Quantum optics experiments using the International Space Station: a proposal

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Abstract. We propose performing quantum optics experiments in a ground-to-space scenario using the International Space Station, which is equipped with a glass viewing window and a photographer’s lens mounted on a motorized camera pod. A dedicated small add-on module with single-photon detection, time-tagging and classical communication capabilities would enable us to perform the first-ever quantum optics experiments in space. We present preliminary design concepts for the ground and flight segments and study the feasibility of the intended mission scenario.

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1. Introduction

Quantum theory was originally developed to describe the smallest entities in physics. Later it turned out that it also makes fascinating predictions over macroscopic distances. Establishing quantum technology in space enables quantum systems to become available as a resource for quantum physics experiments on a global scale and beyond. The successful implementation of such experiments, which are based on the transmission and detection of single photons or entangled photon pairs, would validate the key technology of a quantum transceiver, involving an entangled photon source (EPS), a faint laser pulse source (FPS) and a single-photon counting module. This would represent the first-ever demonstration of a fundamental quantum test (e.g. a Bell-type experiment \cite{1}) and of a quantum communication application (e.g. quantum key distribution, QKD \cite{2}) in space. In this work, we propose a series of experiments with photons, making use of pre-existing infrastructure onboard the International Space Station (ISS), and also of a dedicated small quantum optics payload based solely on state-of-the-art optical and electronic components. The proposed experiments involve the distribution of entangled photon pairs and faint laser pulses from ground to space. In the following, we summarize the relevant quantum communication experiments, present a mission and a preliminary design concept for the ground and the flight segments, and study its feasibility.

The distribution of polarization entangled photon pairs \cite{3} and faint laser pulse decoy-states \cite{4} through the atmosphere has already been demonstrated over a terrestrial horizontal link of up to 144 km between the Canary Islands of La Palma and Tenerife. Recently, successful free-space teleportation has also been demonstrated over 143 km \cite{5}. The distribution of time-bin entanglement inside a laboratory \cite{6} was shown over a coiled 250-km-long fiber. Moreover, a single-photon down-link was emulated using a retro-reflector attached to a satellite reported in \cite{7}.

In order to experimentally test the limits of quantum theory, study the interplay between gravitation and entanglement \cite{8} and eventually establish a worldwide quantum communication network, it is important to significantly expand the distances for distributing quantum systems beyond the capabilities of terrestrial experiments. Due to transmission losses in fiber based quantum channels and detector dark counts, earth-based quantum communication experiments are limited to a distance of the order of 100 km \cite{9}. One approach for bridging distances on a
global scale is the implementation of quantum repeaters, which, however, are in the early stages of development [10]. Another approach is using free-space links involving satellites.

Previously proposed scenarios for quantum experiments using satellites considered down-links to optical ground stations [11]. This has the advantage that the channel loss is reduced compared to an uplink scenario, due to the shower-curtain effect [12] caused by the atmosphere. The disadvantage is that the complex quantum sources have to operate in space, although many of the required components (lasers, crystals, etc) do not yet have a space qualification. In an uplink scenario, which is the subject of this paper, the complex and non-space-qualified sources remain on the ground. However, the higher channel loss can be tolerated using state-of-the-art EPS [13] and FPS [14, 15]. Space-qualified single-photon detectors [16] will be implemented in space, as they are already a well-established technology.

2. The proposal

We propose using an optical ground station (OGS) as a transmitter for sending one photon of an entangled pair, or alternatively faint laser pulses, to the ISS (see figure 1). The space station consists of several manned modules, one of which is the so-called Cupola Module (see figure 2 left) and features a circular NADIR facing glass window 70.6 cm in diameter (see figure 2 middle). A photographer’s lens with a clear aperture of $D_R = 14.3$ cm has been used to take pictures of ground targets with integration times of up to 10 s. In order to compensate for the orbital movement, a motorized camera pod (see figure 2 right) was developed and launched in December 2011. A dedicated photon detection module (including the polarization analysis, electronics, storage and communication capabilities) will have to be developed, launched to the ISS, and attached to the photographer’s lens replacing the camera presently in use.

As a first step, we propose conducting a Bell-type [18] experiment between ground and space in the form of a test of the CHSH-type Bell inequality [19]. This inequality states that under the assumptions of locality and realism, the strength of correlations between dichotomic polarization measurement outcomes cannot lead to a so-called Bell parameter greater than 2. Considering entangled states, quantum mechanics, however, predicts for a certain set of measurement settings a maximal Bell value of $2\times\sqrt{2} \approx 2.8$. This leads to a theoretical contradiction between the predictions of quantum mechanics and classical physics, which can be experimentally tested. In a second series of experiments, the generation of a secret key based on
Figure 2. The Cupola Module (left) features a 70.6 cm window (middle) oriented to the ISS NADIR. The optical receiver is proposed to be implemented in the focal plane of an existing $D_R = 14.3$ cm clear aperture photographer’s lens. This lens is mounted on a motorized camera pod, also called NightPOD (right), which is capable of tracking ground targets for up to 70 s (picture courtesy (left, middle) NASA/JPL-Caltech, (right) ESA/cosine).

the distribution of entangled photon pairs [20], as well as a decoy-state BB84 protocol [21–24] with faint laser pulses is foreseen. As will be discussed later, these experiments are possible within a few orbital passes of the ISS over the transmitter station with the setup sketched in figure 1. Continuative experiments such as quantum teleportation [5, 25], entanglement assisted clock synchronization [26] and also LIDAR [27] experiments at very low light levels are conceivable using the same configuration.

