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Measuring of atmospheric background noise in free-space quantum key distribution systems operating at the 1550 nm wavelength in daylight conditions

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In this work we study the level of the background noise at the 1550 nm wavelength, caused by solar radiation, in free-space quantum key distribution systems. We describe the experimental setup for measuring the mean number of photons arriving at a single-photon detector during a gate. We then provide the methodology for recalculating the mean photon number per gate into the absolute value of spectral radiance at the input of the experimental setup. As a result, we obtain experimental data on the background noise spectral radiance coming from the sky and various vertical surfaces scattering solar radiation. The experimental data is obtained for Moscow under various external conditions, such as weather, season and time of day. Since the obtained data does not depend on the specific parameters of the experimental setup, they can be used to estimate the level of the background noise and the signal-to-noise ratio for any receiving optical communication system, including free-space quantum key distribution.

Keywords: free-space quantum key distribution, methods of limiting background noise, spectral radiance of background noise.

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Introduction

Quantum key distribution (QKD) is an actively developing field of science and technology that is directly related to the task of information security. This technology is currently the only known solution to the problem of secret key distribution for which is provable secure. The basis of the QKD is the transfer of the quantum states of single photons between two parties through an optically transparent channel.

The creation of QKD fiber-optic systems is most developed area currently [1–3]. But there is an alternative solution — transmission of quantum states over an open space within line of sight between two parties [4–7]. These communication channels are called „atmospheric“, as they correspond to the free propagation of radiation through the atmosphere. Such lines are of interest both from the point of view of creating keys between a ground station and a satellite, and between spaced locations on the earth's surface, the laying of optical fiber between which for some reason is impossible or unprofitable.

Free-space quantum key distribution (free-space QKD) systems are not yet as widespread as fiber-optic systems. This is mainly due to scattering, photon absorption, turbulence, unpredictability of weather events, and in space, the complexity and high cost of the necessary equipment and infrastructure. Free-space quantum channels were demonstrated despite these difficulties, both stationary [4–7] and mobile, including the distribution of keys to high altitude platforms and unmanned aerial vehicles [8] over distances of the order of tens of kilometers.

As in classical communication, QKD performance depends on the signal-to-noise ratio (SNR), which directly affects the quantum bit error rate (QBER) in the sifted key. The signal-to-noise ratio is defined as the mean number of signal photons relative to the number of noise photons per gate of single-photon detector (SPD). The signal-to-noise ratio can be increased in classical optical communication systems by increasing the useful signal level. This feature is not available for QKD systems, since they use single-photon or attenuated coherent radiation with an mean photon number per pulse less than one as a useful signal. Thus, the only way to ensure the required signal-to-noise ratio in QKD systems is to reduce noise levels.

The primary noise sources in free-space QKD systems are detector dark counts and background noise, originating mainly from sunlight reflected off surfaces and scattered by the atmosphere, as well as moonlight, starlight, and artificial light sources. However, the background noise makes a significantly greater contribution to the noise in the daytime than the detector dark count [9]. Therefore, the task is to limit background noise when designing free-space QKD systems operating in daytime conditions. The following methods are used to solve this problem: selection of the operating wavelength, spectral, temporal and spatial filtering [9,10], as well as orientation to the north, shielding from direct sunlight by a lens hood and blackening of the scattering surfaces of the transmitter.

Traditionally, the free-space QKD quantum channel uses wavelengths in the near infrared (IR) range that fall within the atmospheric transparency windows — 780 and 850 nm [5,7]. This is attributable to the use of relatively cheap single-photon silicon detectors with high quantum efficiency and low intrinsic noise, the spectral sensitivity of which extends up to 900−1000 nm. However, recently, work has been increasingly appearing with the wavelength of the quantum channel 1550 nm [4,6,11], for which atmospheric transmission is higher compared to 850 nm. This is especially true for systems operating in daylight, since the intensity of solar radiation at 1550 nm is about five times weaker than at 800 nm. In addition, the main type of scattering of solar radiation in the atmosphere is Rayleigh scattering, the intensity of which is proportional to $1/\lambda^4$ and is only 7% of the value at 800 nm at 1550 nm. The total background noise intensity at 1550 nm wavelength accounts for only 3% of the noise level at 800 nm [4].

It was proposed in [12] to use the wavelength of 1370 nm in the region of absorption by water molecules and CO_2, which significantly reduces the intensity of external noise from the Sun and does not significantly increase losses over short distances. The authors measured the noise under various conditions for the selected wavelength using a 10 nm wide filter. The result shows that indoor noise from the Sun is comparable to the dark noise of a single-photon detector.

