Agile: A Time-Series CCD Photometer

1 Overview

Agile is a portable high-speed time-series photometer based on the original design of Argos, a time-series photometer at the 2.1 m telescope at McDonald Observatory (Nather & Mukadam 2004). Agile comprises of a Princeton Instruments Micromax camera with a frame transfer CCD, which has 1 K $\times$ 1 K active pixels, each of size 13 $\mu \times$ 13 μ. Using a focal reducer at the Nasmyth focus of the 3.5 m telescope at Apache Point Observatory (APO), we yield a field of view of approximately 2.5 arcmin$\times$2.5 arcmin with a platescale of 0.145 arcsec/pixel. The CCD is back-illuminated and thinned for improved blue sensitivity and provides a quantum efficiency $\geq$80% in the wavelength range 4500–7500 Å. The unbinned full frame readout time can be as fast as 1.1 s; this is achieved using a low noise amplifier operating at 1 MHz with an average read noise of order 6.9 $\bar{e}$ RMS. At the slow read rate of 100 KHz to be used for exposure times longer than a few seconds, we determine an average read noise of 3.9 $\bar{e}$ RMS.

2 Instrument Timing

Agile does not have a mechanical shutter; the frame transfer operation of the CCD is utilized to end an exposure and initiate the subsequent new exposure. Frame transfer can be triggered by sending a pulse to the electronics controller. Housed in the data acquisition computer Nimble is a PCI Brandywine GPS card that is synchronized to the Observatory's GPS clock. When the observer requests an exposure time of *n* seconds, the GPS-based timer card generates a train of pulses with an even spacing of *n* seconds. These GPS-synchronized pulses are transmitted to the electronics controller, and effectively dictate both the start and end of each exposure. Therefore we expect that both the exposure start and the exposure duration should have an uncertainty smaller than a millisecond.

Operating the instrument in the manner described above requires that the desired exposure time should always be greater than or equal to the sum of the CCD readout time (with the chosen binning and windowing) and the time required to write the image to disk. The data acquisition program typically needs two-hundredths of a second or less to write the image in the buffer to a local disk, and usually about a quarter of a second to write the image to an NFS mounted disk. The write-time to an NFS mounted disk is highly variable and certainly not recommended for exposures shorter than a few seconds. The chosen exposure time must additionally be smaller than 655.34 s (constraint due to the GPS timer card) and should also be an integral multiple of 0.02 s (present software constraint).

It is also possible to operate the CCD camera without controling the exposure time using GPS-synchronized pulses. This mode is presently enabled to allow the observer to acquire bias frames, and gets activated whenever the exposure time is set to zero. However if in the future several observers indicate that their science would benefit from exposure times longer than 655.34s inspite of the high dark current, we can enable the use of internal timing for substantially long exposures acquired at the cost of reduced timing accuracy. We expect the uncertainty in timing may then be of the order of a hundredth of a second or more. Operated in this fashion, Agile will just be an imaging system and should not be called a time-series photometer.

3 Wavelength Response

For higher blue quantum efficiency, we have chosen a CCD with enhanced back-thinning process and a broad-band anti-reflection coating. This gives us >80% peak quantum efficiency in the range 4500–7500 Å. Additionally, the CCD has an ultra-violet coating to enhance the wavelength efficiency of the region 2000–3700 Å to 35% (see the dotted line in Figure 1). As Apache Point Observatory is located at an altitude of 2788 m, we expect to detect at least some of the blue photons in the range of 3200–3700 Å.

