

PROCEEDINGS OF SPIE

Ground-based and Airborne Telescopes IV

**Larry M. Stepp
Roberto Gilmozzi
Helen J. Hall**
Editors

**1–6 July 2012
Amsterdam, Netherlands**

Sponsored by
SPIE

Cooperating Organizations

American Astronomical Society (United States) • Netherlands Institute for Radio Astronomy (ASTRON) (Netherlands) • Ball Aerospace & Technologies Corporation (United States)
Canadian Astronomical Society (CASCA) (Canada) • European Astronomical Society (Switzerland) • ESO—European Southern Observatory (Germany) • International Astronomical Union • Korea Astronomy and Space Science Institute (KASI) (Republic of Korea) • National Radio Astronomy Observatory • POPSud (France) • TNO (Netherlands)

Published by
SPIE

Part One of Three Parts

Volume 8444

Proceedings of SPIE 0277-786X, V.8444

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

Ground-based and Airborne Telescopes IV, edited by Larry M. Stepp, Roberto Gilmozzi, Helen J. Hall,
Proc. of SPIE Vol. 8444, 844401 · © 2012 SPIE · CCC code: 0277-786/12/\$18 · doi: 10.1117/12.981225

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 *Ground-based and Airborne Telescopes IV*, edited by Larry M. Stepp, Roberto Gilmozzi, Helen J. Hall, Proceedings of SPIE Vol. 8444 (SPIE, Bellingham, WA, 2012) Article CID Number.

ISSN: 0277-786X

ISBN: 9780819491459

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 © 2012, 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/12/\$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

- xxi *Conference Committee*
- xxxvii *Introduction*
- xxxix *The cosmic microwave background: observing directly the early universe (Plenary Paper) [8442-506]*
P. de Bernardis, S. Masi, Univ. degli Studi di Roma La Sapienza (Italy)

Part 1

SOLAR TELESCOPES I

- 8444 03 **The 1.6 m off-axis New Solar Telescope (NST) in Big Bear (Invited Paper) [8444-1]**
P. R. Goode, W. Cao, Ctr. for Solar-Terrestrial Research, New Jersey Institute of Technology (United States) and Big Bear Solar Observatory (United States)
- 8444 04 **Applications of infrared techniques in solar telescopes NVST [8444-141]**
Y. Li, F. Xu, S. Huang, G. Liu, Yunnan Astronomical Observatory (China)
- 8444 05 **Introduction to the Chinese Giant Solar Telescope [8444-3]**
Z. Liu, Yunnan Astronomical Observatory (China); Y. Deng, National Astronomical Observatories (China); Z. Jin, Yunnan Astronomical Observatory (China); H. Ji, Purple Mountain Observatory (China)
- 8444 06 **Large-field high-resolution mosaic movies [8444-4]**
R. H. Hammerschlag, Utrecht Univ. (Netherlands); G. Sliepen, Institute for Solar Physics, Royal Swedish Academy of Sciences (Sweden); F. C. M. Bettonvil, ASTRON (Netherlands) and Leiden Observatory (Netherlands); A. P. L. Jägers, Utrecht Univ. (Netherlands); P. Sütterlin, Institute for Solar Physics, Royal Swedish Academy of Sciences (Sweden); S. F. Martin, Helio Research (United States)

SOLAR TELESCOPES II

- 8444 07 **The Advanced Technology Solar Telescope: design and early construction (Invited Paper) [8444-5]**
J. P. McMullin, T. R. Rimmele, S. L. Keil, M. Warner, S. Barden, S. Bulau, S. Craig, B. Goodrich, E. Hansen, S. Hegwer, R. Hubbard, W. McBride, S. Shimko, F. Woeger, J. Ditsler, National Solar Observatory (United States)
- 8444 08 **ATST Enclosure final design and construction plans [8444-6]**
G. Murga, IDOM (United States); H. Marshall, National Solar Observatory (United States); J. Ariño, T. Lorentz, IDOM (United States)

- 8444 09 **Progress making the top end optical assembly (TEOA) for the 4-meter Advanced Technology Solar Telescope** [8444-7]
B. Canzian, L-3 Integrated Optical Systems Brashear (United States); J. Barentine, L-3 Integrated Optical Systems Tinsley (United States); J. Arendt, S. Bader, G. Danyo, C. Heller, L-3 Integrated Optical Systems Brashear (United States)
- 8444 0A **The azimuth axes mechanisms for the ATST telescope mount assembly** [8444-8]
H. J. Kärcher, U. Weis, O. Dreyer, MT Mechatronics GmbH (Germany); P. Jeffers, National Solar Observatory (United States); G. Bonomi, Ingersoll Machine Tools, Inc. (United States)

TELESCOPES FOR SYNOPTIC AND SURVEY OBSERVATIONS I

- 8444 0C **Manufacturing and testing of the large lenses for Dark Energy Survey (DES) at THALES SESO** [8444-10]
D. Fappani, J. Fourez, THALES SESO (France); P. Doel, D. Brooks, Univ. College London (United Kingdom); B. Flaughner, Fermilab Chicago (United States)
- 8444 0D **The Transneptunian Automated Occultation Survey (TAOS II)** [8444-11]
M. J. Lehner, Institute of Astronomy and Astrophysics (Taiwan) and Harvard-Smithsonian Ctr. for Astrophysics (United States) and Univ. of Pennsylvania (United States); S.-Y. Wang, Institute of Astronomy and Astrophysics (Taiwan); C. A. Alcock, Harvard-Smithsonian Ctr. for Astrophysics (United States); K. H. Cook, Institute of Astronomy and Astrophysics (Taiwan); G. Furesz, J. C. Geary, Harvard-Smithsonian Ctr. for Astrophysics (United States); D. Hiriart, Instituto de Astronomía, Univ. Nacional Autónoma de México (Mexico); P. T. Ho, Institute of Astronomy and Astrophysics (Taiwan); W. H. Lee, Instituto de Astronomía, Univ. Nacional Autónoma de México (Mexico); F. Melsheimer, DFM Engineering, Inc. (United States); T. Norton, Harvard-Smithsonian Ctr. for Astrophysics (United States); M. Reyes-Ruiz, M. Richer, Instituto de Astronomía, Univ. Nacional Autónoma de México (Mexico); A. Szentgyorgyi, Harvard-Smithsonian Ctr. for Astrophysics (United States); W.-L. Yen, Z.-W. Zhang, Institute of Astronomy and Astrophysics (Taiwan)
- 8444 0E **NGTS: a robotic transit survey to detect Neptune and super-Earth mass planets** [8444-12]
B. Chazelas, Observatoire de l'Univ. de Genève (Switzerland); D. Pollacco, Queen's Univ. Belfast (United Kingdom) and The Univ. of Warwick (United Kingdom); D. Queloz, Observatoire de l'Univ. de Genève (Switzerland); H. Rauer, Deutsches Zentrum für Luft- und Raumfahrt (Germany) and Technische Univ. Berlin (Germany); P. J. Wheatley, The Univ. of Warwick (United Kingdom); R. West, Univ. of Leicester (United Kingdom); J. Da Silva Bento, The Univ. of Warwick (United Kingdom); M. Burleigh, Leicester Univ. (United Kingdom); J. McCormac, Queen's Univ. Belfast (United Kingdom); P. Eigmüller, A. Erikson, Deutsches Zentrum für Luft- und Raumfahrt (Germany); L. Genolet, Observatoire de l'Univ. de Genève (Switzerland); M. Goad, Univ. of Leicester (United Kingdom); A. Jordán, Pontificia Univ. Católica de Chile (Chile); M. Neveu, Observatoire de l'Univ. de Genève (Switzerland); S. Walker, The Univ. of Warwick (United Kingdom)
- 8444 0F **Design of a compact wide field telescope for space situational awareness** [8444-13]
D. Lee, A. Born, P. Parr-Burman, P. Hastings, B. Stobie, N. Bezawada, UK Astronomy Technology Ctr., Royal Observatory (United Kingdom)

TELESCOPES FOR SYNOPTIC AND SURVEY OBSERVATIONS II

- 8444 OG **OAJ: 2.6m wide field survey telescope** [8444-14]
O. Pirnay, V. Moreau, G. Lousberg, Advanced Mechanical and Optical Systems S.A. (Belgium)
- 8444 OH **Design differences between the Pan-STARRS PS1 and PS2 telescopes** [8444-15]
J. S. Morgan, N. Kaiser, Institute for Astronomy, Univ. of Hawai'i (United States); V. Moreau, AMOS Ltd. (Belgium); D. Anderson, Rayleigh Optical Corp. (United States); W. Burgett, Institute for Astronomy, Univ. of Hawai'i (United States)
- 8444 OI **Ground-based search for the brightest transiting planets with the Multi-site All-Sky CAmERA: MASCARA** [8444-16]
I. A. G. Snellen, R. Stuik, Leiden Observatory, Leiden Univ. (Netherlands); R. Navarro, F. Bettonvil, ASTRON (Netherlands); M. Kenworthy, Leiden Observatory, Leiden Univ. (Netherlands); E. de Mooij, Univ. of Toronto (Canada); G. Otten, Leiden Observatory, Leiden Univ. (Netherlands); R. ter Horst, ASTRON (Netherlands); R. le Poole, Leiden Observatory, Leiden Univ. (Netherlands)
- 8444 OJ **LSST secondary mirror assembly baseline design** [8444-17]
D. R. Neill, W. J. Gressler, J. Sebag, O. Wiecha, National Optical Astronomy Observatory (United States); M. Warner, National Optical Astronomy Observatory (Chile); B. Schoening, J. DeVries, J. Andrew, National Optical Astronomy Observatory (United States); G. Schumacher, National Optical Astronomy Observatory (Chile); E. Hileman, National Optical Astronomy Observatory (United States)

UPGRADES TO EXISTING OBSERVATORIES

- 8444 OK **Current status of the Hobby-Eberly Telescope wide field upgrade** [8444-19]
G. J. Hill, J. A. Booth, M. E. Cornell, J. M. Good, McDonald Observatory, The Univ. of Texas at Austin (United States); K. Gebhardt, The Univ. of Texas at Austin (United States); H. J. Kriel, H. Lee, R. Leck, W. Moriera, P. J. MacQueen, D. M. Perry, M. D. Rafal, T. H. Rafferty, C. Ramiller, R. D. Savage, C. A. Taylor, B. L. Vattiat, McDonald Observatory, The Univ. of Texas at Austin (United States); L. W. Ramsey, The Pennsylvania State Univ. (United States); J. H. Beno, T. A. Beets, J. D. Esguerra, Ctr. for Electromechanics, The Univ. of Texas at Austin (United States); M. Häuser, Univ.-Sternwarte Munich (Germany); R. J. Hayes, J. T. Heisler, I. M. Soukup, J. J. Zierer, M. S. Worthington, N. T. Mollison, D. R. Wardell, G. A. Wedeking, Ctr. for Electromechanics, The Univ. of Texas at Austin (United States)

TELESCOPE MOUNTS AND ENCLOSURES

- 8444 OL **ATST telescope pier** [8444-20]
P. Jeffers, National Solar Observatory (United States); E. Manuel, M3 Engineering & Technology Corp. (United States); O. Dreyer, H. Kärcher, MT Mechatronics GmbH (Germany)
- 8444 OM **Design concepts for the EST mount** [8444-21]
H. J. Kärcher, M. Süß, D. Fischer, MT Mechatronics GmbH (Germany)

- 8444 ON **Progress on the structural and mechanical design of the Giant Magellan Telescope** [8444-22]
M. Sheehan, Giant Magellan Telescope Organization Corp. (United States); S. Gunnels, Paragon Engineering (United States); C. Hull, J. Kern, C. Smith, M. Johns, S. Shectman, Giant Magellan Telescope Organization Corp. (United States)
- 8444 OP **E-ELT dome for modified baseline design** [8444-24]
A. Bilbao, G. Murga, C. Gómez, IDOM (Spain)
- 8444 OQ **The E-ELT project: the dome detailed design study** [8444-25]
G. Marchiori, S. De Lorenzi, A. Busatta, European Industrial Engineering s.r.l. (Italy)

DESIGN TO WITHSTAND EARTHQUAKES

- 8444 OR **Seismic design accelerations for the LSST telescope** [8444-113]
D. R. Neill, National Optical Astronomy Observatory (United States); M. Warner, Cerro Tololo Inter-American Observatory (Chile); J. Sebag, National Optical Astronomy Observatory (United States)
- 8444 OT **Seismic analysis of the LSST telescope** [8444-26]
D. R. Neill, National Optical Astronomy Observatory (United States)

MODELING, MEASUREMENT, AND CONTROL OF WIND BUFFETING

- 8444 OU **GMT enclosure wind and thermal study** [8444-29]
A. Farahani, Giant Magellan Telescope Organization Corp. (United States); A. Kolesnikov, L. Cochran, CPP, Inc. (United States); C. Hull, M. Johns, Giant Magellan Telescope Organization Corp. (United States)
- 8444 OV **Vibration mitigation for wind-induced jitter for the Giant Magellan Telescope** [8444-30]
R. M. Glaese, Moog-CSA Engineering (United States); M. Sheehan, Giant Magellan Telescope Organization (United States)

CONCEPTS FOR FUTURE TELESCOPES

- 8444 OW **Feasibility studies to upgrade the Canada-France-Hawaii Telescope site for the next generation Canada-France-Hawaii Telescope** [8444-31]
K. Szeto, NRC Herzberg Institute of Astrophysics (Canada); M. Angers, C. Breckenridge, Dynamic Structures Ltd. (Canada); S. Bauman, Canada-France-Hawaii Telescope (United States); N. Loewen, Dynamic Structures Ltd. (Canada); D. Loop, A. McConnachie, J. Pazder, NRC Herzberg Institute of Astrophysics (Canada); D. Salmon, Canada-France-Hawaii Telescope Corp. (United States); P. Spano, NRC Herzberg Institute of Astrophysics (Canada); S. Stiemer, The Univ. of British Columbia (Canada); C. Veillet, Canada-France-Hawaii Telescope Corp. (United States)

- 8444 0X **The Astronomical Telescope of New York: a new 12-meter astronomical telescope** [8444-32]
T. Sebring, Xoptx LLC (United States); R. Junquist, Optical Consultant (United States);
C. Stutzki, Stutzki Engineering, Inc. (United States); P. Sebring, Sebring Mechanical Design
(United States); S. Baum, Rochester Institute of Technology (United States)
- 8444 0Y **Reviewing off-axis telescope concepts: a quest for highest possible dynamic range for photometry and angular resolution** [8444-107]
G. Moretto, Institut de Physique Nucléaire de Lyon (France); J. R. Kuhn, Institute for
Astronomy, Univ. of Hawai'i (United States); P. R. Goode, Big Bear Solar Observatory (United
States)

AIRBORNE TELESCOPES I

- 8444 10 **Early science results from SOFIA (Invited Paper)** [8444-35]
E. T. Young, SOFIA Science Ctr., NASA Ames Research Ctr. (United States); T. L. Herter,
Cornell Univ. (United States); R. Güsten, Max-Planck-Institut für Radioastronomie (Germany);
E. W. Dunham, Lowell Observatory (United States); E. E. Becklin, P. M. Marcum, SOFIA
Science Ctr., NASA Ames Research Ctr. (United States); A. Krabbe, Deutsches SOFIA
Institut, Univ. Stuttgart (Germany); B. Andersson, W. T. Reach, SOFIA Science Ctr., NASA
Ames Research Ctr. (United States); H. Zinnecker, SOFIA Science Ctr., NASA Ames Research
Ctr. (United States) and Deutsches SOFIA Institut (Germany)
- 8444 11 **Active damping of the SOFIA Telescope assembly** [8444-36]
P. J. Keas, Moog-CSA Engineering (United States); E. Dunham, Lowell Observatory (United
States); U. Lampater, Deutsches SOFIA Institut, Univ. Stuttgart (Germany); E. Pfüller, SOFIA
Science Ctr., NASA Ames Research Ctr. (United States) and Univ. of Stuttgart (Germany);
S. Teufel, Deutsches SOFIA Institut, Univ. Stuttgart (Germany); H.-P. Roeser, Univ. of Stuttgart
(Germany); M. Wiedemann, J. Wolf, SOFIA Science Ctr., NASA Ames Research Ctr. (United
States) and Univ. of Stuttgart (Germany)
- 8444 12 **Evaluation of the aero-optical properties of the SOFIA cavity by means of computational fluid dynamics and a super fast diagnostic camera** [8444-37]
C. Engfer, E. Pfüller, M. Wiedemann, J. Wolf, Deutsches SOFIA Institut, Univ. of Stuttgart
(Germany) and SOFIA Airborne Systems Operations Ctr, NASA Dryden Flight Research Ctr.
(United States); T. Lutz, E. Krämer, Institute of Aerodynamics and Gas Dynamics, Univ. of
Stuttgart (Germany); H.-P. Röser, Institute of Space Systems, Univ. Stuttgart (Germany)
- 8444 13 **Optical characterization of the SOFIA telescope using fast EM-CCD cameras** [8444-38]
E. Pfüller, J. Wolf, Deutsches SOFIA Institut, Univ. of Stuttgart (Germany) and SOFIA Science
Ctr., NASA Ames Research Ctr. (United States); H. Hall, SOFIA Science Ctr., NASA Ames
Research Ctr. (United States); H.-P. Röser, Institute of Space Systems, Univ. of Stuttgart
(Germany)

AIRBORNE TELESCOPES II

- 8444 14 **SOFIA observatory performance and characterization [8444-39]**
P. Temi, P. M. Marcum, NASA Ames Research Ctr. (United States); W. E. Miller, Orbital Science Corp. (United States); E. W. Dunham, Lowell Observatory (United States); I. S. McLean, Univ. of California, Los Angeles (United States); J. Wolf, Deutsches SOFIA Institut, Univ. of Stuttgart (Germany); E. E. Becklin, SOFIA Science Ctr, NASA Ames Research Ctr. (United States); T. A. Bida, Lowell Observatory (United States); R. Brewster, Orbital Science Corp. (United States); S. C. Casey, SOFIA Science Ctr, NASA Ames Research Ctr. (United States); P. L. Collins, Lowell Observatory (United States); S. D. Horner, NASA Ames Research Ctr. (United States); H. Jakob, Deutsches SOFIA Institut, Univ. of Stuttgart (Germany); S. C. Jensen, NASA Dryden Flight Research Ctr. (United States); J. L. Killebrew, NASA Marshall Space Flight Ctr. (United States); U. Lampater, NASA Ames Research Ctr. (United States); G. I. Mandushev, Lowell Observatory (United States); A. W. Meyer, SOFIA Science Ctr, NASA Ames Research Ctr. (United States); E. Pfueller, A. Reinacher, Deutsches SOFIA Institut, Univ. of Stuttgart (Germany); J. Rho, SOFIA Science Ctr, NASA Ames Research Ctr. (United States); T. L. Roellig, NASA Ames Research Ctr. (United States); M. L. Savage, SOFIA Science Ctr, NASA Ames Research Ctr. (United States); E. C. Smith, NASA Ames Research Ctr. (United States); S. Teufel, M. Wiedemann, Deutsches SOFIA Institut, Univ. of Stuttgart (Germany)
- 8444 15 **The balloon-borne large-aperture submillimeter telescope for polarimetry-BLASTPol: performance and results from the 2010 Antarctic flight [8444-40]**
E. Pascale, P. A. R. Ade, Cardiff Univ. (United Kingdom); F. E. Angilè, Univ. of Pennsylvania (United States); S. J. Benton, Univ. of Toronto (Canada); M. J. Devlin, B. Dober, Univ. of Pennsylvania (United States); L. M. Fissel, Univ. of Toronto (Canada); Y. Fukui, Nagoya Univ. (Japan); N. N. Gandilo, Univ. of Toronto (Canada); J. O. Gundersen, Univ. of Miami (United States); P. C. Hargrave, Cardiff Univ. (United Kingdom); J. Klein, Univ. of Pennsylvania (United States); A. L. Korotkov, Brown Univ. (United States); T. G. Matthews, Northwestern Univ. (United States); L. Moncelsi, California Institute of Technology (United States) and Cardiff Univ. (United Kingdom); T. K. Mroczkowski, California Institute of Technology (United States); C. B. Netterfield, Cardiff Univ. (United Kingdom) and Univ. of Toronto (Canada); G. Novak, Northwestern Univ. (United States); D. Nutter, Cardiff Univ. (United Kingdom); L. Olmi, Univ. of Puerto Rico (United States) and INAF-Osservatorio Astrofisico di Arcetri (Italy); F. Poidevin, G. Savini, Univ. College London (United Kingdom); D. Scott, Univ. of British Columbia (Canada); J. A. Shariff, J. Soler, Univ. of Pennsylvania (United States); N. E. Thomas, Univ. of Miami (United States); M. D. Truch, Univ. of Pennsylvania (United States); C. E. Tucker, Cardiff Univ. (United Kingdom); G. S. Tucker, Brown Univ. (United States); D. Ward-Thompson, Cardiff Univ. (United Kingdom)

GAMMA RAY TELESCOPES

- 8444 17 **Optical design and calibration of a medium size telescope prototype for the CTA [8444-42]**
B. Behera, J. Bähr, Deutsches Elektronen-Synchrotron (Germany); S. Grünewald, Humboldt Univ. (Germany); G. Hughes, Deutsches Elektronen-Synchrotron (Germany); I. Oya, Humboldt Univ. (Germany); D. Melkumyan, S. Schlenstedt, Deutsches Elektronen-Synchrotron (Germany); U. Schwanke, Humboldt Univ. (Germany)

- 8444 18 **Development of a mid-sized Schwarzschild-Couder Telescope for the Cherenkov Telescope Array** [8444-43]
R. A. Cameron, SLAC National Accelerator Lab. (United States)

ASSEMBLY, INTEGRATION, VERIFICATION, AND COMMISSIONING

- 8444 19 **Status and performance of the Discovery Channel Telescope during commissioning (Invited Paper)** [8444-44]
S. E. Levine, T. A. Bida, T. Chylek, P. L. Collins, W. T. DeGroff, E. W. Dunham, P. J. Lotz, A. J. Venetiou, S. Zoonemat Kermani, Lowell Observatory (United States)
- 8444 1A **The Large Binocular Telescope** [8444-45]
J. M. Hill, R. F. Green, D. S. Ashby, J. G. Brynnel, N. J. Cushing, J. K. Little, J. H. Slagle, R. M. Wagner, Large Binocular Telescope Observatory, Univ. of Arizona (United States)
- 8444 1B **New Fraunhofer Telescope Wendelstein: assembly, installation, and current status** [8444-46]
H. Thiele, N. Ageorges, D. Kampf, M. Hartl, S. Egner, Kayser-Threde GmbH (Germany); P. Aniol, Astelco Systems GmbH (Germany); M. Ruder, Tautec (Germany); C. Abfalter, Astelco Systems GmbH (Germany); U. Hopp, R. Bender, C. Gössl, F. Grupp, F. Lang-Bardl, W. Mitsch, Univ.-Sternwarte München (Germany)
- 8444 1C **VST: from commissioning to science** [8444-47]
P. Schipani, INAF - Osservatorio Astronomico di Capodimonte (Italy); M. Capaccioli, INAF - Osservatorio Astronomico di Capodimonte (Italy) and Univ. Federico II of Naples (Italy); C. Arcidiacono, INAF - Osservatorio Astronomico di Bologna (Italy) and INAF - Osservatorio Astrofisico di Arcetri (Italy); J. Argomedo, European Southern Observatory (Germany); M. Dall'Orta, S. D'Orsi, INAF - Osservatorio Astronomico di Capodimonte (Italy); J. Farinato, D. Magrin, INAF - Osservatorio Astronomico di Padova (Italy); L. Marty, INAF - Osservatorio Astronomico di Capodimonte (Italy); R. Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy); G. Umbricco, Univ. of Padua (Italy)
- 8444 1D **Commissioning results from the Large Binocular Telescope** [8444-48]
J. G. Brynnel, N. J. Cushing, R. F. Green, J. M. Hill, D. L. Miller, A. Rakich, K. Boutsia, Large Binocular Telescope Observatory, Univ. of Arizona (United States)
- 8444 1E **Discovery Channel Telescope active optics system early integration and test** [8444-49]
A. J. Venetiou, T. A. Bida, Lowell Observatory (United States)

EXTREMELY LARGE TELESCOPES

- 8444 1F **E-ELT update of project and effect of change to 39m design (Invited Paper)** [8444-50]
A. McPherson, J. Spyromilio, M. Kissler-Patig, S. Ramsay, E. Brunetto, P. Dierickx, M. Cassali, European Southern Observatory (Germany)
- 8444 1G **Thirty Meter Telescope project update (Invited Paper)** [8444-51]
L. Stepp, Thirty Meter Telescope Observatory Corp. (United States)

- 8444 1H **Giant Magellan Telescope: overview (Invited Paper)** [8444-52]
M. Johns, P. McCarthy, K. Raybould, A. Bouchez, A. Farahani, J. Filgueira, G. Jacoby, S. Shectman, M. Sheehan, Giant Magellan Telescope Organization Corp. (United States)
- 8444 1I **Science with the re-baselined European Extremely Large Telescope** [8444-54]
J. Liske, P. Padovani, M. Kissler-Patig, European Southern Observatory (Germany)

