

PROCEEDINGS OF SPIE

# ***Laser Communication and Propagation through the Atmosphere and Oceans X***

**Jaime A. Anguita  
Jeremy P. Bos  
David T. Wayne**  
*Editors*

**1-5 August 2021  
San Diego, California, United States**

*Sponsored and Published by*  
SPIE

**Volume 11834**

Proceedings of SPIE 0277-786X, V. 11834

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

Laser Communication and Propagation through the Atmosphere and Oceans X, edited by  
Jaime A. Anguita, Jeremy P. Bos, David T. Wayne, Proc. of SPIE Vol. 11834, 1183401  
© 2021 SPIE · CCC code: 0277-786X/21/\$21 · doi: 10.1117/12.2606661

Proc. of SPIE Vol. 11834 1183401-1

The papers in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. Additional papers and presentation recordings may be available online in the SPIE Digital Library at [SPIDigitalLibrary.org](http://SPIDigitalLibrary.org).

The papers reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from these proceedings:

Author(s), "Title of Paper," in *Laser Communication and Propagation through the Atmosphere and Oceans X*, edited by Jaime A. Anguita, Jeremy P. Bos, David T. Wayne, Proc. of SPIE 11834, Seven-digit Article CID Number (DD/MM/YYYY); (DOI URL).

ISSN: 0277-786X  
ISSN: 1996-756X (electronic)

ISBN: 9781510645066  
ISBN: 9781510645073 (electronic)

Published by

**SPIE**

P.O. Box 10, Bellingham, Washington 98227-0010 USA

Telephone +1 360 676 3290 (Pacific Time)

[SPIE.org](http://SPIE.org)

Copyright © 2021 Society of Photo-Optical Instrumentation Engineers (SPIE).

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of fees. To obtain permission to use and share articles in this volume, visit Copyright Clearance Center at [copyright.com](http://copyright.com). Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher.

Printed in the United States of America by Curran Associates, Inc., under license from SPIE.

Publication of record for individual papers is online in the SPIE Digital Library.

**SPIE. DIGITAL LIBRARY**

[SPIDigitalLibrary.org](http://SPIDigitalLibrary.org)

---

**Paper Numbering:** A unique citation identifier (CID) number is assigned to each article in the Proceedings of SPIE at the time of publication. Utilization of CIDs allows articles to be fully citable as soon as they are published online, and connects the same identifier to all online and print versions of the publication. SPIE uses a seven-digit CID article numbering system structured as follows:

- The first five digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B ... 0Z, followed by 10-1Z, 20-2Z, etc. The CID Number appears on each page of the manuscript.

# Contents

---

## EXPERIMENTS

---

- 11834 02 Evaluation of instruments for turbulence measurements at 1 km and 13.5 km ranges [11834-4]
- 11834 04 Extended analysis of atmospheric refraction effects captured by time-lapse imaging: long-term trends and machine learning image shift prediction [11834-1]
- 11834 05 Experimental validation and design feasibility of a compact interferometric refractive index structure constant measurement sensor for atmospheric turbulence characterization [11834-2]
- 11834 06 Optical propagation across the Chesapeake Bay: comparison of experiment to theory (Invited Paper) [11834-3]

---

## FSO

---

- 11834 07 Free-space, optical time transfer through a water tank [11834-11]
- 11834 08 A 30-cm Z-process silicon carbide off-axis parabola for lasercom telescope [11834-8]
- 11834 09 Hardware emulation of satellite-to-ground APD-based FSO downlink affected by atmospheric turbulence-induced fading [11834-9]
- 11834 0B External sensor arrays for assisting pointing, tracking, and acquisition in FSO communication [11834-13]

---

## MITIGATION METHODS

---

- 11834 0D Digital adaptive optics for turbulence mitigation [11834-17]
- 11834 0E Learning-based mitigation of atmospheric turbulence effects on high-power laser beams in a simulated environment [11834-14]
- 11834 0F Wavefront sensing for terrestrial, underwater, and space-borne free-space optical communications (Invited Paper) [11834-16]

---

## OAM

---

- 11834 0G Performance of turbulence-impaired dense OAM constellations for data modulation [11834-18]

- 11834 OH **Classification of multiple-state OAM superpositions using convolutional neural networks** [11834-19]
- 11834 OI **Machine learning identification of multiple-state OAM superpositions detected with spatial mode sensors** [11834-20]

---

#### THEORY AND SIMULATION

---

- 11834 OJ **Comparison of single line and broad-spectrum Gaussian beam propagation through turbulence** [11834-24]
- 11834 OK **The azimuthal spectrum of common transmittance functions and random media** [11834-26]
- 11834 OL **Simulation of  $I_m$ -Bessel beam propagation through time-correlated atmospheric turbulence** [11834-27]
- 11834 OM **Statistics of turbulence-induced laser irradiance fluctuations: impact of receiver aperture size** [11834-21]
- 11834 ON **Simulating a 980 nm laser beam propagation through humid air** [11834-22]
- 11834 OO **Semi-analytic simulation of optical wave propagation through turbulence with arbitrary phase screen placement (Invited Paper)** [11834-25]
- 11834 OP **Beam trajectory studies of diurnal refraction effects for a near-ground path involving numerical weather prediction and time-lapse imaging measurements** [11834-23]

---

#### ATMOSPHERIC CHARACTERIZATION: JOINT SESSION WITH 11834 AND 11836

---

- 11834 OQ **Nonlinear dynamics of the laser spot size and pulse duration in turbulence** [11834-28]
- 11834 OS **Statistics of optical turbulence from multi-year sonic anemometer-thermometer observations at a semi-arid region: effects of aerosols and atmospheric boundary layer dynamics** [11834-30]
- 11834 OT **Vertical profiles of turbulence measured with a Rayleigh beacon** [11834-31]

---

#### POSTER SESSION

---

- 11834 OV **Inner scale of turbulence as derived from NAVSLaM and applied to measurements of scintillation** [11834-33]
- 11834 OW **Bit error rate of free-space optical communication systems through exponentiated Weibull turbulent channels: impact of atmospheric aerosol induced warming** [11834-35]