# PROCEEDINGS OF SPIE

# Laser Radar Technology and Applications XXIV

Monte D. Turner Gary W. Kamerman Editors

16–17 April 2019 Baltimore, Maryland, United States

Sponsored and Published by SPIE

**Volume 11005** 

Proceedings of SPIE 0277-786X, V. 11005

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

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 SPIEDigitalLibrary.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 Radar Technology and Applications XXIV, edited by Monte D. Turner, Gary W. Kamerman, Proceedings of SPIE Vol. 11005 (SPIE, Bellingham, WA, 2019) Seven-digit Article CID Number.

ISSN: 0277-786X

ISSN: 1996-756X (electronic)

ISBN: 9781510626751

ISBN: 9781510626768 (electronic)

Published by

SPIE

P.O. Box 10, Bellingham, Washington 98227-0010 USA Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445

Copyright © 2019, 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/19/\$18.00.

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.



**Paper Numbering:** Proceedings of SPIE follow an e-First publication model. A unique citation identifier (CID) number is assigned to each article 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**

vii ix	Authors Conference Committee
SESSION 1	SINGLE PHOTON SENSITIVE LIDAR AND DATE PROCESSING
11005 04	Object detection and recognition using laser radar incorporating novel SPAD technology [11005-6]
11005 05	Embedded implementation of a random feature detecting network for real-time classification of time-of-flight SPAD array recordings [11005-7]
SESSION 2	LIDAR BATHYMETRY
11005 06	Seahawk lidar [11005-13]
11005 07	Optical design of a deep water airborne bathymetric lidar [11005-14]
11005 08	Co-aligned dual wavelength circular scanner for airborne lidar bathymetry [11005-15]
SESSION 3	LIDAR SYSTEMS AND MODELING
11005 0A	Compact lidar polarimetry via time-varying transmit polarization and an elliptical polarization analyzer [11005-2]
11005 OB	Relationship between airborne lidar product specifications and end product requirements [11005-3]
SESSION 4	UAV AND COUNTER-UAV
11005 0C	Real-time counter-UAV system for long distance small drones using double pan-tilt scan laser radar [11005-8]
11005 0D	Tracking and prediction of small unmanned aerial vehicles' flight behavior and three-dimensional flight path from laser gated viewing images [11005-9]
11005 0E	UAV detection, tracking, and classification by sensor fusion of a 360° lidar system and an alignable classification sensor [11005-10]

11005 OF	Development of a small unmanned aerial system-mounted texel camera [11005-11]
11005 0G	Texturing of digital surface maps (DSMs) by selecting the texture from multiple perspective texel swaths taken by a low-cost small unmanned aerial vehicle (UAV) [11005-12]
SESSION 5	AUTONOMOUS VEHICLES
11005 OH	A new lidar scanning system for autonomous vehicles for a reduced calibration processing time [11005-16]
11005 01	Mutual interference potential and impact of scanning lidar according to the relevant vehicle applications [11005-17]
11005 OJ	Signal interactions between lidar scanners [11005-18]
SESSION 6	LIDAR SIGNAL AND DATA PROCESSING
11005 OK	Advances in lidar point cloud processing [11005-19]
11005 0M	Analysis and exploitation of lidar waveform data [11005-21]
11005 ON	Performance assessment of digital modulation and spreading code techniques for lidar with pulse coding [11005-22]
11005 00	Target discrimination using agile multispectral lidar [11005-23]
11005 OP	Real-time realization of digital surface models and slope map using lidar for UAV navigation in challenging environment $[11005\text{-}24]$
SESSION 7	HARSH ENVIRONMENT OPERATIONS AND ENVIRONMENTAL SENSING
11005 0Q	Er:YAG methane lidar laser technology [11005-25]
11005 OR	Optimization of obscurant penetration with next generation lidar technology [11005-26]
SESSION 8	ADVANCED LIDAR COMPONENTS I
11005 OW	Global shutter solid state flash lidar for spacecraft navigation and docking applications [11005-31]
11005 0X	A fiber Kerr effect polarization state generator for temporally multiplexed polarimetric ladar [11005-33]

11005 OY	Comparative characteristics of highly sensitive photodetectors for modern lidar systems [11005-34]
SESSION 9	ADVANCED LIDAR COMPONENTS II
11005 OZ	Comparison of illumination sources for imaging systems for different applications [11005-35]
11005 10	3D imaging with 128×128 eye safe InGaAs p-i-n lidar camera [11005-36]
11005 11	Geiger-mode avalanche photodetector camera technology at Ball Aerospace [11005-37]

### **Authors**

Numbers in the index correspond to the last two digits of the seven-digit citation identifier (CID) article numbering system used in Proceedings of SPIE. The first five 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.

