ADVANCED PHOTOSENSORS FOR LASER BEACON ADAPTIVE OPTICS ON THE STARFIRE OPTICAL RANGE 3.5 M TELESCOPE: PREPRINT

Robert Johnson

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14. ABSTRACT
Total upgrade of 3.5 m sodium guidestar adaptive optics for space situational awareness (NGAS). 24x24 subaperture AO system in compact coude path. High optical throughput; efficient use of sodium beacon and other signals. Using existing 50w sodium laser. Replace all optics except for primary. Replace all sensors.

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Advanced photosensors for laser beacon adaptive optics on the Starfire Optical Range 3.5 m telescope

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Robert Johnson, Ph.D.
Directed Energy Directorate,
Air Force Research Laboratory

Outline

- Background & status
- Motivation
- Status of CCID-66
- Shared MIT Lincoln CCD lot with TMT and Keck
- APD arrays
- Summary
Total Upgrade of 3.5 m

Sodium Guidestar Adaptive Optics for Space Situational Awareness (NGAS)

- 24×24 subaperture AO system in compact coudé path
- High optical throughput: efficient use of sodium beacon & other signals
- Use existing 50 W sodium laser
- Replace all optics except for primary
- Replace all sensors

3.5 m AO Upgrade Status

- Primary removed; plan to recoat mid-Sept.
- Coudé lab gutted; optics benches installed
- Optics: large fraction delivered; mounts in fabrication
- New fast steering mirror and deformable mirror delivered
- CCID-66 complete; electronics in work
- APD arrays: 16×16 subaperture 2nd prototype delivered
Sensors for 3.5 m AO Upgrade

drawing by J. Spinhirne

Arrays for Wavefront Sensing

Better AO performance with low read noise and low latency

Avalanche photodiode arrays

- Geiger mode, no read noise, direct to digital, fast readout
- Drawbacks
  - Crosstalk
  - Probability of detection ≈ 0.5

Approach

- Continue CCD development while working on issues with APD arrays
- CCID-66, 2-stage JFET amplifier
CCID-66 Description

- 160×160 pixels, 21 μm square
- 16×80 pixels per channel with frame store
- 20 channels, 3–10 MHz per channel, > 3000 fps
- 2-stage planar JFET, low cap, high responsivity
- Proven 1.3 e⁻ at 0.5 MHz single-stage planar JFET
- Estimate 8 e⁻ at 5 MHz two-stage planar JFET
- QE 0.8 at 589 nm

WFS Requirements

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Threshold</th>
<th>Goal</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subaperture number (WFS)</td>
<td>—</td>
<td>24×24</td>
<td>24×24</td>
<td>40×40</td>
</tr>
<tr>
<td>Integration time (WFS)</td>
<td>ms</td>
<td>0.25</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Frame rate (WFS)</td>
<td>fps</td>
<td>4000</td>
<td>10000</td>
<td>4000</td>
</tr>
<tr>
<td>Quantum efficiency (WFS)</td>
<td>—</td>
<td>0.45</td>
<td>0.45</td>
<td>0.8</td>
</tr>
<tr>
<td>Read noise</td>
<td>e⁻</td>
<td>8</td>
<td>—</td>
<td>6</td>
</tr>
<tr>
<td>Dark counts</td>
<td>e⁻/ms</td>
<td>10</td>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>%</td>
<td>&lt; 5</td>
<td>&lt; 3</td>
<td>1</td>
</tr>
<tr>
<td>Read-out latency</td>
<td>μs</td>
<td>90</td>
<td>15</td>
<td>200</td>
</tr>
</tbody>
</table>

Requirements are similar for APD WFS. CCD-66 also used for Scoring and FPA Tracker.
24×24 Shack-Hartmann WFS

CCID-66 Latency

- Integrate
- Transfer 83 rows to frame store
- Transfer 37 unused rows to serial register and dump
- Transfer and read out 2 rows
- Transfer and dump 2 rows
- Repeat 11 times
- Latency > 180 μs
  166×0.4μs + (24+11)×16×0.2μs
CCID-66 Progress

- Completed back-illumination processing
- 4 wafers, 32 devices
- MBE passivation: good qe in ultraviolet
- Hydrogen sinter: reduce dark current
- Used new anti-reflection coat
- Packaged with 2-stage TEC
- Delivered to SciMeasure in 2009 July, expect cameras 2009 October