3. Feasibility considerations

In order to assess the feasibility of the proposed experiments, we first need to define the requirements for their successful demonstration. Measurement errors arise from polarization mismatch between the ground and the flight segment and noise events caused by intrinsic detector dark counts, eventual light sources within the detector’s field-of-view (FOV) as well as by multi-pair emissions of the quantum source\(^4\), limiting the obtainable signal-to-noise ratio (SNR). The minimum SNR required to prove the presence of entanglement in a Bell-type experiment is $\text{SNR}_\text{min} = \frac{2}{\sqrt{2} - 1} \approx 4.8$. In a QKD experiment, measurement errors lead to bit errors in the generated key, which have to be corrected using classical post-processing algorithms. Yet, a secret key can only be distilled if the quantum bit error ratio is below 11% [28], corresponding to an SNR > 9. Consequently, the secret key rate also depends on the experimentally obtainable SNR. Note that in a QKD experiment the minimal SNR needs to be higher than in a Bell experiment, as well as the minimum number of measured events. The latter is of the order of $10^4$ in a QKD experiment [29] and only about $10^3$ for violating a CHSH-inequality with a statistical significance of more than three standard deviations.

3.1. The transmitter

An EPS and an FPS will be implemented at an optical ground station. The EPS will emit two photons, each coupled into a separate optical single mode fiber. One photon will be analyzed

\(^4\) Multi-pair emission is only an issue for EPS sources.
and detected locally, and its twin will be sent to the ISS. As a consequence of unavoidable losses already within the EPS, only a fraction of the generated photon pairs are detectable. This coupling efficiency is typically of the order of 50% and already includes losses on optical surfaces, fiber coupling and detection [13]. Specifically, from 20 Mcps pairs generated in the crystal, 10 Mcps single photons in each arm and approximately 5 Mcps entangled pairs can be detected directly at the source. A typical decoy-state FPS on the other hand operates at a repetition rate of 100 MHz [4, 15] emitting a mean single photon number per pulse of up to $\mu = 1$. Here, the photons are already available in a single mode fiber such that no additional coupling losses have to be considered. This results in approximately 40 Mcps detection events locally, assuming a detection efficiency of 50%.

As depicted in figure 3, photons of either source are coupled out of the fiber to the optical path of the OGS and are then guided via a point-ahead and tip/tilt mirror (fine pointing) to the motorized telescope’s (coarse pointing) sending aperture. Note that pointing, acquisition and tracking of low-earth-orbiting satellites is a well-established technology [30, 31]. Additionally, a polarization compensator is used at the ground station to establish a common polarization reference frame between the ground and the flight segment. Time-tagging units will be used to store the timing information of the local events for later analysis at the optical ground station. In the EPS case, the local events are the detection times of the locally measured photons, while for the FPS, these are the laser trigger signals.
3.2. The uplink

A calculation of the attenuation factor for an optical free-space link depending on the diameters of the transmitter $D_T$ and the receiver $D_R$ apertures is given in [32], which also includes pointing errors, optical losses and realistic atmospheric turbulence [33]. Figure 4 shows a plot of the attenuation factor as a function of the on-ground $D_T$ for the lens available onboard the ISS. Assuming that the photographer’s lens has a clear aperture of 14.3 cm, we expect the total link attenuation to be 40 dB. This includes a 20 cm transmitting aperture and an additional $\approx 5$ dB margin for effects not included in the calculation. This result agrees very well with an independent calculation given in [14]. Note that most of the optical ground stations feature even larger sending apertures than 20 cm.

3.3. The receiver

The motorized camera pod, also called NightPOD, is able to tilt the photographer’s lens over a total angle of $72^\circ$ from one window edge to the other\(^5\). This puts a restriction on the minimal

\(^5\) For safety reasons, the NightPOD actually tilts for a total angle of $36^\circ$ only.
elevation angle the ISS needs to be before quantum communication can commence. Depending on the actual roll/yaw/tip angles, this is of the order of 51° and enables quantum communication for a duration of up to 70 s per orbital pass. Furthermore, some 7 to 8 passes of the ISS at nighttime over an OGS in Tenerife (Spain) or Graz (Austria) are to be expected per month. Since the window consists of four vacuum/air spaced layers of broad band coated BK7 glass with a total thickness of 20.8 cm, we are aware of possible polarization effects for flat incident angles of the photons. However, we expect these effects to be negligible for deviations less than ±10° from normal incidence, such that the usable link-time per orbital pass would be reduced to about 20 s in the worst case. Because of this, the number of useful orbital passes would also be reduced.

