Development of a 3.2 Gpixel Camera for the Large Synoptic Survey Telescope (LSST)

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Overview

• Major science drivers
• Critical specifications
• Telescope
• Camera
  ➢ Sensors
  ➢ Readout electronics
Major Science Drivers

- “Synoptic survey” : Comprehensive & multipurpose
- Survey entire visible sky (20,000 deg$^2$) in five filter bands (400 nm – 1,000 nm) every 3 nights
  - Dark matter survey  →  Weak gravitational lensing
  - Dark energy probe  →  Type 1a supernovae discovery > $10^3$/night
- Galactic structure
- Near Earth Objects & Potentially Hazardous Asteroids
- Transient phenomena
Dark Matter Survey
- Weak lensing-

Apparent rotation of ellipticities of faint galaxies
→ Cosmic Shear

T. Tyson
Dark Matter Survey
- Weak lensing -

Strongly lensed galaxy

- Weak lensing -
Measurements of ellipticity correlations of large numbers of faint galaxies
→ “cosmic shear”

Tomographic reconstruction of dark matter density from shear data

T. Tyson

Dark Energy Measurement
- Type 1A Supernovae -

- High statistics measurements of Type 1A SN $\rightarrow > 10^3$ per observing night
- Redshift & distance measurement
  - Fixed luminosity (standard candle) $\rightarrow$ distance
  - *Photometric* redshift measurements in five filter bands to $Z = 1.2$

Deviations from linearity
$\rightarrow$ Acceleration
$\rightarrow$ Dark Energy
$\rightarrow$ Cosmological constant
Differential images of SN 1987A

A. Becker, U. Washington (SDSS)
Critical Specifications
- Telescope -

• Survey telescope figure of merit “Etendue” \((\text{Dia})^2 \times (\text{FoV solid angle})\)

• Large aperture ~ 8.4 m, (6.7 m equivalent clear aperture)
• Large FoV ~ 3.5 deg
• Large focal plane ~ 64 cm diameter
• LSST Etendue ~ 320 \((\text{deg}^2)(\text{m}^2)\)
• High “throughput”
Optics

- Convex secondary
- Location of camera
- Corrector lenses to form flat image plane

8.4 m primary/tertiary 6.7 m effective aperture
Active optics [*]
fl~10 m \(\rightarrow\) fl1.2 beam

[*] Corrects gravitational sag due to mirror inclination

15-19 Sept-'08 TWEPP 2008 Naxos, Greece
Spin casting at the Steward Mirror Lab U. Arizona

Lid is lifted from the primary/tertiary mirror blank 23-July-08
Made possible by grant from Bill Gates, Charles Simonyi – Microsoft Corp.
Critical Specifications
- Camera & Sensors-

- Image sensors
  - Large focal plane → ~ 64 cm dia
  - ~ 200x 16-Mpixel CCD image sensors, 10μ pixels (0.2") → 3.2 Gpixels
  - Back side illuminated
  - Small “Point spread function” – PSF (minimum spot size) < 7.5 μ (10 μ max)
  - Low f-number = 1.2 → must be flat to 10μ (peak-valley) across focal plane
  - High quantum efficiency 400 nm – 1,000 nm (40%, 80%, 40%)
  - Low leakage < ~ 1 e/s per pixel → T~ -100 C
  - High “full well” capacity ~ 100,000 e/pixel
- Back-to-back 15 second exposures on each piece of sky → Cosmic ray rejection
- 2 second readout → low dead time, high throughput
- Sky shot noise limited images → CCD read noise ~ 5 e rms
- Focal plane contained in a contamination free evacuated cryostat to prevent fogging of sensor surfaces

Note: Last three requirements highly constrain the readout topology
Critical Specifications
- Implications for readout & sensors -

Typical sensitivity  \( S = 5 \, \mu V/e \)  
\( \Rightarrow \)  \( C_g \approx 32 \, \text{ff} \)

