Pan-STARRS

Panoramic Survey Telescope and Rapid Response System

Nick Kaiser
John Tonry
Principal Investigator
Camera Team Leader

Presented by
Ken Chambers
Pan-STARRS in a Nutshell

**Telescopes**
- Four 1.8 meter telescopes
- Ritchey-Chretien with 3 element WFC
- 7 square degree FOV
- Atmospheric Dispersion Corrector
- Sited on Mauna Kea or Haleakala
- six filters: g, r, i, z, y, w

**Detector and controllers**
- $10^9$ 0.26” pixels per camera
- Image motion compensation
- 512 channel controller
- 2 second readout
- $4e^{-}$ read-noise

**Data-Processing System**
- Multicolor summed images
- Difference images for detection of moving and variable objects
- Catalogs of static, moving, transient objects

**Published Science Products System**
- Transient alerts
- Moving object detections and orbits
- Database of catalogs, images, metadata

Need funding for operations.
Hope to eventually expand number of telescopes.
Pan-STARRS uses a distributed aperture approach
- an alternative to a “monolithic telescope” approach
- a challenge to detector manufacturers rather than telescope manufacturers

Advantages:
• better match to physics of the earth’s atmosphere
• multiple simultaneous images allows removal of artifacts/cosmic rays
• economies of scale: costs go as $C \propto D^2$ where $?? 2.6$, but $A \propto D^2$
• OTA CCD design dramatically increases yield, reduces cost of chips, making multiple cameras feasible.

Disadvantages:
• independent telescope mounts need more real estate
For $(D \sim 4 r_0)$, $\sim 35\%$ of light is in a single bright speckle. Guiding at $\sim 10\text{Hz}$ gives PSF with diffraction limited core. "Tip-tilt" on large apertures is relatively ineffective.
Orthogonal Transfer Arrays

Orthogonal Transfer Array
A new pixel design to noiselessly remove image motion at high speed (~10 usec)

Normal guiding (0.73")
OT tracking (0.50")

Ken Chambers, IfA, Pan-STARRS

Science with the LSST and Other Large Surveys, Sept 2004
Pan-STARRS Focal Plane

- The Gigapixel Camera is an array of arrays
- Each OTA can assign cells to be guide star cells
- Those can command local cells to track motion of guide stars
Wide Field Synoptic Survey
Science Opportunities

- Pan-STARRS can survey the entire available sky to $R \sim 24$ in less than 7 days.

- Time domain astronomy is really new
  - Transient objects
  - Moving objects
  - Variable objects

- Static sky science in six colors, wide and deep
  - Enabled by stacking repeated scans to form a collection of deep static sky images
Science with Pan-STARRS

Moving Object Science
- PHO's – Potentially Hazardous Objects – Earth threatening asteroids/comets
- OSS – Main Belt and Other Solar System science
- KBO – Kuiper Belt Objects
- SOL – Solar Neighborhood (parallaxes and proper motions)

Static and Invariable Object Science
- WL – Weak Lensing
- LSS – Large Scale Structure
- LSB – Low Surface Brightness and dwarf galaxies
- SPH – Spheroid formation
- EGGS – Extragalactic and Galactic Stellar science

Transient and Variable Object Science
- SNE – Supernovae
- GRB – Gamma Ray Bursts and afterglows
- AGN – Active Galactic Nuclei
- EXO – Exoplanets (from occultation)
- YSO – Young Stellar Objects
- VAR – Variability Science (especially stars)

Serendipity: TGBN (Things that go Bump in the Night)

See Design Reference Missions for PS1 and PS4 on www.pan-starrs.ifa.hawaii.edu
Observable collision risk density

Otherwise known as the `sweet spots' in helio-ecliptic coordinates

- Requires observations at high air mass $>> 1.5$
- Note 20% of ecliptic plane intersects galactic plane – must have good image subtraction in regions of high stellar density
- Requires an atmospheric dispersion corrector if you want to make efficient use of your telescope.
Comments on moving objects and stationary transients

Near earth objects move about a psf in 30 sec
Want to be background limited in at least 30 sec
- Depends on read noise, filter bandpass width, and site sky brightness.
- A distributed aperture of same effective size has same trailing losses as a monolithic, but eliminates cosmic rays etc.

