter) equal to 215 µrad (45 arcsec; corresponding to a circular footprint of 120 m diameter with the satellite at an orbital height of 550 km). Knowledge of the spectral radiance of the area of the OGS then enables one to calculate the expected background count rate. A previous study measured a photon flux of 10^{10} to $2.5 \cdot 10^{11}$ $s^{-1}sr^{-1}m^{-2}$ at the Canary Islands with a spectral band pass filter of 10 nm centered at 810 nm, depending on the moon phase [16]. Consequently, the estimated background count rate is always smaller than 400 cps (counts per second). The background can be further reduced using a narrower bandpass filter. The FOV of the beacon detector is 9 mrad. The compact telescope allows for the entire optics module to be shorter than 200 mm.

The polarization detection unit analyzes the photons captured by the light collection optics in either one of two bases. The random choice between either the horizontal-vertical (HV) or the diagonal-antidiagonal (DA) basis is made by a 50/50 beam splitter (BS) [17]. Following the BS a half-wave plate (HWP) oriented at 22.5° in one of the two paths is used to rotate the polarization direction by 45°. Polarizing beam splitters (PBS) in both paths then enable the polarization analysis. The probability of a photon ending up in the wrong path (e.g., a vertically polarized photon being detected by the "horizontal detector" instead of the "vertical detector") is not larger than 1%, as such a detection error (e_d) increases the coincidence error and therewith reduces the signal-to-noise ratio and visibility. Importantly, this error includes the possible misalignment of the OGS and satellite polarization bases.

All quantum communication protocols based on polarization encoding of the qubits require a shared reference frame between the transmitter (Alice) and receiver (Bob). The moving satellite and the moving mirrors of the transmitter telescope can potentially rotate the plane of polarization. This effect should be compensated by appropriate rotation of the polarization bases of the OGS or satellite [18]. If these bases would be misaligned by 4°, this would contribute 0.48% to the aforementioned polarization detection error. Two options are available: The first is to rotate the OGS polarization basis to adapt to the satellite orientation. A second option entails rotation of the satellite about its seeing axis using an error signal derived from analysis of the separately controlled linear polarization of the OGS beacon laser, combined with data from the satellite's star tracker. Both solutions avoid addition of moving parts (a rotatable HWP) to the satellite. We fully implement the first solution, but equip the satellite with the hardware required for the second option. The OGS laser beacon signal is used to improve absolute accuracy and to improve alignment precision to the 10-µrad level, beyond what would be possible using the star tracker only.

4.2 Time Tagging

The events detected by the Bob quantum receiver can be due to detector dark counts, background (stray) light, or the entangled photons sent by the OGS. Identification of the entangled photons is done by comparing their time of arrival at the NanoBob quantum receiver with the arrival times of the other photon of the entangled pair at the Alice detection unit at the OGS. Such identification through coincidence timing requires a high timing precision if large numbers of photons are involved. A better timing resolution will increase the signal-to-noise ratio by suppressing the number of background or dark counts being accidentally registered as an entangled photon event. With a source single photon generation rate of 100 Mcps, a timing resolution (coincidence time window) better than about 1 ns is required in order to reduce the probability of accidental coincidence to an acceptable minimum.

In order to time stamp the photon arrival a time-tagging module is used, both at the OGS [19] and on the CubeSat. An integrated space-qualified system will be specifically designed using a dedicated integrated circuit implementing time-to-digital conversion (TDC). A short-term stability of the TDC oscillator of 0.1 ppb (10^{-10}) is required, corresponding to a measurement precision of about 10 ps for an average time between photon arrivals that could be as long as roughly 100 ms (10 cps). This can be achieved using a miniature Cesium atomic clock. Long-term clock synchronization between

OGS and satellite is then achieved by the fore-mentioned time correlation technique applied repeatedly on data over intervals of approximately 100 ms [15, 19]. Implementing TDC with a time resolution < 25 ps and jitter < 10 ps in integrated circuitry is challenging but can be done in standard field programmable gated arrays (FPGAs). The combined contribution to the coincidence time window of the detector and electronics jitter on the space segment, and those of a state-of-the-art OGS [19], is about 100 ps.