SITE CHARACTERIZATION, TESTING, AND DEVELOPMENT

- 8444 1J **Opacity measurements at Summit Camp on Greenland and PEARL in northern Canada with a 225-GHz tipping radiometer** [8444-55]
K. Asada, P. L. Martin-Cocher, C.-P. Chen, S. Matsushita, M.-T. Chen, Y.-D. Huang, M. Inoue, Institute of Astronomy and Astrophysics (Taiwan); P. T. P. Ho, Academia Sinica Institute of Astronomy and Astrophysics (Taiwan) and Harvard-Smithsonian Ctr. for Astrophysics (United States); S. N. Paine, Harvard-Smithsonian Ctr. for Astrophysics (United States); E. Steinbring, National Research Council Canada (Canada)
- 8444 1K **Site characterization studies in high plateau of Tibet** [8444-56]
Y. Yao, H. Wang, L. Liu, Y. Wang, X. Qian, J. Yin, National Astronomical Observatories (China)
- 8444 1L **New instruments to calibrate atmospheric transmission** [8444-57]
P. Zimmer, J. T. McGraw, D. C. Zirzow, The Univ. of New Mexico (United States); C. Cramer, K. Lykke, J. T. Woodward IV, National Institute of Standards and Technology (United States)

DESIGN OF TELESCOPES FOR EXTREME ENVIRONMENTS

- 8444 1N **The Greenland Telescope** [8444-59]
P. Grimes, R. Blundell, Smithsonian Astrophysical Observatory (United States)
- 8444 1O **Status of the first Antarctic survey telescopes for Dome A** [8444-60]
Z. Li, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ. of Chinese Academy of Sciences (China); X. Yuan, X. Cui, Nanjing Institute of Astronomical Optics & Technology (China) and Chinese Ctr. for Antarctic Astronomy (China); D. Wang, Nanjing Institute of Astronomical Optics & Technology (China); X. Gong, Nanjing Institute of Astronomical Optics & Technology (China) and Chinese Ctr. for Antarctic Astronomy (China); F. Du, Y. Zhang, Nanjing Institute of Astronomical Optics & Technology (China); Y. Hu, National Astronomical Observatories (China); H. Wen, X. Li, L. Xu, Nanjing Institute of Astronomical Optics & Technology (China); Z. Shang, National Astronomical Observatories (China) and Chinese Ctr. for Antarctic Astronomy (China); L. Wang, Purple Mountain Observatory (China) and Chinese Ctr. for Antarctic Astronomy (China)
- 8444 1P **Ukpik: testbed for a miniaturized robotic astronomical observatory on a high Arctic mountain** [8444-61]
E. Steinbring, B. Leckie, T. Hardy, K. Caputa, M. Fletcher, National Research Council Canada (Canada)
- 8444 1Q **The Gattini South Pole UV experiment** [8444-62]
A. M. Moore, Caltech Optical Observatories (United States); S. Ahmed, California Institute of Technology (United States); M. C. Ashley, The Univ. of New South Wales (Australia);

E. Croner, A. Delacroix, Caltech Optical Observatories (United States); Y. Ebihara, Research Institute for Sustainable Humanosphere, Kyoto Univ. (Japan); J. Fucik, Caltech Optical Observatories (United States); D. Martin, California Institute of Technology (United States); V. Velur, Caltech Optical Observatories (United States); A. Weatherwax, Siena College (United States)

- 8444 1R **PLATO-R: a new concept for Antarctic science** [8444-63]
M. C. B. Ashley, Y. Augarten, C. S. Bonner, M. G. Burton, L. Bycroft, The Univ. of New South Wales (Australia); J. S. Lawrence, Australian Astronomical Observatory (Australia); D. M. Luong-Van, S. McDaid, C. McLaren, G. Sims, J. V. Storey, The Univ. of New South Wales (Australia)

CONTROL OF THERMAL ENVIRONMENT

- 8444 1S **Canada-France-Hawaii Telescope image quality improvement initiative: thermal assay of the observing environment** [8444-64]
K. Thanjavur, K. Ho, S. Gajadhar, M. Baril, T. Benedict, S. Bauman, D. Salmon, Canada-France-Hawaii Telescope (United States)

PROJECT REVIEWS

- 8444 1T **New optical telescope projects at Devasthal Observatory (Invited Paper)** [8444-65]
R. Sagar, B. Kumar, A. Omar, A. K. Pandey, Aryabhata Research Institute of Observational Sciences (India)
- 8444 1U **Towards a national astronomy observatory for the United Arab Emirates** [8444-66]
S. Els, Gaia Data Processing & Analysis Consortium (Spain); J. Maree, S. Al Marri, Y. Al Muqbel, A. Yousif, Emirates Institution for Advanced Science and Technology (United Arab Emirates); H. Al Naimiy, Univ. of Sharjah (United Arab Emirates)
- 8444 1V **The 3,6 m Indo-Belgian Devasthal Optical Telescope: general description** [8444-67]
N. Ninane, C. Flebus, AMOS Ltd. (Belgium); B. Kumar, Aryabhata Research Institute of Observational Sciences (India)
- 8444 1W **Manufacturing optics of a 2.5m telescope** [8444-68]
F. Poutriquet, P. Plainchamp, J. Billel, B. Pernet, T. Lagrange, C. Cavadore, J. Carel, H. Leplan, E. Ruch, R. Geyl, J. Jouve, Sagem Défense Sécurité (France)

ENABLING TECHNOLOGIES FOR EXTREMELY LARGE TELESCOPES I

- 8444 1X **E-ELT optomechanics: overview** [8444-69]
M. Cayrel, European Southern Observatory (Germany)
- 8444 1Y **E-ELT M1 test facility** [8444-70]
M. Dimmler, J. Marrero, S. Leveque, P. Barriga, B. Sedghi, M. Mueller, European Southern Observatory (Germany)

Part 2

- 8444 1Z **Active damping strategies for control of the E-ELT field stabilization mirror** [8444-71]
B. Sedghi, M. Dimmler, M. Müller, European Southern Observatory (Germany)
- 8444 20 **Development of a fast steering secondary mirror prototype for the Giant Magellan Telescope** [8444-117]
M. Cho, National Optical Astronomy Observatory (United States); A. Corredor, C. Dribusch, The Univ. of Arizona (United States); K. Park, Y.-S. Kim, Korea Astronomy and Space Science Institute (Korea, Republic of); I.-K. Moon, Korea Research Institute of Standards and Science (Korea, Republic of); W.-H. Park, College of Optical Sciences, The Univ. of Arizona (United States)
- 8444 21 **Repairing stress induced cracks in the Keck primary mirror segments** [8444-73]
D. McBride, J. S. Hudek, S. Panteleev, W.M. Keck Observatory (United States)

ENABLING TECHNOLOGIES FOR EXTREMELY LARGE TELESCOPES II

- 8444 22 **Alignment algorithms for the Thirty Meter Telescope** [8444-74]
G. Chanan, Univ. of California, Irvine (United States)
- 8444 23 **Phasing metrology system for the GMT** [8444-75]
D. S. Acton, Ball Aerospace & Technologies Corp. (United States); A. Bouchez, Giant Magellan Telescope Project (United States)
- 8444 24 **Performance prediction of the fast steering secondary mirror for the Giant Magellan Telescope** [8444-76]
M. Cho, National Optical Astronomy Observatory (United States); A. Corredor, C. Dribusch, The Univ. of Arizona (United States); W.-H. Park, College of Optical Sciences, The Univ. of Arizona (United States); M. Sheehan, M. Johns, S. Shectman, J. Kern, C. Hull, Giant Magellan Telescope Project (United States); Y.-S. Kim, Korea Astronomy and Space Science Institute (Korea, Republic of); J. Bagnasco, Naval Postgraduate School (United States)
- 8444 25 **Dynamics, active optics, and scale effects in future extremely large telescopes** [8444-77]
R. Bastait, B. Mokrani, Active Structures Lab., Univ. Libre de Bruxelles (Belgium); G. Rodrigues, European Space Agency (Netherlands); A. Preumont, Active Structures Lab., Univ. Libre de Bruxelles (Belgium)

SEGMENTED MIRROR ALIGNMENT, PHASING, AND WAVEFRONT CONTROL

- 8444 26 **The development of the actuator prototypes for the active reflector of FAST** [8444-78]
Q. Wang, M. Wu, M. Zhu, J. Xue, Q. Zhao, X. Gu, National Astronomical Observatories (China)

OBSERVATORY FACILITIES

- 8444 28 **Design, development, and manufacturing of highly advanced and cost effective aluminium sputtering plant for large area telescopic mirrors.** [8444-80]
R. R. Pillai, S. K. K., K. Mohanachandran, N. Sakhamuri, Hind High Vacuum Co. Pvt. Ltd. (India); V. Shukla, A. Gupta, Aryabhata Research Institute of Observational Sciences (India)

SQUARE KILOMETER ARRAY AND SKA PATHFINDERS

- 8444 2A **The Australian SKA Pathfinder (Invited Paper)** [8444-82]
A. E. T. Schinckel, J. D. Bunton, T. J. Cornwell, I. Feain, S. G. Hay, Commonwealth Scientific and Industrial Research Organisation (Australia)
- 8444 2B **LOFAR, the low frequency array (Invited Paper)** [8444-83]
R. C. Vermeulen, ASTRON (Netherlands)

RADIO TELESCOPES

- 8444 2D **The RAEGE VLBI 2010 radiotelescope design** [8444-85]
E. Sust, MT Mechatronics GmbH (Germany); J. López Fernández, Instituto Geográfico Nacional (Spain)
- 8444 2E **Architecture of the metrology for the SRT** [8444-86]
T. Pisanu, F. Buffa, G. L. Deiana, P. Marongiu, INAF - Osservatorio Astronomico di Cagliari (Italy); M. Morsiani, INAF - Istituto di Radioastronomia (Italy); C. Pernechele, INAF - Osservatorio Astronomico di Padova (Italy); S. Poppi, G. Serra, G. Vargiu, INAF - Osservatorio Astronomico di Cagliari (Italy)
- 8444 2F **Requirements and considerations of the surface error control for the active reflector of FAST** [8444-87]
M. Wu, Q. Wang, X. Gu, B. Zhao, National Astronomical Observatories (China)
- 8444 2G **The Sardinia Radio Telescope (SRT) optical alignment** [8444-88]
M. Süß, D. Koch, MT Mechatronics GmbH (Germany); H. Paluszek, Sigma3D GmbH (Germany)

MILLIMETER AND SUBMILLIMETER WAVELENGTH TELESCOPES I

- 8444 2J **Final tests and performances verification of the European ALMA antennas** [8444-91]
G. Marchiori, F. Rampini, European Industrial Engineering s.r.l. (Italy)
- 8444 2K **ALMA system verification** [8444-92]
R. Sramek, K.-I. Morita, M. Sugimoto, P. Napier, M. Miccolis, Joint ALMA Observatory (Chile); P. Yagoubov, European Southern Observatory (Germany); D. Barkats, W. Dent, Joint ALMA Observatory (Chile); S. Matsushita, Academia Sinica Institute of Astronomy and Astrophysics (Taiwan); N. Whyborn, S. Asayama, Joint ALMA Observatory (Chile); J. Marti Canales, European Southern Observatory (Chile); R. Bhatia, E. DuVall, S. Blair, Joint ALMA Observatory (Chile)

MILLIMETER AND SUBMILLIMETER WAVELENGTH TELESCOPES II

- 8444 2M **The CCAT 25m diameter submillimeter-wave telescope** [8444-94]
D. Woody, Owens Valley Radio Observatory (United States); S. Padin, California Institute of Technology (United States); E. Chauvin, B. Clavel, Eric Chauvin Consulting (United States); G. Cortes, Cornell Univ. (United States); A. Kissil, J. Lou, Jet Propulsion Lab. (United States); P. Rasmussen, Owens Valley Radio Observatory (United States); D. Redding, Jet Propulsion Lab. (United States); J. Zolwoker, Cornell Univ. (United States)
- 8444 2N **High performance holography mapping with the LMT** [8444-95]
D. R. Smith, MERLAB, P.C. (United States); K. Souccar, Large Millimeter Telescope, Univ. of Massachusetts Amherst (United States)
- 8444 2O **Photonic local oscillator technics for large-scale interferometers** [8444-96]
H. Kiuchi, M. Saito, S. Iguchi, National Astronomical Observatory of Japan (Japan)

POSTER SESSION: AIRBORNE TELESCOPES

- 8444 2Q **First technological steps toward opening a near-IR window at stratospheric altitudes** [8444-98]
F. Pedichini, M. Centrone, D. Lorenzetti, M. Mattioli, M. Ricci, F. Vitali, INAF - Osservatorio Astronomico di Roma (Italy)
- 8444 2R **SOFIA in operation: telescope performance during the basic science flights** [8444-99]
H. J. Kärcher, MT Mechatronics GmbH (Germany); J. Wagner, A. Krabbe, Deutsches SOFIA Institut, Univ. Stuttgart (Germany); U. Lampater, Deutsches SOFIA Institut, NASA Dryden Flight Research Ctr (United States); T. Keilig, Deutsches SOFIA Institut, Univ. Stuttgart (Germany); J. Wolf, SOFIA Science Ctr., NASA Ames Research Ctr. (United States)
- 8444 2S **A new backup secondary mirror for SOFIA** [8444-100]
M. Lachenmann, M. J. Burgdorf, J. Wolf, Deutsches SOFIA Institut, Univ. Stuttgart (Germany) and SOFIA Science Ctr., NASA Ames Research Ctr. (United States); R. Brewster, Orbital Sciences Corp., NASA Ames Research Ctr. (United States)
- 8444 2T **Upgrade of the SOFIA target acquisition and tracking cameras** [8444-101]
M. Wiedemann, J. Wolf, Deutsches SOFIA Institut, Univ. Stuttgart (Germany) and SOFIA Science Ctr., NASA Ames Research Ctr. (United States); H. Roeser, Institute of Space Systems, Univ. Stuttgart (Germany)

POSTER SESSION: ASSEMBLY, INTEGRATION, VERIFICATION, AND COMMISSIONING

- 8444 2U **The 3,6 m Indo-Belgian Devasthal Optical Telescope: assembly, integration and tests at AMOS** [8444-102]
N. Ninane, C. Bastin, J. de Ville, F. Michel, M. Piérard, E. Gabriel, C. Flebus, AMOS Ltd. (Belgium); A. Omar, Aryabhata Research Institute of Observational Sciences (India)

- 8444 2V **First tests of the compact low scattered-light 2m-Wendelstein Fraunhofer Telescope** [8444-103]
U. Hopp, R. Bender, F. Grupp, Univ.-Sternwarte München (Germany) and Max-Planck-Institut für extraterrestrische Physik (Germany); H. Thiele, N. Ageorges, Kayser-Threde GmbH (Germany); P. Aniol, Astelco Systems GmbH (Germany); H. Barwig, C. Gössl, F. Lang-Bardl, W. Mietsch, Univ.-Sternwarte München (Germany); M. Ruder, Astelco Systems GmbH (Germany)
- 8444 2W **SALT's transition to science operations** [8444-104]
D. A. H. Buckley, J. C. Coetzee, S. M. Crawford, South African Astronomical Observatory (South Africa); K. H. Nordsieck, Space Astronomy Lab., Univ. of Wisconsin-Madison (United States); D. O'Donoghue, South African Astronomical Observatory (South Africa); T. B. Williams, Rutgers, The State Univ. of New Jersey (United States)

POSTER SESSION: CONCEPTS FOR FUTURE TELESCOPES

- 8444 2Y **The QUIJOTE-CMB experiment: studying the polarisation of the galactic and cosmological microwave emissions** [8444-106]
J. A. Rubiño-Martín, Instituto de Astrofísica de Canarias (Spain) and Univ. de La Laguna (Spain); R. Rebolo, Instituto de Astrofísica de Canarias (Spain) and Univ. de La Laguna (Spain) and Consejo Superior de Investigaciones Científicas (Spain); M. Aguiar, Instituto de Astrofísica de Canarias (Spain); R. Génova-Santos, Instituto de Astrofísica de Canarias (Spain) and Univ. de La Laguna (Spain); F. Gómez-Reñasco, J. M. Herreros, R. J. Hoyland, Instituto de Astrofísica de Canarias (Spain); C. López-Caraballo, A. E. Pelaez Santos, Instituto de Astrofísica de Canarias (Spain) and Univ. de La Laguna (Spain); V. Sanchez de la Rosa, A. Vega-Moreno, T. Viera-Curbelo, Instituto de Astrofísica de Canarias (Spain); E. Martínez-Gonzalez, R. B. Barreiro, F. J. Casas, J. M. Diego, R. Fernández-Cobos, D. Herranz, M. López-Cañiego, D. Ortiz, P. Vielva, Instituto de Física de Cantabria, Univ. de Cantabria (Spain); E. Artal, B. Aja, J. Cagigas, J. L. Cano, L. de la Fuente, A. Mediavilla, J. V. Terán, E. Villa, DICOM spol. s.r.o. (Spain); L. Piccirillo, R. Battye, E. Blackhurst, M. Brown, R. D. Davies, R. J. Davis, C. Dickinson, S. Harper, B. Maffei, M. McCulloch, S. Melhuish, G. Pisano, R. A. Watson, Jodrell Bank Ctr. for Astrophysics, The Univ. of Manchester (United Kingdom); M. Hobson, K. Grainge, Cavendish Lab., Univ. of Cambridge (United Kingdom); A. Lasenby, Cavendish Lab., Univ. of Cambridge (United Kingdom) and Kavli Institute for Cosmology, Univ. of Cambridge (United States); R. Saunders, P. Scott, Cavendish Lab., Univ. of Cambridge (United Kingdom)
- 8444 2Z **The next generation of the Canada-France-Hawaii Telescope: science requirements and survey strategies** [8444-108]
A. McConnachie, P. Côté, D. Crampton, NRC Herzberg Institute of Astrophysics (Canada); D. Devost, D. Simons, Canada-France-Hawaii Telescope Corp. (United States); K. Szeto, NRC Herzberg Institute of Astrophysics (Canada)
- 8444 30 **The optics and detector-simulation of the air fluorescence telescope FAMOUS for the detection of cosmic rays** [8444-109]
T. Niggemann, T. Hebbeker, M. Lauscher, C. Meurer, L. Middendorf, J. Schumacher, M. Stephan, RWTH Aachen Univ. (Germany)

POSTER SESSION: CONTROL OF THERMAL ENVIRONMENT

- 8444 31 **Experimental characterization of the turbulence inside the dome and in the surface layer** [8444-110]
A. Ziad, D.-A. Wassila, J. Borgnino, Observatoire de la Côte d'Azur, Univ. de Nice Sophia Antipolis, CNRS (France); M. Sarazin, European Southern Observatory (Germany)
- 8444 32 **Seeing trends from deployable Shack-Hartmann wavefront sensors, MMT Observatory, Arizona, USA** [8444-111]
J. D. Gibson, G. G. Williams, T. Trebisky, MMT Observatory, Univ. of Arizona (United States)
- 8444 33 **An updated T-series thermocouple measurement system for high-accuracy temperature measurements of the MMT primary mirror** [8444-112]
D. Clark, J. D. Gibson, MMT Observatory, Univ. of Arizona (United States)

POSTER SESSION: ENABLING TECHNOLOGIES FOR EXTREMELY LARGE TELESCOPES

- 8444 35 **A spectropolarimetric focal station for the ESO E-ELT** [8444-115]
K. G. Strassmeier, I. Di Varano, I. Ilyin, M. Woche, Leibniz-Institut für Astrophysik Potsdam (Germany); U. Laux, Thüringer Landessternwarte Tautenburg (Germany)
- 8444 37 **Performance of industrial scale production of ZERODUR mirrors with diameter of 1.5 m proves readiness for the ELT M1 segments** [8444-119]
T. Westerhoff, P. Hartmann, R. Jedamzik, A. Werz, SCHOTT AG (Germany)

POSTER SESSION: EXTREMELY LARGE TELESCOPES

- 8444 38 **E-ELT project: geotechnical investigation at Cerro Armazones** [8444-120]
P. Ghiretti, V. Heinz, European Southern Observatory (Germany); D. Pollak, J. Lagos, ARCADIS Chile S.A. (Chile)

POSTER SESSION: GAMMA RAY TELESCOPES

- 8444 39 **Technological developments toward the small size telescopes of the Cherenkov Telescope Array** [8444-121]
R. Canestrari, INAF - Osservatorio Astronomico di Brera (Italy); T. Greenshaw, Univ. of Liverpool (United Kingdom); G. Pareschi, INAF - Osservatorio Astronomico di Brera (Italy); R. White, Univ. of Leicester (United Kingdom)
- 8444 3A **SST-GATE: an innovative telescope for very high energy astronomy** [8444-254]
P. Laporte, J.-L. Dournaux, H. Sol, Observatoire de Paris, CNRS, Univ. Paris Diderot (France); S. Blake, Durham Univ. (United Kingdom); C. Boisson, P. Chadwick, D. Dumas, G. Fasola, F. de Frondat, Observatoire de Paris, CNRS, Univ. Paris Diderot (France); T. Greenshaw, Univ. of Liverpool (United Kingdom); O. Hervet, Observatoire de Paris, CNRS, Univ. Paris Diderot (France); J. Hinton, Univ. of Leicester (United Kingdom); D. Horville, J.-M. Huet, I. Jégouzo, Observatoire de Paris, CNRS, Univ. Paris Diderot (France); J. Schmoll, Durham Univ. (United Kingdom); R. White, Univ. of Leicester (United Kingdom); A. Zech, Observatoire de Paris, CNRS, Univ. Paris Diderot (France)

POSTER SESSION: INDUSTRIAL PERSPECTIVES

- 8444 3B **A new era for the 2-4 meters class observatories: an innovative integrated system telescope-dome** [8444-122]
G. Marchiori, A. Busatta, S. De Lorenzi, F. Rampini, European Industrial Engineering s.r.l. (Italy); C. Perna, G. Vettolani, Istituto Nazionale di Astrofisica (Italy)

POSTER SESSION: MEASUREMENT AND CONTROL OF TELESCOPE VIBRATION

- 8444 3C **Low-frequency high-sensitivity horizontal monolithic folded-pendulum as sensor in the automatic control of ground-based and space telescopes** [8444-123]
F. Acernese, Univ. degli Studi di Salerno (Italy) and Istituto Nazionale di Fisica Nucleare (Italy); R. De Rosa, Istituto Nazionale di Fisica Nucleare (Italy) and Univ. degli Studi di Napoli Federico II (Italy); G. Giordano, Univ. degli Studi di Salerno (Italy); R. Romano, F. Barone, Univ. degli Studi di Salerno (Italy) and Istituto Nazionale di Fisica Nucleare (Italy)
- 8444 3D **Herzberg Institute of Astrophysics' vibration measurement capabilities with applications to astronomical instrumentation** [8444-124]
P. W. G. Byrnes, NRC Herzberg Institute of Astrophysics (Canada)

POSTER SESSION: MILLIMETER AND SUBMILLIMETER WAVELENGTH TELESCOPES II

- 8444 3F **ALMA array element astronomical verification** [8444-126]
S. Asayama, Joint ALMA Observatory (Chile) and National Astronomical Observatory of Japan (Japan); L. B. G. Knee, Joint ALMA Observatory (Chile) and NRC Herzberg Institute of Astrophysics (Canada); P. G. Calisse, Joint ALMA Observatory (Chile) and European Southern Observatory (Chile); P. C. Cortés, Joint ALMA Observatory (Chile) and National Radio Astronomy Observatory (United States); R. Jager, Joint ALMA Observatory (Chile) and European Southern Observatory (Chile); B. López, C. López, Joint ALMA Observatory (Chile); T. Nakos, N. Phillips, Joint ALMA Observatory (Chile) and European Southern Observatory (Chile); M. Radiszcz, Joint ALMA Observatory (Chile); R. Simon, Joint ALMA Observatory (Chile) and National Radio Astronomy Observatory (United States); I. Toledo, Joint ALMA Observatory (Chile); N. Whyborn, Joint ALMA Observatory (Chile) and European Southern Observatory (Chile); H. Yatagai, Joint ALMA Observatory (Chile) and National Astronomical Observatory of Japan (Japan); J. P. McMullin, National Solar Observatory (United States); P. Planesas, Observatorio Astronómico Nacional (Spain)
- 8444 3G **Trajectory generation for parametric rotating scan patterns at the LMT** [8444-127]
D. R. Smith, MERLAB, P.C. (United States); K. Souccar, Large Millimeter Telescope, Univ. of Massachusetts Amherst (United States)
- 8444 3H **Atacama compact array antennas** [8444-128]
M. Saito, National Astronomical Observatory of Japan (Japan) and Joint ALMA Observatory (Chile); J. Inatani, National Astronomical Observatory of Japan (Japan); K. Nakanishi, National Astronomical Observatory of Japan (Japan) and Joint ALMA Observatory (Chile); H. Saito, S. Iguchi, National Astronomical Observatory of Japan (Japan)

- 8444 3I **Very large millimeter/submillimeter array toward search for 2nd Earth** [8444-129]
S. Iguchi, National Astronomical Observatory of Japan (Japan); M. Saito, National
Astronomical Observatory of Japan (Japan) and Joint ALMA Observatory (Chile)
- 8444 3K **ACA phase calibration scheme with the ALMA water vapor radiometers** [8444-253]
Y. Asaki, Institute of Space and Astronautical Science (Japan) and The Graduate Univ. for
Advanced Studies (Japan); S. Matsushita, Academia Sinica Institute of Astronomy and
Astrophysics (Taiwan) and Joint ALMA Observatory (Chile); K.-I. Morita, National
Astronomical Observatory of Japan (Japan) and Joint ALMA Observatory (Chile);
B. Nikolic, Univ. of Cambridge (United Kingdom)

