Stellar calibration of the single-photon receiver for satellite-to-ground quantum key distribution

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Abstract. Satellite quantum communication is the technology that allows to deploy large-scale quantum networks with a communication range of thousands kilometres. We report the ground receiver for downlink quantum key distribution (QKD) with satellite. An optical part of this system including an active tracking loop is mounted on a 600-mm Ritchey-Chretien telescope and permits to distinguish polarization states to perform QKD between ground and satellite. Moreover, a procedure of calibration the receiver using stars with known brightness is presented. Measurements of the photon count rate of stars in the spectral range of 845 nm - 855 nm are performed and compared with an estimate.

1. Introduction
Quantum key distribution (QKD), the technology that allows secure communication immune against future advances in computational power, is now being deployed on a large geographic scale.

The need for cryptography, that is, the encryption of important messages arose in the ancient times and has only grown over the millennia. The today’s most popular encryption algorithm is RSA [1], which is not unbreakable, but hacking it is computationally complex and would take hundreds of years on the best modern supercomputers. Such robustness had been sufficient until in 1994 Shor proposed an algorithm that would have allowed breaking RSA in minutes using a quantum computer [2].

Although the actual large-scale implementation of Shor’s algorithm is some time away, quantum computers already show significant success. Not so long ago Google declared quantum supremacy achievement (quantum devices without error correction can perform a well-defined computational task beyond the capabilities of currently available classical computers) on 53 qubits [3].

Moreover, Chinese physicists published an article in December 2020, where they demonstrated a quantum photon processor with 25 qubits. The calculation speed of the computer is 100 trillion times higher than on any existing classical supercomputer [4]. Having achieved quantum superiority, they thus showed the prospects for the development of a quantum computer based on photons.
The idea to create cryptography unbreakable in principle and counteract the “quantum threat” unsurprisingly also emerged from the quantum world. In fact, the concept of quantum cryptography was proposed even earlier, in 1984, by Bennett and Brassard [5]. It is based on the fact that if one measures the quantum of light, it changes its state.

However, the impossibility of cloning the quantum states, being the basis of quantum cryptography, also limits the transmission distance of the signal over the optical fiber to 100–200 km (limited by fiber loss). This imposes a restriction on the length of the communication line.

Hence, satellite quantum key distribution as a new method to share secret information for extra long distances can be the realization of an alternative way to the fiber optic distribution.

In this paper we present a ground receiver for downlink quantum key distribution with satellite that opens up a possibility for useful quantum cryptography. It is crucial to have the highest possible level of useful signal during the entire communication session with the satellite, therefore we performed a stellar calibration for our receiver.

2. Methods

The Zvenigorod observatory is located about 80 km from Moscow. The observatory station consists of a Ritchey–Chretien Alt-Az telescope with an aperture of 0.6 m and a focal length of 4.8 m, a coarse camera with the field of view (FOV) of $0.7^\circ \times 0.7^\circ$ ($512 \times 512$ pixels, frame rate of 10 Hz) and an optical receiver box mounted on the back of the telescope main mirror.

The coarse-tracking system consists of an alt-azimuth mount and a 70mm-coarse camera in a control loop. The coarse camera identifies optical signals from distant objects such as satellites or stars and then the telescope accurately points to it. Successful testing of a similar system is described in reference [6].

![Figure 1. Experimental set-up. CPL – coupler; POL – polarizer; PBS - polarizing beam splitter cube; HWP – half-wave plate; BS – 50:50 beam splitter; IF1 – interference filter (CWL=850nm; FWHM=10nm); HWP-m – motorized half-wave plate; BE – beam expander; DM – dichroic mirror; L1 – lens (f = 75 mm); FSM – fast steering mirror; RCT – 600-mm-aperture Ritchey-Chretien telescope; CAM1 – fine camera (field-of-view of 4 mrad×4 mrad); IF2 – interference filter (CWL=532 nm; FWHM=10 nm); 5 ch SPDs– 5 channel single photon detectors module; TDC – time to digital converter; PA – polarization analyzer; APS - analysis and processing module, GT – guide telescope, CAM2 – guide telescope camera.](image)
The optical receiver box holds the fine-tracking system as well as the 850-nm photon receiver. It primarily consists of a dichroic mirror (DM), a fast-steering mirror (FSM) and a complementary metal-oxide semiconductor (CMOS) imaging sensor or a fine camera with the FOV of 3 mrad × 3 mrad (640 × 640 pixels, frame rate of 100 Hz). The FSM is used to fine-tune the optical direction based on image data gathered by the fine feedback camera (CMOS). The dichroic mirror is used to separate the reference optical beam from the 850-nm photons, with one going to the fine camera for tracking and the other to an 850-nm photon receiver connected to the four single-photon detectors (SPDs).

