Evaluation of the Photometrics CH250 CCD Camera for use in the NOAA/MLML Marine Optics System

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This report summarizes initial work to incorporate Photometrics CH250 charge-coupled device (CCD) detectors in the NOAA/MLML Marine Optics System (MOS). The MOS spectroradiometer will be used primarily in the Marine Optics Buoy (MOBY) to surface truth the ocean color satellite, SeaWiFS, scheduled for launch later this year. This work was funded through Contract NAS5-31746 to NASA, Goddard Space Flight Center.

For this preliminary work, a Tattletale-7 (TT7) was interfaced to the Photometrics CCD system with prototype circuitry. Forth interrupt routines were written and optimized to acquire data through Photometrics CCD system software. These routines read data (16-bit values from the 512 by 512 element CCD array) and buffer them in the TT7. Benchmark tests show that each interrupt execution requires 8 μsec with the CPU running at 16 MHz. The CCD data rate is 40,000 pixels/sec. Acquiring pixel-by-pixel data from two CCDs (one for the blue, CCD #5, and red, CCD #6, portions of the spectrum) through interrupts requires 64% of the CPU time ($2*40{,}000\ s^{-1} * 8x10^{-6}\ s$). Use of this method requires that no other interrupts such as keyboard input, use of the Time Processing Unit (TPU) are allowed. Full 512x512 images are shown in Figures 1, 2, 3 and 4. Figures 2 and 3 are 10-min dark scans which reveal the presence or absence of patterns on the detectors. CCD #5 has circular patterns while CCD #6 shows none.

Photometrics software was successfully used to acquire subsets of the CCD array, shown in Figure 4 , however it appears that a software error drops out the first pixel of the array. Thus when we expect 512 x 512 data we receive 262143 pixels instead of 262144 or when 50 x 100 data are requested we receive 4999 pixels instead of 5000. Analysis of this situation by logic analyzer confirms that this is a Photometrics problem, not a programming or interfacing error on our part. The same situation applies to parallel or serial binning. Because we will use the CCD system to acquire spectral data, where a column corresponds to wavelength, we will likely use parallel binning to accumulate all charges from a column into the serial register, from which they are shifted to the output node (Figure 5). In parallel binning charges are swept simultaneously from each column into a 512 element serial register, from which the accumulated charges are read in serial fashion. It is also possible to sum the charges across a row (i.e. serial binning) in which a single row of charges is swept into the serial register, and charges from the serial register are accumulated. Serial binning could be used to acquire spectra by rotating the detector 90°.

Photometrics provides a continuous CCD clearing mode, which keeps the array in its zero state while the CCD controller waits for a command. Figure 6 shows two sets of 10 "bias" scans which are essentially dark scans having zero integration time, one without continuous clearing and the second with. The bias of about 1000 analog/digital units (ADU) is a built-in offset to eliminate the possibility of under ranging. It is seen that anomalous values (Figure 6a.) are encountered from the first scan when continuous clearing is disabled. Figure 6 also demonstrates that the serial readout mode is so slow that increased dark currents are accumulated across the CCD array. That is, the later pixels read out contain 10 % higher ADU than the first pixels. This is due to what amounts to a longer integration time. Note also the low (and off scale) value from the first pixel is presumably due to a Photometrics software problem. Figure 6b demonstrates use of continuous clearing, and compares parallel binning with serial binning.

Parallel binning has the desirable characteristic of reducing preamplifier or "readout" noise produced during each conversion of electron count to ADU in the "output node". The preamplifier noise is avoided by electronically sweeping electrons into the serial register when they are accumulated. Figure 6b shows 10 scans obtained in the parallel method. Notice in Figure 6b that the parallel bias values are essentially constant from the first to last pixel.

Photometrics (1993a and 1993b) give the conversion from analog/digital units (ADU) to photoelectrons (e-) at high gain: for CCD #5 = 1.36 e-/ADU; for CCD #6 = 1.27 e-/ADU. This suggests a 7% difference in sensitivity for these two detectors. The bias signal is highly repeatable, and the preamplifier noise is estimated as the root-mean-square difference (RMS) from the mean of a number of bias scans (Figures 7 and 8). Ten bias scans for CCD detectors 5 and 6 using the parallel method gives ±2.7 and 3.8 ADU corresponding to ±3.7 and 4.8 e-. By comparison the serial binning method, which takes 5 times longer than the parallel method, produces twice the noise with RMS noise of ±6.8 and 7.0 ADU or ±9.2 and 8.9 e-. Photometrics (1993a and 1993b) shows RMS noise of 7.3 and 7.4 e- for CCD #5 and 6, respectively. These values are consistent with the observed results (Table 1).

Table 1. Comparison of binning methods for two CCD arrays. Time is the readout time, RMS Noise is the root-mean-square difference from the mean of 10 scans. ADU is analog/digital units and e- is the number of electrons. This RMS noise is the preamplifier noise. Binning methods are illustrated in Figure 5.

CCD	Binning Method	Time (sec)	RMS Preamplifier Noise (ADU)	(e-)
5	Parallel	0.15	2.7	3.7
5	Serial	0.80	6.8	9.2
6	Parallel	0.15	3.8	4.8
6	Serial	0.80	7.0	8.9

Dark currents were determined by integrating for 0.2, 1, 16 and 64 seconds with a closed shutter. The dark current is the mean of 10 dark scans less the mean of 10 bias scans (Figures 9 and 10). Each CCD detector shows its own dark scan characteristics, which should be highly repeatable over a short time span at a steady and low (-40° C) detector temperature. The mean dark scan current shows the expected linear increase with integration time (Table 2, Figure 11a). The rate of accumulation of dark current (0.55 and 0.41 e-/s/pixel) was calculated by regression. Photometrics (1993a and 1993b) gives corresponding values of 0.9 and 1.3 e-/s/pixel for CCD #5 and #6, respectively. We do not know the source of the difference between their results and ours.

A property of CCD detectors is that the Poisson distribution of energy states produces photonic or "shot" noise which is equal to the square root of the accumulated electrons. The RMS noise from the dark scans for increasing integration times and accumulated charges (Table 2) shows the expected square root behavior of photonic noise as illustrated in Figure 11b by the log-log slope of 1/2.

Over long integration times (16 and 64 s) large spikes are observed: regularly in some pixels and randomly in others (Figure 12). For CCD #5 pixels 91, 143 and 491 consistently produced currents 2x or more greater than surrounding pixels. These pixels are evidently defective and represent what is called "cosmetic" defects. Other spikes are not associated with a specific pixel, but occur randomly. These spikes are evidently caused by high energy particles or cosmic rays. The cosmetic defects can be mapped for each detector. The apparent cosmic ray effects must be verified using an independent detector. If these spurious signals persist, data reduction schemes must allow for their removal.

Table 2. Dark current obtained from CCD detectors 5 and 6 by parallel binning. The mean dark current is the spectral mean of pixels 1..511 for 10 scans, after eliminating cosmetic defects. The RMS noise is determined from the 10 scans. "regress" gives the dark current rate from least squares regression.

CCD	Time (sec)	Mean Dark Current (ADU)	(e-)	Slope ΔDark/Δt (e-/s/pixel)	RMS Dark (ADU)	(e-)
5	0.2	42	57	0.55	3.8	5.2
	1	206	281	0.55	6.8	9.2
	16	3392	4613	0.56	25.5	34.7
	64	13285	18068	0.55	55.3	75.2
	regress	208	283	0.55		
6	0.2	32	40	0.39	4.4	5.6
	1	159	203	0.40	6.7	8.5
	16	2617	3324	0.41	25.3	32.1
	64	10491	13323	0.41	57.2	72.6
	regress	164	208	0.41		

A requirement for surface truth work in the MODIS project is to achieve a SNR of 100:1 for water-leaving radiance. SNR for CCDs is computed by Eq. 1 where N is the number of electrons and P is the preamplifier noise (Photometrics, Ltd. 1991). N_{total} is the total number of electrons binned in the serial register from m pixels for a specified integration time. The

$$SNR = \frac{N_{total} - N_{dark}}{\sqrt{(P^2 + N_{total})}} \qquad \text{(Eq.1)}$$

signal is the difference between the total electrons and the dark current, $N_{signal} = N_{total} - N_{dark}$. At this point we are not able to determine noise relative to a radiometic intensity, but some understanding of the limitations in precision can be obtained in terms of the known dark current rate. Set the dark current N_{dark} = mdt, where m is the number of pixels binned (in the range 1..512), d is the dark count rate in electrons/pixel/s, and t is the integration time. The relative signal is N_{signal} = Rmdt, where R is the ratio of production of photo electrons to the dark count rate. R can be determined as a function of the desired SNR by rearranging Eq. 1

$$R = \frac{SNR^2 + SNR\sqrt{(SNR^2 + 4(P^2 + mdt))}}{2mdt} \qquad \text{(Eq. 2)}$$

With a 0.1 s integration time, m = 512 pixels, d =0.55 e-/s/pixel, a preamplifier noise P = 4, and SNR = 100:1 , the required signal is, N_{signal} = 10044 e-. This is converted to 7385 ADUs for CCD #5. In the situation where electrons from 512 pixels are binned, the minimum signal to achieve SNR = 100:1 is only 10044/512 = 20 e- (or 14 ADU) per pixel. Saturation for CCD #5 is achieved in the 16-bit serial register at 65536-1000 ADU (87769 e-) or 126 ADU (171 e-) per pixel. The SNR at saturation is 87741/(sqrt(4^2 + 87769), giving SNR = 296:1. The loss of 1000 ADU is due to the offset to prevent under ranging. We note that the well capacity of each pixel may be as large as 500,000 electrons, thus the CCD precision is limited by the 16-bit serial register not the well capacity. A 9x increase in signal results only in a 3x increase of signal to noise. The dark current rate determined from parallel binning is 208 ADU/s or 0.55 e-/pixel/s. This dark current is less than the 1 e-/pixel/s stated to be a typical dark current for CCDs (Photometrics, Ltd. 1991). To achieve the desired 100:1 SNR, the maximum dark current would be 42750 ADU (64536 - 21786), which is achieved in the maximum integration time of 206 s when all 512 pixels are binned. These calculations are summarized in Table 3 and Fig. 13 for different integration times.