Dominant noise source  \( \Rightarrow \) “kTC noise”

\[
\sigma_{kTC} = \sqrt{k \cdot T \cdot C_g} \Rightarrow \sqrt{\frac{V_T}{S}} \approx 50e \, (\text{cold})
\]

kTC noise easily removed by
- Correlated Double Sampling (Clamp & Sample)
- Dual Slope Integration (optimal)
Dual Slope Integration sequence
a) Reset
b) Integrate baseline up
c) Move charge to output fet
d) Integrate signal down

\[ \sigma = \frac{e_n}{S} \cdot \frac{1}{\sqrt{T_{\text{int}}}} \]

For typical “science grade” CCD

\[ e_n \approx 10 \text{ to } 20 \frac{nV}{\sqrt{Hz}} \]

→ \( T_{\text{read}} > \sim 2 \mu s/\text{pixel} \)
Critical Specifications
- Implications for Sensors -

• At $f_{\text{pixel-read}} = 500$ kpixels/sec $\rightarrow$ 32 sec Read Time (with one output amplifier)

$\rightarrow$ Each CCD must have 16 parallel outputs & electronic readout channels
$\rightarrow$ ~200 sensors $\rightarrow$ 3,200 parallel readout channels

• 16x segments, gap-less
• $\frac{1}{2}$ k x 2k each
• ~40 mm x 40 mm
Critical Specifications
- Implications for Sensor Thickness -

Conflicting requirements →

• Small PSF
  • Blue light has very small absorption length
    → favors thin sensor to minimize diffusion
    → favors full depletion in high resistivity silicon

• High QE in red
  • Red light has very long absorption length
  • Thin sensor would be transparent in red & near IR → favors thick sensor

• Optimization: “Study of Silicon Sensor Thickness Optimization for LSST” [1]
  • Calculations
  • Simulations


Effect of sensor thickness on PSF

Beam divergence: f1.2 beam $\Rightarrow$ 46 deg max

Beam divergence in red, (simulation)

PSF vs Thickness: Divergence + diffusion
$\Rightarrow$ Sets thickness limit $t \leq 100\mu$

LSST acceptable

LSST target
Effect of sensor thickness on QE

Silicon QE @ 1000 nm vs Thickness

To get > 25% QE @ -100°C \( \Rightarrow t \geq 100 \mu \)

Optimal sensor thickness = 100 \( \mu \)
Sensor Requirements cont’

- Temperature Stability -

• Sensor QE is very temperature dependent near ~ 1,000 nm
• For accurate photometry, temperature stability ~ +/- 0.1°C
• Sources of heat
  • CCD gates (small)
  • CCD output amplifiers (medium)
    • Heat radiation through lens (large ~ ½ W per sensor)
• Heat removal by thermal straps to a cryogenic plate
• Thermal control loop
  • High stability temp sensors close to CCD package
  • Heaters → 0 to ~ ¼ W per sensor on sensor package or cold straps
An array of “study” sensors has been produced by
- e2v
- STA/ITL
  - 100μ to 150μ thickness
  - All fully depleted between 10V – 25V “back window bias”
- Sizes 1 MPixels to 16 Mpixels
- Multiple output ports
- Tested @ BNL
- Not final package

“Pre-Production” sensors
- E2v
- STA/ITL
- 100μ thickness
- Final packaging
  - 4 side buttable
  - flat to 6 μ (p-v)
- Expected → Fall 2010
Focal Plane Construction

• 3 x 3 arrays of CCDs are mounted into a precision “Raft”
• 144 Mpixels per Raft
• 21 Rafts are mounted onto a rigid (SiC) “Grid”
• Major issues
  • Each sensor has ~ 150 bond pads
  • Total of ~ 30,000 bond pads
  • Sensors reside in high-vacuum cryostat
  • To avoid 30,000 cryostat feedthroughs, all readout electronics is placed within cryostat.
  • Each Raft is modular. All its readout electronics must reside in the shadow of the Raft.
• Raft electronics is divided into two sections
  • Analog, front end, in cryo-zone (-100C)
  • ADC/digital in warmer zone (-40C)
Camera Overview

- Filters
- Cryostat
- Back End Electronics
- Ethernet
  High level commands
- Shutter
- Front End Electronics
- Utilities, Timing & Control
- Data fibers to DAQ
- FPA
  -100°C
- -40°C
Focal Plane Construction

