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External Referee's Report on the Ph.D. Thesis by **Mykyta Klen** with title
Statistical models and temporal coherence of quantum light in the turbulent atmosphere submitted **for the degree of Doctor of Philosophy**, 104–Physics and astronomy, Field of study: 10–Natural sciences at the **Bogolyubov Institute for Theoretical Physics** of the **National Academy of Sciences of Ukraine.**

The thesis deals with the problem of the description of the propagation of quantum states in the atmosphere. The tools used are the analytical and numerical analysis of the transmission in the presence of turbulence. This issue maintains its centrality as a problem of free space transmissions, which originated in the context of classical communications and for over two decades has also been extended to quantum communications. The Thesis aims to describe the relationship between transmission probability and some parameters such as receiver size and time correlation, useful in encoding states using temporal modes. The thesis elaborates analytical models in an advanced way and compares them with the split step numeric.

The analytical results were obtained with rigor, well representing the famous school of the Bogolyubov Institute od NASU, known internationally. The methodological approach is precise and consistent.

The presentation of the thesis is clear and well written. The candidate has also taken care of the descriptive aspects and listed the innovations and methods in an exhaustive way. The language is very correct. The graphs are clear and so are the references. We can see that the choice of references does not include results from very recent years, thus losing a fair amount of useful results, given the great progress of the sector. Including some of the latter ones would be helpful.

We note that on the development of the numerical analysis, the setting and numerosity of the phase screens are related to the intrinsic atmospheric scale. In this context, a different approaches uses instead the reference to the observation-plane region of interest, and for the spatial frequency limits, the detector scale. This is discussed for example in the manual by Schmidt and detailed in its Chap. 7[1]. A discussion on the relation of this more phenomenological viewpoint would be useful. In this regards, also the analysis of the angle-of-arrival is relevant, as it conditions the optical design of the receiver and of potential turbulence correctors.

We note that the validation of the analytical models are realized by means of numerical simulations, with three different Rytov variances. Now, the probability distribution of transmittance (PDT) and the beam-centroid spread have been assessed for many real channels and may provide a valuable reference for the predictions. This from the pure-wandering case of short tracks to the extreme cases of the Canary link, beside the satellite cases (JAXA, ESA and then CAS). Only to cite our own results, results on the different lengths are reported in literature[2]. A discussion on these references may be useful too.

We note that in the selection of the channel lengths to be analysed, the very short range (interbuilding 100-500 m) and the metropolitan on (3-10 km) were not considered. As they correspond to several applications, a discussion would be useful.

The selection of the wavelength for the quantum states is also relevant. Many results have shown advantages in reduced background light and larger Fried parameter moving toward C-band. Indeed the almost linear scaling of this latter crucial parameter supports the adoption of 1550 nm light. This also allows the use of the telecom technology, that is both very advanced and cheaper than for NIR. Also on the wavelength dependence of the results, a discussion would be useful.

By taking the case of the example of the writing of a flying qubit on a quantum memory in sec. 6.2, the scheme generally considered in the Thesis is of free-space detection. While

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[1] Jason D. Schmidt, Numerical simulation of optical wave propagation with examples in MATLAB, SPIE Press, 2010, ISBN 978-0-8194-8326-3

[2] References in increasing length of the channel.

a. Avesani, M. et al. Full daylight quantum-key-distribution at 1550 nm enabled by integrated silicon photonics. npj Quantum Inf. 7, 93 (2021).

b. Picciariello, F. et al. Intermodal quantum key distribution field trial with active switching between fiber and free-space channels. EPJ Quantum Technol. 12, 6 (2025).

c. Rossi, E. et al. Intermodal quantum key distribution over an 18 km free-space channel with adaptive optics and room-temperature detectors. arXiv:2602.16680 [quant-ph] (2026).

d. Capraro, I. et al. Impact of Turbulence in Long Range Quantum and Classical Communications. Phys. Rev. Lett. 109, 200502 (2012). This is ref. 59 in the Thesis, but the results are not used.

it's possible to interact with the memory active medium with a multimode beam, the subsequent reading pulse cannot reproduce the turbulence-induced spatial spectrum of the writing, causing a significant drop in fidelity. For this reason as well as for more technical ones as the necessary ultranarrow spectral filtering, the memory is usually made to interact with a single spatial mode, either guided or free space. In addition, C-band light usually foresees the quantum measurement and the detection to be realised with single-mode fiber systems. This aspect is imposing a more advanced criteria for the entire transmissivity assessment. Indeed the relation changes from Eq. 5.3 to one in which the integrand function contains the single mode function as $u_t(r,z)\psi^*(r)$ and not just $|u_t(r,z)|^2$. This aspect also relates on the mitigation of turbulence with active/adaptive means, very common for example in the classical coherent detection in satellite communications. This is very relevant in the situation of quantum channels, in which the losses cannot be mitigated by increasing the transmitted power. Some analysis are available, including from ours[3], and a discussion on this aspect would be very useful.

Finally we note that the result about the persistence of quantum entanglement and nonclassicality in general over millisecond to tens-of-milliseconds timescales in turbulent atmospheric channels is a very useful notion for advanced experimental scheme. An analysis of potentialities may be included. As example, it may be used in the study of bringing the Colella-Overhauser-Werner (COW) interference test is the space context for assessing general relativity effect on photonic quantum states with a required relative precision in the phase estimate of the order of 10^{-8} as described in the references[4].

In conclusion, the Thesis is sound and well written and originated significant publications and talks.

Therefore, we strongly recommend the awarding of PhD title to the Candidate.

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[3] Scriminich, A. et al. Optimal design and performance evaluation of free-space quantum key distribution systems. Quantum Sci. Technol. 7, 045029 (2022).

[4] a. Mohageg, M. et al. Towards satellite tests combining general relativity and quantum mechanics through quantum optical interferometry: progress on the deep space quantum link. EPJ Quantum Technol. 12, 78 (2025).

b. Terno, D. R. et al. Proposal for an optical interferometric measurement of the gravitational redshift with satellite systems. Phys. Rev. D 108, 084063 (2023).

c. Wu, H.-N. et al. Single-Photon Interference over 8.4 km Urban Atmosphere: Toward Testing Quantum Effects in Curved Spacetime with Photons. Phys. Rev. Lett. 133, 020201 (2024).

The notes above are intended to suggest integrations which may get even closer the usability of the results to the use of quantum light in both the scientific exploitation of nonclassical behaviour as well as in the many intriguing applications ongoing and foreseen.

Sincerely,

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