The dynamic range of the system is determined by the integration time and the number of pixels binned. In strong light fields scans may be acquired at the minimum integration time of 0.1 s, in which case the dark current is of no consequence (Table 3). The best SNR attainable is 296:1. As the integration time is lengthened to 100 s, the maximum SNR decreases to about 200:1. As the integration time is increased further, the dark current becomes an increasing fraction of the total count. When the integration time reaches 206 s (3.4 min), the dark count reaches it maximum level for which a SNR of 100:1 can be attained by binning all 512 pixels. For integration times greater than 3.4 min, useful data can be obtained by binning some fraction of the array. For example, for each halving of the intensity that causes saturation of 512 pixels in 206 s, will saturate 256 pixels in 412 s and 128 pixels in 824 s, etc. The integration time limit is determined by the dark current rate. In principle the maximum integration time for a detector having a dark current of 0.55 e-/s/pixel is 29 hours.

Table 3. Signal to Noise analysis for CCD array #5. Dark count rate d = 0.55e-/s/pixel; P = 4;m = 512 Electron/ADU = 1.36. R is the rate of production of photoelectrons relative to the dark count rate. Counts are given in both electron units (e-) and in Analog Digital Units (ADU).

	Δt	Dark			Signal		Total		Noise	
SNR	s	e-	ADU	R	e-	ADU	e-	ADU	e-	ADU
100	0.1	28	21	357	10044	7385	10072	7460	100	74
296	0.1	28	21	3110	87741	64511	87769	64536	296	218
100	1.0	282	207	36.5	10289	7566	10571	7773	103	76
295	1.0	282	207	311	87487	64329	87769	64536	296	218
100	10	2816	2071	4.34	12302	9046	15118	11116	123	90
287	10	2816	2071	30.2	84952	62496	87769	64536	296	218
100	100	28160	20706	0.80	22515	16555	50675	37261	225	166
201	100	28160	20706	2.12	59609	43830	87769	64536	296	218
100	206	58141	42750	0.51	29629	21786	87769	64536	296	218

To some extent one can control the gain in the conversion between electrons and ADU. For CCD# 5 the high gain setting used in the preceding examples was a factory setting of 1.36 e-/ADU. By lowering the gain to 7.75 e-/ADU the full depth of the potential wells may be used. In this case, 16-bit saturation in the A/D "output node" is reached with a maximum of 500,000 electrons binned in each of the serial registers, and the corresponding SNR is 707:1. As expected the SNR is proportional to the square root of the electrons representing the signal. With a 5.7:1 decrease in sensitivity, the SNR increases by sqrt(5.7) or 2.4. With this decreased gain, a large SNR of about 700:1 is realized for integration times between 0.1 and 100 s. The integration time limit is reached at t = 25.4 min at which point the SNR drops to 100:1.

Finally, for complete control, the CCD arrays can be read by summing individual pixels. In this method, individual rows constituting a 512 bin spectrum are swept into the serial register. Each pixel from the serial register is then read individually in the output node and arithmetically summed in a computer register. The sequence is repeated for any number (1..512) rows. The observation that the dark count increases with time during the readout (as shown in Fig. 6a) is not important, because each spectral value will contain the same number of rows, hence the same dark count. With this method the preamplifier noise is added with each readout so that the noise is

$$SNR = \frac{N_{total} - N_{dark}}{\sqrt{((m P)^2 + N_{total})}} \qquad \text{(Eq.3)}$$

increased by m times the readout noise, where m is the number of pixels summed arithmetically (Eq. 3). The highest SNR attained by this method is 6400:1 when m = 512. ADU saturation of the output node remains 64536, but the electron count summed arithmetically is 4.49 x 10^7. The signal must be very high to achieve this SNR: R = 1.6 x 10^6 times the dark current for 0.1 s integration and proportionately less for longer integrations. When the rate of production by photons equals the dark current rate (R = 1), the maximum SNR decreases to 3200, and an integration time of 22 hours is required. The advantage of this method is that the 16-bit output node is not a limiting factor and a SNR greater than 300:1 is possible. The disadvantage is that the data acquisition program must sum the ADU counts and some CPU time is required for this. Whether or not the CPU can perform this summation remains to be tested.

Up to this point we have not discussed the sensitivity of the CCD in terms of ADU per photon. That will be determined when the detectors are placed in the spectrograph's optical path and calibrated with standard lamps. Fig. 14 shows the ratio of photoelectric counts to dark counts (R) as a function of integration time and SNR for the parallel binning method.

We appreciate the help of Mike Feinholz and Sarma Lakkaraju who pointed out some errors in these analyses.

References

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Photometrics, Ltd. (1993b) Series 200 Camera System Final Test Report. Job # 92-293-6 Photometrics, Ltd. 3440 East Britannia Drive Tuscon, Az 85706.

Figures.

Figure 1. Image of test pattern using CCD #5. Contrast was adjusted between lightest and darkest pixels.

Figure 2. Dark current image from CCD #5 using a 10 minute integration. Notice the circular pattern, which may have been caused by the manufacturing process.

Figure 3. Dark current image from CCD #6 using a 10 minute integration time. Notice white dots and streaks caused by high energy particles and cosmic rays.

Figure 4. 512 x 512 image and 512x128 and 128x200 subimages from CCD #6.

Figure 5. Schematic showing accumulation of charges using serial and parallel binning methods. In serial binning (top) electrons in a row of pixels are sequentially swept into the serial register and the electrons are combined in the output node. In parallel binning (bottom) all rows are combined in the serial register, from which they are swept into the output node for converting to ADU. Adapted from Photometrics (1991).

Figure 6. Ten replicate bias scans: a) Upper panel shows serial binning without clearing the array. b) Bottom panel shows serial binning and parallel binning using continuous clearing.

Figure 7. RMS noise from CCD #5 determined from 10 bias scans. a) Upper panel shows results from serial binning, mean RMS = 6.8 ADU; b) Lower panel shows results from parallel binning, mean RMS = 2.7 ADU.

Figure 8. RMS noise from CCD #6 determined from 10 bias scans. a) Upper panel shows results from serial binning, mean RMS = 7.0 ADU; b) Lower panel shows results from parallel binning, mean RMS = 3.8 ADU.

Figure 9. Mean dark current from CCD #5 for 10 replicate, parallel-binned scans at integration times of 64, 16, 1, and 0.2 seconds with mean dark currents of 13285, 3392, 206 and 42 ADU respectively. Note the dropout for pixel 1 and the cosmetic defects in three pixels.

Figure 10 Mean dark current from CCD #6 for 10 replicate, parallel-binned scans at integration times of 64, 16, 1, and 0.2 seconds with mean dark currents of 10491, 2617, 159 and 32 ADU respectively. Note the dropout for pixel 1 and the general absence of defective pixels (with the exception of an inverted pixel # 167).

Figure 11 a) Mean (n = 10) dark current by parallel binning for CCD #5 (dots) and CCD #6 (diamonds); b) RMS of the dark current (as above) vs integration time. The line shows the expected square-root distribution.