Distant KBO’s move about a psf in 30 minutes
- To distinguish moving solar system objects from stationary transients with out any other information we must take a 2nd image ~ 30 minutes later
- Pan-STARRS will try to take 95% of the images in pairs separated by a Transient Time Interval (TTI) ~ 30 minutes.
- After a TTI we know whether a transient is a moving solar system object, or a stationary transient.
Pan-STARRS Surveys

- **Solar System (Ecliptic Plane)** – w filter - used primarily to satisfy the observing requirements imposed by the PHO, NEO, MBA, KBO and other SS programs.
- **3?** – g, r, i, z, y for WL, LSN census, and EG object detection & classification programs; primary cadence drivers are the LSN census (and other proper motion studies)
- **Medium-Deep** – g, r, i, z, and y filters; the SNe, LSS, and the EG object detection & classification programs; primary cadence driver being SNe
- **Ultra-Deep** – g, r, i, z, and y filters; EG object detection & classification and, to some extent, SNe programs
- **Object Variability/Auxiliary** – user-defined supporting programs such as stellar variability and the search for extra-solar planets
## Design Reference Mission

<table>
<thead>
<tr>
<th>Mode</th>
<th>PSY</th>
<th>Area</th>
<th>Cad.</th>
<th>w</th>
<th>g</th>
<th>r</th>
<th>i</th>
<th>z</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS NEO</td>
<td>1.1d</td>
<td>7000</td>
<td>h/d/m</td>
<td>27.3</td>
<td>28.3</td>
<td>28.5</td>
<td>24.9</td>
<td>22.3</td>
<td>24.0</td>
</tr>
<tr>
<td>SS KBO</td>
<td>1.0d</td>
<td>133</td>
<td>4 min</td>
<td>29.2</td>
<td>28.6</td>
<td>28.5</td>
<td>24.9</td>
<td>22.3</td>
<td>24.0</td>
</tr>
<tr>
<td>Var.</td>
<td>0.8d</td>
<td>1200</td>
<td>4d</td>
<td>27.1</td>
<td>27.0</td>
<td>27.3</td>
<td>25.0</td>
<td>24.0</td>
<td>26.0</td>
</tr>
<tr>
<td>3?</td>
<td>1.3d</td>
<td>1200</td>
<td>4d</td>
<td>27.1</td>
<td>27.0</td>
<td>27.3</td>
<td>25.0</td>
<td>24.0</td>
<td>26.0</td>
</tr>
<tr>
<td>Med. Deep</td>
<td>0.6d</td>
<td>1200</td>
<td>4d</td>
<td>27.1</td>
<td>27.0</td>
<td>27.3</td>
<td>25.0</td>
<td>24.0</td>
<td>26.0</td>
</tr>
<tr>
<td>Ultra Deep</td>
<td>0.5d</td>
<td>1200</td>
<td>4d</td>
<td>27.1</td>
<td>27.0</td>
<td>27.3</td>
<td>25.0</td>
<td>24.0</td>
<td>26.0</td>
</tr>
</tbody>
</table>

5-? limit (AB)
Total int. (min)
Derived Requirements: Astrometry Performance

8.7.13 astrometric accuracy for commissioning phase: 750 mas
8.7.14 astrometric accuracy for reference catalog phase: 250 mas
8.7.15 astrometric accuracy for normal operations: 100 mas
8.7.20 astrometric reference within 6 months (from end of AP Survey)
8.7.21 astrometric reference astrometry accuracy: 100 mas (abs), 30 mas (rel)
8.7.22 astrometric reference proper motion accuracy: 20 mas / year
Derived Requirements: Photometry Performance

8.7.16 photometric accuracy for commissioning phase: 25 millimags
8.7.17 photometric accuracy for reference catalog phase: 10 millimags
8.7.18 relative photometric accuracy for normal operations: 5 millimags
8.7.19 absolute photometric accuracy for normal operations: 10 millimags
8.7.23 photometric reference within 6 months (from end of AP Survey)
8.7.24 photometric reference global consistency: 5 millimag
8.7.25 photometric reference absolute accuracy: 10 millimag
Taking extraordinary measures to reach photometric requirements

