GPC1 and GPC2, the Pan-STARRS 1.4 gigapixel mosaic focal plane CCD cameras with an on-sky, on-CCD, tip-tilt image compensation

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ABSTRACT

We will report on the on-sky, on-CCD, tip-tilt image compensation performance of GPC1, the 1.4 gigapixel mosaic focal plane CCD camera for wide field surveys with a 7 square degree field of view. The camera uses 60 Orthogonal Transfer Arrays (OTAs) with a novel 4 phase pixel architecture and the STARGRASP controller for closed loop multi-guide star centroiding and image correction. The Pan-STARRS project is also constructing GPC2, the second 1.4 gigapixel camera using 64 OTAs. GPC2 will include design enhancements over GPC1 including a new generation of OTAs, titanium mosaic focal plane with adjustable three point kinematic mounts, cyro flex wiring and the recent software distributed over 32 controllers. We will discuss the design, cost, schedule, tools developed, shortcomings and future plans for the two largest digital cameras in the world.

Keywords: CCD, orthogonal transfer array, tip-tilt

1. INTRODUCTION

The Gigapixel Camera #1 has been in operation since July of 2007 on the Pan-STARRS telescope #1 doing repeated wide field surveys with a 7 square degree field of view. The mosaic focal plane of 60 densely packed CCD Orthogonal Transfer Arrays (OTAs) constitutes the world's largest CCD camera at over 1.4 gigapixels. The (Panoramic Survey Telescope & Rapid Response System) Pan-STARRS telescope #1 (PS1) is at an altitude of approximately 10,000ft on the summit of Haleakala, Hawaii. PS1 has a 1.8 meter primary and wide field Ritchey-Chretien configuration. From the beginning of the Pan-STARRS project, the capability to do on CCD tip/tilt correction was designed into the OTA and electronic controller architecture.

2. GIGAPIXEL CAMERA #1

2.1 Cryostat and focal plane

The relatively compact size of the R-C telescope drove the overall design of the instrument resulting in a short cryostat and a weight specification of less than 440 lb (200 kg). Cryogenic cooling is provided by two single stage CTI Cryogenics 1050 helium closed cycle coolers capable of approximately 80 Watts each of heat lift at 77K. The third lens in the optical system, L3, is also the GPC1 cryostat window with an outer diameter of almost 22 inches (554 mm). With 10 micron pixels, the pixel scale of the camera is 0.26 arcsec/pixel.
GPC1’s mosaic focal plane is composed of 60 OTA, MITLL CCID58s close packed on a custom Carbon Fiber Reinforced Plastic (CFRP) mount assembly designed to meet an overall +/- 20 um co-planarity specification at the detector surfaces. A gantry mounted metrology microscope was used to measure the locations of the OTAs. Astrometric data gathered over three years has verified that the mount assembly has maintained good positional integrity.¹

The fully populated assembly has 60 OTAs arranged in an 8 x 8 grid with the corners unpopulated. The fill factor loss due to inter OTA gaps is 9.3% (for the 3 square degree field of view).

2.2 CCID58 OTAs

The CCID58 OTAs in GPC1 have a novel pixel structure with 4 parallel phases per pixel.² This pixel design allows charge to be moved in both orthogonal directions. This Orthogonal Transfer (OT) mode is the basis for on-sky, on-CCD tip-tilt image correction if proper correction clocking is provided by the controllers.
Each OTA is itself a mosaic of CCD “cells” each with 590 x 598 pixels arranged in an 8 x 8 cell grid. On device logic allows each cell’s parallel clocks to be selectively controlled. Each cell’s serial output amplifier is similarly selectively output. CCID58s are actually two different types of CCDs. The CCID58a has a three phase serial register and the CCID58b has a two phases. GPC1’s focal plane is populated with both types of OTAs, significantly adding to the complexity of the controller software. The performance of these devices has been published previously.3

2.3 STARGRASP controllers

The STARGRASP controllers were specifically designed to support OT operation on large mosaic instruments.4 All control and data communications occurs over 1G fiber Ethernet links. These links along with open network protocols (TCP/IP and UDP) enables scalable processing across multiple networked computers.

To allow the STARGRASP controllers to simultaneously handle device clocking, video cell readouts and incoming OT correction commands, the previously single-threaded software was re-architected to use interrupts. Management of the detector clocking engine was moved to an interrupt context, which effectively provides for a second thread of execution without having to move to a full-blown operating system. Each OT command is processed by the application-level code outside of the interrupt context, and the clocking commands to perform the shift are inserted into the clocking engine stream when possible by the interrupt handler.