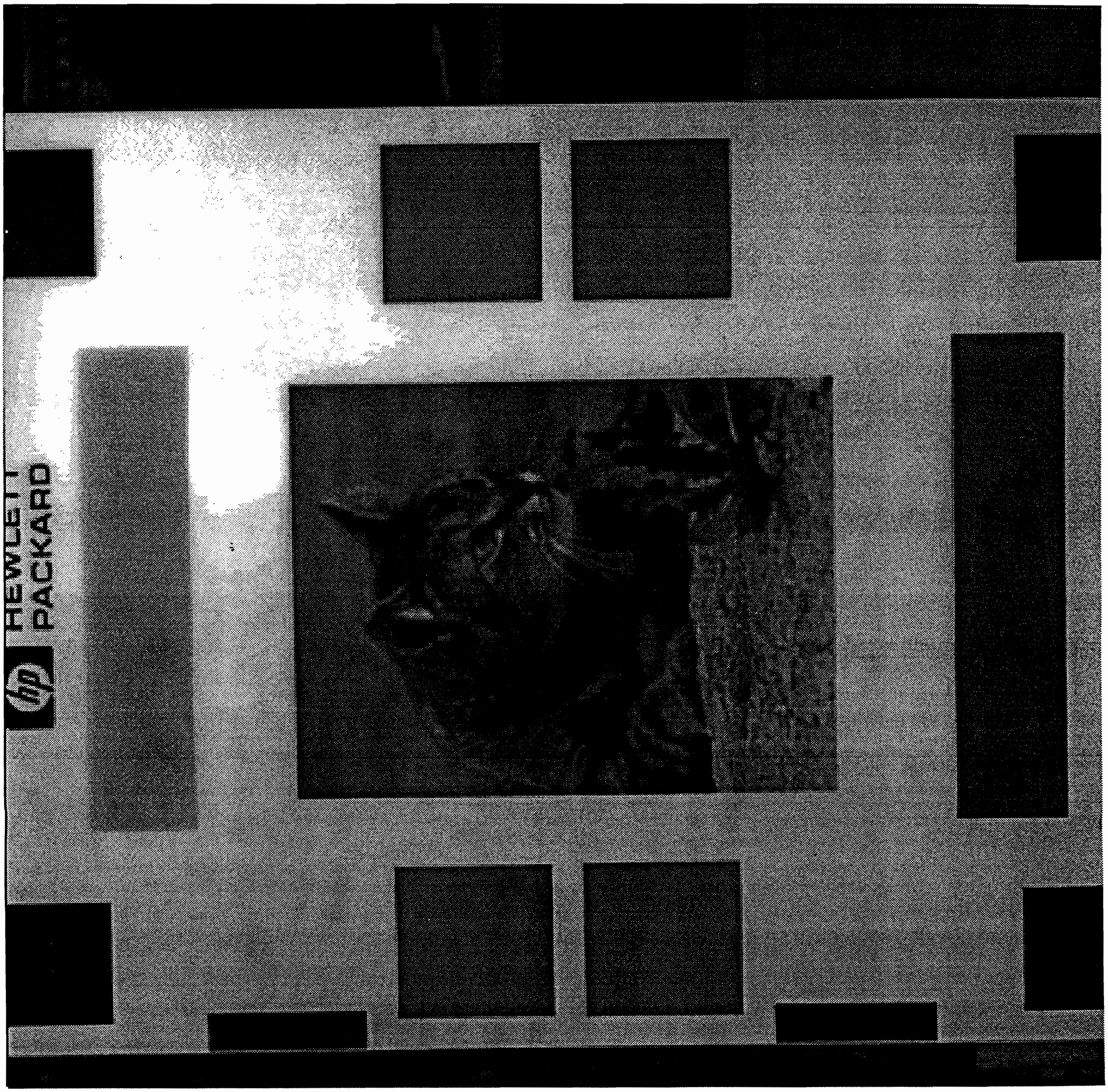
Figure 12 a) Upper panel shows 10 64-second integration scans for CCD #5. b) as above for 16 second integration. The pixels having suspected cosmetic defects are marked by x. Other pixels showing spurious peaks may be due to high energy particles and cosmic rays.

Figure 13. Counting statistics in Analog Digital Units (ADU) for CCD array #5 when 512 rows are binned. Isolines show increasing SNR for integration times between 0.1 and 1000 s. The horizontal line indicates 16-bit saturation when 512 pixels are binned. The maximum SNR is just under than 300:1.

Figure 14. Signal to Noise Ratio (SNR) dependence on the ratio between total photoelectrons per unit dark count (R) and integration time. At short integration times and large SNR, the greater is the number of photoelectrons relative to dark current. The line marked by * shows the 16-bit counting limit when 512 pixels are binned.

Appendix: MatLab program to compute signal-to-noise for CCD arrays.

```
function snr(sig,m,t,d,s,P)
% snr.m
% use as snr(sig,m,t,d,s,P)
% Signal to noise ratio for CCD array
% SNR =  (N-total - N-dark)/sqrt(P^2 + N-total)
% assume N-signal       = R*m*d*t
%        N-dark         =   m*d*t
%        sqrt(N-total)  = photonic noise
%
%input: sig = signal to noise required   eg.  100
%         m = # of pixels binned         eg.  512
%         t = integration time sec       eg.    1
%         d = dark count e-/s/pixel      eg. 0.55
%       s = e-/ADU                       eg. 1.36
%       P = preamplifier noise ADU       eg.    4
%
% output: R = photon number as multiple of dark count in ADU
%         N = total ADU

% Solve quadratic equation for R
% W. Broenkow
% 27 Aug 1994

a = (m*d*t)^2;
b = -sig^2*m*d*t;
c = -(sig^2)*(P^2+m*d*t);
R = (-b+sqrt(b^2-4*a*c))/(2*a);

Ndark   = m*d*t;
Nsignal = R*m*d*t;
Ntotal  = Nsignal + Ndark;
Nnoise  = sqrt(P^2+Ntotal);

fprintf('Photon Rate:  R=%8.2f\n',R);
fprintf('TOTAL:    Ne-= %6.0f Nadu= %6.0f',Ntotal,Ntotal/s);
fprintf('        Ne-/p= %6.0f Nadu/p= %6.0f\n',Ntotal/m,Ntotal/m/s)
fprintf('DARK:     Ne-= %6.0f Nadu= %6.0f',Ndark,Ndark/s);
fprintf('        Ne-/p= %6.2f Nadu/p= %6.2f\n',Ndark/m,Ndark/m/s)
fprintf('SIGNAL:   Ne-= %6.0f Nadu= %6.0f',Nsignal,Nsignal/s);
fprintf('        Ne-/p= %6.0f Nadu/p= %6.0f\n',Nsignal/m,Nsignal/m/s)
fprintf('NOISE:    Ne-= %6.0f Nadu= %6.0f',Nnoise,Nnoise/s);
fprintf('        Ne-/p= %6.0f Nadu/p= %6.0f\n\n',Nnoise/m,Nnoise/m/s)

EXAMPLE:

» snr(100,512,1,.55,1.36,4)
Photon Rate:  R=    36.54
TOTAL:    Ne-=  10571 Nadu=   7773        Ne-/p=     21 Nadu/p=     15
DARK:     Ne-=    282 Nadu=    207        Ne-/p=   0.55 Nadu/p=   0.40
SIGNAL:   Ne-=  10289 Nadu=   7566        Ne-/p=     20 Nadu/p=     15
NOISE:    Ne-=    103 Nadu=     76        Ne-/p=      0 Nadu/p=      0
```



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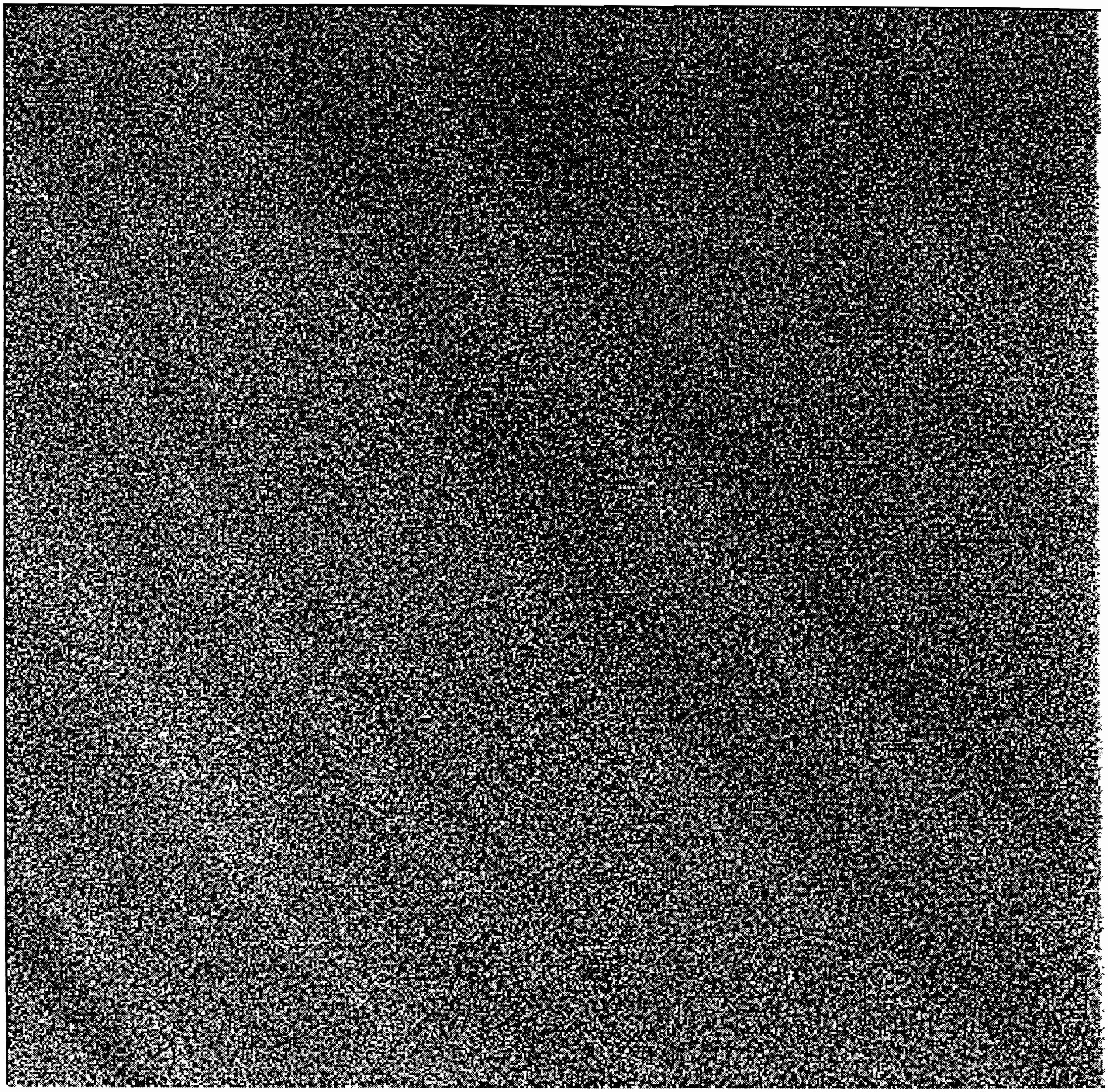


Figure 2. Dark current image from CCD #5 using a 10 minute integration. Notice the circular pattern, which may have been caused by the manufacturing process.

