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Contents

xxxi  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]

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)
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)

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)

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. Flaugher, Fermilab Chicago (United States)

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. Hirlart, 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, Instituto de Astronomía (Taiwan) and Astrophysics (Taiwan)

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)

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 0G  **OAJ: 2.6m wide field survey telescope** [8444-14]
O. Pirnay, V. Moreau, G. Lousberg, Advanced Mechanical and Optical Systems S.A. (Belgium)

8444 0H  **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 0I  **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 0J  **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 0K  **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. Raftery, 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. Esquerra, 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 0L  **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 0M  **Design concepts for the EST mount** [8444-21]
H. J. Kärcher, M. Süß, D. Fischer, MT Mechatronics GmbH (Germany)
Progress on the structural and mechanical design of the Giant Magellan Telescope
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)

E-ELT dome for modified baseline design [8444-24]
A. Bilbao, G. Murga, C. Gómez, IDOM (Spain)

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)

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)

Seismic analysis of the LSST telescope [8444-26]
D. R. Neill, National Optical Astronomy Observatory (United States)

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)

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)

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)
AIRBORNE TELESCOPES I

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. Marckum, 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. Roser, 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); G. I. Mandushev, Lowell Observatory (United States); 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. Grünwald, Humboldt Univ. (Germany); C. B. Netterfield, Cardiff Univ. (United Kingdom); D. Nutter, Cardiff Univ. (United Kingdom); D. 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); 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)
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

Status and performance of the Discovery Channel Telescope during commissioning (Invited Paper) [8444-44]

The Large Binocular Telescope [8444-45]

New Fraunhofer Telescope Wendelstein: assembly, installation, and current status [8444-46]
H. Thiele, N. Ageorges, D. Kampf, M. Harli, 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)

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'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. Umbriaco, Univ. of Padua (Italy)

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)

Discovery Channel Telescope active optics system early integration and test [8444-49]
A. J. Venetiou, T. A. Bida, Lowell Observatory (United States)

EXTREMELY LARGE TELESCOPIES

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)

Thirty Meter Telescope project update (Invited Paper) [8444-51]
L. Stepp, Thirty Meter Telescope Observatory Corp. (United States)
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)

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

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)

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)

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

The Greenland Telescope [8444-59]
P. Grimes, R. Blundell, Smithsonian Astrophysical Observatory (United States)

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)

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)

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);
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, Aryabhatta 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 Muqabel, 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, Aryabhatta Research Institute of Observational Sciences (India)

8444 1W Manufacturing optics of a 2.5m telescope [8444-68]

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 [8444-72]
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)

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. Bastia, 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)

8444 26  The development of the actuator prototypes for the active reflector of FAST [8444-78]
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, Aryabhatta Research Institute of Observational Sciences (India)

SQUARE KILOMETER ARRAY AND SKA PATHFINDERS

8444 2A  The Australian SKA Pathfinder (Invited Paper) [8444-82]

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. Mori, M. Sugimoto, P. Napier, M. Miccolis, Joint ALMA Observatory (Chile); P. Yogoubov, 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. Martí Canales, European Southern Observatory (Chile); R. Bhatia, E. DuVall, S. Blair, Joint ALMA Observatory (Chile)
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)

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)

Photonic local oscillator technics for large-scale interferometers [8444-96]
H. Kiuchi, M. Saito, S. Iguchi, National Astronomical Observatory of Japan (Japan)

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)

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)

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)

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)

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, Aryabhatta Research Institute of Observational Sciences (India)
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. Mitsch, Univ.-Sternwarte München (Germany); M. Ruder, Astelco Systems GmbH (Germany)

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)

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. Aguir, Instituto de Astrofísica de Canarias (Spain); R. Génova-Santos, Instituto de Astrofísica de Canarias (Spain) and Univ. de La Laguna (Spain); F. Gómez-Reñado, 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-Caniego, D. Ortíz, 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, DIFCOM 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)

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)

