National Research University Higher School of Economics

*as a manuscript*

Duplinsky Alexey Valerievich

# Development and research of a polarization reference frame mismatch compensating system for quantum key distribution satellite optical channel

DISSERTATION SUMMARY

Dissertation summary for the purpose of obtaining academic degree

Doctor of Philosophy in Engineering

Academic supervisor:
Doctor of Physical and Mathematical Sciences
Chulkova Galina Merkuryevna

Moscow – 2025

# Introduction

The development of quantum technologies that allow manipulation of individual quantum particles opens up new possibilities for the modern world. In particular, a communication protocol called quantum key distribution (QKD) encodes cryptographic bit sequences using single-photon quantum states [1–4], thereby guaranteeing unconditional security of transmitted data based on the principles of physical laws [5–8]. At the same time, photon losses and the impossibility of silent amplification of single-photon signals limit the practical distance of quantum communication, which currently reaches 1000 kilometers in fiber optic communication lines [9; 10]. However, the use of low-Earth orbit satellites as trusted nodes opens up global applications for this technology, where photon losses are primarily due to beam diffraction and vary quadratically with the distance between the satellite and the ground station [11–15].

As a result, space quantum communications have made significant progress over the past decade [16–18]. The Micius satellite in the 500-kilometer orbit is a landmark scientific project because it demonstrated for the first time quantum communication with false state, entanglement distribution, quantum teleportation, and the deployment of an integrated space-Earth quantum communication network [19–24]. In July 2022, the same scientific team launched Jinan-1, the world's second "quantum" spacecraft in low-Earth orbit, which can realize secure real-time key exchange [25]. Thus, these experiments confirmed that quantum communication in low-Earth orbit is feasible.

**Problem Statement** Satellite applications of quantum key distribution technology provide exciting opportunities for scaling quantum communication networks. At the same time, their practical implementation requires solving many technical challenges. Establishing a stable channel with an object in low Earth orbit and moving at a speed of more than 7.6 km/s for operating a single-photon optical signal with polarization coding places high demands on the devices participating in the sessions. During communication sessions, due to the relative motion of the satellite and the change in the spatial orientation of the device due to the operation of the guidance and stabilization system, the polarization reference system of the satellite rotates relative to the analysis plane of the ground receiving station. This effect leads to an increase in the quantum bit error, which negatively affects the final key volume and its secrecy level. Therefore, during the sessions, it is necessary to synchronize the polarization reference systems, using the orbital data of the satellite for compensation. Polarization encoding is the most suitable way to implement photonic qubits in satellite quantum communication due to its negligible birefringence and the absence of polarization degradation in the atmosphere [26]. According to the widely used BB84 quantum cryptography protocol [1; 2], information is encoded in four photon polarization modes: horizontal (H) and its orthogonal vertical (V), and diagonal (D) and its orthogonal anti-diagonal (A), forming two polarization bases. Each photon polarization mode is randomly selected and shared among legitimate users. To accurately decode quantum states with the lowest possible error rate, it is necessary to optimize the polarization characteristics of QKD optical systems and align the polarization reference frames (PRFs) of the transmitter and receiver throughout the quantum communication session.

**Date of study** The polarization performance of QKD systems is usually maximized by selecting suitable coating materials and arranging optical components and mirrors to compensate for polarization distortions between them [27–30]. For satellite quantum communication, the PRF mismatch is time-dependent due to the relative rotation between the satellite and the ground station, which affects the polarization performance of the receiver [31; 32]. Consequently, numerous studies have been conducted on real-time PRF synchronization between the satellite and the ground station [33–37]. However, the simplest and most effective method is to calculate the relative rotation of the polarization bases between the satellite and the ground station based on the orbit data and dynamically adjust it using a motorized half-wave plate (m-HWP) [27; 32; 38; 39]. The relative motion calculations are carried out based on geometric considerations, with intermediate calculations allowing the satellite orbital data to be integrated into the model using the Kepler equations [38].