3. ON-SKY ORTHOGONAL TRANSFER TESTS

3.1 Methodology

To measure the effectiveness of OT correction, a series of exposures were taken on PS1. They were standard survey fields at 20 second exposure times. For some of the exposures, OT correction was turned on or off for all of the OTAs on the focal plane. In other exposures, only half of the OTAs were OT corrected. Wind speeds during the tests were relatively high at 12 to 14 meters/sec, but still within the normal observing limits for standard observations. The conditions proved to be ideal because the wind caused significant image quality degradation in the non-OT corrected exposures.
3.2 Guide/correction stars and OT speed

Up to 32 guide stars distributed across the whole field of view were acquired at 30Hz readout rate. These stars were evaluated for centroid motion and corresponding OT shift commands were fed back to the controllers before the next 30Hz period.

3.3 Controller generated statistics

The GPC1 camera software automatically generates statistics each exposure for multiple figures of merit. Among these statistics is a point spread function value for each detected object. These values are color coded into a jpeg map of the focal plane. The OT correction improvement on the left half of the focal plane is clearly visible. The blacked out cells are either the guide star cells or bad performance cells.

Figure 5. GPC1 jpeg mosaic of OT exposure

Figure 6. Point Spread Function map of GPC1 with OT correction on the left half
4. POST PROCESSED ANALYSIS AND RESULTS

4.1 SExtractor Analysis

The program SExtractor$^5$ was used to analyze the Full Width Half Maximum (FWHM) flux distribution and the elongation (computed as the ratio of the major over the minor axes) of detected objects. Histogram distributions were then compiled for all of the detected objects.

4.2 FWHM results

The following table summarizes the OT results for the FWHM measurement between the two halves of the focal plane.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Number of detected objects</th>
<th>FWHM median (pixels)</th>
<th>FWHM stdev (pixels)</th>
<th>FWHM median (arcsec)</th>
<th>FWHM stdev (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OT on (half FP)</td>
<td>6819</td>
<td>5.90 pixels</td>
<td>1.6 pixels</td>
<td>1.52 arcsec</td>
<td>0.41arcsec</td>
</tr>
<tr>
<td>OT off (half FP)</td>
<td>7053</td>
<td>8.86 pixels</td>
<td>1.2 pixels</td>
<td>2.29 arcsec</td>
<td>0.31 arcsec</td>
</tr>
</tbody>
</table>

Figure 7. Histogram of measured FWHM OT on vs. off
4.3 Object elongation results

The OT mode was also successful in limiting the elongation of the objects. The following table and histogram depicts the ratio of the derived major over minor axes.

Table 2. Elongation OT correction ON vs. OFF half focal planes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Number of detected objects</th>
<th>Elongation median (major/minor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OT on (half FP)</td>
<td>6791</td>
<td>1.35</td>
</tr>
<tr>
<td>OT off (half FP)</td>
<td>7023</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Figure 8. Histogram of elongation OT on vs. off

4.4 Sky background non-uniformity

The sky background (and some lower signal level objects) on various OT corrected OTAs show a varying amount of non-uniformity. We have called this effect background “leather”. The effect varied between devices with some unaffected by the problem and others severely degraded. The effect also varied across an individual device. We made a rough grouping into “good”, “medium” and “bad” leather devices.
4.5 PS1 Image Process Pipeline Analysis

The Pan-STARRS1 (IPP) Image Processing Pipeline⁶ was used to evaluate the background leather effect. The IPP had a preexisting Charge Transfer Efficiency (CTE) measurement algorithm since the GPC1 detectors suffer reduced CTE in a number of small regions, totaling several percent of the camera. The PS1 image processing pipeline detects and masks these regions by examining the Poisson statistics of flat-field images. Small regions (20x20 pixels) of flat field images are examined and the mean and standard deviation are calculated. The smearing caused by poor CTE has the effect of introducing correlations between neighboring pixel values, with the result that the variance is reduced compared to the expected Poisson value. Any patch for which the standard deviation is less than 50% of the nominal Poisson expectation is flagged. The results for many images are combined, generating a masked region if more than 50% of the individual images are flagged. This automatic analysis yields CTE masks which do an excellent job of following the regions clearly visible by eye.

