# Satellite-based quantum communication terminal employing state-of-the-art technology

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We investigate the design and the accommodation of a quantum communication transceiver in an existing classical optical communication terminal on board a satellite. Operation from a low earth orbit (LEO) platform (e.g., the International Space Station) would allow transmission of single photons and pairs of entangled photons to ground stations and hence permit quantum communication applications such as quantum cryptography on a global scale. Integration of a source generating entangled photon pairs and single-photon detection into existing optical terminal designs is feasible. Even more, major subunits of the classical terminals such as those for pointing, acquisition, and tracking as well as those providing the required electronic, thermal, and structural backbone can be adapted so as to meet the quantum communication terminal needs. © 2005 Optical Society of America

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## 1. Introduction

Quantum communications [1] is becoming a field of increasingly broad technological interest. It has matured from a purely fundamental quantum physics research area to an applied science with huge potential economic impact. The most promising application, quantum cryptography, has been demonstrated in various scenarios [2–7], and initial systems are already commercially available.

A fascinating technological challenge is the establishment of a quantum communication network, which eventually allows quantum communication on a global scale. Most existing implementations of quantum communication schemes are based on the transmission and detection of single photons or entangled photon pairs. With present technology, the distance that can be bridged is limited, basically by attenuation and detection noise, to some hundred kilometers both for fiber systems and for free-space transmission through the atmosphere along the Earth's surface. These limitations could be overcome by the use of space and satellite technology.

Bringing a photon source into space would allow the propagation of single photons or entangled photon pairs in vacuum, therefore enabling larger distances than is possible with ground-based scenarios. Recent feasibility studies conclude that such satellite-based scenarios are already possible with current technology [8–10]. First proof-of-concept experiments have already been carried out using ground-based optical free-space links: In conjunction with faint laser pulses, quantum key distribution has been demonstrated over distances up to 23.4 km [5] and at daylight [4, 11, 12]. Entangled photons have also been successfully distributed via free-space links, and quantum correlations between the photons have been demonstrated, by violating a Bell inequality, over distances from several hundred meters [13] up to 10 km [14, 15]. In all cases, the link attenuation was comparable with the losses that would occur in actual satellite experiments. However, despite these impressive and encouraging results, performing actual satellite experiments will require substantial technological developments for achieving space qualification of the currently used quantum optics devices such as single and entangled photon sources.

In the following we present a preliminary design of a satellite-based quantum communication terminal. It is based on state-of-the-art optical communication terminals, adapted to the needs of quantum communication. After reviewing possible concepts of space-based quantum communication transceivers, we present a trade-off leading to the choice for a possible setup of a first demonstrator. We then elaborate on the system design and link scenario and finally identify critical system parameters.

## 2. Concepts for a Quantum Communication Transceiver

Photonic quantum communication applications rely on the distribution either of single or entangled photon states. Currently the best known sources for generating such photon states are based on spontaneous parametric down conversion (SPDC). SPDC can either serve as a pair–source for entangled photon pairs [16] or as triggered single photon source when one of the photons of the pair is used to indicate the presence of the second photon. Single photons can also be realized in different ways, e.g., by attenuating laser pulses to an extent where, on average, one pulse contains one photon or less.

We distinguish the cases in which a space-based terminal is capable of (i) generating and distributing single photons (i.e., faint laser) or (ii) generating entangled photons and distributing them either sequentially (single photon distribution) or simultaneously (entanglement distribution) to spatially separated receivers.

Common to all quantum communication protocols under investigation is the necessity to have a classical communication channel in parallel to the quantum channel. This is required for establishing the temporal correlation between photons of entangled pairs and between the emission and detection time of single photons, respectively. Since we aim at employing present-day optical terminal technology for realizing the QCT (quantum communication terminal), it suggests itself to implementing the classical channel as a free-space optical channel. (The other possibility would be an RF channel for classical communication.)

We arrive at three options for the quantum communication transceiver design allowing for quantum key distribution:

- Single photon source (SPS) with classical optical communication channel.
- Entangled photon source (EPS) with classical optical communication channel.
- Entangled photon source (EPS) without classical optical communication channel (classical communication is established via an RF channel).