Spatial filtering comprises the reduction of the angular field of the free-space QKD optical receiving system. Since the quantum signal of the transmitter propagates in the atmosphere in the form of a weakly diverging beam, the angular field of the receiver can be reduced to the values of $10-100\,\mu$rad. Limiting of the size of the receiving aperture is another spatial filtering method. The minimum size of the aperture is determined by the maximum allowable resulting losses.

Spectral filtering consists in limiting the operating spectral range of the receiving optical system by installing narrow-band filters. Moreover, the narrower the spectral width of the filter, the more stringent the requirements for wavelength stabilization of the radiation source for the quantum channel.

In addition to reducing the effect of background illumination, temporary filtering also reduces the dark count rate of the detector. This is achieved by reducing the duration of the gate — the time window in which the detector is sensitive to incoming radiation. The detector remains in the closed state until the arrival of the signal photon is expected. Therefore, to increase the efficiency of time filtering, it is necessary to synchronize the transmitter and receiver of the quantum channel with high accuracy.

Thus, for optimal selection of filtration parameters, it is useful to evaluate the external conditions in which the free-space QKD system is expected to operate. For example, the daylight noise from a clear sky was measured in Germany in Ref. [11] during the development of the QKD system for the satellite — the Earth's surface route.

The purpose of this work is to estimate the level of background noise from the sky and various surfaces scattering solar radiation at a wavelength of 1550 nm, which can be used in the future for designing free-space QKD systems. The spectral radiance of noise radiation $L_{b,\lambda}$, $W/(m^2 \cdot sr{\cdot}nm)$ can be used as a characteristic describing the intensity of background noise and independent of the specific parameters of the free-space QKD system. Knowing this value will make it possible to design the parameters of the free-space QKD optical receiving system in such a way that the number of noise counts allows obtaining the secret key in daylight noise conditions.

Experimental setup

A single-photon SPD-NIR detector from AUREA Technology with a multimode fiber connector with a core diameter of $d_c = 50\,\mu$m was chosen as the radiation receiver. Multimode fiber has larger core diameter and numerical aperture values compared to singlemode fiber, which makes it possible to increase the received signal level. The scheme and appearance of the setup are shown in Fig. 1.

When using the fiber end face directly as a receiving aperture, the angular field of the experimental setup turns out to be unacceptably large. The numerical aperture of the OM2 fiber is $NA = 0.2$. When measuring the noise from an object removed at a distance of 1 km, the diameter of the observed area will be 400 m. Thus, the subsequent conversion of the measured number of photons into spectral radiance becomes impossible. The angular field of the receiver was reduced by using F220FC-1550 Thorlabs collimator (collimator *1* in Fig. $1, a$) with an aperture diameter of $D = 6$ mm, numerical aperture of $NA = 0.24$ and a focal length of $f' = 11.29$ mm. Next, the optical characteristics of the setup were experimentally measured. Half of the angular field of the input collimator F220FC-1550 with multimode OM2 fiber was $\theta = 1.218$ mrad, collimator was $D = 4.247$ mm. Thus, the area from which the setup collects the noise radiation is a circle with a diameter of about 2.5 m at a distance of 1 km. The receiving collimator was mounted on the theodolite UOM3 3T2KP to accurately target the setup at the studied object (the noise source) (Fig. $1, c$). The optical axes of the collimator and the telescope of the theodolite were adjusted to achieve

