

# Characterisation of QHY268M for PEST2

TG Tan 17<sup>th</sup> April 2025

## 1 Introduction

This documents the characterisation and testing I did on a QHY268M camera (the ‘Macho Mouse’) destined for a major upgrade of the PEST observatory. Some basic parameters:

- Back illuminated CMOS sensor, Sony IMX571.
- 6252 x 4176, 3.76um pixels (26 Megapixels)
- Native 16-bit A/D

### 1.1 Summary of measurements

#### QHY268M ‘Macho Mouse’ Calibration Sheet

Measurements by TG Tan

<http://pestobservatory.com/>

Selected  
Mode

Model	QHY268M	Mode	#4 Phot 2CMS	#5 HiGain 2CMS	#5 HiGain 2CMS
Sensor	IMX571	Binning	1 x 1	1 x 1	Averaged 2 x 2
Date	8/04/2025				
CCD Temp.	-5 deg C				
Gain setting			0	0	0
Offset:			20	20	20
USB Traffic:			50	50	50
<b>1. System Noise (a) -5 deg C</b>			<b>1 x 1</b>	<b>1 x 1</b>	<b>Averaged 2 x 2</b>
	GAIN:	e-/ADU	1.33	0.80	3.20
	RD NOISE(e-):	e-	6.22	3.51	7.02
<b>2. Bias Level:</b>			<b>ADU</b>	<b>325</b>	<b>322</b>
<b>3. Dark Count: (from QHY)</b>			<b>e-/pix/s</b>	<b>0.0018</b>	<b>0.0018</b>
<b>4. Saturation, deviation from linearity line</b>			<b>1 x 1</b>	<b>1 x 1</b>	<b>Averaged 2 x 2</b>
Non-linear at		16-bit ADU	47500	64500	64500
<b>5. Calculated Quantities</b>			<b>1 x 1</b>	<b>1 x 1</b>	<b>Averaged 2 x 2</b>
	Well Depth:	e-	63,318	51,665	206,658
	Dynamic Range:	levels	10,172	14,722	29,438
	DR, no. of bits	bits	13.3	14	15
	Download time	s		2.8	

## 1.2 Modes:

Several modes are available and it was not immediately clear which I should select for high precision time series photometry.

- #0: Photographic
- #1: High Gain
- #2: Extended Full Well
- #3: Extended Full Well 2CMS
- #4: Photographic 2CMS
- #5: High Gain 2CMS

The 2CMS (Correlated Multiple Sampling) options sample the signal multiple (I saw 'twice' on a discussion thread but don't know if that was official). This reduces read noise while leaving other parameters the same. There being no downside I focused only on the 2CMS modes.

## 2 Selection of Mode, Gain and Offset

### 2.1 Selection criteria

I do high precision time-series differential photometry for exoplanet observations. Precision depends on the number of photons that can be recorded not only for the target star, but also for field stars that may be used in the comparison ensemble. The target may be relatively faint (I currently don't go fainter than mag 13) so read noise should ideally be low. But ensemble stars should be bright, without saturating the sensor, so that their photon noise contribution is small. So large full well would be an advantage.

The parameter that encompasses both is dynamic range: (full well / read noise). Where dynamic range is the same for different choices I would pick the one with highest full well. 'Full well' is the point where the sensor starts to deviate from linearity.

### 2.2 Rationale for my selections

The settings I chose:

- 'High Gain 2CMS' (#5), Gain = 0 and Offset = 20.

Mode #5 was selected because it has the lowest read noise at Gain = 0 and the loss in full well depth compared to Mode #4 is not large. Its well depth is 51.7 ke- compared to Mode #4's 63.3 ke-. Dynamic range is higher in Mode #5 than in Mode #4: 14,700 vs 10,200 (14 stops vs 13.3). In this respect Mode #4 performed worse in my tests than stated on the QHY charts. I had hoped it would have full well depth of 100 ke- but found it to be significantly lower. Mode #5 read noise is better than Mode #4, 3.5 vs 6.2 e-. I did not test Mode #3 because at Gain = 0 it has the same full well and high read noise as Mode #4, according to the QHY charts.

Gain = 0 was chosen in order to use the full well depth available. In some Modes read noise takes a big step down at particular Gain settings e.g. Mode #5 Gain = 56. But there is no dynamic range benefit and full well reduces to <50%, compared to Gain = 0.

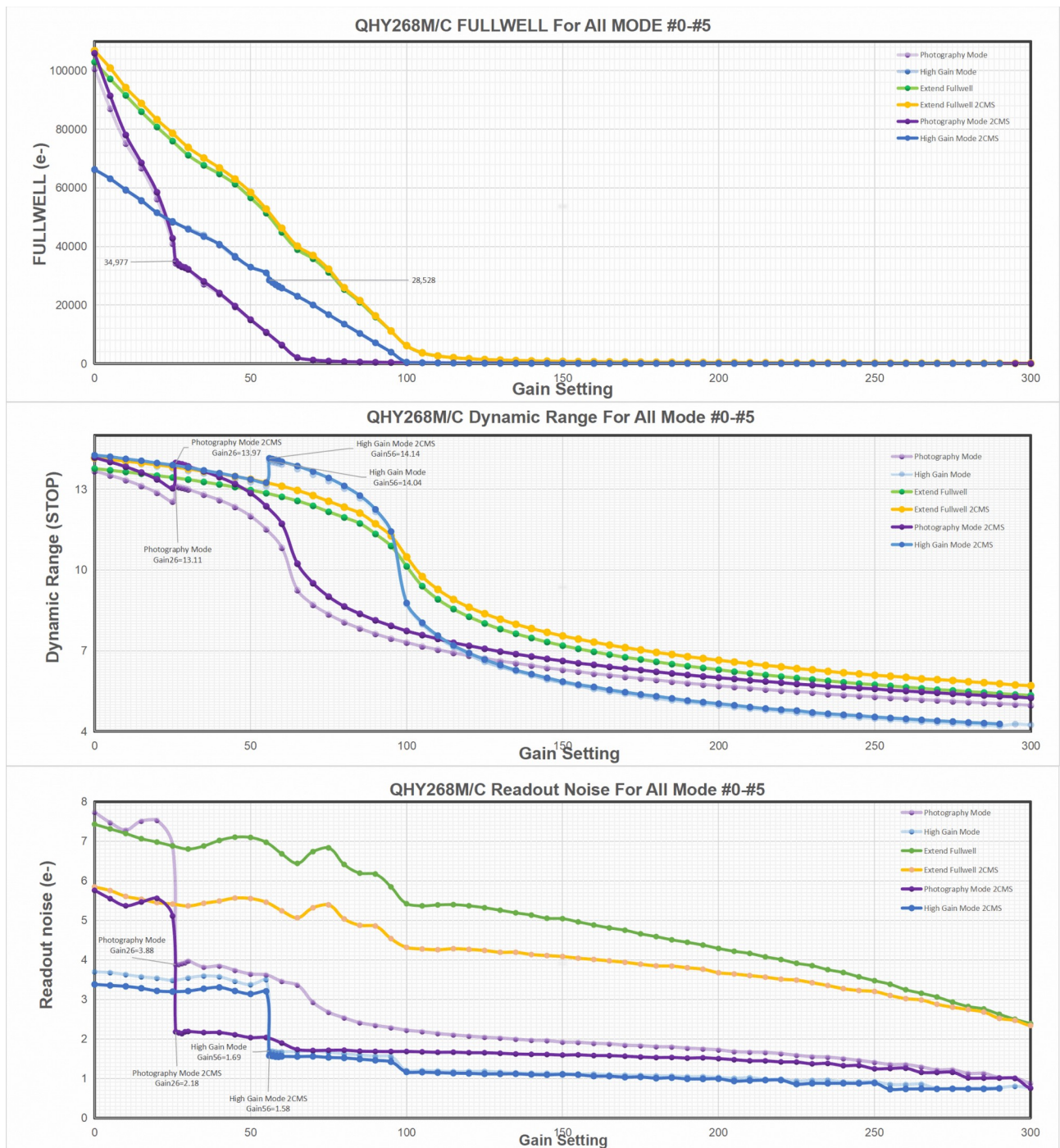
The full well / read noise trade-off is not a straightforward one. I mentioned dynamic range as a optimising criteria, but what really matters is achievable precision. I confirmed these choices using

