

PROCEEDINGS OF SPIE

Adaptive X-Ray Optics

Ali M. Khounsary
Stephen L. O'Dell
Sergio R. Restaino
Editors

3–5 August 2010
San Diego, California, United States

Sponsored and Published by
SPIE

Volume 7803

Proceedings of SPIE, 0277-786X, v. 7803

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

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 *Adaptive X-Ray Optics*, edited by Ali M. Khounsary, Stephen L. O'Dell, Sergio R. Restaino, Proceedings of SPIE Vol. 7803 (SPIE, Bellingham, WA, 2010) Article CID Number.

ISSN 0277-786X

ISBN 9780819482990

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 © 2010, 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/10/\$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 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	Conference Committee
ix	Introduction

SESSION 1 SYNCHROTRON ADAPTIVE X-RAY OPTICS I

7803 02	Hartmann wavefront sensor and adaptive x-ray optics developments for synchrotron applications [7803-01] P. Mercère, M. Idir, Synchrotron SOLEIL (France); G. Dovillaire, X. Levecq, S. Bucourt, Imagine Optic SA (France); L. Escolano, P. Sauvageot, ISP SYSTEM (France)
7803 03	A novel adaptive bimorph focusing mirror and wavefront corrector with sub-nanometre dynamical figure control [7803-02] K. J. S. Sawhney, S. G. Alcock, Diamond Light Source Ltd. (United Kingdom); R. Signorato, Bruker ASC GmbH (Germany)
7803 04	An adaptive optical system for sub-10nm hard x-ray focusing [7803-03] H. Mimura, T. Kimura, H. Yokoyama, Osaka Univ. (Japan); H. Yumoto, SPring-8/Japan Synchrotron Radiation Research Institute (Japan); S. Matsuyama, Osaka Univ. (Japan); K. Tamasaku, Y. Koumura, M. Yabashi, T. Ishikawa, SPring-8/RIKEN (Japan); K. Yamauchi, Osaka Univ. (Japan)

SESSION 2 SYNCHROTRON ADAPTIVE X-RAY OPTICS II

7803 06	Development of spider micro-structured optical arrays for x-ray optics [7803-05] D. Rodriguez Sanmartin, D. Zhang, T. Button, C. Meggs, The Univ. of Birmingham (United Kingdom); C. Atkins, P. Doel, D. Brooks, Univ. College London (United Kingdom); C. Feldman, R. Willingale, Univ. of Leicester (United Kingdom); A. Michette, S. Pfauntsch, S. Sahraei, M. Shand, King's College London (United Kingdom); A. James, G. Willis, Mullard Space Science Lab., Univ. College London (United Kingdom); C. Dunare, T. Stevenson, W. Parkes, Scottish Microelectronics Ctr., The Univ. of Edinburgh (United Kingdom); A. Smith, STFC-Daresbury Lab. (United Kingdom)
7803 07	Adaptive angular control of high-resolution x-ray optics [7803-06] S. Stoupin, F. Lenkszus, R. Laird, K. Goetze, K.-J. Kim, Y. Shvyd'ko, Argonne National Lab. (United States)
7803 08	Optomechanical analysis and design tool for adaptive x-ray optics [7803-07] G. Michels, V. Genberg, Sigmadyne, Inc. (United States)
7803 09	Magnetic smart material application to adaptive x-ray optics [7803-08] M. P. Ulmer, M. E. Graham, S. Vaynman, J. Cao, Northwestern Univ. (United States); P. Z. Takacs, Brookhaven National Lab. (United States)

SESSION 3 ADAPTIVE NORMAL-INCIDENCE TELESCOPES I

- 7803 0B **Review of active optics methods in astronomy from x-rays to the infrared (Invited Paper)** [7803-09]
G. R. Lemaître, Lab. d'Astrophysique de Marseille (France)

SESSION 4 ADAPTIVE NORMAL-INCIDENCE TELESCOPES II

- 7803 0E **Imaging experiment of an adaptive optics with a normal-incident EUV telescope** [7803-12]
H. Murakami, S. Kitamoto, E. Takenaka, T. Shibata, M. Yoshida, K. Higashi, D. Takei, Rikkyo Univ. (Japan)
- 7803 0F **The Naval Research Laboratory MEM adaptive optics program** [7803-13]
S. R. Restaino, T. Martinez, J. R. Andrews, C. C. Wilcox, F. Santiago, U.S. Naval Research Lab. (United States); D. M. Payne, Narrascope, Inc. (United States)