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)
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. Burkepile, 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. Rafał, 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, Aryabhatta 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. Spanò, 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 Bliek, 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. Brethedauer, 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, Q. J. Strydom, C. Sass, South African Astronomical Observatory (South Africa); C. du Plessis, E. Wild, 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)
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-Neto, G. Ramos-Larios, J. P. Phillips, A. Chávez, G. García-Torales, O. Blanco Alonso, T. Oceguera-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)
The 3.6m Indo-Belgian Devasthal Optical: the active M1 mirror support [8444-186]
M. Piérard, C. Flebus, N. Ninane, AMOS Ltd. (Belgium)

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)

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)

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)

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. Dal'Ors, S. D'Ors, INAF - Osservatorio Astronomico di Capodimonte (Italy); J. Farinato, INAF - Osservatorio Astronomico di Padova (Italy); L. Marty, INAF - Osservatorio Astronomico di Padova (Italy); R. Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy); G. Umbrico, Univ. of Padua (Italy)

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)

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)

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 Astéricas, 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. Magrini, 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. Carlborg, 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)
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)

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)

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)

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)

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. Fantel-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

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)

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)

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
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)

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)

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 Aryabhatta Research Institute of Observational Sciences (India); R. N. Banavar, Indian Institute of Technology Bombay (India)

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)

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)

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’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)

POSTER SESSION: PROJECT REVIEWS

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)

Introduction of Chinese SONG Telescope [8444-224]
| 8444 SU | **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 SV | **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 SW | **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. Zacchirolli, J. Roda, M. Morsiani, INAF - Istituto di Radioastronomia (Italy); J. A. López-Pérez, Ctr. Astronómico de Yebes (Spain) |
|---|---|
| 8444 SX | **Structural optimization of the outer ring of FAST Telescope** [8444-228]  
X. Zhang, National Astronomical Observatories of China and Graduate Univ. of Chinese Academy of Sciences (China); H. Li, S. Yang, National Astronomical Observatories (China) |
| 8444 SY | **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 SZ | **Control algorithm for the petal-shape segmented-mirror telescope with 18 mirrors** [8444-230]  
A. Shimono, The Univ. of Tokyo (Japan); F. Iwamura, 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) |
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)

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)

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)

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)

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)

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. Mutohara, 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)
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

Optical system of Chinese SONG Telescope [8444-244]
S. Kou, G. Liu, G. Wang, Nanjing Institute of Astronomical Optics & Technology (China)

Design of an off-axis optical reflecting system [8444-245]
Y. V. Bazhanov, V. B. Vlahko, Precision Systems and Instruments Corp. (Russian Federation)

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)

Fast and compact wide-field Gregorian telescope [8444-249]
M. Bahrami, A. V. Goncharov, National Univ. of Ireland, Galway (Ireland)

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)

Preliminary optical design for the WEAVE two-degree prime focus corrector [8444-251]
T. Ágocs, 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
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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
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Observatory Facilities
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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)

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Poster Session: Gamma Ray Telescopes
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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 Martí 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
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Poster Session: Upgrades to Existing Observatories
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Poster Session: Active Optics and Precision Position Control Mechanisms
Larry M. Stepp, Thirty Meter Telescope Observatory Corporation (United States)

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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)
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.

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The cosmic microwave background: observing directly the early universe

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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 μK 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 μK rms), and in particular its rotational component (less than 0.1 μK 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 $10^3$: 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 blackbody filling the present universe.  

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 $\delta_T$, which can be related to the matter density fluctuations $\Delta \rho$ once a specific class of perturbations is specified;
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: 

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

(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 $(\theta, \phi)$, 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

$$\frac{\Delta T}{T} = \sum \mathcal{a}_{\ell,m} Y_{\ell,m}(\theta, \phi)$$

(2)

the power spectrum of the CMB temperature anisotropy is defined as

$$c_{\ell}^{TT} = \langle TT \rangle = \langle a_{\ell,m} a_{\ell,m}^{*} \rangle$$

(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. 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.

