PROCEEDINGS OF SPIE

Techniques and Instrumentation for Detection of Exoplanets IX

Stuart B. Shaklan
Editor

12–15 August 2019
San Diego, California, United States

Sponsored and Published by
SPIE

Volume 11117

Proceedings of SPIE 0277-786X, V. 11117

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

Techniques and Instrumentation for Detection of Exoplanets IX, edited by Stuart B. Shaklan, Proc. of SPIE
Vol. 11117, 1111723 · © 2019 SPIE · CCC code: 0277-786X/19/$21 · doi: 10.1117/12.2552832

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 *Techniques and Instrumentation for Detection of Exoplanets IX*, edited by Stuart B. Shaklan, Proceedings of SPIE Vol. 11117 (SPIE, Bellingham, WA, 2019) Seven-digit Article CID Number.

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

ISBN: 9781510629271
ISBN: 9781510629288 (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
SPIE.org
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 $21.00 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/$21.00.

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.

SPIEDigitalLibrary.org

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 *Authors*
ix *Conference Committee*

HABEX AND LUVOIR

11117 01 **Standard exoplanet yield evaluation for the LUVOIR and HabEx concept studies** [11117-1]

11117 02 **The LUVOIR Extreme Coronagraph for Living Planetary Systems (ECLIPS) II. Performance evaluation, aberration sensitivity analysis and exoplanet detection simulations** [11117-2]

11117 03 **The LUVOIR Extreme Coronagraph for Living Planetary Systems (ECLIPS) I: searching and characterizing exoplanetary gems** [11117-3]

11117 04 **Habitable Exoplanet Observatory (HabEx) telescope and optical instruments** [11117-4]

11117 05 **Numerical modeling of the Habex coronagraph** [11117-5]

FLIGHT SYSTEMS

11117 07 **The PICTURE-C exoplanetary direct imaging balloon mission: first flight preparation** [11117-7]

DEFORMABLE MIRRORS

11117 09 **High-contrast imaging stability using MEMS deformable mirror** [11117-10]

WFIRST CORONAGRAPH I

11117 0C **The WFIRST coronagraph instrument phase B optical design** [11117-13]

11117 0D **Development of the WFIRST CGI integral field spectrograph** [11117-14]

11117 0F **Directly constraining low-order aberration sensitivities in the WFIRST coronagraph design** [11117-16]

11117 0G **Optimization of Lyot coronagraph focal plane masks for improved low-order wavefront sensing** [11117-17]

WFIRST CORONAGRAPH II

11117 0H **WFIRST Phase B HLC occulter mask baselining and testbed WFC performance validation** [11117-18]

11117 0I **WFIRST low order wavefront sensing and control (LOWFS/C) performance on line-of-sight disturbances from multiple reaction wheels** [11117-19]

11117 0K **Simulating the effects of exozodiacal dust in WFIRST CGI observations** [11117-21]

STARSHADES I

11117 0L **Demonstration of 1e-10 contrast at the inner working angle of a starshade in broadband light and at a flight-like Fresnel number** [11117-22]

11117 0M **Rayleigh scattering in the Princeton starshade testbed** [11117-23]

11117 0N **Hardware demonstration of starshade formation flying sensing and control algorithms** [11117-24]

11117 0P **Advances in starshade technology readiness for an exoplanet characterizing science mission in the 2020's** [11117-26]

STARSHADES II

11117 0Q **Advancements in precision edges for a starshade external occulter** [11117-27]

11117 0S **Mapping the observable sky for a remote occulter working with ground-based telescopes** [11117-30]

GROUND-BASED OBSERVATIONS

11117 0U **Status of the Keck Planet Imager and Characterizer phase II development** [11117-32]

11117 0V **The vortex fiber nulling mode of the Keck Planet Imager and Characterizer (KPIC)** [11117-33]

11117 0W **Demonstrating predictive wavefront control with the Keck II near-infrared pyramid wavefront sensor** [11117-34]