a photometric precision simulator (on spreadsheet). A higher full well than the 51.7 ke- as selected does not improve precision because even a mag 8 star should not saturate with 120s exposures and with these bright stars atmospheric scintillation dominates photon shot noise. But higher read noise has appreciable impact if the target stars are the typical mag 12 or dimmer.

Offset was selected in order not to zero-clip low signals but not so high as to eat into dynamic range as the top of the ADU range hits 16-bit saturation (63,535). This gives a minimum ADU in bias frames of about 250 ADU, and average bias of 322 ADU.

In practice the raw images are binned in software by taking the average of 2x2 pixels. The effective Gain =  $0.8 \times 4 = 3.2$  and Read Noise =  $\text{SQRT}(4 \times 3.51^2) = 7.02$ .

### 2.3 Charts published by QHYCCD





### 3 Calculation of Gain and Read Noise

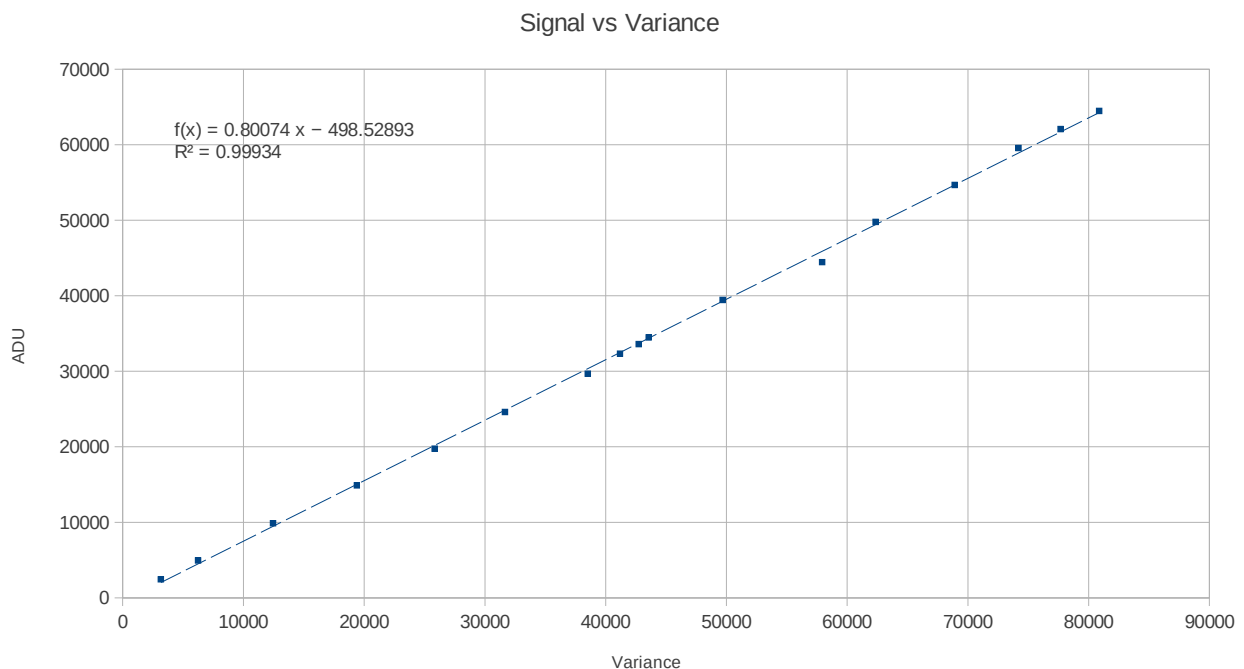
Unless stated otherwise the following are with Mode #5. Summary measurements:

- Gain = 0.80 e-/ADU
- Read noise = 3.51 e-

The gain calculation used Method 1 from Mirametrics: [http://www.mirametrics.com/tech\\_note\\_ccdgain.htm](http://www.mirametrics.com/tech_note_ccdgain.htm)

Several pairs of images over a range of exposures up to saturation were taken. Each pair had the same exposure. A bias level was subtracted from all images, the median levels in the 100 x 100 pix central region normalised, then one member of each pair was subtracted from the other.

Signal (in ADU) and variance (=  $SD^2/2$ . Division by 2 because subtraction doubles the variance) from each of these resulting 100 x 100 areas were plotted. The slope gives the gain, = 0.80 e-/ADU.



Read noise was measured by subtracting 5 pairs of bias frames (i.e. darks with 0.001s exposures), measuring the variance in the central 100 x 100 pix area of the subtraction. The read noise in each frame =  $\text{SQRT}(\text{variance} \times 2) / \text{SQRT}(2) = \text{SQRT}(\text{variance})$ . Average of these 5 subtractions = 4.381 e-. Read noise = 4.381 \* 0.8 = 3.51 e-.