- Co-aligned Sky probes
  - B band tycho
  - V band tycho
  - Sky absorption
  - Sky emission
- Calibration unit for absolute and relative photometry
Final Data Products

Sky, the wallpaper:
- 10 Terapix x 6 colors x N versions

Sky, the movie:
- 10 Tpix x 6 colors x 50 epochs

Sky, the database:
- $2 \times 10^{10}$ objects (x 6 colors x 20-60 epochs)
  - Photometry to < 0.01 mag, astrometry to < 50 mas
  - Photometric redshifts of most of these objects
- $10^9$ proper motions (complete over 3?)
- $10^8$ variable stars and AGN
- $10^7$ asteroids ($10^4$ NEO/PHA)
- $10^7$ transients (SN, GRB, etc.)
- $3 \times 10^5$ stars within 100 pc (with good parallax)
Executive Summary

- No technical show stoppers
  - Lot 1 of new design OTA’s had high yield
  - Digital controller successfully read out CCD at 15 Megapixels per sec with 2.1 ADU read noise
- Team of scientists, scientists who write code, professional software engineers, hardware engineers, managers, technicians, administrative staff on board and working full time.
- MIL-SPEC Systems Engineering is up to speed.
- PS1 the prototype Pan-STARRS telescope on Haleakala is scheduled for first light Jan 1, 2006
- PS4 is scheduled for first light Jan 1, 2008
Talking points....

- LSST should not be discussed as an either/or competitor to Pan-STARRS
- Pan-STARRS will exist before the currently envisioned LSST begins construction.
- Therefore:
  - Astro-photo precursor survey will have been done,
  - A robust data pipeline will have been shaken down,
  - 50% of 300m PH0s will have been discovered, tens of thousands of SNe Ia will have multicolor light curves, etc., etc., etc.,
- Discussion should focus on:
  - What kinds of win-win collaborations can we form
  - How to proceed on the follow-up telescopes:
    - Wide field multi-object spectroscopy
    - Near IR imaging
    - u band survey
POLychromatic Huygens PSF

PAN-STARRS ROUNDED
TUE NOV 25 2003
0.5200 TO 0.8250 MICRONS AT 0.0000, 0.0000 DEG.
IMAGE SIZE IS 19.40 MICRONS SQUARE.
STREHL RATIO: 0.380
CENTER COORDINATES: 0.00000000E+000, 0.00000000E+000

C:\ZEMAX\PANSTARRS\PS-PRELIM-9.ZMX
CONFIGURATION 1 OF 1
<table>
<thead>
<tr>
<th>Polychromatic Huygens PSF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PAN-STARRS ROUNDED</strong></td>
</tr>
<tr>
<td>TUE NOV 25 2003</td>
</tr>
<tr>
<td>0.5200 TO 0.8250 MICRONS AT 0.0000, 0.0000 DEG.</td>
</tr>
<tr>
<td>IMAGE SIZE IS 19.40 MICRONS SQUARE.</td>
</tr>
<tr>
<td>STREHL RATIO: 0.380</td>
</tr>
<tr>
<td>CENTER COORDINATES: 0.00000000E+000, 0.00000000E+000</td>
</tr>
</tbody>
</table>

C:\ZEMAX\PANSTARRS\PS-PRELIM-9.ZMX

`CONFIGURATION 1 OF 1`

*Ken Chambers, IfA, Pan-STARRS*
Design Pan-STARRS Post PDR 3, incorporating an ADC
The design chosen has a rotating prism between fixed lenses. This avoids the large rotary seal and presents less of an engineering challenge and schedule risk.

- Refractive indices match at 656 nm
- Zero deviation
- No added glass/air interfaces
- No large diameter rotating seals
- Relaxed tolerances on the flat surfaces

The design uses a rotating prism between fixed lenses.

