Proof-of-Concept Experiments for Quantum Physics in Space

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ABSTRACT

Quantum physics experiments in space using entangled photons and satellites are within reach of current technology. We propose a series of fundamental quantum physics experiments that make advantageous use of the space infrastructure with specific emphasis on the satellite-based distribution of entangled photon pairs. The experiments are feasible already today and will eventually lead to a Bell-experiment over thousands of kilometers, thus demonstrating quantum correlations over distances which cannot be achieved by purely earth-bound experiments.

Keywords: long distance quantum communication, quantum information, quantum physics

1. INTRODUCTION

Space provides a unique "lab"-environment for quantum entanglement: In the case of massive particles, the weak gravitational interaction enables the expansion of testing fundamental quantum properties to much more massive particles than is possible today.[1] In the case of photons, the space environment allows much larger propagation distances compared to earth-bound free space experiments. This is mainly due to the lack of atmosphere and due to the fact that space links do not encounter the problem of obscured line-of-sight by unwanted objects or due to the curvature of the Earth. Quantum experiments over long distances are usually based on the transmission of photons. Earth-based transmission is limited, however, to some hundred kilometers both for optical fibers[2,3] and for ground-to-ground free-space links.[4] The added value of space will open up new possibilities for true long-distance experiments based on quantum entanglement utilizing satellites.

At present, ESA and NASA are hosting five experimental missions concerned primarily with fundamental physics in space, namely LISA,[5] OPTIS,[6] GP-B,[7] MICROSCOPE[8] and STEP[9] *. We suggest in the following a series of proof-of-concept demonstrations for quantum physics experiments in space. The first part of the paper introduces several fundamental tests concerning both the nature of quantum correlations and the interplay between quantum physics and relativity. In the second part, we identify a test of Bell's inequality over astronomical distances as the first important achievement for entanglement-based quantum experiments in space. We propose a series of experiments consisting of three stages, each based on the other, which will eventually lead to the first satellite-based demonstration of violating a Bell inequality over distances that are not feasible with only earth-bound technology. This will also be of importance for future applications of novel quantum communication technologies based on satellites.[10]

*European Space Agency (ESA); National Aeronautics and Space Administration (NASA); Laser Interferometer Space Antenna (LISA); Satellite Based Optical Test of Special and General Relativity (OPTIS); Gravity Probe-B (GP-B); MICROSatellite pour l'Observation du Principe d'Equivalence (MICROSCOPE); Satellite Test of the Equivalence Principle (STEP)

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2. FUNDAMENTAL TESTS OF QUANTUM PHYSICS IN SPACE

In the following, we conceive experiments for the demonstration of fundamental principles of quantum physics, which make advantageous use of the space infrastructure. Specifically, we will exploit the possibilities of satellite-distributed quantum entanglement with photons. Those experiments, although envisioned to be realizable only as long-term projects, include

- a Bell experiment using only satellites to demonstrate quantum correlations over astronomical distances (see Sect. 2.1.1),
- a Bell experiment utilizing the freedom of choice of human observers as the necessary random element in choosing the measurement basis(see Sect. 2.1.2),
- experiments testing different models considering the collapse of the wave function as a physical process (see Sect. 2.1.3),
- experiments concerning special relativistic and general relativistic effects on quantum entanglement (see Sect. 2.2), and
- Wheeler's delayed choice experiment (see Sect. 2.3).

2.1. Testing Bell-type inequalities

Classical physics is based on the assumptions of locality and realism. Reality supposes that results of measurements are associated to properties that the particles carry prior to and independent of measurements. Locality supposes that the measurement results are independent of any action performed at spacelike separated locations. Local realism imposes certain constraints on statistical correlations of measurements on multi-particle systems (Bell inequalities).[11] Quantum mechanics, however, violates the Bell inequalities and is therefore in contradiction with at least one of the underlying principles. Up to now, many experiments have been performed confirming the quantum mechanical predictions (for an overview of these so-called "Bell experiments" see for example *Tittel and Weihs*[12]). To perform such kind of experiments over long (even astronomic) distances would verify the validity of quantum physics and the preservation of entanglement on these scales (see Sec. 2.1.1). Additionally, a Bell experiment is always the first step towards the experimental realization of entanglement based quantum communication schemes. Furthermore, a possible decay in the quantum correlations can be used to test relativistic influences (see Sec. 2.2) and models proposing a physical collapse of the wave function (see Sec. 2.1.3).

2.1.1. Bell experiments over long distances

Photons are ideal for propagating over long-distances in vacuum. The experimental prerequisites to perform Bell experiments are a source of entangled photons (located in the transmitter terminal) and two analyzing receiver-terminals, which individually can vary their measurement basis and store the arrival time of single-photon detection events with respect to a local time standard. Specifically, in the case of polarization-entangled photons, polarization measurements are performed with varying polarizer settings at each receiver site. To guarantee the independence of the measurements in each of the receiver-terminals, the measurements have to be space-like separated. This is more readily accomplished over large distances between the receiver terminals. In the long run, the optimal solution for a Bell experiment over long distances would be to exclude atmospheric losses by placing both receiver terminals and the transmitter terminal on independent satellites (see fig. 1).

This scheme would allow an almost arbitrary variation of the distances between the different terminals. At the same time, different relative velocities can be chosen, which is also be desirable for other experiments proposed in this paper (e.g. the experiments utilizing special relativistic effects). The actual achievable distance is ultimately limited by the size of the transmitting and receiving telescopes.

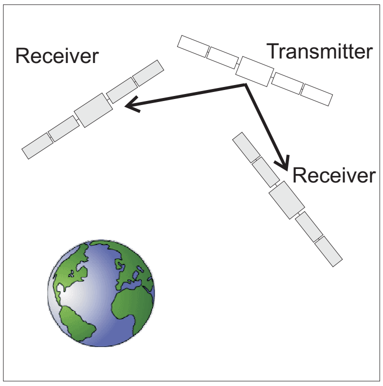

Figure 1. In this scheme all three terminals (one transmitter, two receivers) are placed on satellites. This provides maximal flexibility for a wide range of experiments over long distances without any losses due to atmospheric effects.

2.1.2. An ultimate Bell experiment

A fully conclusive experiment to test the violation of a Bell inequality has to obey true randomness in the choice of the measurement settings: the experimenters' measurement choices have to be assumed to be uncorrelated with properties of the measured system prior to measurement ("free will" criterion).[13] Thus far, all experiments utilized classical or quantum random number automata for the choice of their measurement. However, in a *completely* deterministic universe, the free will criterion may not be met, since these choices of the settings could be conspiratorially correlated with the properties of the measured system [†]. In order to lead the determinism-argument completely *ad absurdum*, we suggest to take the "free-will" criterion literally and involve two human beings in the Bell experiment, who decide on the choice of the measurement settings freely and independent from each other. In this case, a violation of a Bell inequality would imply, for a deterministic view, that even our free will is conspiratorially correlated with the properties of the measured system.

To perform this ultimate Bell experiment, two astronauts have to be placed apart far enough to make sure that their decisions which measurement to perform are space-like separated during the experiments and to ensure that they have sufficient time to make these decisions. Specifically, if we assume a transmitter terminal emitting entangled photon pairs mid-way between the astronauts and if we safely grant each of the astronauts one second of time to make his conscious decision of parameter settings[‡], the two of them would have to be separated by at least two light seconds, i.e. approx. 600 000 km [§]. To reach the necessary distance between the two astronauts, it would suffice to place them in opposing directions at approximately the distance of the moon. One possible scenario is as follows: the two astronauts and the source are all placed in orbits around Earth such that during some periods of time the distances necessary to perform the experiment are reached (see Fig. 2a). Alternatively, it is in principle possible to send only one astronaut to space while the second experimenter stays on Earth. The advantage of a completely space-based scenario is of course the absence of atmospheric losses.