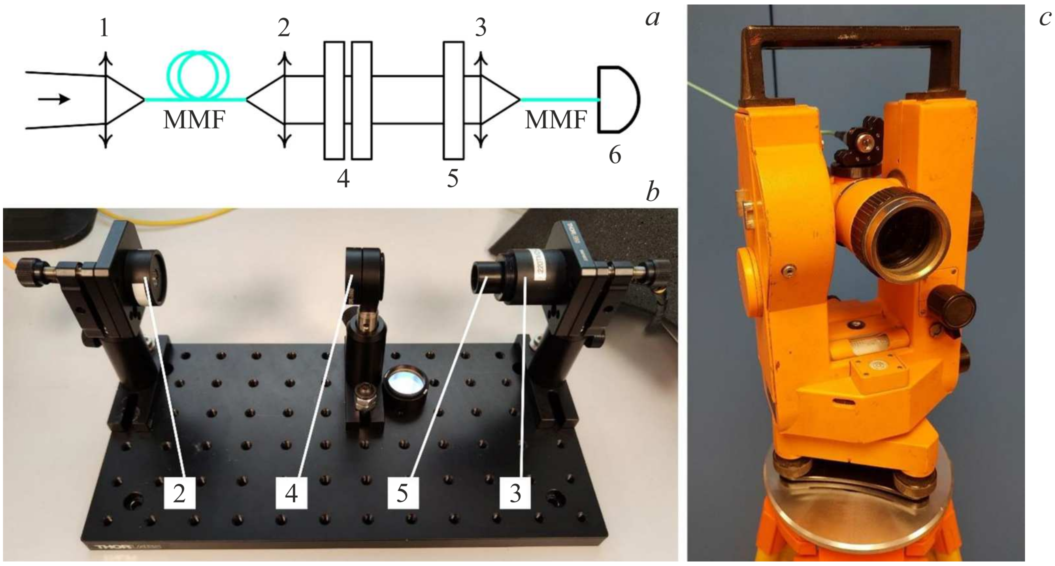

Figure 1. (*a*) The experimental setup for measuring noise: *1, 2, 3* — collimators, *4* — neutral-density filter, *5* — spectral filter, *6* — single photon detector; (*b*) appearance of the optical bench with filters; (*c*) receiving collimator F220FC-1550 mounted on a theodolite.

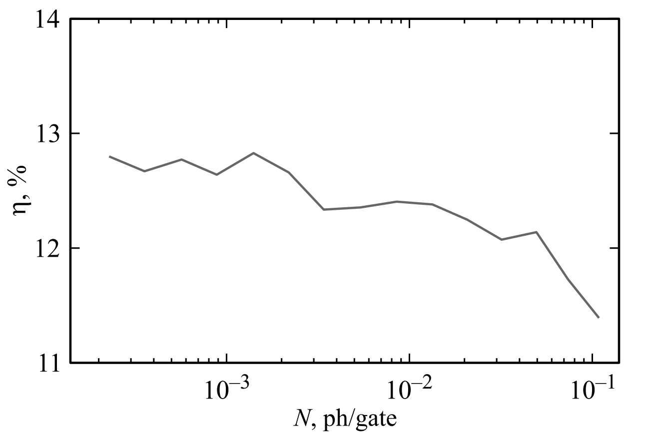

Figure 2. The measured quantum efficiency of SPD-NIR AUREA Technology detector depends on the recorded average number of photons per gate with the following parameters: gate frequency $f_{st} = 1.25$ MHz, gate duration $\Delta t = 20$ ns, set quantum efficiency $\eta = 10\%$, dead time $0.8\,\mu$s.

parallelism. To do this, the theodolite with a collimator was directed to the solar disk, the image of which was displayed in the center of the crosshair of the telescope. The direction of the optical axis of the collimator was changed by adjusting KM05T Thorlabs kinematic mount until the maximum signal was reached at the single-photon detector. The estimated adjustment error was 2 mrad.

The free-space optics filter FL051550-40 Thorlabs (*5* in Fig. 1, *a, b*) with a central wavelength of 1550 nm and a full width at half maximum of 40 nm was used as a spectral filter. This filter has no additional bandwidth over the entire sensitivity range of a single-photon detector from 900 to 1700 nm. An optical bench was assembled (Fig. 1, *b*) with two C220TMD-C and C397TMD-C Thorlabs collimators forming a parallel beam for working with these and other filters. The losses on the optical bench with collimators and a spectral filter were −1.6 dB. The effect of indoor background noise was reduced by by installing a spectral filter directly in front of the C220TMD-C collimator that was connected to a single-photon detector via an OM2 multimode fiber. The detector was connected to a personal computer with special software that allowed long-term recording of the recorded average number of photons per gate N_b, ph/gate.

The quantum efficiency of a single-photon detector was separately calibrated. The graph of the measured dependence of the quantum efficiency of the SPD on the average number of photons per gate detected by the detector is shown in Fig. 2.

The experimental setup was calibrated using a light source with known spectral characteristics of the radiation to verify the correctness of the results obtained. The solar radiation was chosen as such a source, the spectral radiance of which is known and can be obtained from data calculated in the SMARTS [13] program for various conditions, including date, orientation and geographical location. Thus, the dynamic range of the experimental setup should have made it possible to measure both direct solar and atmospheric radiation. The measurements were conducted with fixed characteristics of a single-photon detector for simplifying the comparison of the measurement results. Therefore, NEK01 Thorlabs neutral-density filters pre-calibrated at a wavelength of 1550 nm, were added to the experimental setup to ensure the required dynamic range (4 in Fig. 1, *a, b*).

