

Characterization of wavefront aberration in laser beam propagating over saline water and sands

Songsong Zhu¹, Hong Song^{1,*}, Ping Yang², Quanquan Mu³, Fengzhong Qu^{1,4}, Haocai Huang^{1,4}, Han Ge¹, Jun Han¹, Jianxing Leng¹, Yong Cai⁵, Ying Chen^{1,4}

¹.Ocean College, Zhejiang University, 310058, Hangzhou, China

².Department of Digital Media, Hangzhou Dianzi University, 310018, Hangzhou, China

³.State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics, and Physics, Chinese Academy of Sciences, Changchun, 130033, China

⁴.State Key Lab of Fluid Power Transmission and Control, Zhejiang University, 310007, Hangzhou, China

⁵.Ocean Research Center of Zhoushan, Zhejiang University, Zhoushan, 316021, China

*Corresponding author: hongsong@zju.edu.cn

Abstract—Wireless laser communication is a promising method for communication between islands or terminals over sea. However, the wavefront as well as the intensity of the laser beam are severely influenced by the atmospheric turbulence, which degrades the reliability and performance of the communication system. In this paper, we focus on characterization of wavefront aberration in laser beam propagating over saline water and sands. Both the spatial and temporal characteristics of the wavefront aberration in the laser beam have been investigated by experiments. Results show that the laser beam suffers stronger wavefront aberration when propagating over sands than saline water under the same heating condition.

Keywords—wavefront aberration; characterization; temporal; spatial

I. INTRODUCTION

Wireless laser communication systems (WLC) use laser for data transmission through atmosphere or in deep space [1], with the advantages of a high data rate, no requirement for transmission media, portability, free of electromagnetic interference, etc. These make WLC a promising method for communication between islands or terminals over sea. However, due to the atmospheric turbulence in the air, both intensity and wavefront (i.e. phase) of the laser beam are influenced and the reliability and performance of wireless laser communication is degraded [2].

The difference between marine and land environment mainly lies in temperature and humidity. As the thermal capacity of sea water ($4096 \text{ J/(kg} \cdot ^\circ\text{C)}$) is higher than sands ($920 \text{ J/(kg} \cdot ^\circ\text{C)}$) [3], the temperature of sands is usually higher than sea water under the same heating (or weather) condition, which speeds up the air circulation in land environment and the dynamics of wavefront aberration gets stronger. The marine environment is moister than land, which may add to the spatial distortion in the wavefront. Apart from that, wind in the optical path may also contribute to the wavefront aberration in the beam. Research has been carried out, which mainly

concentrates on the characterization of intensity fluctuation in the laser beam or the refractive index structure parameter of the atmosphere [4, 5]. Some scientists have also been working on the comparison between wavefront in different environments [6, 7].

In this paper, we focus on the characterization of wavefront aberration in the laser beam, where both spatial and temporal characteristics of the aberration are analyzed when the laser beam propagates over saline water and sands. The results may contribute to research on laser communication in a marine environment.

II. Experimental setup

Fig. 1 describes the schematic of the experimental setup and Fig. 2 shows the photo of setup in the laboratory.