### 4 Linearity

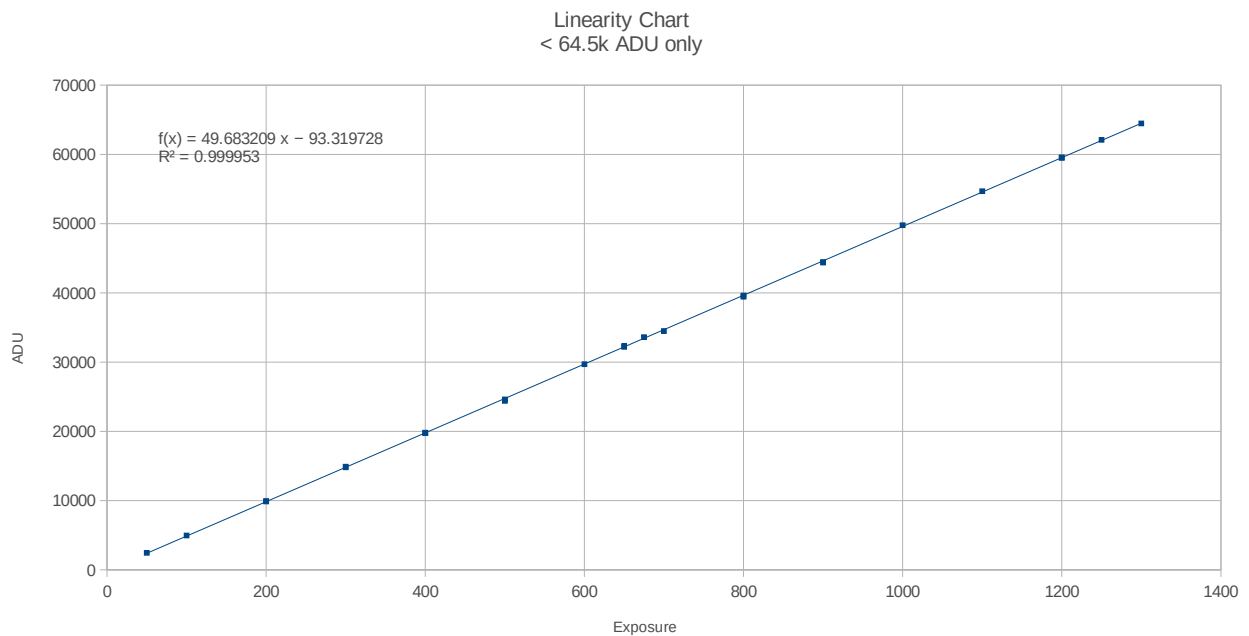
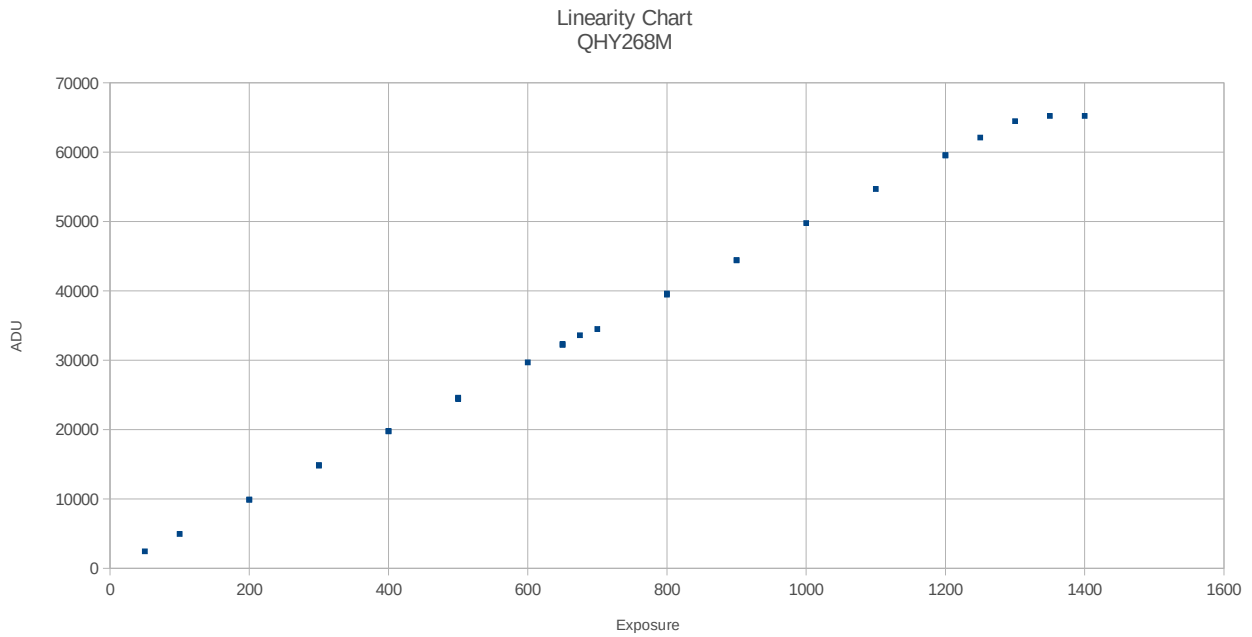
In summary, linearity is excellent in both Modes tested. Importantly, above about 60% full-well (when read and sky noise become less important) it is better than 0.5%.

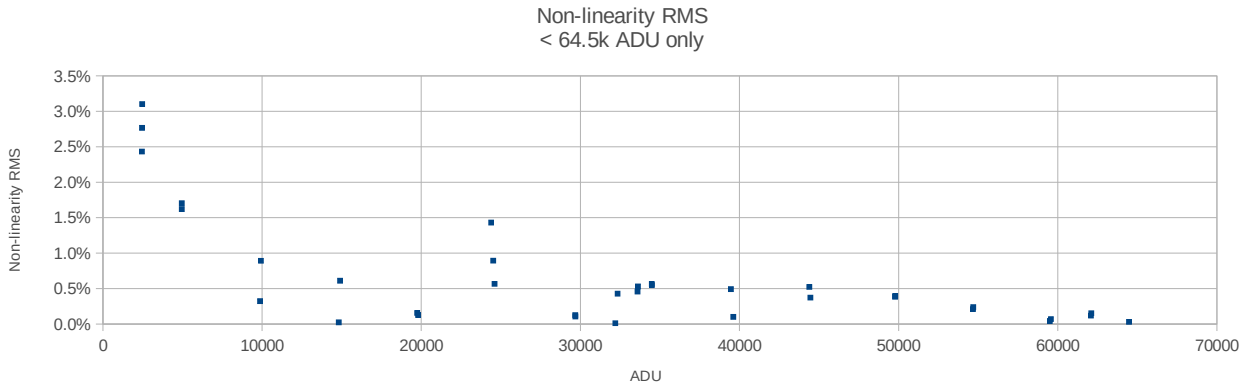
## 4.1 Method

A number of 40s exposures were taken over a range of light values produced by an LED installed in a test nosepiece of the camera, controlled by an Arduino 'blinker' program.

## 4.2 Mode #5

The response is probably linear all the way to the 16-bit ADU limit 65,535 although my testing only confirmed it for up to 64.5 ke-.