Calibration of the experimental setup

The results of experiments for measuring the background noise are data on the average number of photons per gate recorded by SPD-NIR single-photon detector, which is determined by the characteristics of the experimental setup, as well as the time of year and day, weather and atmospheric conditions. Therefore, it is necessary to recalculate the measured average number of photons per gate N_b, ph/gate, to a value independent of the detection parameters, for example, to the spectral radiance of noise $L_{b,\lambda}$, W/(m^2·sr·nm), at the input aperture. This makes it possible to apply the experimental results for designing various optical receiving systems, including free-space QKD receiving modules. Knowing the spectral radiance and optical parameters of a particular receiving system, it is possible to calculate the expected noise value.

The radiant flux power P_b, W, recorded by the experimental setup, can be calculated using the expression

$$P_b = L_{b,\lambda}\Omega_{fov}A_{rec}\Delta\lambda 10^{0.1L_{Rx}},$$

where Ω_{fov} is the solid angle of the field of view of the setup, sr; A_{rec} — the effective area of the input aperture of the setup, m^2; $\Delta\lambda$ — the width of the spectral bandwidth of the setup, m; L_{Rx} — losses introduced by the optical components of the setup, dB.

The spectral bandwidth of the setup is determined by the spectral width of the FL051550-40 filter, which is 40 nm. The number of detected photons per gate is related to the detected flux as follows:

$$N_b = \frac{P_b\Delta t}{hc/\lambda}\eta,$$

where Δt is gate duration of a single-photon detector, s; λ — the central wavelength of the spectral filter, m; η — quantum efficiency of a single-photon detector; $h = 6.626 \cdot 10^{-34}$ J·s — Planck's constant; $c = 3 \cdot 10^8$ m/s — the speed of light in a vacuum.

Taking into account the expressions for the solid angle $\Omega_{fov} = \pi\theta^2$ and the aperture area $A_{rec} = \pi D^2/4$, where θ is the half of the angular field, rad, D is the effective diameter of the entrance aperture of the setup, *m*, the average number of photons per gate detected by the detector is

$$N_b = \frac{L_{b,\lambda}\pi^2(\theta D)^2\lambda\Delta\lambda\Delta t}{4hc}\eta 10^{0.1L_{Rx}}. \quad (1)$$

This expression allows for a theoretical calculation of the average number of photons per gate at a known spectral radiance of the incoming radiation and the parameters of the experimental setup and comparing it with the calibration value. The setup was calibrated on September 3, 2024 at 15:00. For this purpose, the receiving collimator of the setup was directed at the solar disk. All calibration-related values will be indicated by a tilde at the top in the text. The average measured number of photons per gate when installing neutral filters with a total attenuation index of $\tilde{L}_{NF} = -62.55$ dB was

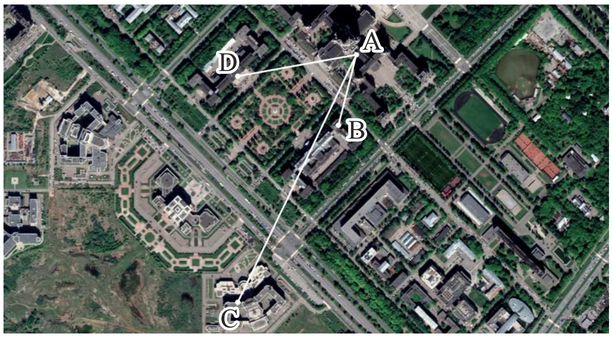

Figure 3. Paths for conducting noise measurement experiments: *A* — the main building of Moscow State University, *B* is the building of the Faculty of Physics of Moscow State University, *C* is the buildings of the Faculty of Fundamental Medicine of Moscow State University, *D* is the building of the Faculty of Chemistry of Moscow State University.

$$\tilde{N}_b = 0.0171 \text{ ph/gate}.$$

According to the Hydrometeorological Center of Russia [14], the meteorological optical range in Moscow at that time was 20 km. The spectral irradiance by direct sunlight from a sun-oriented surface $E_{\text{Sun}} = 216.8$ mW/(m^2·nm) was obtained for these conditions for $\lambda = 1550$ nm using the SMARTS program. Based on the assumption that the solar disk is a Lambert radiator with an angular size of $\theta_{\text{Sun}} = 18' = 4.65$ mrad, the spectral radiance of the radiation arriving at the experimental facility was calculated as follows:

$$\tilde{L}_{b,\lambda} = \frac{E_{\text{Sun}}}{\pi \cdot \sin^2\theta_{\text{Sun}}} = 3192 \text{ W/(m}^2 \cdot \text{nm} \cdot \text{sr)}.$$