## 3. Trade-off Analysis of a Space-Based Quantum Communications Terminal

### 3.A. *Criteria*

A trade-off of the three options for the quantum communications terminal has been performed with the following criteria taken into account:

- QCT physical features: these criteria assess the mass, volume, and power consumption of the option.
- QCT performance: Criteria have been chosen to determine whether the terminal
  - fulfills requirements for performing a certain range of quantum communications experiments,
  - achieves the envisaged scientific results,
  - allows for quantum link experiments that have a potential for applications of commercial interest, and
  - provides a classical optical communications link to ground.
- Risk assessment: a consideration on the risk of the different options has been considered, namely,
  - complexity—assesses the risk associated with the complexity of the corresponding QCT configuration,
  - implementation risk—assesses (in addition to complexity) the risk associated with the implementation of the corresponding QCT configuration (e.g., the dependence of the QCT option on a specific technology that may have some risk associated with it), and
  - qualification status—takes into account technologies that would require a component qualification programme to support the flight development activities.
- Programmatic issues: we consider
  - development costs—assesses the development activities to be performed before a flight program can be initiated,
  - QCT costs—terminal development and production costs, and
  - growth potential—accounts for the system of being able to perform other scientific experiments, to demonstrate possible applications of the technology, or to grow in link capacity.

### *3.B. Trade-Off and Design Selection*

The trade-off matrix is shown in Table 1. It includes a weighting for each of the trade-off criteria, ranging from 0 to 10, and a corresponding score for the three design options. A higher score reflects a more desirable feature. The weighting is the subjective opinion of the authors, reflecting their preferences. The scores result from an educated guess. The rating is the product of weighting and score.

The EPS terminal is larger and heavier than the SPS terminal and also consumes more power. Therefore the score for the physical parameters is significantly lower than for the SPS configuration. However, the range of experiments and their scientific impact is much higher using an EPS terminal than using an SPS terminal. Regarding the risk assessment, the investigated options do not differ significantly. The costs would be considerably lower for a SPS terminal. The total rating speaks for a QCT comprising an entangled photon source and a classical optical communications link.

**Table 1. Trade-Off for an ISS-Based Quantum Link Assessment (SPS, single photon source; EPS, entangled photon source)**

| | | SPS Terminal with Classical Optical Communication | | EPS Terminal with Classical Optical Communication | | EPS Terminal without Classical Optical Communication | |
|---|---|---|---|---|---|---|---|
| Criteria | Weighting | Score | Rating | Score | Rating | Score | Rating |
| **Physical features:** | | | | | | | |
| QCT mass | 5 | 2.5 | 12.5 | 1 | 5 | 1 | 5 |
| QCT size | 10 | 2.5 | 25 | 1 | 10 | 1 | 10 |
| power consumption | 5 | 2 | 10 | 1 | 5 | 3 | 15 |
| **QCT performance:** | | | | | | | |
| Quantum experiments | 10 | 2 | 20 | 5 | 50 | 5 | 50 |
| Scientific impact | 10 | 1 | 10 | 5 | 50 | 5 | 50 |
| Application potential | 10 | 2 | 20 | 5 | 50 | 1 | 10 |
| Classical communications | 5 | 5 | 25 | 5 | 25 | 0 | 0 |
| **Risk assessment:** | | | | | | | |
| QCT complexity | 1 | 2 | 2 | 1 | 1 | 2 | 2 |
| Implementation risk | 5 | 2 | 10 | 2 | 10 | 2 | 10 |
| Qualification status | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| **Programmatics:** | | | | | | | |
| Development costs | 5 | 2 | 10 | 2 | 10 | 3 | 15 |
| QCT cost | 10 | 4 | 40 | 2 | 20 | 3 | 30 |
| Growth potential | 1 | 2 | 2 | 3 | 3 | 2 | 2 |
| **Total rating** | | | **188.5** | | **241** | | **201** |

## 4. Preliminary Design

### *4.A. Block Diagram and Conceptual Design*

The block diagram shown in Fig. 1 illustrates how the QCT can be subdivided in a classical subsystem that comprises the building blocks known from classical optical communication terminals and a quantum subsystem that comprises novel functional elements. The figure shows a QCT for use with an entangled photon source. For single-photon quantum communication experiments only one of the classical subsystems would be needed. The other photon is directly coupled in one of the on-board photon detectors also used for calibration prior to experiments (see below).

