Development of a 3.5 Gigapixel Camera for the Large Synoptic Survey Telescope (LSST)

- John Oliver -
- 28 Mar 2005 -

Contributing institutions (Camera development only)

- SLAC
- Brookhaven Nat'l Lab
- Lawrence Livermore Nat'l Lab
- U. Illinois
- Harvard
- Harvard Smithsonian - CfA
- NOAO
- U. Arizona

Funding agencies (pending)

- DoE
- NSF
- Research Corp
- LSST Corp
- Private donors
The LSST Science Mission

• Weak gravitational lensing \(\Rightarrow\) Dark matter surveys

Reconstructed dark matter map

C. Stubbs

T. Tyson
The LSST Science Mission (cont')

- High statistics Type 1a SN search, ~ $10^5$/yr
- Photometric red shift in 5 filter bands
- Hubble constant, cosmological constant

\[ \text{Redshift} = \frac{\Delta \lambda}{\lambda} \]

C. Stubbs
The LSST Science Mission (cont’)

- Near Earth Asteroids (NEAs)
- Potentially Hazardous Asteroids (PHAs)
- Other Solar System studies
The LSST Science Mission (cont’)

• Galactic structure
The optics: 3 mirror design (Seppala et al)

- Focal plane
  - f/1.25
  - flat
  - 64 cm/dia
  - 3.5 deg FoV

- Correction lenses

- “Long design” has been replaced by “short design” → M3 coincident with M1
- Focal plane much closer to M2
- Optics are “active” (but not “adaptive”) by means of flexure actuators on mirrors for wavefront corrections.
Mirror fab at U. Arizona (not LSST)
The Telescope
Focal Plane Requirements

- $10\mu \times 10\mu$ pixels
- $0.2''/\text{pixel}$
- $64 \text{ cm dia} \rightarrow \sim 3.5 \times 10^9 \text{ pixels}$
- Fill factor $> 90\%$ over FPA
- Flatness: $10\mu$ peak-valley over entire FPA
- Dark current: $\sim 2-4 \text{ e/pixel/s}$
- Read noise: $\sim 5\text{ e}$
- Max charge per pixel: $10^5 \text{ e}$
- Nominal exposure time: $10 \text{ sec}$
- Read time: $2 \text{ sec}$ (1 sec optional)
- PSF (sensor point spread function): $10\mu \text{ fwhm (7.5 m goal)}$
- QE spec

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Min QE</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>55%</td>
<td>60%</td>
</tr>
<tr>
<td>600</td>
<td>80%</td>
<td>85%</td>
</tr>
<tr>
<td>800</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>900</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>1,000</td>
<td>25%</td>
<td>45%</td>
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</table>
Sensor Technologies
-CCDs & Hybrid CMOS*

(Note: Hybrid CMOS under consideration but not described here)

CCDs

Typical CCD specs
- Sensitivity ~ 4 μV/e (~ 30 ff, gain~0.8)
- Voltage noise density: $e_n \sim 10 - 20$ nV/$\sqrt{\text{Hz}}$
- Animation
- Four phase has advantages of
  - Higher well capacity
  - Less “ground bounce” (simultaneous opposite phases)
- “Science grade” CCDs are “back illuminated”
Noise vs readout speed tradeoff

Read techniques (Dual Correlated Sampling)
- Clamp & Sample
- Dual Slope Integration

Push signal charge onto source follower

Source follower output

\[ \text{enc} = \frac{e_n}{S \cdot \sqrt{T_{\text{int}}}} \] not including 1/f
Example

- $T_{\text{int}} = 1\, \mu s$
- $e_n = 20\, \text{nV}/\sqrt{\text{Hz}}$
- $S = 4\, \mu \text{V/e}$
- $F_{\text{nc}} \approx 5\, \text{e rms}$
- Max readout speed < 500 kHz
- Conservative design goal: 250 kHz to 500 kHz pixel read rate
- Required number of CCD channels to achieve 2 second readout @ 250 kpixels/s

$$\frac{(3.5 \cdot 10^9 \text{ pixels})}{(250\, \text{kHz})(2\, \text{sec})} \approx 7,000$$
Baseline LSST Focal plane design

- 200 segmented CCDs
- 32 segments each (0.5 Mpixels), 16 MPixels/CCD
- 6,400 CCD output ports total

Unit cell

- 512 high
- 2k wide
- 20 mm x 5 mm
- Serial registers top and bottom
- 2 output ports

Note: Approximately 100 bond pads left and right sides
Sensor thickness issues[1]

Fundamental trade-offs

• Absorption length
  ➢ Very small at 400nm; blue photons convert at the back window
  ➢ Increases rapidly at 1000 nm: red photons penetrate deeply
  ➢ High QE into the red favors thicker sensors (100s microns or thicker)

• Charge diffusion
  ➢ Deteriorates point spread function
  ➢ Small psf toward the blue favors thin sensors (10s of microns)

• QE near 1000 nm is very temp sensitive
• High QE favors high temperature
• Low pixel leakage current favors low temperature

[1] “Study of Silicon Sensor Thickness Optimization for LSST”
Sensor thickness issues – cont'

Thickness must be of order 100 μ or greater

Ref [1] V. Radeka, P. O'Connor
Sensor thickness issues – cont'

QE vs Thickness & Temp @ $\lambda = 1,000$ nm

Expected range

Ref [1] V. Radeka, P. O'Connor
Point spread function simulations/calculations

\[ \tan^{-1}\left(\frac{1}{2n_f}\right) = 6.37^\circ \text{ max.} \]

\[ I(x) = I_0 \exp\left(-\frac{x}{l_{abs}}\right) \]