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 $c_\ell$s, their distribution is a $\chi^2$ 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 $c_\ell^{TT}$ are a $1/[(\ell+1)]$ trend at low multipoles, produced by the Sachs-Wolfe effect (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, and a damping tail at high multipoles, due to the finite depth of the recombination and free-streaming effects. Detailed models and codes are available to compute the angular power spectrum of the CMB image (see e.g.9,10). The power spectrum $c_\ell^{TT}$ 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 2000 (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

$$c_\ell^{TE} = \langle TE \rangle = \langle a_\ell^T a_\ell^{E,\ast} \rangle$$ (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:

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

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.\(^\text{[50]}\)). 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 $c_{\ell}^{EE}$ 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.\(^\text{[51–54]}\)), 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.\(^\text{[55, 56]}\)). Alternative scenarios, like the cyclic model,\(^\text{[57]}\) do not produce B-modes at all.\(^\text{[58]}\)

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 laboratories\(^\text{[59]}\)).

For long time attempts to measure CMB polarization resulted in upper limits (see e.g.\(^\text{[60–65]}\)). The possibility of detecting the $\langle BB \rangle$ signature of the inflationary gravity waves background renewed the interest in these measurements (\(^\text{[66–80]}\)). The first statistically significant detections of CMB polarization have been reported by the coherent radiometer experiments DASI,\(^\text{[81]}\) CAPMAP,\(^\text{[82]}\) CBI,\(^\text{[83]}\) WMAP for both $\langle TE \rangle$ and $\langle EE \rangle$,\(^\text{[84]}\) and by the bolometric instrument BOOMERanG-03.\(^\text{[85–87]}\) The quality of CMB polarization measurements has improved steadily with the introduction of instruments with detectors arrays, like QUAD,\(^\text{[88–90]}\) BICEP,\(^\text{[81]}\) and QUIET.\(^\text{[92]}\)

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.\(^\text{[93]}\)).

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:\(^\text{[45]}\) 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,\(^\text{[94]}\) 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 blackbody\(^\text{[95]}\) is relatively large (compared to the typical noise of mm-wave detectors), but everything at room temperature emits microwaves.
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.

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, 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.).

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

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

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 $c_\ell^\nu$ 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: $B^2 = e^{-\ell(\ell+1)/\sigma^2}$, with $\sigma = \text{FWHM}/\sqrt{8\ln2}$. 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 $\sim 4$ at $\sim 40$ 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:

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

(7)

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

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 $\theta^{-3}$. 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

$$W \simeq A [B_{\text{sky}}(R)_M \Omega_M + B_{\text{ground}}(R)_S \Omega_S] = A [I_M + I_S]$$

(8)

where $(R)_M$ and $(R)_S$ represent the averages of the angular response $R$ over the main lobe (where $(R)_M \lesssim 1$) and over the sidelobes (where $(R)_S \ll 1$). 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 $(R)_S \ll 4 \times 10^{-5}$ for a 10' FWHM experiment, and $(R)_S \ll 1 \times 10^{-8}$ 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 $\mu K$. 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 $2 \times 10^{-4}$ sr. This relaxes the conditions on sidelobes rejection by a factor $\sim 30000$ 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.\textsuperscript{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 ($\mu K_{CMB}$)) and on the noise of the incoming radiative background, $NET_\gamma$. The latter is computed following\textsuperscript{114} (but see also\textsuperscript{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 $A\Omega = 1 cm^2 sr$, and scales as the square root of these; moreover, in Rayleigh-Jeans conditions, it scales also as the square root of the emissivity $\epsilon$.

