

An updated analysis of satellite quantum-key distribution missions

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Abstract

Quantum key distribution (QKD) is a cryptographic method enabling two parties to establish a private encryption key. The range of communication of ground-based QKD is limited to an order of 100km, due to in-fibre attenuations and atmospheric losses, and the development of quantum repeaters remains technologically challenging. While trusted-node links make communication over large distances possible, satellite-QKD is required for communication over global distances. By using satellites equipped with high-quality optical links, satellite-QKD can achieve ultra-long-distance quantum communication in the 1000-km range. The significant potential of satellite-QKD for the creation of global quantum networks thus makes it a particularly interesting field of research. In this analysis, we begin with an overview of the technical parameters of performing satellite-QKD, including infrastructure and protocols. We continue with a high-level summary of advancements in satellite-QKD by analysing past, present and proposed satellite-QKD missions and initiatives around the world. We conclude by discussing the technical challenges currently faced in satellite-QKD, which can be tackled through future research in this area.

Keywords: quantum, optical communications, QKD, satellite technology

I. Introduction

Quantum Key Distribution (QKD) is a scheme enabling two parties to derive a private and symmetric encryption key. QKD has the potential to significantly advance information security and encryption processes for mankind. The development of quantum computers represents an increasing threat to conventional public key distribution, driving research into new forms of “quantum-safe” encryption techniques [1-2]. QKD is a promising alternative to public key cryptography, providing unconditional security that cannot be obtained by classical cryptographic means as it is founded on the principles of quantum mechanics [3]. QKD is fundamentally based on the fact that quantum information is coded into the degrees of freedom (e.g. polarization states) of individual photons, which prevents successful attempts to measure and clone a quantum bit (in this case a photon). This is due to the fact that it is impossible to clone a quantum state without irreversibly altering its state (also known as the no-cloning theorem) [4], causing it to lose its information. Hence, attempts by third parties to eavesdrop will necessarily lead to detectable errors, making QKD highly secure and resistant to interference.

The general concept behind satellite-QKD is as follows. A trusted satellite conducts QKD with ground stations to establish independent secret keys with each station. To create a common key to be used by a pair of ground stations (for example stations A and B), the satellite broadcasts the bit-wise parity of each individual key, $K_A \oplus K_B$. Since K_A and K_B are independent strings known only to each station, their bit-wise parity does not reveal any useful information to eavesdroppers. Each station can obtain the other's key: For station A to obtain station B's key, it would determine the bit-wise parity of its own key with the broadcast ($K_A \oplus (K_A \oplus K_B) = K_B$). Similarly, station B can obtain station A's key through the operation $K_B \oplus (K_A \oplus K_B) = K_A$.

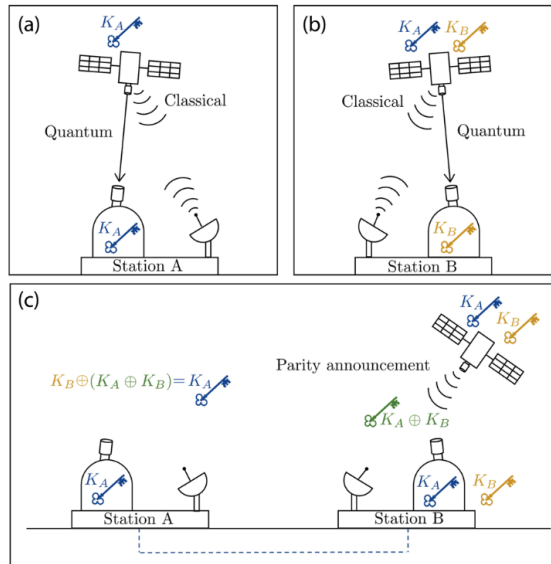


Fig. 1: Illustration of the most common satellite-QKD scheme: the flying trusted-node. In step (a), the satellite establishes a shared secret key K_A with station A by running a QKD protocol, which requires both classical and quantum communication. This step is repeated in (b) to establish a shared secret key K_B , this time with station B located further away. At the end of these steps, the satellite holds both keys, while each station knows only their own. Finally, in step (c), the satellite publicly announces the parity of both keys $K_A \oplus K_B$. This allows station B to determine key K_A , which can then be used to encrypt private communication to A and vice versa [101].

QKD has already been successfully used to distribute secret keys between two parties using fibre networks and free-space ground links [5-7]. Some attempts have even been successful in existing telecommunication infrastructure [8]. However, the main limitation of ground-based QKD is that the maximum communication distance is limited to an order of $\sim 100\text{km}$ [5-7] due to various reasons including atmospheric losses, noise of available single photon detectors, and in-fibre attenuations [9]. Free-space, Earth-bound links are also restricted by the Earth's curvature and atmospheric turbulence [10]. Research has been conducted to develop quantum repeaters (devices that extend the range of quantum communication between sender and receiver) to overcome this problem [11]. However, the development of quantum repeaters remains technologically challenging, as it requires successful entanglement creation over the intermediate distances, as well as storage of the entanglement until entanglement has been established in the adjacent link [12].

There is a need to increase the range of quantum communication for a successful global quantum network to be created. In light of this, a possible solution to this problem is satellite-QKD. Due to low absorption and negligible nonbirefractive character of the atmosphere, optical free space links are superior to fibre links and free-space ground links in achieving ultra-long-distance quantum communication. Hence, optical free space links are currently the most promising channel for large-scale quantum communication by use of satellites and ground stations [13-15]. The usage of a satellite terminal in space makes it possible to develop quantum communication networks on a global scale. Significant experimental efforts have been devoted to investigating the feasibility of satellite-based quantum communications. With the development of new technologies, researchers have extended the communication distance of QKD, entanglement distribution, and quantum teleportation between fixed locations to **1000-km scale** [16], which makes satellite-QKD a very promising solution to the technological challenges mentioned earlier [17]. While there are several improvements to be made, satellite-QKD brings us closer to a global quantum network that enables the sharing of strong encryption keys between any two points on Earth.

This report provides an overview of the research and developments that have contributed to the realization of satellite-QKD. We begin by discussing the various technical parameters of performing satellite-based QKD regarding protocols and infrastructure. We continue with a timeline of the key milestones in the development of satellite-QKD, followed by a summary of globally completed and proposed quantum satellite missions, categorized by specific advancements thus far in satellite-QKD. We conclude by discussing the technical challenges faced and future directions to address these challenges.

II. Technical Parameters of Satellite-QKD

There are several technical parameters that characterise satellite communication links in satellite-QKD, which are expounded below.

a. Orbit Altitude

There are three main classes of satellite orbital altitudes: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO) (sometimes referred to as High Earth Orbit) [18]. LEO is situated from 180 to 2000 km in altitude, MEO is situated from 2,000 to 35,786 km in altitude, and GEO has an altitude of precisely 35,786 km. For past and current satellite-QKD applications, LEO is the most common option (see Section III.), however future projects might seek altitudes in the MEO or GEO range [19].

Due to the proximity of LEO satellites to the surface, losses due to beam diffraction are significantly reduced. However, there is a tradeoff in the high speed of the satellite relative to the Earth, compromising pointing accuracy during signal transmission and limited time period during which QKD can be performed. The converse is true for satellites of higher altitudes: While the satellite is moving more slowly than in LEO (in the case of MEO) or at rest relative to the ground (in the case of GEO) hence enabling QKD to be conducted continuously, much higher losses are experienced when performing QKD at significantly higher altitudes as free space losses increase quadratically with distance.

Polar LEO will pass ground stations at the poles with every orbit, whereas equatorial LEO do so on the equator [18]. Other orbital inclinations will result in less regular ground station passes, and the time of day of flyovers will vary unless the orbit is sun-synchronous. Satellites in GEO are located above the equator and closer to the horizon approaching the poles, disappearing below the horizon at 81° latitude. Hence, the optical link traverses a much larger amount of atmosphere and will suffer additional losses. To provide polar regions with near-constant satellite coverage, such locations might adopt less conventional orbit choices, such as the Molniya highly elliptical orbits [20].

b. Link Configuration

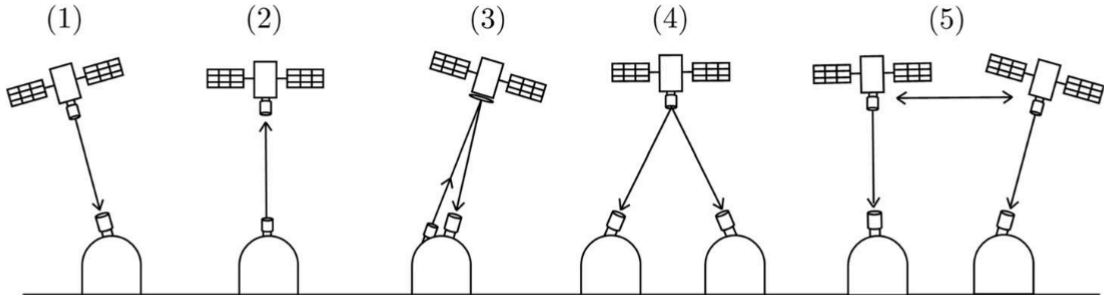


Fig. 2: Illustration of different platforms for performing satellite-QKD. Scenarios (1) and (2) depict a downlink and an uplink respectively, while in scenario (3) a downlink is simulated by using a retro-reflector on board the satellite. In (4) pairs of entangled photons are being transmitted to Earth so that two ground stations can share entangled states. Finally, scenario (5) illustrates how inter-satellite links can allow more complex satellite-QKD networks [101].