Planned CCD Work

- Build and tune electronics (SciMeasure)
- Characterize CCID-66 at SOR
- Shared wafer lot with TMT+Keck
- Improved CCID-66
  - 1 and 2 stage amplifiers
  - 2 phase serial register
  - Dump drain
Shared Wafer Lot

- 160 x 160 pixel adaptive optics (AO) imagers
- 256 x 256 pixel AO imagers
- 1k x 1k imagers
- Polar Coordinate Detector Prototype
- 12 wafer lot
  - split into 3 different implant levels for the planar JFET
  - 4 wafers per split

APD Design Details

- High Fill Factor
- Geiger Mode Operation
- Photoelectrons collected outside of punch-through region diffuse into the cathode for breakdown
- With proper tuning of p+ doping, mostly drift detection with some diffusion
- Photons in center of quad-cell are efficiently collected
APD Array Prototype

APD Array Package

- Lid
- Sensor
- Interposer board
- Interposer spacer
- TEC
- TEC spacer
- Case
APD Electronics

16×16 Prototype Tests

Dark frames (0.5 ms integration)

Mean = 2.7 counts

STD = 2.3 counts
16×16 Prototype Tests

Histograms of Dark Counts (0.5 ms int.)

<table>
<thead>
<tr>
<th></th>
<th>0.5 ms</th>
<th>Mean</th>
<th>STD</th>
<th>Mean Good</th>
<th>STD Good</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>10.3</td>
<td>62.0</td>
<td>2.7</td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td>STD</td>
<td>1.3</td>
<td>1.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Photon Transfer Curve

Read noise 0.6 e−; Gain 1.29 e−/DN
Should be read noise 0 e−; gain 1.0 e−/DN; finer sampling at low flux should show this.
APD Model vs. Data

- Variance
  \[ \tau = 0.00045 \]
  \[ p_r = 0.8 \]
  6-clock-cycle quench (deterministic)

PT data from ten pixels on device #6
Nominal \( \tau \) is 0.000128

Centroiding Accuracy Contours: APD vs. CCD

- CCD (horizontal lines) has unity QE, 27 e- readout noise
- APD (curves) has 50% PDE and varying crosstalk
- Middle graph has 4x longer clock period than left graph, right graph has 4x stochastic prolongation of quench time
- Stochastic quench prolongation produces noisy resetting at high fluxes, degrading performance much more than with just the extra signal blockage

results courtesy of B. Aull
APD Array Status

- BBAPD Lot 2 Complete
- 16×16 & 32×32 quad-cells, test structures
- Tests show high peak field causes tunneling current, initiates linear-mode avalanche near edge of device
- Other wafers will get P implant to reduce field at edge
- SOR2008 ROIC complete
  - Included Tyrell arbiter circuits (resolve crosstalk)
  - Improved reset circuit (< 224 ns)
  - Modified PCB for extra bias voltages

Summary

- Expect CCID-66 camera delivery late 2009
- Shared CCD lot 2010
- Continue APD development
Backup

New 3.5 m Coudé Room

- Turbulence simulator
- In-lab check-out
- DM & FSM not at pupil
- Compact design
- LGS + NGS capability

Image by J. Spinhirne and B. Agena
### New Sensors for 3.5 m

<table>
<thead>
<tr>
<th>Name</th>
<th>Make</th>
<th>Sensor (array size)</th>
<th>Model</th>
<th>λ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGS WFS</td>
<td>MIT/LL</td>
<td>Si APD 32x32 subapertures</td>
<td>APD32</td>
<td>589 ± 15</td>
</tr>
<tr>
<td>LGS WFS Interim</td>
<td>MIT/LL</td>
<td>Si CCD JFET 160x160 pixels</td>
<td>CCID-66</td>
<td>589 ± 15</td>
</tr>
<tr>
<td>NGS WFS</td>
<td>MIT/LL</td>
<td>Si APD 32x32 subapertures</td>
<td>APD32</td>
<td>480 - 640</td>
</tr>
<tr>
<td>NGS WFS Interim</td>
<td>MIT/LL</td>
<td>Si CCD JFET 160x160 pixels</td>
<td>CCID-66</td>
<td>480 - 640</td>
</tr>
<tr>
<td>Tilt+Focus</td>
<td>MIT/LL</td>
<td>Si APD 32x32 subapertures</td>
<td>APD32</td>
<td>480 - 640</td>
</tr>
<tr>
<td>Tilt+Focus Interim</td>
<td>MIT/LL</td>
<td>Si APD 16x16 subapertures</td>
<td>APD16</td>
<td>480 - 640</td>
</tr>
<tr>
<td>J-Band Imager</td>
<td>Teledyne</td>
<td>InGaAs 1020x1020 pixels</td>
<td>Hawaii-1RG</td>
<td>1100 - 1350</td>
</tr>
<tr>
<td>NGS Tracker</td>
<td>TBD</td>
<td>TBD quad cell</td>
<td>TBD</td>
<td>480 - 640</td>
</tr>
<tr>
<td>Scoring Sensor</td>
<td>MIT/LL</td>
<td>Si CCD JFET 160x160 pixels</td>
<td>CCID-66</td>
<td>650 - 1000</td>
</tr>
<tr>
<td>Correlation Tracker</td>
<td>MIT/LL</td>
<td>Si CCD JFET 160x160 pixels</td>
<td>CCID-66</td>
<td>480 - 640</td>
</tr>
<tr>
<td>Acquisition (x3)</td>
<td>Q-Imaging</td>
<td>Si EMCCD 512x512</td>
<td>02v CCD97</td>
<td>480 - 1000</td>
</tr>
</tbody>
</table>