This paper addresses the optical, and in particular, polarization characteristics of devices participating in satellite QKD sessions. The design process of the optical systems of the receiving ground station, as well as the methodology of verification tests and measurements are described. A model for predicting the contribution to the quantum bit error (QBER) in satellite QKD sessions caused by the effect of mismatch of polarization reference systems is implemented. The paper describes the mathematical calculation of the PRF misalignment and provides polarization characteristics of the developed receiving ground station located in Zvenigorod. The results of the PRF misalignment compensation system operation during QKD sessions are presented, and the noise contribution to QBER is determined. The results of laboratory measurements and modeling are confirmed by experimental data obtained during testing sessions with the Micius satellite (QSS). The issues of the possibility of using small spacecraft for QKD are considered, optical characteristics of the developed Impulse-1 small spacecraft and the ground receiving OS for working with it are presented for the purpose of experimental validation of the calculated PRF misalignment functions and studying the influence of the operating features of the small spacecraft orientation and stabilization system on this effect in order to optimize the algorithms for conducting sessions.

**Relevance of the topic.** Thus, the **relevance** of this dissertation is determined by the following aspects: the need to increase the length of quantum key distribution networks by using satellite trusted nodes and the satellite-to-Earth channel with the introduction of satellite QKD receiving stations into the ground infrastructure; the need to minimize the quantum bit error during satellite QKD sessions using compensating systems in order to increase the resulting distribution speed and the volume of the received key; the need to model the effect of mismatch of polarization reference systems in order to predict the discrepancy before sessions and generate compensating functions; the need for experimental confirmation of the developed technical solutions in view of the complexity and sophistication of the implemented satellite QKD channels.

**The purpose of the work.** **The purpose** of this dissertation is to study the influence of the effect of mismatch of polarization reference systems in the satellite-Earth optical communication channel during quantum key distribution sessions, as well as to develop a polarization synchronization system for the optical circuit of the receiving ground station.

**The tasks of the work.** To achieve the stated goal, the following **tasks** were solved:

- Synthesis of the optical circuit of the quantum channel designed for detection of a single-photon signal in the satellite-Earth channel as part of the ground receiving station was performed, calculation of the optical characteristics of the auxiliary systems of the receiving ground station, developed for conducting sessions of satellite quantum key distribution, was performed. Practical implementation of the synthesized optical circuit was carried out, assembly, setup and adjustment of the system were successfully completed.
- Methods and laboratory auxiliary means were developed for setting up a four-channel spatial polarization analyzer used as part of the receiving station for decoding the signal in accordance with the QKD BB84 protocol, as well as for measuring the eigenfunctions of changing the polarization extinction coefficient of the developed optical circuit and in modeling optical radiation from a satellite.
- Mathematical modeling of the effect of misalignment of polarization reference systems during satellite quantum key distribution sessions has been implemented, a calculation method for the compensation function for a motorized half-wave plate for real QKD sessions is given based on the orbital parameters of the satellite and the time of communication. A test session with the Micius satellite was conducted in order to confirm the calculations and experimentally verify the functionality of the misalignment compensation system.
- A method for modeling the optical component of QBER depending on the parameters of a satellite QKD session has been developed. Experimental test sessions of QKD with a cyclic pseudo-random sequence distributed from the satellite were conducted in order to validate the model.

- An analysis of the polarization characteristics of the Vector device for the Impuls-1 MSA and adjustment of its operating parameters were performed, the contribution of the guidance system to the change in the polarization extinction coefficient was measured. Synthesis of the optical scheme of the ground station for experimental analysis of the features of the mismatch of the polarization reference system during sessions with small spacecraft was carried out.

As the **object** of the study, the system of compensation of the mismatch of polarization reference systems for satellite quantum key distribution was chosen. **The subject of the study** is the optical, in particular polarization, characteristics of the elements forming the channel of the QCD satellite-Earth.

**Research methods** In conducting the dissertation research, methods of mathematical and CAD modeling were used, to confirm the operability of the developed systems, laboratory tests were used with the use of electro-optical measuring devices. Experimentally obtained data were used to validate the modeling results.

**Scientific novelty of the work.**

1. The first hybrid optical spatial-fiber circuit of the quantum channel of the receiving station with semiconductor detectors of single photons based on avalanche photodiodes has been developed in Russia, allowing to register a polarization-coded single-photon signal from low-Earth orbit satellites.

2. An original technique for laboratory measurement of the polarization characteristics of the optical circuit of the quantum channel and experimental determination of the polarization extinction functions of the polarization analyzer channels is proposed in order to validate the operability of the station and use the data in modeling.

3. For the first time, a practical mathematical model for predicting the mismatch of polarization reference systems in the satellite channel has been developed, directly and explicitly using the functions of the spatial position of the satellite during the session, as a result of calculations using a simplified model of SGP-4 disturbances using the orbital elements of the satellite.

4. For the first time, a series of test sessions with a satellite were conducted to prepare the ground receiving station for real QKD sessions and validate the model based on the obtained data on the quantum bit error.