The 850-nm photons are obtained by a BB84 passive-basis-choice polarization analysis module, which contains a 50:50 beam splitter, half-wave plate, and polarizing beam splitters after going through a motorized half-wave plate (HWP) and an interference filter (central wavelength of 850 nm, bandwidth of 10 nm). The receiver module is coupled to four single-photon detectors by four multimode optical fibers with core diameters of 105 μm. At 850nm, the SPDs have a quantum efficiency of 50%, an active area of 180 μm, and a dead time of 22 ns. The electric output pulses from all SPDs are fed into a time-to-digital converter (TDC), which records the detecting time and detector channel numbers. The acquired data is stored in the computer for further analysis.

The maximal possible deviation of the telescope from the exact position at the object is limited by two optical fiber parameters: numerical aperture (NA) and core diameter (CD). In our tests, they are equal to 0.22 and 105 μm, respectively.

3. Results
To calibrate the ground receiver in the spectral range 850±5 nm, we use stars with known apparent magnitude in infrared diapason (m) and record the count rate (C) or photons per second, which is proportional to the brightness of the stars. By definition

\[ m = -2.5 \log \left( \frac{C}{C_0} \right) \]

where \( C_0 \) is the count intensity of a star with a zero apparent magnitude.

Furthermore, the turbulence in the atmosphere causes a deviation in the calculation outcome of each star. Figure 2 depicts an example of the count rate fluctuation for the star Etamin, which has an apparent magnitude of 0.23.

![Figure 2](image_url)
Thus, we perform 21 measurements of the count rate from the stars, normalized them for 100% transmission of atmosphere and calculated the average value of coefficient $C_0$ for that case, using equation (1). It equals $3850 \pm 150 \times 10^3$ cps.

![Figure 3. The dependence of the count rate on the magnitude. Measurements were taken on various clear nights of September 2020.](image)

According to the open database, the brightness (L) of a star with a magnitude of zero in the I-spectral range at the Earth's surface is $1.058 \times 10^{-11} \frac{W}{nm \cdot m^2}$. The incident number of photons ($C_0^{th}$) predicted is as follows:

$$C_0^{th} = \frac{L \cdot S \cdot \eta \cdot B}{E_{ph}}, \quad (2)$$

Hence, taking into account $\eta = 0.55$, $S = 0.283 \ m^2$, $B = 10 \ nm$, $C_0^{th}$ equals $51400 \times 10^3$ cps.

Finally, we can calculate the transmittance (T) of our entire optical device, including the telescope, using estimated and experimental measurements as follows:

$$T = \frac{C_0}{C_0^{th}} = 7.5 \pm 0.2\% \quad (3)$$

4. Conclusion

We have shown the transmittance of our receiver using the method of stars measuring in narrow spectral range. This coefficient allows us to assess the quality of the system setup and to improve the system for further experiments. The developed device for satellite QKD opens up a possibility for useful quantum cryptography at a global scale and convenient integration with other quantum networks such as fiber-based networks. It will be interesting to investigate the experimental implementation of space QKD in the backbone network for long-distance transmission.
Acknowledgments
We thank many colleagues at the Russian Quantum Center, QRate, for motivating discussions, management, and coordination. We also thank our colleagues at the Institute of Astronomy of the Russian Academy of Sciences, especially S. Barabanov and M. Nalivkin for their assistance and support. This work is supported by the Russian Science Foundation under project 17-71-20146.

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