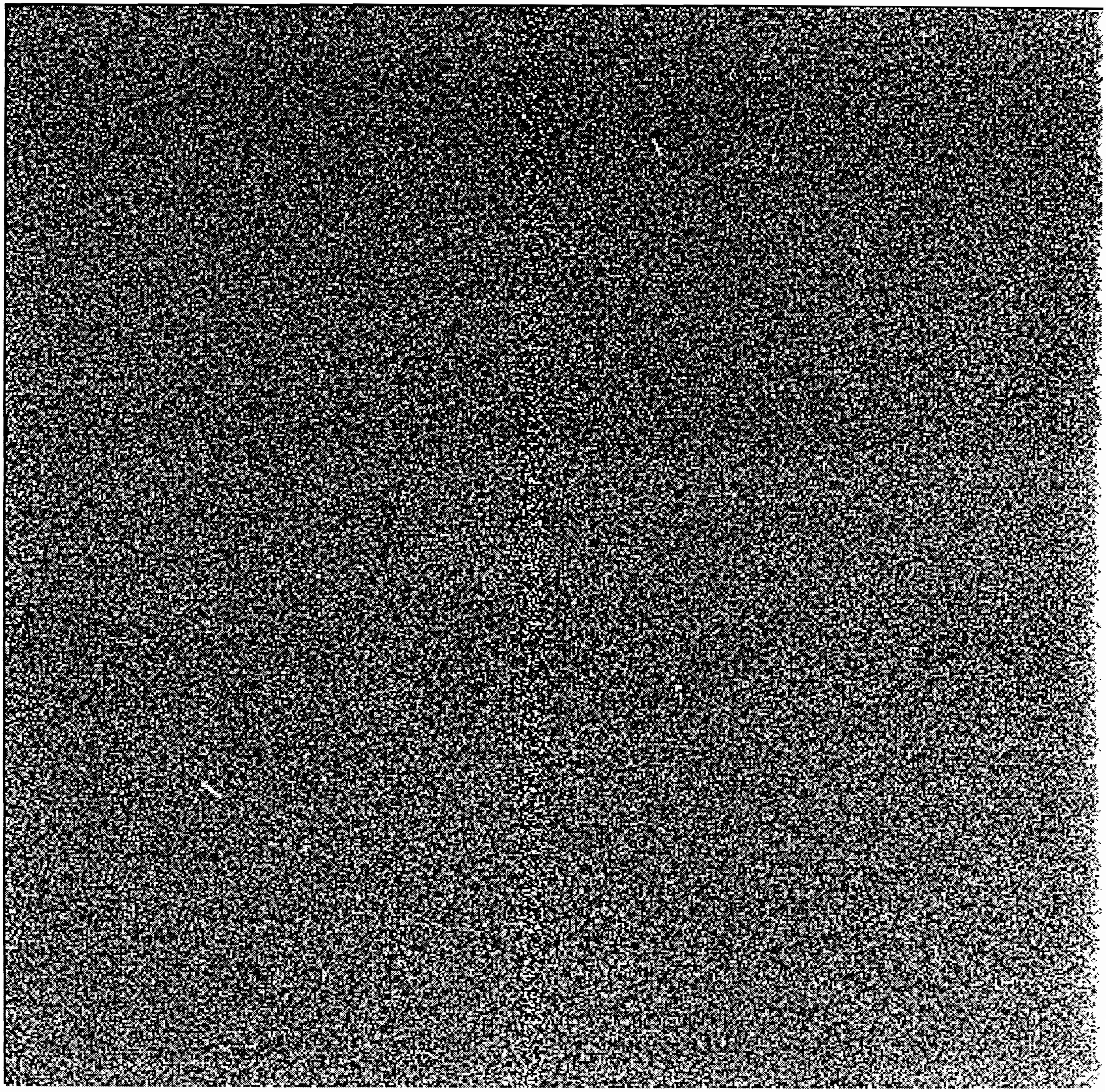


Figure 3. Dark current image from CCD #6 using a 10 minute integration time. Notice white dots and streaks caused by high energy particles and cosmic rays.

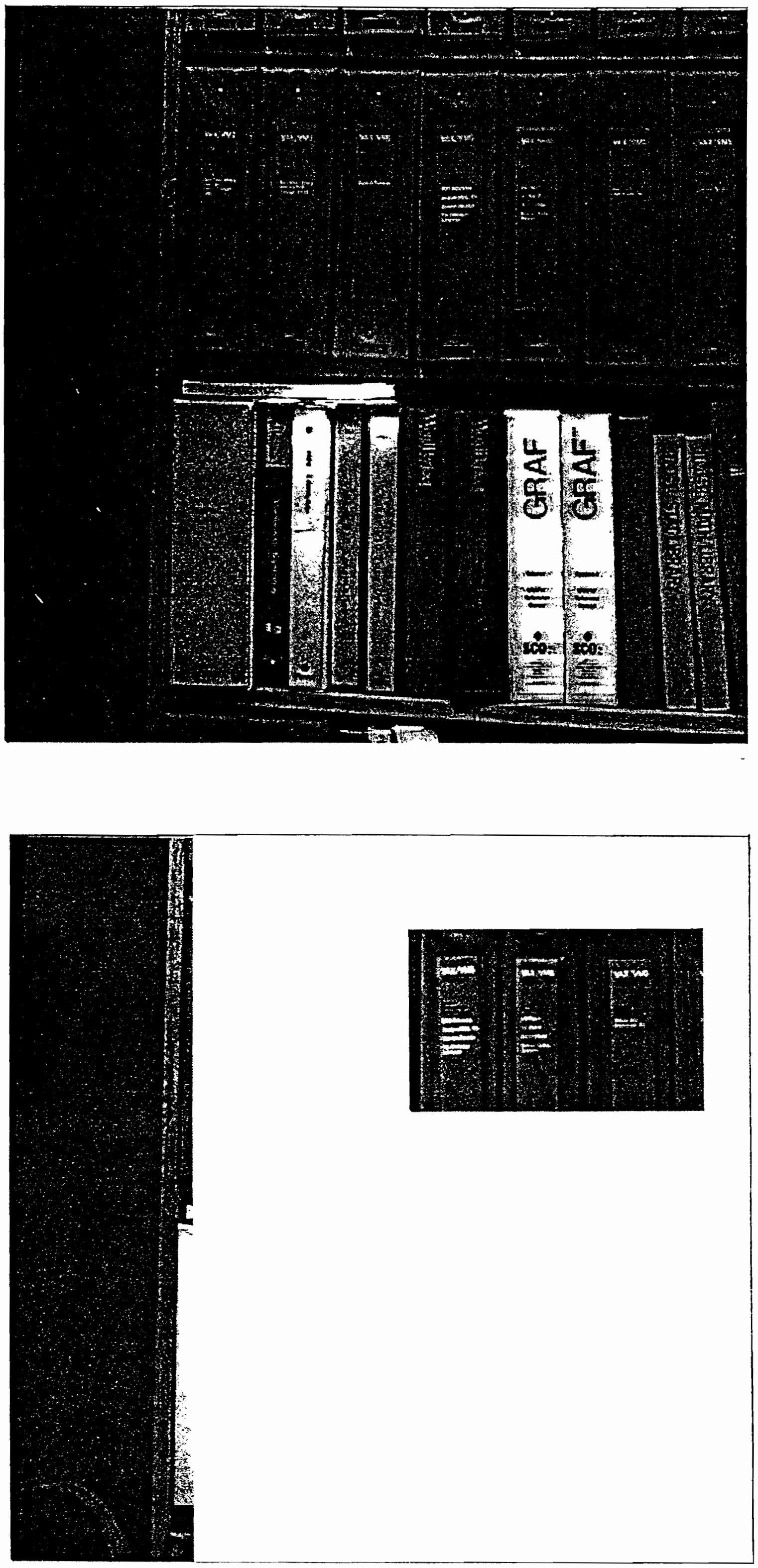
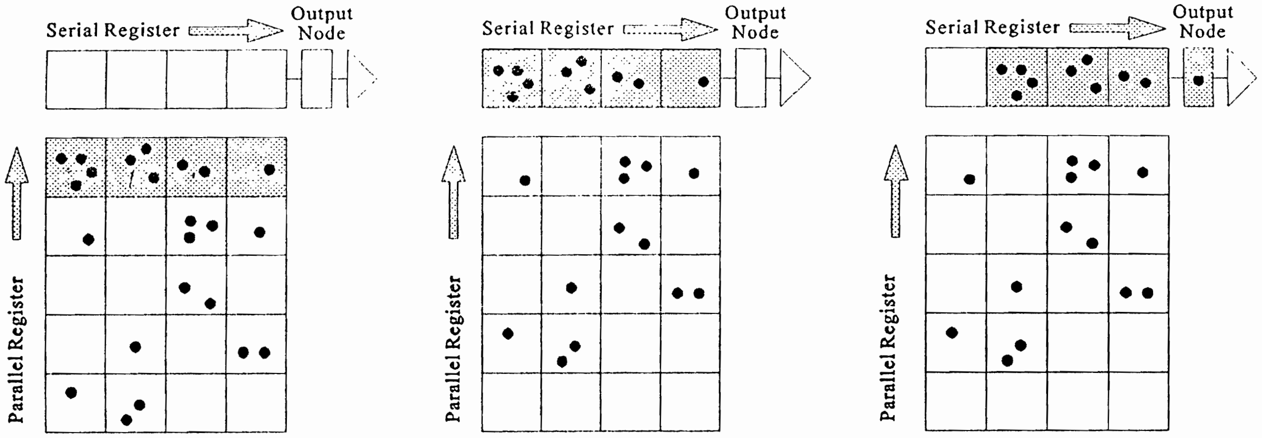
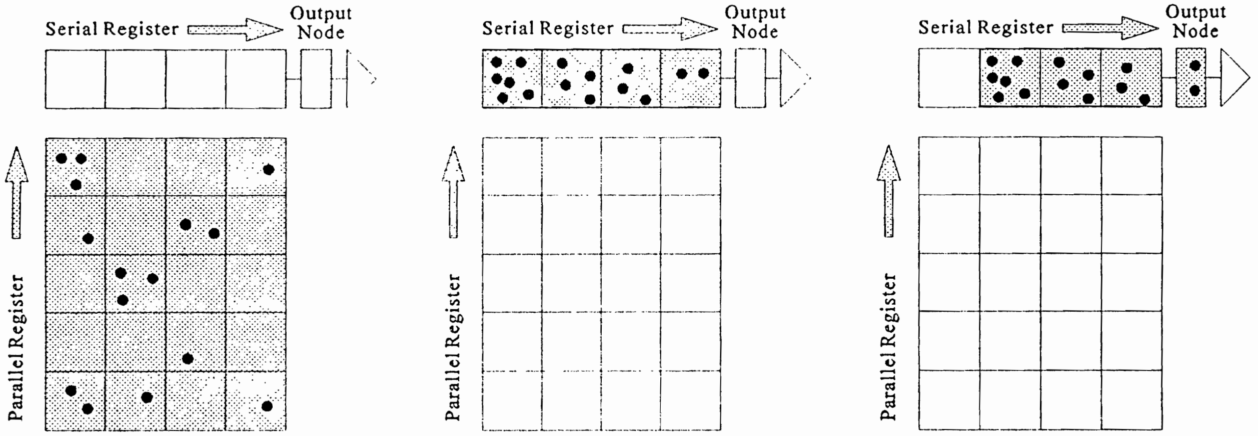