Maximum correction
No correction

![Diagram showing the design with a rotating prism]
ADC prototype during filling procedure

Ken Chambers, IfA, Pan-STARRS

Science with the LSST and Other Large Surveys, Sept 2004
Design Pan-STARRS Final 2: ADC on maximum dispersion

Note:
Box is 5"x5"
At 75° zenith distance, the ADC fully corrects atmospheric dispersion.
Pan-STARRS Focal Plane

- Need wide field (>3°) to meet science goals.
- Desired psf sampling is <0.28"
- Therefore we need >1 billion pixels per focal plane
Detector Enhancements

- Increasing CCD yield will decrease cost
  - $ / device \sim (\$ / lot) / (CCD yield / lot)
- Decrease pixel size (but >8-10\mu m to keep red QE)
  - $ / \text{cm}^2$ means 10\mu m is 44% the cost of 15\mu m
- Remove image motion
  - 20% better psf equivalent to 56% better QE
- Fast readout improves duty cycle (e.g. Suprime!)
  - Readout \sim sky noise dominance << saturation time
- Reengineer CCD/cryostat/electronics/host computer with attention to costs and scalability
The Orthogonal Transfer Array (OTA) – A New Design for CCD Imagers

- A new paradigm in large imagers

OTCCD pixel structure

Basic OTCCD cell

OTA: 8x8 array of OTCCDs
Detector Details – Overview

Each CCD cell of a 4Kx4K OTA
- Independent 512x512 CCD
- Individual or collective addressing
- 2-3 arcmin field of view
- Dead cells excised, yield >50%
- Bad columns confined to cells
- Cells with bright stars for guiding
- 8 output channels per OTA
- Fast readout (8 amps, 2 sec)
- Expect >90% fill factor despite inter-cell gaps, dead cells, and inter-OTA gaps; four telescopes and dithering fills in the gaps.
Increasing CCD yield

- Wafer yields and thinning yields tend to be good.
- Primary cause of dead devices is catastrophic, local defects such as gate to substrate shorts or bad amplifiers.
- Packaging and metrology dictates against very small devices (< 2K).
- A 25% yield of a 2K x 4K CCD implies ~0.1 defect per cm^2 on average.
- Need a way to isolate defects without losing the device.
OTA “Array” Strategy has other Benefits

- Independently addressable cells allow on-chip guiding.
- Independently addressable cells offer some immunity to the effects of very bright stars.
  
  - Bleeding tails or bad columns from bright stars are confined to the cells that contains the stars.
  
  - E.g. Image at right shows a 9th magnitude star with the green grid illustrating the size of the OTA cells. We expect approx 15 stars of this brightness or greater in each PanSTARRS field.
Decreasing Pixel Size

- Lower limits on pixel size
  - Optical performance and f/ratio
  - Charge diffusion versus thick devices for red response
  - Well capacity

- Practical limits (as of today)
  - 12-15 um OK,
  - 8-10 um possible,
  - <8 um unlikely (if thick enough for extended red).
Fast Readout

- Near Earth objects move one psf width in 30 sec
- Therefore we gain no additional S/N beyond ~30 sec exposures, making ~2 sec readout desirable.
- 1 Mpixel/sec per amplifier with 4 e-read noise is achievable but requires care (faster contributes more noise than sky).
- Must have *many* amplifiers
  - 1 Gpix in 2 sec at 1 Mpix/sec requires 500 amps and signal chains!

(Example: CFH Megacam uses ~80 amplifiers, 200 kpix/sec, 20 sec readout.)
Remove Image Motion

- Tip-tilt plate or mirror
  - Limitations on size and speed
  - Ghosts from transmissive tip-tilt plate
  - Full-field correction only

- Atmospheric motions
  - Decorrelate at some angle between 1 and 10 arcmin
  - Amplitude comparable to seeing (removal of all image motion improves net image size by about 20%).
The Orthogonal Parallel Transfer Imaging Camera

- A 4K x 4K camera (10 arcmin FOV) capable of electronically removing image motion via orthogonal transfer at rates up to 100 kHz and capable of tracking and recording guide stars at rates up to 100 Hz.