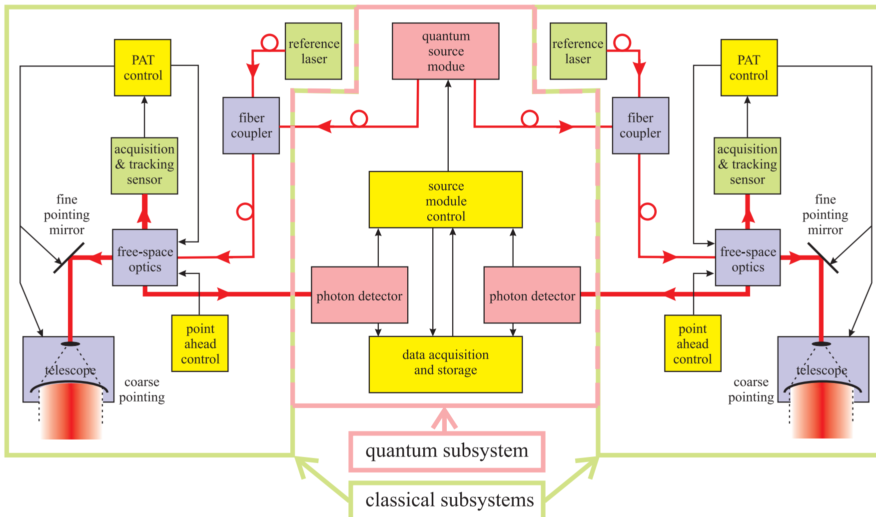


Fig. 1. Block diagram for a quantum communication terminal.

Each of the two classical subsystem consists of the following building blocks:

- A telescope (including coarse pointing mechanism) to receive the reference laser beam from the ground station for PAT and to transmit a QCT reference laser beam as well as the single photon beam,
- a PAT system including fine-pointing and point-ahead mirrors, acquisition and tracking sensor, and point-ahead control,
- a beacon laser for the acquisition process, transmitted via a separate aperture (not shown in block diagram),
- a (linearly polarized) reference laser for PAT and for establishing a temporal and polarization reference between transmitter and receiver station, and
- a fiber and/or free-space coupling interface to the quantum subsystem.

The quantum subsystem comprises

- a quantum source module for generating and preparing the entangled photon pairs,
- a single-photon detection element (providing feedback for the source module), and
- a unit controlling the source performance and data acquisition.

Figure 2 shows a 3D sketch of the integrated QCT payload. The building blocks of the QCT are described in the following.

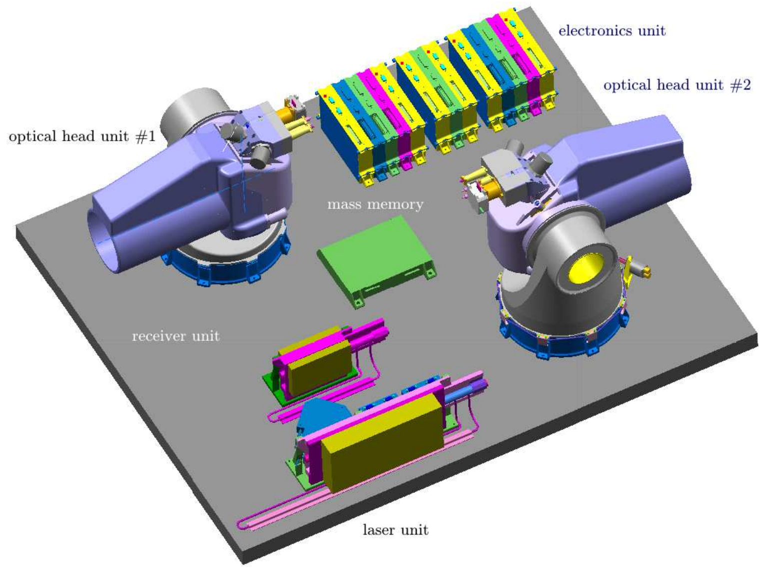


Fig. 2. Entangled photon pair experimental payload.