9 Sensor Raft

- Trimmed for flatness requirement during assembly
- Very high image “fill factor” > ~ 90%

Raft Tower Assembly

Raft
FEE
BEE
21 “Science Rafts”
4 special purpose
“corner Rafts”

~ 64 cm dia

“Guide” sensors for
telescope fine steering

“Wavefront” sensors
determine mirror
distortions for active
mirror adjustments

Cryostat Assembly
Camera with filters
Front End Electronics

• Located within “grid” : Operates at – 100C to – 120C
• Each “FEB” services 24 CCD segments – 6 FEBs per Raft
• Analog functionality in 2 ASICs
  • Analog Signal Processing ASIC (AS PIC)
  • LPNHE/IN2P3 collaboration[1] - France
• Dual Slope Integrator : Programmable gain
• Specs:
  • $e_n < \sim 5 \text{nV/rt(Hz)}$
  • x-talk $< \sim 10^{-3}$ (achieved in 1st version)
• Differential output to Back End Boards (ADCs) via shielded flex cable
• 8 channel ASIC, AMS 0.35μ CMOS @ 5V, ~ 25mW/ch

Front End Electronics – cont

Sensor Control Chip (SCC)

- ORNL – U. Tennessee [1]
- Receives LVDS signals from BEBs → Converts to Clock levels to CCDs
- Parallel gates (4), Serial gates(3), Reset(1)
- Clock Hi/Lo levels in range 0V to ~ 25V, programmable on BEB
- 4 channels per chip, 2 chips per CCD.
- CCD bias level buffers in range up to ~ 30V
- ATMEL BCD-SOI process. HV to 45V
- Status
  - 1st submission tested & fully functional
  - Some pulse shape “wrinkles” (fully understood in simulation)
  - 2nd submission → Fall ’08

Additional FEB functionality

- Temp sensing & other usual monitoring
- Raft heaters → Part of focal plane thermal control loop

Back End Electronics

Raft Control Crate

- 6x Back End Boards (BEBs)
- 24 channels ea, 18 bit 1 MHz ADCs (COTS)
- Temp sensor processing
- Programmable bias & clock levels for FEBs
- Sensor heater control
- Misc slow controls

FPGA (Xilinx) based programmable “Readout State Machine”
- Collects all ADC data @ 100 MHz
- All control loops stored locally
- Responds to high level commands from Timing & Control Module (TCM)
- All Rafts in fully synchronous operation
- “Rocket i/o” data output to drive data fiber to DAQ (~1.6 Gb/s)
- Power PC for non-time critical operations
Back End Electronics

- Data Volume -

• Per image: 3.2 Gpixels $\rightarrow$ ~ 7 GB
• Per minute: 4 images $\rightarrow$ ~28 GB
• Per night: ~ 600 min $\rightarrow$ ~ 16 TB
• Per year: $\rightarrow$ ~ 5 PB

• All fibers received by “Science Data System” – (SLAC)
• Public data set
Additional Electronics Issues
Thermal management

• Thermal paths & modeling
  → ICs and components to ground/thermal planes
  → “Chip scale” packaging
  → Conduction bars
  → Crates/housing
  → Cold plates / cryoplates

Board level  \( R_t \sim 20C/W \) across 2 oz copper plane

Crate level  \( R_t < \sim 0.5C/W \)
Additional Electronics Issues
Contamination & outgassing

• Outgassing materials may condense on sensor surface
• \( \sim 2 \, \text{m}^2 \) of pcb materials in cryostat
• Polyimide pcb construction (if necessary)
• Parylene (vapor deposition) or similar coatings
• Electronics separated from focal plane by molecular barriers (tortuous paths) and separate vacuum pumping
• All in-cryostat materials tested / certified in test “Materials Test Facility” @ SLAC
• Optical loss measurement over LSST pass band & residual gas analyzer (RGA)
Comparison of LSST with existing or in-development cameras

![Comparison of LSST with existing or in-development cameras](chart.png)
CD-1


R & D Camera construction Telescope construction
Telescope and site: Cerro Pachon, Chile