5. An original methodology for studying the effect of mismatch of polarization reference systems when working with small spacecraft is proposed, using the developed Vector device and the polarization channel of the ground station.

**Theoretical and practical significance of the work.** The main task of quantum cryptography is the secure delivery of a secret key to both parties, that is, quantum key distribution (QKD). Using the key obtained in this way (each time new and known only to legitimate users) for encryption can guarantee the secrecy of data transmission. It also follows from the theorem on the prohibition of cloning that the key interceptor will not be able to hide its presence and the system can always detect the interception. The most common QKD protocol at the moment is BB84, which has a strict proof of absolute secrecy. The implementation of a satellite quantum key distribution system allows expanding the boundaries of the use of existing fiber QKD systems. In addition to the possibility of deploying QKD channels to the scale of the entire Earth without using a huge number of trusted nodes, satellite technology will allow extending QKD to objects to which connection by optical fiber is impossible or irrational.

The use of the methods for designing an optical circuit of a ground receiving station for satellite QKD and the methods of polarization laboratory measurements described in this paper, together with the presented calculations and models, allows optimizing the production process and preparation for the practical use of optical ground stations and their practical testing in real communication sessions. The obtained developments were applied to the development and creation of the first in Russia optical receiving station for satellite quantum key distribution by the company OOO "KuSpace Technologies", which made it possible to conduct for the first time in Russia a session of satellite QKD of the Eurasian scale between key consumers in Russia and China at a distance of more than 3500 km, which justifies the successful **implementation result**.

**Provisions submitted for defense.**

1. The use of a multimode fiber with a core diameter of 105 um and a mirror-lens system coupled with a Ritchey-Chritien telescope with an aperture diameter of 0.6 m allows for signal detection in the entire range of residual angular error of the precise pointing contour, corresponding to a field of view of the system of $\pm 15$ urad.

2. A spatial four-channel polarization analyzer allows decoding polarization states in accordance with the BB84 quantum key distribution protocol with an average polarization extinction coefficient (PER) of 0.08%. When used as part of the quantum channel optical scheme, the synchronization of polarization reference frames (PRF) is achieved by a controlled motorized half-wave plate in the range from - 90°to +90°, providing a resulting average PER of the quantum channel in the range from 0.14% to 0.62%.

3. The range of mismatch of polarization reference frames during a test session of quantum key distribution lasting 220 seconds was ±35.7°, with a maximum satellite elevation angle of 33°. Based on the results of distribution of a pseudo-random cyclic sequence of 3 MB in size, the average value of the quantum bit error (QBER) was 0.89%. The root-mean-square error of the optical component prediction QBER using the model was 0.02%

4. The ellipticity of the output optical signal of the Vector payload as part of the small spacecraft Impulse-1 was 2.3°, with the maximum deviation of the mirror of the guidance system, the polarization extinction coefficient reaches 0.37%. The field of view of the optical scheme of the receiving ground station for measuring the polarization characteristics of radiation from the Impulse-1 satellite was ±150urad.

**Validation of the work and reliability of scientific achievements.** The main results of the work were reported at the following conferences:

- Saint-Petersburg OPEN 2022, 9th International School and Conference on Optoelectronics, Photonics, Engineering and Nanostructures. Topic of the report: "Influence of polarization reference frame rotation on ground receiver error rate in satellite quantum key distribution"

- The XIV conference “Computer-aided technologies in applied mathematics - ICAM 2022”. Topic of the report: “Cubesat based scalable quantum key distribution satellite network.”

- Saint-Petersburg OPEN 2024, 11th International School and Conference on Optoelectronics, Photonics, Engineering and Nanostructures. Topic of the report: “Polarization extinction ratio conversion due to pointing system impact in satellite quantum key distribution”.

**The reliability** of the results is based on the correctness of the numerical methods, the experimental study using the satellite, the consistency of the computational estimates and the measurement results.

**Personal contribution of the applicant.** The author of this work took an active part in setting the goal and objectives of the study, as well as in formulating the topic of the dissertation; development and design of the optical scheme of the ground station, its configuration and operation in the laboratory and directly at the Zvenigorod Observatory; implementation of a mathematical model of the mismatch of polarization reference systems; measurement, processing and analysis of data and characteristics of the Vector payload and the development of an optical ground station for sessions with it. Use of the results of the dissertation research by the applicant:

- Research and development work on the topic: “Development of a receiving module for a quantum key distribution system in open space and via satellite-to-Earth channels”, carried out under the Grant Agreement with the Foundation for Assistance to Small Innovative Enterprises.