A different scenario could be combined with a future Mars mission. One experimenter accompanies the mission while the second one stays on Earth (or on-board the ISS to exclude atmospheric influences) and the source of entangled photon pairs is sent to an orbit between the orbits of Earth and Mars. As soon as the necessary distances are reached the experiment can be performed (see Fig. 2b).

2.1.3. Experiments testing the physical collapse of the wave function

In a quantum measurement, we find the system to be in one of the eigenstates of the observable defined by the measurement apparatus. A specific example is the measurement on a wave packet. Such a wave packet is

[†]Note, that this scenario would also make the conceptual distinction between "locality" and "non-locality" obsolete.

[‡]We note that it takes of the order of 0.1 s to make a conscious decision.

[§]That way the astronaut's free choice is made at a time after the entangled photon pair has been emitted and thus cannot influence the creation of the state.

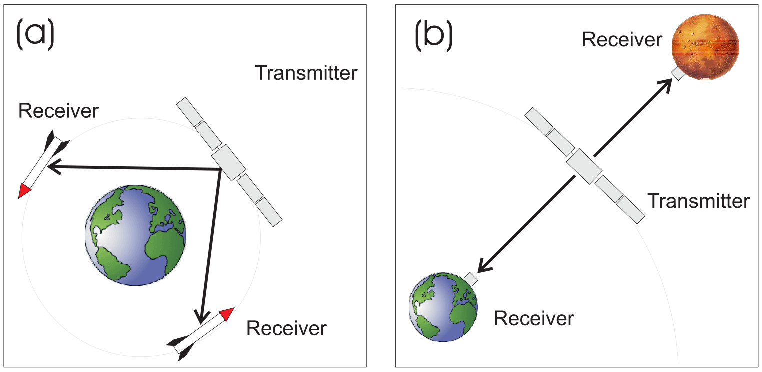

Figure 2. (a)Scenario in which two astronauts and the source of entangled photon pairs are separately orbiting Earth. Due to their different propagation velocities there will naturally be periods of time where the necessary distances are reached. (b) Scenario for a Bell experiment with one astronaut on (or near) Earth, one on (or on the way to) Mars and the source of the entangled photon pairs on an orbit in between.

more or less well-localized, but we can always perform a position measurement on a wave packet which is better localized than the dimension of the packet itself. This so-called "collapse of the wave function" is a change in the quantum state of a system which is sometimes viewed as a real physical process. Although we do not share the view that the collapse of the wave function [¶] is a physical process, we may still ask with which velocity such a collapse would propagate.[14] Experimental tests might exploit the fact that, assuming the collapse takes place in a preferred reference frame, the observation of quantum correlations in a moving reference frame allows to give a lower bound on the speed.[14] Present experiments give lower bounds for the velocity of a potential physical collapse up to 10^7 times the speed of light.[15] Bringing such experiments to space could drastically expand the testable scale, primarily due to the large distances involved and the high speeds of the satellites.

2.2. Tests of special and general relativistic effects on quantum entanglement

2.2.1. Experiments involving special relativistic effects

Due to the potentially high velocities and large distances in space experiments, it might be of interest to consider possible relativistic effects on entanglement, although it is obvious that these effects will not be dominating. A recent overview on many of these effects has been given by *Peres and Terno*.[16]

Recent research shows that the entanglement of polarization-entangled photon pairs depends in general on the observers' reference frame,[17] in other words, polarization entanglement alone is not a Lorentz-invariant scalar. Yet, the overall entanglement in the full Hilbert space of the two photons is preserved under Lorentz transformation, which means that entanglement is effectively transferred between the degrees of freedom polarization and momentum.[18–20] Similar effects can also be observed for massive particles between spin and momentum. Note that, in a standard lab experiment, such transformations would require the use of optical elements such as polarizing beamsplitters.[21]

To test the behaviour of entanglement under Lorentz transformations, scenarios have to be found in which the relative velocities between observers and a transmitter terminal carrying the entangled source is high enough to allow for the measurement of special relativistic effects. To arrive at high relative velocities, the *space–to–space* scenario is again the most flexible one, also since all the other Bell experiments can easily be performed using the same resources.

[¶]The wave function is a purely mathematical description of the knowledge about the system. When the state of a quantum system has a non-zero value at some position in space at some particular time it does not mean that the system is physically present at that point, but only that our knowledge (or lack of knowledge) of the system allows for the possibility of being present at that point at that instant.

2.2.2. Experiments involving general relativistic effects

When sharing entanglement over distances comparable to or greater than the distance Sun - Earth, one has to consider the possibility of gravitational influences on entanglement.

Polarization- and spin-entanglement leads to correlations between the outcomes of polarization (or spin) measurements on both of the particles. Such measurements however, can only have an unambiguous operational meaning if directions like "horizontal" or "vertical" ("up" or "down") on each side are well defined. Many experimental schemes for quantum communication (e.g. quantum key distribution) require a common reference frame between the observers ‖. For two particles moving apart, the initially joint reference frames, which yield perfect correlations will be parallel-transported along their individual trajectories. In general, however, quantum particles need not be associated with a unique trajectory. Therefore, one has to take into account all paths a particle can possibly take and sum up the effects of gravity on the particle along these ways weighted by their probability-amplitudes. For each path, the reference frame yielding perfect correlations will be slightly different. Recently it was suggested, that this can lead to a decrease in the correlations between two particles.[22,23] Bell-experiments over sufficiently large distances might be able to demonstrate such effects although up to now the work on this field is purely conceptual and no theoretical predictions have been made as to quantify the expected decrease in quantum correlations in actual experiments.

2.2.3. Entanglement-Enhanced Interferometry

Quantum entanglement allows to effectively increase the phase-sensitivity $\Delta\Phi$ of interferometers. By preparing specific photon-number entangled states in the arms of an interferometer $\Delta\Phi$ can be improved quadratically from $1/\sqrt{N}$ to $1/N$, where N is the number of photons in the input state entering the interferometer.[24,25] Dowling[26] derived a general formalism valid for fermions and bosons and provided estimates for the performance of optical, atom-beam, and atom-laser interferometers **. For example, an optical entanglement-enhanced interferometer might be up to 10^8 times more sensitive than a regular interferometer for the same number of photons passing through the interferometer ††.

Testing the Lense-Thirring effect using entanglement Though general relativity is in many ways an established theory there are still some of its central predictions that need accurate testing like the Lense-Thirring effect.[27] This effect is due to the dragging of inertial frames in the vicinity of rotating gravitating bodies like Earth, which induces an anisotropy in the surrounding space-time.[28,29] First experimental evidence has already been collected by the LAGEOS and LAGEOS II satellites.[30] In general, this anisotropy is experimentally accessible via the Sagnac effect, by which a preferred direction in an interferometer creates a phase shift between interfering modes (see e.g. *Stedman*[31]). Specifically, a weak gravitational field results in a phase-shift

$$\Delta\Psi = -\frac{4\pi}{\lambda} \oint dx^i h_{0i}, \tag{1}$$

where λ is the mean wavelength in the absence of rotation. $h_{\mu\nu}$ describes the deviation of the metric tensor from the Minkowski-metric ($\eta_{\mu\nu}$) and thus a small deviation from flat space-time: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$. This is an important objective of the HYPER-mission, which will be using "hyper"-cold-atom interferometers with increased experimental resolution to obtain more accurate measurements of the Lense-Thirring effect. An additional increase is to be expected by the use of entanglement-enhanced interferometry (see Sec. 2.2.3). A general requirement for such experiments would be an optical interferometer in space. Since large optical distances should be covered, one can ideally imagine a flotilla configuration of satellites, where optical path lengths can be stabilized down to sub-wavelength scales. Such flotilla configurations are currently being investigated by ESA and NASA as high-resolution telescopes based on nulling interferometry.[32]

‖A counter-example are Bell-type experiments, which do not need a common reference frame.