POSTER SESSION: SOLAR TELESCOPES

- 8444 3L **Functional safety for the Advanced Technology Solar Telescope** [8444-132]
S. Bulau, T. R. Williams, National Solar Observatory (United States)
- 8444 3M **Facility level thermal systems for the Advanced Technology Solar Telescope** [8444-133]
L. Phelps, National Solar Observatory (United States); G. Murga, AEC IDOM (United States);
M. Fraser, M3 Engineering & Technology Corp. (United States); T. Climent, AEC IDOM
(United States)
- 8444 3N **Stray light and polarimetry considerations for the COSMO K-Coronagraph** [8444-134]
A. G. de Wijn, J. T. Burkepille, S. Tomczyk, National Ctr. for Atmospheric Research (United
States); P. G. Nelson, Sierra Scientific Solutions LLC (United States); P. Huang, Consultant
(United States); D. Gallagher, National Ctr. for Atmospheric Research (United States)
- 8444 3O **Quasi-static wavefront control for the Advanced Technology Solar Telescope** [8444-135]
L. C. Johnson, National Solar Observatory (United States); R. Upton, Sigma Space Corp.
(United States); T. Rimmele, S. Barden, National Solar Observatory (United States)
- 8444 3P **Optical design of the COSMO large coronagraph** [8444-136]
D. Gallagher, S. Tomczyk, National Ctr. for Atmospheric Research (United States); H. Zhang,
Nanjing Institute of Astronomical Optics & Tech. (China); P. G. Nelson, Sierra Scientific
Solutions LLC (United States)
- 8444 3S **Behavior of a horizontal air curtain subjected to a vertical pressure gradient** [8444-140]
J. Linden, L. Phelps, National Solar Observatory (United States)

POSTER SESSION: TELESCOPE MOUNTS AND ENCLOSURES

- 8444 3T **ATST telescope mount: machine tool or telescope** [8444-143]
P. Jeffers, National Solar Observatory (United States); G. Stolz, G. Bonomi, Ingersoll Machine
Tools, Inc. (United States); O. Dreyer, H. Kärcher, MT Mechatronics GmbH (Germany)
- 8444 3U **Performance introduction of a 2.5m telescope mount** [8444-144]
G. Wang, B. Gu, S. Yang, X. Jiang, Z. Zhang, Y. Ye, J. Xu, Nanjing Institute of Astronomical
Optics & Technology (China)

- 8444 3V **Installation and verification of high precision mechanics in concrete structures at the example of ALMA antenna interfaces** [8444-145]
V. Heinz, M. Kraus, European Southern Observatory (Germany); E. Orellana, Bautek S.A. (Chile)
- 8444 3W **E-ELT telescope main structure** [8444-146]
A. Orden Martínez, A. Dilla Martínez, N. Ballesteros Pérez, M. Alcantud Abellán, Empresarios Agrupados (Spain)
- 8444 3X **Testing, characterization, and control of a multi-axis, high precision drive system for the Hobby-Eberly Telescope Wide Field Upgrade** [8444-147]
I. M. Soukup, J. H. Beno, The Univ. of Texas Ctr. for Electromechanics (United States); G. J. Hill, J. M. Good, The Univ. of Texas McDonald Observatory (United States); C. E. Penney, T. A. Beets, J. D. Esguerra, R. J. Hayes, J. T. Heisler, J. J. Zierer, G. A. Wedeking, M. S. Worthington, D. R. Wardell, The Univ. of Texas Ctr. for Electromechanics (United States); J. A. Booth, M. E. Cornell, M. D. Rafal, The Univ. of Texas McDonald Observatory (United States)
- 8444 3Y **Enclosure rotation on the Large Binocular Telescope** [8444-148]
J. Howard, R. Meeks, D. Ashby, Large Binocular Telescope Observatory (United States); W. Davison, Steward Observatory, Univ. of Arizona (United States); J. Wiese, J. Urban, R. Hansen, J. Schuh, Large Binocular Telescope Observatory (United States)
- 8444 3Z **The 3,6 m Indo-Belgian Devasthal Optical Telescope: the hydrostatic azimuth bearing** [8444-150]
J. de Ville, M. Piérard, C. Bastin, AMOS Ltd. (Belgium)
- 8444 40 **Telescope positioning and drive system based on magnetic bearings, technical challenges and possible applications in optical stellar interferometry** [8444-151]
R. Lemke, Ruhr-Univ. Bochum (Germany); H. J. Kärcher, MT Mechatronics GmbH (Germany); L. Noethe, European Southern Observatory (Germany)
- 8444 41 **Enclosure design for the ARIES 3.6m optical telescope** [8444-152]
A. K. Pandey, V. Shukla, T. Bangia, Aryabhata Research Institute of Observational Sciences (India); R. D. Raskar, R. R. Kulkarni, A. S. Ghanti, Precision Precast Solutions Pvt. Ltd. (India)
- 8444 42 **An innovative alt-alt telescope for small observatories and amateur astronomers** [8444-153]
M. Riva, S. Basso, R. Canestrari, P. Conconi, D. Fugazza, M. Ghigo, M. Landoni, G. Pareschi, P. Spanó, INAF - Osservatorio Astronomico di Brera (Italy); R. Tomelleri, Tomelleri s.r.l. (Italy); F. M. Zerbi, INAF - Osservatorio Astronomico di Brera (Italy)
- 8444 43 **Prototype enclosure design for the Korea Microlensing Telescope Network (KMTNet)** [8444-154]
N. Kappler, L. Kappler, TBR Construction & Engineering (United States); W. M. Poteet, H. K. Cauthen, CP Systems, Inc. (United States); B.-G. Park, C.-U. Lee, S.-L. Kim, S.-M. Cha, Korea Astronomy and Space Science Institute (Korea, Republic of)

POSTER SESSION: TELESCOPES FOR SYNOPTIC AND SURVEY OBSERVATIONS

- 8444 44 **Initial alignment and commissioning plan for the LSST** [8444-18]
W. J. Gressler, J. Sebag, National Optical Astronomy Observatory (United States);
C. Claver, LSST Corp. (United States)
- 8444 45 **Dark energy camera installation at CTIO: overview** [8444-155]
T. M. C. Abbott, F. Muñoz, A. R. Walker, R. C. Smith, A. Montane, B. Gregory, R. Tighe,
P. Schurter, N. S. van der Blik, G. Schumacher, Cerro Tololo Inter-American Observatory
(Chile)
- 8444 46 **Dark Energy Camera installation at CTIO: technical challenges** [8444-156]
F. Muñoz A., A. Montane, R. Tighe, M. Warner, T. M. C. Abbott, Cerro Tololo Inter-American
Observatory (Chile)
- 8444 47 **Korea Microlensing Telescope Network: science cases** [8444-157]
B.-G. Park, S.-L. Kim, J.-W. Lee, B.-C. Lee, C.-U. Lee, Korea Astronomy and Space Science
Institute (Korea, Republic of); C. Han, Chungbuk National Univ. (Korea, Republic of);
M. Kim, Korea Astronomy and Space Science Institute (Korea, Republic of) and The
Observatories of the Carnegie Institution for Science (United States); D.-S. Moon, Univ. of
Toronto (Canada); H.-K. Moon, Korea Astronomy and Space Science Institute (Korea,
Republic of); S.-C. Rey, Chungnam National Univ. (Korea, Republic of); E.-C. Sung, Korea
Astronomy and Space Science Institute (Korea, Republic of); H. Sung, Sejong Univ. (Korea,
Republic of)
- 8444 48 **Design and development of a wide field telescope** [8444-158]
I. Moon, Korea Research Institute of Standards and Science (Korea, Republic of); S. Lee,
Korea Research Institute of Standards and Science (Korea, Republic of) and Hannam Univ.
(Korea, Republic of); J. Lim, Korea Research Institute of Standards and Science (Korea,
Republic of) and Kyung Hee Univ. (Korea, Republic of); H.-S. Yang, H.-G. Rhee, J.-B. Song,
Y.-W. Lee, Korea Research Institute of Standards and Science (Korea, Republic of);
J.-U. Lee, Cheongju Univ. (Korea, Republic of); H. Jin, Kyung Hee Univ. (Korea, Republic of)
- 8444 4A **Achieving high precision photometry for transiting exoplanets with a low cost robotic DSLR-
based imaging system** [8444-160]
O. Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States)
and Steward Observatory, Univ. of Arizona (United States); F. Martinache, Subaru
Telescope, National Astronomical Observatory of Japan (United States)

POSTER SESSION: UPGRADES TO EXISTING OBSERVATORIES

- 8444 4B **An active surface upgrade for the Delingha 13.7-m Radio Telescope** [8444-163]
D. Yang, Y. Zhang, G. Zhou, National Astronomical Observatories (China) and Nanjing
Institute of Astronomical Optics & Technology (China); A. Li, National Astronomical
Observatories (China) and Nanjing Institute of Astronomical Optics & Technology (China)
and Graduate Univ. of Chinese Academy of Sciences (China); K. Chen, Z. Zhang, G. Li,
National Astronomical Observatories (China) and Nanjing Institute of Astronomical Optics
& Technology (China); Y. Zuo, Y. Xu, Graduate Univ. of Chinese Academy of Sciences
(China)

Part 3

- 8444 4D **Development of a compact precision linear actuator for the active surface upgrade of the Delingha 13.7-m radio telescope** [8444-165]
G. Zhou, Nanjing Institute of Astronomical Optics & Technology (China); A. Li, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ. of Chinese Academy of Sciences (China); D. Yang, Z. Zhang, G. Li, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 4E **Upgrading the TNT Telescope: remote observing and future perspectives** [8444-166]
G. Di Rico, INAF - Osservatorio Astronomico di Teramo (Italy); M. Fiaschi, MFC Elettronica (Italy); G. Valentini, A. Di Cianno, A. Valentini, INAF - Osservatorio Astronomico di Teramo (Italy)
- 8444 4F **ESPRESSO: design and analysis of a Coudé-train for a stable and efficient simultaneous optical feeding from the four VLT unit telescopes** [8444-167]
A. Cabral, A. Moitinho, J. Coelho, J. Lima, Univ. de Lisboa (Portugal); G. Ávila, B.-A. Delabre, European Southern Observatory (Germany); R. Gomes, Univ. de Lisboa (Portugal); D. Mégevand, Observatoire de l'Univ. de Genève (Switzerland); F. Zerbi, INAF - Osservatorio Astronomico di Brera (Italy); P. Di Marcantonio, INAF - Osservatorio Astronomico di Trieste (Italy); C. Lovis, Observatoire de l'Univ. de Genève (Switzerland); N. C. Santos, Ctr. de Astrofísica, Univ. do Porto (Portugal) and Univ. do Porto (Portugal)
- 8444 4G **Recent performance improvements for the Large Binocular Telescope primary mirror system** [8444-169]
R. L. Meeks, D. Ashby, C. Biddick, A. Chatila, M. Gusick, Large Binocular Telescope Observatory, Univ. of Arizona (United States)
- 8444 4H **Modernization of the 1 meter Swope and 2.5 meter Du Pont telescopes at Las Campanas Observatory** [8444-170]
F. Perez, A. Bagish, Carnegie Observatories (United States); G. Bredthauer, Semiconductor Technology Associates (United States); J. Espoz, P. Jones, P. Pinto, Carnegie Observatories (United States)
- 8444 4I **A happy conclusion to the SALT image quality saga** [8444-171]
L. A. Crause, South African Astronomical Observatory (South Africa); D. E. O'Donoghue, Southern African Large Telescope (South Africa); J. E. O'Connor, F. Strümpfer, O. J. Strydom, C. Sass, South African Astronomical Observatory (South Africa); C. du Plessis, E. Wiid, J. Love, Southern African Large Telescope (South Africa); J. D. Brink, South African Astronomical Observatory (South Africa); M. Wilkinson, C. Coetzee, Southern African Large Telescope (South Africa)
- 8444 4J **Facility calibration unit of Hobby Eberly Telescope wide field upgrade** [8444-172]
H. Lee, G. J. Hill, B. Vattiat, McDonald Observatory, The Univ. of Texas at Austin (United States); M. P. Smith, Univ. of Wisconsin-Madison (United States); M. Häuser, Univ. Observatory Munich, Univ. of Munich (Germany)
- 8444 4K **Solid telescopes for interferometric enhancement of existing telescopes** [8444-173]
A. Riva, M. Gai, INAF - Osservatorio Astrofisico di Torino (Italy)

POSTER SESSION: ACTIVE OPTICS AND PRECISION POSITION CONTROL MECHANISMS

- 8444 4L **Optics and the mechanical system of the 62-cm telescope at the Severo Díaz Galindo Observatory in Guadalajara, Jalisco, México** [8444-168]
E. de la Fuente, Univ. de Guadalajara (Mexico); J. M. Nuñez, S. Zazueta, Observatorio Astronómico Nacional, Univ. Nacional Autónoma de México (Mexico); S. E. Ibarra, Univ. de Guadalajara (Mexico); B. García, Observatorio Astronómico Nacional, Univ. Nacional Autónoma de México (Mexico); B. Martínez, Univ. de Guadalajara (Mexico); J. L. Ochoa, G. Sierra, F. Lazo, D. Hirart, Observatorio Astronómico Nacional, Univ. Nacional Autónoma de México (Mexico); L. Corral, J. L. Flores, J. Almaguer, S. Kemp, S. G. Navarro, A. Nigoche-Netro, G. Ramos-Larios, J. P. Phillips, A. Chávez, G. García-Torales, O. Blanco Alonso, T. Ocegüera-Becerra, D. de Alba, R. Bautista, Univ. de Guadalajara (Mexico)
- 8444 4N **Folded Cassegrain sets of the Gran Telescopio Canarias (GTC)** [8444-175]
A. Gomez, R. Sanquirce, G. Murga, B. Etxeita, A. Vizcargüenaga, A. San Vicente, E. Fernandez, O. Vega, IDOM (Spain); B. Siegel, GRANTECAN S.A. (Spain)
- 8444 4O **Design, testing, and installation of a high-precision hexapod for the Hobby-Eberly Telescope dark energy experiment (HETDEX)** [8444-176]
J. J. Zierer, J. H. Beno, D. A. Weeks, I. M. Soukup, The Univ. of Texas at Austin, Ctr. for Electromechanics (United States); J. M. Good, J. A. Booth, G. J. Hill, M. D. Rafal, The Univ. of Texas at Austin, McDonald Observatory (United States)
- 8444 4P **Prototype pipeline for LSST wavefront sensing and reconstruction** [8444-177]
C. Claver, S. Chandrasekharan, M. Liang, National Optical Astronomy Observatory (United States); B. Xin, E. Alagoz, K. Arndt, I. P. Shipsey, Purdue Univ. (United States)
- 8444 4Q **Active optics in Large Synoptic Survey Telescope** [8444-178]
M. Liang, V. Krabbendam, C. F. Claver, S. Chandrasekharan, National Optical Astronomy Observatory (United States); B. Xin, Purdue Univ. (United States)
- 8444 4R **Keck 1 deployable tertiary mirror (K1DM3)** [8444-179]
J. X. Prochaska, C. Pistor, G. Cabak, D. J. Cowley, J. Nelson, Univ. of California Observatories (United States)
- 8444 4S **Metrology systems of Hobby-Eberly Telescope wide field upgrade** [8444-181]
H. Lee, G. J. Hill, M. E. Cornell, B. Vattiat, D. Perry, T. Rafferty, T. Taylor, McDonald Observatory, The Univ. of Texas at Austin (United States); M. Hart, Hart Scientific Consulting International L.L.C. (United States); M. D. Rafal, R. D. Savage, McDonald Observatory, The Univ. of Texas at Austin (United States)
- 8444 4T **Optics derotator servo control system for SONG Telescope** [8444-183]
J. Xu, C. Ren, Y. Ye, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 4U **Active optical control system design of the SONG-China Telescope** [8444-185]
Y. Ye, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ. of Chinese Academy of Sciences (China); S. Kou, D. Niu, Nanjing Institute of Astronomical Optics & Technology (China); C. Li, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ. of Chinese Academy of Sciences (China); G. Wang, Nanjing Institute of Astronomical Optics & Technology (China)

- 8444 4V **The 3,6m Indo-Belgian Devasthal Optical: the active M1 mirror support** [8444-186]
M. Piérard, C. Flebus, N. Ninane, AMOS Ltd. (Belgium)
- 8444 4W **Synchronous redundant control algorithm in the telescope drive system** [8444-187]
C. Ren, Nanjing Institute of Astronomical Optics & Technology (China); Y. Niu, X. Song, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ. of Chinese Academy of Sciences (China); J. Xu, X. Li, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 4X **The M₂&M₃ positioning control systems of a 2.5m telescope** [8444-188]
Y. Ye, C. Pei, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ. of Chinese Academy of Sciences (China); Z. Zhang, B. Gu, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 4Y **Progress of the active reflector antenna using laser angle metrology system** [8444-189]
Y. Zhang, Nanjing Institute of Astronomical Optics & Technology (China) and National Astronomical Observatories (China); J. Zhang, Nanjing Institute of Astronomical Optics & Technology (China) and National Astronomical Observatories (China) and Graduate Univ. of Chinese Academy of Sciences (China); D. Yang, G. Zhou, A. Li, G. Li, National Astronomical Observatories (China)
- 8444 4Z **The active optics system of the VST: concepts and results** [8444-190]
P. Schipani, INAF - Osservatorio Astronomico di Capodimonte (Italy); D. Magrin, INAF - Osservatorio Astronomico di Padova (Italy); L. Noethe, European Southern Observatory (Germany); C. Arcidiacono, INAF - Osservatorio Astronomico di Bologna (Italy) and INAF - Osservatorio Astrofisico di Arcetri (Italy); J. Argomedo, European Southern Observatory (Germany); M. Dall'Ora, S. D'Orsi, INAF - Osservatorio Astronomico di Capodimonte (Italy); J. Farinato, INAF - Osservatorio Astronomico di Padova (Italy); L. Marty, INAF - Osservatorio Astronomico di Capodimonte (Italy); R. Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy); G. Umbricco, Univ. of Padua (Italy)
- 8444 50 **Performance comparison between two active support schemes for 1-m primary mirror** [8444-191]
D. Niu, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ. of Chinese Academy of Sciences (China); G. Wang, B. Gu, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 51 **Design, development, and testing of the DCT Cassegrain instrument support assembly** [8444-192]
T. A. Bida, E. W. Dunham, R. A. Nye, T. Chylek, R. C. Oliver, Lowell Observatory (United States)

POSTER SESSION: ALIGNMENT OF TELESCOPE OPTICS

- 8444 53 **Experience of primary surface alignment for the LMT using a laser tracker in a non-metrology environment** [8444-195]
D. M. Gale, Lab. de Superficies Asféricas, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico)

- 8444 54 **Using a laser tracker for active alignment on the Large Binocular Telescope** [8444-196]
A. Rakich, Large Binocular Telescope Observatory (United States) and European Southern Observatory (Germany)
- 8444 55 **Generic misalignment aberration patterns and the subspace of benign misalignment** [8444-197]
P. L. Schechter, R. S. Levinson, Kavli Institute for Astrophysics and Space Research (United States) and Massachusetts Institute of Technology (United States)
- 8444 56 **The VST alignment: strategy and results** [8444-198]
P. Schipani, INAF - Osservatorio Astronomico di Capodimonte (Italy); L. Noethe, European Southern Observatory (Germany); K. Kuijken, Leiden Univ. (Netherlands); C. Arcidiacono, INAF - Osservatorio Astronomico di Bologna (Italy) and INAF - Osservatorio Astrofisico di Arcetri (Italy); J. Argomedo, European Southern Observatory (Germany); M. Dall'Ora, S. D'Orsi, INAF - Osservatorio Astronomico di Capodimonte (Italy); J. Farinato, D. Magrin, INAF - Osservatorio Astronomico di Padova (Italy); L. Marty, INAF - Osservatorio Astronomico di Capodimonte (Italy); R. Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy); G. Umbrico, Univ. of Padua (Italy)
- 8444 58 **Test system for a Shack-Hartmann sensor based telescope alignment demonstrated at the 40cm Wendelstein Telescope** [8444-200]
S. Bogner, M. Becker, Ernst-Abbe Fachhochschule (Germany); F. Grupp, Max-Planck-Institut für extraterrestrische Physik (Germany) and Univ.-Sternwarte München (Germany); F. Lang-Bardl, Univ.-Sternwarte München (Germany); S.-M. Hu, Shandong Univ. at Weihai (China); M. Beyerlein, J. Lamprecht, J. Pfund, OPTOCRAFT GmbH (Germany); U. Hopp, Univ.-Sternwarte München (Germany); R. Bender, Univ.-Sternwarte München (Germany) and Max-Planck-Institut für extraterrestrische Physik (Germany); B. Fleck, Ernst-Abbe Fachhochschule (Germany)
- 8444 59 **An improved collimation algorithm for the Large Binocular Telescope using source extractor and an on-the-fly reconstructor** [8444-201]
D. L. Miller, A. Rakich, T. Leibold, Large Binocular Telescope Observatory (United States)
- 8444 5A **Features of a laser metrology subsystem for astrometric telescopes** [8444-202]
A. Riva, M. Gai, M. G. Lattanzi, INAF - Osservatorio Astrofisico di Torino (Italy)

POSTER SESSION: DESIGN OF TELESCOPES FOR EXTREME ENVIRONMENTS

- 8444 5B **Conceptual design of a 5-m terahertz telescope at Dome A** [8444-203]
D. Yang, H. Wang, Y. Zhang, Y. Chen, G. Zhou, Nanjing Institute of Astronomical Optics & Technology (China); J. Cheng, National Radio Astronomy Observatory (United States); G. Li, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 5C **New Exoplanet Surveys in the Canadian High Arctic at 80 Degrees North** [8444-204]
N. M. Law, S. Sivanandam, Dunlap Institute for Astronomy & Astrophysics, Univ. of Toronto (Canada); R. Murowinski, National Research Council Canada (Canada); R. Carlberg, W. Ngan, Univ. of Toronto (Canada); P. Salbi, Dunlap Institute for Astronomy & Astrophysics, Univ. of Toronto (Canada); A. Ahmadi, Univ. of Calgary (Canada); E. Steinbring, M. Halman, National Research Council Canada (Canada); J. Graham, Dunlap Institute for Astronomy & Astrophysics, Univ. of Toronto (Canada)

- 8444 5E **An off-axis telescope concept for Antarctic astronomy** [8444-206]
G. Moretto, Lyon Institute of Origins, Institute of Nuclear Physics of Lyon, CNRS (France);
N. Epchtein, Lab. J.L. Lagrange, CNRS, Univ. of Nice Sophia-Antipolis (France); M. Langlois,
I. Vauglin, Ctr. de Recherche Astronomique de Lyon, CNRS (France)
- 8444 5F **The package cushioning design of the first AST3 and its dynamics analysis** [8444-207]
H. Wen, X. Gong, R. Zhang, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 5G **Nonlinear disturbance to Large Optical Antarctic Telescope** [8444-208]
S. Yang, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ.
of Chinese Academy of Sciences (China)
- 8444 5H **Where is Ridge A?** [8444-209]
G. Sims, The Univ. of New South Wales (Australia); C. Kulesa, Univ. of Arizona (United States);
M. C. B. Ashley, The Univ. of New South Wales (Australia); J. S. Lawrence, Macquarie Univ.
(Australia) and Australian Astronomical Observatory (Australia); W. Saunders, Australian
Astronomical Observatory (Australia); J. W. V. Storey, The Univ. of New South Wales
(Australia)
- 8444 5I **Two years of polar winter observations with the ASTEP400 telescope** [8444-210]
L. Abe, J. Rivet, A. Agabi, E. Aristidi, D. Mekarnia, I. Goncalves, T. Guillot, Lab. J.L. Lagrange,
CNRS, Univ. of Nice Sophia-Antipolis (France); M. Barbieri, Lab. J.L. Lagrange, CNRS, Univ. of
Nice Sophia-Antipolis (France) and Univ. of Padova (Italy); N. Crouzet, Space Telescope
Science Institute (United States); F. Fressin, Harvard-Smithsonian Ctr. for Astrophysics (United
States); F. Schmider, Y. Fantei-Caujolle, J. Daban, C. Gouvret, S. Peron, P. Petit, A. Robini,
M. Dugue, E. Bondoux, Lab. J.L. Lagrange, CNRS, Univ. of Nice Sophia-Antipolis (France);
T. Fruth, A. Erikson, H. Rauer, DLR (Germany); F. Pont, A. Alapini, Univ. of Exeter (United
Kingdom); S. Aigrain, Univ. of Oxford (United Kingdom); J. Szulagyi, Konkoly Observatory,
Research Ctr. for Astronomy and Earth Sciences (Hungary); P. Blanc, A. Le Van Suu,
Observatoire de Haute-Provence (France)

POSTER SESSION: OBSERVATORY CONTROL SYSTEMS

- 8444 5J **HETDEX tracker control system design and implementation** [8444-211]
J. Beno, R. Hayes, Ctr. for Electromechanics, The Univ. of Texas at Austin (United States);
R. Leck, McDonald Observatory, The Univ. of Texas at Austin (United States); C. E. Penney,
I. M. Soukup, Ctr. for Electromechanics, The Univ. of Texas at Austin (United States)
- 8444 5K **An upgrade to the telescope control system (TCS) for the Canada-France-Hawaii
Telescope** [8444-212]
K. K. Y. Ho, W. Cruise, J. Thomas, Canada-France-Hawaii Telescope (United States)
- 8444 5L **Automation of the OAN/SPM 1.5-meter Johnson telescope for operations with RATIR**
[8444-214]
A. M. Watson, M. G. Richer, Univ. Nacional Autónoma de México (Mexico); J. S. Bloom,
Univ. of California, Berkeley (United States); N. R. Butler, Arizona State Univ. (United States);
U. Ceseña, D. Clark, E. Colorado, A. Córdova, A. Farah, L. Fox-Machado, Univ. Nacional
Autónoma de México (Mexico); O. D. Fox, NASA Goddard Space Flight Ctr. (United
States); B. García, L. N. Georgiev, J. J. González, G. Guisa, L. Gutiérrez, J. Herrera, Univ.
Nacional Autónoma de México (Mexico); C. R. Klein, Univ. of California, Berkeley (United
States); A. S. Kutyrev, NASA Goddard Space Flight Ctr. (United States) and Univ. of