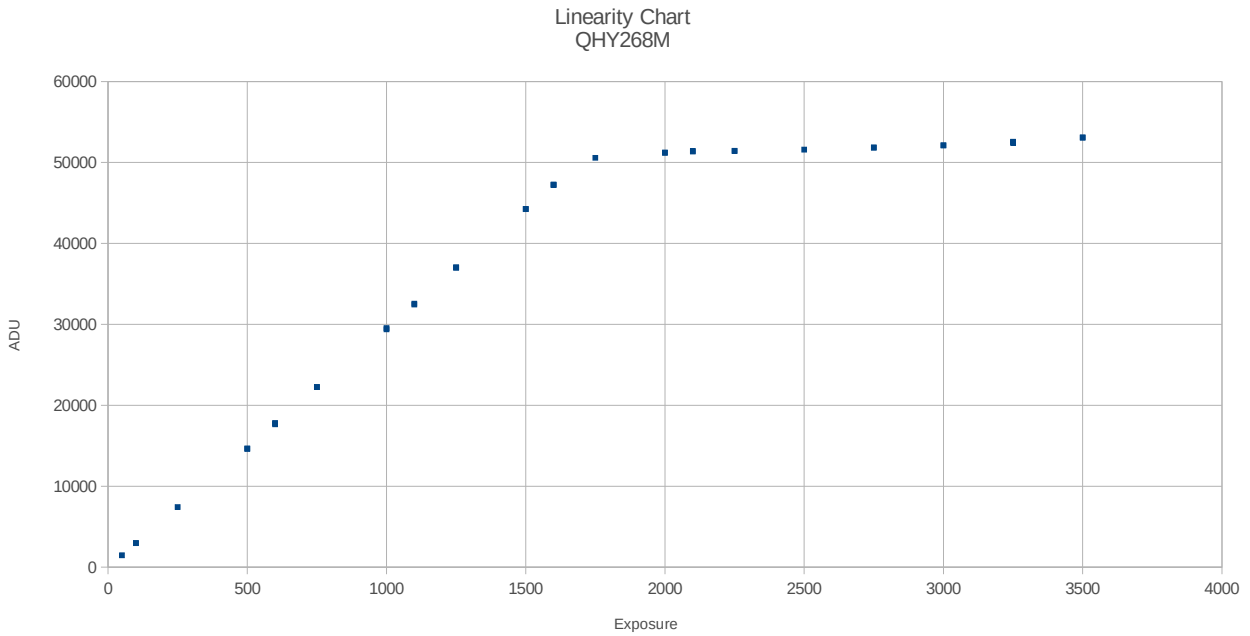
A plot of RMS residuals against a straight line shows less than 0.5% non-linearity over the full range.

Well depth at start of non-linearity =  $64,500 \times 0.80 = 51.7 \text{ ke-}$ .

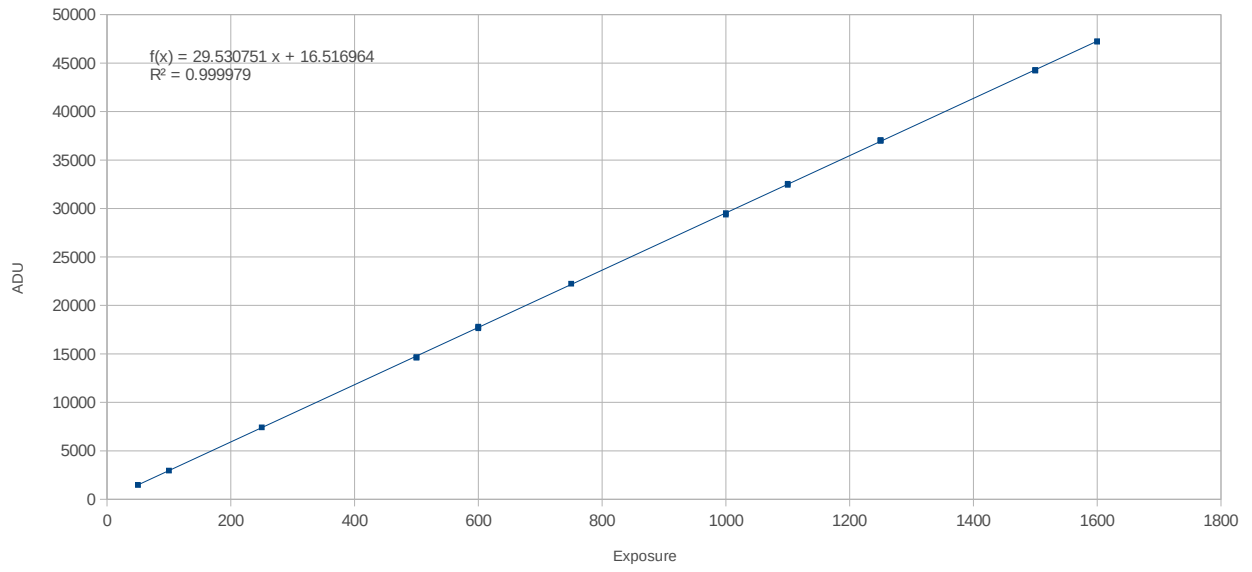
### 4.3 Mode #4

For completeness here are the same charts for Mode #4.

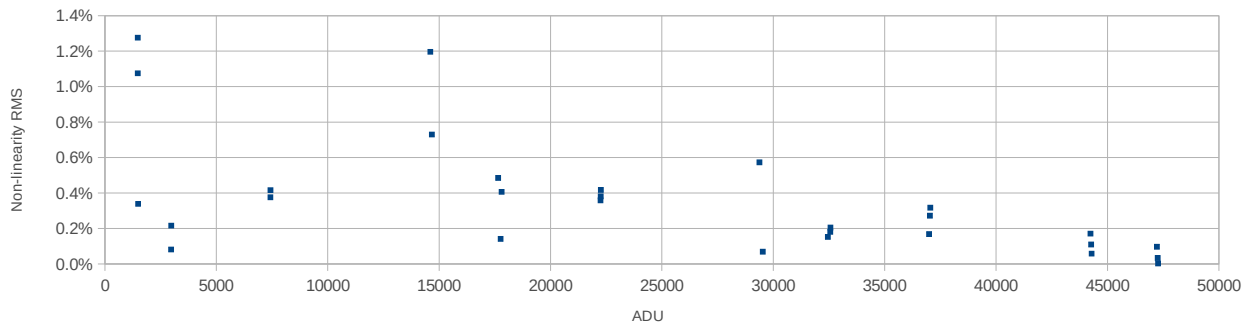
Gain was measured to be  $1.33 \text{ e- /ADU}$ . Linearity is excellent as well. Well depth at start of non-linearity =  $47,500 \times 1.33 = 63.3 \text{ ke-}$ . This is much less than the  $>100 \text{ e-}$  from the QHY charts.



