

OPPONENT'S REVIEW

on the PhD thesis

“Statistical models and temporal coherence of quantum light in the turbulent atmosphere”

written by **Mykyta Klen** under the supervision of Dr. habil. **Andrii Semenov** submitted for obtaining the degree of **Doctor of Philosophy** at **Bogolyubov Institute for Theoretical Physics of the National Academy of Sciences of Ukraine** prepared by Prof. **Leonid Yatsenko**, Institute of Physics, National Academy of Sciences of Ukraine, Kyiv, Ukraine

General assessment and relevance of the research topic

The dissertation of Mykyta Klen is devoted to the theoretical description of atmospheric quantum channels and, in particular, of the statistical properties of optical transmittance and temporal correlations arising during the propagation of light through a turbulent atmosphere.

The topic of the dissertation is highly relevant. Free-space optical links play an increasingly important role in modern quantum technologies, including satellite-based quantum communication, long-distance quantum key distribution, quantum networking, and communication with moving platforms. In all these applications, atmospheric turbulence remains one of the principal factors limiting transmission fidelity and the preservation of quantum properties of light.

While the statistical properties of classical optical fields in turbulent media have been investigated for several decades, many questions related to the statistical description of atmospheric quantum channels remain insufficiently understood. In particular, there is no universally accepted framework for selecting appropriate probability distributions of transmittance (PDTs), the role of temporal correlations in atmospheric channels is only partially understood, and the applicability limits of many existing analytical models remain unclear. The dissertation addresses precisely these issues and therefore lies at the intersection of atmospheric optics, statistical optics, and quantum communication theory.

General characteristics of the dissertation

The dissertation consists of an Introduction, six chapters, Conclusions, and a Bibliography. The work is logically organized and presents a coherent sequence of investigations.

The first part of the dissertation is devoted to numerical modeling of atmospheric channels and to the statistical description of transmittance fluctuations. The author develops and validates a numerical framework based on the sparse-spectrum phase-screen approach and applies it to weak-, moderate-, and strong-turbulence regimes.

The second part focuses on analytical models of the probability distribution of transmittance (PDT). Existing PDT models are systematically compared with numerical simulations, and the assumptions underlying these models are critically examined.

The third part introduces an improved analytical approach based on transmittance-moment matching and develops a modified Circular-beam model.

The fourth part extends the conventional single-time PDT framework to temporally correlated atmospheric channels through the introduction of the Two-Time PDT formalism.

Finally, the developed framework is applied to several representative quantum communication scenarios, including continuous-variable entanglement, discrete-variable entanglement, and adaptive-selection protocols.

The dissertation demonstrates a clear progression from numerical simulations and statistical analysis toward physically motivated analytical models and practical quantum-optical applications.

Scientific novelty and main results

The dissertation contains several original scientific results.

The first important contribution is the systematic investigation of existing analytical PDT models over a broad range of atmospheric conditions. The author demonstrates that the relative size of the receiver aperture with respect to the average beam radius is often more important for determining model accuracy than turbulence strength alone. This conclusion provides a new perspective on the applicability of commonly used PDT models and helps explain why different models perform well in different experimental situations.

A particularly valuable result of the dissertation is the identification of a systematic misspecification bias inherent in beam-shape-based models, including the beam-wandering and elliptical-beam approximations. The author convincingly shows that these models may reproduce certain aspects of the transmittance distribution while simultaneously exhibiting systematic errors in the first moments of the transmittance. This observation clarifies an important limitation of a large class of physically motivated atmospheric-channel models.

To address this problem, the author develops a Transmittance-Moment Matching technique and applies it to the Circular-beam model. The proposed approach significantly improves agreement with numerical simulations while retaining analytical tractability. In my opinion, this result constitutes one of the most original contributions of the dissertation.