**Note, that a direct comparison between atomic and optical interferometers has to take into account the momentum, the flux and the roundtrip time (time needed for a particle to pass through the interferometer) of the particles involved. While photons have clear disadvantages concerning their momentum, atoms suffer from low flux and long roundtrip times.

††With today's state of the art technology, however, the possible flux achievable for single photon interferometers is incomparably higher than for entanglement-enhanced interferometers.

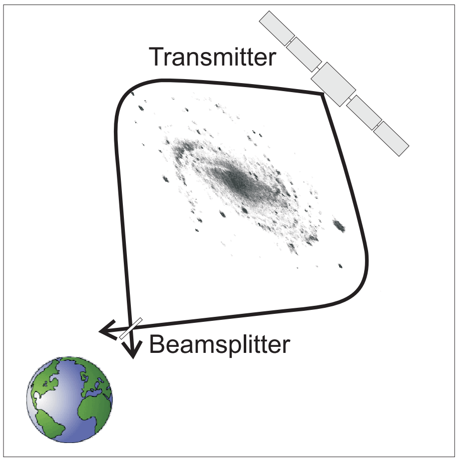

Figure 3. Wheeler's delayed choice experiment: the photons coming from a far source are deflected by a strong gravitational lens and brought together again to be either detected immediately or after overlapping on a beam-splitter.

Testing Gödel's cosmological model In 1949 Gödel suggested an alternative solution for Einstein's field equations of gravitation by assuming a net rotation of the universe as a whole.[33] It was recently pointed out by *Delgado et al.*,[34] how an entanglement-enhanced interferometric resolution might lead to the possibility to experimentally test for Gödel's cosmological model. Since rotating masses are involved, the experimental scheme is naturally equivalent to the one used for the test of the Lense-Thirring effect (see above). Taking into account the overall mass density distribution (Delgado et al. assume $\rho = 2 \cdot 10^{-31} g\ cm^{-3}$) one can predict the rotation-rate for the universe to be $\Omega_U \cong 4 \times 10^{-19} rad\ s^{-1}$, which is still small compared to the rotation rate corresponding to, for example, the Earth's Lense-Thirring effect $\Omega_{TL} \cong 10^{-14} rad\ s^{-1}$.[34] Currently, without using entanglement, the best achievable accuracy is approx. $10^{-16} rad\ s^{-1}$ calculated for the HYPER-interferometer in the course of one year. This means, an experimental run to test for Gödel's model would take some 1000 years to be accomplished. However, taking into account the possibility of entanglement-enhanced interferometry would possibly allow for much shorter, eventually experimentally feasible integration times.

2.3. Wheeler's Delayed Choice experiment

Delayed choice experiments show in an impressive way how physical realism, namely that particles have definite paths (position and momentum are equally well defined), leads to contradictions with either quantum physics or locality (see e.g. *Hellmuth et al.*[35]). They are generally based on the fact, that, depending on the experimental setup, a quantum system can either exist in a superposition of two orthogonal states or is "localized" in one of the two states. However, the decision on the actual setup can be delayed way beyond the time, when the system enters the experimental apparatus. This contradicts the realist notion that the properties of a physical system are predetermined during the *whole* time of the experiment. Taking physical intuition to the extreme, John Wheeler proposed an experiment, in which the experimenter's intervention might be delayed even by some millions of years[36]: Suppose there is a light source at an astronomical distance, emitting single photons in our direction. All these photons have to pass a gravitational lens (e.g. a galaxy or a black hole) in a way that the possible paths (to the right and to the left of the massive object) cross in the vicinity of Earth (see fig. 3). One may now ask, how the photons will behave depending on the experimenter placing a beamsplitter at the intersection or not. Quantum physics predicts that the presence or absence of interference only depends on the actual positioning of the beamsplitter as decided by the experimenter, although in a pure realist's particle-picture the particle had to choose its way maybe millions of years ago. In other words, the realist seems to be "deciding what the photon shall have done after it has already done it!".[37]

For an experimental realization it would not be feasible to bring a single-photon light source to the other end of a galaxy to test these assumptions. However, there have indeed been discovered objects we see twice as

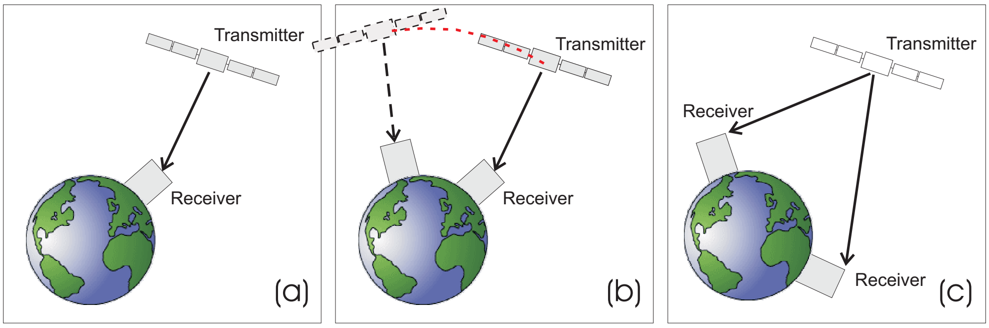

Figure 4. Scenarios for feasible proof-of-concept experiments utilizing entangled photon pairs and satellites.

their light passes on two sides of a gravitational lens.[38, 39] In principle, all one would have to do is placing a beamsplitter in the intersection of the two paths and try to observe interference. Practically, the two possible ways of the photons will slightly differ, i.e. their optical paths will differ by a few lightyears. Therefore one would have to introduce a delay-loop in one of the arms to allow for interference. Obviously, a loop delaying a photon for five years might be hard to realize.

3. FEASIBLE PROOF-OF-PRINCIPLE EXPERIMENTS

After having discussed experiments for fundamental tests of quantum physics in space, we will now provide a roadmap towards first feasible demonstrations of the underlying concepts. This will eventually lead to an experiment in which quantum entanglement is distributed between two ground stations via a satellite link.

It has been argued recently that state-of-the-art technology can already be used to exchange single-photons[40, 41] or even entangled photon pairs[10] via optical free-space links between satellites and/or ground stations thus allowing novel quantum communication protocols such as quantum cryptography in a space setting. The next step is to perform proof-of-principle experiments actually testing these findings using satellite-to-ground links. Both, the distribution of "single-photon" faint-laser pulses and the distribution of entanglement via terrestrial optical free-space links has already been verified experimentally over considerable distances.[42–44] With this in mind we propose three space experiments which will eventually lead to a long-distance Bell experiment. The realization of these experimental schemes is of a modular nature where the source of entanglement is placed within a space-borne transmitter terminal and the measuring units are placed in independent receiver terminals at ground stations. In a first experiment, single photons are sent from the space-borne transmitter terminal to a ground station to demonstrate single-photon quantum cryptography (see fig. 4a). In a second experiment, this scheme is used to demonstrate secure quantum key distribution between two *arbitrary* ground stations by independently establishing a key at each pass of the satellite (see fig. 4b). In a third experiment, entangled photons are distributed to two ground stations simultaneously allowing the violation of a Bell's inequality between independent ground stations separated by more than 1600 kilometers (see fig. 4c).