### Formats of Sensor Data

<table>
<thead>
<tr>
<th>Camera Name (unofficial)</th>
<th>Sensor array size</th>
<th>Pixels vert per channel (read out)</th>
<th>Pixels horiz per channel (read out)</th>
<th>Bits</th>
<th>Pixels per channel</th>
<th>Chans</th>
<th>Pixel rate per channel (Mpix/s)</th>
<th>Total pixel rate (Mpix/s)</th>
<th>Interface (words x bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGS WFS</td>
<td>32x32 subaps</td>
<td>6</td>
<td>32</td>
<td>10</td>
<td>192</td>
<td>4</td>
<td>60</td>
<td>240</td>
<td>CL Medium (4x10)</td>
</tr>
<tr>
<td>LGS WFS Interim</td>
<td>160x160 pixels</td>
<td>6</td>
<td>32</td>
<td>10</td>
<td>192</td>
<td>4</td>
<td>60</td>
<td>240</td>
<td>CL Medium (4x10)</td>
</tr>
<tr>
<td>NGS WFS</td>
<td>32x32 subaps</td>
<td>24</td>
<td>16</td>
<td>14</td>
<td>384</td>
<td>12</td>
<td>3</td>
<td>36</td>
<td>CL Medium (2x16)</td>
</tr>
<tr>
<td>NGS WFS Interim</td>
<td>160x160 pixels</td>
<td>6</td>
<td>32</td>
<td>10</td>
<td>192</td>
<td>4</td>
<td>60</td>
<td>240</td>
<td>CL Medium (4x10)</td>
</tr>
<tr>
<td>Tilt+Focus</td>
<td>32x32 subaps</td>
<td>24</td>
<td>16</td>
<td>14</td>
<td>384</td>
<td>12</td>
<td>3</td>
<td>36</td>
<td>CL Medium (2x16)</td>
</tr>
<tr>
<td>Tilt+Focus Interim</td>
<td>16x16 subaps</td>
<td>24</td>
<td>16</td>
<td>14</td>
<td>384</td>
<td>12</td>
<td>3</td>
<td>36</td>
<td>CL Medium (2x16)</td>
</tr>
<tr>
<td>J-Band Imager</td>
<td>1024x1024 pixels</td>
<td>1016</td>
<td>1016</td>
<td>16</td>
<td>1032256</td>
<td>16</td>
<td>5</td>
<td>80</td>
<td>CL Base (1x16)</td>
</tr>
<tr>
<td>J-Band Imager</td>
<td>1020x1020 pixels</td>
<td>1016</td>
<td>1016</td>
<td>16</td>
<td>1032256</td>
<td>16</td>
<td>5</td>
<td>80</td>
<td>CL Base (1x16)</td>
</tr>
<tr>
<td>NGS Tracker</td>
<td>16x16 subaps</td>
<td>64</td>
<td>16</td>
<td>14</td>
<td>1024</td>
<td>16</td>
<td>3</td>
<td>48</td>
<td>CL Base (2x16)</td>
</tr>
<tr>
<td>NGS Tracker</td>
<td>160x160 pixels</td>
<td>64</td>
<td>16</td>
<td>14</td>
<td>1024</td>
<td>16</td>
<td>3</td>
<td>48</td>
<td>CL Base (2x16)</td>
</tr>
<tr>
<td>Scoring Sensor</td>
<td>160x160 pixels</td>
<td>64</td>
<td>16</td>
<td>14</td>
<td>1024</td>
<td>16</td>
<td>3</td>
<td>48</td>
<td>CL Base (2x16)</td>
</tr>
<tr>
<td>Correlation Tracker</td>
<td>160x160 pixels</td>
<td>64</td>
<td>16</td>
<td>14</td>
<td>1024</td>
<td>16</td>
<td>3</td>
<td>48</td>
<td>CL Base (2x16)</td>
</tr>
<tr>
<td>Acquisition (x3)</td>
<td>512x512 pixels</td>
<td>512</td>
<td>512</td>
<td>14</td>
<td>262144</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>Firewire (IEEE1394)</td>
</tr>
</tbody>
</table>