- MITLL CCID-28
  - 2Kx4K CCD
  - Four-side buttable package
  - Four independently clockable regions per chip
  - Orthogonal Transfer pixels

Ken Chambers, IfA, Pan-STARRS
OPTIC

- Two CCID-28s adjacent to each other
- Four lower parallel regions "guide regions"
- Four upper parallel regions "science regions"
- SDSU-2 electronics, Four video channels, 4e- noise at 125kpix/sec

Tracking/guiding Operation

1. Read out small patch around 1-4 guide stars
2. Centroid; apply prediction and interpolation
3. Apply shifts to science regions
4. If exposure not elapsed, goto 1.
OTCCD Performance: Lab Tests

- In “stare mode” (clock only on readout) CCID28’s are perfectly good CCDs
  - CTI measured at 2E-6 serial and parallel
  - Noise is 3.5-4.0 e- at 1 usec integration (500 kpix/sec)
  - Dark current at –90 is far below sky in broad band filters
  - Full well is at least 80k e-
  - Linearity is at better than 2% to 50k e-
  - No fringing in I band, a few percent in Z band
  - QE is good – typical for IILA backside process.
OTCCD Performance On Sky

- **Astrometry (Monet)**
  - 1-D fit at 8 mas, 2-D fit at 5 mas: no problems with OT pixels

- **Photometry (Howell)**
  - “we expect tht the OTCCDs used by Pan-STARRS will be able to provide relative photometric precisions of better than 2 mmag rms…”

- **Photometry (Saha)**
  - OT pixels perform as well as 3-?, variations in psf from OT tracking do not hinder photometry.

- **Science (Chambers)**
  - “Image quality is *always* superior, and we have obtained the best optical images ever achieved with the 88-inch (0.45 arcsec FWHM in R band).”
  - “Flat fielding is at least as good as 1 part in 1000.”

Ken Chambers, IfA, Pan-STARRS
Orthogonal Transfer Arrays

Orthogonal Transfer Array
A new pixel design to noiselessly remove image motion at high speed (~10 usec)

Normal guiding (0.73")
OT tracking (0.50")

Ken Chambers, IfA, Pan-STARRS
Science with the LSST and Other Large Surveys, Sept 2004
Guided Image Motion

Star #1
(8')

Star #2
(8')

Star #3
(2')

Star #4
(8')

0.32'' FWHM

0.33'' FWHM

Motion (arcsec)

Time (sec)

Ken Chambers, IfA, Pan-STARRS

Science with the LSST and Other Large Surveys, Sept 2004
Differential Image Motion

Star #4 (8')
0.16'' FWHM

Star #3 (2')
0.10'' FWHM

Star #2 (8')
0.18'' FWHM

Star #1
0.12'' FWHM
Image Improvement from Image Motion Compensation

![Graph showing image improvement vs. image separation with two horizontal lines: one indicating no motion correction and the other indicating complete motion correction.](image)

*Ken Chambers, IfA, Pan-STARRS*
Camera Software – Observing Loop

- Receive coords
- Choose GS
- Quick look
- Tweak tel?
- Erase CCD
- Open shutter

- Integrate on GS
- Read GS subarray
- Centroid & flux GS

- Temporal prediction for next GS position

- Spatial prediction for cell’s motion

- Apply OT shifts
  - Guide telescope
  - Update display

- Exposure complete?
  - Read out cells
  - Send data to pipe
Camera Software – Existing Code

- OPTIC software
- “Eight cell” OTA
- Four guide stars
- Complete system:
  - DSP code
  - Interface/device driver
  - Camera control
  - Analysis/prediction
  - Graphical User Interface
- 100 Hz on 1GHz host
Lot 1 Wafer Layout

- Four versions of OTA and wafer splits
  - Different pixel sizes (12 µm vs. 10 µm)
  - Pixel layout (Type 1 vs. Type 2 OT)
  - Metallization variations to improve yield and fill factor
  - Deeper depletion via substrate bias
  - CMOS hybrid option
- Miniature OTA (MOTA)
  - 2×2 array of cells
  - Several versions to explore higher risk but highly desirable new features
    - 2-phase serials
    - Gated amplifier

Ken Chambers, IfA, Pan-STARRS
OTA Lot 1

Pixel structure

Independently Addressable Cell

OTA: 8x8 Array of Cells
Detector Details – Clock and Analog Signals and Cell Addressing