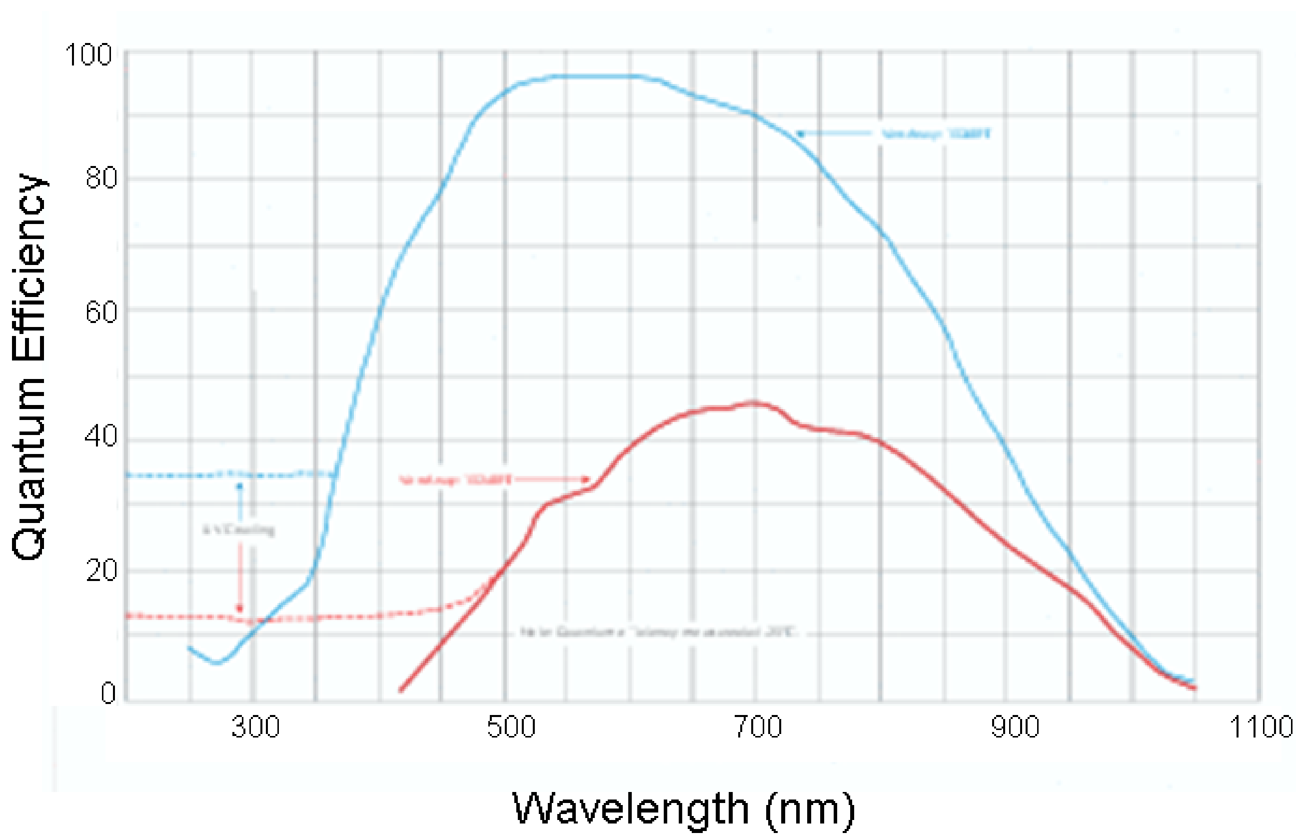

Figure 1: The solid and dotted blue curves indicate the Agile CCD quantum efficiency.

4 Dark Current Characterization

The CCD in the camera is enclosed in vacuum and is thermo-electrically cooled to -40 C. We measured the dark counts as a function of exposure time for 1x1, 2x2, and 3x3 binning (see Figure 2). The unbinned pixel accumulates a dark current of about 6.8 counts/s. With 2x2 binning, we expect to accumulate four times as much dark current as an unbinned pixel; our measured dark current of 26.2 counts/pixel/s agrees with this expectation. For 3x3 binning, our measured value of 65.7 counts/pixel/s is consistent within uncertainties with nine times the dark current of an unbinned pixel. In general, the observer should expect a dark current of n^2 times 6.8 counts/pixel/s for nxn binning at -40 C.

