Advances in AO systems (new technologies)

Seth R. Meeker

383F Adaptive Optics and Astronomical Instrumentation
April 04, 2018
Technology Trade-offs

• NGS wavefront sensor styles
  – Shack-Hartmann vs. Pyramid vs. focal plane
• Deformable mirrors
  – Piezo vs. MEMS vs. Adaptive Secondary
  – Stroke, pitch, actuator count/yield, speed/settling time
• Detectors
  – Visible vs. near-IR
  – Photon counting vs. not (photon starved vs. not)
• Low order wavefront sensors (LOWFS)
• Fiber Injection
Technologies targeted by ELTs

Adaptive Secondaries (Microscale/ADS)
Pyramid WFS

E-ELT NGS: CMOS
E-ELT METIS: SAPHIRA IR-APD
E-ELT EPICS: ?

GMT NGS: OCAM EM-CCD
GMT GMagAO-X: OCAM EM-CCD, ALPAO and BMC DMs

TMT NFIRAOS NGS: FT-CCD, Piezo DMs (Cilas/Xinetics)
TMT PSI: MKIDs
Pyramid Wavefront Sensor

- Improved sensitivity over Shack-Hartmann (-> improved sky coverage)
- Requires modulation of focus around point of pyramid for improved linearity
- Currently deployed on SCExAO, soon on Keck (KPIC) and Magellan (MagAO-X)

Ragazzoni, 1996

Jovanovic et al. 2015

Tozzi et. Al. 2008
Overview of Deformable Mirror Technologies for Adaptive Optics and Astronomy

P-Y Madec
European Southern Observatory, Karl Schwarzschild Str 2, D-85748 Garching

ABSTRACT

From the ardent bucklers used during the Syracuse battle to set fire to Romans’ ships to more contemporary piezoelectric deformable mirrors widely used in astronomy, from very large voice coil deformable mirrors considered in future Extremely Large Telescopes to very small and compact ones embedded in Multi Object Adaptive Optics systems, this paper aims at giving an overview of Deformable Mirror technology for Adaptive Optics and Astronomy.

First the main drivers for the design of Deformable Mirrors are recalled, not only related to atmospheric aberration compensation but also to environmental conditions or mechanical constraints. Then the different technologies available today for the manufacturing of Deformable Mirrors will be described, pros and cons analyzed. A review of the Companies and Institutes with capabilities in delivering Deformable Mirrors to astronomers will be presented, as well as lessons learned from the past 25 years of technological development and operation on sky. In conclusion, perspective will be tentatively drawn for what regards the future of Deformable Mirror technology for Astronomy.

Keywords: deformable mirror, piezoelectric material, electrostrictive material, MEMS, bimorph mirror, membrane mirror, stacked array mirror
Key DM Technologies

Piezoelectric Actuators

- Typically PZT and PMN (lead zirconate titanate and lead manganese niobate) ceramics
- Elongation prop. to applied voltage
- Actuators made from stacks of PZT plates (Cilas)
- TMT prototyping 76x76 actuator piezo DMs from Cilas and AOA Xinetics for NFIRAOS NGS
- Single crystal PMN for drastically increased stroke vs. ceramics (Microscale)

Cilas stack array DM (Pagés et al. 2016)
Key DM Technologies
Microelectromechanical systems (MEMS)

- Boston Micromachines (BMC), ALPAO
- High order (64 across)
- Small pitch (0.4mm, 1.5mm)
- $<100 \, \mu s$ response, limited stroke (3 $\mu m$)
- Larger stroke (10 $\mu m$), slower (0.5 ms)

BMC 4K-DM
Key DM Technologies
Adaptive Secondaries (Voice coil actuators)

- First installed at 6.5m MMT
- LBT, Magellan, VLT examples of current gen
- Microgate/ADS planned for E-ELT, GMT (E-ELT M4 w/ >6300 actuators)
- TMT launched AM2 design study in 2017

Biasi et al. 2010
Review of the latest developments in fast low noise detectors for wavefront sensing in the visible

Sean M. Adkins

W. M. Keck Observatory, 65-1120 Mamalahoa Highway, Kamuela, HI, USA 96743

ABSTRACT

In this paper we describe the development of fast low noise detectors intended primarily for use in Shack Hartmann wavefront sensors for natural and laser guide star wavefront sensing in the future adaptive optics systems of the Thirty Meter Telescope Project and the Next Generation Adaptive Optics system at the W. M. Keck Observatory. This work results from collaboration among the W. M. Keck Observatory, the Thirty Meter Telescope Project, the Lincoln Laboratory of the Massachusetts Institute of Technology, and the Starfire Optical Range of the Air Force Research Laboratory. Testing of backside thinned, packaged detectors has been completed and performance results including read noise, readout speed, charge diffusion, dark current, and quantum efficiency will be reported. Proposed developments of readout systems to compliment this detector will be described, and performance compared to alternative detector solutions.