3.1. Technological baseline and preliminary design

All proposed experiments are based on the preparation and manipulation of photonic entanglement. We will focus here on polarization-entangled photon pairs, since this is most suited for the propagation through the non-birefringent atmosphere.[10]

3.1.1. Transmitter

The transmitter terminal comprises the entangled photon source, modules for polarization-sensitive manipulation and detection of single photons, and a telescope combined with an optical pointing, acquisition and tracking (PAT) system [‡‡] to establish the downlink(see Fig. 5). The photons of each entangled pair are coupled

[‡‡]PAT systems are used to establish and maintain the line-of-sight connection in optical free-space links when the terminals are moving relatively to each other.

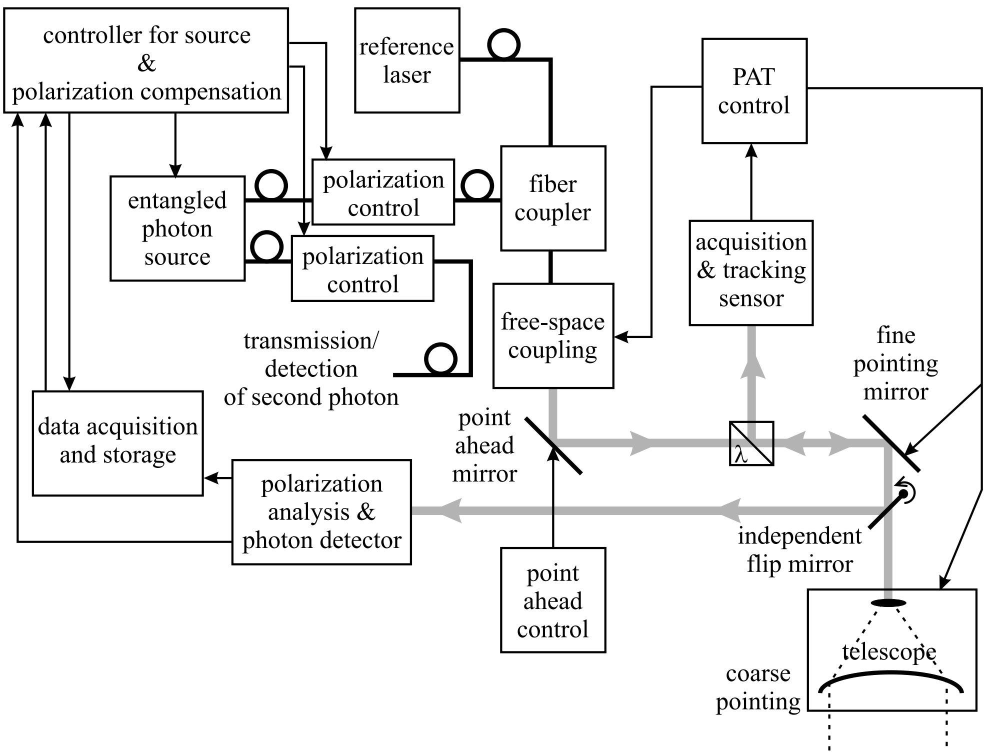

Figure 5. Block diagram of the transmitter terminal.

into optical fibers, which allow polarization control via (piezomechanical) bending of the fibers. Coupling to the classical optical head is then achieved via a fiber coupler. Depending on the stage of the experiment, the two photons of the entangled pair are either both transmitted through separate telescopes or only one is transmitted while the other one is immediately detected. The entangled photon source subsystem comprises additional laser diodes for alignment of the optical fibers. The reference laser of the PAT subsystem is linearly polarized and optionally pulsed to provide both an orientational and a timing reference frame between transmitter and receiver site. A point ahead angle unit (PAA) provides the required non-parallelity between the optical axes of the downlink and the uplink.

We distinguish the following modes of operation of the transmitter terminal: (i) *Standby mode* (A closed optical loop for internal alignment purposes is operational when no downlink is established), (ii)*PAT mode* (When a link is available in principle, the PAT sequence is initiated.), and (iii) *Quantum communication mode* (When the downlink is available, the entangled photon source is operating with the alignment laser diodes being inactive.).

Receiver

The receiver terminal comprises a single-photon analysis and detection subsystem (analogous to the unit used in the transmitter terminal) and an optical subsystem consisting of a telescope and a PAT unit (see Fig. 6). Another polarization analysis subsystem monitors the polarization of the transmitter reference laser, which is used to compensate for any orientational misalignment between transmitter and receiver polarization. The polarization analysis based on the reference laser signal does not require the use of single-photon detectors due to the high intensity of the beam to be analyzed. The signal from this analysis is used to properly orient the polarization in the single-photon beam path. The reference laser of the receiver station(s) is operating at a wavelength differing from the transmitter reference laser in order to keep cross talk sufficiently low.

The modes of operation of the receiver terminal are as follows (for the sake of simplicity, we consider only one of the photons of the entangled pair): (i) *Standby mode* (When the transmitter terminal is in *standby mode*,

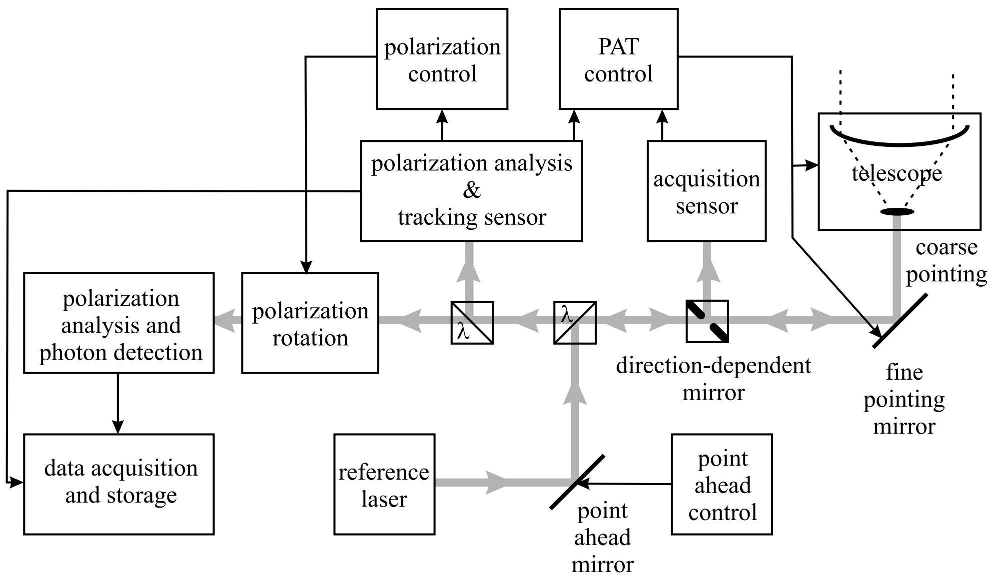

Figure 6. Block diagram of the receiver terminal.

the receiver terminal is not operating.), (ii) *PAT mode* (When a link is available in principle, the PAT sequence is initiated.), and (iii) *Quantum communication mode* (When the downlink is established, the beam received from the reference laser of the transmitter terminal is separated by a dichroic mirror from the single-photon data beam. During the availability of the downlink, data is acquired and stored locally with respect to an accurate local time standard.).

3.2. Experiment 1: Single downlink

For the first experiment, the transmitter terminal is suggested to be placed onto a low-Earth-orbiting (LEO) platform, while one receiver terminal is installed at an optical ground station. Positioning of the transmitter terminal is critical insofar as it requires nadir pointing of the module. One possible platform which fulfills this requirement is one of the external payload facility stations at ESA's Columbus module hosted by the International Space Station (ISS).[45] The receiver module is located at an optical ground station such as ESA's station (OGS) at Tenerife which will have to be adapted to properly interface with the receiver.