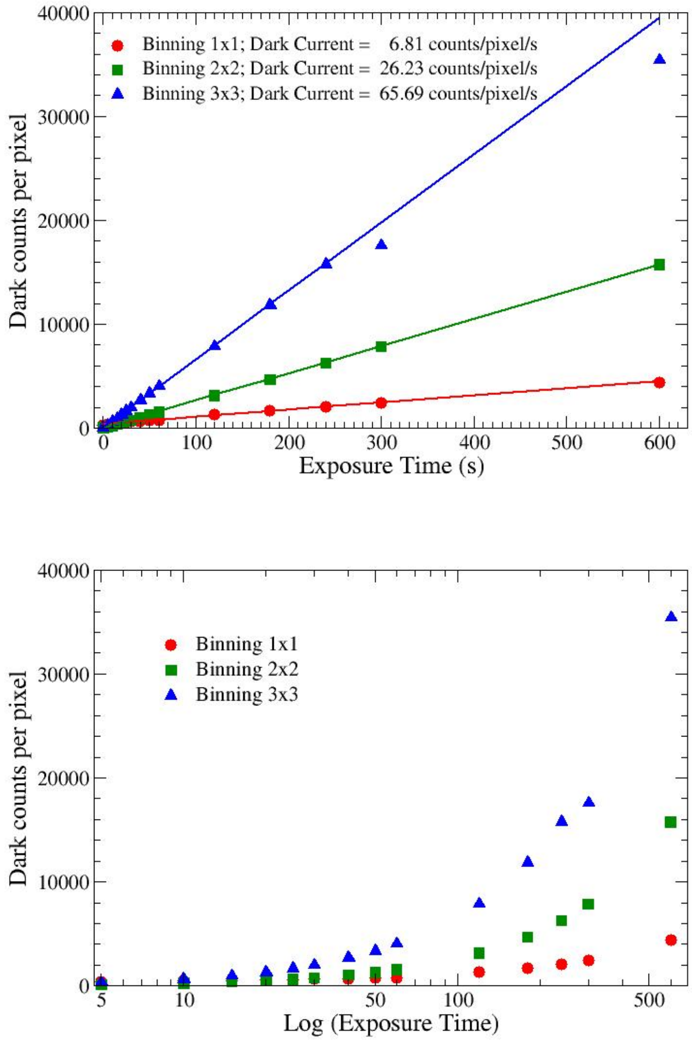

Figure 2: We show the dark counts obtained per pixel as a function of exposure time. With 1x1 binning, we obtain a dark current of 6.8 counts/pixel/s. We expect to obtain n^2 times as much dark current with nxn binning and find that this expectation holds true within uncertainties for 2x2 and 3x3 binning.

5 Linearity and Gain

Agile has two possible read rates of 1 MHz and 100 KHz, and three possible gain settings of high, medium, and low. For each of the six possible combinations as above, we carried out the following process to determine values for the read rate and gain at each setting.

We acquired two consecutive domeflats using the dim quartz lamp with increasing exposure times until saturation. We show the mean counts of both the images along the x axis and the variance in the difference of these images along the y axis. These CCD transfer curves obtained with 1x1 binning show the region of linearity (see Figure 3). The inverse of the slope of the linear regime gives us a value of the gain at that setting. At the read rate of 1 MHz, we determine the high, medium, and low gain settings to correspond to values of 0.95, 1.93, and 3.88 electrons/ADU respectively. At the read rate of 100 KHz, we find that the high, medium, and low gain settings correspond to values of 0.97, 1.96, and 4.10 respectively.

This appears to be counter-intuitive, but it really isn't when we think in terms of the net ADU counts. For example at the read rate of 1 MHz, the high gain setting will yield 31580 ADU or counts for 30000 electrons, while the medium gain setting will yield 15540 counts, and the low gain setting will yield 7730 counts for the same number of electrons. The observer must select the gain setting so that at the desired exposure time, the stars of interest have counts in the linear regime of the CCD. Please note that when using the low gain setting and binning 1x1, the CCD will saturate at about 43000 counts. However when binning 2x2, bear in mind that the saturation point should be given by the digitization limit of 65535 counts.

6 Read Times & Read Noise

We performed the following procedure at each of the six combinations of read rate and gain to measure the read noise at each setting. We acquired a set of 100 bias frames at 1x1 binning and computed a master bias by combining them. We subtracted the master bias from each bias frame, expecting that each frame would then contain noise almost exclusively as a result of read noise. We added a constant value of 10 to each pixel of each of the above frames to bring the minimum pixel values above zero. Next we selected a central square of 800 pixels x 800 pixels and computed the standard deviation of pixel values within the square; this was done to isolate read noise from any gradients or non-uniformities at the CCD edges. Averaging the standard deviation measured for hundred frames and dividing the value by the square root of two, we obtained the read noise in ADU. We used the measured values of gain to calculate the read noise in terms of the number of electrons. We measure the read noise to be 6.62 $\bar{e}$ RMS for the high and medium gain settings at the read rate of 1 MHz. We find that the read noise at the low gain setting is somewhat higher at 7.54 $\bar{e}$ RMS for the read rate of 1 MHz. At the slow read rate of 100 KHz, the high and medium gain settings yield a read noise of 3.66 $\bar{e}$ RMS and the low gain setting yields a read noise of 4.52 $\bar{e}$ RMS.

The readout time for an unbinned full frame is 1.1 s operating at 1 MHz. With 2x2 and 3x3 binning, the readout time of a full frame reduces to 0.462 s and 0.266 s respectively. At the slow read rate of 100 KHz, the readout time for an unbinned full frame is about 10.7 s, and with 2x2 and 3x3 binning, the readout time drops down to 3.1 s and 1.6 s respectively.

