Quantum Photonics Technologies for Space

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Table of contents

A photonic integrated quantum random number generator employable on a CubeSat

Ömer Bayraktar * [1,2], Jonas Pudelko [3,4], Imran Khan [1,2], Gerd Leuchs [1,2], Christoph Marquardt [1,2]

[1] Max Planck Institute for the Science of Light (MPL) – Staudtstr. 2, 91058 Erlangen, Germany
[2] Institute of Optics, Information and Photonics, Friedrich-Alexander University Erlangen-Nürnberg (FAU) – Staudtstr. 7/B2, 91058 Erlangen, Germany
[3] Max-Planck-Institute for the Science of Light – Germany
[4] Institute of Optics, Information and Photonics, Friedrich-Alexander University Erlangen-Nürnberg – Germany

Using a CubeSat as a platform to test new technologies enables rapid development cycles, however, it also poses stringent demands on size, weight and power (SWaP) of the carried payloads. We present the development of a photonic integrated quantum random number generator (QRNG) to be operated on a CubeSat and address the challenges. These advances will increase the technology readiness level (TRL) of the photonic integrated QRNG and pave the way for its employment in space environments, e.g. for use in satellite quantum key distribution.

*Speaker

Wide-angle receiver for long-distance free-space quantum key distribution

Ross Donaldson * [1], Aurora Maccarone [1], Buller Gerald [1], Alessandro Fedrizzi [1]

[1] Heriot-Watt University [Edinburgh] – United Kingdom

Creating a global quantum network has many challenges and may rely on both free-space and in-fibre solutions for its creation. Inherent losses in fibre-optic cables and limitations with current quantum repeater/amplifier technology mean we cannot rely on fibre-optic for long-haul applications. However short transmission networks are still feasible and have been demonstrated. Implementing free-space channels which utilise high-altitude platforms or satellite trusted nodes in orbit is seen as the fastest route to achieving long-haul capabilities. Research initiatives around the globe are already performing proof-of-principle studies and field testing components for satellite-based quantum communications.
As coherent light propagates through the turbulent atmosphere, effects such as wavefront distortion and intensity fluctuation can lead to errors in pointing-and-tracking during the quantum key sharing. The resultant errors can greatly increase the quantum-bit error rate for time-bin quantum key distribution protocols. This is due to the reduction in interferometric visibility with the changing angle-of-incidence as the beam walks. For time-bin quantum key distribution protocols to be considered for use in free-space quantum key distribution, the effects of turbulent atmosphere need to be negated.
Here we will present an overview of a project funded by the UK Quantum Communications Hub. This project investigated the implementation of a time-bin optical receiver and novel single-photon avalanche diode (SPAD) spatial array technology. The receiver was designed to give high performance in the event of multimode free-space channels and pointing-and-tracking errors. The implementation of the SPAD array was proposed to enable us to simultaneously measure quantum bit information and the spatial position of the beam. The presentation will include the optical receiver concept design and a comparison of the performance of the receiver over a range of angles-of-incidence for single and multi-mode signals.

*Speaker

NANOBOB: Quantum Communication with a 12U CubeSat

Erik Kerstel * [1,2], Arnaud Gardelein [3], Mathieu Barthelemy [1,4], The CSUG Team [2†], Sébastien Tanzilli [5], Matthias Fink [6], Siddarth Koduru Joshi [7], Rupert Ursin [6]

[1] Univ. Grenoble Alpes, CNRS, LIPhy, 38000 Grenoble, France
[2] Centre Spatial Universitaire de Grenoble, 38000 Grenoble, France
[3] Air Liquide Advanced Technologies, Grenoble, France
[4] Univ. Grenoble Alpes, IPAG, 38000 Grenoble, France
[5] Univ. Côte d'Azur, CNRS, INPHYNI, Parc Valrose, 06108 Nice, France
[6] Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Vienna, Austria
[7] University of Bristol, Dept. of Electrical and Electronic Engineering, BS8 1UB United Kingdom

