Synoptic?

• syn·op·tic (s-nptk) also syn·op·ti·cal (-t-kl) adj.

• 1. Of or constituting a synopsis; presenting a summary of the principal parts or a general view of the whole.

συνοπτικός
Preface
Introduction
LSST System Design
System Performance
Education and Public Outreach
The Solar System
Stellar Populations
Milky Way & Local Volume Structure
The Transient & Variable Universe
Galaxies
Active Galactic Nuclei
Supernovae
Strong Lenses
Large-Scale Structure
Weak Lensing
Cosmological Physics
“The committee recommends that LSST be submitted immediately for NSF's Major Research Equipment and Facilities Construction (MREFC) consideration with a view to achieving first light before the end of the decade.

The top rank accorded to LSST is a result of (1) its compelling science case and capacity to address so many of the science goals of this survey and (2) its readiness for submission to the MREFC process as informed by its technical maturity, the survey's assessment of risk, and appraised construction and operations costs. Having made considerable progress in terms of its readiness since the 2001 survey, the committee judged that LSST was the most ready-to-go.“

August 13, 2010
The LSST Project – $\pi \times 10^8$

- **Telescope & Site**
  - Telescope Mount
  - Mirrors (M1, M2, M3)
  - Observatory + base facility + ....

- **Data Management**
  - Data movement, storage, analysis

- **Camera**
  - Lenses, filters, sensors, electronics, etc.

*NSF*

*DOE*
The LSST Telescope

Relevant Telescope Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 mirror optical design</td>
<td></td>
</tr>
<tr>
<td>Moving structure: 300 tons</td>
<td></td>
</tr>
<tr>
<td>Altitude/azimuth rotation axes</td>
<td></td>
</tr>
<tr>
<td>Max azimuth axis accel: 10.5 deg/sec²</td>
<td></td>
</tr>
<tr>
<td>Max elevation axis accel: 5.25 deg/sec²</td>
<td></td>
</tr>
<tr>
<td>Camera is cantilevered off the Top End Assembly near the center of rotation</td>
<td></td>
</tr>
<tr>
<td>Camera normally looks down when telescope is pointing near zenith</td>
<td></td>
</tr>
</tbody>
</table>
Telescope Optics

- $f/1.23$

- < 0.20 arcsec FWHM images in six bands: 0.3 - 1 $\mu$m

- 3.5 FOV

- Etendue = 319 $m^2\text{deg}^2$
Primary/Tertiary Mirror (in fabrication)
Large machinery, large piece of glass, nm precision
The Telescope and Site includes the summit and base facilities, telescope system, & calibration hardware.

- **30 m diameter dome**
- **1,380 m² service and maintenance facility**
- **1.2 m diameter atmospheric telescope**
- **Control room and heat producing equipment**
- **Wind and light baffle**
- **300 ton telescope**
- **Service and maintenance cranes**

Base Facility in La Serena
The site has been chosen on Cerro Pachón, Chile
Summit facility final design under contract with ARCADIS Geotecnica, Santiago Chile
Telescope Dome – an interesting set of challenges

- ~14 Deg Stray Light Band
- 3.5 Deg FOV
Telescope Mount

Moving structure: 300 tons
Drive power: 450 hp
Damping: Tuned masses raise damping to 5%
First Frequency: 8.2 hz (loaded structure on bearings, pier, and summit rock)
M1M3 System

Cell deck plate support girders (blue)

M1M3 mirror within Light baffle ring

Cell deck plate with pneumatic support actuators

Mirror location Hardpoint Structure (red)

Vacuum support trusses (green)

Metrology laser tracker access stand and support tube (gray)

Cell shell and floor plate Stiffened against vacuum load

Cutaway View
Mirror supports and actuators
M2 Substrate purchased and completed by Corning using LSST non-federal funding

- M2 Blank Complete & Delivered in November 2009
  - All Requirements Satisfied 2 Months Early
  - Acid Etched Rear/Side Surfaces Ready for Pad Bonding
  - CX Surface Contour Grind ~40 μm from Final Mirror Figure

Fusion Seal
Firing
Sag
Mandrel Loading
Sag to Meniscus Shape
Sagged Surface Generating
Acid Etch Complete
CX Contour Grind Complete
Final Acceptance Complete
Delivery to Storage
Data Management