Keywords: Adaptive Optics, Charge Coupled Device, Detector, EMCCD, CMOS, Shack Hartmann, Laser Guide Star, Wavefront Sensing
Key Detector Technologies
Electron Multiplying CCDs (EMCCDs)

- Benefits of conventional CCD: ~100% fill factor, high QE, and efficient charge transfer
- EMCCD: extended serial register in which avalanche multiplication takes place
- Operated in conventional integrating mode or photon counting
- Noise dominated by clock induced charge; rad testing underway (Harding et al. 2016 JATIS)
- Aging can occur when applying EM gain

Adkins, 2016
Key Detector Technologies
Electron Multiplying CCDs (EMCCDs)

• e2v offers devices up to 1600 x 1600 pixels
• Targeted for WFIRST CGI
• Readily available off the shelf with First Light OCAM2

CCD201-20, 1024x1024
Harding et al. 2016

OCAM2K, first-light.fr
Key Detector Technologies
Scientific CMOS

- Active pixels benefitting from advances in MOSFET transistor technology.
- Per pixel amplification competes with photo-absorption real estate, leads to greater inter pixel variation.
- E-ELT prototyping NGSD 880x840 pixel devices, camera integration in 2018.
- Few e- rms read noise.

Adkins, 2014

Downing et al. 2016
Key Detector Technologies
IR Avalanche Photo Diodes (IR-APDs)

- HgCdTe performance integrated into an avalanche photodiode architecture (single carrier, i.e. only the electrons produce secondary pairs)
- High frame rate for IR-WFS, <1 e- rms read noise
- Limited by dark current for general low background astrophysics

Atkinson et al. 2017
Key Detector Technologies
IR Avalanche Photo Diodes (IR-APDs)

State-of-the-art SAPHIRA array fielded with:
GRAVITY (WFS)
SCExAO (FPWFS)
Robo-AO (T/T)
KPIC (PyWFS, coming soon)

C-RED One camera from First-Light

1024x1024 arrays under development

Leonardo (ne Selex) 320x256 SAPHIRA
Key Detector Technologies
Microwave Kinetic Inductance Detectors (MKIDs)

- Superconducting micro-resonator pixels (operated at ~100mK) where photons impart a frequency shift
- Single photon counting with ~microsecond timing
- Energy resolving with no dispersive element (R~8 for near-IR arrays)
- Continuously read-out with no analogue to read-noise or dark current
- Large pixels (~150 µm), low dynamic range (few thousand : 1)
Key Detector Technologies
Microwave Kinetic Inductance Detectors (MKIDs)

DARKNESS (2016)
10kpix, P3K/SDC

MEC (2018)
20kpix, SCExAO

PICTURE-C (2019)
10kpix, WASP Gondola

KRAKENS (proposed)
30kpix, Keck

Meeker et al. 2018
mazinlab.org
Future Directions
Low-power DMs with integrated ASICs

Wu et al. 2015
Future Directions
AO-fed Fiber Injection for Optical Comm. Downlink

- The Integrated Optical System (IOS) developed at JPL for NASA’s Laser Communication Relay Demonstration (LCRD)
- 28x AO system capable of 20kHz rates for efficient coupling of a satellite downlink laser into fiber.
References

Burvall et al. 2006, Optics Express
Jovanovic et al. 2015, PASP
Tozzi et al. 2008, SPIE

Madec 2012, SPIE
www.iac.es/congreso/AO4ELT5/

Boyer et al. 2016, SPIE
alpao.com
bostonmicromachines.com
Biasi et al. 2010, SPIE

Adkins 2014, SPIE
Harding et al. 2016, JATIS
first-light.fr
Atkinson et al. 2017, A&A

Hall et al. 2016, SPIE
Meeker et al. 2018, PASP accepted
Szypryt et al. 2017, Optics Express
mazinlab.org
Roberts et al. 2016, SPIE
Wu et al. 2015, Applied Optics
Pyramid Wavefront Sensor

- Improved sensitivity over Shack-Hartmann (=> improved sky coverage)
- Requires modulation of focus around point of pyramid for improved linearity
- Currently deployed on SCExAO, soon on Keck (KPIC) and Magellan (MagAO-X)

Burvall et al. 2006
Key Detector Technologies
Polar Coordinate Split Frame Transfer CCD

TMT NFIRAOS

CCID61 from Adkins, 2012