11117 0X **Performance and early science with the Subaru Coronagraphic Extreme Adaptive Optics project** [11117-35]

11117 0Y **Demonstration of multi-star wavefront control using SCExAO** [11117-36]

11117 0Z **EXOhSPEC folded design optimization and performance estimation** [11117-37]

CORONAGRAPH DESIGN AND MODELING I

11117 10 **Effects and mitigation of polarization aberrations in LUVOIR coronagraph** [11117-38]

11117 11 **New concepts for calibrating non-common path aberrations in adaptive optics and coronagraph systems** [11117-39]

11117 12 **Phase-retrieval-based wavefront metrology for high-contrast coronography: 2. Reconstructions through a shaped pupil apodizer** [11117-40]

CORONAGRAPH DESIGN AND MODELING II

11117 16 **Vortex fiber nulling for exoplanet observations: conceptual design, theoretical performance, and initial scientific yield predictions** [11117-43]

11117 17 **Wavefront error tolerancing for direct imaging of exo-Earths with a large segmented telescope in space** [11117-45]

CORONAGRAPH DESIGN AND MODELING III

11117 18 **Maintaining a dark hole in a high contrast coronagraph and the effects of speckles drift on contrast and post processing factor** [11117-46]

11117 19 **Demonstration of multi-star wavefront control for WFIRST, Habex, and LUVOIR** [11117-47]

11117 1A **A multi-object spectrograph using single-mode fibers with a coronagraph: progress towards laboratory results on the high-contrast testbed for segmented telescopes** [11117-48]

11117 1C **Minimum number of observations for exoplanet orbit determination** [11117-50]

11117 1D **Exploration of the dynamical phase space of stars with known planets** [11117-51]

POSTER SESSION

11117 1F **Scalar vortex coronagraph mask design and predicted performance** [11117-61]

11117 1H **Critical characteristics of coronagraph masks influencing high contrast performance** [11117-63]

11117 1I **Shaped pupil coronagraph design for Subaru high-contrast imaging with reduction of the inner working angle for earth-like planet detection** [11117-64]

11117 1K **Sequential generalized likelihood ratio test for planet detection with photon-counting mode** [11117-67]

11117 1L **Modeling the scatter of sunlight from starshade edges** [11117-68]

11117 1M **Highly replicable, low-cost, portable, general-purpose, high-resolution spectrometer with applications in stellar studies and exoplanet science** [11117-69]

11117 1O **First results of the 4-fiber upgrade of the high-resolution comb calibrated spectrograph FOCES** [11117-71]

11117 1P **Self-nulling spectrograph for star glare rejection** [11117-72]

11117 1Q **The low-order wavefront control system for the PICTURE-C mission: deformable mirror anti-aliasing through temporal dithering** [11117-73]

11117 1R **Decoupling the image-plane and low-order wavefront sensors for the PICTURE-C coronagraph** [11117-74]

11117 1S **Status of commissioning stabilized infrared Fizeau interferometry with LBTI** [11117-75]

LABORATORY DEMONSTRATIONS I

11117 1U **Design description and commissioning performance of a stable coronagraph technology development testbed for direct imaging of Earth-like exoplanets** [11117-52]

11117 1V **Testbed demonstration of high-contrast coronagraph imaging in search for Earth-like exoplanets** [11117-53]

11117 1W **The high-contrast spectroscopy testbed for segmented telescopes (HCST): new wavefront control demonstrations** [11117-54]

11117 1X **Novel implementation of a Kalman filter for speckle nulling with a fiber injection unit** [11117-55]

LABORATORY DEMONSTRATIONS II

11117 1Z **Design and modeling of the off-axis parabolic deformable mirror laboratory** [11117-57]

11117 22 **Developing linear dark-field control for exoplanet direct imaging in the laboratory and on ground-based telescopes** [11117-65]

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.