3.2.1. Availability of ISS–to–ground link

The ISS orbits at an altitude of around 400 km, the inclination angle is 51° and one orbit lasts for 92 minutes. The possible duration of a communication link depends on the height above sea level, the geographical latitude and altitude of the ground station and the minimum elevation angle (the elevation angle for which communication is possible may be restricted by atmospheric conditions or limited line of sight near ground). Figure 7 shows schematically the trajectory of the ISS over a ground station. We have highlighted the part where a link is possible, i.e. for elevation angles exceeding a certain minimum value. The link duration for a certain ground station does not only depend on the elevation angle but also on the longitudinal shift (Δ longitude) of the individual pass-over. In Fig. 8 corresponding numerical values for the OGS can be read off. The results for other ground stations mentioned in Section 3.4.1 do not differ significantly. Orbits with a value for Δ longitude $< 25°$ will yield useful link durations. This will be experienced for some 14% of all the orbits. With 15 orbits per day this results in two useful links within 24 hours.

3.2.2. Description of experiment

In the first stage, only one of the photons of an entangled pair is transmitted to a ground station while the other photon is directed to the polarization-analysis subsystem, where it is detected with respect to one of four

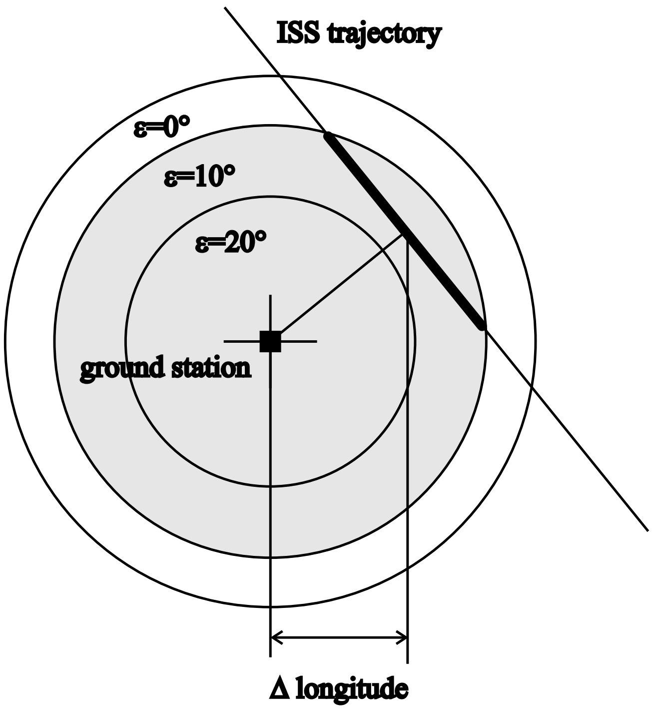

Figure 7. Trajectory of ISS over the field-of-view of a ground station. The possible duration of communication depends on the minimum elevation angle ε and the longitudinal shift (Δ longitude) between the ground station and the space station in its zenith.

polarization states (out of two non-orthogonal bases, i.e. for example $\{0°,90°\}$ and $\{45°,135°\}$). Its detection also serves as a trigger event, indicating that a single photon is emitted along the downlink. Polarization and detection time (with respect to a local time standard) are locally stored.

At the receiver, two signals generated by the transmitter have to be processed: the single photons representing the quantum communication and the reference laser beam. They are spatially separated by making use of their different wavelengths (single photons: $\lambda \approx 800\ nm$, reference laser: $\lambda \approx 950\ nm$). Since the reference laser is linearly polarized, a polarization analysis of the transmitted beam could be used to find the relative rotational orientation between transmitter and receiver terminal (Note that it is useful, though not always mandatory, to establish a common reference frame for the polarizers onboard the transmitter and for those of the receiver. This can easily be done by calibrating all linear optical elements with respect to a laboratory reference frame.). The corresponding feedback signal is used to control the state of polarization (SOP) in the single photon beam to compensate for orientational misalignment. The single photons in the quantum communication channel are then randomly detected with respect to one of two polarization bases, which are chosen equivalent to the bases used on-board the transmitter terminal (e.g. $\{0°,90°\}$ and $\{45°,135°\}$). Polarization and detection time (with respect to a local time standard) are locally stored.

With a presumed pair generation rate of 500 000 per second and an estimated loss of 6.5 dB for the local detection of qubits (this is a result of optical losses and finite detection efficiency) one can expect a count rate of approx. 112 000 s^{-1} single photons within the transmitter terminal itself. With the total attenuation of $25dB + 6.5dB = 31.5dB$ for the downlink,[10] we arrive at a count rate of approx. $350s^{-1}$ caused by the qubits at the receiver terminal. As outlined in an earlier paper,[10] we assume a total background count rate of approx.$1000s^{-1}$ for night-time operation, which leads to 1350 counts s^{-1} for the entire detection process. The final signal rate (defined by the number of joint detection events at the transmitter and receiver terminal) is then expected to be approx.$80s^{-1}$ (i.e. the pair generation rate reduced by the total link attenuation of $31.5dB + 6.5dB = 38dB$). For a link duration of 300 seconds this accumulates to a net qubit transmission of

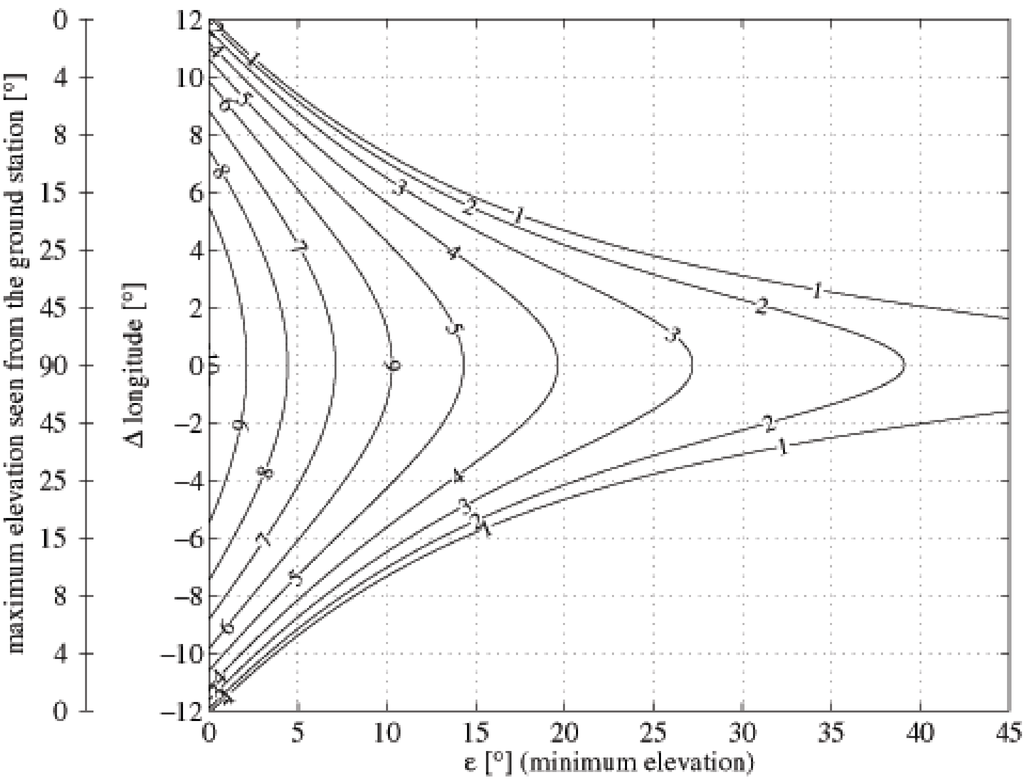

Figure 8. Maximum duration of communication between ISS and the OGS (given in minutes by the numbers inserted along the lines) as a function of the elevation angle and the difference in longitude of the ground station and the satellite when in zenith.