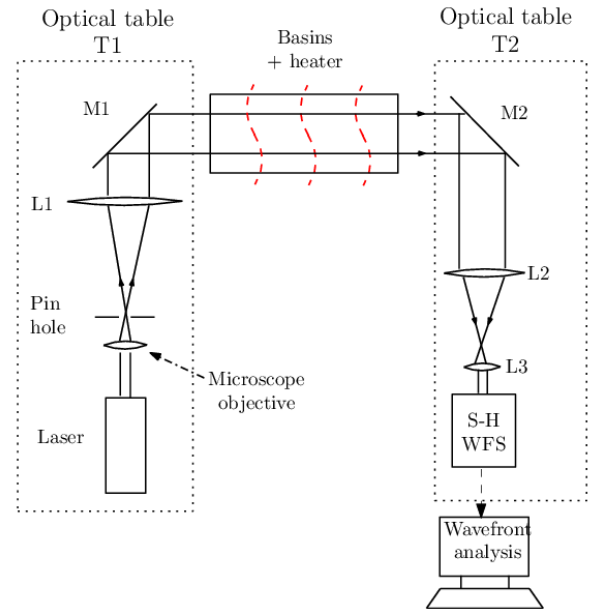


Fig. 1 Schematic of the experimental setup

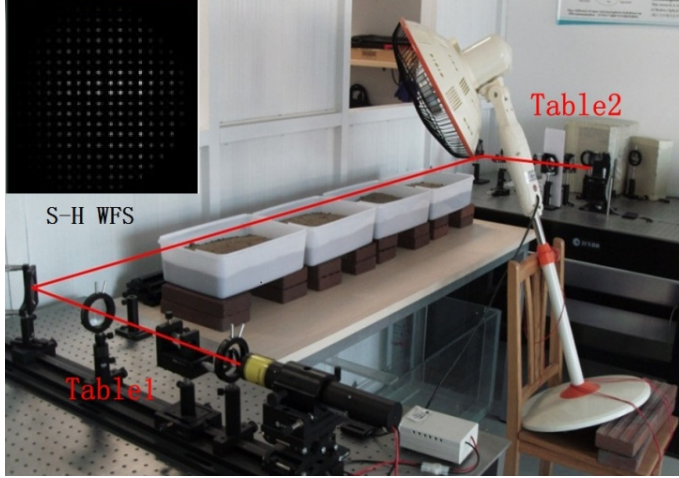


Fig. 2 Photo of setup in the laboratory

The beam is generated by a HeNe laser (632 nm, 2 mW) on the optical table T1. The laser beam goes through a polarizer where its intensity is changed and is filtered by a spatial filter consisting of a microscope objective (20 $\times$) and a pin hole ($\varnothing=20\text{ }\mu\text{m}$). The filtered light is collimated by lens L1, reflected by flat mirrors M1 and M2 successively and travels to the Shack-Hartmann wavefront sensor (S-H WFS) on the optical table T2 after the collimation of lens L2 and L3.

The S-H WFS consists of an orthogonally distributed lenslets array and a camera (see the image captured by the WFS in Fig. 2). Pitch between neighboring lenslets is about 0.15 mm. The camera (ASI035MM, ZW Optical) has a maximal frame rate of 150 fps. Fig. 3 shows the working principle of the S-H WFS [8, 9]. The wavefront aberration in the incident laser beam is converted into spots displacements in the image sensor of the camera which is located in the focal plane of the lenslets. By images analysis, the spots locations can be achieved and spots displacements are determined by comparing current locations with a reference. The WFS images are fed to a control PC via USB interface. The WFS used in the setup are generously supported by OKO Tech, Delft, The Netherlands [10].

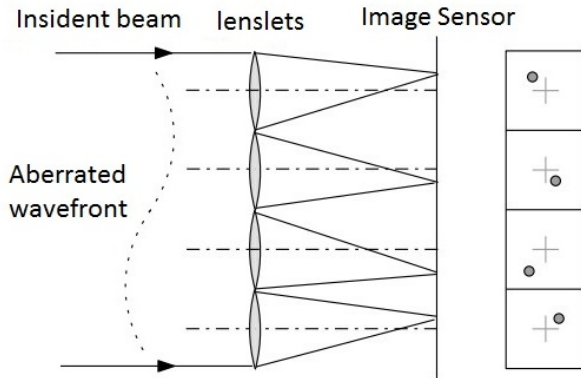


Fig. 3 Working principle of Shack-Hartmann wavefront sensor

As can be seen in Fig. 2, four basins (40 cm $\times$ 25 cm) are placed on the table between Table 1 and Table 2. Either sands

or saline water is filled into these basins to simulate the land or the marine environment respectively. The laser beam propagates over the four basins with sands or saline water before it gets to the WFS. To simulate the sun radiation, a heater is radiating both the air and saline water (or sands) in the basins.

In all of our experiments, the distance between the laser beam and the material is fixed to 4 cm. Some bricks are also used under the basins to guarantee the distance.

III. EXPERIMENT

Wavefront aberration in the laser beam varies both spatially and temporally. As the spatial and temporal characteristics of the wavefront aberration changes with the environmental conditions, two influential factors have been considered during the experiment: (1) material in the basins (sands or saline water), (2) heating duration.

Experiments are arranged as follows (in *pseudo code*):

For material=sands, saline water

For heating time=0:5:30 minutes

Capture 1000 frames from WFS.

(Single data set).

End

End

During each experiment, only one factor (material or heating duration) is changed so that the effect of that single factor can be determined.

In the very beginning, 100 images from the WFS are captured with the basins empty and the heater turned off. These 100 images are averaged and 23 spots with high signal-to-noise ratio are selected as measurement channels. The locations of these 23 spots are analyzed and recorded as a reference for the following experiments.

During single experiment, 1000 frames of the WFS images are captured and saved (called *single data set* in this paper) every 5 minutes. In total, 14 sets of data are captured where 7 sets are captured when the basins are filled with sands and another 7 with saline water. The data acquisition process is illustrated in Fig. 4.

