MMT Wavefront Sensor Science Camera
Commissioning Report

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Ian Czekala, Felix Handte

Harvard University
Department of Astronomy
60 Garden Street MS 10
Cambridge, MA 02138

`iczekala@cfa.harvard.edu`

ABSTRACT

Summary of tests done on the new Wavefront Sensor Science Camera installed at the Multiple Mirror Telescope (MMT) carried out during June - August 2012. The camera was installed at the MMT on July 30th - Aug 1st, 2012 during the summer shutdown period.

1. Camera Specifications and Lab Setup

The camera is an Apogee e2v CCD42-40 chip with dimensions 2048 × 2048 pixels. Due to size constraints, the camera is thermoelectrically cooled, and does not use liquid nitrogen or other coolants. Specifications from the Apogee catalog are listed in § A.

We performed the commissioning testing of the camera at Cambridge Discovery Park. We took flat field images by simulating a flat field lamp with an optical fiber projected onto the white wall. We analyzed the images with a combination of `ds9`, `IRAF`, and `pyFITS`.

We installed the camera at the f/5 wavefront sensor at the MMT during July 30th – August 1st, 2012.

2. Filters and Filter Wheel

The camera has a Sloan filter set of u', g', r', i', z' installed in a filter wheel (Figure 1).

The transmission fraction of the filter set as determined by the manufacturer, Omega Optical, is shown in Figure 2. Text files of the transmission data for each filter are available on the MMT website at `http://www.cfa.harvard.edu/mmti/wfs.html` or by email request.

3. Chip patterns

We determined that there is a "cross-hatching" pattern that is intrinsic to the sensitivity of the pixels, ie, this does not influence the bias or dark currents, but shows up in the flat frames (Figure 3). This pattern can be removed by flat fielding the images. The pattern is an illumination response to the chip, and is on the order of $< 1\%$ of the counts in the image. These pixels have a different response to the light, and this response changes with the wavelength of light. There is also a "swoosh" like pattern that arcs from one corner of the chip to the other, which can also be removed by flat-fielding.

4. Gain and Readnoise

We determined the gain and read noise of the chip in the following manner:

Take two flats and two bias images, called f_1, f_2, b_1, and b_2.

Subtract the two bias frames and two flat frames

$$b_{12} = b_1 - b_2 \tag{1}$$

$$f_{12} = f_1 - f_2 \tag{2}$$

Measure the mean value m and standard deviation σ for each of the frames in a clean portion.

$$\text{Inverse gain } = g = \frac{m_{f_1} + m_{f_2} - m_{b_1} - m_{b_2}}{\sigma^2_{f_{12}} - \sigma^2_{b_{12}}} \tag{3}$$

$$\text{Read noise} = n = g\sigma_{b_1} \tag{4}$$

We determine that the **gain** = 1.26 and the **read noise** = 9.5.

Referenced from Memo by Nelson Caldwell, February 5th, 1999.

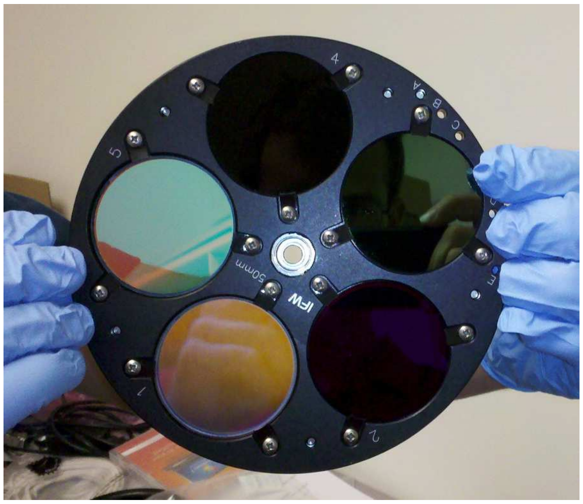

Fig. 1.— Filter wheel with Sloan filter set installed. Filter order 1:r', 2:i', 3:z', 4:u', 5:g'.

