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Citation for published version (APA):
van Vliet, V., van der Heide, S., van den Hout, M., & Okonkwo, C. (2022). Turbulence Characterisation for Free Space Optical Communication Using Off-Axis Digital Holography. *OSA Technical Digest Series*, *2022*, Article SpTu3G.1. https://doi.org/10.36227/techrxiv.20072948.v1, https://doi.org/10.1364/SPPCOM.2022.SpTu3G.1

DOI:
10.36227/techrxiv.20072948.v1
10.1364/SPPCOM.2022.SpTu3G.1

Document status and date:
Published: 17/06/2022

Document Version:
Accepted manuscript including changes made at the peer-review stage

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SUBMISSION DATE / POSTED DATE

15-06-2022 / 17-06-2022

CITATION

van Vliet, Vincent; van der Heide, Sjoerd; van den Hout, Menno; Okonkwo, Chigo (2022): Turbulence Characterisation for Free Space Optical Communication Using Off-Axis Digital Holography. TechRxiv. Preprint. https://doi.org/10.36227/techrxiv.20072948.v1

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Turbulence Characterisation for Free Space Optical Communication Using Off-Axis Digital Holography

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Abstract: An optical turbulence generator is characterised using digital holography, measuring the amplitude and phase of the perturbed optical field and enabling analysis of turbulence effects and development of mitigation techniques.

1. Introduction

Free-space optical (FSO) communication promises significant benefits compared to radio frequency, e.g. large bandwidth, high data rate, no licensing restrictions, increased security against eavesdropping, small, light and low-power equipment. Consequently, FSO communication has gained interest for a variety of applications, including ground-to-satellite/satellite-to-ground communication, backhaul for wireless networks, and last mile access [1].

Critical to the deployment of FSO communication links is mitigation of perturbations induced by atmospheric effects, with optical turbulence being the main consideration in clear air conditions. Moreover, digital signal processing (DSP) for high-speed FSO transmission have to be developed as direct reuse of conventional fibre-channel DSP is impossible due to significant differences in the nature of the channels [2]. Originating in the field of astronomy [3], an optical turbulence generator (OTG) allows for emulation of turbulent atmospheric channels in a laboratory setting, enabling the efficient development, testing, and validation of DSP and mitigation strategies.

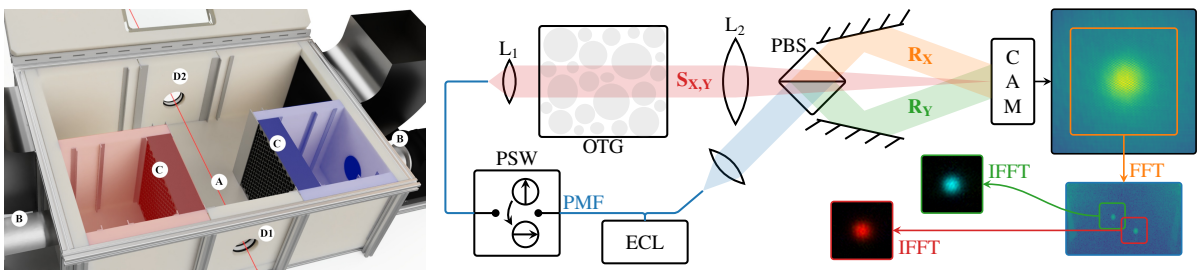
In this work, we present characterisation of turbulence in an OTG [4] for emulating a ground-to-satellite channel while simultaneously recording the complete perturbed optical field of a beam propagating through the turbulence using off-axis digital holography (DH) [5]. Here, the OTG is characterised for a ground-to-satellite link.

2. Characterisation

The optical turbulence characterised in this work is produced in an OTG through the forced mixing of two air flows in a compact chamber. Fig. 1a shows the design of the OTG [4]. At constant and equal air volumes, the turbulence strength is a function of the temperature difference (ΔT) between the two flows [6].

The off-axis DH measurement setup [5], shown in Fig. 1b, measures the complete optical field including amplitude and phase for both polarisations of a signal field S by interfering it with flat-phase orthogonally-polarised reference beams R. The camera records this beat-interference and a fast Fourier transform (FFT) converts it from the spatial to the angular domain, after which x- and y-polarisation interference patterns can be separated due to the angular separation in the free-space optical setup. An inverse fast Fourier transform (IFFT) converts the filtered interference patterns back to the spatial domain, which now includes phase information, completing the signal field extraction procedure. The beam centroid in spatial domain, i.e. the position on the camera, and the beam centroid in angular domain, i.e. the angle of incidence, are found by maximising the power of the digital overlap integral between extracted signal field and a digitally-generated TEM_{00} target field. Then, the position and angle in the camera plane are back-propagated to the plane of lens L_2 for further analysis.