Another important achievement is the introduction of the Two-Time PDT framework for the description of temporally correlated atmospheric channels. Unlike conventional PDT approaches, which assume statistically independent realizations, the proposed formalism explicitly incorporates temporal correlations between consecutive transmission events. This extension is particularly relevant for modern high-repetition-rate quantum communication systems. Within this framework, the author introduces the aperture-averaged spatial coherence radius as a characteristic parameter describing the persistence of temporal correlations. The obtained results demonstrate that temporal correlations may remain significant on millisecond timescales, which is directly relevant for quantum communication protocols employing quantum memories or adaptive-selection techniques.

The final chapter successfully demonstrates how the developed statistical framework can be applied to realistic quantum-optical problems. In particular, the dissertation quantifies the influence of atmospheric turbulence on continuous-variable entanglement, discrete-variable entanglement, and the preservation of nonclassicality under adaptive-selection protocols.

Reliability and validity of the obtained results

The conclusions of the dissertation are supported by extensive numerical simulations and by detailed comparisons between different analytical approaches.

The numerical framework is based on well-established phase-screen techniques and incorporates the sparse-spectrum method to improve the representation of low-frequency turbulence components. The analysis covers a wide range of atmospheric conditions and includes weak, moderate, and strong turbulence regimes.

The author consistently compares analytical predictions with numerical simulations and employs quantitative measures, including the Kolmogorov–Smirnov statistic, to evaluate model performance. Such systematic validation significantly strengthens the credibility of the obtained results.

An additional strength of the dissertation is that the author does not merely compare different models but also critically examines the statistical assumptions on which these models are based. In particular, the validity of Gaussian beam-centroid statistics, independence assumptions, and Gaussian statistics of beam-shape parameters is investigated directly using numerical data.

The presented results appear internally consistent and scientifically sound.

Publications and personal contribution of the author

The main results of the dissertation have been published in four scientific publications, including three papers in *Physical Review A* and one conference proceeding. Particularly

noteworthy are the publications: M. Klen and A. A. Semenov, Phys. Rev. A 108, 033718 (2023) and M. Klen, D. Vasylyev, W. Vogel, and A. A. Semenov, Phys. Rev. A 109, 033712 (2024). Three publications appeared in a leading international journal indicating that the obtained results have undergone rigorous international peer review.

The dissertation clearly identifies the personal contribution of the candidate. The numerical simulations, statistical analysis, development of the Transmittance-Moment Matching approach, and a substantial part of the theoretical investigations were carried out directly by Mykyta Klen. Therefore, there is no doubt that the main scientific results presented in the dissertation belong to the candidate.

Critical remarks and questions to the candidate

The dissertation makes a very positive overall impression and contains a number of original scientific results. The remarks listed below do not reduce the scientific value of the work and should primarily be regarded as points for discussion and possible directions for future research.

1. Physical interpretation of the Beta-distribution model

One of the central conclusions of the dissertation is that the empirical Beta-distribution model frequently outperforms physically motivated PDT models over a broad range of atmospheric conditions. While this conclusion is convincingly supported by numerical simulations, the physical origin of the success of the Beta-distribution remains insufficiently discussed. The model appears primarily empirical, and its connection to the underlying physical mechanisms of atmospheric turbulence is not entirely clear.

Question 1.

Can the author provide a physical interpretation explaining why the Beta-distribution reproduces atmospheric transmittance statistics so successfully over such a broad parameter range?

Question 2.

Have alternative bounded distributions, such as logistic-normal distributions or other transformations of Gaussian random variables, been considered and compared with the Beta-distribution model?

2. Limitations of beam-shape-based models

The dissertation convincingly demonstrates the existence of misspecification bias in beam-wandering and elliptical-beam models. The proposed explanation attributes this bias primarily to higher-order beam-shape deformations that are not captured by low-order beam parameters. However, it remains somewhat unclear to what extent the observed discrepancies originate from smooth higher-order deformations and to what extent they are associated with the formation of speckle structures under turbulent propagation.