SESSION 5 ACTIVE GRAZING-INCIDENCE TELESCOPES I

- 7803 0H **High-resolution x-ray telescopes** [7803-15]
S. L. O'Dell, NASA Marshall Space Flight Ctr. (United States); R. J. Brissenden, W. N. Davis, Smithsonian Astrophysical Observatory (United States); R. F. Elsner, NASA Marshall Space Flight Ctr. (United States); M. Elvis, M. Freeman, T. Gaetz, P. Gorenstein, Smithsonian Astrophysical Observatory (United States); M. V. Gubarev, NASA Marshall Space Flight Ctr. (United States); D. Jerius, M. Juda, Smithsonian Astrophysical Observatory (United States); J. J. Kolodziejczak, NASA Marshall Space Flight Ctr. (United States); S. S. Murray, Smithsonian Astrophysical Observatory (United States) and Johns Hopkins Univ. (United States); R. Petre, NASA Goddard Space Flight Ctr. (United States); W. Podgorski, Smithsonian Astrophysical Observatory (United States); B. D. Ramsey, NASA Marshall Space Flight Ctr. (United States); P. B. Reid, Smithsonian Astrophysical Observatory (United States); T. Saha, NASA Goddard Space Flight Ctr. (United States); D. A. Schwartz, Smithsonian Astrophysical Observatory (United States); S. Trolter-McKinstry, Pennsylvania State Univ. (United States); M. C. Weisskopf, NASA Marshall Space Flight Ctr. (United States); R. H. T. Wilke, Pennsylvania State Univ. (United States); S. Wolk, Smithsonian Astrophysical Observatory (United States); W. W. Zhang, NASA Goddard Space Flight Ctr. (United States)
- 7803 0I **Technology challenges of active x-ray optics for astronomy** [7803-16]
P. B. Reid, W. Davis, D. A. Schwartz, Harvard-Smithsonian Ctr. for Astrophysics (United States); S. Trolter-McKinstry, R. H. T. Wilke, The Pennsylvania State Univ. (United States)
- 7803 0J **On-orbit adjustment concepts for the Generation-X Observatory** [7803-17]
D. A. Schwartz, R. Brissenden, M. Freeman, T. Gaetz, P. Gorenstein, D. Jerius, M. Juda, P. Reid, S. Wolk, Harvard-Smithsonian Ctr. for Astrophysics (United States); T. Saha, W. Zhang, NASA Goddard Space Flight Ctr. (United States); S. O'Dell, NASA Marshall Space Flight Ctr. (United States); S. Trolter-McKinstry, D. Wilke, The Pennsylvania State Univ. (United States)
- 7803 0K **Thermal shaping of thin glass substrates for segmented grazing incidence active optics** [7803-18]
L. Proserpio, M. Civitani, INAF-Osservatorio Astronomico di Brera (Italy) and Univ. degli Studi dell'Insubria (Italy); M. Ghigo, G. Pareschi, INAF-Osservatorio Astronomico di Brera (Italy)

- 7803 OL **3D characterization of thin glass x-ray mirrors via optical profilometry** [7803-19]
M. Civitani, INAF-Osservatorio Astronomico di Brera (Italy) and Univ. degli Studi dell'Insubria (Italy); M. Ghigo, O. Citterio, P. Conconi, D. Spiga, G. Pareschi, INAF-Osservatorio Astronomico di Brera (Italy); L. Proserpio, INAF-Osservatorio Astronomico di Brera (Italy) and Univ. degli Studi dell'Insubria (Italy)

SESSION 6 ACTIVE GRAZING-INCIDENCE TELESCOPES II

- 7803 OM **Development of net-shape piezoelectric actuators for large x-ray optics** [7803-20]
D. Rodriguez Sanmartin, D. Zhang, T. Button, C. Meggs, The Univ. of Birmingham (United Kingdom); C. Atkins, P. Doel, D. Brooks, Univ. College London (United Kingdom); C. Feldman, R. Willingale, Univ. of Leicester (United Kingdom); A. James, G. Willis, Mullard Space Science Lab., Univ. College London (United Kingdom); A. Smith, STFC-Daresbury Lab. (United Kingdom)
- 7803 ON **The performance of thin shell adaptive optics for high angular resolution x-ray telescopes** [7803-21]
C. Feldman, R. Willingale, Univ. of Leicester (United Kingdom); C. Atkins, D. Brooks, Univ. College London (United Kingdom); T. Button, The Univ. of Birmingham (United Kingdom); P. Doel, Univ. College London (United Kingdom); A. James, Mullard Space Science Lab., Univ. College London (United Kingdom); C. Meggs, D. Rodriguez-Sanmartin, The Univ. of Birmingham (United Kingdom); A. Smith, STFC-Daresbury Lab. (United Kingdom); C. Theobald, G. Willis, Mullard Space Science Lab., Univ. College London (United Kingdom)
- 7803 OO **PZT piezoelectric films on glass for Gen-X imaging** [7803-22]
R. H. T. Wilke, S. Troler-McKinstry, The Pennsylvania State Univ. (United States); P. B. Reid, D. A. Schwartz, Harvard-Smithsonian Ctr. for Astrophysics (United States)
- 7803 OP **Finite element analyses of thin film active grazing incidence x-ray optics** [7803-23]
W. N. Davis, P. B. Reid, D. A. Schwartz, Harvard-Smithsonian Ctr. for Astrophysics (United States)
- 7803 OQ **Adaptive grazing incidence optics for the next generation of x-ray observatories** [7803-24]
C. Lillie, Northrop Grumman Aerospace Systems (United States); D. Pearson, A. Plinta, B. Metro, E. Lintz, Northrop Grumman Xinetics (United States); D. Shropshire, R. Danner, Northrop Grumman Aerospace Systems (United States)