Linearity Chart  
< 47.5k ADU only



Non-linearity RMS  
< 47.5k ADU only



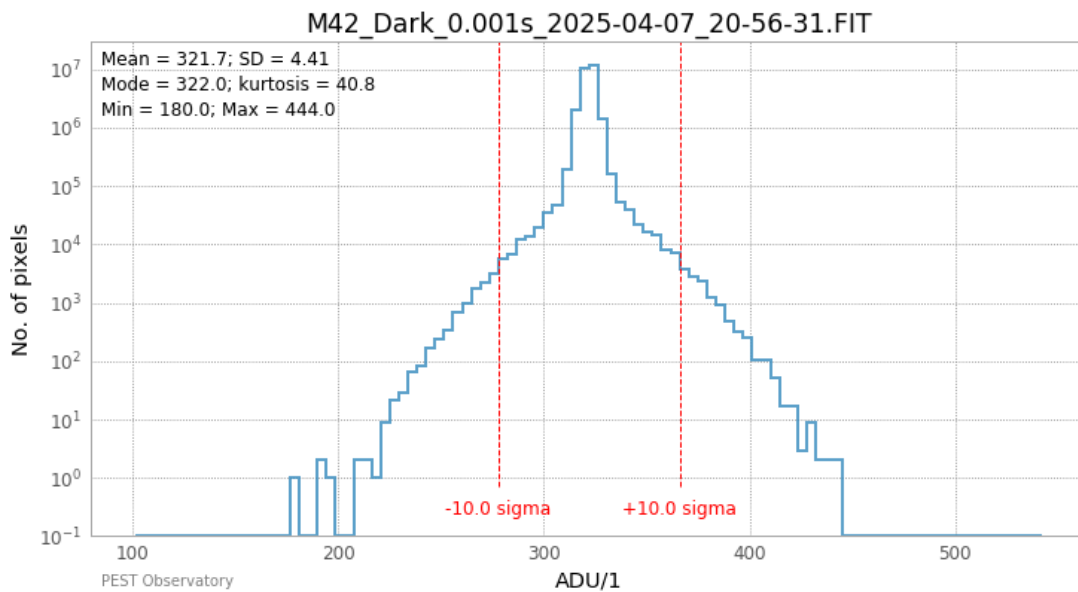
## 5 Characterisation of Random Telegraph Noise (RTS)

In this section I take a look at whether the sensor suffers from RTS and what impact it might have on photometry. My previous tests (<http://pestobservatory.com/cmos-for-photometry/>) on a QHY183M showed that RTS is present but would not have significant effect on photometry.

In summary I come to the same conclusion, although in detail there are some quantitative differences in behaviour. Unless noted otherwise all examples in this section use Mode #5.

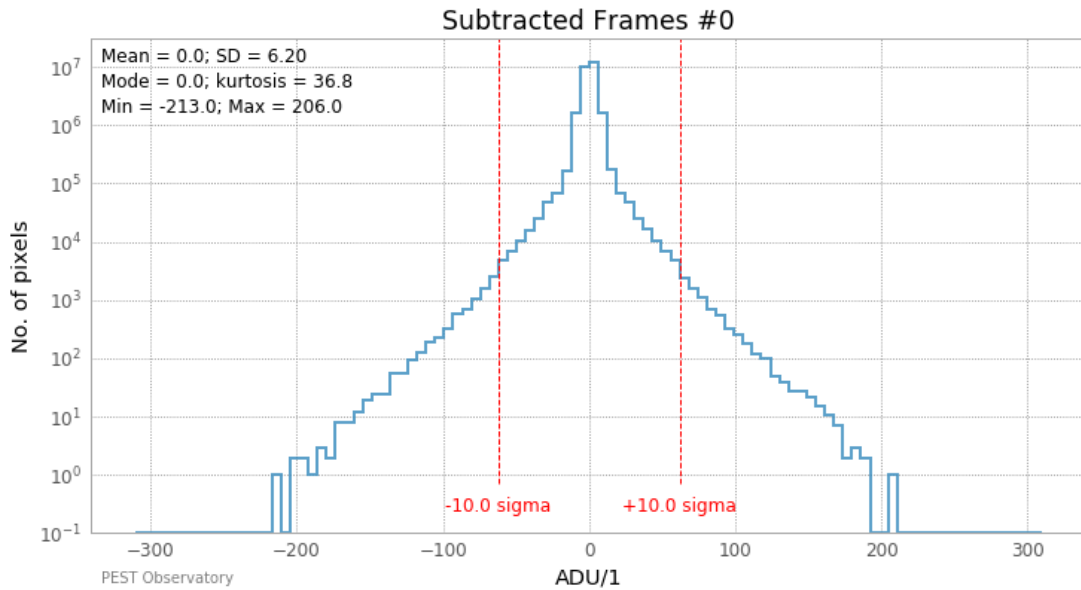
### 5.1 Is there RTS?

A histogram of a bias frame exposure 0.001s is shown. The now familiar CMOS type distribution is evident with the noise 'wings' being wider than gaussian. Kurtosis = 40.8 rather than 3.0 for a gaussian.



The wide spread of points may be evidence of some fixed pattern, rather than intrinsic noise, with some pixels always brighter or dimmer than others. That would not matter for photometry because they will be normalised through image calibration (darks and flats). To check, I cancel out any fixed pattern by subtracting one bias frame from another.

I acquired 200 bias frames then paired them off at random and did subtraction for each pair. Below a histogram for an example subtracted fits file.



The wide wings of the histogram are still there so they are not from some subtractable fixed pattern. There are 10,000's of pixels outside the +/-10 sigma bounds.

So RTS is present. But just how they impact photometry will depend on how they behave from frame to frame. If they just have large scatter the effect would just be like a higher read noise. And do bad pixels continue to be bad pixels? Perhaps the random noise could happen to any of the 26m pixels in the sensor. That would reduce the impact on photometry, but also make the problem harder to fix.