- International experiment on the first satellite quantum key distribution in Russia (jointly with the Chinese University USTC) from the PRC satellite "Micius".

- Development of the first satellite laser communication device "Vector" in Russia for the small cubesat-format spacecraft "Impulse-1" (developed jointly with the NUST MISIS University), which was successfully launched into orbit on June 27, 2023, as part of the Roscosmos program "UniverSat2023".

**Publications on the topic of the dissertation.** List of all publications of the author on the topic of the dissertation:

1. A. Khmelev, **A. Duplinsky**, R. Bakhshaliev, E. Ivchenko, L. Pismeniuk, V. Mayboroda, I.Nesterov, A. Chernov, A. Trushechkin, E. Kiktenko, V. Kurochkin, A. Fedorov / Eurasian-scale experimental satellite-based quantum key distribution with detector efficiency mismatch analysis // Opt. Express. — 2024. — T. 32, № 7. — C. 11964—11978. **Q1**

2. A.V. Miller, L.V. Pismeniuk, **A.V Duplinsky**,V.E. Merzlinkin, A.A. Plukchi, K.A. Tikhonova, I.S. Nesterov, D.O. Sevryukov, S.D. Levashov, V.V. Fetisov, S.V. Krasnopejev, R.M. Bakhshaliev / Vector—towards quantum key distribution with small satellites // EPJ Quantum Technol. — 2023. — T. 10, № 1. — C. 52. **Q1**

3. A. V. Khmelev, **A.V Duplinsky**, V. L. Kurochkin, Yu. V. Kurochkin / Semi-Empirical Satellite-to-Ground Quantum Key Distribution Model for Realistic Receivers // Entropy. — 2023. — T. 25, № 4. — C. 670. **Q2**

4. **A.V. Duplinsky**, A.V. Khmelev, V.E. Merzlinkin, L.V. Pismenyuk, R.M. Bakhshaliev, K.V. Tikhonova, I.S. Nesterov, V.L. Kurochkin, Yu.V. Kurochkin / Cubesat based scalable satellite network for quantum key distribution // Vestnik Tomskogo gosudarstvennogo universiteta. Upravlenie, vychislitelnaja tehnika i informatika – Tomsk State University Journal of Control and Computer Science- 2023. - Vol. 63. - P. 103-110. **Q4**

5. V.E. Merzlinkin, A.V. Khmelev, **A.V Duplinsky**, V.L. Kurochkin / Polarization compensation design for free-space quantum communication transmitter // St. Petersburg State Polytechnical University Journal. Physics and Mathematics. — 2022. — T. 15, S3. 3. — C. 202—206. **Q4**

6. **A.V Duplinsky**, A.V. Khmelev, V.E. Merzlinkin, V.L. Kurochkin, V.Yu. Kurochkin / Influence of polarization reference frame rotation on groundreceiver error rate in satellite quantum key distribution // St. Petersburg State Polytechnical University Journal. Physics and Mathematics. — 2022. — T. 15, S3. 2. — C. 61—64. **Q4**

7. V. Kurochkin, A. Khmelev, V. Mayboroda, R. Bakhshaliev, **A. Duplinsky**, Yu. Kurochkin / Elements of satellite quantum network // International Conference on Micro-and Nano-Electronics 2021. T. 12157. — SPIE. 2022. — C. 492—499.

8. K.A. Barbyshev, **A.V Duplinsky**,A.V. Khmelev, V.L. Kurochkin / Efficiency of Ground Station for Quantum Communication // Bulletin of the Russian Academy of Sciences: Physics. — 2024. — T. 88, № 6. — C. 946—954. **Q4**

9. **A.V Duplinsky**, A.V. Khmelev, R.M. Bakhshaliev, D.O. Sevryukov, K.A. Barbyshev, V.L. Kurochkin / Polarization extinction ratio conversion due to pointing system impact in satellite quantum key distribution // St. Petersburg Polytechnic University Journal: Physics and Mathematics. — 2024. — T. 76, № 3.2. — C. 88—92. **Q4**

**Structure and volume of the dissertation.** The dissertation consists of an introduction, literature review, 4 chapters, conclusion and bibliography. The total volume of the dissertation is 108 pages, with 45 figures and 9 tables. The list of references includes 83 sources. The dissertation research has the following structure:

- Chapter 1 presents the calculation and synthesis of the quantum channel of the optical scheme of the receiving station used for QRD sessions with the satellite. The concept of the receiving station is described, the boundary conditions are determined based on the technical characteristics for modeling and ray tracing using CAD. The practical implementation of the developed optical scheme is presented.