California Observatories/Lick Observatory, Univ. of California (United States); F. Lazo, W. H. Lee, E. López, E. Luna, B. Martínez, F. Murillo, J. M. Murillo, J. M. Núñez, Univ. Nacional Autónoma de México (Mexico); J. Prochaska, Univ. of Maryland, College Park (United States); J. Ochoa, F. Quirós, Univ. Nacional Autónoma de México (Mexico); D. A. Rapchun, NASA Goddard Space Flight Ctr. (United States) and Global Science & Technology (United States); C. Román-Zúñiga, G. Valyavin, Univ. Nacional Autónoma de México (Mexico)

- 8444 5M **Control system for the first three Antarctic Survey Telescopes (AST3-1)** [8444-216]
X. Li, D. Wang, L. Xu, J. Zhao, F. Du, Y. Zhang, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 5N **Development of an EtherCAT enabled digital servo controller for the Green Bank Telescope** [8444-217]
P. G. Whiteis, M. J. Mello, National Radio Astronomy Observatory (United States)
- 8444 5O **Design and development of telescope control system and software for the 50/80 cm Schmidt telescope** [8444-218]
T. S. Kumar, Indian Institute of Technology Bombay (India) and Aryabhata Research Institute of Observational Sciences (India); R. N. Banavar, Indian Institute of Technology Bombay (India)
- 8444 5P **Upgrading the MMT primary mirror actuator test stand: a unique vehicle for evaluating EtherCAT as a future I/O standard for systems** [8444-219]
D. Clark, S. Schaller, MMT Observatory, Univ. of Arizona (United States)
- 8444 5Q **MMT nightly tracking logs: a web-enabled database for continuous evaluation of tracking performance** [8444-220]
D. Clark, J. D. Gibson, D. Porter, T. Trebisky, MMT Observatory, Univ. of Arizona (United States)
- 8444 5R **Pointing and tracking results of the VST telescope** [8444-221]
P. Schipani, INAF - Osservatorio Astronomico di Capodimonte (Italy); C. Arcidiacono, INAF - Osservatorio Astronomico di Bologna (Italy) and INAF - Osservatorio Astrofisico di Arcetri (Italy); J. Argomedo, European Southern Observatory (Germany); M. Dall'Orta, S. D'Orsi, INAF - Osservatorio Astronomico di Capodimonte (Italy); J. Farinato, D. Magrin, INAF - Osservatorio Astronomico di Padova (Italy); L. Marty, INAF - Osservatorio Astronomico di Capodimonte (Italy); R. Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy); G. Umbriaco, Univ. of Padua (Italy)

POSTER SESSION: PROJECT REVIEWS

- 8444 5S **Design and fabrication of three 1.6-meter telescopes for the Korea Microlensing Telescope Network (KMTNet)** [8444-223]
W. M. Poteet, H. K. Cauthen, CP Systems, Inc. (United States); N. Kappler, L. G. Kappler, TBR Construction & Engineering (United States); B.-G. Park, C.-U. Lee, S.-L. Kim, S.-M. Cha, Korea Astronomy and Space Science Institute (Korea, Republic of)
- 8444 5T **Introduction of Chinese SONG Telescope** [8444-224]
G. Wang, S. Kou, D. Niu, Z. Zhang, X. Jiang, C. Ren, Nanjing Institute of Astronomical Optics & Technology (China)

8444 5U **Perspectives of astronomy in Kazakhstan: from new ground-based telescopes to space ones** [8444-225]
Ch. T. Omarov, Fessenkov Astrophysical Institute (Kazakhstan); Zh. Sh. Zhantayev, National Ctr. of Space Research and Technology (Kazakhstan)

8444 5V **Deployment status of the Las Cumbres Observatory Global Telescope** [8444-226]
A. J. Pickles, W. Rosing, J. Martinez, B. J. Fulton, D. Sand, Las Cumbres Observatory Global Telescope Network (United States)

POSTER SESSION: RADIO TELESCOPES

8444 5W **The microwave holography system for the Sardinia Radio Telescope** [8444-227]
G. Serra, P. Bolli, INAF - Osservatorio Astronomico di Cagliari (Italy); G. Busonera, CRS4 (Italy); T. Pisanu, S. Poppi, F. Gaudiomonte, INAF - Osservatorio Astronomico di Cagliari (Italy); G. Zacchiroli, J. Roda, M. Morsiani, INAF - Istituto di Radioastronomia (Italy); J. A. López-Pérez, Ctr. Astronómico de Yebes (Spain)

8444 5X **Structural optimization of the outer ring of FAST Telescope** [8444-228]
X. Zhang, National Astronomical Observatories (China) and Graduate Univ. of Chinese Academy of Sciences (China); H. Li, S. Yang, National Astronomical Observatories (China)

8444 5Y **Experimental study on the damping of FAST cabin suspension system** [8444-229]
H. Li, J. Sun, National Astronomical Observatories (China); X. Zhang, National Astronomical Observatories (China) and Graduate Univ. of Chinese Academy of Sciences (China); W. Zhu, G. Pan, Q. Yang, National Astronomical Observatories (China)

POSTER SESSION: SEGMENTED MIRROR ALIGNMENT, PHASING, AND WAVEFRONT CONTROL

8444 5Z **Control algorithm for the petal-shape segmented-mirror telescope with 18 mirrors** [8444-230]
A. Shimono, The Univ. of Tokyo (Japan); F. Iwamuro, M. Kurita, Kyoto Univ. (Japan); Y. Moritani, Kyoto Univ. (Japan) and Hiroshima Univ. (Japan); M. Kino, Nagoya Univ. (Japan); T. Maihara, Nano-Optonics Energy Inc. (Japan); H. Izumiura, National Astronomical Observatory of Japan (Japan); M. Yoshida, Hiroshima Univ. (Japan)

8444 60 **How to calibrate edge sensors on segmented mirror telescopes** [8444-231]
C. Shelton, L. C. Roberts, Jet Propulsion Lab. (United States)

8444 61 **Outdoors phasing progress of dispersed fringe sensing technology in NIAOT, China** [8444-232]
Y. Zhang, X. Cui, G. Liu, Y. Wang, J. Ni, H. Li, Y. Zeng, A. Li, Y. Li, Nanjing Institute of Astronomical Optics & Technology (China); Z. Wu, Nanjing Institute of Astronomical Optics & Technology (China) and Graduate Univ. of Chinese Academy of Sciences (China)

POSTER SESSION: SITE CHARACTERIZATION, TESTING, AND DEVELOPMENT

- 8444 62 **The new TNG-DIMM: calibrations and first data analysis** [8444-233]
E. Molinari, A. G. de Gurtubai, Telescopio Nazionale Galileo (Spain); A. della Valle, INAF - Osservatorio Astronomico di Bologna (Italy); S. Ortolani, Univ. degli Studi di Padova (Italy); J. San Juan, A. F. Martinez Fiorenzano, Telescopio Nazionale Galileo (Spain); V. Zitelli, INAF - Osservatorio Astronomico di Bologna (Italy)
- 8444 64 **Atmospheric turbulence measurements at Ali Observatory, Tibet** [8444-235]
L. Liu, National Astronomical Observatories (China) and Lab. Lagrange, CNRS, Univ. de Nice Sophia-Antipolis (France); Y. Yao, National Astronomical Observatories (China); J. Vernin, M. Chadid, Lab. J.L. Lagrange, CNRS, Univ. de Nice Sophia-Antipolis (France); Y. Wang, H. Wang, J. Yin, National Astronomical Observatories (China); C. Giordano, Lab. J.L. Lagrange, CNRS, Univ. de Nice Sophia-Antipolis (France); X. Qian, National Astronomical Observatories (China)
- 8444 68 **Dust concentration and soil properties at the TMT candidate sites** [8444-239]
S. G. Els, Gaia Data Processing & Analysis Consortium (Spain) and Cerro Tololo Inter-American Observatory (Chile) and TMT Observatory Corp. (United States); R. Riddle, Thirty Meter Telescope Observatory Corp. (United States) and Caltech Optical Observatories (United States); M. Schöck, W. Skidmore, T. Travouillon, Thirty Meter Telescope Observatory Corp. (United States)
- 8444 69 **Surface layer turbulence measurements on the LSST site El Peñon using microthermal sensors and the lunar scintillometer LuSci** [8444-240]
J. Sebag, National Optical Astronomy Observatory (United States); P. Zimmer, J. Turner, J. McGraw, The Univ. of New Mexico (United States); V. Krabbendam, National Optical Astronomy Observatory (United States); A. Tokovinin, E. Bustos, M. Warner, CTIO (Chile); O. Wiecha, National Optical Astronomy Observatory (United States)
- 8444 6A **Overview of site monitoring at the SAAO** [8444-241]
T. Pickering, South African Astronomical Observatory (South Africa) and Southern African Large Telescope (South Africa); S. M. Crawford, South African Astronomical Observatory (South Africa); L. Catala, South African Astronomical Observatory (South Africa) and Univ. of Cape Town (South Africa); D. Buckley, South African Astronomical Observatory (South Africa); A. Ziad, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice (France); R. Wilson, Univ. of Durham (United Kingdom)
- 8444 6B **Evaluations of new atmospheric windows at thirty micron wavelengths for astronomy** [8444-242]
T. Miyata, S. Sako, T. Kamizuka, Institute of Astronomy, The Univ. of Tokyo (Japan); T. Nakamura, Institute of Astronomy, The Univ. of Tokyo (Japan) and The Univ. of Tokyo (Japan); K. Asano, M. Uchiyama, M. Konishi, Institute of Astronomy, The Univ. of Tokyo (Japan); M. Yoneda, Planetary Plasma and Atmospheric Research Ctr., Tohoku Univ. (Japan); N. Takato, Subaru Telescope, National Astronomical Observatory of Japan (United States); Y. Yoshii, M. Doi, K. Kohno, K. Kawara, M. Tanaka, K. Motohara, T. Minezaki, T. Tanabe, T. Morokuma, Y. Tamura, Institute of Astronomy, The Univ. of Tokyo (Japan); T. Aoki, T. Soyano, K. Tarusawa, Kiso Observatory, Institute of Astronomy, The Univ. of Tokyo (Japan); H. Takahashi, S. Koshida, N. M. Kato, Institute of Astronomy, The Univ. of Tokyo (Japan)

- 8444 6C **Atmospheric seeing measurements obtained with MISOLFA in the framework of the PICARD Mission** [8444-243]
R. Ikhlef, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice Sophia Antipolis (France) and Observatoire d'Alger, Ctr. de Recherche en Astronomie, Astrophysique et Géophysique (Algeria); T. Corbard, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice Sophia Antipolis (France); A. Irbah, Lab. Atmosphères, Milieux, Observations Spatiales, CNRS, Univ. Versailles St-Quentin (France); F. Morand, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice Sophia Antipolis (France); M. Fodil, Observatoire d'Alger, Ctr. de Recherche en Astronomie, Astrophysique et Géophysique (Algeria); B. Chauvineau, P. Assus, C. Renaud, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice Sophia Antipolis (France); M. Meftah, S. Abbaki, Lab. Atmosphères, Milieux, Observations Spatiales, CNRS, Univ. Versailles St-Quentin (France); J. Borgnino, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice Sophia Antipolis (France); E. M. Cissé, E. D'Almeida, A. Hauchecorne, Lab. Atmosphères, Milieux, Observations Spatiales, CNRS, Univ. Versailles St-Quentin (France); F. Lalcare, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice Sophia Antipolis (France); P. Lesueur, M. Lin, Lab. Atmosphères, Milieux, Observations Spatiales, CNRS, Univ. Versailles St-Quentin (France); F. Martin, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice Sophia Antipolis (France); G. Poiet, Lab. Atmosphères, Milieux, Observations Spatiales, CNRS, Univ. Versailles St-Quentin (France); M. Rouzé, Ctr. National d'Études Spatiales (France); G. Thuillier, Lab. Atmosphères, Milieux, Observations Spatiales, CNRS, Univ. Versailles St-Quentin (France); A. Ziad, Observatoire de la Côte d'Azur, CNRS, Univ. de Nice Sophia Antipolis (France)

POSTER SESSION: TELESCOPE OPTICAL DESIGNS

- 8444 6D **Optical system of Chinese SONG Telescope** [8444-244]
S. Kou, G. Liu, G. Wang, Nanjing Institute of Astronomical Optics & Technology (China)
- 8444 6E **Design of an off-axis optical reflecting system** [8444-245]
Y. V. Bazhanov, V. B. Vlahko, Precision Systems and Instruments Corp. (Russian Federation)
- 8444 6G **Dome flat-field system for 1.3-m Araki Telescope** [8444-248]
T. Yoshikawa, Y. Ikeda, N. Fujishiro, Koyama Astronomical Observatory, Kyoto Sangyo Univ. (Japan); S. Ichizawa, Cybernet Systems Co., Ltd. (Japan); A. Arai, M. Isogai, A. Yonehara, H. Kawakita, Koyama Astronomical Observatory, Kyoto Sangyo Univ. (Japan)
- 8444 6H **Fast and compact wide-field Gregorian telescope** [8444-249]
M. Bahrami, A. V. Goncharov, National Univ. of Ireland, Galway (Ireland)
- 8444 6I **Optical design for amateur reflecting telescopes based on tilted axial-symmetrical planoidal mirror** [8444-250]
S. A. Chuprakov, Institute of Solar-Terrestrial Physics (Russian Federation)
- 8444 6J **Preliminary optical design for the WEAVE two-degree prime focus corrector** [8444-251]
T. Agócs, ASTRON (Netherlands); D. C. Abrams, D. Cano Infantes, N. O'Mahony, Isaac Newton Group of Telescopes (Spain); K. Dee, Engineering & Project Solutions Ltd. (United Kingdom); J.-B. Daban, C. Gouvret, S. Ottogalli, Observatoire de la Côte d'Azur, Lab. Lagrange, CNRS, Univ. de Nice Sophia Antipolis (France)

Author Index

Conference Committee

Symposium Chairs

Mark M. Casali, European Southern Observatory (Germany)

Kathryn A. Flanagan, Space Telescope Science Institute (United States)

Symposium Cochairs

Gillian S. Wright, UK Astronomy Technology Centre (United Kingdom)

Luc Smiard, National Research Council Canada (Canada)

Conference Chairs

Larry M. Stepp, Thirty Meter Telescope Observatory Corporation (United States)

Roberto Gilmozzi, European Southern Observatory (Germany)

Helen J. Hall, NASA Ames Research Center (United States)

Conference Program Committee

Torben E. Andersen, Lund Observatory (Sweden)

Matthew Colless, Anglo-Australian Observatory (Australia)

Jean-Gabriel Cuby, Observatoire Astronomique de Marseille-Provence (France)

Xiangqun Cui, Nanjing Institute of Astronomical Optics & Technology (China)

Richard F. Green, Large Binocular Telescope Observatory (United States) and The University of Arizona (United States)

Frank W. Kan, Simpson Gumpertz & Heger Inc. (United States)

Jeffrey R. Kuhn, University of Hawai'i (United States)

Heather K. Marshall, National Solar Observatory (United States)

Javier Marti Canales, European Southern Observatory (Chile)

Simon J. E. Radford, California Institute of Technology (United States)

Göran Sandell, SOFIA/Universities Space Research Association (United States)

Jason Spyromilio, European Southern Observatory (Germany)

Donald W. Sweeney, LSST Corporation (United States)

Tomonori Usuda, Subaru Telescope, National Astronomical Observatory of Japan (United States)

Session Chairs

Solar Telescopes I

Jeffrey R. Kuhn, University of Hawai'i (United States)

Solar Telescopes II

Jeffrey R. Kuhn, University of Hawai'i (United States)

Telescopes for Synoptic and Survey Observations I

Tomonori Usuda, Subaru Telescope, National Astronomical
Observatory of Japan (United States)

Telescopes for Synoptic and Survey Observations II

Richard F. Green, Large Binocular Telescope Observatory
(United States)

Upgrades to Existing Observatories

Richard F. Green, Large Binocular Telescope Observatory
(United States)

Telescope Mounts and Enclosures

Frank W. Kan, Simpson Gumpertz & Heger Inc. (United States)

Design to Withstand Earthquakes

Larry M. Stepp, Thirty Meter Telescope Observatory Corporation
(United States)

Modeling, Measurement, and Control of Wind Buffeting

Heather K. Marshall, National Solar Observatory (United States)

Concepts for Future Telescopes

Torben Andersen, Lund Observatory (Sweden)

Industrial Perspectives

Torben Andersen, Lund Observatory (Sweden)

Airborne Telescopes I

Helen J. Hall, NASA Ames Research Center (United States)

Airborne Telescopes II

Jeffrey R. Kuhn, University of Hawai'i (United States)

Gamma Ray Telescopes

Göran Sandell, SOFIA/Universities Space Research Association
(United States)

Assembly, Integration, Verification, and Commissioning
Jason Spyromilio, European Southern Observatory (Germany)

Extremely Large Telescopes
Helen J. Hall, NASA Ames Research Center (United States)

Site Characterization, Testing, and Development
Helen J. Hall, NASA Ames Research Center (United States)

Design of Telescopes for Extreme Environments
Jean-Gabriel Cuby, Observatoire Astronomique de Marseille-Provence (France)

Control of Thermal Environment
Jean-Gabriel Cuby, Observatoire Astronomique de Marseille-Provence (France)

Project Reviews
Donald W. Sweeney, LSST Corp. (United States)

Enabling Technologies for Extremely Large Telescopes I
Larry M. Stepp, Thirty Meter Telescope Observatory Corporation (United States)

Enabling Technologies for Extremely Large Telescopes II
Heather K. Marshall, National Solar Observatory (United States)

Segmented Mirror Alignment, Phasing, and Wavefront Control
Larry M. Stepp, Thirty Meter Telescope Observatory Corporation (United States)

Observatory Facilities
Larry M. Stepp, Thirty Meter Telescope Observatory Corporation (United States)

Square Kilometer Array and SKA Pathfinders
Frank W. Kan, Simpson Gumpertz & Heger Inc. (United States)

Radio Telescopes
Göran Sandell, NASA Ames Research Center (United States)

Millimeter and Submillimeter Wavelength Telescopes I
Helen J. Hall, NASA Ames Research Center (United States)

Millimeter and Submillimeter Wavelength Telescopes II
Javier Marti Canales, European Southern Observatory (Chile)

Poster Session: Airborne Telescopes

Helen J. Hall, NASA Ames Research Center (United States)

Jeffrey R. Kuhn, University of Hawai'i (United States)

Poster Session: Assembly, Integration, Verification, and Commissioning

Jason Spyromilio, European Southern Observatory (Germany)

Poster Session: Concepts for Future Telescopes

Torben Andersen, Lund Observatory (Sweden)

Poster Session: Control of Thermal Environment

Jean-Gabriel Cuby, Observatoire Astronomique de Marseille-Provence (France)

Poster Session: Design to Withstand Earthquakes

Larry M. Stepp, Thirty Meter Telescope Observatory Corporation (United States)

Poster Session: Enabling Technologies for Extremely Large Telescopes

Larry M. Stepp, Thirty Meter Telescope Observatory Corporation (United States)

Heather K. Marshall, National Solar Observatory (United States)

Poster Session: Extremely Large Telescopes

Helen J. Hall, NASA Ames Research Center (United States)

Poster Session: Gamma Ray Telescopes

Helen J. Hall, NASA Ames Research Center (United States)

Poster Session: Industrial Perspectives

Torben Andersen, Lund Observatory (Sweden)

Poster Session: Measurement and Control of Telescope Vibration

Helen J. Hall, NASA Ames Research Center (United States)

Poster Session: Millimeter and Submillimeter Wavelength Telescopes II

Javier Marti Canales, European Southern Observatory (Chile)

Poster Session: Solar Telescopes

Jeffrey R. Kuhn, University of Hawai'i (United States)

Xiangqun Cui, Nanjing Institute of Astronomical Optics & Technology (China)

Poster Session: Telescope Mounts and Enclosures

Frank W. Kan, Simpson Gumpertz & Heger Inc. (United States)

Poster Session: Telescopes for Synoptic and Survey Observations

Tomonori Usuda, Subaru Telescope, National Astronomical
Observatory of Japan (United States)

Richard F. Green, Large Binocular Telescope Observatory
(United States)

Poster Session: Upgrades to Existing Observatories

Richard F. Green, Large Binocular Telescope Observatory
(United States)

Poster Session: Active Optics and Precision Position Control
Mechanisms

Larry M. Stepp, Thirty Meter Telescope Observatory Corporation
(United States)

Poster Session: Alignment of Telescope Optics

Helen J. Hall, NASA Ames Research Center (United States)

Poster Session: Design of Telescopes for Extreme Environments

Jean-Gabriel Cuby, Observatoire Astronomique de Marseille-
Provence (France)

Poster Session: Observatory Control Systems

Larry M. Stepp, Thirty Meter Telescope Observatory Corporation
(United States)

Poster Session: Project Reviews

Donald W. Sweeney, LSST Corporation (United States)

Poster Session: Radio Telescopes

Göran Sandell, NASA Ames Research Center (United States)

Poster Session: Segmented Mirror Alignment, Phasing, and Wavefront
Control

Xiangqun Cui, Nanjing Institute of Astronomical Optics & Technology
(China)

Poster Session: Site Characterization, Testing, and Development

Helen J. Hall, NASA Ames Research Center (United States)

Poster Session: Telescope Optical Designs

Helen J. Hall, NASA Ames Research Center (United States)

Introduction

The large number of submissions to and excellent attendance at the Ground-based and Airborne Telescopes IV conference reflects the strong and growing interest in the astronomical and engineering communities. More than 250 papers were submitted to this year's conference, the largest number in the series' history. This year's conference included 28 oral sessions and two poster sessions.

Good progress was reported on many ongoing and planned programs. Excellent invited papers were presented on ALMA, ASKAP, ATST, CTA, DCT, DOT, E-ELT, FAST, GMT, KDUST, LMT, LOFAR, LSST, MeerKAT, NST, SKA, SOFIA, and TMT.

The technical subjects covered in the papers are similar to previous conferences, with some evolution of emphasis. Papers were presented on many current and proposed optical-IR telescope projects, and attendance was strong as always in the session on the ELT projects. Many aspects of telescope design were covered, including structures and enclosures, control systems, active optics, thermal and vibration control, and alignment and control of segmented mirrors.

We heard reports on several solar telescope projects in two conference sessions, one of which was devoted to ATST. There were two sessions on airborne telescopes, with one devoted to SOFIA, which has recently started science operations. The increasing importance of survey telescopes was evident with two sessions devoted to telescopes for synoptic and survey observations. Another area of increased interest is gamma ray telescopes, which also had its own session at this conference.

Development of new radio telescopes remains a strong area, occupying one full day in the conference. The progress of SKA was reflected in a separate SKA session with four invited papers. Millimeter and submillimeter telescopes filled two sessions, with one session devoted to ALMA, which has started science operations this year.

It is clear that our understanding of the properties of astronomical sites is continuing to improve, and there is a growing interest in the design of telescopes to operate in extreme environments, particularly the Arctic and Antarctic. Another area of increasing interest is the design of telescopes to withstand earthquakes, with new approaches presented at the conference.

The chairs would like to thank the SPIE symposium organizers, the GB&AT program committee, the session chairs, the authors and all the conference participants for making this year's conference so successful.

Larry M. Stepp
Roberto Gilmozzi
Helen J. Hall

The cosmic microwave background: observing directly the early universe

Paolo de Bernardis^a and Silvia Masi^a

^aDipartimento di Fisica, Sapienza Università di Roma, P.le A. Moro 2 00185 Roma, Italy

ABSTRACT

The Cosmic Microwave Background (CMB) is a relict of the early universe. Its perfect 2.725K blackbody spectrum demonstrates that the universe underwent a hot, ionized early phase; its anisotropy (about 80 μ K rms) provides strong evidence for the presence of photon-matter oscillations in the primeval plasma, shaping the initial phase of the formation of structures; its polarization state (about 3 μ K rms), and in particular its rotational component (less than 0.1 μ K rms) might allow to study the inflation process in the very early universe, and the physics of extremely high energies, impossible to reach with accelerators. The CMB is observed by means of microwave and mm-wave telescopes, and its measurements drove the development of ultra-sensitive bolometric detectors, sophisticated modulators, and advanced cryogenic and space technologies. Here we focus on the new frontiers of CMB research: the precision measurements of its linear polarization state, at large and intermediate angular scales, and the measurement of the inverse-Compton effect of CMB photons crossing clusters of Galaxies. In this framework, we will describe the formidable experimental challenges faced by ground-based, near-space and space experiments, using large arrays of detectors. We will show that sensitivity and mapping speed improvement obtained with these arrays must be accompanied by a corresponding reduction of systematic effects (especially for CMB polarimeters), and by improved knowledge of foreground emission, to fully exploit the huge scientific potential of these missions.