2400 qubits. One can expect erroneous coincident detection events on the order of $2s^{-1}$, which yields a bit error of approx. 2.5%.

After the experiment, the local data is corrected for varying signal propagation times and for varying local time standards (the latter should be negligible when atomic clocks are being used, while the signal propagation time could be monitored during the experiment by periodically pulsing the transmitter reference laser. This would allow to take into account a varying transmitter-receiver distance along the orbit.). After this data correction the data sets will be compared with each other to obtain first information about the link quality such as efficiency and atmospheric effects. Eventually, a BB84 quantum key distribution protocol[46] can be established by openly comparing certain subsets of the locally stored data sets. Then the net key bit rate and the quantum bit error rate (QBER) of the quantum key distribution protocol will be evaluated. Given the above approximations, a raw key generation rate of 1.2 kbit per link duration of approx. 5 minutes might be expected, since in only half of the cases the joint measurements on the photon pair will have been performed along the same basis at the receiver and the transmitter.

3.3. Experiment 2: Two independent single-photon downlinks

Experiment 2 will establish a quantum key exchange between two independent ground stations over distances not feasible with Earth-bound technology. No modification of the space module is required but a second (independent) ground station has to be equipped with an additional receiver module. This second ground station can be located at any arbitrary global position which allows optical contact with the ISS.

3.3.1. Description of experiment

In order to achieve a key exchange between separate ground stations via ISS, each of the two ground stations will independently establish a quantum key with the space-based transmitter terminal as is described for Experiment 1 (see Section 3.2.2). Since the space platform has access to both keys, it can send a logical combination of the keys (e.g. logically connected by XOR) via classical communication channels publicly (i.e. not secured) to either of the ground stations, where the key of the other ground station can be generated. In principle, a key exchange can thus be achieved between arbitrary ground stations. However, in this scenario the security requirement upon the transmitter terminal is as high as for the ground station. This requirement could be overcome if one distributes entangled qubits directly to different ground stations (see Experiment 3, Section 3.4). In this case, the satellite does not obtain any knowledge about the distributed key.

With respect to qubit transmission and key exchange rates the same estimates apply as above for Experiment 1 (see Sect. 3.2.2).

3.4. Experiment 3: Simultaneous entangled-photon downlink

A highly desirable prerequisite for Experiment 3 is a successful completion of all stages of Experiments 1 and 2. This includes the successful establishment and characterization of a downlink quantum channel as well as the realization of the BB84 quantum cryptography protocol. In Experiment 3, timing and orientational synchronization has to be established simultaneously between two ground stations and the ISS. This represents another degree of complexity compared to Experiment 2, where the two ground stations have been addressed independently. However, Experiment 3 will allow a test of Bell's inequality over distances only achievable with space technology, and, additionally, a demonstration of quantum key distribution based on entanglement[47] which relaxes the security requirements for the satellite significantly as in this case the satellite would not hold any information about the generated key.

The locations of the two ground stations have to be chosen in such a way that a simultaneous link between ISS and the ground stations can be established (see Section 3.4.1). In order to demonstrate features unique for this experiment, the distance between the two ground stations should be chosen sufficiently large, i.e. beyond distances which can be bridged with optical fiber technology (which is limited to a few 100 km). At the same time, a modification of the transmitter terminal is required. It now has to include two separate telescopes together with two independent PAT subsystems. This design could already be applied in Experiments 1 and 2 by using a flip mirror in one of the telescopes' input ports to direct the photon beam to the analyzer subsystems. With such a transmitter design, no further modification would be necessary when proceeding from Experiments 1 and 2 to Experiment 3.

3.4.1. Simultaneous link between ISS and two ground stations

The scenario illustrating possible simultaneous links between the ISS and two ground stations is presented in Fig. 9. The link duration now depends on the distance between the stations, the angles φ and ξ (resulting from the geographical position of the two stations), and the minimum acceptable elevation angle. Table 1 gives the corresponding values for four representative scenarios.

	distance	φ	ξ
Tenerife ↔ Calar Alto	1638 km	40.9	28.0
Tenerife ↔ Matera	3309 km	33.3	25.7
Calar Alto ↔ Matera	1698 km	19.0	19.4
Calar Alto ↔ Sierra Nevada	76 km	166.8	22.0

Table 1. Distances between ground stations and angles φ and ξ as shown in Fig. 9.

In Fig. 10 we present link durations for the optimum case, where the ISS passes both ground stations in the symmetric way indicated in Fig. 9. For each scenario a maximum range of longitude for which a link can be established results from the geographical position of the stations involved. It is some 25° for the link with Calar Alto and Tenerife or Matera, some 10° for Tenerife and Matera. The two stations in Calar Alto and Sierra

Nevada are so close to each other that the longitudinal range is 36°. The corresponding link rates are tow per day for Calar Alto and Tenerife or Matera, one for Tenerife and Matera and three per day for Calar Alto and Sierra Nevada.

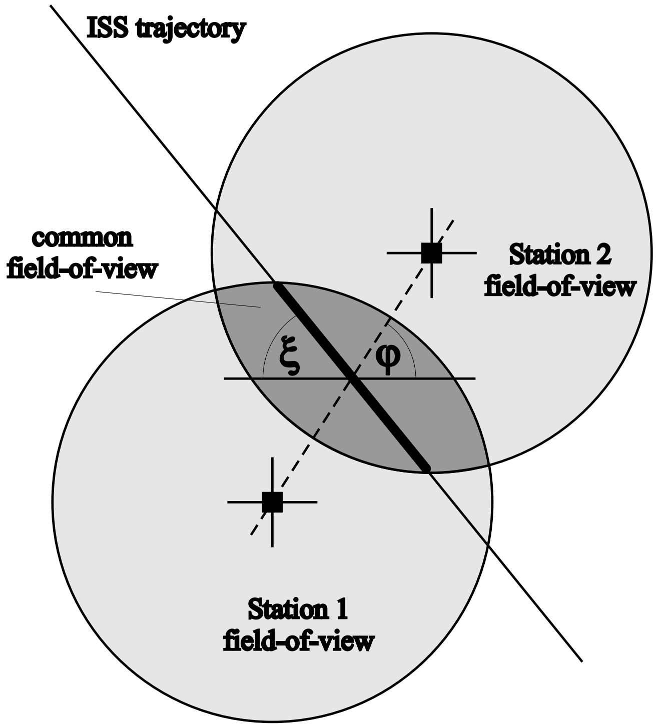

Figure 9. Trajectory of ISS over the field-of-view of two ground stations (the angles φ and ξ are measured with respect to a line parallel to the equator).

3.4.2. Description of experiment

Both photons of the entangled pair are now transmitted simultaneously to two separate ground stations via independent telescopes. Therefore, at the transmitter, no analysis and detection of single photons takes place during quantum communication.

The situation at the receiver stations is equivalent to Experiment 1 (see Section 3.2.2). At each of them, the single-photon quantum communication signal is separated from the reference laser beam, where the latter serves both as a rotational reference with respect to the transmitter terminal (i.e. it provides a control signal to actively achieve proper orientation of polarization by rotating the polarization in the quantum communication channel) and allows for signal propagation measurement to correct for varying link distance along the orbit. The single photons from the quantum communication channel are then detected with respect to one of two (non-orthogonal) polarization bases. Polarization and detection time (with respect to a local time standard) are locally stored. Before a comparison of the locally acquired data can take place, the data is corrected for varying signal propagation times and varying local time standards.