Quantum Key Distribution (QKD), i.e., the quantum secure exchange of secret keys 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. Quantum information can be coded into polarization states of single photons. In a properly designed experiment, an eavesdropping attempt by a third party ("Eve"), would necessarily lead to detectable errors, since the no-cloning theorem states that an arbitrary unknown quantum state cannot be copied perfectly. 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. However, losses limit the maximum distance between two parties to a few hundreds of km, as the no-cloning theorem prohibits the use of standard optical amplifiers. Much progress has been made in the development of quantum repeaters, but this remains an extremely challenging solution. For the foreseeable future, satellites are the only option enabling to go beyond the limits posed by fiber absorption or Earth's curvature for exchanging secret keys on a global scale. In this scheme, the satellite exchanges different secure keys with different optical ground stations (OGSs). Performing bitwise XOR operations on the keys [1,2], the different OGSs can be connected securely, with the satellite acting as a trusted node. NanoBob will demonstrate optical quantum communication in free space between an OGS and a nanosatellite in an uplink configuration. Placing the entangled photon source ("Alice") on the ground, the space segment contains Bob's detection system only: less power consuming, smaller and less complex, thus

*Speaker

†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), Etienne LeCoarer (UGA), Juana Rodrigo (Rolls Royce), Thierry Sequies (UGA), Vincent Borne (UGA), Guillaume Bourdarot (UGA), Jean-Yves Burlet (UGA), Alexis Christidis (UGA), Jesus Segura (UGA), Benoit Boulanger (UGA), Véronique Boutou (UGA), Mylène 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).

increased reliability. The space segment payload is also versatile: the receiver is compatible with multiple QKD protocols and other quantum physics experiments, such as investigating entanglement decoherence in a gravitational potential. To our knowledge, NanoBob, having completed its Mission Definition Review following CNES/ESA guidelines, is so far the most advanced European project focusing on the use of entangled photons and a CubeSat platform [3]. In order to extend the geographical reach of the OGSs at the metropolitan scale and the number of end-users that can exploit the same OGS we will design a synchronized quantum network, thus demonstrating a complete infrastructure for global and metropolitan scale QKD. 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 while enabling the satellite to have a maximum of encounters with different OGSs in a variety of locations. A Size, Mass and Power analysis has shown that the payload is compatible with the 12U CubeSat standard form factor [4]. Using conservative estimates of the relevant experimental parameters we have performed a detailed analysis of the typical encounter between satellite and OGS and the associated atmospheric attenuation. This in turn enables the calculation of the rate at which secure keys can be constructed (Fig. 2). With expected rates well over 100 kbits per encounter we can estimate that with current technology a single CubeSat can already distribute secure keys globally at a price level below 100 €/kbit.

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Satellite Laser Ranging in Graz - an overview

Georg Kirchner * [1], Franz Koidl [1], Michael Steindorfer [1], Peyjuan Wang [1]

[1] Space Research Institute, Department Satellite Geodesy, Austrian Academy of Science, Lustbuehelstrasse 46, A-8042 Graz, Austria

The SLR station Graz is ranging routinely to ¿ 150 satellites from LEO to GEO, using a 2 kHz laser, and achieving singel-shot accuracies of 2-3 mm; Normal-Point accuracy is ¡ 1 mm. In addition, since 2012 we have started to develop hardware, software and methods to range also to - uncooperative, i.e. without retroreflectors - space debris targets. We are also determining spin parameters of targets, using the kHz laser and - simultaneously -l also single-photon sensitive light curve recording systems. In 2017, we successfully tracked the Chinese satellite Micius, performing QKD from space to ground.