Keywords: cosmic microwave background, millimeter wave telescope, array of bolometers

1. INTRODUCTION

We live in an expanding universe, cooling down from a state of extremely high density and temperature, the big bang. In our universe the ratio between the density of photons (the photons of the cosmic microwave background) and the density of baryons is of the order of 10^9 : this abundance of photons dominated the dynamics of the Universe in the initial phase (first 50000 years). During the first 380000 years the universe was ionized and opaque to radiation, due to the tight coupling between photons and charged baryons. Radiation thermalized in this primeval fireball, producing a blackbody spectrum. When the universe cooled down below 3000K, neutral atoms formed (recombination), and radiation decoupled from matter, traveling basically without any further interaction all the way to our telescopes. Due to the expansion of the universe, the wavelengths of photons expand (by the same amount all lengths expanded, a factor of 1100). What was a glowing 3000K blackbody 380000 years after the big bang, has been redshifted to millimeter waves, and is now observable as a faint background of microwaves. This is the cosmic microwave background, which has been observed as a 2.725K blackbody filling the present universe.¹

The CMB is remarkably isotropic. However, it is widely believed that the large scale structure of the universe observed today (see e.g.²) derives from the growth of initial density seeds, already visible as small anisotropies in the maps of the Cosmic Microwave Background. This scenario works only if there is dark (i.e. not interacting electromagnetically) matter, already clumped at the epoch of CMB decoupling, gravitationally inducing anisotropy in the CMB. There are three physical processes converting the density perturbations present at recombination into *observable* CMB temperature fluctuations $\Delta T/T$. They are: the photon density fluctuations δ_γ , which can be related to the matter density fluctuations $\Delta\rho$ once a specific class of perturbations is specified;

Further author information: (Send correspondence to PdB)

PdB.: E-mail: paolo.debernardis@roma1.infn.it, Telephone: 39 06 49914 271

SM: E-mail: silvia.masi@roma1.infn.it, Telephone: +39 06 49914 271

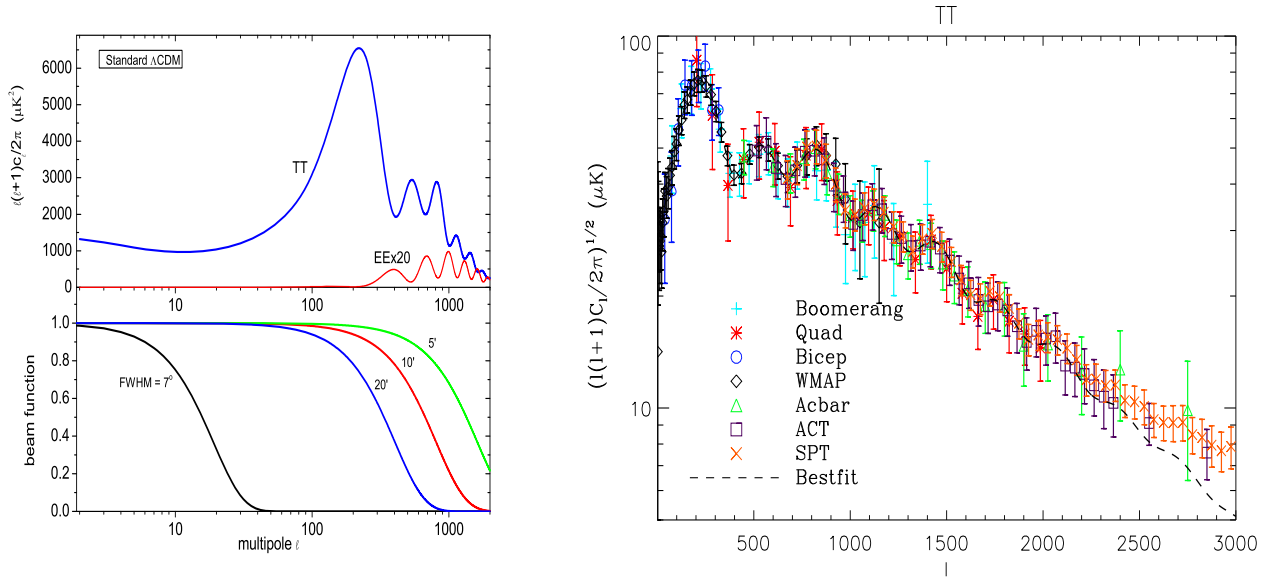


Figure 1. **Left-Top:** Angular power spectrum for CMB anisotropy (TT) and for EE polarization. The latter has been amplified 20 times to make it visible in the same plot of TT. The angular scale γ corresponding to multipole ℓ is approximately $\gamma(^{\circ}) = 180/\ell$. **Left-Bottom:** Filter functions of CMB telescopes with different angular resolutions. A FWHM smaller than 1° is needed to be sensitive to the "acoustic peaks" due to photon-baryon oscillations in the early universe. The curves are labeled with the beam FWHM. Differential instruments will not be sensitive to multipoles $\ell < 180/\alpha(^{\circ})$ where α is the angular separation of the beam switch; experiments scanning a limited sky region with angular size θ cannot be sensitive to multipoles with $\ell < 180/\theta(^{\circ})$. **Right:** Selected recent measurements of the angular power spectrum of CMB anisotropy.

the gravitational redshift of photons scattered in an over-density or an under-density with gravitational potential difference $\Delta\phi_r$; the Doppler effect produced by the proper motion with velocity v of the electrons scattering the CMB photons. In formulas:

$$\frac{\Delta T}{T}(\vec{n}) \approx \frac{1}{4}\delta_{\gamma r} + \frac{1}{3}\frac{\Delta\phi_r}{c^2} - \vec{n} \cdot \frac{\vec{v}_r}{c} \quad (1)$$

where \vec{n} is the line of sight vector and the subscript r labels quantities at recombination.

Our description of fluctuations with respect to the FRW isotropic and homogeneous metric is totally statistical. So we are not able to forecast the map $\Delta T/T$ as a function of (θ, ϕ) , but we are able to predict its statistical properties. If the fluctuations are random and Gaussian, all the information encoded in the image is contained in the angular power spectrum of the map, detailing the contributions of the different angular scales to the fluctuations in the map. In other words, the power spectrum of the image of the CMB details the relative abundance of the spots with different angular scales.

If we expand the temperature of the CMB in spherical harmonics, we have

$$\frac{\Delta T}{T} = \sum a_{\ell,m}^T Y_{\ell}^m(\theta, \phi) \quad (2)$$

the power spectrum of the CMB temperature anisotropy is defined as

$$c_{\ell}^{TT} = \langle TT \rangle = \langle a_{\ell,m}^T a_{\ell,m}^{T,*} \rangle \quad (3)$$

with no dependence on m since there are no preferred directions. Since we have only a statistical description of the observable, the precision with which the theory can be compared to measurement is limited both by

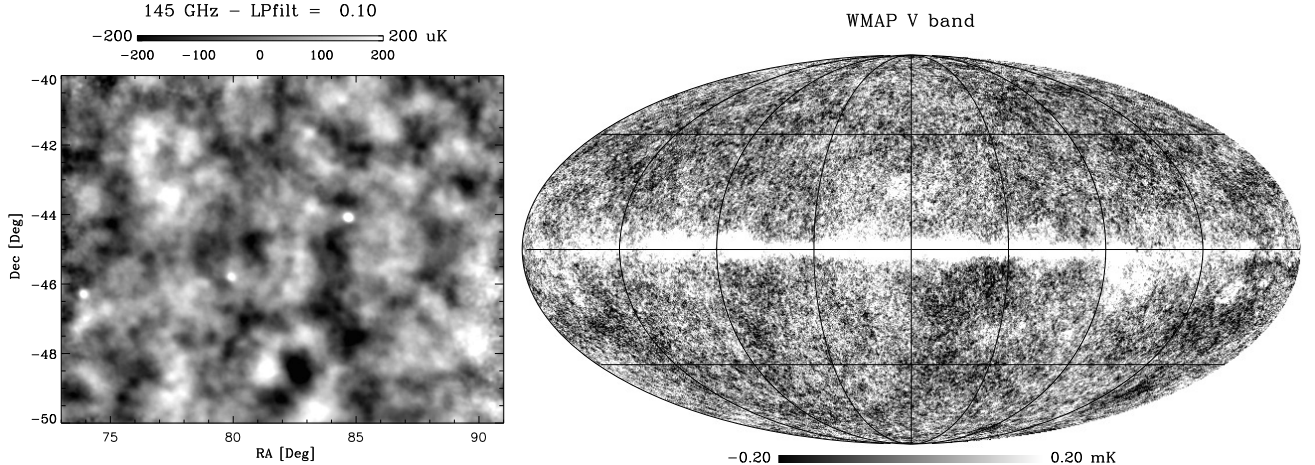


Figure 2. **Left:** The first map of the CMB with angular resolution and signal to noise ratio sufficient to resolve degree-sized causal horizons in the early universe was obtained by the BOOMERanG experiment, at 145 GHz, using an off-axis telescope flown on a stratospheric balloon.¹¹ The structures visible in the map are CMB anisotropies, while the contamination from local foregrounds and from instrument noise are both negligible. **Right:** The WMAP satellite has mapped the whole sky, confirming the ubiquitous presence of causal horizons, and allowing a precise determination of the power spectrum of CMB anisotropy and of the cosmological parameters.^{12,13}

experimental errors *and* by the statistical uncertainty in the theory itself. Each observable has an associated cosmic and sampling variance, which depends on how many independent samples can be observed in the sky. In the case of the c_ℓ s, their distribution is a χ^2 with $2\ell + 1$ degrees of freedom, which means that low multipoles have a larger intrinsic variance than high multipoles (see e.g.³).

Theory predicts the angular power spectrum of CMB anisotropy with remarkable detail, given a model for the generation of density fluctuations in the Universe, and a set of parameters describing the background cosmology. Assuming scale-invariant initial density fluctuations, the main features of the power spectrum c_ℓ^{TT} are a $1/[\ell(\ell + 1)]$ trend at low multipoles, produced by the Sachs-Wolfe effect⁴ (second term in equation 1); a sequence of peaks and dips at multipoles above $\ell = 100$, produced by acoustic fluctuations in the primeval plasma of photons and baryons,⁵⁻⁷ and a damping tail at high multipoles, due to the finite depth of the recombination and free-streaming effects.⁸ Detailed models and codes are available to compute the angular power spectrum of the CMB image (see e.g.^{9,10}). The power spectrum c_ℓ^{TT} derived from the current best-fit cosmological model is plotted in fig.1 (top panel).

High signal-to-noise maps of the CMB have been obtained since year 2000¹¹ (see fig.2). From such maps, the power spectrum of CMB anisotropy is now measured quite well (see e.g.^{11,13-27} and fig.1, right panel); moreover, higher order statistics are now being measured with the accuracy required to constrain cosmological parameters (see e.g.²⁸). Despite of the very small signals, the measurements from independent experiments, using diverse experimental techniques, are remarkably consistent. Moreover, an adiabatic inflationary model, with cold dark matter and a cosmological constant, fits very well the measured data (see e.g.^{12,18,29-45}).

The CMB is expected to be slightly polarized, since most of the CMB photons undergo a last Thomson scattering at recombination, and the radiation distribution around the scattering centers is slightly anisotropic. Any quadrupole anisotropy in the incoming distribution produces linear polarization in the scattered radiation. The main term of the local anisotropy due to density (scalar) fluctuations is dipole, while the quadrupole term is much smaller. For this reason the expected polarization is quite weak (⁴⁶⁻⁴⁹). The polarization field can be expanded into a curl-free component (E-modes) and a curl component (B-modes). Six auto and cross power spectra can be obtained from these components: $\langle TT \rangle$, $\langle TE \rangle$, $\langle EE \rangle$, $\langle BB \rangle$, $\langle TB \rangle$, and $\langle EB \rangle$. For example

$$c_\ell^{TE} = \langle TE \rangle = \langle a_{\ell,m}^T a_{\ell,m}^{E,*} \rangle \quad (4)$$

where the $a_{\ell,m}^E$ and $a_{\ell,m}^B$ decompose the map of the Stokes parameters Q and U of linear polarization in spin-2 spherical harmonics:

$$(Q \pm iU)(\theta, \phi) = \sum_{\ell m} (a_{\ell m}^E \mp i a_{\ell m}^B) {}_{\pm 2}Y_{\ell m}(\theta, \phi) \quad (5)$$

Due to the parity properties of these components, standard cosmological models have $\langle TB \rangle = 0$ and $\langle EB \rangle = 0$. Linear scalar (density) perturbations can only produce E-modes of polarization (see e.g.⁵⁰). In the concordance model, $\langle EE \rangle \sim 0.01 \langle TT \rangle$, making $\langle EE \rangle$ a very difficult observable to measure. The power spectrum c_{ℓ}^{EE} derived from the current best-fit cosmological model is plotted in fig.1 (top-left panel).

Tensor perturbations (gravitational waves) produce both E-modes and B-modes. If inflation happened (see e.g.⁵¹⁻⁵⁴), it produced a weak background of gravitational waves. The resulting level of the B-modes depends on the energy scale of inflation, but is in general very weak (see e.g.^{55,56}). Alternative scenarios, like the cyclic model,⁵⁷ do not produce B-modes at all.⁵⁸

There is a strong interest in measuring CMB polarization, and in particular the B-modes, because their detection would represent the final confirmation of the inflation hypothesis, and their level would constrain the energy-scale of the inflation process, which, we know, happened at extremely high energies (which cannot be investigated on earth laboratories⁵⁹).

For long time attempts to measure CMB polarization resulted in upper limits (see e.g.⁶⁰⁻⁶⁵). The possibility of detecting the $\langle BB \rangle$ signature of the inflationary gravity waves background renewed the interest in these measurements (⁶⁶⁻⁸⁰). The first statistically significant detections of CMB polarization have been reported by the coherent radiometer experiments DASI,⁸¹ CAPMAP,⁸² CBI,⁸³ WMAP for both $\langle TE \rangle$ ⁷⁷ and $\langle EE \rangle$,⁸⁴ and by the bolometric instrument BOOMERanG-03.⁸⁵⁻⁸⁷ The quality of CMB polarization measurements has improved steadily with the introduction of instruments with detectors arrays, like QUAD,⁸⁸⁻⁹⁰ BICEP,⁹¹ and QUIET.⁹²

Recent measurements of the angular power spectra of CMB polarization are collected in fig.3. The polarization power spectra measured by these experiments are all consistent with the forecast from the “concordance” model best fitting the WMAP $\langle TT \rangle$ power spectrum. In addition, they constrain the optical depth to reionization (the process ionizing the universe when the first massive stars formed), which is not well constrained by anisotropy measurements alone (see e.g.⁹³).

The WMAP data have sufficient coverage to allow a stacking analysis and show the irrotational pattern of polarization pseudovectors around cold and hot spots of the CMB sky:⁴⁵ a clear visual demonstration of the polarization produced by density perturbations in the early universe.

To date, measurements of the rotational component of the polarization field $\langle BB \rangle$ resulted in upper limits, implying a ratio of tensor to scalar fluctuations $r \lesssim 0.3$.

2. OBSERVING THE CMB

The CMB is a diffuse mm-wave source, filling the sky (with a photon density of $\sim 400\gamma/cm^3$) and very faint with respect to radiation produced in the same wavelength range by our living environment and by the instruments used to measure it (the telescope, the optical system, the filters, the detector). The greatest difficulty in measuring the CMB is to reduce the contamination from other sources.

Measuring the specific brightness of the CMB with the COBE-FIRAS instrument required cooling cryogenically the spectrometer (a Martin-Puplett Fourier-Transform Spectrometer) and the bolometric detectors, and launching it in a 400 km orbit. The first operation reduced drastically the emission of the instrument and the noise of the detectors, the second minimized the emission of the earth atmosphere. The COBE-FIRAS was a null-instrument, comparing the specific sky brightness, collected by a multi-mode Winston concentrator,⁹⁴ to the brightness of an internal cryogenic blackbody reference. The output was precisely nulled (within detector noise) for $T_{ref}=2.725$ K . This implies that the brightness of the empty sky is a blackbody at the same temperature, and that the early universe was in thermal equilibrium. The brightness of a 2.725K blackbody⁹⁵ is relatively large (compared to the typical noise of mm-wave detectors), but everything at room temperature emits microwaves

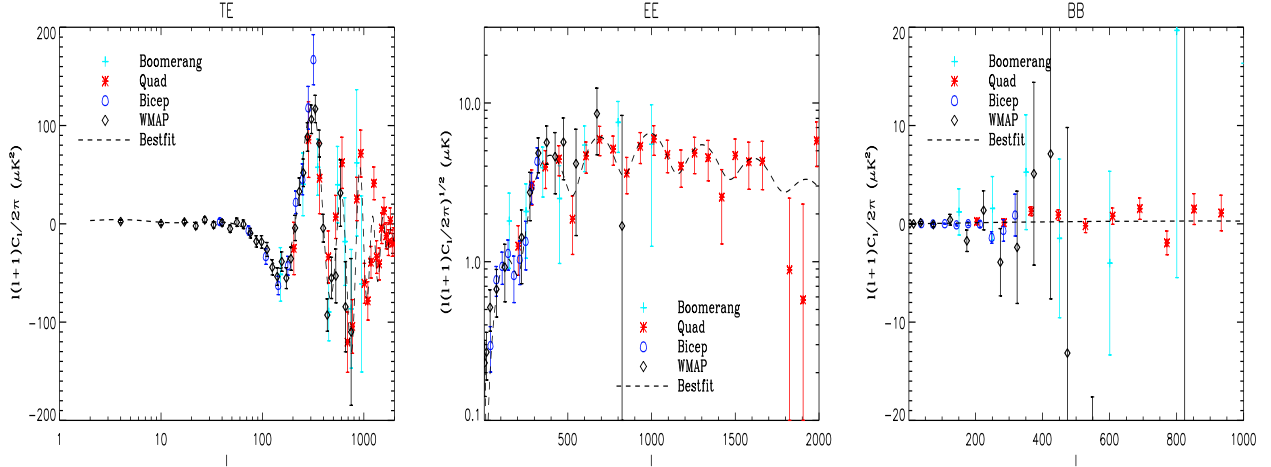


Figure 3. **Left:** Recent selected measurements of the angular cross-spectrum Temperature-E-modes-polarization $\langle TE \rangle$. **Center:** Recent selected measurements of the angular power spectrum of E-modes-polarization $\langle EE \rangle$. **Right:** Recent selected measurements (upper limits) of the angular power spectrum of B-modes-polarization $\langle BB \rangle$. Note the different vertical scales for the three plots. The dashed line is the model prediction for the same cosmological parameters best fitting $\langle TT \rangle$ measurements.

in the same frequency range: the instrument itself, the surrounding environment, the earth atmosphere. A room-temperature blackbody is orders of magnitude brighter than the CMB. Low emissivity, reflective surfaces must be used to shield the instrument, which needs to be cooled to cryogenic temperatures. Also, to avoid a very wide dynamic range, a cryogenic reference source should be used in the comparison. All this drove the design of the COBE-FIRAS instrument.¹

The FIRAS one can be considered a definitive measurement of the spectrum of the CMB in the mm range: the deviations from a pure blackbody are less than 0.01% in the peak region, small enough to be fully convincing about the thermal nature of the CMB. However, there are regions of the spectrum where small deviations from a pure blackbody could be expected.

The ARCADE experiment,^{96,97} another cryogenic flux collector working with coherent detectors from a stratospheric platform, focused on the low frequency end of the spectrum, looking for cm-wave deviations. In addition to emission from unresolved extragalactic sources, processes like the reionization due to the first stars, and particle decays in the early universe, would heat the diffuse matter, which in turn would cool, injecting the excess heat in the CMB (see e.g.⁹⁸).

CMB anisotropy and polarization measurements target at much smaller brightnesses. The specific brightness of CMB anisotropy (and its polarization) is a modified blackbody

$$\Delta B = B(\nu, T_{CMB}) \frac{x e^x}{e^x - 1} \frac{\Delta T}{T} \quad ; \quad x = \frac{h\nu}{kT} \quad (6)$$

peaking at 220 GHz, and with $\Delta T/T$ of the order of 30 ppm, resulting in very faint brightness differences. However, in differential measurements common mode signals (coming from the average CMB but also from the instrument and the environment) can be rejected with high efficiency.

The focus here shifts on angular resolution (i.e. size of the telescope), sensitivity (i.e. noise of the detectors and photon-noise from the radiative background), and mapping speed.

2.1 Angular Resolution and Sidelobes

Theory predicts a power spectrum c_ℓ^{**} with important features at degree and sub-degree angular scales (i.e. multipoles above $\ell = 100$, see top panel of Fig.1). Resolving those features requires sub-degree angular resolution.

In the bottom panel of Fig.1 we plot the window function (i.e. the sensitivity of the instrument to different multipoles) for Gaussian beams with different *FWHM*: $B_\ell^2 = e^{-\ell(\ell+1/2)/\sigma^2}$, with $\sigma = FWHM/\sqrt{8\ln 2}$.⁹⁹

At the frequency of maximum specific brightness of the CMB (160 GHz), and for a FWHM of 10', the diameter of the entrance pupil of a diffraction-limited optical system has to be around 0.8 m. However, to reduce the spillover from strong sources in the sidelobes, it is needed to oversize the entrance pupil (i.e. the diameter of the collecting mirror/lens) leaving a guard-ring around the entrance pupil. The aperture stop is placed in a cold part of the system, effectively apodizing the illumination of primary light collector. So, at least meter-sized telescopes are needed to explore the features of the angular power spectrum of the CMB, while 10m class telescopes are needed to study its finest details.

Bolometric systems are capable of integrating many radiation modes, boosting their sensitivity at the cost of a corresponding increase in the size of the entrance pupil. At lower frequencies, where the atmosphere is more transparent, the required telescope size increases by a large factor (for example by a factor ~ 4 at ~ 40 GHz), entering in the realm of large and expensive telescope structures, including compact interferometric systems.

For all these reasons, CMB telescopes cannot easily be cooled at cryogenic temperatures to reduce their radiative background, unless they are operated in space (see below).

The control of telescope sidelobes is also extremely important. If ground pickup is not properly minimized, the nuisance signal coming from the earth emission in the far sidelobes can be comparable or larger than the CMB anisotropy signal. The detector will receive power from the boresight, pointed to the sky, but also from all the surrounding sources, weighted by the angular response R as follows:

$$W(\theta, \phi) = A \int_{4\pi} B(\theta', \phi') R(\theta - \theta', \phi - \phi') d\Omega \quad (7)$$

where $B(\theta, \phi)$ is the brightness from direction (θ, ϕ) .

Beyond the main beam (off-axis angles $\theta \gg \lambda/D$) the envelope of the angular response R for a circular aperture in diffraction limited conditions scales as θ^{-3} . For a ground based experiment, where the sky fills the main beam with solid angle $\Omega_M \ll 1$ sr and the emission from ground fills a large solid angle in the sidelobes $\Omega_S \sim 2\pi$ sr, the detected signal can be approximated as

$$W \simeq A [B_{sky} \langle R \rangle_M \Omega_M + B_{ground} \langle R \rangle_S \Omega_S] = A [I_M + I_S] \quad (8)$$

where $\langle \rangle_{M,S}$ represent the averages of the angular response R over the main lobe (where $\langle R \rangle_M \lesssim 1$) and over the sidelobes (where $\langle R \rangle_S \ll 1$). In the case of a 2.725K sky emission and of a 250K ground emission, for example, in order to have $I_S \ll I_M$ we need $\langle R \rangle_S \ll 4 \times 10^{-5}$ for a 10° FWHM experiment, and $\langle R \rangle_S \ll 1 \times 10^{-8}$ for a 10' FWHM experiment. Hence the necessity of additional shields surrounding the telescope, to increase the number of diffractions that radiation from the ground must undergo before reaching the detectors.

The situation is even worse in the case of anisotropy measurements, where the interesting signal is of a few μK . Here a differential instrument is needed, which helps in reducing the sidelobes contribution to the measured signal. The last resource is to send the instrument far from the earth, so that the solid angle occupied by ground emission is $\ll 2\pi$. This is the case for the WMAP and Planck space missions, devoted to CMB anisotropy and polarization measurements. They both operate from the Lagrange point L2 of the sun-earth system, where the solid angle occupied by the earth is only 2×10^{-4} sr. This relaxes the conditions on sidelobes rejection by a factor ~ 30000 with respect to ground-based or balloon-borne experiments.

The telescope and shields configurations are optimized using numerical methods (see e.g. www.ticra.com), normally based on the geometrical theory of diffraction¹⁰⁰ to speed-up the computations (see e.g.¹⁰¹).

To reduce the sidelobes, off-axis telescope designs are preferred, and complemented by extensive ground and sun shields (see e.g.^{85, 102–110}). In particular, compact test range telescope configurations offer wide focal planes (allowing the use of large format detector arrays, see below), with excellent cross-polarization quality (which is essential for CMB polarization studies) see e.g.^{111, 112}

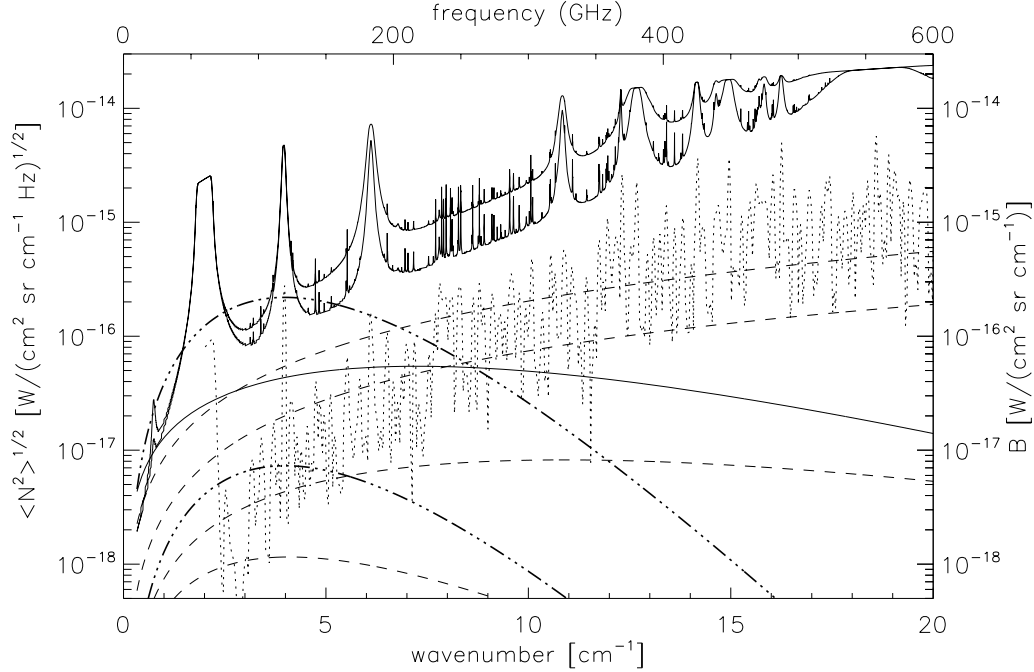


Figure 4. Photon noise from the natural radiative background and from the instrument (left scale) compared to CMB anisotropy and polarization signals (right scale). The two top continuous lines represent the noise due to quantum fluctuations of atmospheric emission, for 2 mm PWV and 0.5 mm PWV, typical of a high altitude ground based observatory. The dotted line is the noise due to quantum fluctuations of the emission from the residual atmosphere, at balloon (41 km) altitude. The lower thin continuous line is the photon noise of the CMB itself. The dashed lines represent the noise produced by a low-emissivity ($\epsilon = 5 \times 10^{-3}$) optical system at different temperatures (300K, 40K, 4K, 1.5K from top to bottom). The dot-dashed lines represent a typical CMB anisotropy brightness fluctuation (corresponding to $\Delta T_{CMB} = 90 \mu K$, higher line) and a typical CMB polarization fluctuation (corresponding to $\Delta T_{CMB} = 3 \mu K$, lower line).