*gray = SOR Fabric interface*
### Types of Sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Pixels (total)</th>
<th>Pixel Size (μm)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT Lincoln APD16</td>
<td>32×32</td>
<td>50</td>
<td>NGS Tracker, Tilt+Focus</td>
</tr>
<tr>
<td>MIT Lincoln APD32</td>
<td>64×64</td>
<td>50</td>
<td>LGS WFS, NGS WFS Tilt+Focus</td>
</tr>
<tr>
<td>MIT Lincoln CCID-66</td>
<td>160×160</td>
<td>21</td>
<td>Scoring Sensor, FPA Tracker</td>
</tr>
<tr>
<td>Teledyne Hawaii-IRG</td>
<td>1000×1000</td>
<td>18</td>
<td>J-Band Imager</td>
</tr>
<tr>
<td>MIT Lincoln 1 k×1 k</td>
<td>1000×1000</td>
<td>13</td>
<td>L-Band Imager</td>
</tr>
<tr>
<td>e2v CCD97</td>
<td>512×512</td>
<td>16</td>
<td>Acquisition</td>
</tr>
</tbody>
</table>

Discussed in this talk

### Selected Requirements

<table>
<thead>
<tr>
<th>Sensor</th>
<th>λ (μm)</th>
<th>Read noise (e−)</th>
<th>Dark count (e−/ms/pix)</th>
<th>Frame rate (10%/s)</th>
<th>Crosstalk (%)</th>
<th>Latency (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGS WFS</td>
<td>0.589±0.015</td>
<td>0 [0]</td>
<td>0.5 [0.5]</td>
<td>4 [10]</td>
<td>5 [3]</td>
<td>90 [15]</td>
</tr>
<tr>
<td>Tilt+Focus</td>
<td>0.48 – 0.64</td>
<td>0 [0]</td>
<td>0.5 [0.5]</td>
<td>2 [4]</td>
<td>5 [3]</td>
<td>90 [15]</td>
</tr>
<tr>
<td>I-Band</td>
<td>0.65 – 1.0</td>
<td>20</td>
<td>10 [1]</td>
<td>0.004</td>
<td>3 [1]</td>
<td>—</td>
</tr>
</tbody>
</table>
CCID-66 AR Coating

Mira Design Details

- InGaAs diode array
- Indium bump-bonds to ROIC
- Each pixel has an amplifier
- Voltage signals output to a multiplexer
- 16 channels in parallel, 16-bit digitizer
- Read-out takes approx. 0.7 sec
- No anti-blooming, no guide window
SciMeasure electronics: functions divided into modules

courtesy of R. Dueck

SciMeasure electronics and camera head for CCID-26
16×16 APD Prototype Tests

Mean

STANDARD DEVIATION

APD Model Results

- 30 MHz polling clock, 0.1 ms integration time
- Roll-over due to dead time
- At low flux, single detector slope is unity even with crosstalk
- At low flux, quad response is non-Poissonian with crosstalk

results courtesy of B. Aull
Mira QE at 1230 nm

Source: Teledyne_FPA_Performance_156_report.pdf

Mira Noise

Source: Teledyne_FPA_Performance_156_report.pdf
Mira Dark Current

Source: Teledyne_FPA_Performance_156_report.pdf

Mira test parameters

- Measure
  - read noise, gain, well capacity (PTC)
  - dark current
  - quantum efficiency (1250, 1064, 1550 nm)
- Full frame, slow (low noise) readout
- Temperature controlled 85 kelvins
Read noise ≈ 62 e–
Gain ≈ 2.1 e–/count
1016×1016 pixels
> 99 percent operable
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