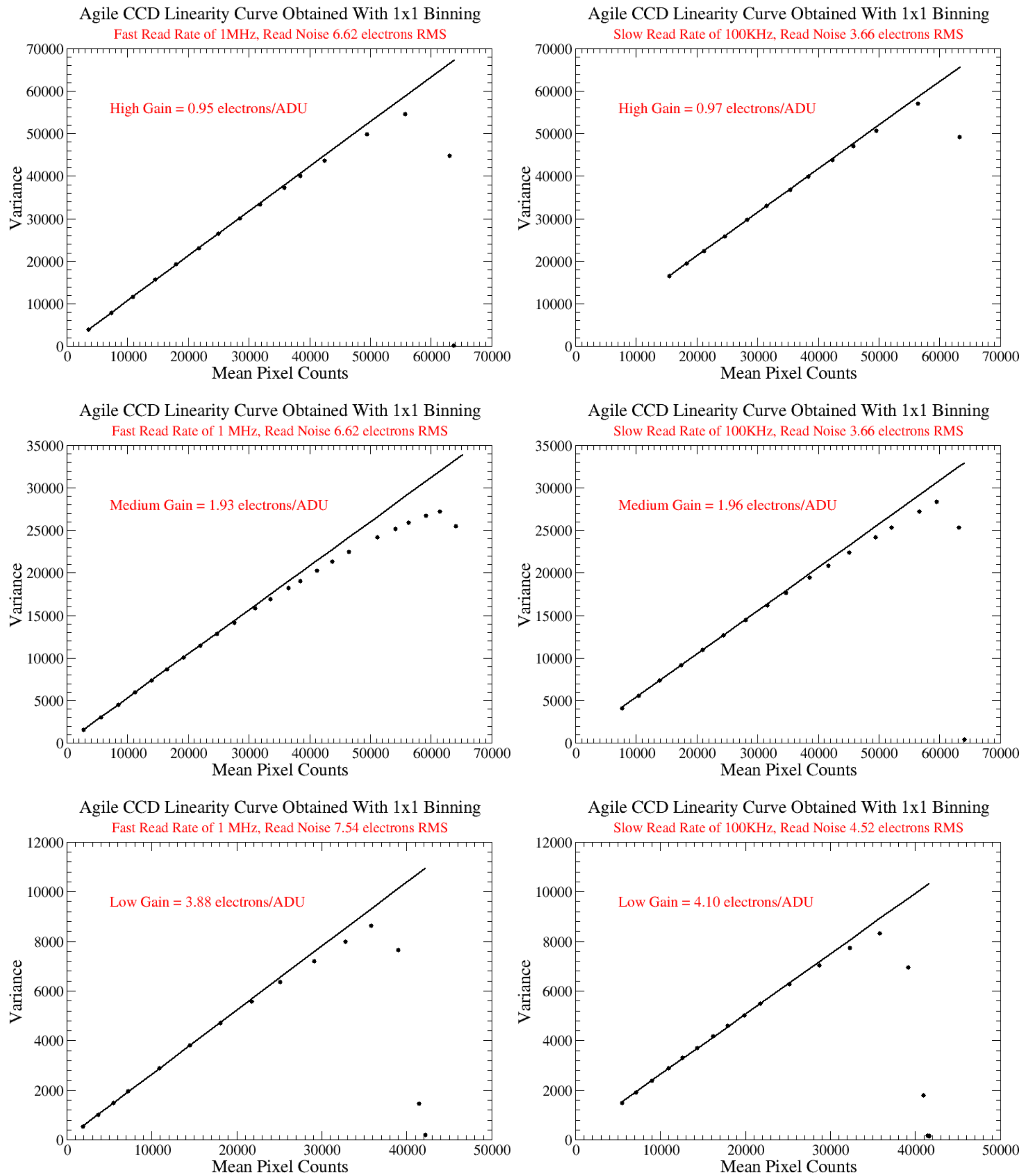

Figure 3: The CCD transfer curves show the linear regime of the CCD for each setting of read rate and gain. Please note that when binning 1x1 at the low gain setting, the CCD will saturate at about 43000 counts. However when binning 2x2, bear in mind that the saturation point should be given by the digitization limit of 65535 counts.

7 Throughput Measurements

We indicate below the throughput measurements acquired for standard stars observed using Agile with the Johnson U, B, V, R, and I filters respectively. These measurements should be helpful to a future observer in estimating an exposure time for his/her target. Since we did not acquire these measurements at zenith, we have attempted to correct the measured counts for extinction. We clearly state the assumed extinction values employed in the correction for different filters with different effective wavelengths (see Figure 4).