Quantum communication links with a satellite can be classified either as uplinks or downlinks. This results in several possible configurations for performing QKD with satellites depending on the types of links that are used [21-23].

In a downlink configuration (Scenario 1), the satellite sends signals to the ground. Downlinks are usually recommended for operational QKD, and the only type of link that has been demonstrated [24]. The primary source of optical losses is beam diffraction, which increases with the square of link length, and downlinks always have lower losses for any ground-satellite segment. This arises because atmospheric properties such as turbulence cause the optical beam to wander, which translates into a less accurate ground transmitter compared to a space-based transmitter.

In an uplink configuration (Scenario 2), the ground station sends signals to a receiver in space. The main advantage of using an uplink is that it is not necessary to locate a quantum light source in space, but only to place a receiver on board the satellites [25]. There is a lower photon detection rate on board the satellite and hence a significantly smaller amount of data to be stored and exchanged via a classical, authenticated but non-secure communication channel. It also makes attacks that target receivers significantly more difficult [26]. However, a disadvantage of using uplinks is a greater uplink loss of $\sim 10\text{dB}$ due to atmospheric turbulence, which is most significant in the first 20 km above the Earth's surface. These extra losses are significant when weighed against the advantages of locating quantum light sources on the ground. To overcome this challenge, signal-to-noise ratio filters can be used to discard data at high noise levels, reducing the number of photons required for error correction and privacy amplification [27].

Retro-reflectors on the satellite (Scenario 3) can also be used to create downlinks by modulating signals sent from the ground as they bounce off back to a receiver also on the ground [28]. The challenge here is to develop fast modulating retro-reflectors, and to develop countermeasures that prevent an eavesdropper from sampling the state of the retro-reflector while QKD is being carried out.

In a double downlink configuration (Scenario 4), a source of entangled photon pairs located in the satellite transmits photon pairs to the ground, with each photon in a pair being transmitted to each ground station in communication [29]. This configuration allows the realization of entanglement-based QKD directly between the ground stations, without using the satellite as a trusted node.

Inter-satellite links (Scenario 5) allow for communication between two satellites in the same orbit (intra-orbit links between satellites in LEO, MEO or GEO) or in different orbits (inter-orbit link) [30]. A combination of inter-layer and intra-layer links, called constellations of satellites (see Section IV.) can enable more complex satellite-QKD architectures by allowing each system to collaborate with other systems. This increases the quality of satellite services, decreases the unavailability of services and integrates different services in a single system [31].

c. DV-QKD or CV-QKD

QKD protocols can be divided into two categories: discrete-variable quantum key distribution (DV-QKD) or continuous-variable quantum key distribution (CV-QKD). In DV-QKD, information is encoded onto discrete degrees of freedom of optical signals. In CV-QKD, information is encoded in the quadratures of randomly selected coherent states and measured using either homodyne or heterodyne detection [32-33]. While most satellite QKD projects have chosen to implement discrete-variable schemes, significant research has been dedicated to both approaches leading to increasing key generation rates and improved compatibility with current communications infrastructure. However, both approaches are limited in that physical communication channels introduce transmission losses that increase exponentially with distance, greatly limiting the secure key rates that can be achieved over long ranges. There is also a need to reduce the reliance on classical communication between the two parties when establishing the final key [33-34].

d. Photon Sources

For DV-QKD, there are two main photon sources: weak coherent pulses (WCP) or polarization-entangled photon-pairs.

Short attenuated pulses from laser diodes provide controlled weak coherent pulses needed to provide photon states for DV-QKD to enhance the security of these systems. However, each pulse has a finite probability of containing more than a single photon [35-36]. Decoy-states have hence been created to reduce the likelihood of photon-number splitting attacks and thus detect eavesdropping. One party randomly chooses between two intensities of coherent state signals, which is revealed publicly to the other party after quantum communication, improving the tolerance to losses compared to the typical prepare-and-measure BB84 protocol that does not employ decoy-states. This increases the transmission distance and rate of key generation [37]. To address the need for active polarization manipulation, the usage of four laser diodes in a single transmitter [35] exploits the high degree of polarization of the diodes, allowing each diode to be identified with a unique polarization state. Using a single laser diode coupled to four waveguides, the side-channel accessible by potential eavesdroppers was closed. Each waveguide was capable of a fixed amount of polarization rotation and the signals were then recombined to result in a single-mode output with four possible polarization states.

Entanglement-based QKD schemes require the generation of photons using polarization entangled photon-pair sources. These sources are based on bulk-crystal, collinear, spontaneous parametric downconversion (SPDC), either periodically-poled potassium titanyl phosphate (PPKTP) or single-domain crystals such as beta barium oxide (BBO). SPDC is a non-linear optical process where a photon spontaneously splits into two other photons of lower energies [38]. In particular, Type II spontaneous parametric down-conversion produces photon pairs that emerge on two cones where the vertically polarized photon is on the upper cone and the horizontally polarized photon is on the lower cone [39]. A free-space link is then used to distribute one photon from the entangled pair to Alice, while the other is transmitted to Bob [39].

d. QKD Protocols

Several protocols exist to implement QKD between two parties, which can be subdivided into prepare-and-measure (decoy-state BB84) or entanglement-based protocols.

d(i). Prepare-and-measure protocol: Decoy-state BB84

Alice encodes each classical bit into the polarization state of an individual photon before transmitting it to Bob. Alice prepares the photon state by randomly choosing between the Z basis (horizontal, $|H\rangle$, or vertical, $|V\rangle$) and X basis ($\pm 45^\circ$ i.e. $\frac{1}{\sqrt{2}}|H\rangle \pm \frac{1}{\sqrt{2}}|V\rangle$), and assigning the states in each basis the values 0 or 1. After choosing the basis, Alice, using a true active random number generator, randomly selects one of the two states and sends it to Bob, who performs a set of measurements on the incoming signals to retrieve the classical data encoded in their states. Bob, using a passive random choice generator (e.g. beamsplitters), randomly selects one of the two bases and performs a measurement, recording the result as classical bits. This repeats for many signals, after which Alice and Bob announce the basis they have chosen for each measurement in the measurement set on a classical communication channel. They keep the measurements that they obtained using the same basis, and discard the measurements that they obtained using different bases. From the preserved signals, a random subset is selected to determine the relative error. In the situation of a sufficiently low error rate ($<11\%$), error-correcting codes and privacy amplification are applied to obtain the final shared secret key [40-43].

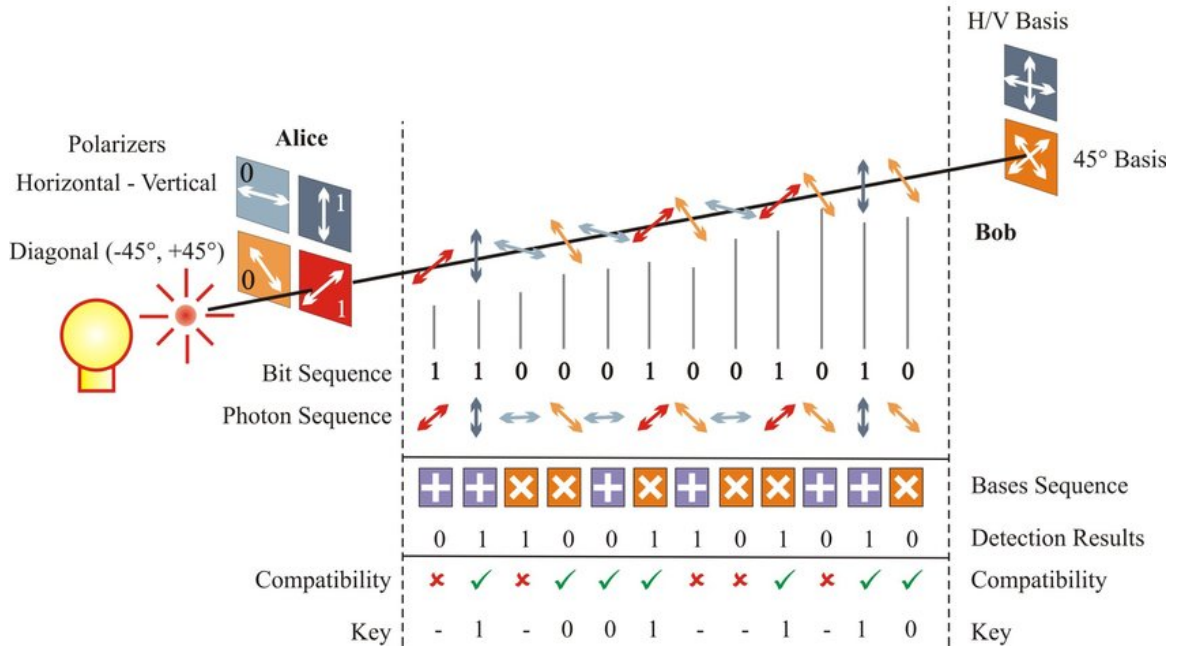


Fig. 3: Key exchange in BB84 Protocol implemented with polarization of photons [44]