Figure 4. 512 x 512 image and 512x128 and 128x200 subimages from CCD #6.

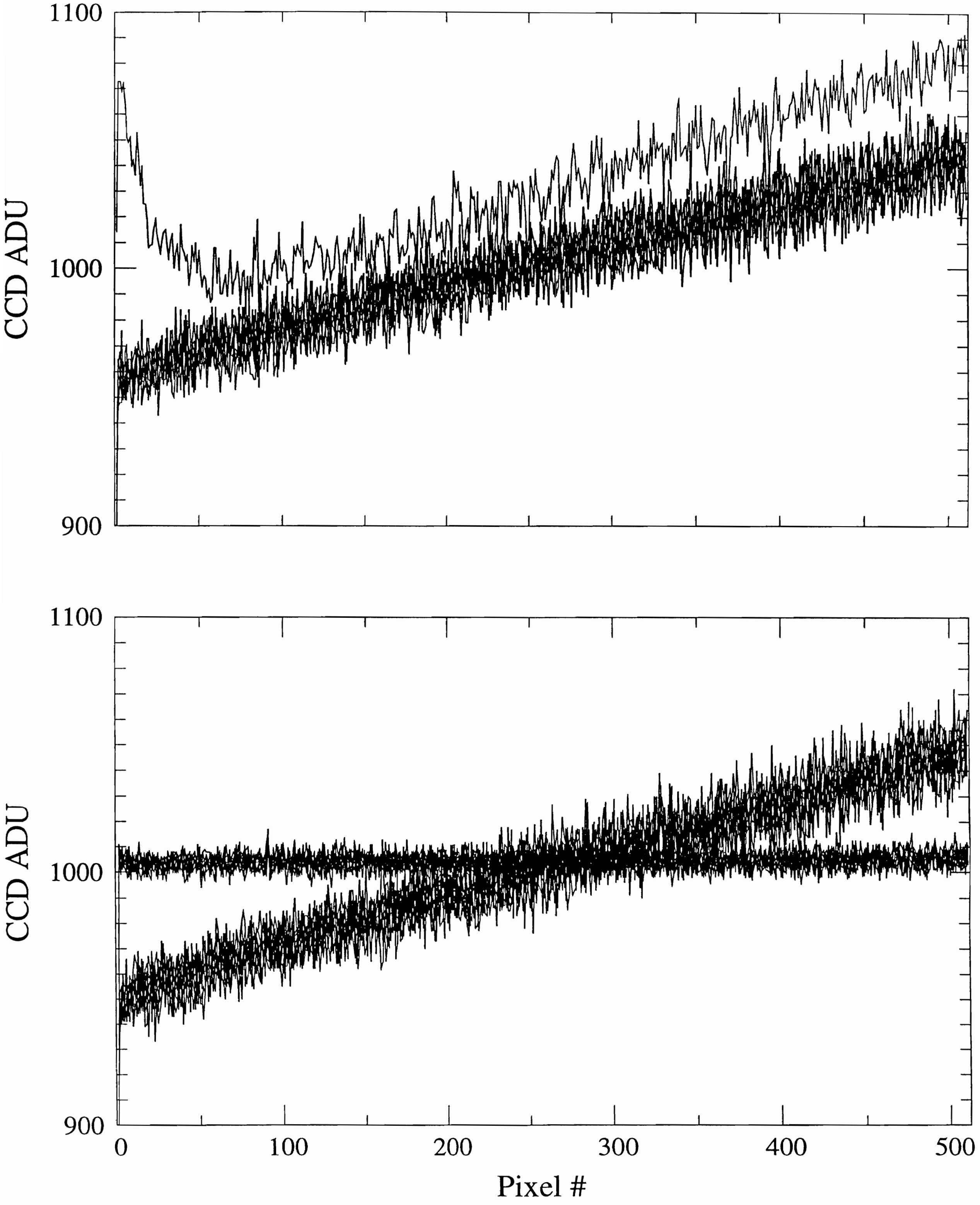


Serial Binning



Parallel Binning

Figure 5. Schematic showing accumulation of charges using serial and parallel binning methods. In serial binning (top) electrons in a row of pixels are sequentially swept into the serial register and the electrons are combined in the output node. In parallel binning (bottom) all rows are combined in the serial register, from which they are swept into the output node for converting to ADU. Adapted from Photometrics (1991).



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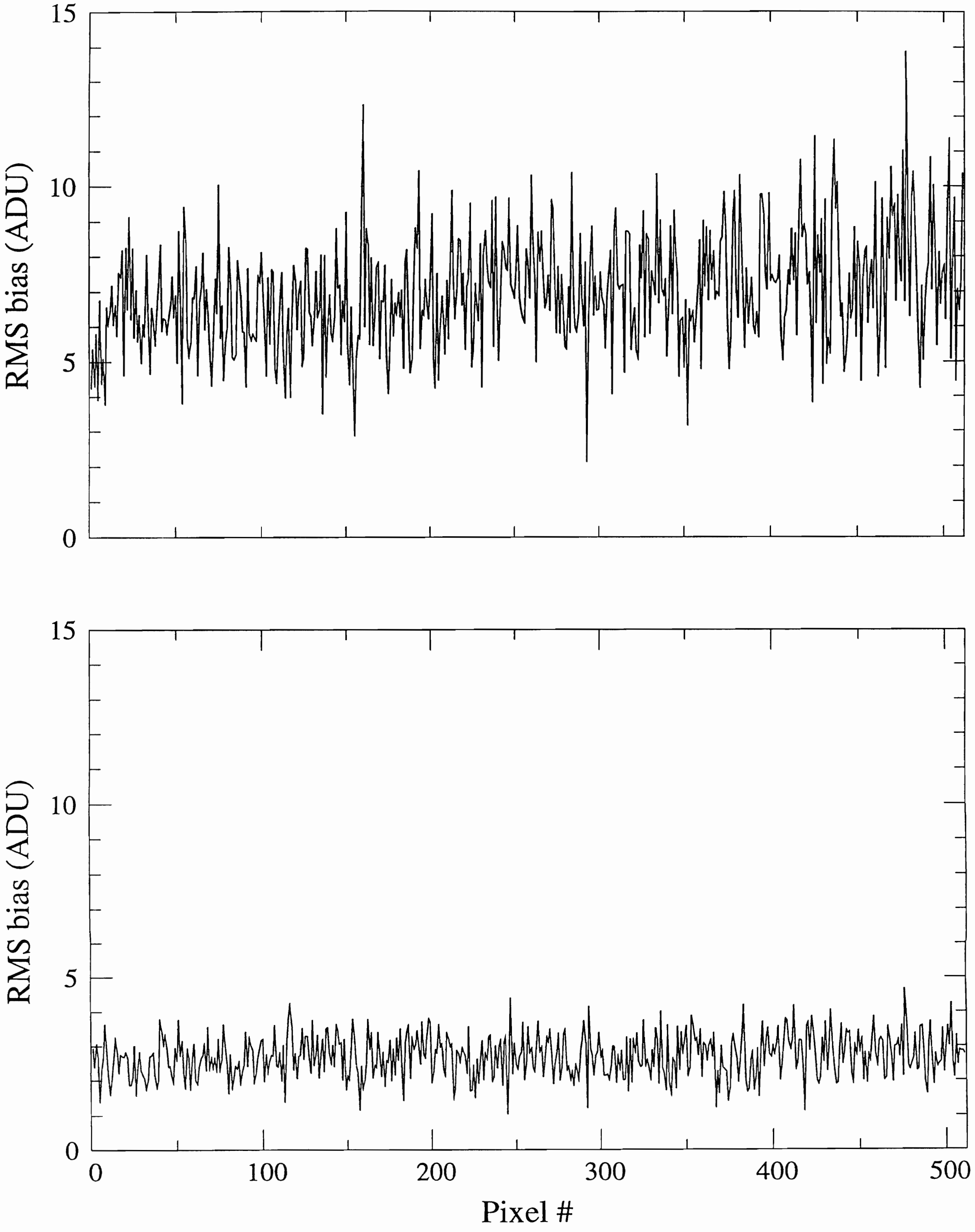