- Data from Camera –
  - 3 GigaPixels, 2 Bytes/Pixel = 6GB – every 18 s (no “Trigger”!!!)
  - 1200 GB / hour → 12 TB / observing night (ATLAS ~ 16TB/day)
- However, LSST must do fast alerts to Astronomical Community!
  Image stream from camera generates real-time transient alerts
  - Difference image based
  - 60s latency, requires ~37 TFLOPS
- Process entire survey data annually to produce a Data Release
  - Self consistent set of data products, all w/same algorithms
  - Full survey depth to SRD requirements
  - 68 PB images in survey year 10, requires ~ 300 TFLOPS
- Produce calibration data products needed by above
  - Support challenging SRD photometry requirements
Data Management II

- Make data available to scientists, with enough processing cycles and support to make it useful
  - ~57 TFLOPS, 13 PB storage dedicated for users
Data Management World View

Site Roles and their Functions

- **Base Facility**
  Real-time Processing and Alert Generation, Long-term storage (copy 1)

- **Archive Center**
  Nightly Reprocessing, Data Release Processing, Long-term Storage (copy 2)

- **Data Access Centers (DACs)**
  Data Access and User Services

- **System Operations Center (SOC)**
  System Supervisory Monitoring Control & End User Support/Help Desk

* Co-located DAC shares infrastructure with Archive Center
** Co-located DAC shares infrastructure with Base Facility
The Camera......

- 3.2 Gigapixels
- 0.2 arcsec pixels
- 9.6 square degree FOV
- 2 second readout
- 6 filters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>1.65 m</td>
</tr>
<tr>
<td>Length</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Weight</td>
<td>3000 kg</td>
</tr>
<tr>
<td>F.P. Diam</td>
<td>634 mm</td>
</tr>
</tbody>
</table>
Unique technical challenges drive camera design

- Very large field of view (9.6 square degree FOV) implies a physically large focal plane (64-cm diameter) with small (10 μm) pixels
  ⇒ Mosaic of a large number (189) of sensors with narrow interchip gaps (250 μm)

- Fast f/1.2 beam leads to short depth-of-focus
  ⇒ Tight alignment and flatness tolerances (15 μm p-to-v) on the sensor array

- Broad spectral coverage (350 – 1040nm)
  ⇒ Deep, fully depleted CCDs, but with minimal charge spreading; 6 filters

- Fast readout to maintain high efficiency given the short exposures (3.2 Gigapixels in 2 seconds)
  ⇒ Parallelized design and sensors which are highly segmented (16 readout ports)

- Large number of signal lines and large cryostat & low noise
  ⇒ Electronics must be implemented in the cryostat

- Camera located in the telescope beam
  ⇒ Tight constraints on envelope, mass, & heat dissipation
Integrated complex sub-systems tightly packaged within the telescope’s optical constraints
Walk-through 1: Overall view

- Camera housing and back flange
- L1-L2 Lens assembly
Walkthrough 2: Camera partial assembly showing Auto Changer

Filter Auto Changer

Filter

Transmission (%)

Wavelength (nm)

u g r i z y

Wavelength (nm)

u g r i z y
Walkthrough 3: Camera partial assembly showing Shutter
Walkthrough 4: Camera partial assembly showing Carousel, Cryostat, and detector plane past L3 lens.
Walkthrough 5: Cryostat section showing detectors, structure and thermal control elements

Science Raft Tower
- 3 x 3 array of science sensors
- Front end electronics

Corner Raft Tower
- 2 guide sensors
- 1 wavefront sensor
- Front end electronics

Grid assembly
- Cesic®

L3 lens assembly
The Sensors subsystem consists of the 21 “science rafts” that make up the 3.2Gpix focal plane.

**4K x 4K CCD**
- 10µm pixels, .2 arc sec
- extended red response
- 16 outputs
- 5µm flatness
- Back-side illuminated

**FOCAL PLANE WITH 21 SCIENCE RAFTS + 4 CORNER RAFTS**

**RAFT**
- 9 CCDs
- coplanarity 6.5µm

**TOWER**
- CCDs + front end electronics
- 180K operation
- An autonomous, fully-testable and serviceable 144 Mpixel camera
CCDs

- Charge Coupled Devices –
  - Willard Boyle, George Smith (invented 1969, Nobel 2009)

- Areal array –
  - “parallel shifts” – data to output register (2k)
  - “serial shifts” – data to electronics (512)
# CCD Challenges