Control circuitry for parallel clocks

Control circuitry for multiplexing video outputs

Ken Chambers, IfA, Pan-STARRS
Physical Layout of OTA Logic

- Approximately 40 MOSFETs (nMOS)
- Area \( \sim 0.06 \text{ mm}^2 \sim 400 \text{ pixels} \) (<0.15% of OT cell)
- Power dissipation \(~5 \text{ mW}~\) is somewhat high; lower power alternatives under study
- Layout verified for functionality and performance using standard CAD tools
OTCCD On-Telescope Testing Summary

- Mauna Kea has median seeing of 0.3" at altitudes above 500m, lower turbulence has very wide isokinetic angle
- Seeing in excess of 0.3" is almost always highly correlated over angles of greater than 10 arcmin
- At the north galactic pole each 10 x 10 arcmin area
  - has one star at R < 12.5 on average;
  - an OTA subtends four times this area.
- Nominal guiding strategy
  - use all stars with R < 12.5 for guiding,
  - 4 per OTA, 240 per focal plane,
  - linear interpolation of guide star positions used to correct each cell’s location,
  - median residual image motion should be less than 0.2" FWHM.
OTA Pinouts

- OTA realization
  - Pinouts defined
  - Package in fabrication
  - Connectors identified
  - Flexprint being designed
  - Cryostat feedthrough
  - Connections to controller
OTA Package Wirebond Ceramic

- Details of Multilayer Ceramic PGA

- Internal 3 routing layers plus groundplane to isolate digital from analog layers.

- Includes space for temperature sensing diode attached to ceramic.
OTA Package with Flexcircuit
OTA Package Details

OTA die

Moly Frame, Mounting Feet and Alignment Pins

Multilayer ALN Ceramic PGA

Flexcircuit

Ken Chambers, IfA, Pan-STARRS

Science with the LSST and Other Large Surveys, Sept 2004
OTA Handling Mount

- Mount designed for rapid and safe handling of OTAs during testing phases.
Four-OTA Module

4-OTA Flexcircuit

Controller Electronics
Eight-OTA "Bars" = Focal Plane Row

1 Bar

2 Bars
Complete 64-OTA GPC Focalplane
Complete 64-OTA GPC Focalplane
Complete 64-OTA GPC Focalplane
Electronics – Signal Chain

- SDSU dual channel video board
  - 2 channels
  - 150 kpixel/sec
  - CDS, 16 bit ADC
  - 15 W power

- Analog Devices 9826
  - 3 channels (RGB)
  - 15 Mpixel/sec
  - CDS, 16 bit ADC
  - 250 mW power
ADC9826 Testing

- Extensive testing with prototype daughterboard mounted on modified Leach system.

- CCID20 performance adequate with multiple sampling and digital subtraction.
  - ADC9826 = 2.1 ADU Read Noise with (4 signal samples – 4 pedestals)/4 at 1.2 usec per pixel. Linearity good to 1%.
  - Leach Datel ADC937 = 2.33 ADU Read Noise, at ~4 usec/pixel.
Completed CAD DAQ3U_proto

- 14 layer PCB
- 50 Ohm controlled impedance stackup
- Matched length on critical connections
- 672 and 74 ball BGAs
IOTA Controller

- SDSU controller
  - 8 channels = 1 OTA
  - 500 kpix/sec
  - 100W power

- IOTA controller
  - 16 channels = 2 OTA
  - 1000 kpix/sec
  - 25W power
Prototype Design for 1x4 OTA Controller

DAQ3U = 100mm ? 160mm
PCB slot pitch = 20.32mm ? 5
SLOTS = 101.6mm

100BT switch

Pixelserver PC 1U
Electronics – Building Blocks

QUOTA
(Quad OTA building block, 8K x 8K “host computer unit cell”)

Ken Chambers, IfA, Pan-STARRS
2-row OTA Controller “Rack”

- IOTA3U controller operates 4 OTAs
- For a 8 x 8 OTA focal plane, 2 rows of 1 x 8 OTA’s
- Each row has 8 IOTA3U controllers.

1Gb ethernet

LAN Switch

Pixel Server

Power Supply

1Gb ethernet
Computer Cluster and Pipeline

- Sixteen QUOTAs, (32K x 32 K) times 4 telescopes
- Four 4Kx4K OTAs, controller, Gbit fiber
- One CCD host and pipeline computer
- Host computers organized by field of view.