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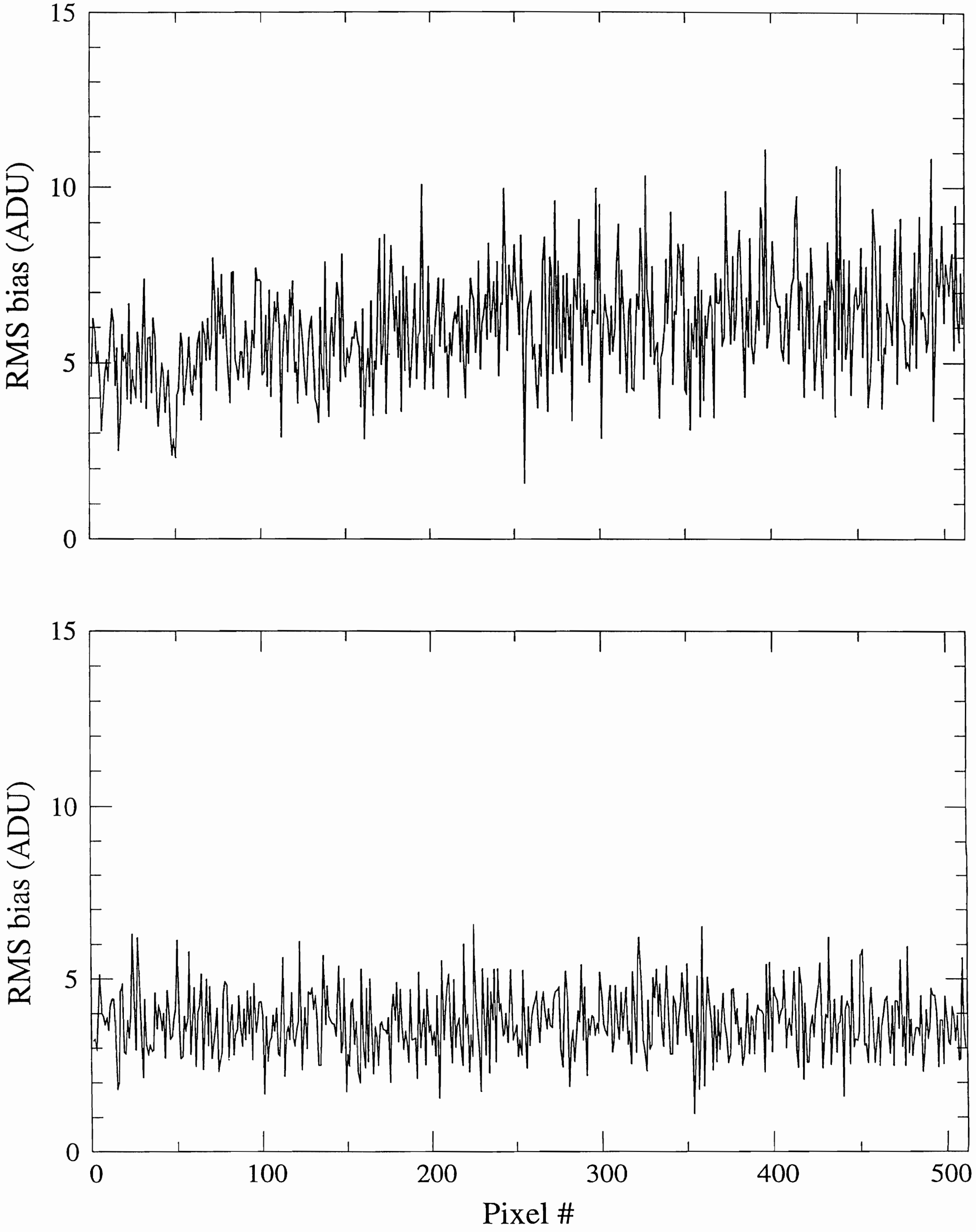

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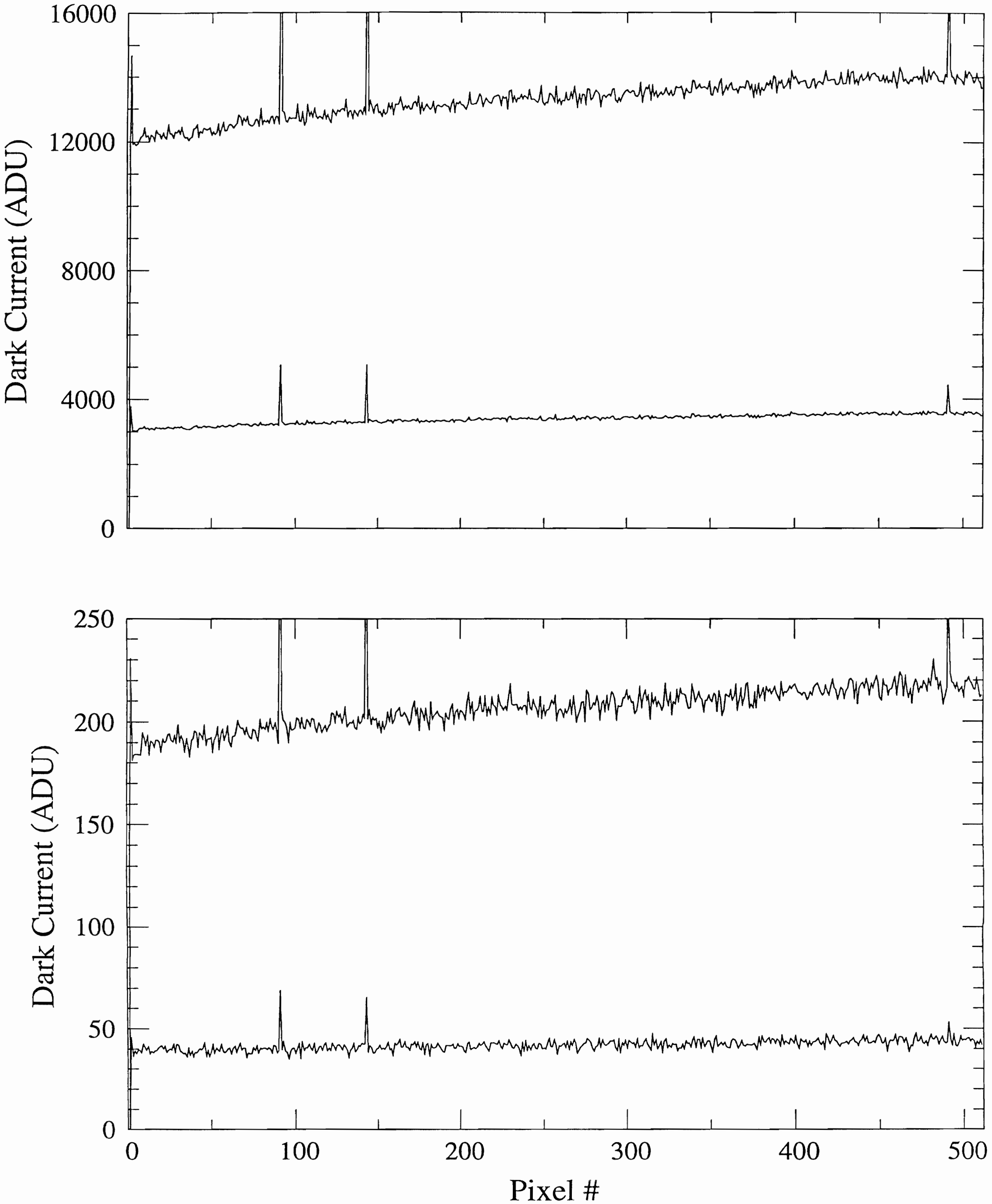