d(ii). Entanglement-based protocols

A maximally entangled photon pair, usually in the polarization degree of freedom, is split such that one photon is transmitted to Alice, while the other is transmitted to Bob. The entangled states are perfectly correlated such that if Alice and Bob both measure their photons with the same basis, they will always get the same answer with 100% probability. Both parties make independent decisions to measure the photons in either the Z or X basis. Since eavesdropping inevitably affects the entanglement between the two photons in an entangled pair, it detectably reduces the degree of violation of Bell's inequality.

In the BBM92 protocol, parameter estimation, error correction, and privacy amplification occur in the same manner as in the BB84 protocol. The main advantage of the BBM92 protocol is that it removes the need for Alice to make an active random choice when encoding states into the photons, and the measurement devices for Alice and Bob are identical [45].

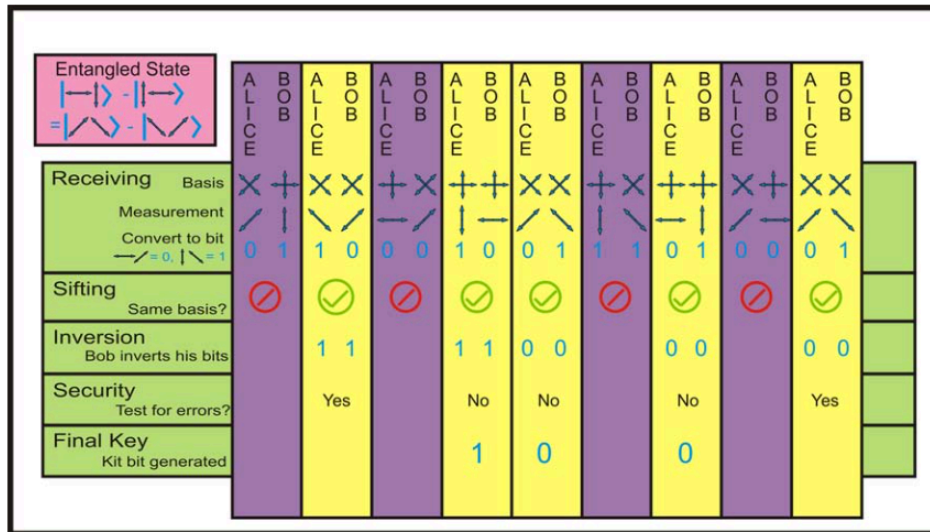


Fig. 4: Complete BBM92 Protocol. Alice and Bob each receive one photon from a stream of entangled photon pairs, they randomly pick a basis to measure each photon in, get a measurement result, convert their result to a classical bit, sift their results down to only those where they measured in the same basis, use 10% of their measurements to estimate the quantum bit error rate (QBER), and generate a final secure key from the rest of their measurement results [46].

Alternatively, the E91 protocol [47], through the Bell test, will determine whether the photon-pair correlations between Alice and Bob violate the Bell inequality, confirming the quantum nature of the link and hence its inherent security. After receiving each photon from an entangled pair, Alice and Bob measure the polarization state of every photon in a randomly chosen basis for each photon and note its arrival time. Using a noiseless, authenticated but non-secure public communication channel, Alice and Bob will compare the photon arrival times and the basis in which each photon was measured, preserving the measurements that were conducted using the same basis as the measurement set. By conducting the Bell test on this measurement set, should this correspond to the value expected from Bell's inequality, no local realism was introduced to the system and thus there were no eavesdroppers [48]. This protocol is resistant to eavesdropping as information is only obtained when Alice or Bob perform measurements and key sifting. Eavesdroppers also cannot inject their own data, as doing so would necessarily lead to detection

when the Bell's inequality value is too low [49]. After both Alice and Bob obtain the sifted key, similar error correction and privacy amplification processes will be performed to obtain a quantum secured secret key [50].

The E91 measurement scheme is less efficient in its use of photon pairs as the Bell inequality test requires more polarization settings to be monitored. However, entanglement-based protocols have shown to be more tolerant to loss than prepare-and-measure protocols due to the intrinsic timing correlation between photon-pairs generated in the SPDC process [51]. A typical setup is shown below, using active polarization rotators (PR), polarizing beam-splitters (PBS) and avalanche photodiodes (APD) [49].

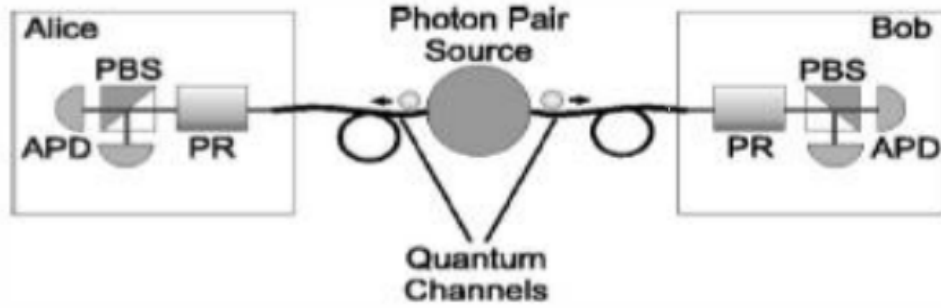


Fig. 5: System using entangled photon pairs [102]

f. Optical Links

f(i). Transmitters & Receivers

Optical links use optical telescopes at the photon source transmitter and at the receiver to beam the photons between satellite and ground station. There are two main types of telescopes: refractive (or transmissive) and reflective [52]. Refractive telescopes use lenses, while reflective telescopes use concave parabolic mirrors. In general, reflective mirrors can be made larger and more durable than lenses. Because only one side of the mirror is used to focus the light, the other side can be placed against a surface for support, enabling a mirror to be much larger relative to a lens. In fact, the largest optical telescope in the world at the Keck Observatory in Hawaii is a reflecting telescope [53]. The larger the collection device, the more light can be directed to the eyepiece, and the brighter the objects appear [54].

However, while the large size of the primary mirror is advantageous for a reflector, this same feature can quickly emphasize the optical aberrations of the telescope. To minimize polarization effects at large angles of incidence, a two-mirror assembly can be used as a tangentially directed one-wave linear retarder. The primary mirror of reflective telescopes acts as a tangentially directed half-wave linear retarder and almost completely depolarizes the linearly polarized component of the light. The secondary mirror, often placed within the path of the beam to block part of the primary mirror, introduces an additional half-wave of linear retardance. Hence, each mirror depolarizes alone but together the two-mirror assembly preserves the polarization state [55].

Comparing space and ground-based telescopes, ground-based telescopes are much larger and consequently can capture more light. Practically speaking, they are less costly, easier to maintain and upgrade, have a much lower risk of being damaged. However, atmospheric distortion is a major issue, and Earth's atmosphere absorbs a lot of the infrared and ultraviolet light that passes through it. While space-based telescopes are smaller, more expensive and difficult to maintain, they can detect frequencies and wavelengths across the entire electromagnetic spectrum [56].