### 4.B. Laser Unit

The laser unit consists of two beacon lasers for pointing and acquisition, two reference lasers for polarization reference and for the downlink classical communication channel, and the quantum source module.

The latter module includes a UV laser system for driving the SPDC, a down-conversion crystal, optics for coupling of down-converted light into a single-mode fibers, and a polarization controller. Polarization control is needed for compensating any drifts of the state of polarization within the terminal. The relative alignment of the UV laser, the non-linear crystal and the single mode fibers must be kept at high mechanical stability.

The optical source for the classical optical downlink is a multi quantum well laser diode operating at $\lambda = 1060\,\text{nm}$ and directly modulated at a data rate of $100\,\text{Mbit/s}$. The main reason for the selection of this transmitter type has been the stringent optical isolation requirements of the optical channel together with the overall link efficiency for the classical optical communications channel.

### 4.C. Receiver Unit

The receiver consists of two single-photon detector modules implemented in the form of avalanche photodiodes (APDs) operating in the Geiger mode. The APDs have to be cooled to an operating temperature of about $-30\,°\text{C}$, stabilized to $\pm 1\,°\text{C}$. Therefore this unit is separated from the laser unit.

### 4.D. Optical Head Unit

Each of the optical head units comprises an optical bench and a telescope. Within the optical bench the outgoing beams from the reference laser and the quantum source module are collimated and guided to the telescope after passing a point ahead mirror and a fine pointing mirror. There is the possibility for directing photons from the quantum source into the photon detector for calibration or when performing an experiment where only one of the two entangled photons is transmitted to another terminal while the other is analyzed on site.

Furthermore the optical bench includes the acquisition and tracking sensor, the latter also used for reception of an uplink classical communication signal at a wavelength of 980 nm.

The optical head unit is based upon the Contraves OPTEL-25 that has a telescope with an external aperture of 13.5 cm and which is gimballed in two axes such that it can achieve full hemispherical pointing capabilities [17, 18].

### 4.E. Electronics Unit

The electronics unit for the EPS terminal comprises the electronics needed for the control and operation of each optical head unit and the classical communications channel as well as the electronics for the quantum channel. The latter consists of an entangled photon source controller, a polarization controller, a data acquisition electronics, and a mass memory.

The data acquisition and storage module with a memory capacity of 1 GByte is capable of processing timing information concerning the detected photons with a resolution of 1 ns during an experimental run. The module is also required for data analysis. The exchange of timing information does not necessarily have to occur simultaneously with the quantum signal transmission; i.e., it is possible to postprocess the data.

The entangled source controller enables monitoring of the laser diode performance within the source module by measuring the spectral and spatial properties of relevance for entanglement generation.

## 5. Experimental Scenario

The access statistics, link duration and pointing, acquisition and tracking parameters for an optical link from the ISS (International Space Station) to a ground station as well as simultaneous optical links to two ground stations (see Fig. 3) were analyzed. Three optical ground stations were taken into account, namely, Tenerife (Spain), Calar Alto (Spain), and Matera (Italy).

### 5.A. Link Duration

Given the location of the space terminal on the ISS and the geographic position of the ground station, links with duration of 200 s (average) are expected for performing a quantum communication link experiment [18]. At least one link with such a duration is predicted per day in order to achieve an efficient mission.

The results presented in Tables 2, 3 apply for single downlink scenarios with any of the stations and for scenarios where the ISS simultaneously links with Tenerife and Calar Alto or with Matera and Calar Alto. For a simultaneous link between ISS, Tenerife, and Matera, both the frequency and duration of possible links are considerably worse because of the large distance between those two ground stations.

The link ranges depend on the allowed elevation parameter as seen from the ground station. If elevation is constrained to values $> 30°$, link distances may become as large as 700 km. In case of low elevation $(\geq 5°)$, link distances of up to 1800 km will occur. At low elevation angles atmospheric attenuation increases.