Then the theoretical number of noise photons per gate can be obtained using the expression (1), taking into account the following parameters of the experimental setup: angular field $\theta = 1.218$ mrad, effective aperture diameter $D = 4.247$ mm, center wavelength $\lambda = 1550$ nm, spectral filter width $\Delta\lambda = 40$ nm, receiver gate duration $\Delta t = 20$ ns, receiver quantum efficiency $\eta = 12.5\%$, optical system loss by 1550 nm $L_{Rx} = -1.6$ dB:

$$\tilde{N}_b^{\text{theor}} = \frac{\tilde{L}_{b,\lambda}\pi^2(\theta D)^2\lambda\Delta\lambda\Delta t}{4hc}\eta 10^{0.1}\left(L_{Rx} + \tilde{L}_{NF}\right) = 0.063 \text{ ph/gate}.$$

The error can be calculated by comparing the obtained value with the calibration value:

$$\frac{\tilde{N}_b^{\text{theor}} - \tilde{N}_b}{\tilde{N}_b^{\text{theor}}}100\% = 73\%.$$

The error is associated with the unaccounted losses: in the receiving collimator, in multimode fiber with a length

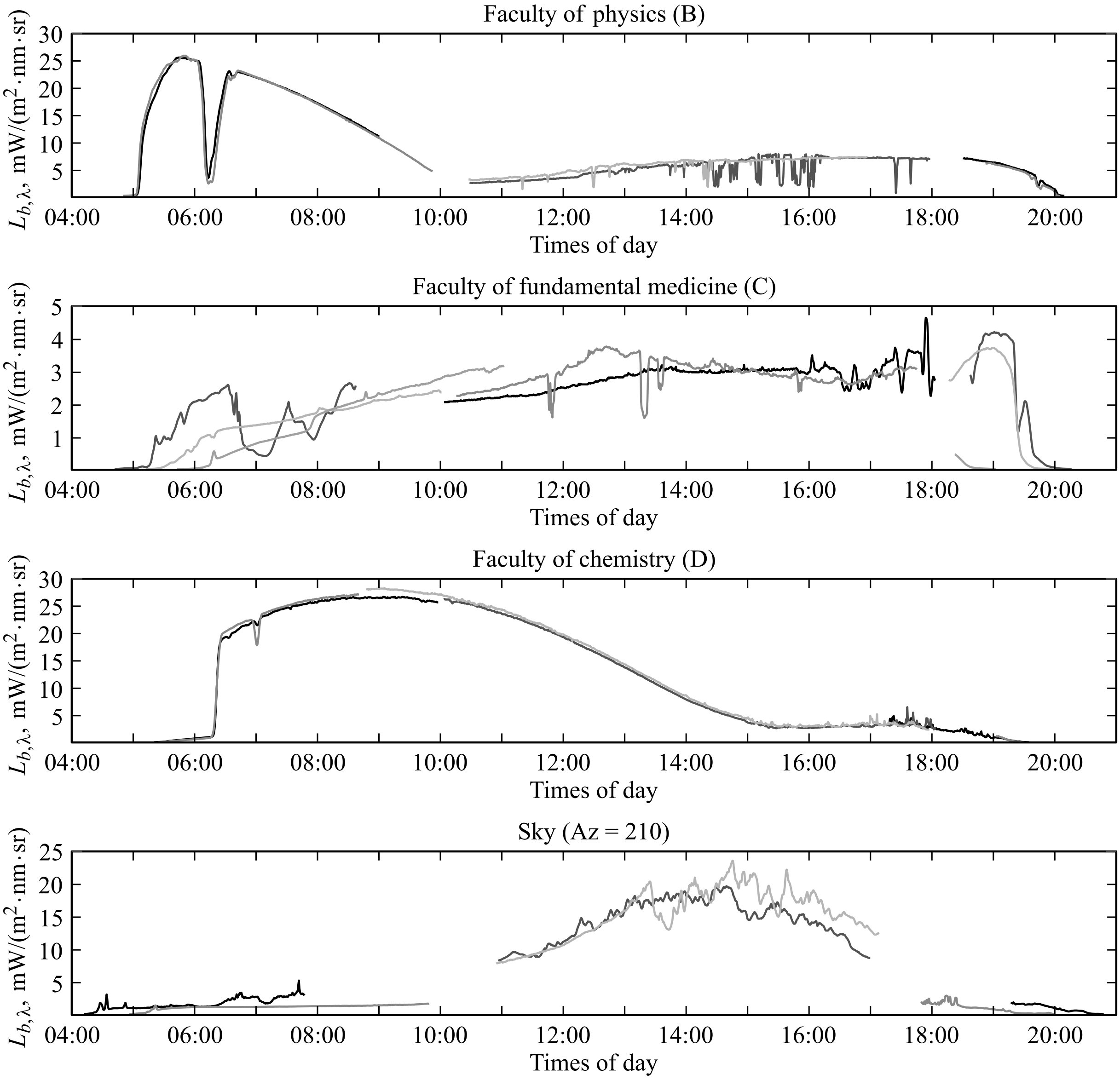

Figure 4. The results of measuring the spectral radiance of background noise at a wavelength of 1550 nm from July to September for Moscow in clear and partly cloudy weather.