*Speaker

Turbulent phenomena in free-space quantum communication channels: theoretical models and laboratory study

Konstantin Kravtsov * [1,2], Artyom Zhutov [1], Igor Radchenko [2], Sergei Kulik [1]

[1] Quantum Technology Centre of Moscow State University – Russia
[2] A.M. Prokhorov General Physics Institute RAS – Russia

Atmospheric turbulence is the main limitation on the performance of free-space communication channels in air. As satellite-to-ground quantum state exchange relies heavily on such channels, it is important to understand these limits and be able to predict them. In this work we demonstrate a universal framework that allows to calculate channel properties based on the parameters of the turbulence, especially when approaching single mode channel performance or utilizing spatial mode multiplexing.
Turbulent effects in free-space optical communications were extensively studied in the 1970s, but found solutions mainly apply to the limit of large channel loss (~10 dB and more). At the same time, development of quantum technologies in space requires low-loss communication channels whose performance approaches the single-mode limit. Moreover, high dimensional quantum state exchange may rely on the preservation of the spatial modal structure. Both options face severe obstructions due to the atmospheric turbulence, and the present study is aimed at learning the performance in these novel arrangements.
We will show how the atmosphere distorts propagating signals and will provide simple analytical relations for the resulting probability density functions of the channel transmission. We also provide a framework that allows to obtain much more precise performance characteristics via numerical integration in various channel configurations. Finally, we demonstrate experimental tools that may be used for modeling atmospheric channels in the lab for preliminary device testing before performing actual field trials.

*Speaker

Detection of single photon quantum interference modifications caused by space-time curvature

Piergiovanni Magnani * [1], Francesco Vedovato [2], Matteo Schiavon [2], Daniele Dequal [2], Giuseppe Vallone [2], Paolo Villoresi [2]

[1] Politecnico di Milano – Italy
[2] University of Padova – Italy

Single photon quantum interference, a phenomenon occurring in non classical light, is modulated by phase differences arising between superimposed quantum states undergoing alternative paths. The resulting phase differences can be generated, among other causes, by photons frequency variations occurring at the different parts of the 'optical circuit'.
A photon propagating in a curved space-time (typically over long distances) is perceived/measured by different observers to be at different frequencies primarily due to:

- velocities of the observers causing primary (classical like) Doppler effects;
- 'red/blue-shift' type effects caused by General Relativistic time dilation (metric coefficients depending on gravitational potentials-mass distribution);
- Time dilation associated to 'Special Relativistic like signature' of the fundamental tensor (of general form 1-v2/c2 and typical of pseudo-Euclidean space)
- 'bending' of photon trajectory (null geodesic of the curved of space-time);

All effects are in general superimposed and mixed and of much different orders of magnitude. The space-time metric considered is the Schwarzschild one which, in Schwarzschild coordinates, assume a diagonal form. Other effects like 'frame dragging', caused by the off-diagonal terms of the fundamental tensor present in General Relativistic Kerr like metric (obtained when Einstein equations are solved considering a 'spinning' earth) are not considered since extremely small.

Experiments involving propagation of photons over long distances between Ground Station and Space platform can be devised to detect/verify the effects caused by space-time curvature. These experiments are sometimes named 'optical COW' since they assess phase modifications utilizing photons rather than particles (neutron) like initially used in the COW experiment.

The definition of such an 'optical COW' experimental configuration would require a careful assessment of the expected nominal performances, sensitivity to the possible disturbing parameters and technological feasibility in general. Furthermore due to the very large scale variation

*Speaker

among the various effects an accurate compensation/nulling of the largest and less interesting one (i.e. primary classical Doppler effect contribution) need be done.

The proposed paper discusses some experimental configuration based on Space Platform and Ground station aiming at the detection of relativistic related photon quantum interference modifications with a first coarse indication of expected performances.

Quantum Research CubeSat (QUARC)

Luca Mazzarella * [1], Lowe Christopher [2], David Lowndes [3], Steve Greenland [4], Steve Owens [2], Hina Khan [2], Malcolm Macdonald [2], John Rarity [3], Daniel Oi [1]

[1] University of Strathclyde – United Kingdom
[2] Scottish Centre of Excellence in Satellite Applications – United Kingdom
[3] University of Bristol – United Kingdom
[4] Craft Prospect LTD – United Kingdom

The Quantum Research CubeSat (QUARC) is a proposal to offer secure quantum key distribution (QKD) communication from a 6U nanosatellite platform. Due to the relatively low cost for CubeSats compared to traditional, large satellite platforms, the scope to deploy a large number of platforms and offer greater coverage, would mitigate some of the risk associated with poor performance due to cloud cover. In this work, we present the results of our analysis in terms of key provision and the results of a preliminary hardware development to support future in-orbit demonstration.