Synchronized readouts, shared guide star info, common pipeline.

8 Gbyte per minute, 10 Tbyte per night, 3 Pbyte per year.
Four OTAs in Test Cryostat

- Simultaneous testing of 4 OTAs.
- Cooling with a single IGC-Polycold Cryotiger. Cryotiger can mount on side plate or on back plate.
- Flexcircuit perforate cryostat wall on two sides.
- Simple and safe device installation and removal. All access from the front.
- Room on focalplane for additional components (e.g. calibrated photodiodes).
Four OTAs in Test Cryostat Focalplane

- OTAs mounted on pitch to be used in GPC.
- Gap size equals one OTA width.
- Allows accurate prototyping of internal flexcircuit.

4-OTA flexcircuit: 2 positions used for device testing
OTA Test Bench

[Diagram with labeled components like OTA, Light seal, Servo, UV fiber, 45mm shutter, Lens, Iris diaphragm, 1.S., Order blocker wheel, Interchange with turret or slide in vertical plane, Screen #2, LCD screen, and adjust for focus.]
Integrating Sphere and Lens
LCD Screen onto OTAs
OTB Capabilities

- Four OTAs tested simultaneously
  - 300 OTAs for PS-4 is only 75 OTB cycles
  - 100% computer control, 100% simultaneous capability
  - Full testing possible in a single OTB cycle

- Xrays
  - Gain and noise
  - CTE
  - Charge diffusion

- Flatfield
  - Quantum efficiency
  - Cosmetics
  - Fringing
  - Linearity

- Imaging
  - Cross talk
  - OT performance
  - Pixelserver and pipeline software performance
  - Charge diffusion?
X-ray Testing – Charge Diffusion

- Charge diffusion will be more important in the future.
  - Better red response requires thicker devices.
  - CCD cost is proportional to area, so smaller pixels are desirable.
  - Diffusion is proportional to CCD thickness.
- The distribution of split pixel values is sensitive to the charge diffusion, and Fe55 X-rays can provide a sensitive measure of diffusion length – 0.33 pixel = 57 μm in this case.
Tests with OPTIC using a calcite block to make extrafocal images

OPTIC design has 0.5” disk at 4” separation

PS design could be as much as an 8” disk at 10” separation, enough for 50-100 resolution elements over pupil.
**In/extra Focal Images for Pan-STARRS**

For Pan-STARRS, in and extra focal images were taken.

- **Extra**
  - $r = 1.6$ deg, SS filter
  - Nominal intra- and extra focal images, 4.4” diameter pupil
  - 0.01 deg secondary tilt
  - 100$\mu$m secondary decenter

**Table:**

<table>
<thead>
<tr>
<th>Extra</th>
<th>Intra</th>
<th>Extra – Intra</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Extra Image]</td>
<td>![Intra Image]</td>
<td>![Extra-Intra Image]</td>
</tr>
</tbody>
</table>

*Ken Chambers, IfA, Pan-STARRS*
Complete GPC Camera

Ken Chambers, IfA, Pan-STARRS

Science with the LSST and Other Large Surveys, Sept 2004
Final Data Products

Sky, the wallpaper:
- 10 Terapix x 6 colors x N versions

Sky, the movie:
- 10 Tpix x 6 colors x 50 epochs

Sky, the database:
- $2 \times 10^{10}$ objects (x 6 colors x 20-60 epochs)
  - Photometry to < 0.01 mag, astrometry to < 50 mas
  - Photometric redshifts of most of these objects
- $10^9$ proper motions (complete over 3?)
- $10^8$ variable stars and AGN
- $10^7$ asteroids ($10^4$ NEO/PHA)
- $10^7$ transients (SN, GRB, etc.)
- $3 \times 10^5$ stars within 100 pc (with good parallax)
Pan-STARRS Design Philosophy

Given the following constraints:
- Construction time ~ 1 year per meter aperture
- Telescope cost rises faster than $D^2$
- Pixel size limited to >10\(?\)m, desire 0.3” pixels requires a focal length of <8m
- Optical design for a large \(?\) becomes very expensive for fast f-ratios
- Costs of CCD detectors have been falling
  - (O)MEGACAMs: ~$8-10M for \(~3 \times 10^8\) pixel or ~2-3c/pixel
  - Today it is possible to do a factor of 10 better
- We believe it is cheaper and better to build an a survey instrument from an array of telescopes and detectors.
Pan-STARRS Surveys

- **Solar System (Ecliptic Plane)** – used primarily to satisfy the observing requirements imposed by the PHO, NEO, MBA, KBO and other SS programs.