of 50 m, and on optical connections. Thus, it is necessary to introduce a correction factor in the expression (1) that takes into account the discrepancy between theoretical and experimental data:

$$K_1 = \frac{\tilde{N}_b}{\tilde{N}_b^{\text{theor}}} = 0.27.$$

Taking into account the obtained calibration values for this experimental setup, a coefficient can be calculated for converting the number of photons recorded by the setup into the spectral radiance of the background noise at the input aperture:

$$L_{b,\lambda} = \frac{4hc}{\pi^2(\theta D)^2\lambda\Delta\lambda\Delta t\eta 10^{0.1L}K_1}N_b = K_2 N_b.$$

By opening K_1, we get a simplified expression for determining the conversion factor K_2:

$$K_2 = \frac{4hc\tilde{N}_b^{\text{theor}}}{\pi^2(\theta D)^2\lambda\Delta\lambda\Delta t\eta 10^{0.1(L_{Rx}+L_{NF})}\tilde{N}_b}$$

$$= \frac{4hc\frac{\tilde{L}_{b,\lambda}\pi^2(\theta D)^2\lambda\Delta\lambda\Delta t}{4hc}\eta 10^{0.1(L_{Rx}+\tilde{L}_{NF})}}{\pi^2(\theta D)^2\lambda\Delta\lambda\Delta t\eta 10^{0.1(L_{Rx}+L_{NF})}\tilde{N}_b}$$

$$= \frac{\tilde{L}_{b\lambda}}{\tilde{N}_b}10^{0.1\tilde{L}_{NF}}10^{-0.1L_{NF}}.$$

Thus, for this experimental setup, the conversion factor is determined as follows:

$$K_2(L_{NF}) = 103.8 \cdot 10^{-0.1L_{NF}}\ \text{mW/(m}^2\cdot\text{nm}\cdot\text{sr)},$$