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Specification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large field of view implies physically large focal plane (64cm $\Phi$)</td>
<td>Modular mosaic focal plane construction</td>
<td>21 rafts $\times$ 9 4K CCDs/raft 189 CCDs total 3.1Gpix</td>
</tr>
<tr>
<td>Fast f/1.2 beam, shallow depth of focus</td>
<td>Tight alignment and flatness tolerance</td>
<td>Flatness: 5$\mu$m Alignment (z axis): 10$\mu$m</td>
</tr>
<tr>
<td>Plate scale 20”/mm</td>
<td>Small pixels, close butting</td>
<td>Pixel: 10$\mu$m Chip-chip gap: 250$\mu$m</td>
</tr>
<tr>
<td>Fast readout (2s) with low noise (5 e$^-$)</td>
<td>Highly parallel readout electronics</td>
<td>16 amplifiers/4K CCD</td>
</tr>
<tr>
<td>Broadband, high spectral sensitivity</td>
<td>Thick silicon sensor, back illuminated, AR coat</td>
<td>100$\mu$m thickness for IR sensitivity Thin conductive window</td>
</tr>
<tr>
<td>Seeing-limited image quality</td>
<td>Internal electric field to minimize diffusion</td>
<td>High resistivity, biased silicon (&gt; 3 k$\Omega$-cm, -50V)</td>
</tr>
</tbody>
</table>
LSST’s high throughput goals

• The largest focal plane
  – LSST: 3.2Gpix (189 CCDs)
  – PanSTARRS GPC1: 1.4Gpix (60 CCDs)
  – HyperSuprimeCam: 940Mpix (112 CCDs)
  – DECam: 500Mpix (60 CCDs)
  – CFHT MegaCam: 340Mpix (36 CCDs)

• The fastest focal ratio
  – LSST: f/1.23
  – SuprimeCam: f/1.87
  – DECam: f/2.7
  – PanSTARRS: f/4
  – CFHT MegaCam: f/4.2

• The fastest readout time
  – LSST: 2s
  – PanSTARRS GPC1: 6s
  – DECam: 17s
  – CFHT MegaCam: 40s
  – Suprime-Cam: 18s
The 4K x 4K LSST sensor reference design

- Sixteen 1-Mpix segments
- 10µm pixels
- 100µm thick, 5kΩ-cm Si
- 42mm
- Transparent, conductive entrance window on back side
- Bonding pads
- Serial Shift 512 → Parallel Shift ← 2000
- Guard ring
LSST CCD Layout
## New technology needed for LSST sensors

<table>
<thead>
<tr>
<th>Feature</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick, high-$\rho$ bulk Si</td>
<td>100µm, &gt; 3kΩ·cm</td>
</tr>
<tr>
<td>Highly transmissive, biased window</td>
<td>&lt;&lt;10nm, -50V</td>
</tr>
<tr>
<td>Flat Si surface</td>
<td>5µm peak-valley</td>
</tr>
<tr>
<td>Package dimensional control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>⊥ optic axis: 5µm</td>
</tr>
<tr>
<td></td>
<td>Chip-chip gap 250µm</td>
</tr>
<tr>
<td></td>
<td>Thermally stable</td>
</tr>
<tr>
<td>Parallel, multiport readout</td>
<td>16 amplifiers</td>
</tr>
<tr>
<td>Low-noise outputs</td>
<td>&lt; 6e$^-$ at 500kHz</td>
</tr>
<tr>
<td>Reproducible and high yield</td>
<td>No individual device tuning</td>
</tr>
</tbody>
</table>

**semiconductor**  **mechanics**  **amplifiers**  **production**
Edge effects

Chip-chip gap 0.25mm (5”)

Image-image gap 2.21mm (44”)
[row direction]

Distance into silicon (µm)

First one-two pixels from edge will have larger effective area due to field distortion
Phase 1 device tests -- laboratory

**Quantum efficiency**

**e2v**

- Temperature: T = -70°C
- Thickness: 100μm

**STA/ITL**

**Charge diffusion (xray PSF)**
Phase 1 sensor flatness

e2v

ITL

measurements by P. Takacs, BNL
I. Kotov
A CCD Electrically.....
NGC891
Highly integrated, in-cryostat electronics

- Total of 3.024Gpix in focal plane
- Goal is 2s readout with 6e- noise
- CCD readout rate must be below ~600kHz to achieve noise figure → CCDs must be segmented into 1-Mpix segments with individual readout amplifiers
- Choose 4Kx4K CCD format with 16 2048 x 512 pixel segments – Total wire count to CCDs ~15,000
- Impractical to take this many wires through vacuum barrier → Implement compact (ASIC-based) electronics chain in cryostat

**ASPIC** *(video processing)*  **SCC** *(clock/bias generation)*  **TOWER** *(144Mpix FPA module)*
Raft-Centric Electronics System

