CMOS sensor for TAOS 2

Shiang-Yu Wang (王祥宇)
Academia Sinica,
Institute of Astronomy & Astrophysics
Taiwan American Occultation Survey

Institute of Astronomy & Astrophysics, Academia Sinica, Taiwan
Sun-Kun King, Typhoon Lee, Matthew Lehner, Andrew Wang, Shang-Yu Wang, Chih-Yi Wen

Institute of Astronomy, National Central University, Taiwan
Wen-Ping Chen, Kiwi Zhang,

The Harvard Smithsonian Center for Astrophysics, USA
Charles Alcock, Federica Bianco, Rahul Dave, Pavlos Protopapas

Yonsei University, Korea
Yong-Ik Byun

Lawrence Livermore National Laboratory, USA
Kem Cook, Stuart Marshall (now SLAC), Rodin Porrata (now Berkeley)

University of California, Berkeley, USA
Chyng-Lan Liang, John Rice
The Solar system we learned

View looking down from above the Sun

View looking from the edge of the solar system
Perfect diffraction

Fast photometry
Many stars
Multi-telescopes
Some Statistics

• 5Hz observation with 110ms exposures from 2005 with 3 telescopes
• 4 telescopes operation from August 2008
• 5,000,000 star hours of data accumulated
• $2.7 \times 10^{10}$ flux measurement
• More than 30 TB raw images accumulated

No occultation event found!
Upper limits set from TAOS data
# TAOS 1 vs TAOS 2

<table>
<thead>
<tr>
<th>Design</th>
<th>TAOS 1</th>
<th>TAOS 2</th>
<th>FR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observable nights</td>
<td>50nts/yr</td>
<td>250nts/yr</td>
<td>5</td>
</tr>
<tr>
<td>Aperture</td>
<td>0.5m</td>
<td>1.3m</td>
<td>6.2</td>
</tr>
<tr>
<td>Background</td>
<td>16e-</td>
<td>2e-</td>
<td>7.28</td>
</tr>
<tr>
<td>Exposure time</td>
<td>105ms</td>
<td>50ms</td>
<td>0.47</td>
</tr>
<tr>
<td>Detection limits</td>
<td>2 km</td>
<td>0.7km</td>
<td>2</td>
</tr>
<tr>
<td>Field of view</td>
<td>1.7°x1.7°</td>
<td>1.7° φ</td>
<td>0.785</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

The limiting magnitude will be 4 mag fainter to get 10x more stars.
TAOS 2 telescope

- 1.3 m f/4 system
- 39.8 arc sec/mm
- The fully shielded and unvignetted field of view (FOV) will be 154-mm in diameter (1.7-degrees).
- The energy concentration will be 80% of incident light to fall within 1.0 arc second diameter.
Camera for TAOS 2

• Basic requirements:
  – 20Hz sampling
  – 10~16 micron pixels (0.4”~0.64”)
  – Cover 1.7 degree field, 2.27 square degrees
  – Readout noise limited, read noise should be as low as possible
  – Dark level < 0.1 e-/frame

• Preferable feature
  – Different sampling rate for different stars
  – Possibility to read the whole frame very few minutes
Current TAOS camera

- 5Hz sampling with 1MHz output rate
- Zipper mode readout
  - Shutter kept open
  - Read certain rows each time
  - Sky stacked
  - Streaks during row shifting
Possible sensor for TAOS 2

• CCD based device
  – > 20MHz/ch pixel rate
  – Low noise required
  – Frame transfer needed
  – 200M pixels to be read in each frame
  – Selective read electronics needed

• CMOS based device
  – 70 windows in each 1k x 1k region
  – Fast programmable windows needed (<0.5ms window switching time)
  – Reasonable data rate
Possible TAOS 2 sensor

EMCCD from e2v
- 20 MHz readout with $<2e^-$ read noise
- Frame transfer buffer
- Custom chip needed for large array
- Excess noise for bright stars

Hybrid CMOS from Teledyne
- 2k x 2k with 18 microns
- CDS noise around 20 e- @ 1MHz
- Window mode with single output