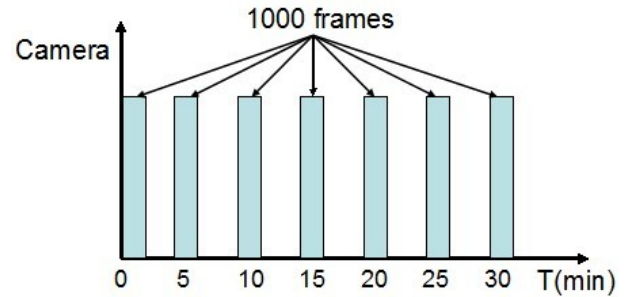


Fig. 4 Time sequence for image acquisition

IV. RESULTS AND ANALYSIS

1. Spatial Characteristic

Spatial characteristic of the wavefront aberration in the laser beam is investigated by calculating the standard deviation of the spots displacements in single frames. According to statistics and probability theory [11], standard deviation shows how much variation or dispersion exists from the mean value of all the data. A low standard deviation indicates that the data points tend to be very close to the mean; high standard deviation indicates that the data points are spread out over a large range of values. In our experiments, a high standard deviation of the spots displacements indicates that the laser beam suffers more serious wavefront aberration caused by atmospheric turbulence.

The measurement vector $p(j)$ from the j -th frame is defined as

$$p(j) = \begin{bmatrix} d(1, j) \\ d(2, j) \\ \dots \\ d(i, j) \\ \dots \\ d(N, j) \end{bmatrix} \quad (1)$$

where $d(i, j)$ represents the displacement (either x-displacement or y-displacement) of the i -th spot in the j -th frame. Vector $p(j)$, $j=1, 2, \dots, M$, represents the displacements of 23 spots in the j -th frame and M is the number of frame, i.e. $M=1000$. N is the length of the measurement vector, i.e. $N=46$.

The standard deviation of $p(j)$ is calculated as

$$\sigma(j) = \frac{1}{N-1} \sqrt{\sum_{i=1}^N [d(i, j) - \overline{p(j)}]^2} \quad (2)$$

where $\sigma(j)$ represents the standard deviation of the measurement vector $p(j)$ and $\overline{p(j)}$ is the mean of $p(j)$, defined as

$$\overline{p(j)} = \frac{1}{N} \sum_{i=1}^N d(i, j) \quad (3)$$

Averaged standard deviation of 1000 frames is calculated as

$$\bar{\sigma} = \frac{1}{M} \sum_{j=1}^M \sigma(j) \quad (4)$$

Use this method to calculate average standard deviation at each time point for the two materials.

Fig. 5 shows the average standard deviation for the sands is larger than the saline water at all time instants under investigation, which means the spots in the images for the sands have larger displacements. The reason for this phenomenon is that the sands has a smaller thermal capacity, which makes the temperature difference between the air and sands is larger than that between the air and saline water. The atmospheric turbulence grows more serious as the temperature of the sands develops. The average standard deviation for sands is 1.02 pixel at $T=30$ min, and the value for saline water is 0.85 pixel.

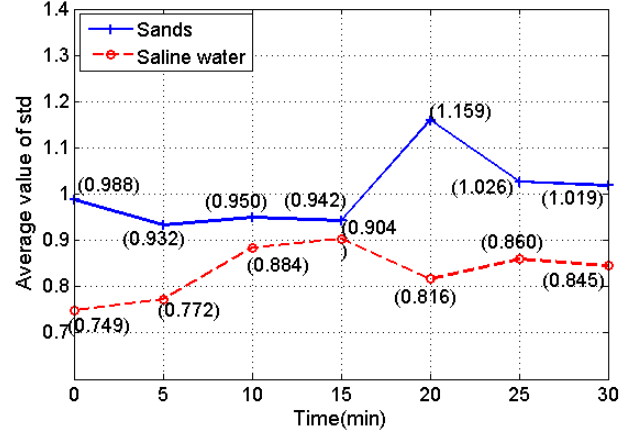


Fig. 5 Averaged standard deviation $\bar{\sigma}$ of spots displacement for sands and saline water

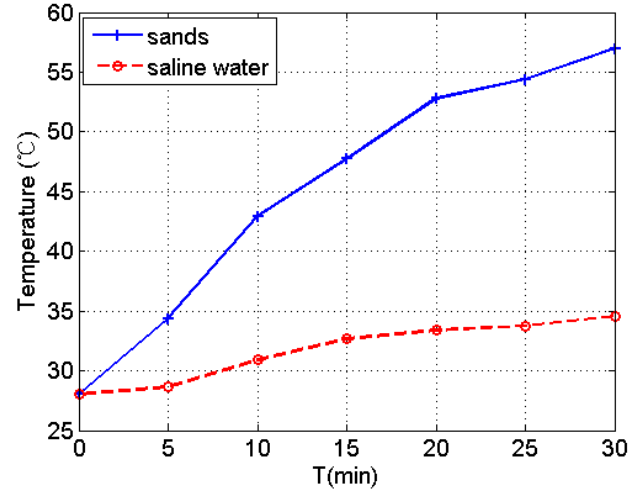


Fig. 6 Temperature for two materials

The temperature for the two materials is showed in Fig. 6 which is measured for every five minutes.