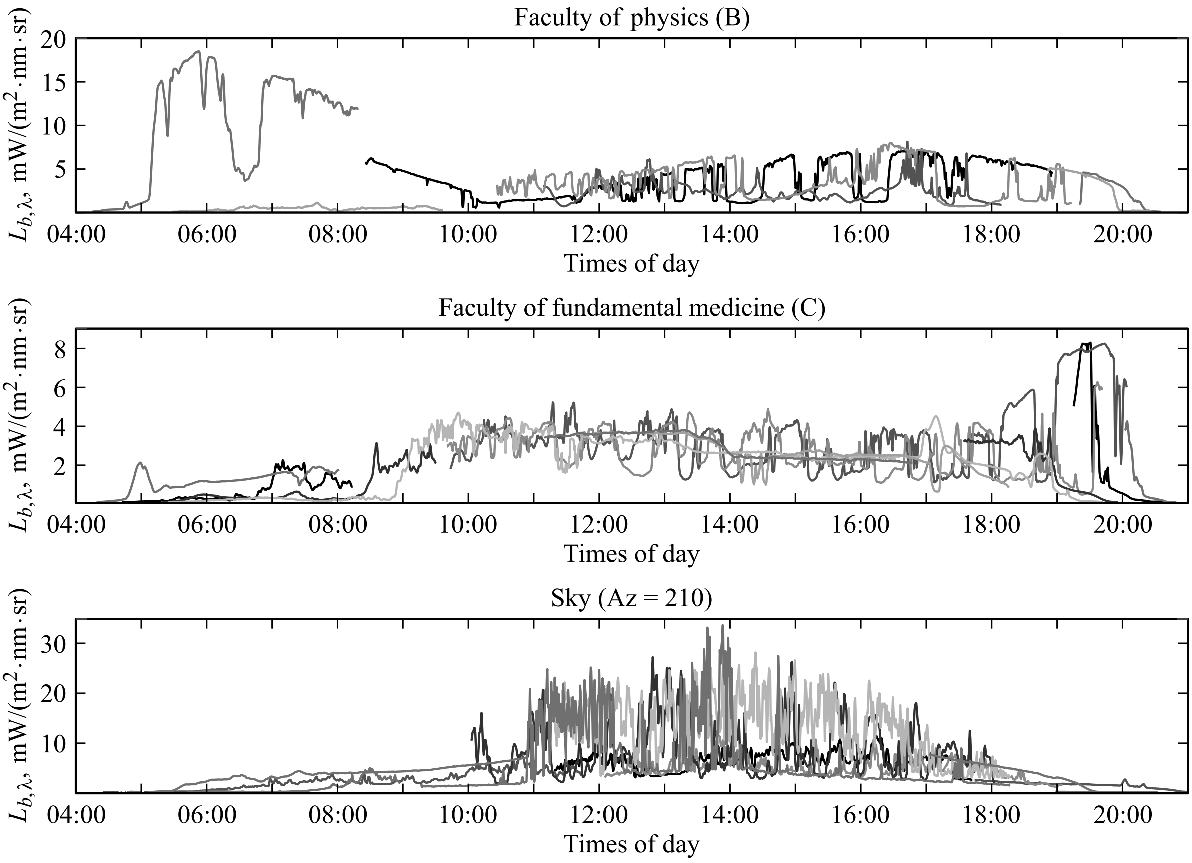

Figure 5. The results of measuring the spectral radiance of background noise at a wavelength of 1550 nm from July to September for Moscow in cloudy weather.

where $L_{NF} < 0$ is the attenuation introduced by the installed neutral filters, dB.

Measurement results

The experiment to measure background noise was conducted from July to September 2024 for three horizontal atmospheric paths (Fig. 3) with lengths of 200 m (AB), 750 m (AC) and 330 m (AD), as well as from the sky.

The experimental setup was located in the main building of Lomonosov Moscow State University(A). Background noise measurements were carried out from the buildings of the Faculty of Physics (B), the Faculty of Fundamental Medicine (C) and the Faculty of Chemistry (D), as well as from the sky above C. The background noise signal was recorded by the experimental setup from 4:00 to 21:00. The signal at night was lower than the intrinsic noise level of the single-photon detector, equal to $2 \cdot 10^{-5}$ ph/gate. The results of the measurement series, recalculated into the values of the spectral radiance of the radiation coming to the input of the installation, are shown in Fig. 4–6. The curves corresponding to the various measurements are represented in shades of gray.

A vertical surface oriented at 45° relative to the north direction was observed for the Faculty of Physics (B). The surface was illuminated by direct sunlight from 5:00 to 10:00 in the period from August 14 to August 19. The decrease in the signal at 6:15 is attributable to the shadow falling on the observed area. Similarly, the wall of the Faculty of Chemistry (D) oriented at 135° to the north was observed from August 28 to August 30. The wall was exposed to a direct sunlight from 6:30 a.m. to 3 p.m. At the same time, the maximum spectral radiance of the radiation reflected from these surfaces was 25.7 and 28 mW/(m^2·sr·nm) for the Physics and Chemistry faculties, respectively. From 10:00 for the physics faculty and from 15:00 for the chemistry faculty, the observed surfaces were in shadow. The spectral radiance of the light reflected from them was attributable to atmospheric scattering and amounted to 3–7 mW/(m^2·sr·nm). These values are close to the results obtained for the Lomonosov building (C), the observed surface of which was always in shadow during the experiment. When observing the sky above the horizon, even in clear weather, there was a slight haze, while the maximum brightness was 23.3 mW/(m^2·sr·nm).

Comparing the graphs in Fig. 4 and 5, it is possible to conclude that an increase of cloud cover leads to a decrease of the spectral radiance of the reflecting surface when it is illuminated by direct sunlight. The brightness of the shaded surface, on the contrary, increases as the