Magnitude	Counts Acquired (ADU)	Counts at Zenith (ADU)
U		
14.589	989.4	1065.6
13.75	2587	2785.5
17.53	97.5	105.0
12.962	4385.9	5176.3
14.916	845.6	998.2
13.453	3139.1	3705.9
14.766	1060.1	1251.1
11.156	28151.5	33226.8
15.264	529.9	626.4
13.404	3324.6	3925.3
B		
15.781	3179.3	3386.1
13.48	26033.4	27743
16.188	2149.4	2291.1
V		
16.11	4659.3	4885.5
12.77	98189	102964
14.74	16259.1	17051.6
R		
16.272	4007.5	4187
12.365	140937	147251
13.786	38779	40516.6
I		
16.644	2040	2095.2
11.971	121904	125267
12.789	62238.6	63902.2

Table 1: Standard Star throughput values acquired using Johnson U, B, V, R, & I filters

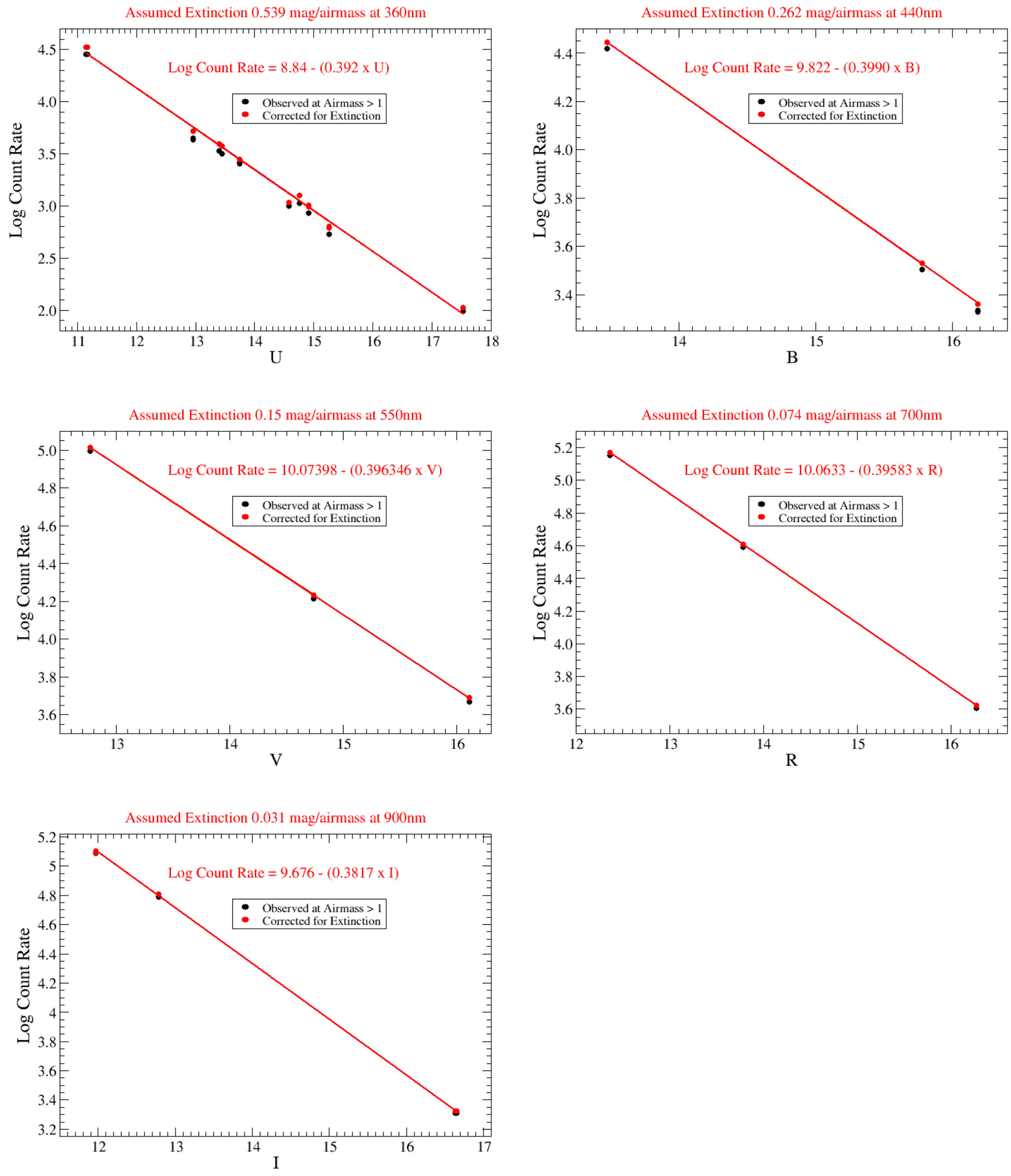

Figure 4: Standard Star throughput values acquired using Johnson U, B, V, R, & I filters