The actual sidelobes pattern is usually measured with strong far-field sources (like a Gunn oscillator in the focus of a large telescope, producing a plane-wave to illuminate the telescope of the instrument). For space missions, where the operating environment can be very different from the laboratory conditions, the sidelobes are measured during the mission, using the Moon or the Sun (see e.g.¹¹³).

2.2 Sensitivity

The sensitivity of a detector measuring CMB anisotropy depends on detector performance (usually quantified by its intrinsic noise equivalent temperature, NET_i , in CMB temperature fluctuation units (μK_{CMB})) and on the noise of the incoming radiative background, NET_γ . The latter is computed following¹¹⁴ (but see also^{115,116}): it depends on the emission of the instrument itself (presence of warm lenses, mirrors, windows) and on the atmosphere above the operation site (the telescope can be ground-based, on a stratospheric balloon, or on a satellite). Operating above the earth atmosphere photon noise is reduced, and the instrument must be cooled cryogenically to exploit the optimal environmental conditions. In figure 4 we compare the photon noise from the natural radiative background and from the instrument to the signal to be detected, for several typical situations. Keep in mind that photon noise $\langle N^2 \rangle^{1/2}$ in figure 4 is given for unit optical bandwidth (1 cm^{-1}), unit electrical bandwidth (1 Hz, roughly corresponding to 1 s of integration), and for a throughput $A\Omega = 1 \text{ cm}^2 \text{ sr}$, and scales as the square root of these; moreover, in Rayleigh-Jeans conditions, it scales also as the square root of the emissivity ϵ .

From figure 4 it is evident that ground-based observations are limited to low frequencies ($\lesssim 40 \text{ GHz}$) and the W and D bands (note, however, that only quantum fluctuations have been plotted here, while turbulence,

winds, instabilities can increase atmospheric noise significantly). Balloon-borne telescopes can work with room-temperature telescopes, while to exploit the low radiative background of space the telescope should be cooled to at least 40K, and better below 4K if high frequency measurements are planned.

Quite recently mm-wave bolometers operated below 0.3K have achieved background limited conditions (i.e. $NET_i \lesssim NET_\gamma$). This is the case of the bolometers of the HFI instrument¹¹⁷ aboard of the Planck satellite, where the telescope is cooled radiatively to 40K.¹¹⁸ For these detectors $NEP_i \lesssim 10^{-17} W/\sqrt{Hz}$ (¹¹⁹), and a cold optical system is required, to exploit their excellent performance (compare this NEP_i to the photon noise in fig. 4, for a typical throughput $A\Omega \sim \lambda^2 \sim 0.05cm^2sr$).

2.3 Mapping Speed

Once background-limited conditions are reached, the only way to improve the performance of a CMB survey is to increase the number of detectors simultaneously scanning different directions, i.e. to produce large arrays of mm-wave detectors. This will boost the mapping speed of the experiment, by a factor of the order of the number of detectors in the focal plane. The need for large arrays required an important technology development to achieve fully automated production of a large number of pixels. This is very difficult to achieve in the case of coherent detectors, because of the cost and the power dissipation of each amplifier. In the case of bolometers and other incoherent detectors (like KIDs and CEBs, see below), it has been possible to devise pixel architectures which can be completely produced by photolithography and micromachining, with low cost and negligible power per pixel.

Bolometers are thermal detectors, absorbing radiation and sensing the resulting temperature increase. For a review of CMB bolometers development and operation see e.g.^{120,121} The development of fully lithographed arrays is the result of a long process started with the development of the so-called spider-web bolometer,¹²² followed by the polarization sensitive bolometer (PSB).¹²³ Several of these devices were arranged on the same wafer.¹²⁴ Then voltage-biased Transition Edge superconducting Sensors (TES) were developed (see e.g.¹²⁵⁻¹²⁹ and integrated on the array wafer (see e.g.¹³⁰⁻¹³⁷). In parallel to the development of the TES bolometers, a large effort has been spent in the development of the readout electronics, which uses SQUIDs to read and multiplex a large number of detectors with a limited number of wires, thus maintaining the heat load on the cryostat at manageable levels.^{138,139} These detectors have been installed at large CMB telescopes (ACT, SPT, APEX ...) with excellent performance, providing high resolution CMB measurements. Antenna coupling to the radiation, dual polarization sensitivity, and even spectral filtering are now also integrated in the TES wafers (see e.g.¹⁴⁰⁻¹⁴⁶), producing powerful imaging/polarimetry/spectrometry capabilities in a lightweight block.

In addition to TESs, the quest for large mm-wave cameras for CMB research drove the development of other non-coherent detection technologies.

In the MKIDs (microwave kinetic inductance detectors) low energy photons (like CMB photons, in the meV range) break Cooper pairs in a superconducting film, changing its surface impedance, and in particular the kinetic inductance L_k . The change is small, but can be measured using the film as the inductor in a superconducting resonator, which can have very high merit factor Q , up to $\simeq 10^6$, and thus be very sensitive to the variations of its components. Many independent MKIDs are arranged in an array, and shunt the same line, where a comb of frequencies fitting the resonances of the pixels is carried. CMB photons absorbed by a given pixel produce a change in the transmission of a single frequency of the comb. So MKIDs are intrinsically multiplexable, requiring only two shielded cables to supply and read hundreds of pixels. The initial KID concept,¹⁴⁷ where mm-wave photons are antenna coupled to the resonator, has evolved in the LEKID (Lumped Elements Kinetic Inductance Detector) concept,^{148,149} where the resonator is shaped as an efficient absorber of mm-waves analogous to bolometer absorbers. The great advantage of MKIDs with respect to TES is that the fabrication process is significantly simpler, and also the readout electronics requires only a wide-band amplifier cryogenically cooled. Today, MKID arrays are produced in many laboratories (see e.g.¹⁵⁰⁻¹⁵²) and are starting to be operated at large telescopes (see e.g.^{153,154}).

In a Cold Electron Bolometer (CEB)¹⁵⁵ the signal power collected by an antenna is capacitively coupled to a tunnel-junction (SIN) sensor and is dissipated in the electrons which act as a nanoabsorber; it is also removed from the absorber in the form of hot electrons by the same SIN junctions. This electron cooling provides

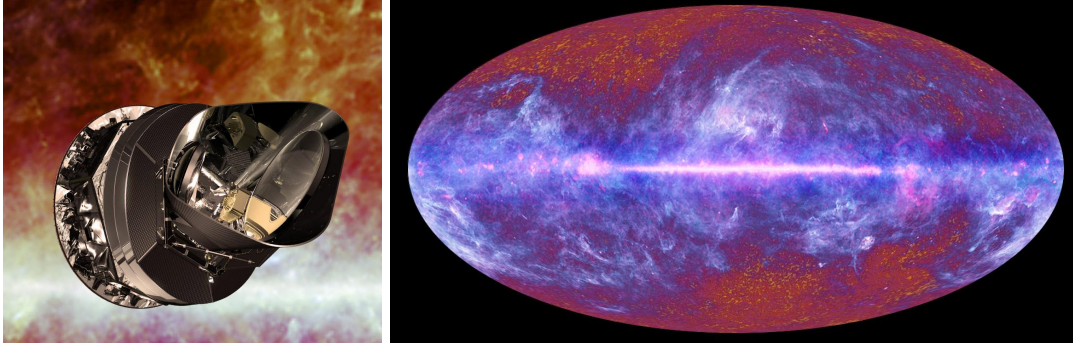


Figure 5. **Left:** The Planck satellite, scanning the sky in the mm/submm from the Lagrangian point L2 of the sun-earth system. **Right:** Map of the sky in Galactic coordinates, obtained from the full sky surveys of Planck at nine frequencies. The maps have been linearly combined in two ways: the red-yellow palette evident at high galactic latitudes is the combination maximizing CMB signals. Here the horizon-sized spots are ubiquitous and dominant at high galactic latitudes. The blue-white palette is the combination maximizing the local foreground. The power of wide frequency coverage is evident: from this map it is possible to monitor the faintest interstellar clouds at high galactic latitudes. Figure credit: European Space Agency.

strong negative electrothermal feedback, improving the time-constant, the responsivity and the NEP.¹⁵⁶ Since the thermistor is the gas of electrons, confined in a ~ 100 nm junction and thermally insulated from the rest of the sensor, these detectors should be quite immune to cosmic-rays hits, an important nuisance for TES and KIDs in space. Moreover, these detectors promise very good performance in a wide range of radiative backgrounds, while efficient multiplexing schemes are still to be developed.

3. CURRENT TRENDS IN CMB RESEARCH

We have entered the era of precision observations of the CMB.

Planck¹⁵⁷ has produced a shallow survey of the whole sky in nine mm - submm bands (centered at 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz). Taking advantage of the wide frequency coverage and of the extreme sensitivity of the measurements, it is possible to separate efficiently the different contributions to the brightness of the sky along each line of sight (see figure 5).

While it is evident from fig.5 that foreground emission can be important even at high galactic latitudes, it is also clear that the multifrequency survey of Planck allows to detect and remove tiny contaminations from thin interstellar clouds. With the foregrounds under control, Planck is expected to produce very precise measurements of CMB anisotropy and polarization in the next data release, early in 2013.

High-resolution anisotropy measurements are now performed mainly in the direction of clusters of galaxies (SZ effect) and to search for non-Gaussianity of the CMB. High sensitivity polarization measurements aim at measuring B-modes from inflation and from lensing of E-modes. We will outline here a few, selected issues that we consider relevant for the continuation of these studies.

3.1 Sunyaev-Zeldovich Effect and spectral anisotropy measurements

The Sunyaev-Zeldovich (SZ) effect¹⁵⁸ is the energization of CMB photons crossing clusters of galaxies, due to the inverse Compton effect with the hot intergalactic plasma. The order of magnitude of the effect can be estimated noticing that the optical depth for a rich cluster is $\tau \sim n_e \sigma_T \ell \lesssim 0.01$ and the fractional energy gain of each interacting photon is of the order of $kT_e/m_e c^2 \sim 0.01$, so the fractional CMB temperature change will be $\Delta T/T \sim \tau kT_e/m_e c^2 \lesssim 10^{-4}$: a large signal if compared to the primordial CMB anisotropy. The SZ effect is thus a powerful tool for studying the physics of clusters and using them as cosmological probes (see e.g.¹⁵⁹⁻¹⁶¹). Large mm-wave telescopes (^{109,110,136}), coupled to imaging multi-band arrays of bolometers, are now operating in excellent sites and produce a number of detections and maps of the SZ effect in selected sky areas, discovering new clusters, and establishing cluster and cosmological parameters.

From the Planck data an early catalogue of massive clusters detected via the SZ effect has been extracted.¹⁶² This consists of 169 known clusters, plus 20 new discoveries, including exceptional members.¹⁶³ All these measurements take advantage of the extreme sensitivity of bolometers, with their excellent performance in the frequency range 90-600 GHz where the spectral signatures of the SZ effect lie.

Several components contribute to the signal detected from the line of sight crossing the cluster: a thermal component due to the inverse Compton effect; a Doppler component, caused by the collective motion of the cluster with respect to the CMB restframe; a non-thermal component caused by a non-thermal population of electrons, produced by e.g. the AGNs present in the cluster, relativistic plasma in cluster cavities, shock acceleration; the intrinsic anisotropy of the CMB; the emission of dust, free-free and synchrotron in our Galaxy and in the galaxies of the cluster. Since the spectrum of thermal SZ significantly departs from the spectra of the foreground and background components, multi-frequency SZ measurements allow the estimation of several physical parameters of the cluster, provided there are more observation bands than parameters to be determined, or some of the contributions are known to be negligible. In¹⁶⁴ we have analyzed how different experimental configurations perform in this particular components separation exercise. Ground-based few-band photometers cannot provide enough information to separate all physical components, because atmospheric noise limits the number of useful independent bands. These instruments need external information (optical, X-ray, far-IR, etc.) to produce mainly measurements of the optical depth of the thermal SZ (see e.g.¹⁶⁵⁻¹⁷²).

Future space-based spectrometers can cover the full range of interesting frequencies and offer much more information. A cryogenic differential imaging Fourier Transform Spectrometer (FTS) in the focal plane of a space mission with a cold telescope, like Millimetron,¹⁷³ would be a powerful experiment, measuring accurately all the parameters of a cluster. The FIRAS experiment has demonstrated the power of these large-throughput, wide frequency coverage instruments, which are intrinsically differential. In that case one of the two input ports collected radiation from the sky, while the other port was illuminated by an internal blackbody: the perfect nulling of the measured difference spectrum demonstrated accurately the blackbody nature of the cosmic microwave background. In this implementation, the two input ports of the instrument collect radiation from two contiguous regions of the focal plane of the same telescope (see left panel of fig.6). In this way only the anisotropic component of the brightness distribution produces a measurable signal, while the common-mode signals from the instrument, the telescope, and the CMB itself are efficiently rejected. The FTS is sensitive to a wide frequency band (say 70 - 1000 GHz for SZ studies), so photon noise is the limiting factor. In fig.6 we compare what can be achieved with a warm system on a stratospheric balloon¹⁷⁴⁻¹⁷⁶ (center panel) to what can be ultimately achieved with a cold system in deep space¹⁶⁴ (right panel). In both cases important improvements with respect to the state-of-the-art determination of cluster parameters are expected. The intermediate case of a cold spectrometer coupled to a warm telescope in a Molniya orbit has been studied in¹⁷⁷.

Other important scientific targets of these instruments are the measurement of the C^+ and CO lines, in the redshift desert and beyond, for a large number of galaxies, and spectral observations of a number of processes in the early universe and in the recombination and reionization eras (see e.g.^{177, 179-183}).

3.2 B-modes of CMB polarization

Measuring the tiny B-modes signal is a formidable experimental challenge. For this reason it is very important that independent teams develop advanced experiments, using different techniques and methods. Only independent consistent detections will provide convincing evidence for the existence of B-modes.

The mainstream in this field is the use of large arrays of single-mode bolometric polarimeters, using a polarization modulator in the optical path (as close as possible to the input port of the instrument, to avoid modulating instrumental polarization) to modulate only the polarized part of the incoming signal. The throughput of the telescope has to be very large, of the order of $\sum_{i=1}^n N_i \lambda_i^2 / F_i$, where the number of detectors N_i in each band i is of the order of 10^3 , and the filling factor of the focal plane is $F_i \lesssim 1$.

The removal of the polarized foreground (mainly produced by the interstellar medium) is a matter of the utmost importance. It has been analyzed in great detail, most recently in the framework of the Planck mission (see e.g.¹⁸⁴⁻¹⁸⁶ and references therein) and of future missions devoted to CMB polarization (see e.g.¹⁸⁷). The solution is to carry out surveys with wide frequency coverage, from tens of GHz (to survey strongly polarized

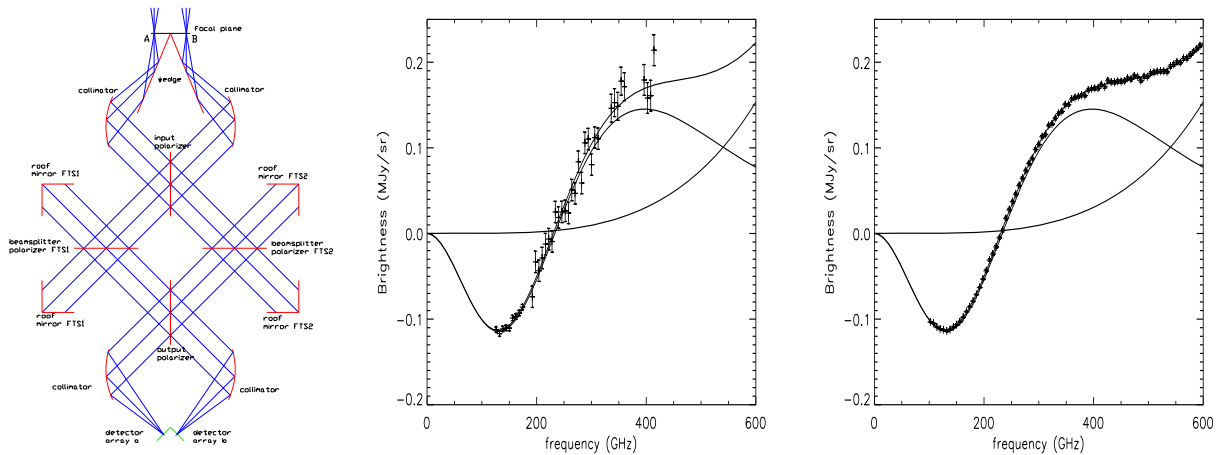


Figure 6. **Left** : Block-diagram of a differential FTS. This very symmetrical configuration reduces instrumental offsets and doubles the efficiency with respect to the standard MPI FTS.¹⁷⁸ **Center** : Simulated observations of a rich cluster of galaxies with a warm differential FTS aboard of a stratospheric balloon, like OLIMPO. **Right** : Same for a differential FTS aboard of a satellite in L2, with a large (10m) cold (4K) telescope, like Millimetron. In both cases, 3 hours of observation are assumed, and bolometer performance limited only by the radiative background. The two continuous lines represent the SZ effect from the plasma in the cluster and differential emission of interstellar dust, the two main components of the measured brightness.

synchrotron emission) to several hundreds of GHz (to survey polarized emission from interstellar dust). For this reason a number of bands $n \sim 10$ is required to separate the foreground components from the primordial CMB signal. Accommodating all the bands in the focal plane of the telescope exacerbates the large throughput problem for these systems, also because only the center region of the focal plane has optimal polarization efficiency and beam-symmetry properties. Multichroic pixels including bolometric detectors in 3 or more bands under the same microlens have been developed,¹⁴⁶ allowing a very efficient use of focal plane space. This approach has been proposed for the LiteBIRD satellite.¹⁸⁸

In the case of incoherent detectors, intrinsically insensitive to the polarization status of the incoming power, the classic Stokes polarimeter requires a half-wave plate retarder plus a polarizer. If the HWP is rotated with a rotation rate θ , the linearly polarized part of the incoming signal is modulated at 4θ , while the unpolarized and the circular polarization components are not modulated. Wide-band retarders can be obtained in transmission using a sandwich of birefringent crystals (see e.g.^{189–193}) or suitable meta-materials assembled with metal meshes.¹⁹⁴ In reflection, a rotation mirror / polarizer combination¹⁹⁵ can be used, or a translating polarizer / mirror assembly (Variable Delay Modulator¹⁹⁶), or a translating circular polarizer / mirror combination (Transational Polarization Rotator¹⁹⁷). The main issues with these modulators is the equalization of the transmission (reflection) for the two orthogonal polarizations (any mismatch, even at a level of 1%, will produce a comparatively very large 2θ signal) and the need to cool at cryogenic temperatures the modulator, to reduce its (polarized) emission (see¹⁹⁸ for a discussion).

Reaching satisfactory performance over a wide frequency band and a wide throughput is problematic. In the case of the dielectric HWP, a sandwich of differently oriented plates is required, following the Pancharatman¹⁹⁹ recipe. This approach is suitable for accurate measurements of CMB polarization in the range 120-450 GHz.²⁰⁰ However, it is currently impossible to obtain large-diameter ($\gtrsim 30\text{cm}$) slabs of sapphire (or any other birefringent crystal suitable for mm wavelengths), so their use is limited to medium throughput systems. Using metal meshes might solve the problem, but requires a careful equalization of the conductivity of the meshes. In the case of the mirror/polarizer combination, which can be produced in very large sizes, the operative band is restricted to $\sim 20\%$ of the center frequency. It is possible, however, to operate the modulator at multiples of a fundamental frequency, with decreasing fractional bandwidth, as proposed in.²⁰¹

A Martin-Puplett Fourier Transform Spectrometer,¹⁷⁸ with the two input ports *A* and *B* (fig.6) co-aligned to look at the same sky patch, becomes a polarimeter. In fact, it produces at the two output ports *a* and *b*, with

polarization x and y , the following 4 signals, which can be detected by 4 independent detectors: $[I_{a,x}(z) - \langle I_{a,x} \rangle] \propto \int (E_{B,x}^2(\sigma) - E_{A,y}^2(\sigma)) \cos(4\pi\sigma z) d\sigma$; $[I_{a,y}(z) - \langle I_{a,y} \rangle] \propto \int (E_{B,y}^2(\sigma) - E_{A,x}^2(\sigma)) \cos(4\pi\sigma z) d\sigma$; $[I_{b,x}(z) - \langle I_{b,x} \rangle] \propto \int (E_{A,x}^2(\sigma) - E_{B,y}^2(\sigma)) \cos(4\pi\sigma z) d\sigma$; $[I_{b,y}(z) - \langle I_{b,y} \rangle] \propto \int (E_{A,y}^2(\sigma) - E_{B,x}^2(\sigma)) \cos(4\pi\sigma z) d\sigma$, where σ is the wavenumber and z is the position of the moving mirror. Summing and subtracting the Fourier-transformed signals from detectors couples it is possible to estimate the *frequency spectra* of the Stokes parameters of the incoming radiation. This is the principle of operation of the proposed PIXIE experiment,¹⁸² a space-based large-throughput spectro-polarimeter covering the frequency range 30-6000 GHz. The optical axis of the spectro-polarimeter is aligned to the spin axis of the satellite, so that any polarization signal becomes spin-synchronous. In this configuration, the specifications for beam ellipticity, and beam, gain and polarization mismatch for the four detectors are very stringent. These could be relaxed with the use of a rotating achromatic HWP at the entrance of the system, but it is currently impossible to fabricate a high-efficiency highly-balanced HWP over such a wide frequency range.

There is a long list of potential systematic effects in Stokes polarimeters (see e.g.²⁰²), and the requirements for a clean detection of B-modes are extremely stringent (see e.g. table 6.1 in²⁰³). A few examples: tens of mK signals at $2\dot{\theta}$ are produced by the unpolarized 2.7K background, modulated by $\sim 1\%$ efficiency mismatch between the ordinary and extraordinary rays in the waveplate. The emission of a mismatched HWP also produces tens of mK signals at $2\dot{\theta}$, unless its temperature is below 2K. These signals challenge the dynamic range of the detector, which is optimized for measuring CMB polarization signals $\sim 10^4$ times smaller. Any non-linearity in the detector can convert part of this $2\dot{\theta}$ signal into a $4\dot{\theta}$ signal, producing a large offset in the polarization measurement. If part of the emission of the polarizer is reflected back by the waveplate, it is modulated at $4\dot{\theta}$, contributing with additional \sim few μK signals to the offset. A possible solution to this problem is the step and integrate strategy (see e.g.²⁰⁴). At variance with the continuous rotation strategy, here the HWP is kept steady during sky scans, and angular steps are performed at the turnarounds. All the systematic effects generated internally to the instrument produce a constant offset during each scan, which can be removed, while the sky polarization is modulated at the (very low) frequency of the repetition of the scans. In addition to these effect, other noticeable sources of systematic problems are the ellipticity of the main beam ($< 10^{-4}$), the level of its polarized sidelobes ($< 10^{-6}$), the instrumental polarization ($< 10^{-4}$), the relative gain calibration ($< 10^{-5}$): all these convert unpolarized brightness fluctuations into apparent B-modes signals; an error in the main polarimeter axis angle ($< 0.2^\circ$) and the cross-polar response ($< 3 \times 10^{-3}$) convert E-modes into apparent B-modes; moreover, the relative pointing of differenced observation directions must be < 0.1 arcsec to avoid conversion of brightness fluctuations into apparent B-mode signals. Pathfinder experiments are the best way to find and test the best mitigation methods for all these subtle systematic effects. Current attempts exploit different techniques, ranging from ground-based coherent polarimeters, like QUIET,⁹² to ground-based bolometer arrays with HWP, like POLARBEAR,²⁰⁵ to ground-based bolometric interferometers, like QUBIC,²⁰⁶ to stratospheric balloons like SPIDER,²⁰⁷ EBEX,²⁰⁸ and LSPE.²⁰⁹ Using completely independent techniques, these experiments provide a powerful test set for any detection of B-modes in the CMB, in view of a post-Planck next generation space mission for the CMB.