With an estimated total link attenuation of approx. $31.5dB$ (we assume a loss of $25dB + 6.5dB = 31.5dB$ for each of the downlinks), one can, in the ideal case, expect a count rate of approx. $1350s^{-1}$ single photon counts in total at each of the receiver terminals for night-time operation (here, too, this number includes background radiation). The final coincidence rate (defined by the number of joint detection events between the two receiver terminals) is then calculated by attenuating the available 500 000 counts/s by $63dB$, yielding 0.25 counts/s. For a link duration of 300 seconds this accumulates to a net bit transmission of 75 bits. One can expect erroneous coincident detection events on the order of 2.5 per 100 seconds, which results in a bit error of approx. 10%.

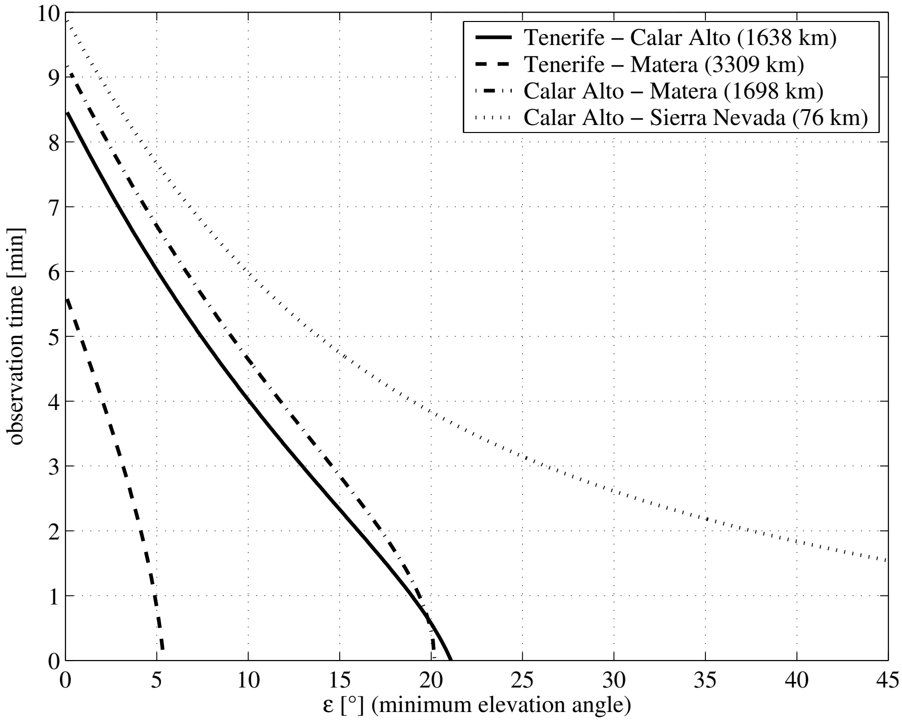

Figure 10. Maximum duration of simultaneous communication between ISS and two ground stations as a function of the elevation angle. (The distance cited in the insert is that between the stations.)

The first step to be performed will be a test of Bell's inequality between the two ground stations. Note once more that, due to the large distance between the two ground stations, such a test cannot be performed without employing an Earth-orbiting satellite. In a first set of measurements, the entangled quantum state is characterized with respect to its polarization correlations by keeping the analyzer bases at both receiving stations fixed at $\{0^\circ, 90^\circ\}$ and $\{45^\circ, 135^\circ\}$ (except for a varying compensation of the transmitter rotation). When comparing the data sets of the two receiver stations, all the joint detection events measured with analyzer settings with parallel and 45° relative orientation (eight probabilities for joint events in total) provide already certain bounds for the degree of purity and entanglement of the state.

In a further set of measurements, one of the receiver stations keeps the orientation of its analyzing bases fixed at $\{0^\circ, 90^\circ\}$ and $\{45^\circ, 135^\circ\}$, while at the other station the analyzing bases are rotated by 22.5°, resulting in the basis sets $\{22.5^\circ, 112.5^\circ\}$ and $\{67.5^\circ, 157.5^\circ\}$ (e.g. by applying an offset angle to the polarization compensation controlled via the reference laser beam). The data set of 16 different polarization correlations between the two ground stations already allows a test of the violation of a Bell inequality of the CHSH type.[48] In addition, strict Einstein locality conditions can be obeyed by randomly switching the measurement basis at both receiver stations.[49]

The second stage of the experiment is a combination of the measurements described above. With equivalent orientation of the analyzer modules in the $\{0^\circ, 90^\circ\}$ and $\{45^\circ/135^\circ\}$ bases at both receiver stations, the coincidence events measured in the same basis (e.g. in the $\{45^\circ, 135^\circ\}$ basis for both receiver stations) allow to establish a quantum cryptographic key analogous to Experiment 1 (see Section 3.2.2). Additionally, both of the receiver stations are allowed to randomly rotate their analyzer basis by 22.5°, thus also performing a test of Bell's inequality. The violation of a Bell inequality is sufficient as a security proof of the quantum key distribution protocol.[50–52] Net key bit rate, QBER and degree of security of the quantum key distribution will be evaluated. Given the above approximations, a raw key generation rate of 600 bits per link duration of approx. 5 minutes might be expected.

4. CONCLUSIONS

We conclude that present day technology enables us to bring quantum entanglement into space thus taking advantage of this unique "lab" environment. It allows us to perform fundamental tests of quantum physics, above all a test of Bell's inequality, at distances far beyond the capabilities of Earth-bound laboratories. In the first stages, those distances might not be astronomical, as would be the case when using a flotilla of satellites, but already with the use of a LEO-based transmitter and two Earth-bound receivers one can overcome the Earth-bound limitations by several orders of magnitude. Although there exists not yet a space-qualified source of entangled photons, the system complexity of present diode setups is sufficiently low to consider space qualification a feasible task. In the long run, placing both the source and the receivers in space additionally opens up the possibilities to perform novel tests of quantum physics making specific use of the added value of space.

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REFERENCES

1. M. Arndt, O. Nairz, and A. Zeilinger, "Interferometry with macromolecules: Quantum paradigms tested in the mesoscopic world," in *Quantum [Un]Speakables. From Bell to Quantum Information*, R. A. Bertlmann and A. Zeilinger, eds., pp. 333–350, Springer, (Berlin), 2002.
2. E. Waks, A. Zeevi, and Y. Yamamoto, "Security of quantum key distribution with entangled photons against individual attacks," *Phys. Rev. A* **65**, p. 52310, 2002.
3. N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, "Quantum cryptography," *Rev. Mod. Phys.* **74**, pp. 145–195, 2002.
4. H. Horvath, L. A. Arboledas, F. J. Olmo, O. Jovanović, M. Gangl, W. Kaller, C. Sánchez, H. Sauerzopf, and S. Seidl, "Optical characteristics of the aerosol in spain and austria and its effect on radiative forcing," *J. Geophys. Res.* **107(D19)**, p. 4386, 2002.
5. E. S. Agency, "Lisa," 2003. http://sci.esa.int/.
6. C. Lämmerzahl, H. Dittus, A. Peters, and S. Schiller, "Optis: a satellite-based test of special and general relativity," *Classical and Quantum Gravity* **18**, pp. 2499–2508, 2001.
7. NASA and S. University, "Gravity probe b," 2003. http://einstein.stanford.edu/.
8. P. Touboul and M. Rodrigues, "The microscope space mission," *Classical and Quantum Gravity* **18**, pp. 2487–2498, 2001.
9. NASA and S. University, "Satellite test of the equivalence principle," 2003. http://einstein.stanford.edu/STEP.
10. M. Aspelmeyer, T. Jennewein, M. Pfennigbauer, W. Leeb, and A. Zeilinger, "Long-distance quantum communication with entangled photons using satellites." quant-ph/0305105, 2003.
11. J. Bell *Physics* **1**, p. 195, 1964.
12. W. Tittel and G. Weihs, "Photonic entanglement for fundamental tests and quantum communication," *Quantum Information & Computation* **1**(2), pp. 3–56, 2001. Renton Press.
13. J. S. Bell, "Free variables and local causality," *Dialectica* **39**, p. 103, 1985.
14. V. Scarani, W. Tittel, H. Zbinden, and N. Gisin, "The speed of quantum information and the preferred frame: Analysis of experimental data," *Phys. Lett. A* **276**, pp. 1–7, 2000.
15. H. Zbinden, J. Brendel, N. Gisin, and W. Tittel, "Experimental test of nonlocal quantum correlation in relativistic configurations," *Phys. Rev. A* **63**, p. 022111, 2001.
16. D. R. T. Asher Peres, "Quantum information and relativity theory." quant-ph/0212023, 2002.
17. A. J. Bergou, R. M. Gingrich, and C. Adami, "Entangled light in moving frames." quant-ph/0302095, 2003.
18. P. M. Alsing and G. J. Milburn, "Lorentz invariance of entanglement," *quant-ph/0203051* , 2002.
19. R. M. Gingrich and C. Adami, "Quantum entanglement of moving bodies," *quant-ph/0205179* , 2002.