To establish the optical link, a coarse level of mechanical pointing between the satellite and ground station is achieved via satellite orbit determination data (including radar tracking, GPS and star tracker measurements). Two orthogonal axes of rotation are required to track an object across the sky. By mounting the telescope on a two-axis gimbal, one of three gimbal configurations can be used to achieve coarse level pointing for larger spacecraft: altitude over azimuth (Alt-Az), altitude over altitude (Alt-Alt), equatorial, or a combination of the three [57]. For nanosatellites, the entire satellite is usually reoriented. Optical beacons on the ground and satellite can be used for fine-pointing, which is further enhanced by optical beam-steering systems that account for atmospheric turbulence.

f(ii). Quantum Bit Error Rate (QBER)

Quantum bit error rate (QBER) is the percentage of the sifted raw key that does not match between Alice and Bob. QBER is generally a direct measure for the secrecy of Alice and Bob's strings since any eavesdropping strategy would perturb the correlations between them [58]. Once QBER exceeds the threshold of 11% QKD protocols based on BB84 will be aborted. The links are where the largest losses from noise and background photons from stray light occur and thus have the biggest impact on the QBER.

Stray light can be minimized through extensive optical blacking measures, however even after extensive filtering [59], it is advised that DV-QKD is conducted at night until better solutions are found [60-61]. It is possible to achieve this by performing DV-QKD at other wavelengths with alternative detectors [62] if suitable light sources can be found. On the other hand, CV-QKD can be conducted during the day as the optical systems used have a sufficiently small spectral bandwidth that allows much of the background to be filtered [63].

f(iii). Pointing error

To establish an optical link, there are three stages of pointing, each with increasing accuracy. In the first stage, to achieve a broad level of mechanical pointing between the satellite and the ground, the satellite's orbit must be determined using radar tracking, GPS or star tracker measurements, and this data is exchanged through radio frequency links. In the second stage, a more specific level of mechanical pointing is achieved using laser beacons both on the ground and the satellite. In the third and final stage, the finest level of pointing can be achieved through optical beam-steering systems that serve to correct for atmospheric turbulence.

As mentioned in Section IIb., transmitter pointing accuracy is less significant in uplink than downlink configurations due to atmospheric turbulence. A 2 μ rad rms

error in the pointing of a 20 cm downlink transmitter would introduce 4 dB of loss compared with <1 dB for a 20cm uplink transmitter. Jitter and imperfections in the tracking systems should be minimized so their contributions to beam broadening are much less than those caused by diffraction and atmospheric turbulence. The receiver system need only point to an accuracy within its field of view, e.g., 50 μ rad [64].

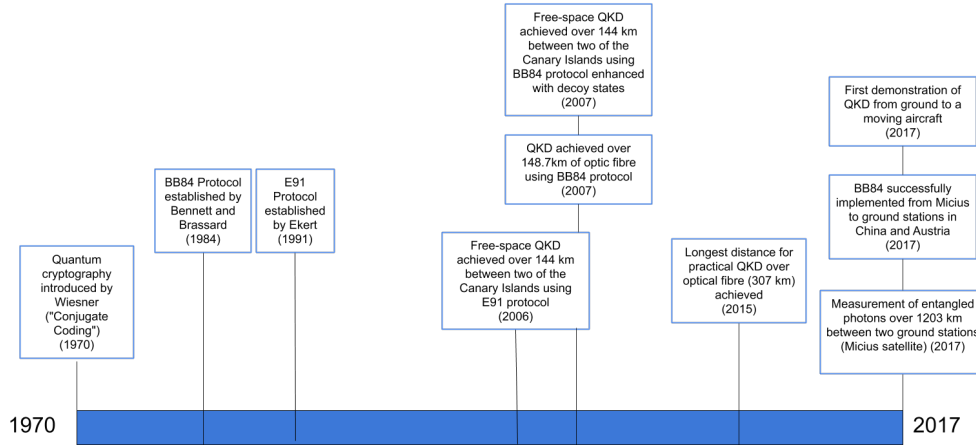
f(iv). Wavelength of signal photons

There are 2 major wavelength regimes for a quantum channel, depending on the level of expected background photons: 800nm (near the peak quantum efficiency of detectors) and 1500nm (telecom wavelength, traditionally used in optical fibre for its minimum transmission losses). Many optical link systems are limited by the availability of suitable laser sources, specifically in the availability of laser wavelengths. For optical links using SPDC sources, the limiting factor is not photon generation, but the ability of the single photon detectors to distinguish between the photons arriving with small timing separations. Thus to reduce time jitter, the avalanche volume of the photodiode and hence detection efficiency is compromised [65]. Wavelength conversion efficiency is also another constraint as that of SPDC is low; the highest conversion efficiency obtained is 4×10^{-6} [66]. Wavelength determination in terms of channel considerations is based on wavelength-dependent losses such as atmospheric absorption, diffraction losses and detection efficiency.

III. Advances in Satellite-QKD & Summary of completed and proposed missions

Below is a timeline and summary of completed and proposed satellite-QKD missions, organised by general areas of advancement in satellite-QKD.

Timeline



Advancement 1: Creating a highly accurate optical link (<5 mrad pointing error)

Mission	Aim	Satellite	Key Findings	Status, Date
Toyoshima et al. [67]	Measuring polarization characteristics of artificial laser source in space through LEO-to-ground atmospheric transmission paths	OICETS 570kg satellite	Polarization preserved within rms error 1.6°. Degree of polarization 99.4±4.4% through space-to-ground atmosphere	Completed, 2009
Yin et al. [68]	Space-ground transmission of quasi-single-photon source using retroreflectors in LEO satellite	CHAMP 500kg satellite	Signal-to-noise ratio of 16:1, sufficient for quantum links for unconditionally secure QKD	Completed, 2013
Vallone et al. [69]	Preservation of polarization state from LEO-to-ground using satellite corner cube retroreflectors as quantum transmitters in orbit	Jason-2 510kg satellite Larets 21kg satellite Starlette 48kg satellite Stella 48kg satellite	Experimental realization of quantum communication from several satellites acting as quantum transmitter and with the MLRO as the receiver. QBER 6.5%	Completed, 2015
QUBE [70]	Testing essential systems for quantum key generation, optical downlink (LEO-to-ground), and attitude control	3U CubeSat	Once operational in orbit, many new conclusions can be drawn. Follow-up missions will improve QKD in multi-satellite systems and global availability of data encryption through quantum communication.	Proposal, 2018

Advancement 2: Creating sources compatible with launch and space environments

Mission	Aim	Satellite	Key Findings	Status, Date
QUESS [71]	Establish space platform with long-distance satellite and ground quantum channel	Micius 600kg satellite	Entanglement distribution of 1203 km, teleportation up to 1400 km and BB84 QKD up to 1200 km. QBER ~1%, sifted key rate 14kbps	Completed, 2012

Advancement 3: Versatility - Ability to conduct multiple QKD protocols

Mission	Aim	Satellite	Key Findings	Status, Date
NanoBob [72]	Photon entanglement uplink experiment. Full quantum communication link >500 km. Versatile payload compatible with a variety of protocols.	12U CubeSat	Entangled photon source on ground, space segment contains “Bob” detection system only, possible implementation in 12U CubeSat. Receiver compatible with multiple QKD protocols and other quantum physics experiments	Proposal, 2017
QEYSSat [86]	Encryption key generation through quantum uplinks, involving quantum receiver onboard satellite that measures quantum signals sent from photon sources on ground. Investigate long-distance quantum entanglement.	-	-	Funded Mission
NanoQEY [103]	Demonstrate long-distance QKD between two distant ground stations on Earth using optical uplink. Distribute ≥ 10 kbit of secure key between two ground stations, with satellite as trusted node. Perform Bell tests for entangled photons between ground and space	NEMO (Nanosatellite for Earth Monitoring and Observation) (QKD receiver designed by Institute for Quantum Computing, University of Waterloo)	-	Proposal, 2014

Advancement 4: Increasing cost-efficiency by reducing size

Mission	Aim	Satellite	Key Findings	Status, Date
Takenaka et al. [73]	First downlink microsatellite quantum communication experiment (50kg-class)	SOCRATES 48 kg satellite	Feasible. <5% QBER and $99.4 \pm 4.4\%$ degree of polarization with rms error	Completed, 2017
Tang et al. [74]	In-orbit photon counting experiment measuring polarization correlation between photon pairs in nanosatellite	Galassia 1.65kg 2U CubeSat	In-orbit photon correlations exhibit a contrast of $97 \pm 2\%$, matching ground-based tests	Completed, 2016

Advancement 5: Increasing range

Mission	Aim	Satellite	Key Findings	Status, Date
Günthner et al. [75]	Preservation of quantum coherence properties of quantum states in GEO (propagation over 38,600km to ground)	Alphasat I-XL 6649kg satellite	Quantum limited states arrive at the ground station despite long propagation path Upper bound for atmospheric and technical excess noise of 0.8 ± 2.4	Completed, 2017
Dequal et al. [76]	First single photon exchange spanning a distance exceeding 7000 km (MEO)	LAGEOS-2 411kg satellite	Feasible. QBER $\sim 3.6\%$, signal-to-noise ratio 1.5, 3 count/s. Stable photon transmission for most of passage of MEO satellite.	Completed, 2016

