

PROCEEDINGS OF SPIE

Laser Communication and Propagation through the Atmosphere and Oceans III

**Alexander M. J. van Eijk
Christopher C. Davis
Stephen M. Hammel**
Editors

**17–19 August 2014
San Diego, California, United States**

Sponsored and Published by
SPIE

Volume 9224

Proceedings of SPIE 0277-786X, V. 9224

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 III, edited by Alexander M. J. van Eijk,
Christopher C. Davis, Stephen M. Hammel, Proc. of SPIE Vol. 9224, 922401 © 2014 SPIE
CCC code: 0277-786X/14/\$18 · doi: 10.1117/12.2086634

Proc. of SPIE Vol. 9224 922401-1

The papers included 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. The papers published in these proceedings 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 this book:

Author(s), "Title of Paper," in *Laser Communication and Propagation through the Atmosphere and Oceans III*, edited by Alexander M. J. van Eijk, Christopher C. Davis, Stephen M. Hammel, Proceedings of SPIE Vol. 9224 (SPIE, Bellingham, WA, 2014) Article CID Number.

ISSN: 0277-786X

ISBN: 9781628412512

Published by

SPIE

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

Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445

SPIE.org

Copyright © 2014, Society of Photo-Optical Instrumentation Engineers.

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 copying fees. The Transactional Reporting Service base fee for this volume is \$18.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923. Payment may also be made electronically through CCC Online at 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. The CCC fee code is 0277-786X/14/\$18.00.

Printed in the United States of America.

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



SPIDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first 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, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four 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. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID Number.

Contents

vii	<i>Authors</i>
ix	<i>Conference Committee</i>
xiii	<i>Introduction</i>

FUNDAMENTALS OF TURBULENCE

9224 02	Propagation of a Gaussian-beam wave in general anisotropic turbulence (Invited Paper) [9224-1]
9224 04	Modeling of power spectral density of modified von Karman atmospheric phase turbulence and acousto-optic chaos using scattered intensity profiles over discrete time intervals [9224-3]
9224 05	Statistics of the turbulent phase in strong scintillation conditions [9224-4]
9224 06	Modeling of the turbulent phase in strong scintillation conditions [9224-5]
9224 07	Extended BKB model utilizing regional weather data for C_n^2 measurement [9224-67]

SYSTEMS

9224 08	A flexible cross-talk simulator for multiple spatial-mode free-space optical communication (Invited Paper) [9224-6]
9224 09	Performance analysis of MIMO FSO systems with radial array beams and finite sized detectors [9224-7]
9224 0A	Massive MIMO-OFDM indoor visible light communication system downlink architecture design [9224-8]

ADAPTIVE OPTICS AND SIMULATION

9224 0C	Atmospheric effects and ultimate ranging accuracy for lunar laser ranging (Invited Paper) [9224-10]
9224 0D	World wide study of the performance of a sodium guidestar [9224-11]
9224 0E	Intelligent correction of laser beam propagation through turbulent media using adaptive optics [9224-12]
9224 0F	Current status and challenges in optical turbulence simulations in various layers of the Earth's atmosphere [9224-13]

BEAM RECONSTRUCTION AND FOCUSING

- 9224 OG **Phase and amplitude wave front sensing and reconstruction with a modified plenoptic camera** [9224-14]
- 9224 OH **Advanced TIL system for laser beam focusing in a turbulent regime** [9224-15]
- 9224 OI **Evolution of laser-induced plasma in solvent aerosols** [9224-16]
- 9224 OJ **Applications of laser-induced filaments for optical communication links** [9224-17]

IMAGING AND NON-GAUSSIAN BEAMS

- 9224 OK **Visualizing the effects of distributed volume Non-Kolmogorov and anisotropic turbulence on incoherent long horizontal-path imaging** [9224-18]
- 9224 OL **Examining the validity of using a Gaussian Schell Model for modeling an extended beacon on a rough perfectly reflecting surface** [9224-19]
- 9224 OM **Scintillation reduction in multi-Gaussian Schell-model beams propagating in atmospheric turbulence** [9224-20]
- 9224 ON **Laboratory implementation of partially coherent beams with super-Gaussian distribution** [9224-21]
- 9224 OO **3D geometric modeling and simulation of laser propagation through turbulence with plenoptic functions** [9224-22]

ATMOSPHERIC EFFECTS I

- 9224 OP **A hierarchy of atmospheric effects and laser beam detection (Invited Paper)** [9224-23]
- 9224 OQ **A reconsideration of the best wavelengths for free-space optics** [9224-24]
- 9224 OR **Simultaneous atmospheric extinction and scintillation estimation using a modulated beacon** [9224-25]
- 9224 OS **Investigation of scintillometer designs for dynamic path measurement** [9224-26]
- 9224 OT **Propagation of light through ship exhaust plumes** [9224-27]