Adams, Arielle M., 0X Afshar, Saeed, 05 Ahmido, Tariq, 0O Alahmadi, Yousef, OZ Arens, Michael, 0E Boadanov, S. V., OY Borgmann, Björn, OE Bourbeau, Tyler N., 0W Bradley, C. P., 10 Brassard, Hermann, OP Broadwater, Joshua, 00 Brown, Eric A., 06, 08 Budge, Scott E., OF, OG Burns, Patrick, 0Q Cao, Xiaoying, 0R Carr, Domenic, 06 Chen, Moran, 0Q Choi, Wonju, 0C Christnacher, Frank, 0D Christodoulides, Demetrios, 0X

Church, Philip, 0R Coopmans, Calvin, 0F Craney, Thomas A., 06, 08 Dahlin, Michael J., 0W Davis, Andrew S., 0M Day, Geoffrey S., 04 Delic, Dennis V., 04, 05 Devrelis, Vladimyros, 04

Dhulla, V., 10 Driggers, Ronald, 0Z Earhart, Patrick, 11 Eom, Jeongsook, 0I, 0N Fahmy, Ahmed T., 0P Furxhi, Orges, 0Z Gaylord, Thomas K., 0J Gholipour Vazimali, Milad, 0Z

Givigi, Sidney, 0P
Hamilton, Tara Julia, 05
Hammer, Marcus, 0E
Hansell, Joe, 0Q
Hebel, Marcus, 0E
Irwin, Ronda, 11
Joyce, Robert A., 04
Keyser, Christian K., 0A, 0X
Khan, Danish, 0C
Khatiwada, Bikalpa, 0G
Kim, Byeong Hak, 0C
Kim, Gunzuna, 01, 0N

Kim, Hyunsuk, 06

Kim, Min Young, OC
Kondratko, Piotr K., 11
Kosty, Jonathan, 06
Laurenzis, Martin, 0D
Lee, A. O., 10
Levin, E. V., 0Y
Litvinovitch, Slava, 0Q
Lopez-Aviles, Helena, 0X
Lussana, Rudi, 05
Martin, Richard K., 0A
Massoud, Ali, 0P
Matheson, Justin, 0R
Mau, Joyce, 05
McManamon, P. F., 10
Medbery, Jim, 11

Meraz, Nathan D., 06, 07, 08 Metcalf, Jeremy P., 0M Miwa, Tetsuharu, 0H Mukherjee, S. S., 10 Nguyen, Khanh, 0X

Nguyeri, Kridrin, OX Noureldin, Aboelmagd M., OP Olsen, Richard C., OM Pachowicz, David, OQ Panella, Aaron, 05 Park, Joong Yong, 06, 08 Park, Yongwan, OI, ON Patel, Priyank, 06 Pfennigbauer, Martin, OK Popko, Gerald B., OJ Pozdnyakov, Y. I., OY Rebert, Martin, OD Reinhardt, A. D., 10

Rudd, Willian J., 0Q Ruekgauer, Thomas E., 00 Sawruk, Nicholas W., 0Q Schertzer, Stéphane, OD Short, Bradley W., OW Shpakovsky, T. S., OY Shubin, V. E., 0Y Shushakov, D. A., 0Y Smith, Barnaby W., 04 Sornsin, Beth A., OW Strevey, Amber, 11 Świerkowski, Leszek, 04 Treiber, Mark, 0B Trumpf, Jochen, 05 Tuell, Grady, 06, 07, 08 Ullrich, Andreas, 0K

Rov. Gilles, OR

Valenta, Christopher R., 06, 0J van Schaik, André, 05 We, GwangJae, 06 Weiler, Chad, 0O Welch, Trevor, 0F Woods, William F., 04

## **Conference Committee**

#### Symposium Chairs

Jay Kumler, JENOPTIK Optical Systems, LLC (United States)
Ruth L. Moser, Air Force Research Laboratory (United States)

#### Symposium Co-chair

John M. Pellegrino, Georgia Institute of Technology (United States)

#### Conference Chairs

Monte D. Turner, U.S. Air Force (United States)
Gary W. Kamerman, Argo Al, LLC (United States)

#### Conference Program Committee

Philip Gatt, Lockheed Martin Coherent Technologies (United States)
 Hans D. Hallen, North Carolina State University (United States)
 Richard M. Heinrichs, MIT Lincoln Laboratory (United States)
 Thomas J. Karr, Defense Advanced Research Projects Agency (United States)

Martin Laurenzis, Institut Franco-Allemand de Recherches de Saint-Louis (France)

**Lori A. Magruder**, Applied Research Laboratories, The University of Texas at Austin (United States)

Vasyl Molebny, National Taras Shevchenko University of Kyiv (Ukraine) Upendra N. Singh, NASA Langley Research Center (United States) Ove Steinvall, FOI-Swedish Defence Research Agency (Sweden) Grady Tuell, 3D Ideas, LLC (United States) Andreas Ullrich, RIEGL Laser Measurement Systems GmbH (Austria)

#### Session Chairs

- Single Photon Sensitive Lidar and Date Processing Monte D. Turner, U.S. Air Force (United States)
- 2 Lidar Bathymetry Grady Tuell, 3D Ideas, LLC (United States)
- 3 Lidar Systems and Modeling Martin Laurenzis, Institut Franco-Allemand de Recherches de Saint-Louis (France)

- 4 UAV and Counter-UAV

  Monte D. Turner, U.S. Air Force (United States)
- 5 Autonomous Vehicles
  Gary W. Kamerman, Argo Al, LLC (United States)
- Lidar Signal and Data Processing
   Richard M. Heinrichs, MIT Lincoln Laboratory (United States)
- 7 Harsh Environment Operations and Environmental Sensing Vasyl Molebny, National Taras Shevchenko University of Kyiv (Ukraine)
- 8 Advanced Lidar Components I Andreas Ullrich, RIEGL Laser Measurement Systems GmbH (Austria)
- 9 Advanced Lidar Components II Andreas Ullrich, RIEGL Laser Measurement Systems GmbH (Austria)