If—in order to avoid background radiation from the Sun—experiments may only take place during the night, the average access durations stay almost the same, while the access gap duration increases. It can even happen that for an entire period of more than 10 days no access is possible.

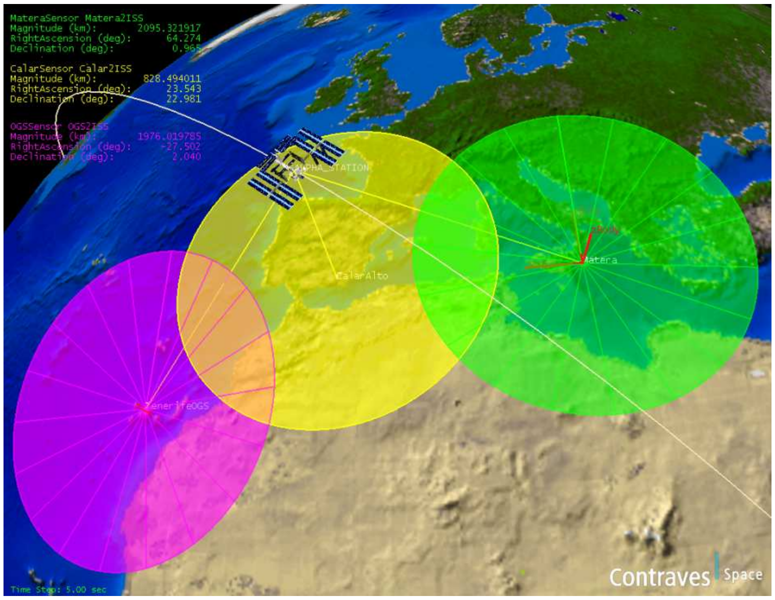


Fig. 3. Configuration for simultaneous link access investigation to at least two of three selected ground stations.

### 5.B. Link Attenuation

Based on the values for the link distance and the atmospheric attenuation for the different scenarios considered, we will now estimate the link attenuation to be expected. If the receiver is in the transmitter's far field, i.e., $L \geq D_T^2/\lambda$ and the transmit telescope is diffraction limited, the link attenuation for space-to-ground links can be approximated by

$$A = \frac{L^2\left(\theta_T^2 + \theta_{atm}^2\right)}{D_R^2} \frac{1}{T_T\left(1 - L_P\right) T_R} 10^{A_{atm}/10} \tag{1}$$

with the equivalent divergence angle resulting from the transmit telescope [20]

$$\theta_T = 1.27 \frac{\lambda}{D_T} \tag{2}$$

and an additional divergence caused by atmospheric turbulence

$$\theta_{atm} = 2.1 \frac{\lambda}{r_0}. \tag{3}$$

Here $L$ is the link distance, $\lambda$ is the wavelength, and $D_T$ and $D_R$ the diameters of the transmit and receive telescopes. With $T_T$ and $T_R$ we denote the transmission factors $(\leq 1)$ of the telescopes, $L_P$ is the pointing loss due misalignment of transmitter and receiver and $A_{atm}$ is the atmospheric attenuation, being a function of elevation angle and wavelength (see Subsection 5.A). In the very simple model we apply, the atmospheric turbulence can be accounted for by introducing an equivalent telescope aperture, the so-called Fried parameter $r_0$, corresponding to the atmosphere's coherence length $r_0 = 2.1\rho_0$ [21]. We assume that the divergence due to turbulence adds quadratically to the geometric divergence of the beam for the uplink [22], while it is negligible for the downlink [23].