ATMOSPHERIC EFFECTS II

- 9224 OU **Atmospheric limitations on the performance of electro-optical systems: a brief overview (Invited Paper)** [9224-28]
- 9224 OV **Turbulence estimation and mitigation in horizontal path imaging** [9224-29]

- 9224 OW **Impact of large-scale atmospheric refractive structures on optical wave propagation** [9224-30]
- 9224 OX **Estimation of optical turbulence in the atmospheric surface layer from routine meteorological observations: an artificial neural network approach** [9224-31]
- 9224 OY **Reconstructing the prevailing meteorological and optical environment during the time of the Titanic disaster** [9224-32]

PROPAGATION

- 9224 10 **Real-time hardware background subtraction using an adjustable gain balance amplified photodetector** [9224-34]
- 9224 11 **Enhanced backscatter of optical beams reflected in atmospheric turbulence** [9224-35]
- 9224 12 **Experimental results on the enhanced backscatter phenomenon and its dynamics** [9224-36]

UNDERWATER COMMUNICATION

- 9224 13 **Optimum LED wavelength for underwater optical wireless communication at turbid water** [9224-37]
- 9224 14 **Modulated retro reflector for VLC applications** [9224-38]
- 9224 15 **Statistical characterization of fluctuations of a laser beam transmitted through a random air-water interface: new results from a laboratory experiment** [9224-39]
- 9224 16 **Multiple phase-screen simulation of oceanic beam propagation** [9224-40]
- 9224 17 **A novel method to optimize the wavelength for underwater free-space optical communications** [9224-41]

NOVEL APPLICATIONS AND DESIGNS

- 9224 18 **Statistical characteristics of free space optical systems employing reception spatial diversity** [9224-42]
- 9224 19 **Optical ranging and communication method based on all-phase FFT** [9224-43]
- 9224 1A **Turbulence channel test and analysis for NLOS UV communication** [9224-44]
- 9224 1B **Inter-satellite coherent optical communication locked frequency analysis and method** [9224-45]

POSTER SESSION

- 9224 1E **Indoor demonstration of free-space picosecond two-way time transfer on single photon level** [9224-49]
- 9224 1F **Effects of de-blurring on background modeling used for surveillance in long-distance horizontal imaging** [9224-50]
- 9224 1I **Indoor visible light communication: modeling and analysis of multi-state modulation** [9224-53]

NOVEL APPLICATIONS AND DESIGNS II

- 9224 1Q **Post-image acquisition processing approaches for coherent backscatter validation** [9224-68]

Authors

Numbers in the index correspond to the last two digits of the six-digit citation identifier (CID) article numbering system used in Proceedings of SPIE. The first four digits reflect the volume number. Base 36 numbering is employed for the last two digits and indicates the order of articles within the volume. Numbers start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B...0Z, followed by 10-1Z, 20-2Z, etc.