2. Temporal Characteristic

Temporal characteristic of the wavefront aberration is investigated by looking at the power spectral density (PSD) of the spots displacements, from which the power distribution in frequency scale can be seen. In our work, the PSD of the spots displacements has been calculated as

$$q(i) = \begin{bmatrix} d(i, 1) \\ d(i, 2) \\ \dots \\ d(i, j) \\ \dots \\ d(i, M) \end{bmatrix} \quad (5)$$

$$P(i) = \text{PSD}(q(i)) \quad (6)$$

$$\overline{P} = \frac{1}{N} \sum_{i=1}^N P(i) \quad (7)$$

where $q(i)$ represents the time sequence from the i -th measurement channel. Length of $q(i)$ is $M=1000$ in our case. $P(i)$ is the PSD of $q(i)$, which is computed using Welch's method [12]. $\bar{P}$ is the average PSD for all measurements.

Fig. 7 shows the averaged PSD of 3 datasets corresponding to $t=0$, 15 min and 30 min. The linear trend in the vector $q(i)$ has been removed. The plot corresponding to $T=0$ min is used for reference of noise level in the setup. The initial difference between the sands and saline water is negligible as compared with $T=30$ min. It can be seen that most power distributes at low frequencies. As the heating duration increases, the difference in PSD between sands and saline water gets clearly visible from the plots. For heating duration $T=30$ min, the PSD for saline water is around $0.01 \text{ px}^2/\text{Hz}$ for the whole frequency range under investigation; but the PSD for sands reaches more than $0.06 \text{ px}^2/\text{Hz}$ for frequency lower than 1 Hz, which clearly shows that the wavefront aberration for sands has faster dynamics than saline water. The reason for this still lies in the bigger temperature difference between sands and air.

V. CONCLUSIONS AND FUTURE WORK

Wavefront aberration in the laser beam is measured and analyzed when the laser beam propagates over sands and saline water. The temperature difference between air and sands is larger than that between air and saline water under the same heating conditions, which results in greater atmospheric turbulence for the air above the sands and the laser beam suffers stronger wavefront aberrations when it propagates over sands. Both spatial and temporal characteristics of the aberration have been analyzed. The average standard deviation of the spots displacements for the two materials has been calculated. The average standard deviation for sands is 1.02 px and 0.85 px for saline water. PSD lines are analyzed in the paper with a comparison of the two materials, which clearly shows that the wavefront aberration for sands has significantly faster dynamics than that for saline water.

Our future work will focus on the characterization of the wavefront aberration in a real marine environment.