Advancement 6: Moving Receiver Platforms

Mission	Aim	Vehicle	Key Findings	Status, Date
Nauerth et al. [77]	Ascertain feasibility of BB84 QKD between ground station and airplane moving at angular velocity similar to LEO satellite	Dornier 228 utility aircraft moving at 290km/h	Feasible using advanced pointing tracking system. Compensated for mutual rotations of sender/receiver. QBER 4.8% at 20km range, sifted key rate 145 bit/s, angular speed of 4 mrad/s	Completed, 2013

Bourgoin et al. [78]	First demonstration of optical QKD link to moving receiver platform (truck) traveling at equivalent angular speed of satellite at 600km altitude	Pickup truck (receiver) driven at 33km/h (angular speed of 13 mrad) ~650m from transmitter	Feasible. QBER 6.55%. Sifted key rate 40 bit/s, angular speed. Mean angular deviation after stabilisation of 0.005° at transmitter	Completed, 2015
Wang et al. [79]	Assessing performance under rapid motion, altitude change, vibration, random movement of satellites in high-loss regime using floating hot-air balloon platform	Hot-air balloon with angular velocity 10.5 mrad/s, average angular acceleration at 1.7 mrad/s ²	Feasible. QBER 4.04%, sifted key rate 48bit/s at 96km range. Fine tracking accuracy < 5 μ rad	Completed, 2013
Pugh et al. [104]	Investigate utilization of intrinsic strong correlation between pump and output photon spatial modes in SPDC process to mitigate negative effects of atmospheric beam wander.	-	Demonstrates viability of QEYSSAt payload. Prototypes on aircraft and ground close to requirements for satellite uplink.	Completed, 2016

Advancement 7: Polarisation-entangled photon pairs

Mission	Aim	Satellite	Key Findings	Status, Date
SpooQySats [80]	Establish space worthiness of highly-miniaturised, polarisation-entangled, photon pair sources	3U CubeSat nanosatellites	Can enable highly secure uplinks and downlinks, symmetric encryption key sharing between optical ground stations	To be launched from ISS in June 2018
CQuCom [81]	LEO-to-ground transmission of entanglement and QKD	6U CubeSat	High pointing accuracy required to minimize link loss	Proposal, 2017

Advancement 8: Performing free-space daylight QKD

Mission	Aim	Satellite	Key Findings	Status, Date
Liao et al. [82]	Overcome noise from sunlight, demonstrate free-space daytime QKD over 53 km	-	Feasible, compatible with ground fibre networks. Total channel of ~48 dB for 1550 nm free-space working wavelength	Completed, 2017
Gong et al. [83]	Experimentally demonstrate free-space satellite-to-ground QKD in the presence of urban daylight. Develop stochastic parallel gradient descent (SPGD) algorithm with deformable mirror to improve signal-to-noise ratio.	-	Feasible. 8 km QKD experiment demonstrated over 7 hours throughout daytime via an intra-city free-space link. Final secure key rate of the QKD is 98~419 bps throughout the majority of the daylight hours.	Completed, 2018
Peloso et al. [84]	Demonstrated the continuous running of free-space entanglement QKD system over several full day-night cycles in variable weather conditions	-	Feasible. Combination of filtering techniques used to overcome the highly variable illumination and transmission conditions. Continuously generate error corrected, privacy amplified key at an average rate of 385 bps	Completed, 2008
Ko, et al. [85]	Analyze QBER and key rates for different combinations of filtering techniques in a free-space BB84 QKD system operating over 275m in daylight. Optimize conditions of filtering techniques to obtain the maximum secure key rate.	-	QKD system that generates nighttime secure key rate of 341.17 kbps could not generate secure keys in daylight. Noise-filtering combination of 1 nm spectral BPF, 2.5 ns temporal selection, and spatial field of view (FOV) of 566 μ rad used. Daytime secure key rate of 191.11 kbps can be achieved using additional filtering techniques with a signal window of 1.75 ns and an FOV of 283 μ rad.	Completed, 2018

Advancement 9: Increasing feasibility of uplink transmission

Mission	Aim	Satellite	Key Findings	Status, Date
QEYSSat [86]	Minimize losses in uplink QKD. Conduct fundamental tests of long-distance quantum entanglement	Microsatellite	Involves quantum receiver onboard satellite that measures quantum signals sent up from the ground	Proposal, 2015
NanoBob [72]	Photon entanglement uplink experiment. Full quantum communication link >500 km. Versatile payload compatible with a variety of protocols.	12U CubeSat	Tradeoff between uplink losses and versatility. Higher uplink loss (~10 dB) accompanied by lower photon detection rate on satellite and significantly less data to be stored and exchanged	Proposal, 2018
Schiedl et al. [87]	Uplink entanglement-based quantum optics experiments (ground-to-space)	International Space Station	Quantum link can be maintained for 20–70s within one orbital pass. Violation of Bell inequality by 3 standard deviations of statistical significance possible within one satellite pass ($>10^3$ coincidences identified).	Proposal, 2013
Q ³ Sat [88]	Demonstrate feasibility of establishing Q.Com uplink (ground-to-LEO) with 3U CubeSat. Leverage latest advancements in nanosatellite body-pointing to show that CubeSat can generate quantum-secure key	3U CubeSat	Feasible. Q.Com achieved over thousands of kilometers via single trusted node. Relatively cheap (<200,000 €). Ignoring finite key effects, pair of ground stations can exchange 13×10^6 secure bits a year. Can be used for Bell tests, clock synchronization, measuring light pollution, earth/atmosphere observations at beacon wavelengths, and studying effect of gravity on quantum systems	Feasibility Study, 2018

Advancement 10: Others

Mission	Aim	Satellite	Key Findings	Status, Date
CAPSat [89]	Demonstrate active liquid cooling system. Simultaneously reduce vibrations and change pointing direction. Develop single-photon annealing technique to extend the lifetime of radiation-damaged APDs	3U CubeSat	Investigate 3 experiments utilizing on-board payloads: strain-actuated deployable panels Active thermal system for small spacecraft Single-photon avalanche detectors	Proposal, 2016
SpaceQUEST [90]	Investigate novel concepts for space communication systems. Propose experiments for demonstration of fundamental principles of quantum physics that will benefit from environmental conditions in space (lack of atmospheric disturbance/absorption allowing very long propagation distances)	International Space Station	Quantum communication protocols for space applications: 1. QKD using single and entangled photons 2. Quantum state teleportation 3. Quantum dense coding 4. Quantum communication complexity	Proposal, 2008
Zeitler et al. [91]	Communicating single-photon ququart states from LEO-to-ground between two remote parties through SuperDense Teleportation using hyperentangled photon pairs	International Space Station	Average fidelity of 87.01%, $\sim 2 \times 44\%$ classical limit. Compared to quantum teleportation and remote state preparation, requires less classical information and fewer experimental resources. Exponentially larger state space volume than the lower dimensional general states with the same number of state parameters.	Proposal, 2015

QuCHAP-IDQuantique [92]	Establish quantum-safe communication networks based on high-altitude platforms	High-altitude platforms	-	Ongoing, 2015
QKDsats [93] by Arqit	Launch a constellation of small low-cost low Earth orbit satellites equipped with QKD payloads	-	-	Proposal, 2018
Qubesat [94] by CQT and RAL	Use QKD technology to test the secure distribution of cryptographic keys between Singapore and the UK	-	-	Funded Mission

IV. Challenges and Future Directions of Satellite-QKD

While the above missions have enabled significant advancement of satellite-QKD, there are still a number of technical challenges that can be tackled with further research and future missions.

Firstly, research can be conducted to investigate further reductions in satellite size. With microsatellites (wet mass from 10 to 100 kg) and nanosatellites (wet mass from 1 to 10 kg), further advancements can be made to create a highly accurate optical link with <5 mrad pointing error. There is also a need to create sources compatible with launch and space environments. The above advancements have been achieved with minisatellites (e.g. Micius-type satellites) but not with microsatellites or nanosatellites (e.g. Qubesat). This will not only increase the accuracy and precision of the satellites, but also improve cost-efficiency when the capabilities of microsatellites and nanosatellites are advanced. Reducing satellite size without compromising accuracy hence reduces the cost of a single satellite, and increases the possibility of launching many satellites, enabling the improvement of the spatiotemporal coverage of satellite constellations.