- Chapter 2 describes laboratory tests and measurements of the polarization characteristics of the developed optical scheme, polarization extinction coefficients are determined using laboratory measurements. The design of the source of polarization states and the technique of its calibration for measuring the polarization characteristics of the main telescope and the optical scheme itself are described.

- Chapter 3 presents a mathematical model for calculating the functions of mismatch of polarization reference systems during QKD sessions, which allows using laboratory test data to predict the contribution of this effect to the final quantum bit error during communication sessions. The results of experimental sessions with the satellite are presented and an assessment of the model's reliability is made based on the quantum bit error data.

- Chapter 4 analyzes the features of the potential use of the MSC in QKD sessions, reflects the optical characteristics of the developed Vector payload device, proposes a method for studying the effect of mismatch of polarization reference systems when working with the Impuls-1 MSC, and develops a receiving OS for its implementation.

# References


1. *Bennett C. H.*, *Brassard G.* Quantum cryptography: public key distribution and coin tossing // In International Conference on Computer System and Signal Processing. — 1984. — Issue 1. — P. 175–179.
2. Experimental quantum cryptography / C. H. Bennett [et al.] // Journal of Cryptology. — 1992. — Issue 5. — P. 3–28.
3. *Ekert A. K.* Quantum cryptography based on Bell's theorem // Phys. Rev. Lett. — 1991. — Vol. 67, issue 6. — P. 661–663.
4. Quantum cryptography / N. Gisin [et al.] // Rev. Mod. Phys. — 2002. — Vol. 74, issue 1. — P. 145–195.
5. *Renner R.*, *Gisin N.*, *Kraus B.* Information-theoretic security proof for quantum-key-distribution protocols // Phys. Rev. A. — 2005. — Vol. 72, issue 1. — P. 012332.
6. The security of practical quantum key distribution / V. Scarani [et al.] // Rev. Mod. Phys. — 2009. — Vol. 81, issue 3. — P. 1301–1350.
7. Practical challenges in quantum key distribution / E. Diamanti [et al.] // npj Quantum Information. — 2016. — Vol. 2, no. 1. — P. 16025.
8. Secure quantum key distribution with realistic devices / F. Xu [et al.] // Rev. Mod. Phys. — 2020. — Vol. 92, issue 2. — P. 025002.
9. Twin-field quantum key distribution over a 511 km optical fibre linking two distant metropolitan areas / J.-P. Chen [et al.] // Nature Photonics. — 2021. — Vol. 15, no. 8. — P. 570–575.
10. Experimental Twin-Field Quantum Key Distribution over 1000 km Fiber Distance / Y. Liu [et al.] // Phys. Rev. Lett. — 2023. — Vol. 130, issue 21. — P. 210801.
11. A comprehensive design and performance analysis of low Earth orbit satellite quantum communication / J.-P. Bourgoin [et al.] // New Journal of Physics. — 2013. — Vol. 15, no. 2. — P. 023006.

12. Finite key performance of satellite quantum key distribution under practical constraints / J. S. Sidhu [et al.] // Communications Physics. — 2023. — Vol. 6. — P. 1–12.
13. Semi-Empirical Satellite-to-Ground Quantum Key Distribution Model for Realistic Receivers / A. V. Khmelev [et al.] // Entropy. — 2023. — Vol. 25, no. 4.
14. *Pirandola S.* Satellite quantum communications: Fundamental bounds and practical security // Phys. Rev. Res. — 2021. — Vol. 3, issue 2. — P. 023130.
15. Finite key effects in satellite quantum key distribution / J. Sidhu [et al.] // npj Quantum Information. — 2022. — Vol. 8. — P. 18.
16. *Bedington R.*, *Mantilla J.*, *Ling A.* Progress in satellite quantum key distribution // npj Quantum Information. — 2017. — Vol. 3.
17. Advances in space quantum communications / J. S. Sidhu [et al.] // IET Quantum Communication. — 2021. — Vol. 2, no. 4. — P. 182–217.
18. Micius quantum experiments in space / C.-Y. Lu [et al.] // Rev. Mod. Phys. — 2022. — Vol. 94, issue 3. — P. 035001.
19. Satellite-to-ground quantum key distribution / S.-K. Liao [et al.] // Nature. — 2017. — Vol. 549, no. 7670. — P. 43–47.
20. Satellite-to-Ground Entanglement-Based Quantum Key Distribution / J. Yin [et al.] // Phys. Rev. Lett. — 2017. — Vol. 119, issue 20. — P. 200501.
21. Satellite-based entanglement distribution over 1200 kilometers / J. Yin [et al.] // Science. — 2017. — Vol. 356, no. 6343. — P. 1140–1144. — eprint: `https://www.science.org/doi/pdf/10.1126/science.aan3211`.
22. Ground-to-satellite quantum teleportation / J.-G. Ren [et al.] // Nature. — 2017. — Vol. 549, no. 7670. — P. 70–73.
23. Satellite-Relayed Intercontinental Quantum Network / S.-K. Liao [et al.] // Phys. Rev. Lett. — 2018. — Vol. 120, issue 3. — P. 030501.
24. An integrated space-to-ground quantum communication network over 4,600 kilometres / Y.-A. Chen [et al.] // Nature. — 2021. — Vol. 589, no. 7841. — P. 214–219.