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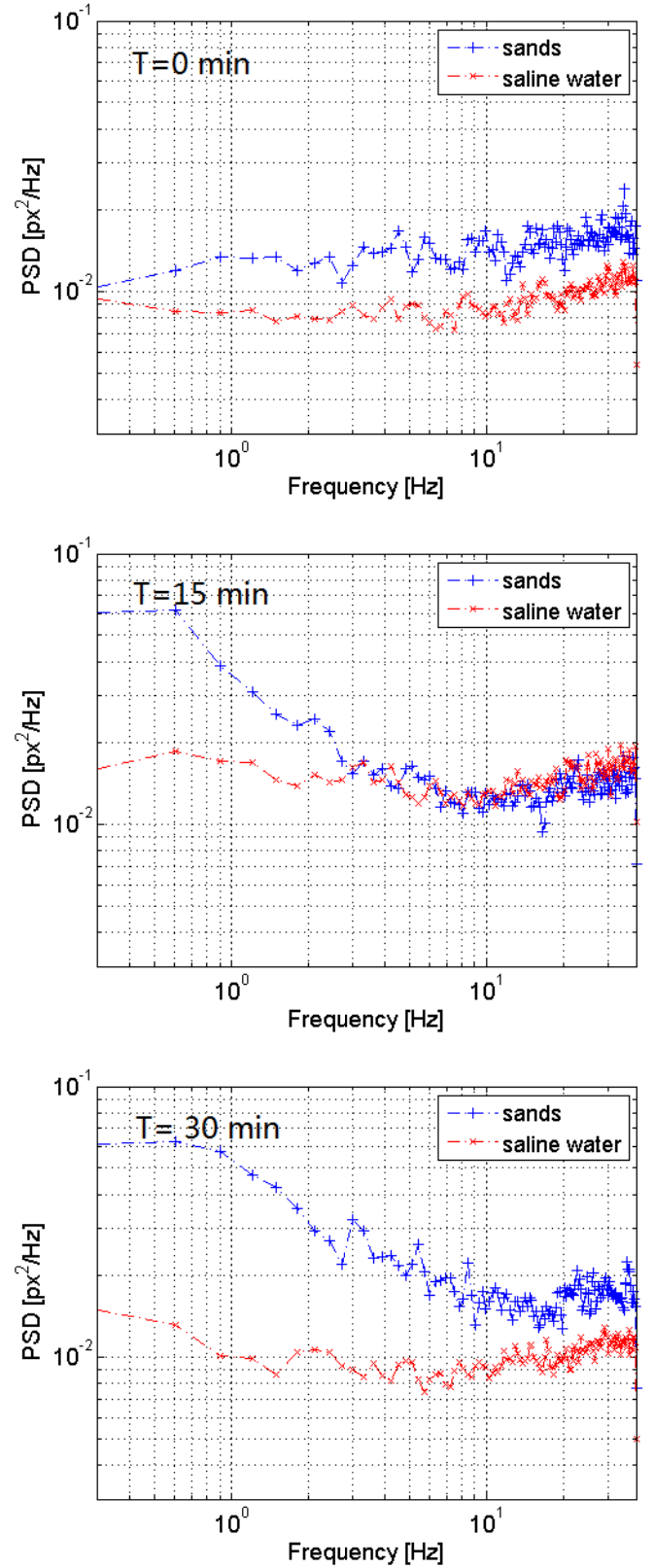


Fig. 7 Power spectra density of the spots displacements for heating duration $T=0, 15$ min and 30 min.

REFERENCES

- [1] A. K. Majumdar and J. C. Ricklin, Free-space laser communications: principles and advances vol. 2: Springer, 2008.
- [2] S. Hammel, "Turbulence effects on laser propagation in a marine environment," in Proc. SPIE, 2007, p. 670804.
- [3] M. H. Sharqawy, J. H. Lienhard and S. M. Zubair, "Thermophysical properties of seawater: A review of existing correlations and data," Desalination and Water Treatment, vol. 16, pp. 354-380, 2010.
- [4] C. N. Reinhardt, S. M. Hammel, K. McBryde, and D. Tsintikidis, "Improved vertical refractive-index structure parameter model for the maritime atmosphere based on local bulk meteorological measurements," in SPIE Optical Engineering+ Applications, 2012, p. 85170L-85170L-10.
- [5] V. Sergeev and M. C. Roggemann, "Monitoring the statistics of turbulence: Fried parameter estimation from the wavefront sensor measurements," Applied Optics, vol. 50, pp. 3519-3528, 2011.
- [6] S. Zhu, H. Song, P. Yang, H. Liu, R. Lan, Y. Liu, H. Huang, F. Qu, J. Leng, and Y. Chen, "Wavefront Aberration Characterization and Correction for Laser Beam Propagating Over Saline Water and Sands," in Mechatronic Systems, 2013, pp. 243-248.
- [7] M. Chang, C. O. Font, F. Santiago, Y. Tza Luna, E. Roura, and S. R. Restaino, "Marine environment optical propagation measurements," in Optical Science and Technology, the SPIE 49th Annual Meeting, 2004, pp. 40-46.
- [8] Azucena, J. Crest, J. Cao, W. Sullivan, P. Kner, D. Gavel, D. Dillon, S. Olivier, and J. Kubby, "Wavefront aberration measurements and corrections through thick tissue using fluorescent microsphere reference beacons," Optics express, vol. 18, p. 17521, 2010.
- [9] H. Li, Z. Wang, X. Liu, P. Wei, M. Ming, and H. Meng, "Application of Shack-Hartmann wavefront sensor in optical testing," Journal of Applied Optics, vol. 1, p. 026, 2012.
- [10] M. Loktev, O. Soloviev, G. Vdovin, Adaptive optics guide: OKO Technologies, 2008, available at <http://www.okotech.com/>.
- [11] R. L. Plackett, "Studies in the History of Probability and Statistics. XXIX The discovery of the method of least squares," Biometrika, vol. 59, pp. 239-251, 1972.
- [12] Welch, P.D, "The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Averaging Over Short, Modified Periodograms," IEEE Trans. Audio Electroacoustics 15, pp.70-73, 1967.