20. H. Li and J. Du, "Preserving spin entanglement under lorentz transformations," *quant-ph/0211159* , 2002.
21. M. Zukowski and J. Pykacz, "Bell's theorem: Proposition of realizable experiment using linear momenta," *Phys. Lett. A* **127**, pp. 1–6, 1988.
22. H. v. Borzeszkowski and M. B. Mensky, "EPR effect in gravitational field: Nature of non-locality," *Physics Letters A* **269**, pp. 204–208, 2000.
23. H. Terashima and M. Ueda, "Einstein-podolsky-rosen correlation in the gravitational field," *quant-ph/0307114* , 2003.
24. C. M. Caves, "Quantum-mechanical noise in an interferometer," *Phys. Rev. D* **23**(8), pp. 1693–1708, 1981.
25. J. Jacobson, G. Björk, I. Chuang, and Y. Yamamoto, "Photonic de broglie wavelength," *Phys. Rev. Lett.* **74**, p. 4835, 1995.
26. J. P. Dowling, "Correlated input-port, matter-wave interferometer: Quantum-noise limits to the atom-laser gyroscope," *Phys. Rev. A* **57**(6), pp. 4736–4746, 1998.
27. J. Lense and H. Thirring, "über den Einfluss der Eigenrotation der Zentralkörper auf die Bewegung der Planeten und Monde nach der Einsteinschen Gravitationstheorie," *Phys. Z.* **19**, pp. 156–163, 1918.
28. C. W. Misner, K. S. Thorne, and J. A. Wheeler, *Gravitation*, Freeman, San Francisco, 1973.
29. I. Ciufolini and J. A. Wheeler, *Gravitation and Inertia*, Princeton Univ. Press, Princetion, NJ, 1995.
30. I. Ciufolini, E. Pavlis, F. Chieppa, and J. P.-M. E. Fernandes-Vieira, "Test of general relativity and measurement of the Lense-Thirring effect with two earth satellites," *Science* **279**, pp. 2100–2103, 1998.
31. G. E. Stedman, "Ring-laser tests of fundamental physics and geophysics," *Rep. Prog Phys.* **60**, pp. 615–688, 1997.
32. M. Ollivier, J. Mariotti, A. Leger, P. Sekulic, J. Brunaud, and G. Michel, "Nulling interferometry for the DARWIN space mission," in *Proc. SPIE 4006*, pp. 354–358, SPIE, 2000.
33. K. Gödel, "An example of a new type of cosmological solutions of Einstein's field equations of gravitation," *Rev. Mod. Phys.* **21**, pp. 447–450, 1949.
34. A. Delgado, W. P. Schleich, and G. Süssmann, "Quantum gyroscopes and Gödel's universe: Entanglement opens a new testing ground for cosmology," *New J. Phys.* **4**(37), 2002.
35. T. Hellmuth, H. Walther, A. Zajonc, and W. Schleich, "Delayed-choice experiments in quantum interference," *Phys. Rev. A* **35**(6), pp. 2532–2541, 1987.
36. J. A. Wheeler, "Mathematical foundations of quantum mechanics," *New York: Academic press* , pp. 9–48, 1978.
37. W. A. Miller and J. A. Wheeler, "Delayed-choice experiments and bohr's elementary quantum phenomenon," *Proc. Int. Symp. Foundations of Quantum Mechanics* , pp. 465–471, (Tokyo), 1983.
38. P. Schneider, J. Ehlers, and E. Falco, *Gravitational Lenses*, Springer-Verlag, Berlin, 1992.
39. D. Walsh, R. F. Carswell, and R. J. Weyman, "0957+561 A,B: twin quasistellar objects or gravitational lens?," *Nature* **279**, p. 381, 1979.
40. J. E. Nordholt, R. Hughes, G. L. Morgan, C. G. Peterson, and C. C. Wipf, "Present and future free-space quantum key distribution," in *Free-Space Laser Communication Technologies XIV*, *Proceedings of SPIE* **4635**, p. 116, SPIE, 2002.
41. J. G. Rarity, P. R. Tapster, P. M. Gorman, and P. Knight, "Ground to satellite secure key exchange using quantum cryptography," *New Journal of Physics* **4**, p. 82, 2002.
42. R. J. Hughes, J. E. Nordholt, D. Derkacs, and C. G. Peterson, "Practical free-space quantum key distribution over 10 km in daylight and at night," *New Journal of Physics* **4**, pp. 43.1–43.14, 2002.
43. C. Kurtsiefer, P. Zarda, M. Halder, H. Weinfurter, P. Gorman, P. Tapster, and J. Rarity, "A step towards global key distribution," *Nature* **419**, p. 450, 2002.
44. M. Aspelmeyer, H. R. Böhm, T. Gyatso, T. Jennewein, R. Kaltenbaek, M.Lindenthal, G. Molina-Terriza, A. Poppe, K. Resch, M. Taraba, R. Ursin, P. Walther, and A. Zeilinger, "Long-distance free-space distribution of quantum entanglement," *Science* **301**, p. 621, 2003.
45. W.Carey, D.Isakeit, M.Heppener, K.Knott, and J.Feustel-Büechl, "The International Space Station European users guide," tech. rep., European Space Agency, ISS User Information Centre (MSM-GAU), ESTEC, 2001.

46. C. H. Bennett and G. Brassard in *Proceedings of IEEE International Conference on Computers, Systems, and Signal Processing, Bangalore, India*, p. 175, IEEE, (New York), 1984.
47. A. K. Ekert, "Quantum cryptography based on Bell's theorem," *Phys. Rev. Lett.* **67**(6), p. 661, 1991.
48. J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, "Proposed experiment to test local hidden-variable theories," *Phys. Rev. Lett.* **23**, pp. 880–884, 1969.
49. G. Weihs, T. Jennewein, C. Simon, H. Weinfurter, and A. Zeilinger, "Violation of Bell's inequality under strict Einstein locality conditions," *Phys. Rev. Lett.* **81**, pp. 5039–5043, 1998.
50. C. A. Fuchs, N. Gisin, R. B. Griffiths, C.-S. Niu, and A. Peres, "Optimal eavesdropping in quantum cryptography. I. information bound and optimal strategy," *Phys. Rev. A* **56**, pp. 1163–1172, 1997.
51. V. Scarani and N. Gisin, "Quantum communication between n partners and bell's inequalities," *Phys. Rev. Lett.* **87**, p. 117901, 2001.
52. A. Acin, L. Masanes, and N. Gisin, "Equivalence between two-qubit entanglement and secure key distribution," *quant-ph/0303053* , 2003.