*Speaker

Silicon detectors and CMOS smart sensors for space applications

Matteo Perenzoni [1] *

[1] Fondazione Bruno Kessler, via Sommarive 18, 38123 Trento, Italy

Detecting light with silicon sensors that are customized for the space application can add value and open new possibilities: in particular, specialized silicon detectors such as SDD (silicon-drift detectors), SiPM (silicon photomultipliers) and CMOS SPAD (single-photon avalanche diodes) with embedded smart electronics enable applications like x- and gamma-ray spectroscopy, and 3D flash lidar.

*Speaker

Efficient solid-state quantum light sources for free-space quantum networks

Niccolo Somaschi * [1]

[1] Quandela – Centre National de la Recherche Scientifique - CNRS, QUANDELA : ruede Paris - 91400 - Orsay - France – France

With quantum-key-distribution (QKD) technologies commercially available and currently successfully implemented in several cities around the world, space is well assumed as the unique route allowing for long distance quantum communication. Several ground-breaking results have been in fact achieved in the past years, proving the feasibility of free-space QKD by taking advantage of existing infrastructures and laser technologies.
For the development of quantum networks towards the realisation of a "quantum internet", which go beyond point-to-point QKD protocols, new tools must be developed: quantum repeaters. Either by implementing "memory based" or "measurement based" quantum repeaters, the quantum information is generated in a node as a stream of entangled photons which are redistributed over several terminals, all sharing entanglement with the initial node. As such, one will require highly pure states of quantum light, generated by true emitters of single-photons, that standard laser technologies cannot provide efficiently even with the use of well-known non-linear processes (example spontaneous-parametric-down-conversion, i.e. SPDC).

Quandela fabricates and commercializes efficient sources of pure single-photons based on a fully integrated technology developed at the "Centre of Nanosciences and Nanotechnologies" (CNRS/UPSud) in the group of Prof. Pascale Senellart. By placing a single semiconductor quantum-dot in an optical cavity in a fully controlled way, we obtain single-photon sources with single-photon purity and indistinguishability over 95%, and brightness exceeding by a factor 20 the one of currently used sources based on SPDC [1-2]. Such performances allow for the implementation of several protocols for the efficient generation of large clusters of entangled photons for ground-to-space quantum communication and vice-versa.
In this talk I will give a brief overview about the technology at the core of Quandela and discuss how these devices can be used as building-blocks for the realisation of free-space quantum networks.

*Speaker

Integrated quantum photonics for manipulation of photonic quantum states

Nicolo Spagnolo * [1]

[1] Dipartimento di Fisica, Sapienza Università di Roma piazzale Aldo Moro 5, 00185 Rome, Italy

Photonic technologies represent one of the most promising platforms for the implementation of quantum information protocols, such as quantum communication, simulation and sensing. Recent results have shown the possibility of significantly increase the complexity of the implemented photonic systems in the quantum domain by using an integrated photonic approach.We will present recent advancements in integrated quantum photonics. We will show the capability to integrate different optical elements for passive and active manipulation of photonic quantum states, and to perform quantum experiments within such platform.

*Speaker

Quantum Communications and Fundamental Physics in Space

Giuseppe Vallone [1,2] *

[1] Dipartimento di Ingegneria de l'Informazione [Padova] (DEI) – Department of Information Engineering Via Gradenigo, 6/B 35131- Padova Italy, Italy
[2] Istituto di Fotonica e Nanotecnologie (IFN) – via Trasea 7, 35131 Padova, Italy

We here review our results on satellite quantum communications, by exploiting different degrees of freedom of the photon, such as polarization or time-bin. We also present our recent realization of the Wheeler's delayed-choice Gedankenexperiment along a space channel. Our results extend the validity of wave-particle duality at the spatial scale of LEO satellites. We also describe how to implement other fundamental tests of quantum mechanics in Space.