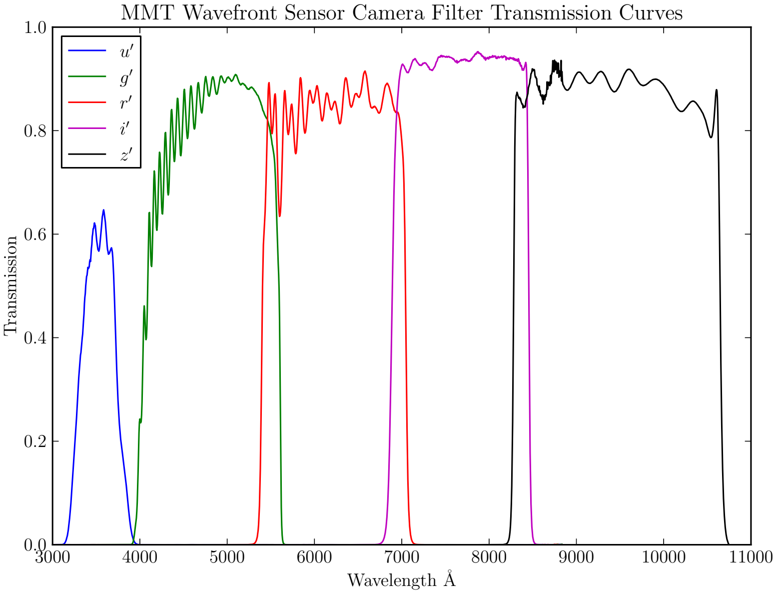

Fig. 2.— Transmission curves of the Sloan filter set on the MMT Camera. ASCII files of the data are available on the instrument website at `website`