Question 3.

To what extent does the author attribute the limitations of beam-shape-based models to turbulence-induced speckle formation rather than to smooth beam-shape distortions?

Question 4.

Has the author performed a direct analysis of spatial intensity distributions to quantify the role of speckles in the observed model discrepancies?

3. Physical interpretation of the Transmittance-Moment Matching procedure

The proposed Transmittance-Moment Matching technique represents one of the most original results of the dissertation. At the same time, the procedure effectively transfers the influence of higher-order beam deformations into modified effective beam-size statistics. As a consequence, the effective beam-size parameter loses part of its direct geometrical interpretation.

Question 5.

To what extent does the effective beam-size parameter retain a clear physical meaning after the Transmittance-Moment Matching procedure is applied?

Question 6.

Is it possible to generalize the moment-matching approach to the elliptical-beam model, or does the increased number of parameters fundamentally limit such a generalization?

4. Temporal correlations and the frozen-turbulence approximation

The analysis of temporal correlations constitutes one of the most interesting parts of the dissertation. However, the entire treatment is based on Taylor's frozen-turbulence approximation, in which temporal evolution arises solely from wind-driven translation of a static turbulence pattern. Although this approximation is widely used in atmospheric optics, real atmospheric turbulence also exhibits intrinsic temporal evolution ("boiling"), which may contribute to decorrelation.

Question 7.

How sensitive are the obtained temporal correlation times and the introduced coherence radius to deviations from the frozen-turbulence approximation?

Question 8.

In the hypothetical absence of wind, what physical mechanism would determine the characteristic decorrelation time of atmospheric transmittance?

5. Aperture-averaged spatial coherence radius

The aperture-averaged spatial coherence radius introduced in the dissertation provides a useful quantitative characterization of temporal correlations. Nevertheless, the term "coherence radius" may potentially be confused with traditional measures of optical-field coherence.

Question 9.

Would it be more appropriate to interpret the introduced quantity as a correlation length of transmittance fluctuations rather than as a coherence radius in the traditional optical sense?

6. Applicability of the obtained results to atmospheric quantum communication

The final chapter demonstrates several important applications to continuous-variable and discrete-variable quantum communication protocols. At the same time, a significant part of the dissertation is devoted to the statistical description of atmospheric propagation itself and would remain relevant even in purely classical optical communication systems.

Question 10.

Which of the results obtained in the dissertation does the author consider to be genuinely specific to quantum communication, and which results should be regarded as more general contributions to statistical atmospheric optics?

Overall assessment

Despite the remarks listed above, I emphasize that they do not affect the overall positive evaluation of the dissertation. On the contrary, they reflect the breadth of the investigated problems and the fact that the dissertation raises several interesting questions deserving further study.

The dissertation presents a coherent and scientifically mature investigation of atmospheric quantum channels. The work combines advanced numerical simulations with analytical modeling and successfully bridges the gap between atmospheric optics and quantum communication theory.

Particularly noteworthy are the systematic analysis of existing PDT models, the identification of misspecification bias in beam-shape-based descriptions, the development of the Transmittance-Moment Matching approach, and the introduction of the Two-Time PDT framework for temporally correlated atmospheric channels.

The scientific results are original, well substantiated, and published in reputable international journals. The dissertation demonstrates a high level of theoretical rigor and makes a substantial

contribution to the statistical description of atmospheric quantum channels and their applications in quantum communication.

Final conclusion

In my opinion, the dissertation entitled “**Statistical Models and Temporal Coherence of Quantum Light in the Turbulent Atmosphere**” submitted by **Mykyta Klen** constitutes a completed and original scientific work that contains significant new results in the field of atmospheric quantum optics and quantum communication. The dissertation satisfies the requirements for the degree of Doctor of Philosophy, and its author, **Mykyta Klen**, deserves to be awarded the degree of **Doctor of Philosophy in Physics**.

Leonid Yatsenko