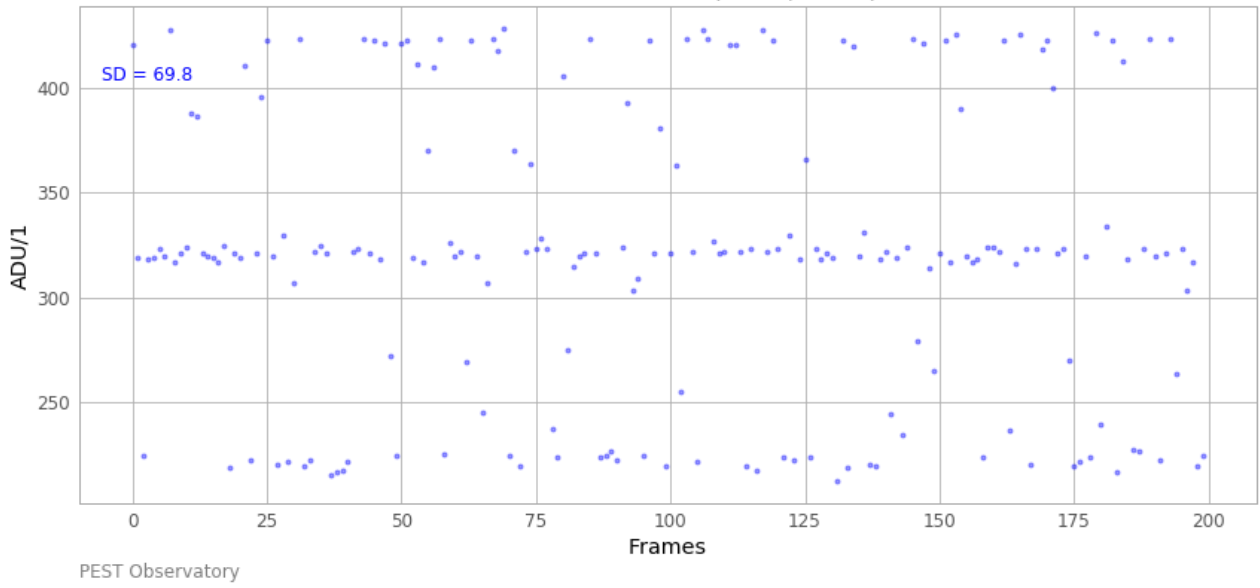
## 5.2 Outlier pixel behaviour

From subtraction of each bias pair, I identified every pixel with deviation greater than 10 sigma. The 10-sigma figure was chosen to limit the number of pixels identified from each frame. But the number of pixels identified as being RTS affected still totalled >311,000. We will see later if all of these are indeed RTS affected, or just have anomalously high scatter for other reasons.

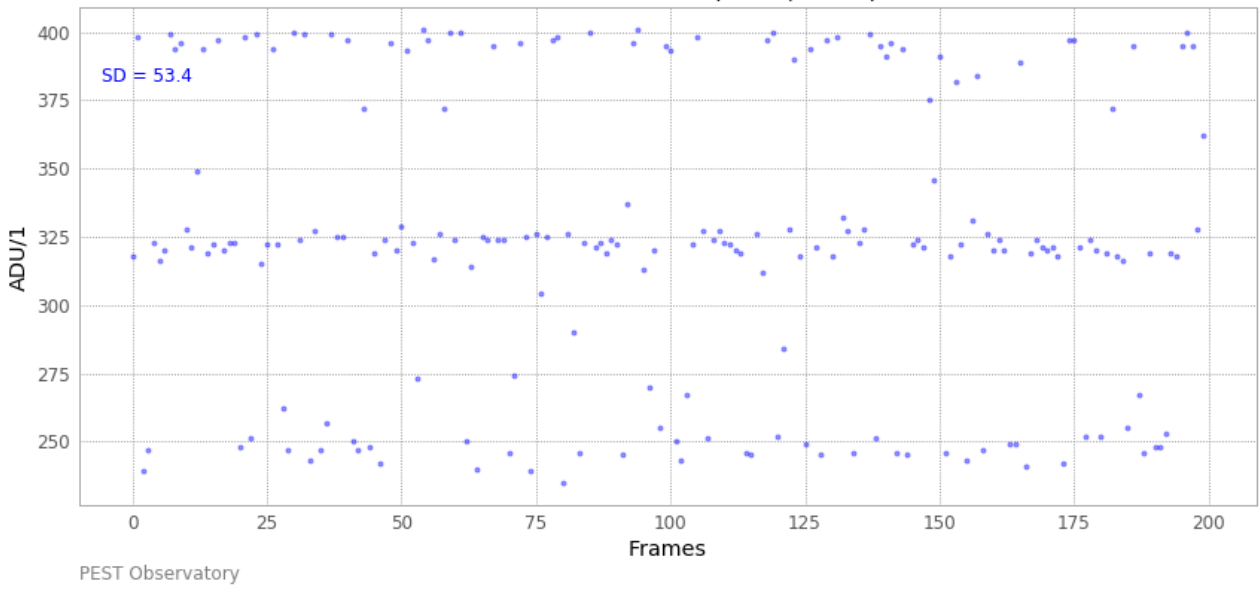
I counted the number of times each pixel was outside of the 10-sigma limits in each of the 100 frame subtractions, and used that to sort the resulting list of suspect pixels. The ADU level in each of the 200 bias frames of the worst of those pixels was then plotted.

Some examples:

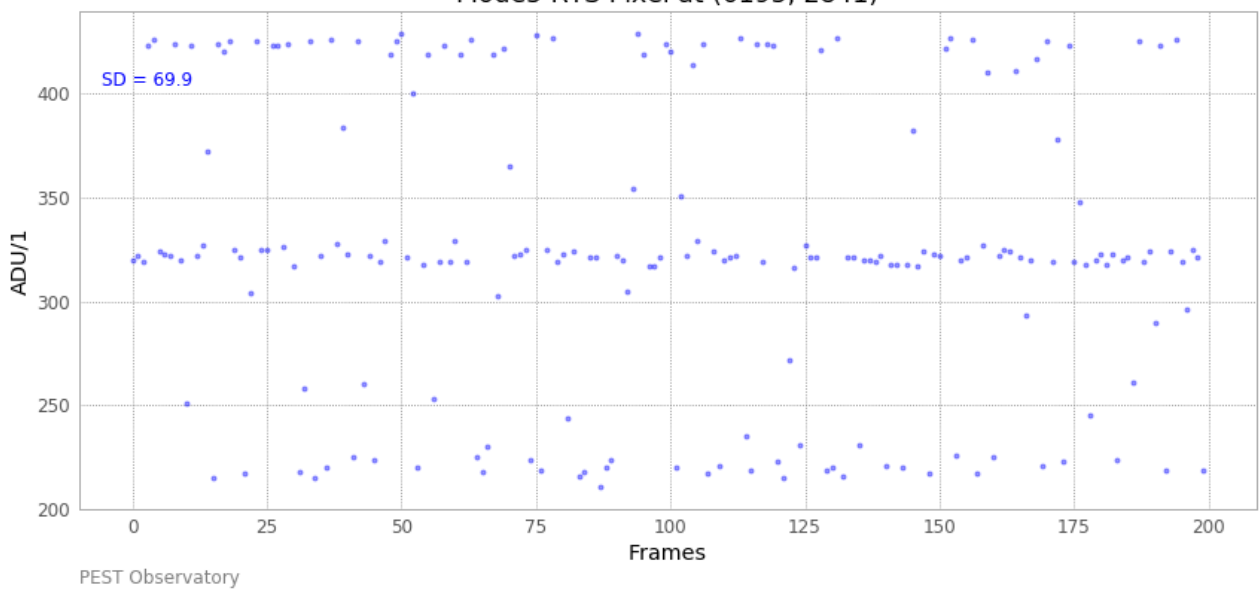
Mode5 RTS Pixel at (6195, 2842)