Alagao, Mary Angelie, 0Z
Anglada-Escudé, Guillem, 0Z, 1M
Arney, G., 03
Arya, Manan, 0P
Aukkaravittayapun, Suparerk, 0Z
Baker, Clark, 1M
Balasubramanian, Kunjithapatham, 0H, 0L, 1H, 1U, 1V
Bartos, Randall, 0U
Basinger, Scott A., 0H
Batalha, Natasha, 16, 1D
Belikov, Ruslan, 03, 0Y, 19, 22
Bendek, Eduardo, 0Y, 19
Bender, Ralf, 1O
Bolcar, Matthew, 02, 03
Bond, Charlotte Z., 0U, 0V, 0W
Boonsri, Chantira, 0Z
Bradford, Samuel, 0P
Bradley, Christine, 1L
Brady, Gregory R., 12
Brandt, Timothy D., 0X
Breckinridge, James, 05
Brooks, Keira, 12
Buisset, Christophe, 0Z
Cady, Eric, 0H, 1H
Cahoy, Kerri L., 0K
Calvin, Benjamin, 0U
Campbell, David, 0Z
Cetre, Sylvain, 0U, 0W
Chakrabarti, Supriya, 07, 1Q, 1R
Charton, Julien, 1Q
Chilcote, Jeffrey, 0X
Choochalerm, Piyamas, 0Z
Chui, Talso, 1U, 1V
Coker, Carl T., 1A, 1W
Colborn, Jennah K., 0U
Cook, Timothy A., 07, 1Q, 1R
Coyle, Laura E., 17
Creager, Brandon, 0C
Crill, Brendan, 1U, 1V
Currie, Thayne, 0X, 0Y, 1I, 22
Davis, Jeffrey, 05
Debes, John, 0K
Delacroix, Christian, 1I
Delorme, Jacques-Robert, 0U, 0V
Ditto, Thomas D., 1P
Douglas, Ewan S., 0K
Dula, Walker, 01
Dumont, Philip, 0L
Echeverri, Daniel, 0U, 0V, 16, 1A, 1V, 1W
Echternach, Pierre, 1H
Errmann, Ronny, 0Z
Ertel, Steve, 1S
Fahrenschon, Vanessa, 1O
Ferguson, Maxwell, 0Q
Fienup, James R., 10
Finn, Susanna C., 1Q
Freebury, Gregg, 0P
Fregoso, Felipe, 0I
Galvin, Michael, 0L
Gascón, Carlos, 1D
Gaylin, Samuel, 0D
Gerard, Benjamin, 0X
Gersh-Range, Jessica A., 1I
Gill, John, 1U
Gong, Qian, 0D
Graham, James, 0W
Greer, Frank, 1H
Grenz, Paul, 1S
Groff, Tyler D., 02, 0D, 0X, 1Z
Grupp, Frank, 1O
Guyon, Olivier, 0X, 0Y, 22
Hagopian, John, 12
Harness, Anthony, 0L, 0M, 0N
Harvey, David, 0D
Hayama, Thomas, 0V
Hénault, François, 11
Henze, Chris, 19
Hewawasam, Kuravi, 07, 1Q, 1R
Hildebrant, Sergei, 0S
Hilgemann, Evan, 0P, 0Q
Hinz, Phil, 1S
Hopp, Ulrich, 1O
Horning, Andrew, 1C
Howe, Glenn A., 07, 1Q, 1R
Hu, Mengya (Mia), 1K
Jensen-Clem, Rebecca, 0U, 0W
Jones, Hugh R. A., 0Z, 1M
Joseph, Joane F., 1I
Jovanovic, Nemanja, 0U, 0V, 0X, 16, 1A, 1W, 1X
Juanola-Parramon, Roser, 02, 03, 1Z
Kasdin, N. Jeremy, 0L, 0N, 0X, 18, 1I, 1K
Keithly, Dean, 01
Kellermann, Hanna, 1O
Kern, Brian D., 0F, 0H, 0I, 1U, 1V
Kinzly, Nathaniel, 1D
Knight, J. Scott, 17
Krist, John E., 02, 04, 05, 0C, 0H