A frame is recorded every 3 ms, alternating between x- and y-polarised signals using a polarisation switch (PSW). The beam centroid in the L_2 plane is calculated for each recorded frame as explained above for a capture



(a) (b)

Figure 1: **(a)** Render of the OTG used in this work [4]. (A): mixing chamber, (B): (hot-)air blowers, (C): metal mesh to laminarise flow, (D1) and (D2): laser window panels. **(b)** Schematic of experimental free-space optical off-axis DH setup and signal field extraction DSP. L_1 and L_2: lenses with focal distances $f_1 = 4.51$ mm and $f_2 = 750$ mm, $S_{X,Y}$: signal to be characterised, R_X and R_Y: reference beams, ECL: external cavity laser, PMF: polarisation-maintaining fibre, PBS: polarisation beam splitter. Note that $S_{X,Y}$ passes over the PBS. Adapted from [5].

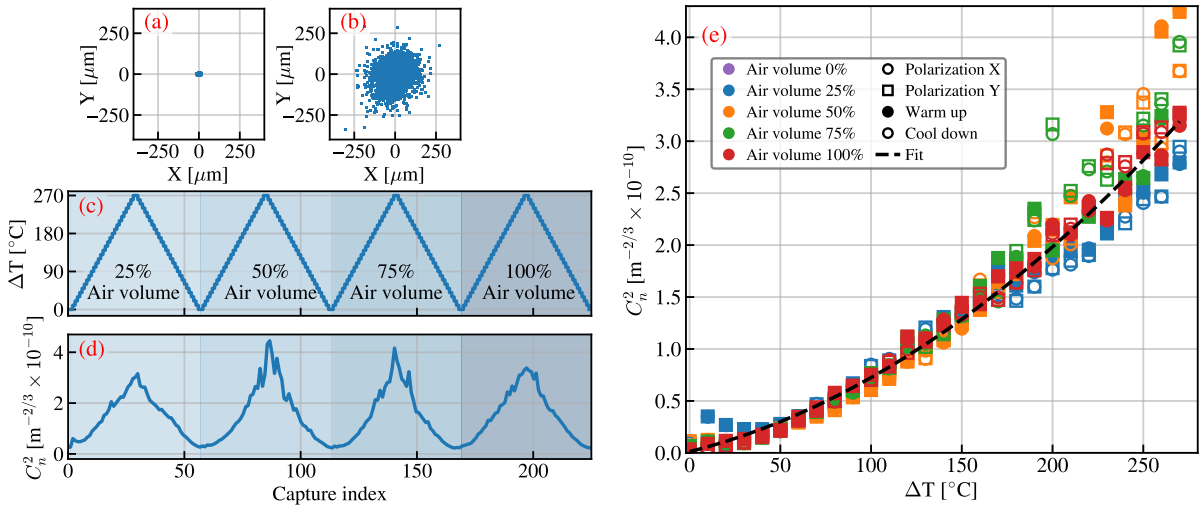


Figure 2: **(a-b)** Beam centroid displacement for captures (10,000 frames) with air volume 25%, $\Delta T = 0\,°\mathrm{C}$ and air volume 75%, $\Delta T = 270\,°\mathrm{C}$, respectively **(c)** Graphical representation of the measurement procedure **(d)** C_n^2 evolution during measurement procedure **(e)** C_n^2 characterisation results with a second degree polynomial fit.

of 10,000 frames. The variance of these beam centroids describes the turbulence strength according to the beam wander variance characterisation technique [7]. In this technique, the corresponding turbulence strength in a ground-to-satellite channel is determined in terms of the commonly used measure of turbulence strength C_n^2 using

$$C_n^2 = 4.287\left(W_0/\pi\right)^2\left(2W_0\right)^{-5/3}L^{-3}\langle r_c^2\rangle \tag{1}$$

with W_0 the $1/\mathrm{e}^2$ beam radius, L the propagation distance through the OTG, and $\langle r_c^2\rangle$ the beam wander variance.

In an automated measurement procedure, captures are taken for numerous OTG settings. Fig. 2c shows a graphical representation of the measurement procedure. A small beam ($W_0 = 0.44\,\mathrm{mm}$) is used to ensure that beam wander is the most prominent atmospheric effect. One may use a larger beam to introduce more scintillation.

3. Results

The results for the characterisation of the OTG are shown in Fig. 2. In line with the expectations, stronger turbulence is observed for increased ΔT. Fig. 2a-b show the beam centroid displacement for captures with different settings. The evolution of the turbulence strength during the measurement procedure is shown in Fig. 2d. Fig. 2e shows that no clear dependence on air volume or polarisation can be distinguished.

Additional to the information required for characterisation, the complete perturbed optical fields have been recorded, allowing further analysis in the digital domain, e.g. evaluation of fibre coupling efficiency, receiver technologies, and mitigation strategies. More results and further analysis can be found in [4].

4. Conclusions

A method to determine the strength of optical turbulence produced in an OTG and simultaneously measure the complete optical field of the distorted signal using off-axis DH is presented and demonstrated for a ground-to-satellite link scenario. This method allows emulation of atmospheric optical turbulence in a laboratory setting enabling efficient development, testing, and validation of DSP and mitigation strategies for FSO communication.

Funding received from KPN-TU/e Smart Two, the Dutch NWO Gravitation Program (Grant Number 024.002.033) and NWO Perspectief project Optical Wireless Superhighways: Free photons

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