Next, extensions to higher orbits beyond LEO can be investigated. While satellite-QKD missions have been conducted in MEO and GEO ranges (see Section III. Advancement 5), LEO is still the common choice for most applications. LEO is advantageous in its proximity to the surface, thereby reducing beam diffraction losses. Satellites in MEO and GEO are not only at higher altitudes and greater distances from the ground, they must be shrouded to prevent the reflection of sunlight to the ground station. Using brighter transmitters and improving link performance can reduce signal losses, but the performance of MEO and GEO satellites under these conditions will still be less than that of LEO. While LEO is advantageous in its reducing beam diffraction losses, the high speed of satellites in LEO relative to the Earth compromises pointing accuracy during signal transmission and restricts the time period during which QKD can be performed to a small window. Satellites in MEO and GEO, while suffering higher losses, move much more slowly (MEO) or are at rest relative to the ground (GEO), enabling QKD to be conducted continuously. It is necessary to move to higher altitudes as entanglement-QKD implemented using a double-downlink configuration from MEO/GEO can cover very large distances, which greatly facilitates the progression towards building global quantum networks. Concurrent efforts to reduce signal losses in satellites at higher orbits will enable us to reap the benefits of accurate signal transmission and continuous QKD.

The superconducting nanowire single photon detector (SNSPD) is a novel technology that has great potential to advance satellite-QKD missions and quantum technologies involving single-photon detection and advanced photon counting applications. SNSPDs comprise solid-state and optic aspects enabling high-rate (1.3 GBit s⁻¹) quantum key distribution for long-range quantum communication (>1200 km) as well as space communication (239,000 miles). SNSPDs perform excellently in four single-photon relevant characteristics for UV to mid-IR wavelength ranges: high detection efficiency, low false-signal rate, low uncertainty in photon time arrival and fast reset time, though they cannot be optimized simultaneously. They often outperform the best available semiconductor based single-photon detectors [95]. This makes them attractive for several applications in space technologies, nearly

commercial quantum systems and quantum optics [96]. However, SNSPDs are currently limited by the availability of cooling technologies, and all past experimental demonstrations have had ground-based applications [97]. This limits their application to satellite-QKD missions using downlink configurations where photon detectors are located at one of the ground stations. Further development in SNSPDs allowing them to operate in space can allow them to be incorporated in a greater variety of satellite-QKD missions, specifically those involving uplink configurations.

Future research can also look into the consolidation of experimental evidence of different link types facilitating comparative analysis. There have been several missions investigating the feasibility of uplink transmission (see Section III. Advancement 8). Consolidation of experimental evidence of different link types will allow us to directly compare the accuracy of optical links with various configurations.

The creation of constellations of QKD satellites can bring us closer to large-scale or even global quantum networks that enable the sharing of symmetric encryption keys between any two points on Earth. A constellation model is described which enables QKD-derived encryption keys to be established between any two ground stations with low latency [98]. To provide global real-time quantum communication connectivity, a feasible solution is the building of a satellite constellation (SC), composed of multiple quantum satellites operating in LEO, and high-earth-orbits (HEO), including GEO satellites [99]. Investigations into regional and eventual global networks can be made, as well as considering the use of inter-satellite QKD links for the transfer of keys between LEO trusted-node QKD satellites, GEO relay satellites and ground stations.

Additionally, comparing DV-QKD and CV-QKD protocols is a potential area for further research. Historically, most missions, including those discussed in Section III, make use of discrete-variable schemes such as photon polarization, where information is encoded onto discrete degrees of freedom of optical signals. Further investigations can be made into CV-QKD, which involves encoding information in the quadratures of randomly selected coherent states (such as position or momentum). Comparisons of the performance of the two classes of protocols can be made using metrics such as relative secret key rates, transmission distances, communication overheads and computing resource requirements of error correction codes.

Finally, while daytime QKD has been experimentally proven to be feasible from space, further investigations into daytime QKD from the ground can be made. A significant challenge of implementing free-space QKD systems in daylight is the impact of scattered background noise photons from sunlight. This hence requires elaborate elimination in spectral, temporal, and spatial domains to decrease the QBER and guarantee the system's security [100]. While space-based daylight QKD has been relatively successful, different combinations of filtering techniques can be investigated to increase the accuracy of ground-based daytime QKD.

In conclusion, significant progress has been made in satellite-QKD in recent years. While there are still a number of technological challenges to overcome through further research, many advances have been made thus far, bringing us closer to robust, accurate and quantum-safe encryption methods, and potentially a global quantum network in the near future.

V. Bibliography

- [1] Information Assurance Directorate, National Security Agency/Central Security Service, “Commercial National Security Algorithm Suite and Quantum Computing FAQ”, Identifier: MFQ-U-OO-815099-15 (2016).
- [2] Campagna M, Chen L, Dagdelen Ö, Ding J, Fernick JK, Gisin N, Hayford D, Jennewein T, Lütkenhaus N, Mosca M, Neill B, Pecen M, Perlner R, Ribordy G, Schanck JM, Stebila D, Walenta N, Whyte W, Zhang Z. Quantum safe cryptography and security. vol. 8. 2015. p. 1-63.
- [3] Gisin, N., Ribordy, G., Tittel, W. and Zbinden, H., “Quantum cryptography”, *Rev. Mod. Phys.* 74, 145 (2002).
- [4] Wootters WK, Zurek WH.. A single quantum cannot be cloned. *Nature*. 1982; 299:5886:802–3. <http://doi.org/10.1038/299802a0>
- [5] Takesue, H. *et al.* Quantum key distribution over a 40-dB channel loss using superconducting single-photon detectors. *Nature Photonics* 1, 343-348 (2007).
- [6] Stucki, D. *et al.* High rate, long-distance quantum key distribution over 250 km of ultra low loss fibres. *New J. Phys.* 11, 075003 (2009).
- [7] Liu, Y. *et al.* Decoy-state quantum key distribution with polarized photons over 200 km. *Opt. Express* 18, 8587-8594
- [8] Aleksic S, Winkler D, Franzl G, Poppe A, Schrenk B, Hipp F. Quantum Key Distribution Over Optical Access Networks. *Proc. 18th European Conference on Network and Optical Communications & 8th Conference on Optical Cabling and Infrastructure (NOC-OC&I)*,
- [9] Scarani, V. *et al.* The security of practical quantum key distribution. *Reviews of Modern Physics* 81, 1301-1350 (2009).
- [10] Erik Kerstel, Arnaud Gardelein , Mathieu Barthelemy. Matthias Fink, Siddarth Koduru Joshi, Rupert Ursin. (2017) Nanobob: A Cubesat Mission Concept For Quantum Communication Experiments In An Uplink Configuration
- [11] Briegel HJ, Dür W, Cirac JI, Zoller P (1998) Quantum repeaters: the role of imperfect local operations in quantum communication. *Phys Rev Lett* 81(26):5932
- [12] Hevner R, Holemans W, Pui-Suari J, Twiggs R (2011). An Advanced Standard for CubeSats. In 25th Annual AIAA/USU Conference on Small Satellites (abstr. SSC11-II-3).
- [13] Villoresi, P. *et al.* Experimental verification of the feasibility of a quantum channel between space and Earth. *New J. Phys.* 10,033038 (2008)
- [14] Bonato, C., Tomaello, A., Da Deppo, V., Naletto, G. & Villoresi, P. Feasibility of satellite quantum key distribution. *New J. Phys.* 11, 045017 (2009).
- [15] Nordholt, J.E., Hughes, R.J., Morgan, G.L., Peterson, C.G. & Wipf, C.C. Present and future free-space quantum key distribution. *Proc. SPIE* 4635, 116 (2002).
- [16] Yin J, Ren JG, Lu H, Cao Y, Yong HL, Wu YP, Liu C, Liao SK, Zhou F, Jiang Y, Cai XD, Xu P, Pan GS, Jia JJ, Huang YM, Yin H, Wang JY, Chen YA, Peng CZ, Pan JW. Quantum teleportation and entanglement distribution over 100-kilometre free-space channels. *Nature*. 2012 Aug 9;488(7410):185-8. doi: 10.1038/nature11332.
- [17] Rideout, D. *et al.* Fundamental quantum optics experiments conceivable with satellites—reaching relativistic distances and velocities. *Class. Quantum Gravity* 29, 224011 (2012).
- [18] NASA Earth Observatory. Catalog of Earth Satellite Orbits. <https://earthobservatory.nasa.gov/features/OrbitsCatalog> (2009)
- [19] Sheng-Kai, L. *et al.* Ground test of satellite constellation based quantum communication ArXiv preprint 1611.09982v1 (2016).
- [20] Kidder, S. Q. & Vonder Haar, T. H. On the use of satellites in molniya orbits for meteorological observation of middle and high latitudes. *J. Atmos. Ocean. Technol.* 7, 517–522 (1990).
- [21] Rideout, D. *et al.* Fundamental quantum optics experiments conceivable with satellites—reaching relativistic distances and velocities. *Class. Quantum Gravity* 29, 224011 (2012).
- [22] Nordholt, J. E., Hughes, R. J., Morgan, G. L., Peterson, C. G. & Wipf, C. C. Present and future free-space quantum key distribution. in *High-Power Lasers and Applications*, 116–126 (International Society for Optics and Photonics, 2002).
- [23] Rarity, J. G., Gorman, P. M., Knight, P., Weinfurter, H. & Kurtsiefer, C. Quantum communications in space. *Optical Science and Technology, SPIE's 48th Annual Meeting*, 240–251 (International Society for Optics and Photonics, 2004).
- [24] Sheng-Kai, L. *et al.* Satellite-to-ground quantum key distribution ArXiv preprint 1707.00542v1 (2017).
- [25] Jennewein, T. *et al.* QEYSSAT: A mission proposal for a quantum receiver in space. *Proc. SPIE* 8997, 89970A (2014).
- [26] Makarov, V. *et al.* Creation of backdoors in quantum communications via laser damage. *Phys. Rev. A* 94, 030302 (2016).
- [27] Capraro, I. *et al.* Impact of turbulence in long range quantum and classical communications. *Phys. Rev. Lett.* 109, 1–5 (2012).
- [28] Vallone, G. *et al.* Experimental satellite quantum communications. *Phys. Rev. Lett.* 115, 1–5 (2015).
- [29] Perdigués Armengol, J. M. *et al.* Quantum communications at ESA: Towards a space experiment on the ISS. *Acta Astronaut.* 63, 165–178 (2008).
- [30] Liao, S.-K. *et al.* Long-distance free-space quantum key distribution in daylight towards inter-satellite communication. *Nat. Photon.* 11, 509 E2 80 93513 (2017).
- [31] ARES Consortium. Inter-Satellite Links and ARES Capabilities. <http://www.ares-consortium.org/it/wp-content/uploads/2016/10/13.10.16-ISL-ARES-Capabilities-.pdf> (n.d.)
- [32] Diamanti, E. & Leverrier, A. Distributing secret keys with quantum continuous variables: principle, security and implementations. *Entropy* 17, 6072–6092 (2015).
- [33] Grosshans, F. *et al.* Quantum key distribution using gaussian-modulated coherent states. *Nature* 421, 238–241 (2003).
- [34] Jouguet, P., Kunz-Jacques, S., Leverrier, A., Grangier, P. & Diamanti, E. Experimental demonstration of long-distance continuous-variable quantum key distribution. *Nat. Photonics* 7, 378–381 (2013).
- [35] Weier, H., Schmitt-Manderbach, T., Regner, N., Kurtsiefer, C. & Weinfurter, H. Free space quantum key distribution: towards a real life application. *Fortschr. Phys.* 54, 840–845 (2006).
- [36] Jofre, M. *et al.* Fast optical source for quantum key distribution based on semiconductor optical amplifiers. *Opt. Express* 19, 3825 (2011).
- [37] A Yassien, Fuad, Tawfeeq, Shelan & I Khalil, Ahmed & R Aziz, Farah. (2010). Generation of Weak Coherent Pulses for Quantum Cryptography Systems. 1-8.
- [38] Couteau, Christopher. Spontaneous parametric down-conversion. *Contemporary Physics*. 1-14. 10.1080/00107514.2018.1488463. {2018}
- [39] Erven, Chris. On Free Space Quantum Key Distribution and its Implementation with a Polarization-Entangled Parametric