Sensors + Analog Processing + Clock and Bias drive
-100C

Digitization, digital muxing, power regulation, clock generation, etc.
-40C
ASPIC Specifications – IN2P3*
(Analog Signal Processing Integrated Circuit)

- Operates at a temperature of 173K
- Noise:
  - $en < 5nV/\sqrt{Hz}$ maximum noise density
  - $enc < 7\mu V_{\text{rms}}$ maximum input noise @ 500ns integration time (~$2e^-$)
  - Note: Either or both of the above may be met. If, for example, at very long integration time, $en$ will rise but
    $enc$ will fall, and still be an advantage.
- Operation @ 250kHz to 500kHz
- 0.05% maximum crosstalk between channels @ 500kHz
- 100k $e^-$ full well capacity (350 to 400 mV maximum input)
- 0.5% linearity (defined over 0 to 100k $e^-$)
- Differential output
- Output load 50pF // 1k
- Power supply 5V / Gnd - reference $V_{\text{ref}} = 2.5V$
- Power dissipation 25mW / channel
- The ASPIC is designed in 0.35μm 5V CMOS technology from AMS.

* With some help from Mitch and John Oliver
ASPIC – Correlated Double Sampler / Dual Slope Integrator

Noise vs Temperature
Chip 38 and 39

Nominal Gain

As PIC Noise (µV)

Hot
Cold
Hot
Cold

First Amplifier
Programmable Integration time
Integrators

CDS switches

Single ended to differential

Fig 1 Dual Slope Integration sequence

ADC (ADN)

Input voltage (mV)

-150000 -100000 -50000 0 50000 100000 150000

-6000 -5000 -4000 -3000 -2000 -1000 0

Integration Time
Isolation Time

One of the 2 Differential Channel output

CCD Reset
CCD Output
ASPIC Reset
ADC Sampling

Large Synoptic Survey Telescope
### SCC - ORNL
(Sensor Control Chip)

<table>
<thead>
<tr>
<th>Switch 1_2</th>
<th>Load</th>
<th>Frequency</th>
<th>Rise Time</th>
<th>Fall Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>340 pF</td>
<td>1 MHz</td>
<td>35.5 ns</td>
<td>32.5 ns</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Switch 1_4</th>
<th>Load</th>
<th>Frequency</th>
<th>Rise Time</th>
<th>Fall Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95 nF</td>
<td>1.6 kHz</td>
<td>7.3 us</td>
<td>7.5 us</td>
</tr>
</tbody>
</table>
Front End Board - Penn

3 ASPICs  
(24 Channels)  

6 SCCs
Back End Board - Harvard

- Power and Bias
- SPI bus
- SPI CS Address
- Geographical Address
- CCD Data Bus
- CCD Timing
- Local Registers
- CPLD
- SPI DMUX
- ADC Interface
- ADC Data Buffer
- CCD Clock Select (Based on Geo addr)
- Bias Voltage
- Heater
- Temp Sensor
- CCD ADC x24
- CCD analog signals (24)
- ASPIC / SCC SPI Configuration
- Heater
- Temp Sensor
- Back End Board - Harvard

Penn Seminar January 2011
“Vertical Slice Tests” – Penn – ASPIC2
Input (mV) vs. DSI_Out (mV)

\[ y = 4.5565x + 23.493 \]

\[ R^2 = 0.9999 \]

DSI_Out Gain:
75 µV per count

Gain (Input vs. Output):
4.6 mV out per mV in
“Vertical Slice Test” - Harvard

microV (referred to input)
Other LSST Electronics

• Power Supplies
• Electro-Optical Converters (DAQ)
• Clock generation and distribution
• Controls for:
  – Shutter
  – Filters
  – Pumps
  – Cooling
Location, Location, Location
How to annoy traditionalists....
Things not mentioned….

- Thermal design
- Grounding & Shielding
- Optical design / filter characteristics
- Camera and Observatory Control Systems
- Data Acquisition System
- Data bases – meta-data for everything
- Image processing (data cleaning and frame co-adding)
- Vacuum design
- Cleanliness, contamination control
- Focal Plane alignment (ppm!)
- Metrology
- Mechanical design
- Calibration
- Observing simulator / planner
First Light – 2018???
Synoptic!
Backup......
LSST Boxes
Camera Boxology
Calypso has an LSST test camera installed with phase 1 prototype sensor

- LSST’s 1.2 meter diameter Telescope on Kitt Peak
- Observing Operations conducted regularly
- LSST U, Y3, and Y4 as well as Sloan filter set on telescope
Data Management III