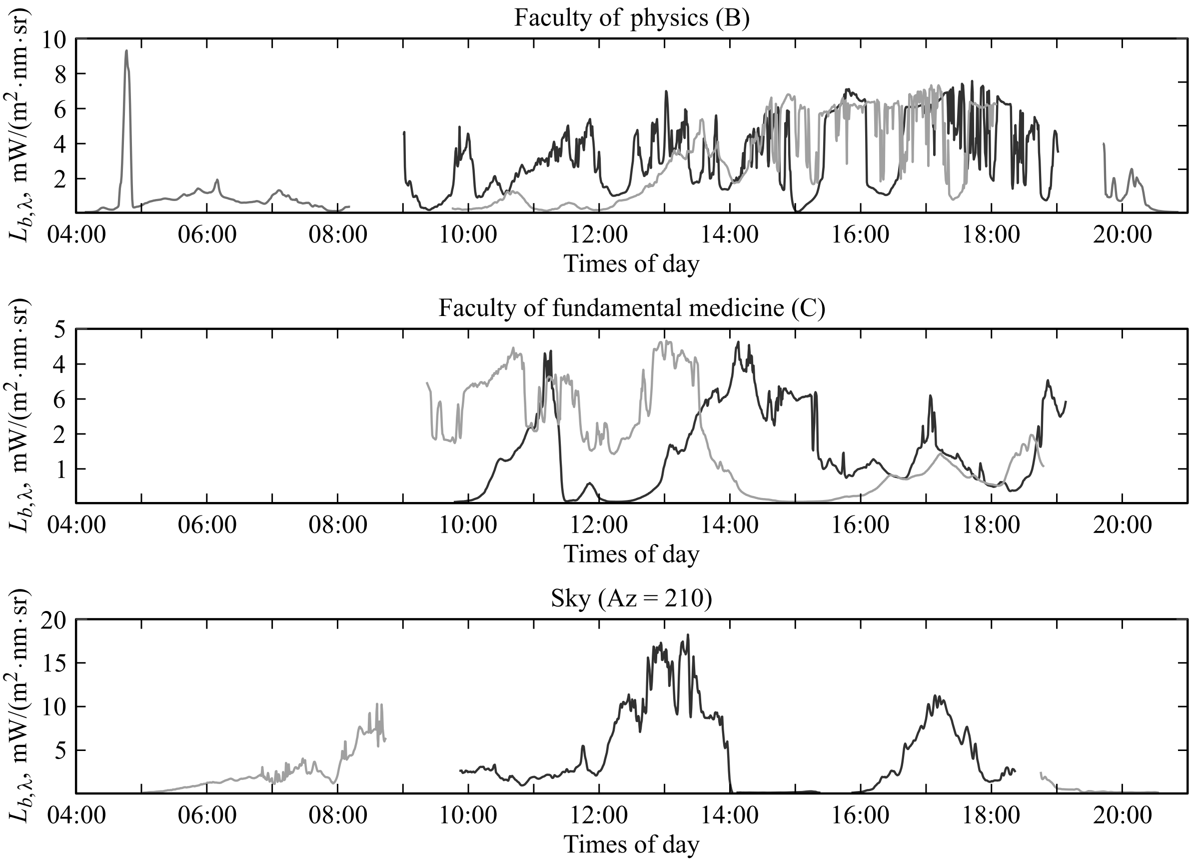

Figure 6. The results of measuring the spectral radiance of background noise at a wavelength of 1550 nm from July to September for Moscow in the rain.

intensity of the radiation scattered by the atmosphere increases, which is confirmed by the results obtained for the sky. Thus, the presence of clouds led to an increase of the brightness of the observed wall of the Lomonosov building from 4.2 mW/(m^2·sr·nm) for clear weather to 8.1 mW/(m^2·sr·nm) for cloudy, and the sky radiation increased to 33.2 mW/(m^2·sr·nm).

The spectral radiance of the surfaces in the shadow and the sky in the conditions of cumulonimbus clouds remained at the same level as in the clear weather (Fig. 6). However, the signal decreased to a noise level regardless of the observed surface during raining. Therefore, it is possible to talk about constraints in the operation of free-space QKD systems associated with an increase of absorption in the atmospheric channel in conditions of intense precipitation, fog or dust storm.

Conclusion

The creation of free-space QKD systems is a rather complicated process, which is usually carried out with incomplete information about the features of the optical radiation propagation enviroment. Therefore, at the initial stage of their design, it is necessary to take into account the absorption, scattering, turbulence of the atmosphere characteristic of the proposed path and, of course, backgrong noise from solar radiation, if the free-space QKD is designed to operate in daytime conditions.

This paper presents an experimental setup and technique that makes it possible to measure the absolute value of the spectral radiance of the noise radiation for the proposed path in the selected spectral range, as well as its measurements at a wavelength of 1550 nm for horizontal paths in the conditions of Moscow. The obtained data on the spectral radiance of the noise radiation using the expression (1) make it possible to estimate the number of illumination photons detected by the free-space QKD system with known parameters such as the effective size of the input aperture, the angular field, the width of the spectral filter and the duration of the receiver gate; and to determine the signal-to-noise ratio under various external conditions with a known useful signal level.

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Conflict of interest

The authors declare that they have no conflict of interest.

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