*Speaker

Feasibility study of satellite continuous-variable QKD

Luis Trigo Vidarte [1,2], Víctor Román Rodríguez * , Daniele Dequal [3], Eleni Diamanti [2], Anthony Leverrier [4], Paolo Villoresi [5,6], Giuseppe Vallone [5,6]

[1] Institut d'Optique Graduate School – Institut d'Optique Graduate School (IOGS) – Palaiseau, France
[2] LIP6 UPMC – Université Pierre et Marie Curie - Paris 6 – 4 place Jussieu 75005 Paris, France
[3] Agenzia Spaziale Italiana ((ASI)) – Italy
[4] Inria de Paris – Institut National de Recherche en Informatique et en Automatique – 2 rue Simone Iff -CS 42112 -75589 Paris Cedex 12, France
[5] Dipartimento di Ingegneria de l'Informazione [Padova] (DEI) – Department of Information Engineering Via Gradenigo, 6/B 35131- Padova Italy, Italy
[6] Istituto di Fotonica e Nanotecnologie (IFN) – via Trasea 7, 35131 Padova, Italy

Achievable distance remains one of the main limitations for the practical deployment of quantum key distribution (QKD) systems. Quantum repeaters will provide a flexible solution for this problem in the future, but for the moment the performance of these systems is well below the requirements of practical QKD scenarios. One alternative is to extend the range using trusted nodes, but this would require a network of nodes that is perhaps not flexible or scalable. In the short term, satellite communications is the most promising technology to extend QKD
over intercontinental distances. A decoy-state QKD protocol link of 1200 km has been recently achieved using a low Earth orbit (LEO) satellite [1] proving the feasibility of this approach, but many challenges remain to be solved before QKD over satellite becomes a commercial reality, cost reduction being one of the most important. In this work we perform a feasibility study of a satellite-to-ground link implementing continuous-variable (CV) QKD [2] taking into account the different parameters involved such a communication link (beam wandering, pointing accuracy, turbulence, orbit, telescopes...). Particular attention is put in the possibility of using telecommunication wavelength at 1550 nm and a system that does not require to transmit the phase reference (or local oscillator) typically used in CV-QKD through the channel. The altitude of the satellite and the optics involved determine the average attenuation of the channel: the downlink LEO configuration (where the sender-Alice is placed on the satellite and the receiver-Bob on the ground) is the one providing best performance in terms of instantaneous key rates, but the time of passage in this case is relatively short so alternative orbits are also studied (e.g.: GNSS, GEO) since they can provide other advantages at the expense of key rate. Furthermore, we study the uplink case since in some cases this configuration may be preferable. One of the main differences between a free-space and a fibre link is the variation of the channel transmittance (T) with time. This is a key parameter in the estimation of the excess noise in CV-QKD, hence it is crucial to have a good estimation of its value. For this, a strong classical reference signal has to be sent in order to enable the transmittance estimation. This allows the classification (binning) of symbols into intervals of T; the CV-QKD protocol can then be applied to the symbols in each interval. Since there will be some uncertainty in that classification, the effect

*Speaker

of this variance is also considered in the final key rate. As the number of available symbols per satellite pass is limited, a trade-off between the size of the interval and the number of symbols in each interval has to be achieved. The experimental realization of a complete satellite system involves very expensive processes like rocket launching and mission control, so it is convenient to have a simpler device that can emulate the same effects at a fraction of the cost. We propose a hardware channel emulator that can be used to mimic the different effects that can appear over a free space satellite channel. The implementation is done using commercial fibre and free space components that can be placed between Alice and Bob. The feasibility analysis that we provide gives an estimation of the expected key rate under different conditions corresponding to currently achievable ground-to-satellite links. The channel emulator under study will then provide a practical way to evaluate in practice the performance of different configurations for Alice and Bob before a deployment in orbit.