4. CONCLUSIONS

The future of CMB studies is bright. A large community has grown around the success of CMB missions, producing large amounts of excellent data. The experiments have drifted from a situation where sensitivity was the issue to a situation where control of systematic effects is the main problem. So we are facing very difficult challenges, with the ambition of understanding the most distant phenomena happening in our universe, analyzing tiny signals embedded in an overwhelming noisy background. When we approached CMB research for the first time, in 1980, measuring the intrinsic anisotropy of the CMB was considered almost science-fiction. Today CMB anisotropy is measured in a single pass with scanning telescopes using large arrays of bolometers. This experience makes us confident that much more is coming in this field, with the enthusiastic contribution of young researchers and the cross-fertilization between cosmologists, astrophysicists, solid-state / detector physicists, optics experts.

ACKNOWLEDGMENTS

This work has been supported by the Italian Space Agency contract I/043/11/0 "A differential spectrometer for Millimetron - phase A" and I/022/11/0 "Large Scale Polarization Explorer", and by the Italian MIUR PRIN-2009 project "mm and sub-mm spectroscopy for high resolution studies of primeval galaxies and clusters of galaxies". We thank dr. Luca Pagano for assembling the collection of CMB measurements in fig.1 and fig.3.

REFERENCES

- [1] Mather, J. C., Fixsen, D. J., and Shafer, R. A., e. a., "Calibrator Design for the COBE Far-Infrared Absolute Spectrophotometer (FIRAS)," *The Astrophysical Journal* **512**, 511–520 (Feb. 1999).
- [2] Padmanabhan, T., [*Structure Formation in the Universe*] (June 1993).
- [3] White, M., Krauss, L. M., and Silk, J., "Cosmic Variance in Cosmic Microwave Background Anisotropies: From 1 degrees to COBE," *The Astrophysical Journal* **418**, 535 (Dec. 1993).
- [4] Sachs, R. K. and Wolfe, A. M., "Perturbations of a Cosmological Model and Angular Variations of the Microwave Background," *The Astrophysical Journal* **147**, 73 (Jan. 1967).
- [5] Sunyaev, R. A. and Zeldovich, Y. B., "Small-Scale Fluctuations of Relic Radiation," *Astrophysics and Space Science* **7**, 3–19 (Apr. 1970).
- [6] Peebles, P. J. E. and Yu, J. T., "Primeval Adiabatic Perturbation in an Expanding Universe," *The Astrophysical Journal* **162**, 815 (Dec. 1970).
- [7] Hu, W. and White, M., "Acoustic Signatures in the Cosmic Microwave Background," *The Astrophysical Journal* **471**, 30 (Nov. 1996).
- [8] Hu, W. and White, M., "The Damping Tail of Cosmic Microwave Background Anisotropies," *The Astrophysical Journal* **479**, 568 (Apr. 1997).
- [9] Hu, W. and Dodelson, S., "Cosmic Microwave Background Anisotropies," *Annual Review of Astronomy and Astrophysics* **40**, 171–216 (2002).
- [10] Lewis, A., Challinor, A., and Lasenby, A., "Efficient Computation of Cosmic Microwave Background Anisotropies in Closed Friedmann-Robertson-Walker Models," *The Astrophysical Journal* **538**, 473–476 (Aug. 2000).
- [11] de Bernardis, P., Ade, P. A. R., and Bock, J. J. e. a., "A flat Universe from high-resolution maps of the cosmic microwave background radiation," *Nature* **404**, 955–959 (Apr. 2000).
- [12] Bennett, C. L., Hill, R. S., and Hinshaw, G. e. a., "First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Foreground Emission," *The Astrophysical Journal Supplements* **148**, 97–117 (Sept. 2003).
- [13] Larson, D., Dunkley, J., and Hinshaw, G. e. a., "Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Power Spectra and WMAP-derived Parameters," *The Astrophysical Journal Supplements* **192**, 16 (Feb. 2011).
- [14] Wright, E. L., Mather, J. C., and Bennett, C. L. e. a., "Preliminary spectral observations of the Galaxy with a 7 deg beam by the Cosmic Background Explorer (COBE)," *The Astrophysical Journal* **381**, 200–209 (Nov. 1991).
- [15] Lee, A. T., Ade, P., and Balbi, A. e. a., "A High Spatial Resolution Analysis of the MAXIMA-1 Cosmic Microwave Background Anisotropy Data," *The Astrophysical Journal Letters* **561**, L1–L5 (Nov. 2001).
- [16] de Bernardis, P., Ade, P. A. R., and Bock, J. J. e. a., "Multiple Peaks in the Angular Power Spectrum of the Cosmic Microwave Background: Significance and Consequences for Cosmology," *The Astrophysical Journal* **564**, 559–566 (Jan. 2002).
- [17] Halverson, N. W., Leitch, E. M., and Pryke, C. e. a., "Degree Angular Scale Interferometer First Results: A Measurement of the Cosmic Microwave Background Angular Power Spectrum," *The Astrophysical Journal* **568**, 38–45 (Mar. 2002).
- [18] Ruhl, J. E., Ade, P. A. R., and Bock, J. J. e. a., "Improved Measurement of the Angular Power Spectrum of Temperature Anisotropy in the Cosmic Microwave Background from Two New Analyses of BOOMERANG Observations," *The Astrophysical Journal* **599**, 786–805 (Dec. 2003).

- [19] Grainge, K., Carreira, P., and Cleary, K. e. a., “The cosmic microwave background power spectrum out to $l=1400$ measured by the Very Small Array,” *Monthly Notices of the Royal Astronomical Society* **341**, L23–L28 (June 2003).
- [20] Jones, W. C., Ade, P. A. R., and Bock, J. J. e. a., “A Measurement of the Angular Power Spectrum of the CMB Temperature Anisotropy from the 2003 Flight of BOOMERANG,” *The Astrophysical Journal* **647**, 823–832 (Aug. 2006).
- [21] Kuo, C. L., Ade, P. A. R., and Bock, J. J. e. a., “Improved Measurements of the CMB Power Spectrum with ACBAR,” *The Astrophysical Journal* **664**, 687–701 (Aug. 2007).
- [22] Hinshaw, G., Spergel, D. N., and Verde, L. e. a., “First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: The Angular Power Spectrum,” *The Astrophysical Journal Supplements* **148**, 135–159 (Sept. 2003).
- [23] Hinshaw, G., Nolta, M. R., and Bennett, C. L. e. a., “Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Temperature Analysis,” *The Astrophysical Journal Supplements* **170**, 288–334 (June 2007).
- [24] Nolta, M. R., Dunkley, J., and Hill, R. S. e. a., “Five-Year Wilkinson Microwave Anisotropy Probe Observations: Angular Power Spectra,” *The Astrophysical Journal Supplements* **180**, 296–305 (Feb. 2009).
- [25] Reichardt, C. L., Ade, P. A. R., and Bock, J. J. e. a., “High-Resolution CMB Power Spectrum from the Complete ACBAR Data Set,” *The Astrophysical Journal* **694**, 1200–1219 (Apr. 2009).
- [26] Fowler, J. W., Acquaviva, V., and Ade, P. A. R. e. a., “The Atacama Cosmology Telescope: A Measurement of the $600 < l < 8000$ Cosmic Microwave Background Power Spectrum at 148 GHz,” *The Astrophysical Journal* **722**, 1148–1161 (Oct. 2010).
- [27] Das, S., Marriage, T. A., and Ade, P. A. R. e. a., “The Atacama Cosmology Telescope: A Measurement of the Cosmic Microwave Background Power Spectrum at 148 and 218 GHz from the 2008 Southern Survey,” *The Astrophysical Journal* **729**, 62 (Mar. 2011).
- [28] Das, S., Sherwin, B. D., and Aguirre, P. e. a., “Detection of the Power Spectrum of Cosmic Microwave Background Lensing by the Atacama Cosmology Telescope,” *Physical Review Letters* **107**, 021301 (July 2011).
- [29] de Bernardis, P., de Gasperis, G., and Masi, S. e. a., “Detection of cosmic microwave background anisotropy at 1.8 deg: Theoretical implications on inflationary models,” *The Astrophysical Journal Letters* **433**, L1–L4 (Sept. 1994).
- [30] Bond, J. R., Jaffe, A. H., and Knox, L., “Estimating the power spectrum of the cosmic microwave background,” *Physical Review D* **57**, 2117–2137 (Feb. 1998).
- [31] Bond, J. R., Jaffe, A. H., and Knox, L., “Radical Compression of Cosmic Microwave Background Data,” *The Astrophysical Journal* **533**, 19–37 (Apr. 2000).
- [32] Dodelson, S. and Knox, L., “Dark Energy and the Cosmic Microwave Background Radiation,” *Physical Review Letters* **84**, 3523–3526 (Apr. 2000).
- [33] Tegmark, M. and Zaldarriaga, M., “Current Cosmological Constraints from a 10 Parameter Cosmic Microwave Background Analysis,” *The Astrophysical Journal* **544**, 30–42 (Nov. 2000).
- [34] Tegmark, M. and Zaldarriaga, M., “New Microwave Background Constraints on the Cosmic Matter Budget: Trouble for Nucleosynthesis?,” *Physical Review Letters* **85**, 2240–2243 (Sept. 2000).
- [35] Bridle, S. L., Zehavi, I., and Dekel, A. e. a., “Cosmological parameters from velocities, cosmic microwave background and supernovae,” *Monthly Notices of the Royal Astronomical Society* **321**, 333–340 (Feb. 2001).
- [36] Douspis, M., Bartlett, J. G., and Blanchard, A. e. a., “Concerning parameter estimation using the cosmic microwave background,” *Astronomy and Astrophysics* **368**, 1–14 (Mar. 2001).
- [37] Lange, A. E., Ade, P. A., and Bock, J. J. e. a., “Cosmological parameters from the first results of Boomerang,” *Physical Review D* **63**, 042001 (Feb. 2001).
- [38] Jaffe, A. H., Ade, P. A., and Balbi, A. e. a., “Cosmology from MAXIMA-1, BOOMERANG, and COBE DMR Cosmic Microwave Background Observations,” *Physical Review Letters* **86**, 3475–3479 (Apr. 2001).
- [39] Lewis, A. and Bridle, S., “Cosmological parameters from CMB and other data: A Monte Carlo approach,” *Physical Review D* **66**, 103511 (Nov. 2002).

- [40] Netterfield, C. B., Ade, P. A. R., and Bock, J. J. e. a., “A Measurement by BOOMERANG of Multiple Peaks in the Angular Power Spectrum of the Cosmic Microwave Background,” *The Astrophysical Journal* **571**, 604–614 (June 2002).
- [41] Spergel, D. N., Verde, L., and Peiris, H. V. e. a., “First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters,” *The Astrophysical Journal Supplements* **148**, 175–194 (Sept. 2003).
- [42] Tegmark, M., Strauss, M. A., and Blanton, M. R. e. a., “Cosmological parameters from SDSS and WMAP,” *Physical Review D* **69**, 103501 (May 2004).
- [43] Spergel, D. N., Bean, R., and Doré, e. a., “Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology,” *The Astrophysical Journal Supplements* **170**, 377–408 (June 2007).
- [44] Komatsu, E., Dunkley, J., and Nolta, M. R. e. a., “Five-Year Wilkinson Microwave Anisotropy Probe Observations: Cosmological Interpretation,” *The Astrophysical Journal Supplements* **180**, 330–376 (Feb. 2009).
- [45] Komatsu, E., Smith, K. M., and Dunkley, J. e. a., “Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation,” *The Astrophysical Journal Supplements* **192**, 18 (Feb. 2011).
- [46] Rees, M. J., “Polarization and Spectrum of the Primeval Radiation in an Anisotropic Universe,” *The Astrophysical Journal Letters* **153**, L1 (July 1968).
- [47] Kaiser, N., “Small-angle anisotropy of the microwave background radiation in the adiabatic theory,” *Monthly Notices of the Royal Astronomical Society* **202**, 1169–1180 (Mar. 1983).
- [48] Hu, W. and White, M., “A CMB polarization primer,” *New Astronomy* **2**, 323–344 (Oct. 1997).
- [49] Kamionkowski, M., Kosowsky, A., and Stebbins, A., “Statistics of cosmic microwave background polarization,” *Physical Review D* **55**, 7368–7388 (June 1997).
- [50] Seljak, U., Pen, U.-L., and Turok, N., “Polarization of the Microwave Background in Defect Models,” *Physical Review Letters* **79**, 1615–1618 (Sept. 1997).
- [51] Mukhanov, V. F. and Chibisov, G. V., “Quantum fluctuations and a nonsingular universe,” *ZhETF Pis'ma Redaktsiiu* **33**, 549–553 (May 1981).
- [52] Guth, A. H. and Pi, S.-Y., “Fluctuations in the new inflationary universe,” *Physical Review Letters* **49**, 1110–1113 (Oct. 1982).
- [53] Linde, A. D., “Chaotic inflation,” *Physics Letters B* **129**, 177–181 (Sept. 1983).
- [54] Kolb, E. W. and Turner, M. S., [*The early universe.*] (1990).
- [55] Copeland, E. J., Kolb, E. W., and Liddle, A. R. e. a., “Observing the inflation potential,” *Physical Review Letters* **71**, 219–222 (July 1993).
- [56] Turner, M. S., “Recovering the inflationary potential,” *Physical Review D* **48**, 5539–5545 (Dec. 1993).
- [57] Steinhardt, P. J. and Turok, N., “A Cyclic Model of the Universe,” *Science* **296**, 1436–1439 (May 2002).
- [58] Boyle, L. A., Steinhardt, P. J., and Turok, N., “New duality relating density perturbations in expanding and contracting Friedmann cosmologies,” *Physical Review D* **70**, 023504 (July 2004).
- [59] Liddle, A. R., “The inflationary energy scale,” *Physical Review D* **49**, 739–747 (Jan. 1994).
- [60] Caderni, N., Fabbri, R., and Melchiorri, B. e. a., “Polarization of the microwave background radiation. II. An infrared survey of the sky,” *Physical Review D* **17**, 1908–1918 (Apr. 1978).
- [61] Nanos, Jr., G. P., “Polarization of the blackbody radiation at 3.2 centimeters,” *The Astrophysical Journal* **232**, 341–347 (Sept. 1979).
- [62] Lubin, P. M. and Smoot, G. F., “Polarization of the cosmic background radiation,” *The Astrophysical Journal* **245**, 1–17 (Apr. 1981).
- [63] Masi, S., “Search for the Cosmic Background Polarization,” in [*Gamow Cosmology*], 310 (1986).
- [64] Partridge, R. B., Nowakowski, J., and Martin, H. M., “Linear polarized fluctuations in the cosmic microwave background,” *Nature* **331**, 146 (Jan. 1988).
- [65] Wollack, E. J., Devlin, M. J., and Jarosik, N. e. a., “An Instrument for Investigation of the Cosmic Microwave Background Radiation at Intermediate Angular Scales,” *The Astrophysical Journal* **476**, 440 (Feb. 1997).

- [66] Keating, B. G., O'Dell, C. W., and de Oliveira-Costa, A. e. a., "A Limit on the Large Angular Scale Polarization of the Cosmic Microwave Background," *The Astrophysical Journal Letters* **560**, L1–L4 (Oct. 2001).
- [67] Subrahmanyam, R., Kesteven, M. J., and Ekers, R. D. e. a., "An Australia Telescope survey for CMB anisotropies," *Monthly Notices of the Royal Astronomical Society* **315**, 808–822 (July 2000).
- [68] Hedman, M. M., Barkats, D., and Gundersen, J. O. e. a., "New Limits on the Polarized Anisotropy of the Cosmic Microwave Background at Subdegree Angular Scales," *The Astrophysical Journal Letters* **573**, L73–L76 (July 2002).
- [69] Piccirillo, L., Ade, P. A. R., and Bock, J. J., e. a., "QUEST-A 2.6-m mm-wave telescope for CMB polarization studies," in [*Astrophysical Polarized Backgrounds*], Cecchini, S., Cortiglioni, S., Sault, R., and Sbarra, C., eds., *American Institute of Physics Conference Series* **609**, 159–163 (Mar. 2002).
- [70] Delabrouille, J. and Kaplan, J., "Measuring CMB polarization with the Planck HFI," in [*Astrophysical Polarized Backgrounds*], Cecchini, S., Cortiglioni, S., Sault, R., and Sbarra, C., eds., *American Institute of Physics Conference Series* **609**, 135–143 (Mar. 2002).
- [71] Masi, S., de Bernardis, P., and de Troia, G. e. a., "Scanning polarimeters for measurements of CMB polarization," in [*Experimental Cosmology at Millimetre Wavelengths*], de Petris, M. and Gervasi, M., eds., *American Institute of Physics Conference Series* **616**, 168–174 (May 2002).
- [72] Villa, F., Mandolesi, N., and Bersanelli, M. e. a., "The low frequency instrument of the Planck mission," in [*Astrophysical Polarized Backgrounds*], Cecchini, S., Cortiglioni, S., Sault, R., and Sbarra, C., eds., *American Institute of Physics Conference Series* **609**, 144–149 (Mar. 2002).
- [73] Kovac, J. M., Leitch, E. M., and Pryke, C. e. a., "Detection of polarization in the cosmic microwave background using DASI," *Nature* **420**, 772–787 (Dec. 2002).
- [74] Johnson, B. R., Abroe, M. E., and Ade, P. e. a., "MAXIPOL: a balloon-borne experiment for measuring the polarization anisotropy of the cosmic microwave background radiation," *New Astronomy Reviews* **47**, 1067–1075 (Dec. 2003).
- [75] Keating, B. G., Ade, P. A. R., and Bock, J. J. e. a., "BICEP: a large angular scale CMB polarimeter," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], Fineschi, S., ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4843**, 284–295 (Feb. 2003).
- [76] Keating, B. G., O'Dell, C. W., and Gundersen, J. O. e. a., "An Instrument for Investigating the Large Angular Scale Polarization of the Cosmic Microwave Background," *The Astrophysical Journal Supplements* **144**, 1–20 (Jan. 2003).
- [77] Kogut, A., Spergel, D. N., and Barnes, C. e. a., "First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Temperature-Polarization Correlation," *The Astrophysical Journal Supplements* **148**, 161–173 (Sept. 2003).
- [78] Farese, P. C., Dall'Oglio, G., and Gundersen, e. a., "COMPASS: An Upper Limit on Cosmic Microwave Background Polarization at an Angular Scale of 20'," *The Astrophysical Journal* **610**, 625–634 (Aug. 2004).
- [79] Cortiglioni, S., Bernardi, G., and Carretti, E. e. a., "The Sky Polarization Observatory," *New Astronomy* **9**, 297–327 (May 2004).
- [80] Cartwright, J. K., Pearson, T. J., and Readhead, A. C. S. e. a., "Limits on the Polarization of the Cosmic Microwave Background Radiation at Multipoles up to $l \sim 2000$," *The Astrophysical Journal* **623**, 11–16 (Apr. 2005).
- [81] Leitch, E. M., Kovac, J. M., and Halverson, N. W. e. a., "Degree Angular Scale Interferometer 3 Year Cosmic Microwave Background Polarization Results," *The Astrophysical Journal* **624**, 10–20 (May 2005).
- [82] Barkats, D., Bischoff, C., and Farese, e. a., "First Measurements of the Polarization of the Cosmic Microwave Background Radiation at Small Angular Scales from CAPMAP," *The Astrophysical Journal Letters* **619**, L127–L130 (Feb. 2005).
- [83] Readhead, A. C. S., Myers, S. T., and Pearson, T. J. e. a., "Polarization Observations with the Cosmic Background Imager," *Science* **306**, 836–844 (Oct. 2004).

- [84] Page, L., Hinshaw, G., and Komatsu, E. e. a., “Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Polarization Analysis,” *The Astrophysical Journal Supplements* **170**, 335–376 (June 2007).
- [85] Masi, S., Ade, P. A. R., and Bock, J. J. e. a., “Instrument, method, brightness, and polarization maps from the 2003 flight of BOOMERanG,” *Astronomy and Astrophysics* **458**, 687–716 (Nov. 2006).
- [86] Piacentini, F., Ade, P. A. R., and Bock, J. J., e. a., “A Measurement of the Polarization-Temperature Angular Cross-Power Spectrum of the Cosmic Microwave Background from the 2003 Flight of BOOMERANG,” *The Astrophysical Journal* **647**, 833–839 (Aug. 2006).
- [87] Montroy, T. E., Ade, P. A. R., and Bock, J. J. e. a., “A Measurement of the CMB EE Spectrum from the 2003 Flight of BOOMERANG,” *The Astrophysical Journal* **647**, 813–822 (Aug. 2006).
- [88] Ade, P., Bock, J., and Bowden, M. e. a., “First Season QUaD CMB Temperature and Polarization Power Spectra,” *The Astrophysical Journal* **674**, 22–28 (Feb. 2008).
- [89] Pryke, C., Ade, P., and Bock, J. e. a., “Second and Third Season QUaD Cosmic Microwave Background Temperature and Polarization Power Spectra,” *The Astrophysical Journal* **692**, 1247–1270 (Feb. 2009).
- [90] Brown, M. L., Ade, P., and Bock, J. e. a., “Improved Measurements of the Temperature and Polarization of the Cosmic Microwave Background from QUaD,” *The Astrophysical Journal* **705**, 978–999 (Nov. 2009).
- [91] Chiang, H. C., Ade, P. A. R., and Barkats, D. e. a., “Measurement of Cosmic Microwave Background Polarization Power Spectra from Two Years of BICEP Data,” *The Astrophysical Journal* **711**, 1123–1140 (Mar. 2010).
- [92] QUIET Collaboration, Bischoff, C., Brizius, A., and Buder, I. e. a., “First Season QUIET Observations: Measurements of Cosmic Microwave Background Polarization Power Spectra at 43 GHz in the Multipole Range $25 \leq \ell \leq 475$,” *The Astrophysical Journal* **741**, 111 (Nov. 2011).
- [93] Mortonson, M. J. and Hu, W., “Reionization Constraints from Five-Year WMAP Data,” *The Astrophysical Journal Letters* **686**, L53–L56 (Oct. 2008).
- [94] Welford, W. T. and Winston, R., [*The optics of nonimaging concentrators - Light and solar energy*], New York: Academic Press, 1978 (1978).
- [95] Fixsen, D. J., “The Temperature of the Cosmic Microwave Background,” *The Astrophysical Journal* **707**, 916–920 (Dec. 2009).
- [96] Fixsen, D. J., Kogut, A., and Levin, S. e. a., “The Temperature of the Cosmic Microwave Background at 10 GHz,” *The Astrophysical Journal* **612**, 86–95 (Sept. 2004).
- [97] Fixsen, D. J., Kogut, A., and Levin, S. e. a., “ARCADE 2 Measurement of the Absolute Sky Brightness at 3–90 GHz,” *The Astrophysical Journal* **734**, 5 (June 2011).
- [98] Burigana, C., de Zotti, G., and Danese, L., “Analytical description of spectral distortions of the cosmic microwave background,” *Astronomy and Astrophysics* **303**, 323 (Nov. 1995).
- [99] Silk, J. and Wilson, M. L., “Residual fluctuations in the matter and radiation distribution after the decoupling epoch,” *Physica Scripta* **21**, 708–713 (1980).
- [100] Keller, J. B., “Geometrical theory of diffraction,” *Journal of the Optical Society of America (1917-1983)* **52**, 116 (Feb. 1962).
- [101] O’Sullivan, C., Murphy, J. A., and Yurchenko, V. e. a., “The quasi-optical performance of CMB astronomical telescopes,” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **6472** (Feb. 2007).
- [102] dall’Oglio, G. and de Bernardis, P., “Observations of cosmic background radiation anisotropy from Antarctica,” *The Astrophysical Journal* **331**, 547–553 (Aug. 1988).
- [103] Benoît, A., Ade, P., and Amblard, e. a., “Archeops: a high resolution, large sky coverage balloon experiment for mapping cosmic microwave background anisotropies,” *Astroparticle Physics* **17**, 101–124 (May 2002).
- [104] Piacentini, F., Ade, P. A. R., and Bhatia, R. S. e. a., “The BOOMERANG North America Instrument: A Balloon-borne Bolometric Radiometer Optimized for Measurements of Cosmic Background Radiation Anisotropies from 0.3 deg to 4 deg,” *The Astrophysical Journal Supplements* **138**, 315–336 (Feb. 2002).
- [105] Miller, A., Beach, J., and Bradley, S., e. a., “The QMAP and MAT/TOCO Experiments for Measuring Anisotropy in the Cosmic Microwave Background,” *The Astrophysical Journal Supplements* **140**, 115–141 (June 2002).