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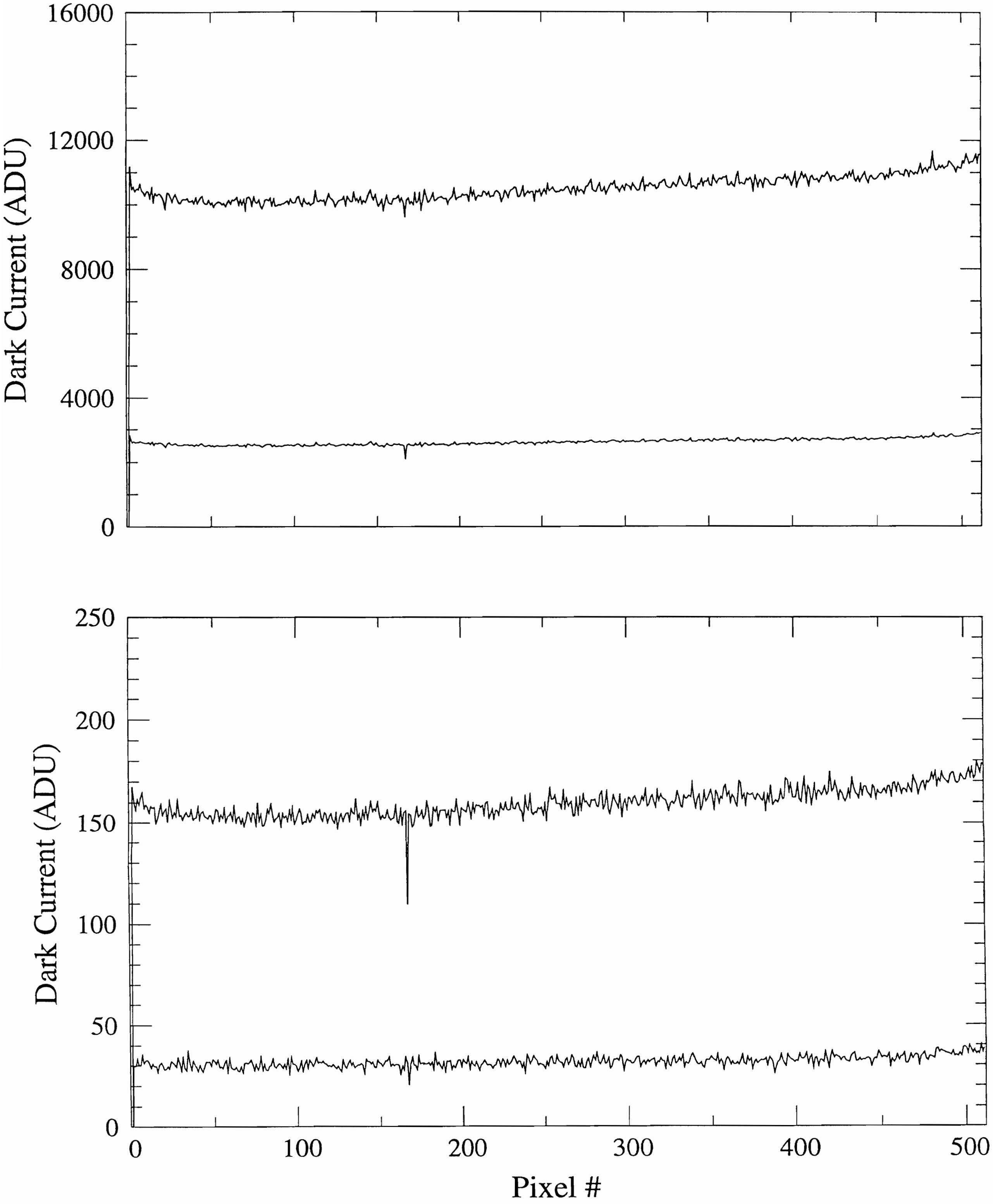

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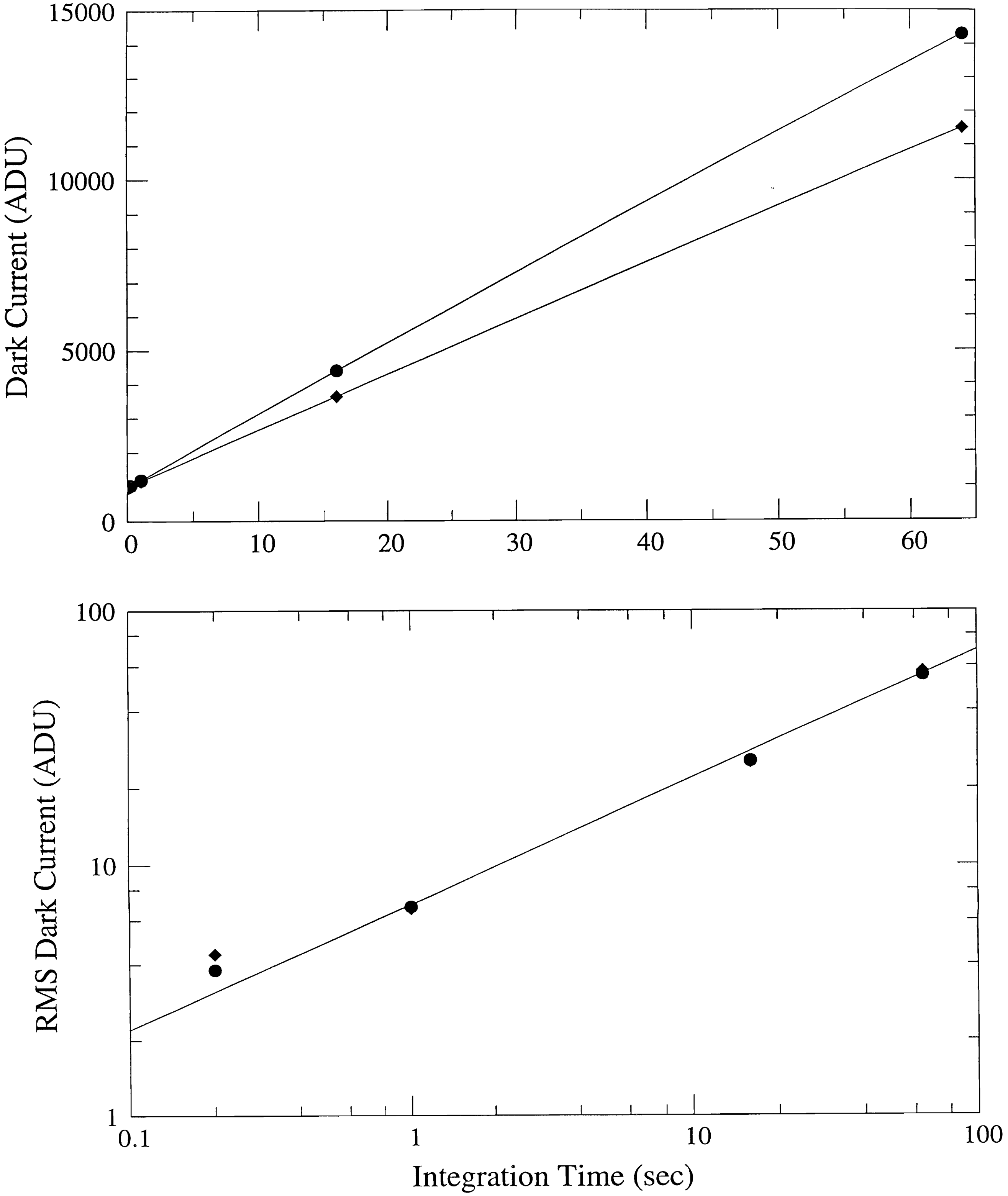

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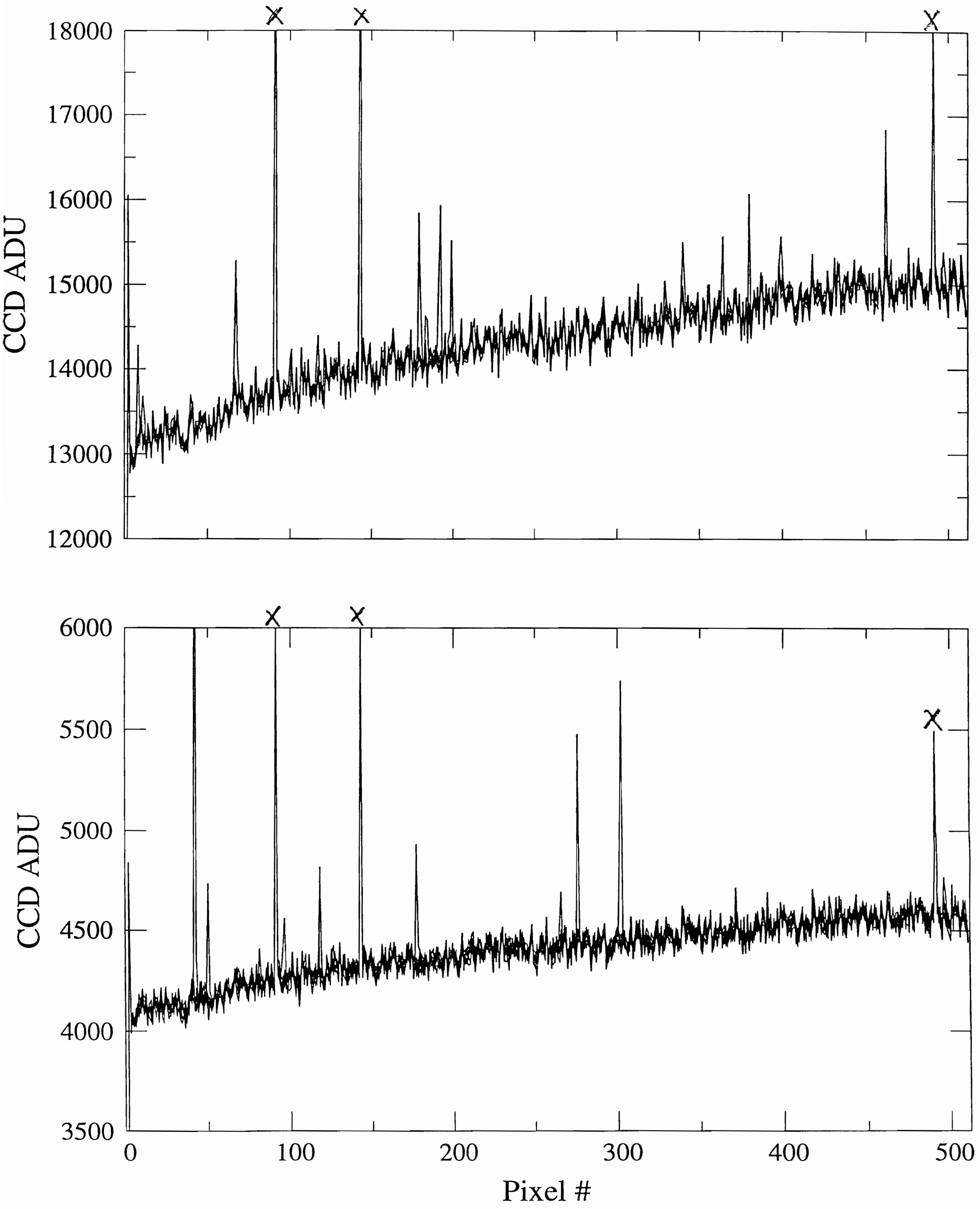