The CTE code was modified to evaluate the sky background leather, which has the opposite indicator of increasing the standard deviation in the sample patches. A histogram plot shows the OT on data in red and OT off in black. Although the main peaks are close, an appreciable number of sample boxes had increased standard deviation (above the sky flux and read noise).
It is also instructive to look at the location of the background leather on the focal plane. The figures illustrate the impact of OT correction on the noise characteristics of the devices. Each pixel in these images represents a 32x32 patch on the original GPC1 image. After overscan correction, we determined robust (outlier-rejecting) measures of the mean and standard deviations for each of these patches. The images show the standard deviation, with a color scale ranging from dark at 10 DN to light at 160 DN. The mean (sky) flux in these images is ~160 ADU, for an expected Poisson standard deviation of 14 - 15 (gain of 1 and read noise of 6-8 ADU). Aside for the obvious ~8 OTAs with poor performance across the whole device, we saw no correlation to a particular MITLL production lot or device type.

Figure 11. Background standard deviation, OT on (half) , OT on (all devices), black = zero ADU, white 100ADU.
5. BACKGROUND “LEATHER” REDUCTION EXPERIMENTS

5.1 Parallel clock timing tests

To reduce the background leather effect, on-sky tests were later performed where the parallel clock times were progressively increased. This technique was tried versus increasing parallel voltage swings to preserve the ongoing survey operating conditions. The slower parallel timing made a significant improvement but increased off pixel glows in many of the OTAs.

![Figure 13. "Good, Medium, Bad" cells after parallel clocking changes](image)

A second series of experiments were conducted during the daytime with a simulated sky background. To generate this, the camera shutter (two blade slit) was scanned across the focal plane with the dome lights on. These tests duplicated the on-sky test results to first order. The flowing figures were taken at reduced light levels and color stretched to emphasize the off pixel glows. It should be noted that some devices do not exhibit bright glows or significant background leather degradation. Further tests are planned to optimize this mode.

![Figure 14. OT clocking, nominal vs. longer parallels (note glows)](image)
6.  GIGAPIXEL CAMERA #2

6.1  GPC2 overview

The Pan-STARRS is nearing the completion of a second Gigapixel Camera. The intended use will be on the Pan-STARRS2 telescope also located on Haleakala, Hawaii. With an overall similar physical envelope and 64 OTAs, the design of GPC2 closely follows GPC1 with four notable differences.

6.2  CCID71 OTAs

The Pan-STARRS detector development has continued at MTILL with the current production of CCID71 OTAs. The CCID71 has the same 4 phase pixel layout, but has an increased fill factor with 592x600 pixels per cell. There is only a single version of serial register (with two phases) and an additional Output Gate (OG2) has been added for suppression of serial clock feedthrough.

![CCID71 cell architecture](image)

The CCID71 anti reflection coating has also been more optimized in the shorter wavelengths.

6.3  CCID71 Package

A new package was developed for the CCID71. It is a hybrid INVAR frame which holds an ALN ceramic (with 100 pin fine pitch connector) and copper heat spreader. The INVAR frame also has three kinematic contact points for the 100tpi screws that will be mounted in the focal plane. Finite element analysis and cold metrology measurements have been successfully conducted. To overcome the relatively coarse position adjustment resolution of the screws, we intend to use the metrology microscope for accurate positioning.

![CCID71 package](image)

6.4  Titanium Focal Plane

We have opted to use titanium for the focal plane mount assembly. Although it will be heavier than CFRP it was chosen because of the ability to add multiple detailed mounting features and machine in house.
6.5 GPC2 Cryogenic Flex wiring

Pixel row to row crosstalk noise between adjacent OTAs was encountered in the GPC1 which used a single rigid-flex assembly to connect 4 OTAs at a time. For GPC2, individual flex cables have been developed and tested. This design is also in use on the WIYN telescope partial One Degree Imager (pODI) and has maintained good vacuum integrity.

7. STATUS AND COST

The GPC2 costs are expected to be comparable to GPC1 (broken down in the following figure:

![GPC1 Costs](image)
The schedule is paced by the CCID71 production effort. Several “pathfinder” devices have been received and tested. When the first production devices are available the project is planning to assemble GPC2 with a partially populated focal plane to do image quality and acceptance tests of the PS2 telescope. This first configuration is expected to have ~25 good CCID71 OTAs and is scheduled for integration in the first quarter of 2013.

REFERENCES