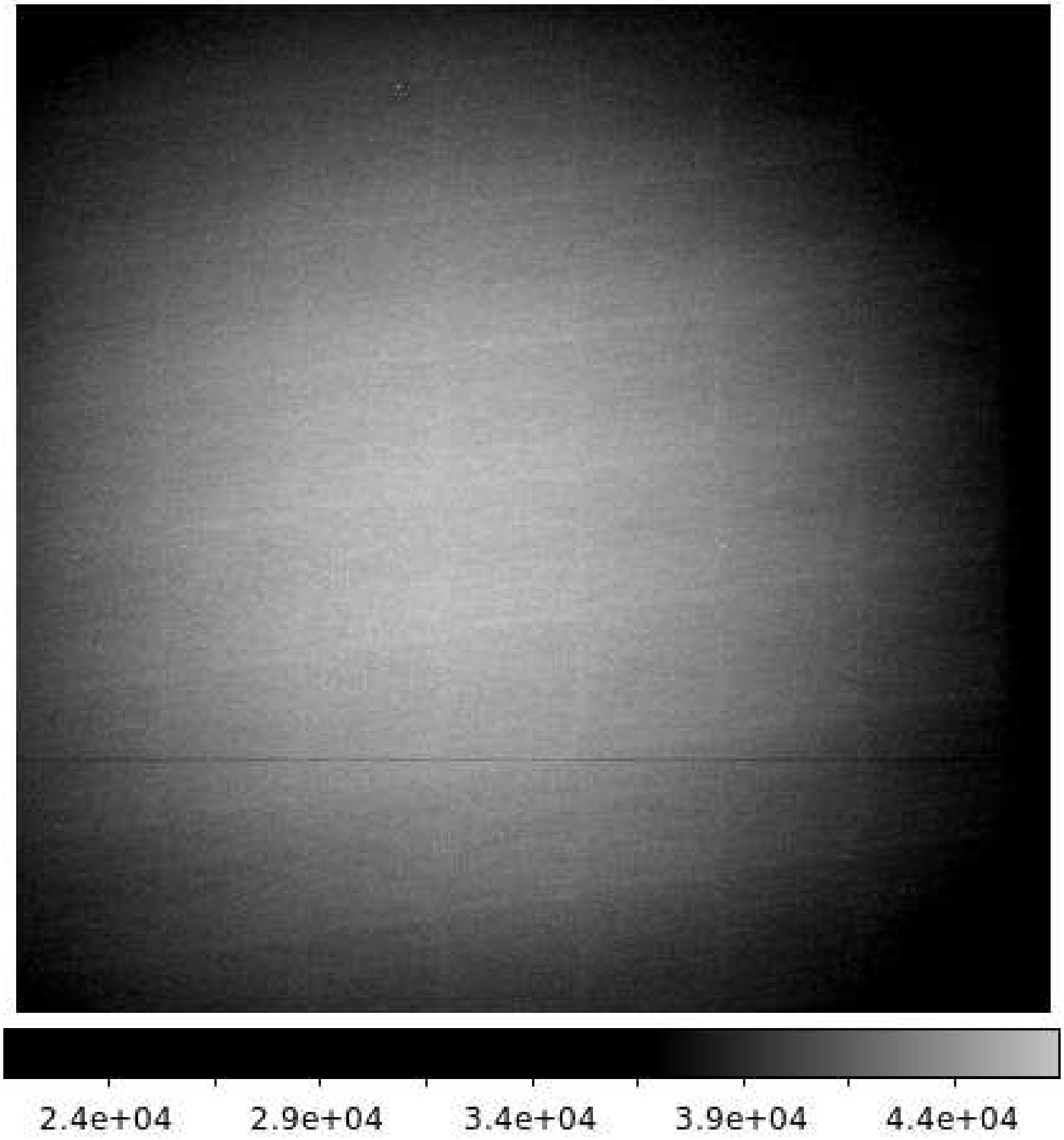

Fig. 3.— Raw flat frame with g' filter (no bias subtraction or dark current correction). This pattern does not show up in the dark or bias images. This illumination pattern is repeatable and can be removed by flat-fielding.

5. Dark Current

We measured the dark current and its dependence on temperature. The chip is equipped with the ability to "preflash" the chip (for more, see § 6), we also tested to see if the preflash affects dark current, which it does not. The results of our tests are shown in Table 1.

6. Preflash and Persistence

The camera is equipped with an infrared monochrome preflash, designed to make uniform the number of counts trapped in each well of the CCD. The primary purpose of the preflash is to ensure that residual charge from previous exposures does not bias certain regions of the chip. We performed tests to determine the effect that the preflash would have on science images.

Through testing of the timing of the preflash and shutter trigger, we determined that the preflash operates in the following manner. Before a commanded exposure and while the shutter is still closed, the chip will preflash, filling the wells of the CCD, and then *read out* this charge from the entire chip, which takes approximately 12 seconds for 1x1 binning and 6 seconds for 2x2 binning. After this preflash charge is read out, the shutter will open to begin exposing for the commanded image.

Preflash does not induce any pixel to pixel variations due to trapped charge in CCD wells. Using a camera lens, we focused light onto a subregion of the chip and then exposed to saturation. Immediately after readout, we took a bias frame. We noticed no residual charge present at the interface between the saturated regions and the underexposed regions of the CCD. There are no pixel-specific persistence patterns induced by the preflash.

Preflash does not affect the dark current or the bias level of the chip. We determined that the preflash *does not* affect either the dark current or the bias level, however these quantities are of course sensitive to the temperature of the chip.

Preflash helps prepare the CCD after a saturated image. If in any given exposure without preflash, a small region of the CCD is saturated, the camera is generally successful at reading out all of the charge off of the chip, so that the next image may be taken without worrying about residual change. However, if a large portion of the chip is saturated, or if the saturated region is near the last rows to be read out, there may be some residual charge present in the next exposure, rendering the next exposure useless (see a1 and a2, Figure 4). Because the preflash reads out the chip once before the exposure of the next image, it is an excellent safeguard against residual charge contamination (see b1 and b2, Figure 4).