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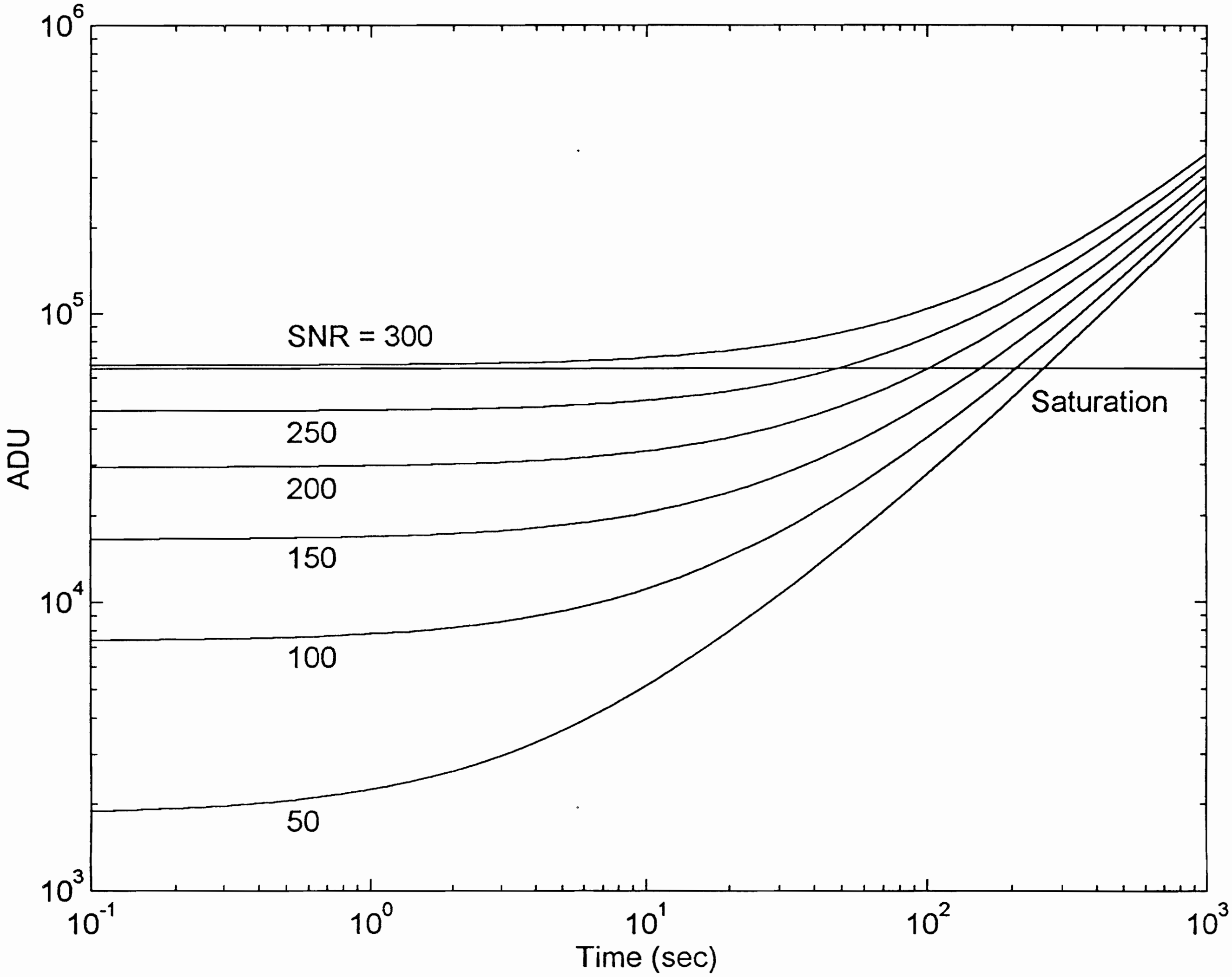

Figure 13. Counting statistics in Analog Digital Units (ADU) for CCD array #5 when 512 rows are binned. Isolines show increasing SNR for integration times between 0.1 and 1000 s. The horizontal line indicates 16-bit saturation when 512 pixels are binned. The maximum SNR is just under than 300:1.

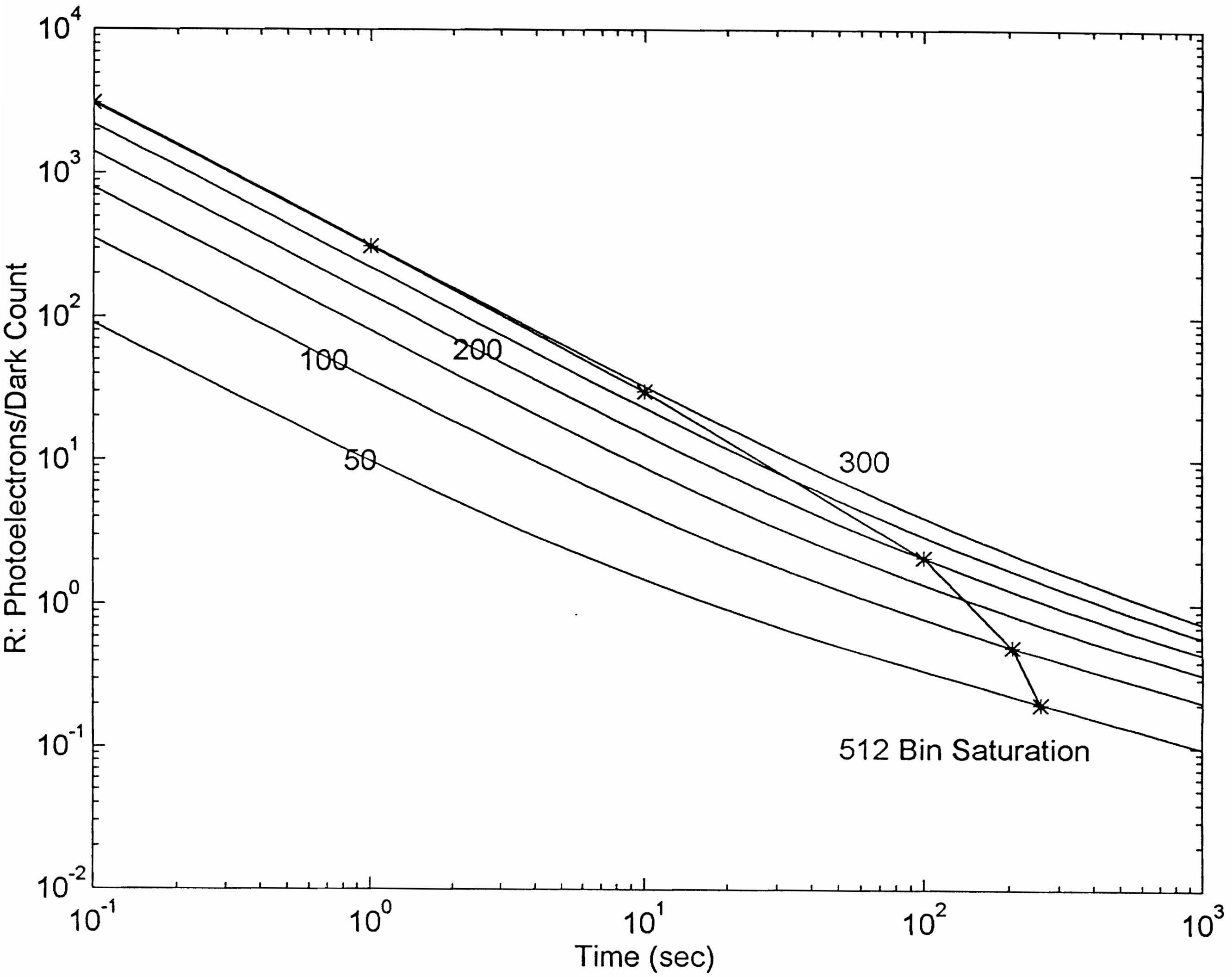

Figure 14. Signal to Noise Ratio (SNR) dependence on the ratio between total photoelectrons per unit dark count (R) and integration time. At short integration times and large SNR, the greater is the number of photoelectrons relative to dark current. The line marked by * shows the 16-bit counting limit when 512 pixels are binned.