Fraunhofer IOSB

Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB

Head of institute
Prof. Dr.-Ing. Habil. Jürgen Beyerer

Director Ettlingen, Division Manager Defense
Prof. Dr. rer. nat. habil. Marc Eichhorn

Gutleuthausstrasse 1
76275 Ettlingen

Dr. Giacomo Sorelli
Quantum Superresolution Group Leader
Phone + 49 7243 992 244
giacomo.sorelli@iosb.fraunhofer.de
www.iosb.fraunhofer.de

Fraunhofer IOSB | Gutleuthausstrasse 1 | 76275 Ettlingen

Bogolyubov Institute for Theoretical Physics
of the National Academy of Sciences of Ukraine

Ettlingen, 18. June 2026

Report on the PhD Thesis "Statistical Models and Temporal Coherence of Quantum Light in the Turbulence Atmosphere" by Mykyta Klen

The PhD thesis *Statistical Models and Temporal Coherence of Quantum Light in the Turbulent Atmosphere* by Mykyta Klen identifies the transmittance of a free-sapce optical channel as the key parameter governing the transmission of quantum states of light through the atmosphere. Using advanced and extended numerical simulations this work systematically studies statiscal and temporal property of this crucial parameter and analyses its impact on non-classical (entangled and squeezed) states of light.

The thesis consists of an Abstract, seven chapters, Conclusions, a Bibliography, and a list of the author's publications and conference contributions. The work is based on three papers published in *Physical Review A* and one paper published in the proceedings of the SPIE conference *Quantum Technologies for Defense and Security*. Mykyta Klen is the first author of two of these publications, and the impact of his numerical simulation framework is evident throughout all four. The thesis is well structured and presents the author's published work as a coherent and logically connected body of research, while placing it within the broader context of classical and quantum optics in atmospheric channels. I particularly appreciated the historical introduction to the background material and the way the thesis develops from a rigorous critical assessment of results from classical optics to their application in practical quantum-state propagation scenarios. Overall, I believe this work is highly relevant for the design of free-space quantum communication systems and paves the way for the study and deployment of other quantum optical technologies, such as imaging and sensing, in turbulence-affected environments.

The first chapter serves as an introduction, motivating the work, outlining the research objectives and methods, and summarizing the main results and their impact. Chapter 2 presents the theoretical background in quantum and atmospheric optics. The propagation of quantum states through the atmosphere is described by an input–output relation for the Glauber P-function in a lossy channel with random transmittance. Within this framework, the probability distribution of transmittance (PDT) is identified as the key quantity characterizing the channel. Several analytical models for the PDT are presented and classified as either physically motivated or empirical. Finally, the split-step method is introduced as an accurate numerical approach for simulating wave

Ettlingen, 18. June 2026

propagation through the atmosphere, and the sparse-spectrum method is identified as an effective technique for generating turbulence phase screens.

Chapter 3 is dedicated to the validation of the analytical PDT models introduced in Chapter 2. This validation is carried out through extensive numerical simulations of three turbulence channels with weak, moderate, and strong turbulence strengths, respectively. The Kolmogorov–Smirnov statistic is used to quantify the deviation between the cumulative distributions predicted by the analytical models and those obtained from the numerically reconstructed PDTs. The analysis reveals that physically motivated models generally perform worse than empirical ones. In particular, the empirical model based on the Beta distribution is generally in good agreement with the numerically reconstructed PDTs, as it is able to reproduce the variations in skewness observed when varying the radius of the channel's collecting aperture.

Chapter 4 is dedicated to understanding why physically motivated models fail to predict the correct transmittance statistics. These models rely on simplistic assumptions regarding the statistical properties of beam-shape parameters, and in this chapter Mykyta Klen investigates, through numerical simulations, whether these assumptions are justified. Chapter 5 introduces a new physically motivated model constructed by matching the first two moments of the transmittance distribution. This model performs significantly better than approaches based on beam-shape statistics and provides a valuable, computationally efficient PDT model that depends on only a few experimentally accessible parameters.