7. Shutter and Illumination Correction

Several of the science applications for the camera may require short exposure times where the time devoted to opening and closing the shutter will be significant. In reality, this means that the outer regions of the chip will be underexposed compared to the central region of the CCD. We wrote a software package[1] to calculate and correct for the motion of the shutter by using a series of twilight flats.

By taking a series of twilight flats under different sky brightness and for a variety of exposure times, we can calculate the amount of missing light due to shutter travel, and then generate a master "shutter map" that can be used to correct science frames to the correct level of illumination.

$$\text{illumination map} = \frac{\text{amount of time exposed}}{\text{amount of time commanded to expose}} = \frac{t_{\text{exp}} - t_{\text{shutter}}}{t_{\text{exp}}} \tag{5}$$

The "shutter map," or a 2D frame representing the time that each pixel is covered by the shutter, can be derived for each exposure

$$t_{\text{shutter}} = t_{\text{exp}}(1 - \text{illumination map}) \tag{6}$$

Then, to correct a given user frame (with exposure time t_{exp},

$$\text{corrected frame} = \frac{\text{user frame}}{\text{illumination map}} = \frac{\text{user frame} \times t_{\text{exp}}}{t_{\text{exp}} - t_{\text{shutter}}} = \frac{\text{user frame}}{1 - t_{\text{shutter}}/t_{\text{exp}}} \tag{7}$$

The inferred shutter opening and closing time ($\sim$ 20ms) is consistent with the shutter travel time measured by audio recording and analysis.

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[1] Code: `https://github.com/iancze/ShutterCorrect/`
Documentation: `https://github.com/iancze/ShutterCorrect/wiki`