Down Conversion Source. (2019)

- [40] Bennett CH, Brassard G. Quantum cryptography: Public key distribution and coin tossing. Theoretical Computer Science, 560:P1, 7 E2 80 9311. 2014. doi:10.1016/j.tcs.2014.05.025.
- [41] Bennett, C. H. Quantum cryptography: public key distribution and coin tossing. Int. Conf. Comput. Syst. Signal Process. IEEE 1984, 175–179 (1984).
- [42] Bennett, C. H. Quantum cryptography using any two nonorthogonal states. Phys. Rev. Lett. 68, 3121 (1992).
- [43] Scarani, V., Acin, A., Ribordy, G. & Gisin, N. Quantum cryptography protocols robust against photon number splitting attacks for weak laser pulse implementations. Phys. Rev. Lett. 92, 057901 (2004).
- [44] Mavroeidis, Vasileios & Vishi, Kamer & Zych, Mateusz & Jösang, Audun.. The Impact of Quantum Computing on Present Cryptography. International Journal of Advanced Computer Science and Applications. 9.10.14569/IJACSA.2018.090354. Image URL https://www.researchgate.net/figure/Key-exchange-in-the-BB84-protocol-implemented-with-polarization-of-photons-adapted-from_fig1_324115273 (2018)
- [45] Bennett, C. H., Brassard, G. & Mermin, N. D. Quantum cryptography without bell's theorem. Phys. Rev. Lett. 68, 557 (1992).
- [46] Erven, Chris. On Free Space Quantum Key Distribution and its Implementation with a Polarization-Entangled Parametric Down Conversion Source. (2019)
- [47] Ekert, A. K. Quantum cryptography based on bell's theorem. Phys. Rev. Lett. 67, 661 (1991).
- [48] Singh, H., Gupta, D.L., & Singh, A.K. Quantum Key Distribution Protocols: A Review. (2014)
- [49] Acin, A. et al. Device-independent security of quantum cryptography against collective attacks. Phys. Rev. Lett. 98, 230501 (2007).
- [50] Ling, A. et al. Experimental quantum key distribution based on a Bell test. Phys. Rev. A. 78, 020301 (2008).
- [51] Scheidl, T. et al. Feasibility of 300 km quantum key distribution with entangled states. New. J. Phys. 11, 085002 (2009).
- [52] Vaonis. Reflector vs. Refractor Telescopes. <https://vaonis.com/reflector-vs-refractor-telescopes> (2018)
- [53] Howell, E. Keck Observatory: Twin Telescopes on Mauna Kea. (2018)
- [54] Carr, K. The Advantages and Disadvantages of Reflecting Telescopes. (2018)
- [55] Russell A. Chipman, Daniel M. Brown, and James P. McGuire, "Polarization aberration analysis of the advanced x-ray astrophysics facility telescope assembly," Appl. Opt. 31, 2301-2313 (1992)
- [56] The University of Arizona. Space versus Ground Telescopes. <https://research.arizona.edu/learn-more/space-versus-ground-telescopes> (n.d.)
- [57] DFM Engineering Inc. Satellite Tracking Telescopes. <http://www.dfmengineering.com/news/SatelliteTrackingTelescopes.pdf> (n.d.)
- [58] Mafu, M., Petruccione, F. Derivation of the quantum bit-error-rate for BB84 protocol based on the phase-covariant cloning machine. (n.d.)
- [59] Peloso M. P., Gerhardt I., HoC., Lamas-Linares A. & Kurtsiefer C. Daylight operation of a free space, entanglement-based quantum key distribution system. New J. Phys. 11, 13 (2009).
- [60] Er-Long, M. et al. Background noise of satellite-to-ground quantum key distribution. New. J. Phys. 7, 215 (2005).
- [61] Tomaello, A., Bonato, C., Da Deppo, V., Naletto, G. & Villoresi, P. Link budget and background noise for satellite quantum key distribution. Adv. Space Res. 47, 802–810 (2011).
- [62] Benton, D. M., Gorman, P. M., Tapster, P. R. & Taylor, D. M. A compact free space quantum key distribution system capable of daylight operation. Opt. Commun. 283, 2465–2471 (2010).
- [63] Günthner, K. et al. Quantum-limited measurements of optical signals from a geostationary satellite. Optica 4, 611 (2017).
- [64] Bourgoin, J.-P. et al. A comprehensive design and performance analysis of low Earth orbit satellite quantum communication. New. J. Phys. 15, 023006 (2013).
- [65] Couteau, Christopher. Spontaneous parametric down-conversion. Contemporary Physics. 1-14. 10.1080/00107514.2018.1488463. (2018)
- [66] Matthias Bock, Andreas Lenhard, Christopher Chunnillall, and Christoph Becher, "Highly efficient heralded single-photon source for telecom wavelengths based on a PPLN waveguide," Opt. Express 24, 23992-24001 (2016)
- [67] Toyoshima, M. et al. Polarization measurements through space-to-ground atmospheric propagation paths by using a highly polarized laser source in space. Opt. Express 17, 22333–22340 (2009).
- [68] Yin, J. et al. Experimental quasi-single-photon transmission from satellite to earth. Opt. Express 21, 20032 (2013).
- [69] Vallone, G. et al. Experimental satellite quantum communications. Phys. Rev. Lett. 115, 1–5 (2015).
- [70] Haber, R., Garbe, D., Busch, S., Rosenfeld, W., & Schilling, K. (2018). Qube - A CubeSat for Quantum Key Distribution Experiments.
- [71] Pan, J.-w Quantum science satellite. Chin. J. Sp. Sci. 34, 547–549 (2014).
- [72] Kerstel, Erik & Gardelein, A & Barthelemy, Mathieu & CSUG Team, The & Fink, Matthias & Koduru Joshi, Siddarth & Ursin, Rupert. (2017). Nanobob: A Cubesat Mission Concept For Quantum Communication Experiments In An Uplink Configuration. EPJ Quantum Technology. 5. 10.1140/epjqt/s40507-018-0070-7.
- [73] Takenaka, H., Carrasco-Casado, A., Fujiwara, M., Kitamura, M., Sasaki, M. & Toyoshima, M. Satellite-to-ground quantum-limited communication using a 50-kg-class microsatellite. Nat. Photon. (2017).
- [74] Tang, Z. et al. Generation and analysis of correlated pairs of photons aboard a nanosatellite. Phys. Rev. Appl. 5, 054022 (2016).
- [75] Günthner, K. et al. Quantum-limited measurements of optical signals from a geostationary satellite. Optica 4, 611 (2017)
- [76] Dequal, D. et al. Experimental single-photon exchange along a space link of 7000 km. Phys. Rev. A 93, 010301 (2016).
- [77] Nauerth, S. et al. Air-to-ground quantum communication. Nat. Photonics 7, 382–386 (2013).
- [78] Bourgoin, J.-P. et al. Free-space quantum key distribution to a moving receiver. Opt. Express 23, 33437–33447 (2015).
- [79] Wang, J.-Y. et al. Direct and full-scale experimental verifications towards ground- satellite quantum key distribution. Nat. Photonics 7, 387–393 (2013).
- [80] Bedington, R. et al. Nanosatellite experiments to enable future space-based QKD missions. Quantum Technol. 3, 12 (2016).
- [81] Oi, D. K. et al. CubeSat quantum communications mission. EPJ Quantum Technol. 4, 6 (2017).