Figure 4 shows the resulting link attenuation for an ISS-to-ground scenario at the wavelength $\lambda = 808$ nm for $r_0 = 10$ cm. For the downlink case we assumed transmit and receive

**Table 2. Key Performance Parameters for an ISS Single Optical Downlink to Tenerife, Calar Alto, or Matera at Different Minimum Ground Elevation Angles [18, 19]**

| Ground Station Elevation | Average Access Duration | Maximum Access Gap Duration | Average Access Gap Duration | Link Range | Atmospheric Attenuation @ 808 nm |
|---|---|---|---|---|---|
| | [Minutes] | [Hours] | [Hours] | [km] | [dB] |
| $>5°$ | 5.5 | $<15$ | $<1.8$ | $<1800$ | 9.6 |
| $>15°$ | 3.5 | $<17$ | $<9.0$ | $<1200$ | 3.6 |
| $>30°$ | 2.0 | $<40$ | $<25$ | $<700$ | 2.2 |

**Table 3. Key performance Parameters for an ISS Simultaneous Optical Downlink at Different Minimum Ground Elevation Angles [18, 19][a]**

| Ground Station Elevation | Average Access Duration | Maximum Access Gap Duration | Average Access Gap Duration | Link Range | Atmospheric Attenuation @ 808 nm |
|---|---|---|---|---|---|
| | [Minutes] | [Hours] | [Hours] | [km] | [dB] |
| $>5°$ | 3.0 | $<17$ | $<1.8$ | $<1800$ | 9.6 |
| $>10°$ | 1.5 | $<22$ | $<5.0$ | $<1200$ | 3.6 |
| $>15°$ | 0.3 | $<70$ | $<8.0$ | $<700$ | 2.2 |

[a]The values shown apply, with good approximation, both for links with Tenerife/Calar Alto and Calar Alto/Matera.

telescope diameters of 13.5 cm and 100 cm, respectively. For the uplink case, transmit and receive telescopes diameters are to be interchanged.

## 6. Critical Parameters and Technologies

### 6.A. Space QCT Parameters

The space QCTs shall have a design life of 3 years; the operational life should be 1 year. The physical dimensions and mass as well as the required power for the entire terminal must not exceed the specifications given for Columbus external pallet payloads as provided by ESA [24]. They are $H \times B \times T = 139 \times 117 \times 86\ cm^3$, 290 kg, and 1.25 kW, respectively.

The terminal should be able to operate within a thermal environment of $-35$ °C to $+$ 60 °C. However, temperature environment of the entangled photon source (in particular the nonlinear crystal) needs to be stabilized to $\pm 0.1$ °C, which asks for good thermal isolation and an extra thermal control.

### 6.B. Ground Parameters

The reference laser must not operate at the same wavelength as the quantum channel. It must be optically well isolated within the receiver terminal; i.e., stray light and backscattering into the signal receive path should be clearly below the level of background radiation. We expect a background radiation of $10^3 - 10^4$ photons/s/nm during nighttime for a diffraction limited receive telescope with a diameter of 1 m.

### 6.C. Quantum Channel Parameters

The two driving requirements concerning the quantum channel are the attenuation, which must not exceed 60 dB in order to achieve a SNR $> 6.8$ dB, and the time resolution below 1 ns to allow for pulse repetition rates in the range of $10^6$/s. A SNR below the stated value would make impossible any quantum communication protocol, and lower pulse repetition

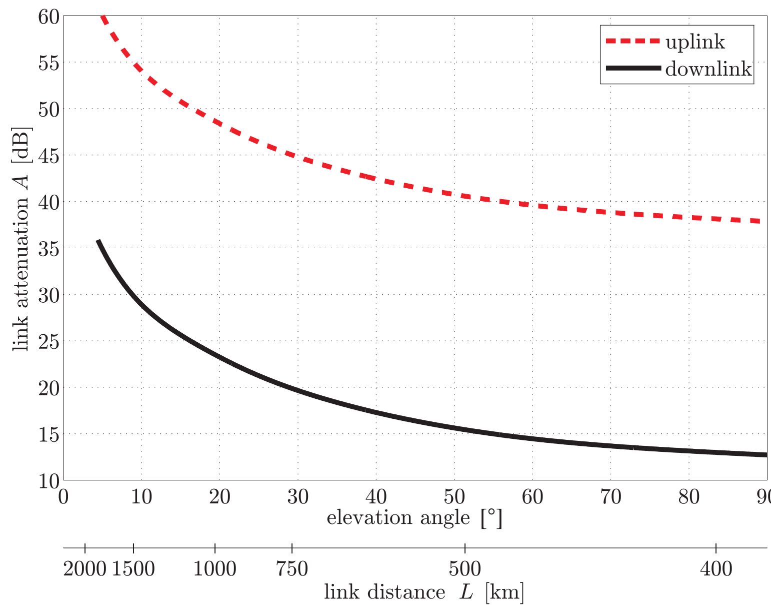


Fig. 4. Link attenuation for uplink and downlink as a function of the elevation angle and the corresponding link distance for $\lambda = 808$ nm. We assumed $T_T = T_R = 0.8$ and $L_P = 0.2$.

rates would increase the minimum duration of a useful experimental run beyond possible link times of LEO-to-ground links.