Andrews, Larry C., 02, 07, 1Q	Liao, Linchao, 1A
Arnon, Shlomi, 13, 14	Liner, Andrej, 1I
Avramov-Zamurovic, S., 0M	Linhart, Pavel, 1E
Basu, Santasri, 0L	Lovern, Mike, 0J
Basu, Sukanta, 0F, 0W, 0X, 0Y	Mack, A., 0T
Baykal, Yahya, 09	Majumdar, Arun K., 15
Belichki, Sara B., 07, 1Q	Malek-Madani, R., 0M
Blazej, Josef, 1E	Markov, Vladimir B., 0H
Bos, Jeremy P., 0K	Martinek, Radek, 1I
Cauble, Galen D., 10	McCrae, Jack E., 0L
Chamotskii, Mikhail, 05, 06	McGirr, Scott, 0I
Chatterjee, Monish R., 04	Mohamed, Fathi H. A., 04
Chen, Gang, 0A, 19, 1A	Nelson, C., 0M
Coffaro, Joseph T., 07, 1Q	Nelson, William, 0G, 0O, 11, 12
Crabbs, R., 02	Neuner, Burton, III, 17
Currie, Douglas G., 0C	Nunalee, Christopher G., 0F, 0W, 0Y
Davis, Christopher C., 0E, 0G, 0O, 11, 12	Palastro, J. P., 1I
de Oliveira, Jose Paulo G., 18	Panich, Michael G., 07, 1Q
deGrassie, John Stephen, 0P, 0Q	Pascoguin, B. Melvin, 17
Elkabetz, Adiel, 1F	Phillips, Ronald L., 02, 07, 1Q
Farwell, Nathan H., 16	Prochazka, Ivan, 0C, 1E
Fiorino, Steven T., 0D, 0F, 0L, 0W, 0Y	Reinhardt, Colin N., 0Q, 0R, 0S
Fountain, Wayne, 07	Rosenkrantz, Etai, 13, 14
Gbur, G., 0M	Rudiger, Joshua J., 0Q
George, Robert, 0I	Sadler, Brian M., 1A
Gibson, Kristofor B., 0V	Schleijpen, H. M. A., 0T
Gladysz, Szymon, 0U	Seiffer, Dirk, 0U
Gökçe, Muhsin C., 09	Shang, She, 1B
Gu, Y., 0M	Shapiro, Jeffrey H., 08
Gudimetla, V. S. Rao, 0K	Siegenthaler, John, 15
Guo, Haichao, 1B	Siska, Petr, 1I
Hammel, Stephen M., 0P, 0Q, 0R, 0S, 0V	Smith, Christopher A., 1Q
He, Ping, 0F, 0W, 0Y	Song, Dawei, 1B
Hening, Alexandru, 0I, 0J	Spencer, Mark F., 0L
Hyde, Milo W., 0L	Sprangle, Phillip A., 0H
Kaganovich, Dmitry, 0H	Stein, Karin, 0U
Kamacioğlu, Canan, 09	Ting, Antonio C., 0H
Khizhnyak, Anatoliy I., 0H	Tomov, Ivan V., 0H
Ko, Jonathan, 0E, 0G, 12	Tucker, Frank M., 07
Kodet, Jan, 1E	Uysal, Murat, 09
Korobkin, Dmitry V., 0H	van Eijk, Alexander M. J., 0T
Korotkova, Olga, 0M, 0N, 16	van Iersel, M., 0T
Koudelka, Petr, 1I	Vasinek, Vladimir, 1I
Land, Phillip, 15	Vitasek, Jan, 1I
Lang, Tian, 0A, 1A	Voelz, David G., 0N
Lasher, Mark, 0J	Vorontsov, Mikhail A., 0F, 0W, 0Y
Latal, Jan, 1I	Wang, Yao, 0X
Li, Xiaojun, 1B	Wayne, David T., 0J, 0R, 0S, 10
Li, Zening, 0A, 19, 1A	Wroblewski, Ronald, 0I

Wu, Chensheng, 0E, 0G, 0O, 11, 12
Xiao, Xifeng, 0N
Yitzhaky, Yitzhak, 1F
Zepp, Andreas, 0U
Zuraski, Steven M., 0D

Conference Committee

Program Track Chairs

Stephen M. Hammel, Space and Naval Warfare Systems Command
(United States)

Alexander M. J. van Eijk, TNO Defence, Security and Safety
(Netherlands)

Conference Chairs

Alexander M. J. van Eijk, TNO Defence, Security and Safety
(Netherlands)

Christopher C. Davis, University of Maryland, College Park
(United States)

Stephen M. Hammel, Space and Naval Warfare Systems Command
(United States)

Conference Program Committee

Larry C. Andrews, University of Central Florida (United States)

Jaime Anguita, Universidad de Los Andes (Chile)

Shlomi Arnon, Ben-Gurion University of the Negev (Israel)

Mikhail S. Belen'kii, Trex Enterprises Corporation (United States)

Matthew M. Bold, Lockheed Martin Space Systems Company
(United States)

Jeremy P. Bos, Air Force Research Laboratory (United States)

Mikhail I. Charnotskii, National Oceanic and Atmospheric
Administration (United States)

Gang Chen, University of California, Riverside (United States)

Jony Jiang Liu, U.S. Army Research Laboratory (United States)

Arun K. Majumdar, Naval Air Warfare Center Weapons Division
(United States)

Vladimir B. Markov, Advanced Systems & Technologies, Inc.
(United States)

Stuart D. Milner, University of Maryland, College Park (United States)

Dominic C. O'Brien, University of Oxford (United Kingdom)

Ronald L. Phillips, Florida Space Institute (United States)

William S. Rabinovich, U.S. Naval Research Laboratory (United States)

Michael C. Roggemann, Michigan Technological University
(United States)

Karin Stein, Fraunhofer-Institut für Optronik, Systemtechnik und
Bildauswertung (Germany)

Thomas Weyrauch, University of Dayton (United States)
Otakar Wilfert, Brno University of Technology (Czech Republic)
Heba Yuksel, Bogaziçi Üniversitesi (Turkey)