25. Microsatellite-based real-time quantum key distribution / Y. Li [et al.] // Nature. — 2025. — Vol. 640. — P. 47–54.

26. Polarization measurements through space-to-ground atmospheric propagation paths by using a highly polarized laser source in space / M. Toyoshima [et al.] // Opt. Express. — 2009. — Vol. 17, no. 25. — P. 22333–22340.

27. Polarization design for ground-to-satellite quantum entanglement distribution / X. Han [et al.] // Opt. Express. — 2020. — Vol. 28, no. 1. — P. 369–378.

28. Polarization-maintaining design for satellite-based quantum communication terminals / J. Wu [et al.] // Optics Express. — 2020. — Vol. 28, no. 8. — P. 10746–10759.

29. Polarization extinction ratio conversion due to pointing system impact in satellite quantum key distribution / A. V. Duplinsky [et al.] // St. Petersburg State Polytechnical University Journal. Physics and Mathematics. — 2024. — Vol. 17, no. 3.2. — P. 88–92.

30. Experimental validation of dynamic polarization compensation in ground-satellite quantum key distribution / C. Wang [et al.] // Sci. China Phys. Mech. Astron. — 2014. — Vol. 57, no. 1. — P. 1233–1237.

31. Influence of polarization reference frame rotation on ground-receiver error rate in satellite quantum key distribution / A. Duplinsky [et al.] // St. Petersburg State Polytechnical University Journal. Physics and Mathematics. — 2022. — Vol. 15. — P. 61–64.

32. Influence of satellite motion on polarization qubits in a Space-Earth quantum communication link / C. Bonato [et al.] // Opt. Express. — 2006. — Vol. 14, no. 21. — P. 10050–10059.

33. Development of the polarization tracking scheme for free-space quantum cryptography / M. Toyoshima [et al.] // Atmospheric Propagation V. Vol. 6951 / ed. by G. C. Gilbreath, L. M. Wasiczko. — International Society for Optics, Photonics. SPIE, 2008. — P. 69510I.

34. Polarization-Basis Tracking Scheme in Satellite Quantum Key Distribution / M. Toyoshima [et al.] // International Journal of Optics. — 2011. — Vol. 2011, no. 1. — P. 254154.

35. Real time basis-deviation measurement system based on BB84 module / M. Zhang [et al.] // International Symposium on Photoelectronic Detection and Imaging 2013: Laser Communication Technologies and Systems. Vol. 8906 / ed. by K. E. Wilson [et al.]. — International Society for Optics, Photonics. SPIE, 2013. — P. 890629.
36. Polarization tracking for quantum satellite communications / G. Wang [et al.] // Sensors and Systems for Space Applications VII. Vol. 9085 / ed. by K. D. Pham, J. L. Cox. — International Society for Optics, Photonics. SPIE, 2014. — 90850T.
37. Detection and compensation of basis deviation in satellite-to-ground quantum communications / M. Zhang [et al.] // Opt. Express. — 2014. — Vol. 22, no. 8. — P. 9871–9886.
38. General model on polarization compensation in satellite-to-ground quantum communication / M. Li [et al.] // Optical Engineering. — 2013. — Vol. 52, no. 4. — P. 045001.
39. Research on polarization compensation for practical satellite-based quantum key distribution / W.-B. Luo [et al.] // Optics Communications. — 2024. — Vol. 570. — P. 130925.