### *6.D. Classical Channel Parameters*

To provide the classical communication necessary to perform quantum communication experiments, a data exchange on the order of 90 MByte during a 5 minute experimental run has to be provided. This corresponds to a data rate of some 2.4 MByte/s. The classical communication link shall achieve a bit error rate of $10^{-6}$.

### *6.E. Pointing, Acquisition, and Tracking Parameters*

In order not to lose favorable orbital passes, acquisition and tracking should be possible regardless of any bright celestial body—except the Sun and the Moon—within the terminal's field of view. The maximum time required for acquisition of the link shall be 45 s. During tracking, the burst error probability should be lower than $10^{-6}$.

To obtain sufficient link duration, we have established the following requirements. For the ground stations, acquisition shall be possible when the link is above 5° elevation angle. For the space terminal, the quantum communications link shall be maintained for azimuth angles between $-180°$ and $+180°$ and for elevation angles between $-20°$ and $+70°$. The azimuth and elevation slew rate achievable by the space terminal when not tracking shall be at least 10°/s. Tracking of the link shall be possible for any rate of change of the terminal azimuth and elevation angle that does not exceed 1°/s. The required azimuth rate for the ground terminal is in the range of 0.2–1.0°/s, and the elevation rate needed is 0.01–0.2°/s.

### *6.F. Quantum Sources*

Current single-photon sources and entangled photon sources typically operate in a laboratory environment and have not yet undergone space qualification. The nonlinear optical processes involved rely on long-term, stable single-frequency operation of pump lasers in the UV. Also, single-mode fiber coupling might be crucial to generate the needed quality of entanglement.

## 7. Conclusion

We have presented a concept for a space-based quantum communication terminal that is feasible with state-of-the-art technology. The terminal is capable of producing entangled photon pairs. It has the flexibility to either detect one of the photons on-board and transmit the second one to a ground station (or satellite), or distribute simultaneously both photons towards two independent ground stations or (satellites). The first scenario allows for secure quantum key distribution between the satellite and one ground station. Furthermore, it allows the establishment of a secret key between remotely separated ground-based locations after the satellite has passed both of them at different times. The second case also allows us to perform fundamental tests of quantum correlations, e.g., by violating a Bell inequality, over distances that cannot be achieved by ground-based laboratories alone.

We have performed a parameter study of the space-based terminal based on the specifications of the existing OPTEL terminal developed by Contraves Space and we have also studied several experimental scenarios considering operation of the terminal from a LEO platform (e.g., ISS). Finally, we have identified critical parameters for follow-up hardware developments. The benefit of the proposed design lies in the fact that major subunits of the classical terminals like those for pointing, acquisition and tracking as well as those providing the required electronic, thermal, and structural backbone can be inherited without major modification.

## Acknowledgment

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[20] For the $e^{-2}$ beam divergence of a Gaussian beam, $\theta_G$, one obtains a value of approx $2\times 0.9\lambda/D_T$ from Fig. 9 of Ref. [25]. To convert this into the equivalent beam divergence, defined as yielding the same on-axis intensity as a beam with a top-hat profile carrying identical power, one easily finds that a beam with a Gaussian profile and a full $e^{-2}$ beam divergence $\theta_G$ produces the same on-axis intensity as a beam with top-hat profile and full beam divergence $\theta_T = \theta_G/\sqrt{2}$. We thus arrive at a beam divergence of $\theta_T = \left(2\times 0.9/\sqrt{2}\right)\lambda/D_T = 1.27\lambda/D_T$.

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