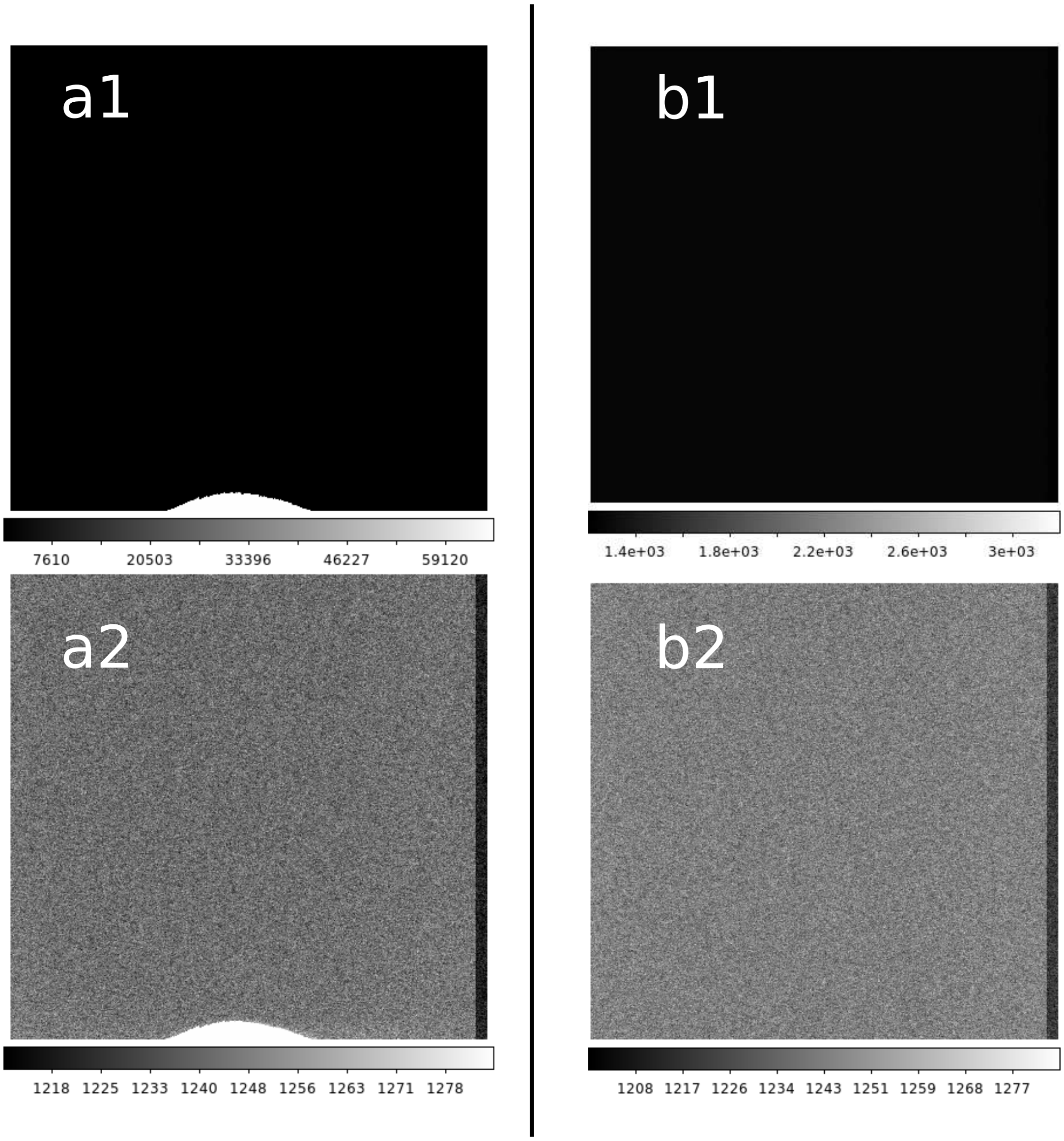

Fig. 4.— Bias frames taken immediately after a flat field which fully saturating the chip. Bias frame **a** was taken without the preflash, while bias frame **b** was taken with the preflash. View **1** is using a min-max contrast scaling to show that the region at the bottom of the bias frame is either saturated (**a1**) or unsaturated (**b1**), while view **2** is the same bias frames as in **a1** and **b2** but using IRAF zscaling to show that the rest of the frame shows normal structure appropriate for a bias frame. The residual charge present in frame **a** occured for 4/4 trials with no preflash while no spillover charge was present for the 4/4 trials with the preflash (**b**).