From figure 4 it is evident that ground-based observations are limited to low frequencies ($\lesssim 40$ 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.
$NET_i \lesssim NET_0$). This is the case of the bolometers of the HFI instrument\textsuperscript{117} aboard of the Planck satellite,
where the telescope is cooled radiatively to 40K.\textsuperscript{118} For these detectors $NEP_i \lesssim 10^{-17} W/\sqrt{Hz}$ \textsuperscript{(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.\textsuperscript{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,\textsuperscript{122}
followed by the polarization sensitive bolometer (PSB).	extsuperscript{123} Several of these devices were arranged on the same
wafer.\textsuperscript{124} Then voltage-biased Transition Edge superconducting Sensors (TES) were developed (see e.g.\textsuperscript{125–129}
and integrated on the array wafer (see e.g.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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 $\sim 10^6$, and thus be very sensitive to the variations of
its components. Many independent MKIDs are arranged in an array, an 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,\textsuperscript{147} where mm-wave
photons are antenna coupled to the resonator, has evolved in the LEKID (Lumped Elements Kinetic Inductance
Detector) concept,\textsuperscript{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.\textsuperscript{150–152}) and are starting to be operated at large
telescopes (see e.g.\textsuperscript{153, 154}).

In a Cold Electron Bolometer (CEB)\textsuperscript{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
We have entered the era of precision observations of the CMB.

Planck\textsuperscript{157} 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) effect\textsuperscript{158} 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 \( \Delta T/T \sim \tau kT_e/m_e c^2 \lesssim 10^{-4} \); 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.\textsuperscript{159–161}).

Large mm-wave telescopes (\textsuperscript{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.\textsuperscript{162} This consists of 169 known clusters, plus 20 new discoveries, including exceptional members.\textsuperscript{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. In\textsuperscript{164} 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.\textsuperscript{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,\textsuperscript{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 balloon\textsuperscript{174-176} (center panel) to what can be ultimately achieved with a cold system in deep space\textsuperscript{164} (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 in\textsuperscript{177}.

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.\textsuperscript{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.\textsuperscript{184-186} and references therein) and of future missions devoted to CMB polarization (see e.g.\textsuperscript{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. **Center**: Simulated observations of a rich cluster of galaxies with a warm differential FTS aboard a stratospheric balloon, like OLIIMO. **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. Multicolor pixels including bolometric detectors in 3 or more bands under the same microlens have been developed, allowing a very efficient use of focal plane space. This approach has been proposed for the LiteBIRD satellite.

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 \( \dot{\theta} \), the linearly polarized part of the incoming signal is modulated at \( 4\dot{\theta} \), 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 combination\(^{195}\) can be used, or a translating polarizer / mirror assembly (Variable Delay Modulator\(^{196}\)), or a translating circular polarizer / mirror combination (Transational Polarization Rotator\(^{197}\)). 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 \( 2\dot{\theta} \) signal) and the need to cool at cryogenic temperatures the modulator, to reduce its (polarized) emission (see\(^{198}\) 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 Pancharatman\(^{199}\) 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 $\sigma$ is the wavenumber and $z$ is the position of the moving mirror. Summing and subtracting the Fourier-transformed signals from detectors couples it 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,\textsuperscript{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.\textsuperscript{202}), and the requirements for a clean detection of B-modes are extremely stringent (see e.g. table 6.1 in\textsuperscript{203}). A few examples: tens of mK signals at $2\theta$ 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 $2\theta$, unless its temperature is below 2K. These signals challenge the dynamic range of the detector, which is optimized for measuring CMB polarization signals $\sim 10^8$ times smaller. Any non-linearity in the detector can convert part of this $2\theta$ signal into a $4\theta$ 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 $4\theta$, contributing with additional $\sim$ few $\mu$K signals to the offset. A possible solution to this problem is the step and integrate strategy (see e.g.\textsuperscript{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,\textsuperscript{92} to ground-based bolometer arrays with HWP, like POLARBEAR,\textsuperscript{205} to ground-based bolometric interferometers, like QUBIC\textsuperscript{206} to stratospheric balloons like SPIDER\textsuperscript{207} EBEX,\textsuperscript{208} and LSPE.\textsuperscript{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.
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REFERENCES


[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).