Chapter 6 studies the two-time PDT, which describes how two consecutive pulses separated by a time interval t are affected by a turbulent channel. The two-time PDT is reconstructed from numerical simulations in which, according to Taylor’s hypothesis, the phase screens are shifted by a constant transverse wind velocity. The spatial coherence radius is introduced to derive the characteristic time scale over which the channel transmittance remains correlated. Interestingly, this quantity appears to depend only weakly on the turbulence strength, while showing a strong dependence on the aperture radius. Finally, the conditional PDT, expressing the transmittance distribution at time t given that a transmittance larger than a specified threshold was observed at time 0, is derived. This quantity is particularly relevant for adaptive free-space communication protocols that exploit favorable channel realizations, for example by transmitting quantum states only when the channel is known to be in a high-transmittance state. The conditional PDT therefore provides information on how long such favorable conditions are likely to persist.

Chapter 7 applies the results of the previous chapter to evaluate how entanglement between two successive pulses survives atmospheric propagation. The problem is investigated for both continuous-variable and discrete-variable quantum states. Finally, the efficiency of an adaptive transmission protocol in preserving the non-classicality of squeezed states is assessed. Both analyses account for relevant experimental non-idealities, including detector noise and losses in a quantum memory.The concluding chapter summarizes the main results and discusses some limitations of the current numerical framework. It also identifies possible extensions that could enable less systematic, but more realistic, analyses of specific atmospheric channels.

Mykyta Klen has demonstrated the ability to conduct high-quality independent scientific research. He developed a highly reliable numerical framework and used it to systematically and rigorously assess several widely accepted models in atmospheric optics. Based on this analysis, he identified their limitations and derived more suitable models for the study of atmospheric transmittance. The results presented in the thesis satisfy the criteria of originality, scientific rigor, and relevance expected of a doctoral dissertation. I therefore recommend that Mykyta Klen be awarded the degree of Doctor of Philosophy.

Ettlingen, 18. June 2026

Questions that could be addressed during the defense:

1) Can we have some physical intuition on the plateau of the numerical PDT observed for a focused beam in intermediate turbulence in Fig. 3.8?
2) Given the strong dependence of the PDT on the aperture size, diffraction-induced beam broadening appears to play an important role. The channels investigated in the thesis are classified through their Rytov variance, which combines diffraction effects (through the propagation distance z_{ap}) and turbulence effects (through the turbulence structure constant Cn^2). It would therefore be interesting to compare two channels with the same Rytov variance but different values of z_{ap} and Cn^2. Would one expect the resulting PDTs to be essentially identical, suggesting that the Rytov variance is the dominant parameter, or could significant differences arise from the separate contributions of diffraction and turbulence? In other words, is the behavior of the PDT primarily diffraction-dominated, turbulence-dominated, or determined by the interplay between the two effects?
3) How can I physically interpret the supperssion of diagonal points in Fig. 4.4?
4) In the thesis, a constant wind velocity for all phase screens is used to derive the two-time PDT. This simplification is justified by the need to maintain the model "identifiable and tractable". Another common approach to account for imogenities, while keeping the model "identifiable and tractable" is to draw the screens velocities from a Gaussian distribution with given mean and variance. Could one expect significant changes in the results from moving to a less homogeneous model?
5) In Chapter 6, the temporal properties of the channel are presented in terms of absolute wind-induced shifts (cm). Since the relevant scales are ultimately determined by turbulence and beam propagation, would it be more informative to express these results in terms of characteristic turbulence-induced length scales, such as the Fried parameter r_0 or the long-term beam radius W_{LT}? Would such a normalization reveal a more universal behavior across different channel conditions?
6) The characteristic pulse rate for adaptive free-space quantum communication is determined by the ratio v/ρ_0, where ρ_0 is the spatial coherence radius and v is the transverse wind speed. This quantity appears conceptually similar to the Greenwood frequency, which scales as v/r_0 and sets the required correction-loop bandwidth in adaptive optics. In both cases, the underlying requirement is that the channel remains sufficiently correlated between its characterization and the subsequent action, whether transmitting a quantum state or applying a wavefront correction. Could the author comment on the relationship between these two quantities?
7) How was the threshold used in the study of the adaptive protocol in Section 7.3 chosen? I would expect a trade-off between exploiting only the highest-transmittance channel realizations and maintaining a sufficiently large number of transmission opportunities. Can the author comment on this interplay? More specifically, is there an optimal threshold that balances the quality of the transmitted quantum states against the resulting communication rate?

Giacomo Sorelli