- [106] Crill, B. P., Ade, P. A. R., and Artusa, D. R. e. a., “BOOMERANG: A Balloon-borne Millimeter-Wave Telescope and Total Power Receiver for Mapping Anisotropy in the Cosmic Microwave Background,” *The Astrophysical Journal Supplements* **148**, 527–541 (Oct. 2003).
- [107] Page, L., Jackson, C., and Barnes, C. e. a., “The Optical Design and Characterization of the Microwave Anisotropy Probe,” *The Astrophysical Journal* **585**, 566–586 (Mar. 2003).
- [108] Martin, P., Riti, J.-B., and de Chambure, D., “Planck Telescope: optical design and verification,” in [*5th International Conference on Space Optics*], Warmbein, B., ed., *ESA Special Publication* **554**, 323–331 (June 2004).
- [109] Carlstrom, J. E., Ade, P. A. R., and Aird, e. a., “The 10 Meter South Pole Telescope,” *Publications of the Astronomical Society of the Pacific* **123**, 568–581 (May 2011).
- [110] Swetz, D. S., Ade, P. A. R., and Amiri, M. e. a., “Overview of the Atacama Cosmology Telescope: Receiver, Instrumentation, and Telescope Systems,” *The Astrophysical Journal Supplements* **194**, 41 (June 2011).
- [111] Grimes, P. K., Ade, P. A. R., and Audley M. D., e. a., “Clover - Measuring the Cosmic Microwave Background B-mode Polarization,” in [*Twentieth International Symposium on Space Terahertz Technology*], Bryerton, E., Kerr, A., and Lichtenberger, A., eds., 97 (Apr. 2009).
- [112] Buder, I., “Q/U Imaging Experiment (QUIET): a ground-based probe of cosmic microwave background polarization,” in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V. Edited by Holland, Wayne S.; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 7741, pp. 77411D-77411D-11 (2010).*], **7741** (July 2010).
- [113] Barnes, C., Hill, R. S., and Hinshaw, e. a., “First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Galactic Signal Contamination from Sidelobe Pickup,” *The Astrophysical Journal Supplements* **148**, 51–62 (Sept. 2003).
- [114] Lewis, W. B., “Fluctuations in streams of thermal radiation,” *Proceedings of the Physical Society* **59**, 34–40 (Jan. 1947).
- [115] Lamarre, J. M., “Photon noise in photometric instruments at far-infrared and submillimeter wavelengths,” *Applied Optics* **25**, 870–876 (Mar. 1986).
- [116] Zmuidzinas, J., “Thermal noise and correlations in photon detection,” *Applied Optics* **42**, 4989–5008 (Sept. 2003).
- [117] Lamarre, J. M., Puget, J. L., and Bouchet, F. e. a., “The Planck High Frequency Instrument, a third generation CMB experiment, and a full sky submillimeter survey,” *New Astronomy Reviews* **47**, 1017–1024 (Dec. 2003).
- [118] Planck HFI Core Team, Ade, P. A. R., Aghanim, N., and Ansari, R. e. a., “Planck early results. IV. First assessment of the High Frequency Instrument in-flight performance,” *Astronomy and Astrophysics* **536**, A4 (Dec. 2011).
- [119] Holmes, W. A., Bock, J. J., and Crill, B. P. e. a., “Initial test results on bolometers for the Planck high frequency instrument,” *Applied Optics* **47**, 5996 (Nov. 2008).
- [120] Richards, P. L., “Bolometric Detectors for Measurements of the Cosmic Microwave Background,” *Journal of Superconductivity, vol. 17, issue 5, pp. 545-550* **17**, 545–550 (Oct. 2004).
- [121] Richards, P. L., “Progress in bolometric CMB measurements,” in [*Background Microwave Radiation and Intracluster Cosmology. Edited by F. Melchiorri and Y. Rephaeli. Proceedings of the International School of Physics “Enrico Fermi”, Course CLIX, held at Verenna on Lake Como, Villa Monastero, July 6-16, 2005. Part of the Italian Physical Society series. ISBN 1-58603-585-1 (IOS); ISBN 88-7438-025-9 (SIF); Library of Congress Catalog Card No. 2005937974. Published by IOS Press, The Netherlands, and Società Italiana di Fisica, Bologna, Italy, 2005, p.339*], Melchiorri, F. and Rephaeli, Y., eds., 339 (2005).
- [122] Mauskopf, P. D., Bock, J. J., and del Castillo, H. e. a., “Composite infrared bolometers with Si₃N₄ micromesh absorbers,” *Applied Optics* **36**, 765–771 (Feb. 1997).
- [123] Jones, W. C., Bhatia, R., Bock, J. J., and Lange, A. E., “A Polarization Sensitive Bolometric Receiver for Observations of the Cosmic Microwave Background,” in [*Millimeter and Submillimeter Detectors for Astronomy. Edited by Phillips, Thomas G.; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 4855, pp. 227-238 (2003).*], Phillips, T. G. and Zmuidzinas, J., eds., **4855**, 227–238 (Feb. 2003).

- [124] Mauskopf, P. D., Gerecht, E., and Rownd, B. K., “BOLOCAM: A 144 Element Bolometer Array Camera for Millimeter-Wave Imaging,” in [*Imaging at Radio through Submillimeter Wavelengths*], Mangum, J. G. and Radford, S. J. E., eds., **217**, 115 (2000).
- [125] Irwin, K. D., “An application of electrothermal feedback for high resolution cryogenic particle detection,” *Applied Physics Letters* **66**, 1998–2000 (Apr. 1995).
- [126] Lee, A. T., Richards, P. L., and Nam, S. W. e. a., “A superconducting bolometer with strong electrothermal feedback,” *Applied Physics Letters* **69**, 1801–1803 (Sept. 1996).
- [127] Lee, S.-F., Gildemeister, J. M., Holmes, W., Lee, A. T., and Richards, P. L., “Voltage-Biased Superconducting Transition-Edge Bolometer with Strong Electrothermal Feedback Operated at 370 mK,” *Applied Optics* **37**, 3391–3397 (June 1998).
- [128] Gildemeister, J. M., Lee, A. T., and Richards, P. L., “A fully lithographed voltage-biased superconducting spiderweb bolometer,” *Applied Physics Letters* **74**, 868 (Feb. 1999).
- [129] Gildemeister, J. M., Lee, A. T., and Richards, P. L., “Monolithic arrays of absorber-coupled voltage-biased superconducting bolometers,” *Applied Physics Letters* **77**, 4040 (Dec. 2000).
- [130] Benford, D. J., Voellmer, G. M., and Chervenak, J. A. e. a., “Design and Fabrication of Two-Dimensional Superconducting Bolometer Arrays,” in [*Millimeter and Submillimeter Detectors for Astronomy. Edited by Phillips, Thomas G.; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 4855, pp. 552-562 (2003).*], Phillips, T. G. and Zmuidzinas, J., eds., **4855**, 552–562 (Feb. 2003).
- [131] Niemack, M. D., Zhao, Y., and Wollack, E. e. a., “A Kilopixel Array of TES Bolometers for ACT: Development, Testing, and First Light,” *Journal of Low Temperature Physics* **151**, 690–696 (May 2008).
- [132] Mehl, J., Ade, P. A. R., and Basu, K. e. a., “TES Bolometer Array for the APEX-SZ Camera,” *Journal of Low Temperature Physics* **151**, 697–702 (May 2008).
- [133] Kuo, C. L., Bock, J. J., Bonetti, J. A., Brevik, J., Chattopadhyay, G., Day, P. K., Golwala, S., Kenyon, M., Lange, A. E., LeDuc, H. G., Nguyen, H., Ogburn, R. W., Orlando, A., Transgrud, A., Turner, A., Wang, G., and Zmuidzinas, J., “Antenna-coupled TES bolometer arrays for CMB polarimetry,” in [*Millimeter and Submillimeter Detectors and Instrumentation for Astronomy IV. Edited by Duncan, William D.; Holland, Wayne S.; Withington, Stafford; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 7020, pp. 70201I-70201I-14 (2008).*], **7020** (Aug. 2008).
- [134] Orlando, A., Aikin, R. W., and Amiri, M. e. a., “Antenna-coupled TES bolometer arrays for BICEP2/Keck and SPIDER,” in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V. Edited by Holland, Wayne S.; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 7741, pp. 77410H-77410H-10 (2010).*], **7741** (July 2010).
- [135] Pajot, F., Prele, D., and Zhong, J. e. a., “Large submillimeter and millimeter detector arrays for astronomy: development of NbSi superconducting bolometers,” in [*Infrared, Millimeter Wave, and Terahertz Technologies. Edited by Zhang, Cunlin; Zhang, Xi-Cheng; Siegel, Peter H.; He, Li; Shi, Sheng-Cai. Proceedings of the SPIE, Volume 7854, pp. 78540U-78540U-7 (2010).*], **7854** (Nov. 2010).
- [136] Schwan, D., Ade, P. A. R., and Basu, K. e. a., “Invited Article: Millimeter-wave bolometer array receiver for the Atacama pathfinder experiment Sunyaev-Zel’dovich (APEX-SZ) instrument,” *Review of Scientific Instruments*, Volume 82, Issue 9, pp. 091301-091301-24 (2011). **82**, 091301 (Sept. 2011).
- [137] Staniszewski, Z., Aikin, R. W., and Amiri, M. e. a., “The Keck Array: A Multi Camera CMB Polarimeter at the South Pole,” *Journal of Low Temperature Physics* **167**, 827–833 (June 2012).
- [138] Lanting, T. M., Arnold, K., and Cho, H.-M. e. a., “Frequency-domain readout multiplexing of transition-edge sensor arrays,” *Nuclear Instruments and Methods in Physics Research A* **559**, 793–795 (Apr. 2006).
- [139] Battistelli, E. S., Amiri, M., and Burger, B. e. a., “Functional Description of Read-out Electronics for Time-Domain Multiplexed Bolometers for Millimeter and Sub-millimeter Astronomy,” *Journal of Low Temperature Physics* **151**, 908–914 (May 2008).
- [140] Myers, M. J., Holzappel, W., and Lee, A. T. e. a., “Arrays of antenna-coupled bolometers using transition edge sensors,” *Nuclear Instruments and Methods in Physics Research A* **520**, 424–426 (Mar. 2004).
- [141] Myers, M. J., Holzappel, W., and Lee, A. T. e. a., “An antenna-coupled bolometer with an integrated microstrip bandpass filter,” *Applied Physics Letters* **86**, 114103 (Mar. 2005).

- [142] Myers, M. J., Ade, P., and Arnold, K. e. a., “Antenna-coupled bolometer arrays using transition-edge sensors,” *Nuclear Instruments and Methods in Physics Research A* **559**, 531–533 (Apr. 2006).
- [143] O’Brient, R., Ade, P. A. R., and Arnold, K. e. a., “A Multi-Band Dual-Polarized Antenna-Coupled TES Bolometer,” *Journal of Low Temperature Physics* **151**, 459–463 (Apr. 2008).
- [144] O’Brient, R., Ade, P., and Arnold, K. e. a., “Sinuous-Antenna coupled TES bolometers for Cosmic Microwave Background Polarimetry,” *THE THIRTEENTH INTERNATIONAL WORKSHOP ON LOW TEMPERATURE DETECTORS-LTD13. AIP Conference Proceedings, Volume 1185*, pp. 502-505 (2009). **1185**, 502–505 (Dec. 2009).
- [145] O’Brient, R., Ade, P., and Arnold, K. e. a., “A dual-polarized multichroic antenna-coupled TES bolometer for terrestrial CMB Polarimetry,” in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V. Edited by Holland, Wayne S.; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 7741*, pp. 77410J-77410J-10 (2010).], **7741** (July 2010).
- [146] O’Brient, R., Ade, P., and Arnold, K. e. a., “A Log-Periodic Channelizer for Multichroic Antenna-Coupled TES-Bolometers,” *IEEE Transactions on Applied Superconductivity*, vol. 21, issue 3, pp. 180-183 **21**, 180–183 (June 2011).
- [147] Day, P. K., LeDuc, H. G., and Mazin, B. A. e. a., “A broadband superconducting detector suitable for use in large arrays,” *Nature* **425**, 817–821 (Oct. 2003).
- [148] Doyle, S., Naylon, J., and Mauskopf, P. e. a., “Lumped element kinetic inductance detectors for far-infrared astronomy,” in [*Millimeter and Submillimeter Detectors and Instrumentation for Astronomy IV. Edited by Duncan, William D.; Holland, Wayne S.; Withington, Stafford; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 7020*, pp. 70200T-70200T-10 (2008).], **7020** (Aug. 2008).
- [149] Doyle, S., Mauskopf, P., and Zhang, J. e. a., “A review of the lumped element kinetic inductance detector,” in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V. Edited by Holland, Wayne S.; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 7741*, pp. 77410M-77410M-10 (2010).], **7741** (July 2010).
- [150] Yates, S. J. C., Baselmans, J. J. A., and Barends, R. e. a., “Antenna coupled Kinetic Inductance Detectors for space based sub-mm astronomy,” in [*Nineteenth International Symposium on Space Terahertz Technology*], Wild, W., ed., 140 (Apr. 2008).
- [151] Maloney, P. R., Czakon, N. G., and Day, P. K. e. a., “MUSIC for sub/millimeter astrophysics,” in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V. Edited by Holland, Wayne S.; Zmuidzinas, Jonas. Proceedings of the SPIE, Volume 7741*, pp. 77410F-77410F-11 (2010).], **7741** (July 2010).
- [152] Calvo, M., Giordano, C., and Battiston, R. e. a., “Development of Kinetic Inductance Detectors for Cosmic Microwave Background experiments,” *Experimental Astronomy* **28**, 185–194 (Dec. 2010).
- [153] Monfardini, A., Swenson, L. J., and Bidaud, A. e. a., “NIKA: A millimeter-wave kinetic inductance camera,” *Astronomy and Astrophysics* **521**, A29 (Oct. 2010).
- [154] Monfardini, A., Benoit, A., and Bidaud, A. e. a., “A Dual-band Millimeter-wave Kinetic Inductance Camera for the IRAM 30 m Telescope,” *The Astrophysical Journal Supplements* **194**, 24 (June 2011).
- [155] Kuzmin, L. S., “On the concept of a hot-electron microbolometer with capacitive coupling to the antenna,” *Physica B Condensed Matter* **284**, 2129–2130 (July 2000).
- [156] Tarasov, M. A., Kuzmin, L. S., and Kaurova, N. S. e. a., “Cold-Electron Bolometer Array Integrated with a 350 GHz Cross-Slot Antenna,” in [*Twenty-First International Symposium on Space Terahertz Technology*], 256–261 (Mar. 2010).
- [157] Planck Collaboration, Ade, P. A. R., Aghanim, N., and Arnaud, M. e. a., “Planck early results. I. The Planck mission,” *Astronomy and Astrophysics* **536**, A1 (Dec. 2011).
- [158] Sunyaev, R. A. and Zeldovich, Y. B., “The Observations of Relic Radiation as a Test of the Nature of X-Ray Radiation from the Clusters of Galaxies,” *Comments on Astrophysics and Space Physics* **4**, 173 (Nov. 1972).
- [159] Birkinshaw, M., “The Sunyaev-Zel’dovich effect,” *Physics Reports* **310**, 97–195 (Mar. 1999).
- [160] Carlstrom, J. E., Holder, G. P., and Reese, E. D., “Cosmology with the Sunyaev-Zel’dovich Effect,” *Annual Review of Astronomy and Astrophysics* **40**, 643–680 (2002).

- [161] Rephaeli, Y., Sadeh, S., and Shimon, M., “The Sunyaev Zeldovich effect,” *Nuovo Cimento Rivista Serie* **29**, 120000–18 (Dec. 2006).
- [162] Planck Collaboration, Ade, P. A. R., Aghanim, N., and Arnaud, M. e. a., “Planck early results. VIII. The all-sky early Sunyaev-Zeldovich cluster sample,” *Astronomy and Astrophysics* **536**, A8 (Dec. 2011).
- [163] Planck Collaboration, Aghanim, N., Arnaud, M., and Ashdown, M. e. a., “Planck early results. XXVI. Detection with Planck and confirmation by XMM-Newton of PLCK G266.6-27.3, an exceptionally X-ray luminous and massive galaxy cluster at $z \sim 1$,” *Astronomy and Astrophysics* **536**, A26 (Dec. 2011).
- [164] de Bernardis, P., Colafrancesco, S., and D’Alessandro, G. e. a., “Low-resolution spectroscopy of the Sunyaev-Zel’dovich effect and estimates of cluster parameters,” *Astronomy and Astrophysics* **538**, A86 (Feb. 2012).
- [165] Hincks, A. D., Acquaviva, V., and Ade, P. A. R. e. a., “The Atacama Cosmology Telescope (ACT): Beam Profiles and First SZ Cluster Maps,” *The Astrophysical Journal Supplements* **191**, 423–438 (Dec. 2010).
- [166] Marriage, T. A., Acquaviva, V., and Ade, P. A. R. e. a., “The Atacama Cosmology Telescope: Sunyaev-Zel’dovich-Selected Galaxy Clusters at 148 GHz in the 2008 Survey,” *The Astrophysical Journal* **737**, 61 (Aug. 2011).
- [167] Brodwin, M., Ruel, J., and Ade, P. A. R. e. a., “SPT-CL J0546-5345: A Massive $z > 1$ Galaxy Cluster Selected Via the Sunyaev-Zel’dovich Effect with the South Pole Telescope,” *The Astrophysical Journal* **721**, 90–97 (Sept. 2010).
- [168] Hand, N., Appel, J. W., and Battaglia, N. e. a., “The Atacama Cosmology Telescope: Detection of Sunyaev-Zel’dovich Decrement in Groups and Clusters Associated with Luminous Red Galaxies,” *The Astrophysical Journal* **736**, 39 (July 2011).
- [169] Sehgal, N., Trac, H., and Acquaviva, V. e. a., “The Atacama Cosmology Telescope: Cosmology from Galaxy Clusters Detected via the Sunyaev-Zel’dovich Effect,” *The Astrophysical Journal* **732**, 44 (May 2011).
- [170] Foley, R. J., Andersson, K., and Bazin, G. e. a., “Discovery and Cosmological Implications of SPT-CL J2106-5844, the Most Massive Known Cluster at $z > 1$,” *The Astrophysical Journal* **731**, 86 (Apr. 2011).
- [171] Story, K., Aird, K. A., and Andersson, K. e. a., “South Pole Telescope Detections of the Previously Unconfirmed Planck Early Sunyaev-Zel’dovich Clusters in the Southern Hemisphere,” *The Astrophysical Journal Letters* **735**, L36 (July 2011).
- [172] Williamson, R., Benson, B. A., and High, F. W. e. a., “A Sunyaev-Zel’dovich-selected Sample of the Most Massive Galaxy Clusters in the 2500 deg² South Pole Telescope Survey,” *The Astrophysical Journal* **738**, 139 (Sept. 2011).
- [173] Wild, W., Kardashev, N. S., and Likhachev, S. F. e. a., “Millimetron: a large Russian-European submillimeter space observatory,” *Experimental Astronomy* **23**, 221–244 (Mar. 2009).
- [174] Masi, S., Battistelli, E., and Brienza, D. e. a., “OLIMPO,” *Memorie della Società Astronomica Italiana* **79**, 887 (2008).
- [175] Conversi, L., Fiadino, P., and de Bernardis, P. e. a., “Extracting cosmological signals from foregrounds in deep mm maps of the sky,” *Astronomy and Astrophysics* **524**, A7 (Dec. 2010).
- [176] Schillaci, A. and de Bernardis, P., “On the effect of tilted roof reflectors in Martin-Puplett spectrometers,” *Infrared Physics and Technology* **55**, 40–44 (Jan. 2012).
- [177] de Bernardis, P. and Sagace Team, “SAGACE: The Spectroscopic Active Galaxies and Clusters Explorer,” in [*Twelfth Marcel Grossmann Meeting on General Relativity*], 2133 see also astro-ph/1002.0867 (2010).
- [178] Martin, D. H. and Puplett, E., “Polarised interferometric spectrometry for the millimeter and submillimeter spectrum,” *Infrared Physics* **10**, 105–109 (1970).
- [179] de Bernardis, P., Dubrovich, V., and Encrenaz, P. e. a., “Search for LiH lines at high redshift,” *Astronomy and Astrophysics* **269**, 1–6 (Mar. 1993).
- [180] Basu, K., Hernández-Monteagudo, C., and Sunyaev, R. A., “CMB observations and the production of chemical elements at the end of the dark ages,” *Astronomy and Astrophysics* **416**, 447–466 (Mar. 2004).
- [181] Dubrovich, V., Bajkova, A., and Khaikin, V. B., “Spectral spatial fluctuations of CMBR: Strategy and concept of the experiment,” *New Astronomy* **13**, 28–40 (Jan. 2008).

- [182] Kogut, A., Fixsen, D. J., and Chuss, D. T. e. a., “The Primordial Inflation Explorer (PIXIE): a nulling polarimeter for cosmic microwave background observations,” *JCAP* **7**, 25 (July 2011).
- [183] Gong, Y., Cooray, A., and Silva, M. e. a., “Intensity Mapping of the [C II] Fine Structure Line during the Epoch of Reionization,” *The Astrophysical Journal* **745**, 49 (Jan. 2012).
- [184] Leach, S. M., Cardoso, J.-F., and Baccigalupi, C. e. a., “Component separation methods for the PLANCK mission,” *Astronomy and Astrophysics* **491**, 597–615 (Nov. 2008).
- [185] Ricciardi, S., Bonaldi, A., and Natoli, P. e. a., “Correlated component analysis for diffuse component separation with error estimation on simulated Planck polarization data,” *Monthly Notices of the Royal Astronomical Society* **406**, 1644–1658 (Aug. 2010).
- [186] Armitage-Caplan, C., Dunkley, J., Eriksen, H. K., and et al., “Large-scale polarized foreground component separation for Planck,” *Monthly Notices of the Royal Astronomical Society* **418**, 1498–1510 (Dec. 2011).
- [187] Errard, J. and Stompor, R., “Astrophysical foregrounds and primordial tensor-to-scalar ratio constraints from cosmic microwave background B-mode polarization observations,” *Physical Review D* **85**, 083006 (Apr. 2012).
- [188] Hazumi, M., “Future cmb polarization measurements and japanese contributions,” *Progress of Theoretical Physics Supplement* **190**, 75–89 (2011).
- [189] Hanany, S., Hubmayr, J., and Johnson, B. R. e. a., “Millimeter-wave achromatic half-wave plate,” *Applied Optics* **44**, 4666–4670 (Aug. 2005).
- [190] Johnson, B. R., Collins, J., and Abroe, M. E. e. a., “MAXIPOL: Cosmic Microwave Background Polarimetry Using a Rotating Half-Wave Plate,” *The Astrophysical Journal* **665**, 42–54 (Aug. 2007).
- [191] Savini, G., Pisano, G., and Ade, P. A. R., “Achromatic half-wave plate for submillimeter instruments in cosmic microwave background astronomy: modeling and simulation,” *Applied Optics* **45**, 8907–8915 (Dec. 2006).
- [192] Pisano, G., Savini, G., and Ade, P. A. R. e. a., “Achromatic half-wave plate for submillimeter instruments in cosmic microwave background astronomy: experimental characterization,” *Applied Optics* **45**, 6982–6989 (Sept. 2006).
- [193] Bryan, S. A., Montroy, T. E., and Ruhl, J. E., “Modeling dielectric half-wave plates for cosmic microwave background polarimetry using a Mueller matrix formalism,” *Applied Optics* **49**, 6313 (Nov. 2010).
- [194] Zhang, J., Ade, P. A. R., and Mauskopf, P. e. a., “Polypropylene embedded metal mesh broadband achromatic half-wave plate for millimeter wavelengths,” *Applied Optics* **50**, 3750–3757 (July 2011).
- [195] Siringo, G., Kreysa, E., and Reichertz, L. A. e. a., “A new polarimeter for (sub)millimeter bolometer arrays,” *Astronomy and Astrophysics* **422**, 751–760 (Aug. 2004).
- [196] Krejny, M., Chuss, D., and D’Aubigny, C. D. e. a., “The Hertz/VPM polarimeter: design and first light observations,” *Applied Optics* **47**, 4429 (Aug. 2008).
- [197] Chuss, D. T., Wollack, E. J., and Pisano, G. e. a., “A Translational Polarization Rotator,” *ArXiv e-prints astro-ph/1206.2284* (June 2012).
- [198] Salatino, M., de Bernardis, P., and Masi, S., “A cryogenic waveplate rotator for polarimetry at mm and submm wavelengths,” *Astronomy and Astrophysics* **528**, A138 (Apr. 2011).
- [199] Pancharatnam, S., “Achromatic combinations of birefringent plates Part II. An achromatic quarter-wave plate,” *Proc. Indian Acad. Sci.* **41**, 137 (Jan. 1955).
- [200] Bao, C., Gold, B., Baccigalupi, C., and Didier, J. e. a., “The Impact of the Spectral Response of an Achromatic Half-wave Plate on the Measurement of the Cosmic Microwave Background Polarization,” *The Astrophysical Journal* **747**, 97 (Mar. 2012).
- [201] The COrE Collaboration, Armitage-Caplan, C., Avillez, M., and Barbosa, D. e. a., “COrE (Cosmic Origins Explorer) A White Paper,” *ArXiv e-prints astro-ph/1102.2181* (Feb. 2011).
- [202] Salatino, M. and de Bernardis, P., “On Stokes polarimeters for high precision CMB measurements and mm Astronomy measurements,” *ArXiv e-prints astro-ph/1006.3225* (June 2010).
- [203] Bock, J., Church, S., and Devlin, M. e. a., “Task Force on Cosmic Microwave Background Research,” *ArXiv Astrophysics e-prints astro-ph/0604101* (Apr. 2006).

- [204] de Bernardis, P., Aiola, S., and Amico, G. e. a., “SWIPE: a bolometric polarimeter for the Large-Scale Polarization Explorer,” in [*Ground-based and Airborne Instrumentation for Astronomy IV. Edited by McLean, Ramsay, Takami. Proceedings of the SPIE, (2012).*], (Aug. 2012).
- [205] Arnold, K., Ade, P. A. R., and Anthony, A. E. e. a., “The POLARBEAR CMB polarization experiment,” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7741** (July 2010).
- [206] Qubic Collaboration, Battistelli, E., and Baú, A. e. a., “QUBIC: The QU bolometric interferometer for cosmology,” *Astroparticle Physics* **34**, 705–716 (Apr. 2011).
- [207] Filippini, J. P., Ade, P. A. R., and Amiri, M. e. a., “SPIDER: a balloon-borne CMB polarimeter for large angular scales,” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7741** (July 2010).
- [208] Reichborn-Kjennerud, B., Aboobaker, A. M., Ade, P., and et al., “EBEX: a balloon-borne CMB polarization experiment,” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7741** (July 2010).
- [209] The LSPE collaboration:, Aiola, S., and Amico, G. e. a., “The Large-Scale Polarization Explorer (LSPE),” in [*Ground-based and Airborne Instrumentation for Astronomy IV. Edited by McLean, Ramsay, Takami. Proceedings of the SPIE, (2012).*], (Aug. 2012).