Mode5 RTS Pixel at (3731, 3740)



Mode5 RTS Pixel at (6195, 2841)



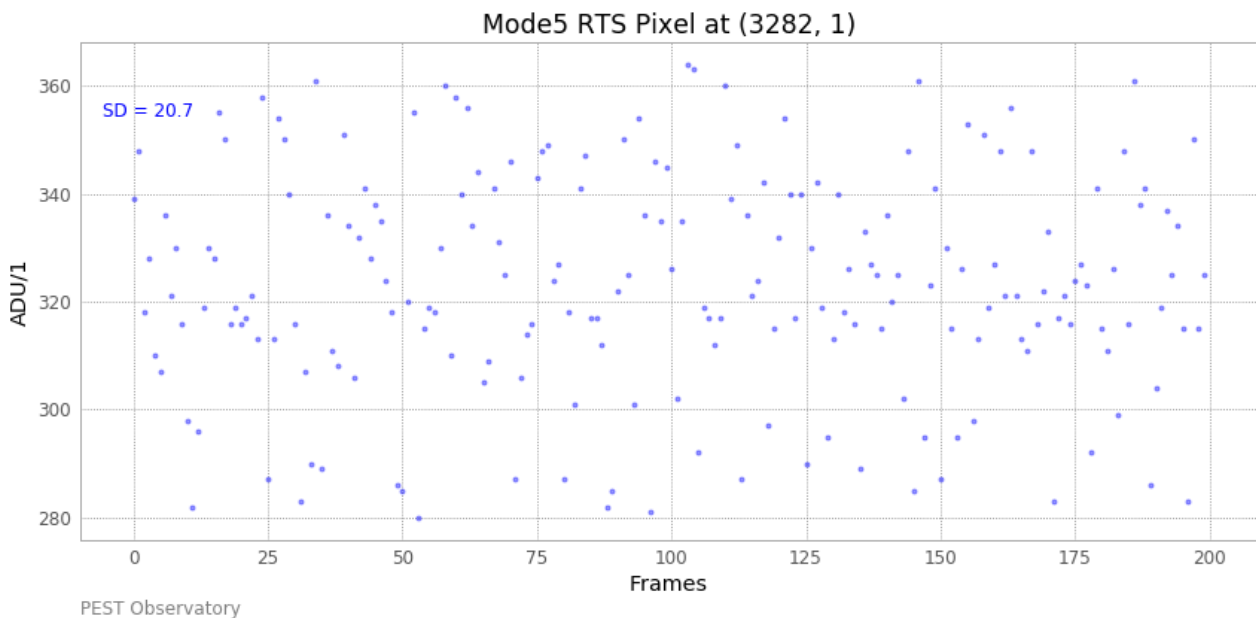
The pixels jump between 3 distinct levels. The central one of  $ADU = \sim 325$  is the offset or 'pedestal' level corresponding to no signal. But there are alternative levels 75 or 100 above and below.

We can infer that the characteristic of a particular pixel being 'RTS affected' persists over many exposures. In fact we will see later that it persists across different camera Modes as well.

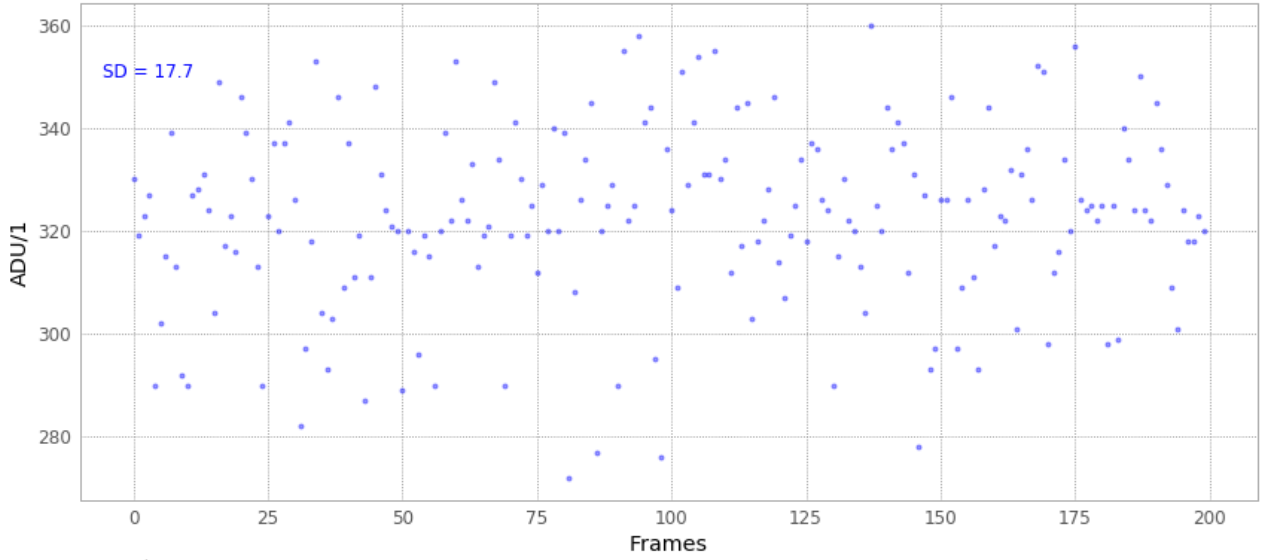
### 5.3 How many pixels are 'RTS affected'?

The previous test procedure produced a list of over 311,000 pixels with scatter over 10-sigma of the bulk scatter measured across the sensor, i.e. in the wings of the histogram. We have also seen that the worst of these (in terms of number of subtractions where this pixel is in the wings of the histogram) show the multi-modal ADU values characteristic of RTS. How about the 'least bad' among the 311,000? If these also show clear RTS behaviour then we can infer that the population of RTS pixels is at least 311,000 out of 26m, or  $>1.2\%$ .

Here are some plots of these 'least bad' pixels.