Both options are very expensive!
Is monolithic CMOS the solution?
CMOS sensor we need

- Format: > 2K x 2K
- Pixel size: 10~16 microns
- QE: > 80% from 500~750nm
- Read noise: < 2e-
- Full well: > 60000e-
- Window switching time: < 0.5ms
- Total pixel rate: > 20Mpixel/s
- Dark rate: < 1e-/s
- Non destructive read mode supported
## Commercial CMOS sensor

<table>
<thead>
<tr>
<th></th>
<th>CANON 50D</th>
<th>CANON 5D</th>
<th>QSI532</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effective sensor size</strong></td>
<td>22.3 mm x 14.9 mm</td>
<td>35.8 mm x 23.9 mm</td>
<td>14.9 mm x 10.3 mm</td>
</tr>
<tr>
<td><strong>Pixel number</strong></td>
<td>4752 x 3168</td>
<td>4368 x 2912</td>
<td>2184 x 1472</td>
</tr>
<tr>
<td><strong>Pixel size</strong></td>
<td>4.7 microns</td>
<td>8.2 microns</td>
<td>6.8 microns</td>
</tr>
<tr>
<td><strong>Data coding</strong></td>
<td>14 bits</td>
<td>12 bits</td>
<td>16 bits</td>
</tr>
<tr>
<td><strong>gain @ ISO 400</strong></td>
<td>0.57 e-/ADU</td>
<td>3.99 e-/ADU</td>
<td>1.31 e-/ADU</td>
</tr>
<tr>
<td><strong>Readout noise</strong></td>
<td>19.04 ADU (2.7 e-)</td>
<td>3.77 ADU (3.8 e-)</td>
<td>-</td>
</tr>
<tr>
<td><strong>Thermal signal @ 22°C</strong></td>
<td>0.06 e-/sec</td>
<td>0.63 e-/sec</td>
<td>-</td>
</tr>
<tr>
<td><strong>Full well</strong></td>
<td>8 700 e-</td>
<td>15 800 e-</td>
<td>85 000 e-</td>
</tr>
<tr>
<td><strong>Dynamic range</strong></td>
<td>1770</td>
<td>1930</td>
<td>7450</td>
</tr>
</tbody>
</table>

[Graph showing pixel quantum efficiency versus wavelength for different sensors.](http://www.astrosurf.com/buil/index.htm)
CMOS development @ Sarnoff

- Led by Jim Janesick
- CfA supported the study for x-ray sensors
- 3T, 5T and 6T structure studied
- More than 5 shuttle runs prototype @MOSIS/TSMC and Jazz semiconductor
Issues studied in prototypes

- Sensitivity
- Noise
- Full well
- Quantum efficiency
- Thermal current
- CCE, CTE
- On chip CDS
- Radiation damages

Details refers to Paper series in SPIE proceeding 6276, 6295, 6690, 7439, 7742 by Jim Janesick
“Fundamental performance differences between CMOS and CCD imagers”
BIG MIN I

- 1536 x 1536 x 8 um 5T pinned photo diode (PPD)
BIG MIN II

• 1024x1024 16 micron pixels
• Improved buried channel MOSFET
• Window read by addressing each row and read certain columns.
• To be delivered this month
• Meet the lowest TAOS specs
SoloHI sensor

• Solar Orbiter Heliospheric Imager on board of ESA Solar Orbiter mission
• 4k x4k 10 micron device
Development issues

• Non destructive read: not possible for current 5T structure
• Full well: better to have > 100000e-
• Package: backside illumination and small footprint for closely packed focal plane
• Foundry service: large format prototype requires stitching capability
Our Plan

• Single chip camera completed this summer
  – Readout system build by John Geary (CfA) with BIG MIN II array

• Multi-chip camera with BIG MIN II in one year

• Development of TAOS custom array
  – SoLoHI array to be the backup choice
  – Alternatives from e2v and Canon

• First full camera within two years

Good chance to get local industry involved in the development