Kuan, Gary, 04, 05
Laginja, Iva, 03, 12, 17
Lam, Ray, 1U
Leboulleux, Lucie, 17
Leckngam, Apichat, 0Z
Lewis, Nikole K., 0K, 1D
Lhospice, Esther, 0Z
Lilley, Scott, 0U
Lisman, Douglas, 0P, 0Q
Llop-Sayson, Jorge, 1A, 1W, 1X
Lozi, Julien, 0X, 0Y
Macintosh, Bruce, 0K
Mahiou, Pierre, 1Q
Maier, Erin, 1S
Mamajek, Eric, 01
Manthena, Raju, 1L
Marley, Mark, 1D
Marois, Christian, 0X
Martel, Jason, 07, 1Q, 1R
Martin, Stefan, 04, 05, 0Q, 1L
Martin, William E., 0Z, 1M
Martinache, Frantz, 0X
Marx, David S., 0H, 0I, 1U, 1V
Mather, John, 0S
Mawet, Dimitri, 04, 05, 0U, 0V, 0W, 16, 1A, 1F, 1W, 1X
McEwen, Eden, 0U, 0W
McGuire, James, 0C
McKeithen, Dylan, 0Q, 1L
Mejia Prada, Camilo, 09, 0I, 1H, 1U, 1V
Mendillo, Christopher B., 07, 1Q, 1R
Mennesson, Bertrand, 01, 05
Milani, Kian, 0K
Mkrtichian, David, 0Z
Moody, Dwight, 0H, 1H, 1U, 1V
Morgan, Rhonda, 01, 1C
Moriarty, Christopher, 12
Morrissey, Grady, 1W
Morzinksi, Katie, 1S
Mountcastle, Rose, 0D
Mugnier, Laurent, 17
Muller, Richard, 0L, 1H
N'Diaye, Mamadou, 12
Nemati, Bijan, 0H
Nicolaeff, Nicholas, 0D
Nielson, Eric, 1C
Noss, James, 17
Paenoi, Jitsupa, 0Z
Palacios, Leonel M., 0N
Panyaphirawat, Thirasak, 0Z
Patterson, Keith D., 0C, 0I, 1H, 1U, 1V
Peretz, Eliad, 0S
Petrone, Peter, 12
Pezzato, Jacklyn, 0U, 0V
Pluzhnik, Eugene, 0Y, 19, 22
Poberezhskiy, Ilya Y., 0H
Pogorelyuk, Leonid, 18
Por, Emiel H., 17
Prasit, Apirat, 0Z
Pueyo, Laurent, 02, 03, 17
Ragland, Sam, 0W
Rattanasoon, Somsawat, 0Z
Redding, D., 03
Riggs, A.J. Eldorado, 03, 0F, 0G, 0H, 1A, 1F, 1H, 1W
Rizzo, Maxime J., 0D
Roberge, A., 03
Rodgers, Michael, 0C
Ruane, Garreth, 02, 03, 04, 05, 0F, 0U, 0V, 16, 1A, 1F, 1U, 1V, 1W
Rud, Mayer, 0C
Rupp, Jordan, 1U
Saini, Navtej, 05
Saltarelli, Nicholas, 0Q
Sauvage, Jean-François, 17
Savransky, Dmitry, 01, 1D
Scowen, Paul, 04
Seager, Sara, 0S
Seo, Byoung-Joon, 0H, 0I, 1H, 1U, 1V
Serabyn, Eugene, 09, 0V, 1F
Serabyn, Eugene, 16
Shaklan, Stuart, 01, 0L, 0P, 0Q, 0S, 1A, 1L
Shaw, John, 0I, 1U, 1V
Shelton, Chris, 0I
Shi, Fang, 09, 0C, 0I, 1U, 1V
Shields, Joel, 0I
Sidick, Erkin, 0G
Siegler, Nicholas, 1U, 1V
Sirbu, Dan, 03, 0Y, 19
Sithajan, Sirinrat, 0Z
Slonaker, Richard, 0S
Soto, Gabriel, 01
Soummer, Rémi, 03, 12, 17
Spalding, Eckhart, 1S
St. Laurent, Kathryn, 17
Stahl, Philip, 05
Stapelfeldt, Karl, 01
Stark, C., 03
Steeves, John, 0P, 0Q
Stern, Daniel, 04
Stone, Jordan, 1S
Subedi, Hari B., 1Z
Sun, He, 1K, 1W
Tang, Hong, 0C, 1U, 1V
Titus, John, 0D
Trauger, John, 05, 1U, 1V
Truong, Tuan, 0I
Turmon, Michael, 01
Vanderbei, Robert J., 1I
Vaz, Amali, 1S
Vievard, Sébastien, 0X
Vuong, Simon, 0L
Wallace, James K., 0U, 0V, 16
Wang, Jason, 0U, 0V, 16
Wang, Liang, 1O
Webb, David, 0P, 0Q
Wetherell, Ed, 0U
White, Victor, 0L, 1H, 1U
Will, Scott D., 03, 10
Willems, Phillip, 0L, 0M, 0S