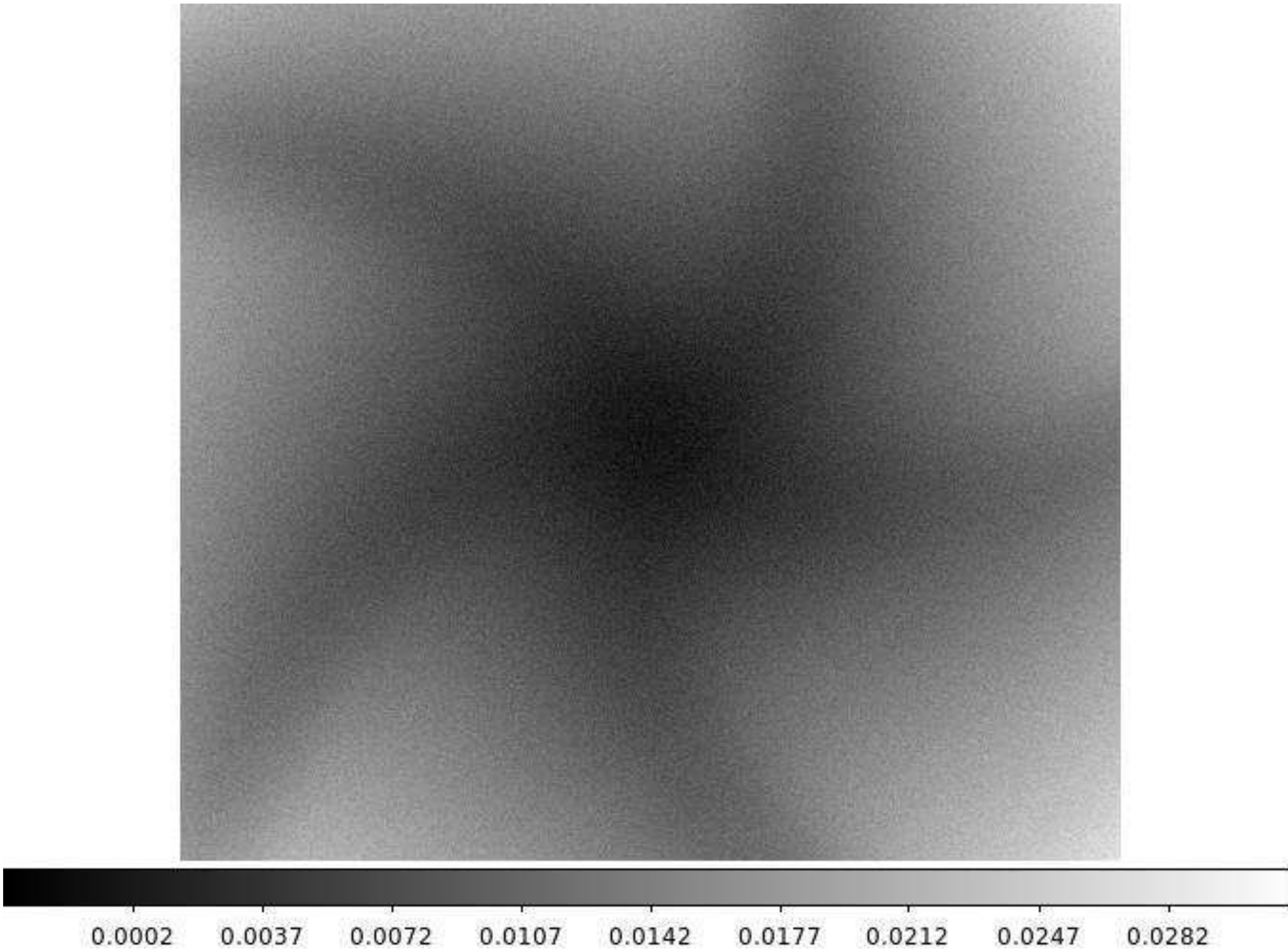

Fig. 5.— Map of the shutter time using dome flats.

8. Acknowledgements

The MMT Wavefront Sensor Camera was commissioned on behalf of a larger team consisting of Warren Brown, John Roll, Joe Zajac, and Steve Amato. Special thanks to Jonathan Irwin and the MEarth team for valuable advice about the Apogee cameras.

Table 1. Dark Current

Temperature (°C)	Preflash	e^-/s
-9.6	No	3.30
-13.6	No	1.74
-14.3	No	1.27
-15.1	Yes	1.22
-20.2	Yes	0.56
-20.4	No	0.55
-21.4	No	0.52

A. Apogee Specifications

The following are the Apogee specifications from the catalog. Where we have confirmed or measured the value in the lab, it is stated.

Camera model e2V CCD42-40

Pixel size 13.5μm square pixels

Linear full well 100K e^-

Dynamic range (dB) 80

QE at 400nm 55%

Peak QE 96%

Read noise 10 e^- (we measure 9.5 e^-)

Gain we measure 1.26

Cooling (Δ° C) 40

Dark current 0.9 e/p/s (we measure 0.55 e/p/s at -20.4 ° C)

Deep cooling dark current 0.1 e/p/s

Chip dimensions 2048 × 2048 pixels