Author Index

Conference Committee

Program Track Chair

Carolyn A. MacDonald, University at Albany (United States)

Conference Chairs

Ali M. Khounsary, Argonne National Laboratory (United States)

Stephen L. O'Dell, NASA Marshall Space Flight Center (United States)

Sergio R. Restaino, U.S. Naval Research Laboratory (United States)

Conference Cochairs

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

John A. Wellman, Xinetics, Inc. (United States)

Kazuto Yamauchi, Osaka University (Japan)

Program Committee

Simon G. Alcock, Diamond Light Source Ltd. (United Kingdom)

Klaus Attenkofer, Argonne National Laboratory (United States)

Kevin L. Baker, Lawrence Livermore National Laboratory (United States)

Raymond Barrett, European Synchrotron Radiation Facility (France)

Paul A. Bierden, Boston Micromachines Corporation (United States)

Daniele Cocco, Sincrotrone Trieste S.C.p.A. (Italy)

Robert F. Fischetti, Argonne National Laboratory (United States)

Michael Hart, The University of Arizona (United States)

Mourad Idir, Synchrotron SOLEIL (France)

Daniel Lopez, Argonne National Laboratory (United States)

Carolyn A. MacDonald, University at Albany (United States)

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

Riccardo Signorato, Bruker ASC GmbH (Germany)

Robert K. Tyson, The University of North Carolina at Charlotte (United States)

Melville P. Ulmer, Northwestern University (United States)

Richard Willingale, University of Leicester (United Kingdom)

Session Chairs

- 1 Synchrotron Adaptive X-ray Optics I
 Ali M. Khounsary, Argonne National Laboratory (United States)
 Kevin L. Baker, Lawrence Livermore National Laboratory (United States)
- 2 Synchrotron Adaptive X-ray Optics II
 Kazuto Yamauchi, Osaka University (Japan)
 Raymond Barrett, European Synchrotron Radiation Facility (France)
- 3 Adaptive Normal-Incidence Telescopes I
 Stephen L. O'Dell, NASA Marshall Space Flight Center (United States)
 Paul A. Bierden, Boston Micromachines Corporation (United States)
- 4 Adaptive Normal-Incidence Telescopes II
 Stuart B. Shaklan, Jet Propulsion Laboratory (United States)
 Mourad Idir, Synchrotron SOLEIL (France)
- 5 Active Grazing-Incidence Telescopes I
 Sergio R. Restaino, U.S. Naval Research Laboratory (United States)
 Daniel Lopez, Argonne National Laboratory (United States)
- 6 Active Grazing-Incidence Telescopes II
 Michael Hart, The University of Arizona
 Simon G. Alcock, Diamond Light Source Ltd. (United Kingdom)

Introduction

Adaptive optics is a rapidly evolving field with a broad range of applications, from ophthalmology to optical communications to astronomy. Specific applications include laser beam forming and correction, laser materials processing, confocal microscopes, scanning optical systems, optical probes, micro-optic couplings, and in-vivo retinal mapping. Technical advances—including manufacturing developments such as Micro-Electro-Mechanical Systems (MEMS) combined with batch processing—and ensuing cost reductions are likely to effect an even broader range of applications.

Developed originally for correcting atmospherically induced wave-front errors, most adaptive optics operate in the IR and visible spectral bands. However, there is no fundamental reason why they cannot be extended beyond—including in the X-ray band. On the other hand, some specific technical issues of active optics for grazing-incidence mirrors differ from those for normal-incidence mirrors.

This is the inaugural conference in a biennial series planned for SPIE Optics + Photonics. It serves as a forum for reporting and reviewing developments in "traditional" adaptive optics, for examining their extension and application to X-ray optic, and for reporting progress in what we broadly (and loosely) term "Adaptive X-ray Optics".

Two main objectives guide and drive this endeavor. One is to provide capabilities for dynamic or quasi-static adjustment of otherwise static optical systems, thus improving imaging quality and increasing the versatility of X-ray optical systems. The other objective, somewhat related to the first, is to provide real-time corrections to X-ray optical systems.

This Conference comprised six sessions. The first two sessions concentrated on the burgeoning efforts to apply adaptive techniques to X-ray synchrotron optics. The third and fourth sessions focused on normal-incidence telescopes—drawing lessons on progress in deformable traditional optics in sensing, actuation, and correction. The last two sessions centered on grazing-incidence telescopes, where the need for remotely (in-space) adjustable optics is being examined primarily for figure correction of highly nested, lightweight X-ray telescopes.

We thank the speakers and session chairs for contributing to a timely and useful conference. We are grateful to the Conference co-chairs (Drs. Stuart B. Shaklan, John Wellman, and Kazuto Yamauchi) and other members of the Program Committee for their assistance in organizing the Conference. Finally, we appreciate the help of the SPIE staff.

**Ali M. Khounsary
Stephen L. O'Dell
Sergio R. Restaino**