Modelling trusted node QKD satellite constellations

Tom Vergoossen * [1], Sergio Loarte [2], Robert Bedington [1], Ling Alexander [1,3]

[1] Centre for Quantum Technologies, National University of Singapore – Singapore
[2] Department of Space Engineering, Delft University of Technology – Netherlands
[3] Department of Physics, National University of Singapore – Singapore

A single trusted node QKD satellite in a polar orbit can allow secure keys to be shared between any two ground stations when the satellite flies over. Such flyover occasions for any specific location are limited however, particularly over equatorial regions. Cloud cover and daylight further constrain the opportunities when QKD can be performed. The nearest term implementation of a large scale global QKD network with many optical ground stations will therefore require constellations of QKD capable satellites.

Based on work published by IQC we have developed Matlab models of free-space QKD links and we have combined these with the AGI STK software package to model satellite-to-ground and inter-satellite QKD for various constellation and ground station combinations. The satellites are modelled as trusted nodes with comparable specifications to the Chinese Micius satellite whose results were used to verify the Matlab model. The operational concept is that the satellites build up a buffer of secure key with every ground station they pass. At a later time, when two ground nodes wish to communicate securely, a symmetric key can be produced by performing an XOR on the buffered keys held within the satellites for the two ground nodes. These XOR keys are delivered classically via relay nodes in higher orbits (e.g. geostationary) to allow for secure communications with minimal latency. Inter-satellite QKD links are not required, but can be used to balance the stored keys between satellites and thus maximise the options available for XOR keys. Trade-offs of different constellation types, key usage patterns, and ground node arrangements will be discussed along with the latest satellite QKD developments from CQT.

*Speaker

Range Dependence of an Optical Pulse Position Modulation Link in the Presence of Background Noise

Wojciech Zwolinski * [1], Marcin Jarzyna [2], Konrad Banaszek [2]

[1] Faculty of Physics, University of Warsaw, – Poland
[2] Centre of New Technologies, University of Warsaw – Poland

We analyze the information efficiency of a deep-space optical communication link with background noise employing the pulse position modulation (PPM) format and a direct-detection receiver based on Geiger mode photon counting. The efficiency, quantified using Shannon mutual information, is optimized with respect to the PPM order under the constraint of a given average signal power in simple and complete decoding scenarios. We show that the use of complete decoding, which retrieves information from all combinations of detector photocounts occurring within one PPM frame, allows one to achieve information efficiency scaling as the inverse of the square of the distance, i.e. proportional to the received signal power. This represents a qualitative enhancement compared to simple decoding, which treats multiple photocounts within a single PPM frame as erasures and leads to inverse-quartic scaling with the distance. The optimal operating regime requires a careful adjustment of the PPM order to the system characteristics, growing as square of the covered distance. We provide easily computable formulas for the link performance in the limit of diminishing signal power. Typical order of improvement in information rate can be seen in Figure 1.

*Speaker

Time dilation in quantum systems for testing quantum and gravity interface

Magdalena Zych [1] *

[1] University of Queensland, Australia

Relativistic gravity is usually considered to be irrelevant in the regime where quantum effects play a role — experimentally probing this regime is still an open challenge. I will show that testing effects of gravitational time dilation in composite quantum systems is a worthwhile path towards experimental exploration of the quantum and gravity interface. For composite particles, time dilation generically leads to entanglement between external and internal degrees of freedom. Analogous effects arise also for photons due to the Shapiro delay. For sufficiently complex systems, time dilation leads to a decoherence mechanisms suppressing their centre of mass coherence. Even though time dilation due to weak gravity on Earth is small, the resulting effects can become measurable with nascent quantum technologies.

*Speaker

List of participants

- Bayraktar Ömer
- Bessire Bänz
- Bodenmann Dominik
- Diaz-Otero Francisco
- Donaldson Ross
- Kerstel Erik
- Kirchner Georg
- Kravtsov Konstantin
- Lauber Pierre
- Magnani Piergiovanni
- Mazzarella Luca
- Oi Daniel
- Perenzoni Matteo
- Roman Rodriguez Victor
- Schiavon Matteo
- Shaukat Muzzamal
- Somaschi Niccolo
- Spagnolo Nicolo'
- Stefanov André
- Vallone Giuseppe
- Vazquez-Castro Angeles
- Vergoossen Tom
- Wildfeuer Christoph
- Zbinden Hugo
- Zwolinski Wojciech
- Zych Magdalena