PSF degradation due to:
- Charge diffusion
- Beam spreading to point of photon conversion
- Monte Carlo simulation

Ref [1] especially P. Takacs
Point spread function simulations/calculations – cont’

(a) (b) (c)

psf degradation due to beam divergence only

Note: psf for short wavelength can be improved somewhat by defocus (into Si)

Ref [1] P. Takacs
PSF FWHM – divergence component (μm)

<table>
<thead>
<tr>
<th>λ [nm]</th>
<th>( I_{\text{in}} ) [μm]</th>
</tr>
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<tbody>
<tr>
<td>300</td>
<td>997</td>
</tr>
<tr>
<td>200</td>
<td>981</td>
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<tr>
<td>100</td>
<td>948</td>
</tr>
<tr>
<td>50</td>
<td>905</td>
</tr>
<tr>
<td>10</td>
<td>782</td>
</tr>
<tr>
<td>2</td>
<td>565</td>
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**Focus displacement (μm)**

<table>
<thead>
<tr>
<th>-25</th>
<th>15</th>
<th>5</th>
<th>25</th>
</tr>
</thead>
</table>

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**PSF as a function of focal plane displacement** (a) without diffusion; (b) with diffusion. Symbols are results of Monte-Carlo simulations, lines are analytic model based on geometrical optics. Sensor thickness 100mm; temperature 173K; substrate resistivity 10 kW-cm, n-type; average electric field 2000 V/cm. The LSST plate scale is 0.2" per 10mm pixel.” Ref [1]
Sensor Packaging
- Sensor/Substrate Connection -

MIT-LL

Sensor/"handle" wafer combination

Substrate (e.g. Silicon nitride)
Sensor Packaging
- Sensor/Substrate Connection -

MIT-LL

Etch to backside of bond pad
Sensor Packaging
- Sensor/Substrate Connection -

MIT-LL

Wirebond to AlN
Sensor Packaging
- Sensor/Substrate Connection -

E2V

Sensor

Substrate (e.g. Silicon nitride)
Sensor Packaging

- Sensor/Substrate Connection -

E2V

Wirebond to substrate
Sensor Packaging  
- Sensor/Substrate Connection -

STA

Sensor  
Indium bump bonds

Substrate (e.g. Silicon nitride)
Sensor Packaging
- Sensor/Substrate Connection -

STA

Epoxy underfill
**Sensor Packaging**

- Completed packaging concept -

**Vendor guarantees**

- Flatness of sensor surface
- Parallelism to mounting studs
- To 5μ p-v
- Current “state of the art” is 5μ – 10μ.

Improvements in progress

- Nine such modules mounted to a local “raft” structure
- 25 rafts mounted to a stiff “integrating structure”
Raft Structure

T. Thurson, SLAC
Integrating structure FEA ~ 1 μ gravity deflections (steel)

Structure is actuated in x, y, & θ
Raft structure

FPA structure

raft cage

cold post

raft backplane
Electronics support cage

Raft platform

Front-end readout board

Raft backplane

Cold plate

To back-end electronics

3 X 3 CCDs

Electronics support cage

P. O'Connor, BNL
Additional focal plane elements

- Wavefront sensors (e.g. “Schack-Hartman”) provide feedback (slow) to active mirror control.

- Guide sensors on known stars to provide feedback to x,y, & theta motion to focal plane array
- High frame rate ~ 100 Hz
Camera Dewar & Electronics

Design goals
- Highly integrated: 2 orders of magnitude larger channel count than existing telescopes (both ports & pixels)
- Photons in → photons out (data fibers), minimum Dewar penetrations

CCDs
Front End Cards
Dual Slope Integrator
ASIC

“Cold” thermal zone ~ -100°C

Back End Cards
ADCs, Frame Buffers

Single ~2.4 Gb/s fiber per Datacard

“Warm” thermal zone ~ -20°C to -40°C

Dewar wall

• Timing & control interface
• “Engineering” data readout
• ~ 10^3 total Dewar penetrations

Data Card
Fiber driver

Data Bus
Timing Bus

Control interface

28 Mar 2005

BNL Instrumentation Seminar
Single CCD “slice”

Front End Module (FEM)

CLK Translator ASIC

Logic level control/timing signals (LVDS on flex-cable)

“Back End Electronics” “slice” of a “Data Card”

Timing bus

CCD

(2x) 16 ch Signal Processor ASICS (DCS)

Misc DACs, regs, Temp sensors etc

Low level analog signals (differential analog on flex cable)

COTs 16-bit ADCs

(2x) Frame buffers (256 Mb DRAMs)

Data bus

4k x 4k CCD w/32 read ports

4k x 4k CCD w/32 read ports

Front End Module (FEM)

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Data bus

4k x 4k CCD w/32 read ports
Additional camera features

- "Guide sensors" in focal plane with feedback to x-y motion of FPA to offset "wind-shake"
- "Wavefront sensors" as feedback to mirrors’ "active optics"
- Single Ethernet control cable in
  - 20 – 30 optical data fibers (~ 2 Gb/s) out to DAQ
  - ~ 40,000 bond pads on CCDs → ~1,000 Dewar penetrations
Project Status (FPA)

• 2005
  ➢ Design studies
  ➢ Simulations
  ➢ Vendor discussions (sensors, CCDs & Hybrid CMOS)
  ➢ Electronics prototyping, ASIC designs
  ➢ Proposals
  ➢ Telescope site selection (Chile, Mexico-Baja)

• 2006
  ➢ Sensor prototypes & testing
  ➢ Electronics development,

• 2007
  •
  •
  •
  •

• 2012 ➔ First light