4.3 Single Photon Detection

At the current state of technology, only Silicon-based Avalanche Photo Diodes (Si-APD) in the 800-nm range combine a sufficiently high photon detection efficiency (PDE) and low jitter with a low dark count rate (DCR). Si-APDs have been operated and characterized in space or under space radiation conditions. This has shown the need for special measures to keep the DCR below acceptable levels, especially after longer times in a space environment [20, 21, 22]. To our knowledge, no similar space heritage exists for SPDs based on Indium Gallium Arsenide, let alone Mercury Cadmium Telluride. The NanoBob quantum channel will use red-enhanced Si-APDs with an improved sensitivity towards 800 nm (PDE = 40%), low reverse voltage (50 V), small jitter (90 ps), and low DCR [23]. Additionally, the specified DCR of 25 cps was demonstrated at a temperature of -5 °C, much higher than the -30 °C targeted in our system. A passive detector cooling scheme was designed to stabilize the detector temperature to within 1 °C of the set point.

4.4 Pointing, Acquisition, and Tracking

The current demonstrated state-of-the-art in terms of attitude determination and control appears to be held by the XACT family of Acquisition Determination and Control Systems manufactured by Blue Canyon Technologies [24]. Their XACT-15 module has space heritage on two 3U CubeSat spacecraft [25, 26]. It has demonstrated to exceed its specifications of a pointing accuracy < 50 µrad (11 arcsec) and a pointing knowledge < 30 µrad (6 arcsec) (both 1-sigma) for the two cross-star tracker-bore sight axes. The pointing accuracy about the bore axis is specified to be < 120 µrad (25 arcsec). Furthermore, the dynamic tracking error (1-sigma) of the XACT unit as a function of the slewing rate for the two cross axes is largely unaffected for slewing rates < 1°/s. Even the dynamic tracking error about the bore sight axis does not exceed 480 µrad (100 arcsec), which is still well within our requirements. The Blue Canyon XACT-50, which is identical to the XACT-15 except for its larger 50 mNms reaction wheels, is capable of a slewing rate of at least 1 °/s in any axis, as long as the moment of inertia in the slewing axes is below 2.8 kgm^2 [27]. The moments of inertia of the NanoBob satellite are about one-twentieth of this value.

At a satellite altitude of 550 km it takes the beacon laser photons at least 1.83 ms to arrive at the satellite. To compensate the OGS telescope will need to point ahead by several tens of µrad. This has no major consequence for the reception of the satellite's beacon signal considering the relatively large FOV of the beacon receiver (the unvignetted FOV of the Coudé system of the ESA OGS equals 2.4 mrad). Knowledge of the attitude (orientation) of the satellite is typically limited to about 50 µrad by star tracker performance. While this is almost an order of magnitude smaller than the satellite's quantum channel FOV, this may not be sufficient for accurate pointing due to ephemeris uncertainty that limits the ability to accurately transfer the attitude knowledge in the inertial frame to the Earth-fixed frame. On the other hand, the OGS requires accurate knowledge of the satellite position in the Earth-fixed frame in order to accurately track the satellite. For the same reason as before, data from the star tracker may not be precise enough. The positioning error of a Commercial-Of-The-Shelf (COTS) GPS receiver can be as large as 10 m [28]. To provide an additional, and more accurate way to align both the OGS telescope and satellite receiver we will implement a two-way beacon (guide star) system, allowing for relatively fast closed-loop control of the satellite attitude, as well as satellite tracking by the OGS telescope. The initial choice of wavelength for the beacon lasers is in the NIR C-band around 1550 nm as here efficient lasers and detectors are easily available and the atmospheric transmission is high. Moreover, the wavelength is retina-safe, and directly compatible with existing telecommunication hardware and infrastructure.

5. CONCLUSIONS

We have presented the results of a feasibility study that shows that quantum key distribution is feasible between an optical ground station equipped with an entangled photon source and a 12U CubeSat in an uplink configuration. Using the satellite as a trusted relay station, information theoretically secure keys can be exchanged between OGSs on a global scale. Taking into account the year-round atmospheric conditions at the Tenerife El Teide observatory [19] and the satellite's orbit, we can expect to generate roughly $2\ 10^7$ secure bits per year with a single CubeSat. The combined production and launch cost of a single satellite is approximately 1.5 M€, or 40 €/kbit if the satellite remains operational for two years. A synchronized quantum network using a recently developed scheme can extend the quantum secure link at the metropolitan scale around each OGS [13].

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