Session Chairs

- 1 Fundamentals of Turbulence
Christopher C. Davis, University of Maryland, College Park
(United States)
Alexander M. J. van Eijk, TNO Defence, Security and Safety
(Netherlands)
- 2 Systems
Mikhail I. Charnotskii, National Oceanic and Atmospheric
Administration (United States)
Christopher C. Davis, University of Maryland, College Park
(United States)
- 3 Adaptive Optics and Simulation
Karin Stein, Fraunhofer-Institut für Optronik, Systemtechnik und
Bildauswertung (Germany)
Stephen M. Hammel, Space and Naval Warfare Systems Command
(United States)
- 4 Beam Reconstruction and Focusing
Heba Yuksel, Bogaziçi Üniversitesi (Turkey)
Colin Reinhardt, Space and Naval Warfare Systems Center Pacific
(United States)
- 5 Imaging and Non-Gaussian Beams
Arun K. Majumdar, Naval Air Warfare Center Weapons Division
(United States)
Christopher C. Davis, University of Maryland, College Park
(United States)
- 6 Atmospheric Effects I
Jeremy P. Bos, Air Force Research Laboratory (United States)
Alexander M. J. van Eijk, TNO Defence, Security and Safety
(Netherlands)
- 7 Atmospheric Effects II
Douglas G. Currie, University of Maryland, College Park
(United States)
David T. Wayne, Space and Naval Warfare Systems Center Pacific
(United States)

- 8 Propagation
John S. deGrassie, Space and Naval Warfare Systems Center Pacific
(United States)
Stephen M. Hammel, Space and Naval Warfare Systems Center
Pacific (United States)
- 9 Underwater Communication
Gang Chen, University of California, Riverside (United States)
David T. Wayne, Space and Naval Warfare Systems Center Pacific
(United States)
- 10 Novel Applications and Designs
Christopher C. Davis, University of Maryland, College Park
(United States)
Alexander M. J. van Eijk, TNO Defence, Security and Safety
(Netherlands)

Introduction

This is the third in a series of annual conferences on the combined topics of laser communication and propagation effects through the atmosphere and ocean. There are well-established technologies in free space optical (FSO) communication, yet many challenges remain in obtaining reliable link and network performance in the face of atmospheric conditions—especially turbulence.

Several papers presented at the conference discussed theoretical analysis and simulation of turbulence effects, such as anisotropic and non-Kolmogorov turbulence, and scintillation, especially in conditions of strong turbulence. Many of these papers described variants of phase screen analysis as a way to simulate wave propagation through turbulence. Beyond its effects on FSO, systems turbulence also affects imaging through the atmosphere, and there was an invited paper that described how the atmosphere is the limiting factor in the performance of electro-optic systems of all kinds. A number of papers discussed how meteorological measurements could enable the estimation of turbulence conditions that affect FSO and imaging systems.

The use of powerful tools from numerical weather prediction (NWP) provided an exciting new direction for the assessment of large-scale refractive effects. Several papers described the estimation and simulation of optical turbulence for different atmospheric layers. The capability for NWP to reconstruct three-dimensional optical refractivity was utilized in a fascinating paper describing the contributions of the meteorological and optical environment to the Titanic disaster.

The effect of the atmosphere on directed energy (laser) weapons was the subject of several papers. Paper topics included scintillation measurements in dynamic scenarios, and modeling for both beam effects as well as the detection of laser beams. Measurement research was described, including Shack-Hartmann wave-front sensors, and the use of modified plenoptic cameras for distortion characterization.

Several papers discussed the development of ways to improve the focusing of energy on a distant target, either by adaptive optics mitigation of laser beam distortion, or by using phase conjugation of a target illumination laser, or through the exploitation of enhanced back scatter (EBS). A new way for observing EBS in a single camera frame was described. Other high-energy laser effects discussed included plasma formation, filaments, and their applications. A number of papers discussed how different kinds of laser beams, such as the multi-Gaussian Schell beam, Bessel beams, and Airy beams propagate through turbulence, and whether these beams offer advantages over single Gaussian beams.

An invited paper discussed the effects of the atmosphere on millimeter precision lunar ranging and how such observations can provide deep insight into fundamental physics. A second invited paper discussed how multi-spectral modes can provide efficient data transport in terms of bits/photon and spectral efficiency in terms of bits/sec-Hz and how cross-talk in such applications is affected by turbulence. The continuing interest in visible light communication (VLC) using LED illumination sources was discussed in papers describing MIMO techniques, modulation schemes, and retro-reflectors.

Finally, the 'Oceans' part of the conference title was well represented, with papers concentrating on underwater communications, examining the best wavelengths to use in different water conditions, and effects at the air-water interface. The expansion of topics presented at the conference included non-line-of-sight UV communications, light propagation through ship exhaust plumes, and time transfer using picosecond lasers at the single photon level.

Alexander M. J. van Eijk
Christopher C. Davis
Stephen M. Hammel