- **3?** – used primarily to satisfy the observing requirements of the WL, LSN census, and EG object detection & classification programs; primary cadence drivers are the LSN census (and other proper motion studies)

- **Medium-Deep** – the SNe, LSS, and the EG object detection & classification programs; primary cadence driver being SNe

- **Ultra-Deep** – EG object detection & classification and, to some extent, SNe programs

- **Object Variability/Auxiliary** – mostly user-defined supporting programs such as stellar variability and the search for extra-solar planets
## Design Reference Mission

<table>
<thead>
<tr>
<th>Mode</th>
<th>PSY</th>
<th>Area</th>
<th>Cad.</th>
<th>w</th>
<th>g</th>
<th>r</th>
<th>i</th>
<th>z</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS NEO</td>
<td>1.1d</td>
<td>7000</td>
<td>h/d/m</td>
<td>27.3</td>
<td>28.6</td>
<td>28.5</td>
<td>24.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2b</td>
<td></td>
<td></td>
<td>300</td>
<td>7400</td>
<td>4400</td>
<td>4400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS KBO</td>
<td>1.0d</td>
<td>3?</td>
<td>hdmy</td>
<td>26.3</td>
<td>29.2</td>
<td>29.5</td>
<td>27.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2b</td>
<td></td>
<td></td>
<td>60</td>
<td>22000</td>
<td>2600</td>
<td>1900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Var.</td>
<td>0.8d</td>
<td>133</td>
<td>4 min</td>
<td>29.2</td>
<td>28.6</td>
<td>28.5</td>
<td>24.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.8b</td>
<td></td>
<td></td>
<td>7400</td>
<td>12000</td>
<td>4400</td>
<td>4400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3?</td>
<td>1.3d</td>
<td>3?</td>
<td>14d</td>
<td>25.9</td>
<td>25.6</td>
<td>25.4</td>
<td>23.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5b</td>
<td></td>
<td></td>
<td>30</td>
<td>30</td>
<td>60</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Med. Deep</td>
<td>0.6d</td>
<td>1200</td>
<td>4d</td>
<td>27.1</td>
<td>27.0</td>
<td>27.3</td>
<td>25.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9b</td>
<td></td>
<td></td>
<td>271</td>
<td>460</td>
<td>1200</td>
<td>1900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultra Deep</td>
<td>0.5d</td>
<td>28</td>
<td>4d</td>
<td>29.1</td>
<td>29.0</td>
<td>28.0</td>
<td>27.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.7b</td>
<td></td>
<td></td>
<td>10000</td>
<td>18000</td>
<td>6300</td>
<td>6700</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5-? limit (AB)

Total int. (min)

Ken Chambers, IfA, Pan-STARRS

Science with the LSST and Other Large Surveys, Sept 2004
Science with Pan-STARRS

Moving Object Science
- NEO – Near Earth Object threat
- OSS/MBO – Main Belt and Other Solar System science
- KBO – Kuiper Belt Objects
- SOL – Solar Neighborhood (parallaxes and proper motions)

Static and Invariable Object Science
- WL – Weak Lensing
- LSS – Large Scale Structure
- LSB – Low Surface Brightness and dwarf galaxies
- SPH – Spheroid formation
- EGGS – Extragalactic and Galactic Stellar science

Transient and Variable Object Science
- AGN – Active Galactic Nuclei
- SNE – Supernovae
- GRB – Gamma Ray Bursts and afterglows
- EXO – Exoplanets (from occultation)
- YSO – Young Stellar Objects
- VAR – Variability Science (especially stars)

TGBN (Things that go Bump in the Night)