For maintaining the optical link with an OGS, coarse pointing with a pointing error less than $10' \approx 50 \mu \text{rad}$ has already been archived by the NightPOD motor. Commercially available single-photon detection modules for measuring the impinging photons use silicon-based avalanche photo-diodes (Si-APD) with an active area of up to 500 $\mu$ m. These modules will be placed after the polarization analysis in the focal plane of the $f = 400 \text{ mm}$ lens, which corresponds to a FOV of approximately 1 mrad. Hence, the detector’s visible footprint diameter at the ground is approximately 400 m for the ISS (at 400 km height) being at zenith and approximately 500 m for the ISS being at an elevation angle of 51°. Based on our experiences from ground-based experiments so far [3, 4], we expect background counts from light sources within that FOV to be of the order of some 100 cps, depending on the actual location of the OGS. For example, the OGS of the European Space Agency in Tenerife (Spain) is located far outside any artificial light sources at an astronomical site. The coarse pointing capability of the NightPOD is sufficient to keep the impinging single photons on the detector’s active area. Nevertheless, a fine pointing facility (tip/tilt mirror or the NightPOD motorized axis) together with a CCD camera might be necessary for pointing and tracking purposes to compensate vibrational effects of the space station (see figure 3). The initial pointing will require the ISS orbit telemetry data to be available to the NightPOD.

The envisaged dedicated quantum payload consists of a 50 : 50 beam-splitter, a half-wave plate and polarizing beam-splitters, such that the polarization of the photons is randomly analyzed either in the $H/V$ or the $\pm 45^\circ$ basis. An extra half-wave-plate at the entrance of the detection module enables measurement in another pair of complementary linear polarization bases, as is required by the CHSH-inequality. During data accumulation, a time-tagging unit stores the timing and detector-channel information to a local storage drive for transmission to the ground via RF at some later time. In order to find the associated detection events between ground and space, the cross-correlation of the individual time-tag data sets is calculated. In a QKD experiment, the remaining errors in the quantum key are eliminated during post processing using classical algorithms. These algorithms require classical communication between the satellite and the ground and can be executed directly with the time-tagging units.

3.4. Experiments

As discussed above, the loss over the optical uplink from the OGS to the ISS will be around 40 dB. Hence, for a Bell-type experiment we expect 1 kcps single photons from the source being detected, corresponding to 500 cps detected entangled photon pairs. For QKD based on an FPS decoy-state source, we expect 4 kcps detection events at the space station. We study the experimental imperfections mentioned earlier in more detail and base our considerations on

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Figure 5. This graph shows the obtainable SNR in a Bell experiment as a function of the attenuation factor for different background levels (solid lines, right axis). Additionally, the expected secure key rate in an FPS decoy-state protocol is depicted (dashed lines, left axis). The experimental parameters of the EPS, the FPS and the single-photon detectors are described in the main text.

A theoretical model devised in [34]. Figure 5 shows the SNR of a Bell-type experiment, and the secret key rate in a QKD experiment, as a function of the attenuation through the uplink from the OGS to the ISS, for different levels of background counts in the space-based detectors. From the graph we see that, for a Bell-type experiment with a link attenuation as expected for the herein proposed mission concept, an SNR of up to 1 : 15 can be achieved with a realistic background count rate of 1 kcps. As mentioned earlier, the quantum efficiencies of the single-photon detectors are approximately 50% with a dark count rate of about 500 cps. We are aware of radiation effects typically increasing the dark counts [17], but this can be mitigated by proper shielding. In fact, the background counts can go up to about 10 kcps, leading to an SNR of 1 : 5, which is still above the limit for a violation of the CHSH inequality. This margin, with respect to the tolerable background rate, would support the scientific claim to have distributed entanglement between the ground and flight segment. Regarding the distribution of a secure quantum key, the situation becomes critical at higher background levels. Yet, assuming 1 kcps background counts, the successful demonstration of QKD seems to be possible, too.

4. Conclusion

As discussed above, the quantum link can be maintained for up to 20–70 s within one orbital pass (see figure 1). Hence, the scientific goal of violating a Bell inequality by three standard deviations of statistical significance is possible within one satellite pass, since more than $10^3$
coincidences will then have been identified. The same is true for the QKD experiment based on the FPS decoy-state protocol. In this case, more than $10^4$ events would have been collected after one orbital pass.

We have shown that by using existing infrastructure inside the ISS, one can perform quantum communication experiments over a distance of 400 km by adding only a scientific payload the size of a photographer’s camera (see figure 3). Note that this distance can eventually be extended to 1800 km using the side-windows of the Cupola Module. Both major scientific goals could be achieved with only a few orbital passes of the ISS over the OGS. A successful demonstration of these experiments will provide the basis for a whole variety of additional future experiments (e.g. quantum communication in a down-link or even an inter-satellite link scenario) and will prove the feasibility of global quantum communication using state-of-the-art technology as a kind of path-finder mission.

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