- [82] Liao S.K., Yong H.L., Liu C, Shentu G.L. Li D.D., Lin J., Dai H., Zhao S.Q., Li B., Guan J.Y., Chen W., Gong Y.H., Li Y., Lin Z.H., Pan G.S., Pelc J.S., Fejer M.M., Zhang W.Z., Liu W.Y., Yin J., Ren J.G., Wang X.B., Zhang Q., Peng C.Z., Pan J.W. Long-distance free-space quantum key distribution in daylight towards inter-satellite communication. *Nature Photonics* 11, pages 509–513 (2017)
- [83] Yun-Hong Gong, Kui-Xing Yang, Hai-Lin Yong, Jian-Yu Guan, Guo-Liang Shentu, Chang Liu, Feng-Zhi Li, Yuan Cao, Juan Yin, Sheng-Kai Liao, Ji-Gang Ren, Qiang Zhang, Cheng-Zhi Peng, and Jian-Wei Pan, "Free-space quantum key distribution in urban daylight with the SPGD algorithm control of a deformable mirror," *Opt. Express* 26, 18897-18905 (2018)
- [84] Peloso, Matthew & Gerhardt, Ilja & Ho, Caleb & Lamas-Linares, Antia & Kurtsiefer, Christian. Daylight operation of a free space, entanglement-based quantum key distribution system. *New Journal of Physics*. 11. 10.1088/1367-2630/11/4/045007. (2008)
- [85] Ko, Heasin & Kim, Kap-Joong & Choe, Joong-Seon & Choi, Byung-Seok & Kim, Jong-Hoi & Baek, Yongsoon & Youn, Chun Ju. Experimental filtering effect on the daylight operation of a free-space quantum key distribution. *Scientific Reports*. 8. 10.1038/s41598-018-33699-y. (2018)
- [86] Jennewein, T. et al. QEYSSAT: A mission proposal for a quantum receiver in space. *Proc. SPIE* 8997, 89970A (2014).
- [87] Scheidl, T., Wille, E. & Ursin, R. Quantum optics experiments using the International Space Station: a proposal. *New. J. Phys.* 15, 043008 (2013).
- [88] Neumann, S.P., Joshi, S.K., Fink, M., Scheidl, T., Blach, R., Scharlemann, C.A., Abouagaga, S., Bamberg, D., Kerstel, E., Barthélemy, M.J., & Ursin, R. Q³ Sat: quantum communications uplink to a 3U CubeSat—feasibility & design. (2018)
- [89] University of Illinois at Urbana-Champaign. Illinois wins nasa awards for three cubesat missions. <https://aerospace.illinois.edu/news/illinois-wins-nasa-awards-three-cubesat-missions> (2016).
- [90] Perdigues Armengol, J. M. et al. Quantum communications at ESA: Towards a space experiment on the ISS. *Acta Astronaut.* 63, 165–178 (2008).
- [91] Zeidler, C., Graham, T. M., Chapman, J., Bernstein, H. & Kwiat, P. G. Super-dense teleportation for space applications. *Proc. SPIE* 9739, 973912 (2016).
- [92] Eurostars. QuCHAP. <https://www.eurostars-eureka.eu/project/id/9667> (2015)
- [93] Pultarova, T. Along with communications, quantum clocks and gravity sensors are emerging as early adopters of quantum technologies. <https://eandt.theiet.org/content/articles/2019/04/unleashing-quantum-into-the-world/> (2019)
- [94] SpaceTech Asia. UK and Singapore to collaborate on quantum CubeSat. <http://www.spacetechnasia.com/uk-and-singapore-to-collaborate-on-quantum-cubesat/> (2018)
- [95] Chandra M Natarajan *et al.* Superconducting nanowire single-photon detectors: physics and applications. *Supercond. Sci. Technol.* 25 063001 (2012)
- [96] Holzman, I. and Ivry, Y. Superconducting Nanowires for Single - Photon Detection: Progress, Challenges, and Opportunities. *Adv. Quantum Technol.*, 2: 1800058. doi:10.1002/qute.201800058 (2019)
- [97] Lixing You, Jia Quan, Yong Wang, Yuexue Ma, Xiaoyan Yang, Yanjie Liu, Hao Li, Jianguo Li, Juan Wang, Jingtao Liang, Zhen Wang, and Xiaoming Xie, "Superconducting nanowire single photon detection system for space applications," *Opt. Express* 26, 2965-2971 (2018)
- [98] Vergoossen, Tom & Loarte, Sergio & Bedington, Robert & Kuiper, Hans & Ling, Alexander. (2019). Satellite constellations for trusted node QKD networks.
- [99] University of Science and Technology of China. A Step Towards Satellite Constellation-Based Quantum Communication. <https://en.ustc.edu.cn/2018/0625/c5395a268248/pagem.htm> (n.d.)
- [100] Ko, Heasin & Kim, Kap-Joong & Choe, Joong-Seon & Choi, Byung-Seok & Kim, Jong-Hoi & Baek, Yongsoon & Youn, Chun Ju. (2018). Experimental filtering effect on the daylight operation of a free-space quantum key distribution. *Scientific Reports*. 8. 10.1038/s41598-018-33699-y.
- [101] Bedington, R., Miguel Arrazola Mantilla, J. & Ling, A. (2017). Progress in satellite quantum key distribution. *npj Quantum Information*. 3. 10.1038/s41534-017-0031-5.
- [102] Singh H., Gupta, D.L., A.K Singh. (2014). Quantum Key Distribution Protocols: A Review. *IOSR Journal of Computer Engineering (IOSR-JCE)*. eVolume 16, Issue 2, Ver. XI (Mar-Apr. 2014)
- [103] T. Jennewein, C. Grant, E. Choi, C. Pugh, C. Holloway, J. P. Bourgoin, H. Hakima, B. Higgins, and R. Zee. The NanoQEY Mission: Ground to Space Quantum Key and Entanglement Distribution Using a Nanosatellite. In Gruneisen, MT and Dusek, M and Rarity, JG and Lewis, KL and Hollins, RC and Merlet, TJ and Toet, A, editor, *EMERGING TECHNOLOGIES IN SECURITY AND DEFENCE II AND QUANTUM-PHYSICS-BASED INFORMATION SECURITY III*, volume 9254 of *Proceedings of SPIE*. SPIE, 2014. Conference on Emerging Technologies in Security and Defence II and Quantum- Physics-based Information Security III, Amsterdam, NETHERLANDS, SEP 22-23, 2014.
- [104] C. J. Pugh, P. Kolenderski, C. Scarcella, A. Tosi, and T. Jennewein. Towards correcting atmospheric beam wander via pump beam control in a down conversion process. *OPTICS EXPRESS*, 24(18):20947– 20955, SEP 5 2016.