Wilson, Daniel, 0H, 1H, 1U, 1V
Wizinowich, Peter, 0U, 0W
Xin, Yeyuan, 1X
Xin, Yinzi, 0K
Yee, Karl, 0L, 1H, 1U
Zhang, Manxuan (Rebecca), 12, 1X
Zhao, Feng, 0C
Zhou, Hanying, 0H, 1H
Zimmer, Robert, 1U, 1V
Zimmerman, Neil T., 02, 03, 0D

Conference Committee

Program Track Chair

Oswald H. Siegmund, University of California, Berkeley (United States)

Conference Chair

Stuart B. Shaklan, Jet Propulsion Laboratory (United States)

Conference Program Committee

Olivier Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States) and Research Corporation of University of Hawaii (United States) and The University of Arizona (United States)
Bruce A. Macintosh, Stanford University (United States)
Dimitri P. Mawet, Caltech (United States)
M. Charley Noecker, Jet Propulsion Laboratory (United States)
Rémi Soummer, Space Telescope Science Institute (United States)

Session Chairs

1 Decadal Large Mission Concepts and Technology I: Joint Session with Conferences 11115, 11116, 11117, and 11118
Allison A. Barto, Ball Aerospace (United States)

2 Decadal Large Mission Concepts and Technology II: Joint Session with Conferences 11115, 11116, 11117, and 11118
Tony B. Hull, The University of New Mexico (United States)
Stuart B. Shaklan, Jet Propulsion Laboratory (United States)

3 HabEx and LUVOIR
Stuart B. Shaklan, Jet Propulsion Laboratory (United States)

4 Flight Systems
Tyler D. Groff, NASA Goddard Space Flight Center (United States)

5 Deformable Mirrors
Tyler D. Groff, NASA Goddard Space Flight Center (United States)

6 WFIRST Coronagraph I
Eduardo A. Bendek, Jet Propulsion Laboratory (United States)

7 WFIRST Coronagraph II
Ruslan Belikov, NASA Ames Research Center (United States)

8 Starshades I
Dan Sirbu, NASA Ames Research Center (United States)

10 Ground-based Observations
A.J. Eldorado Riggs, Jet Propulsion Laboratory (United States)

11 Coronagraph Design and Modeling I
Stuart B. Shaklan, Jet Propulsion Laboratory (United States)

12 Coronagraph Design and Modeling II
Roser Juanola-Parramon, NASA Goddard Space Flight Center (United States)

13 Coronagraph Design and Modeling III
Matthew R. Bolcar, NASA Goddard Space Flight Center (United States)