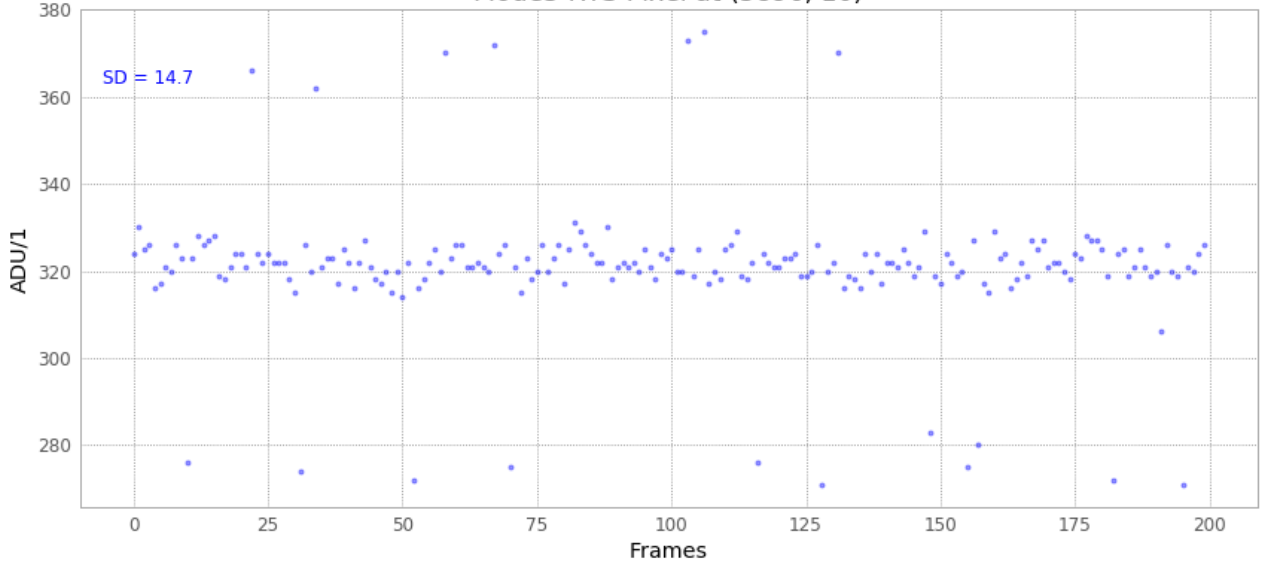


Mode5 RTS Pixel at (71, 3)



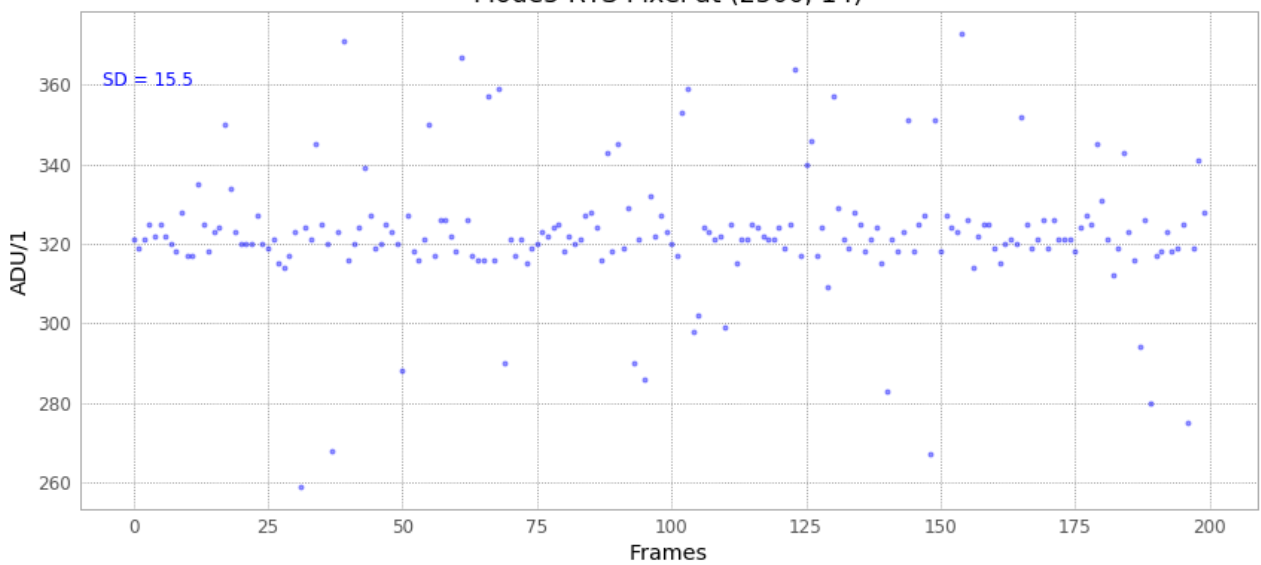
PEST Observatory

Mode5 RTS Pixel at (5896, 10)



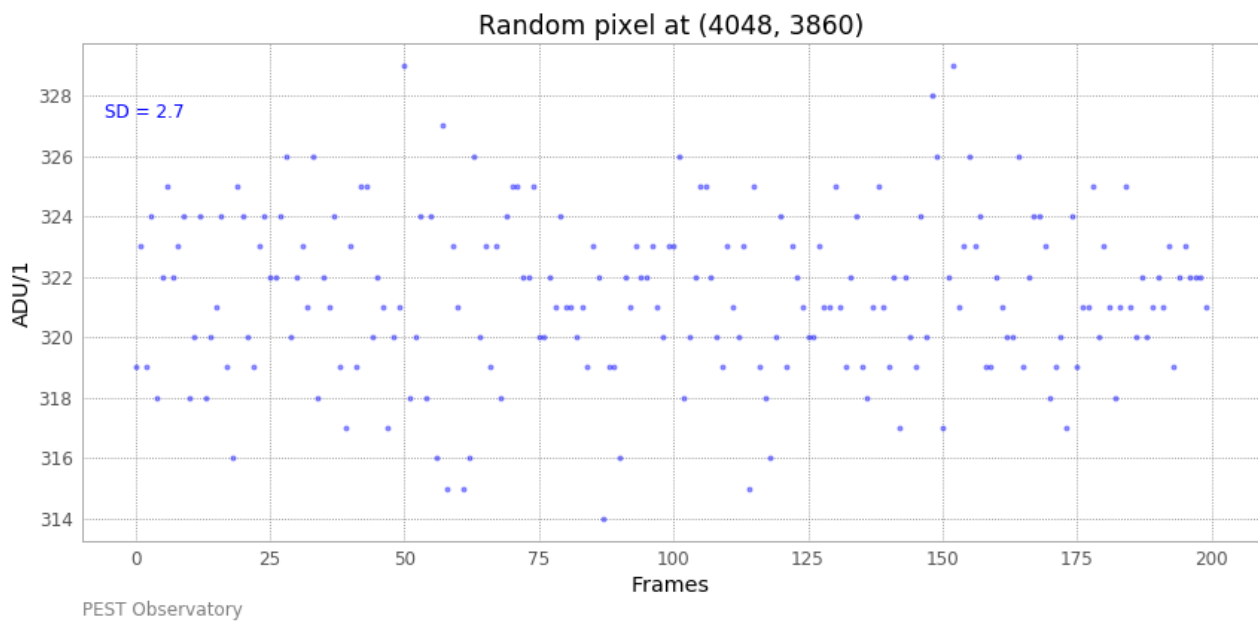
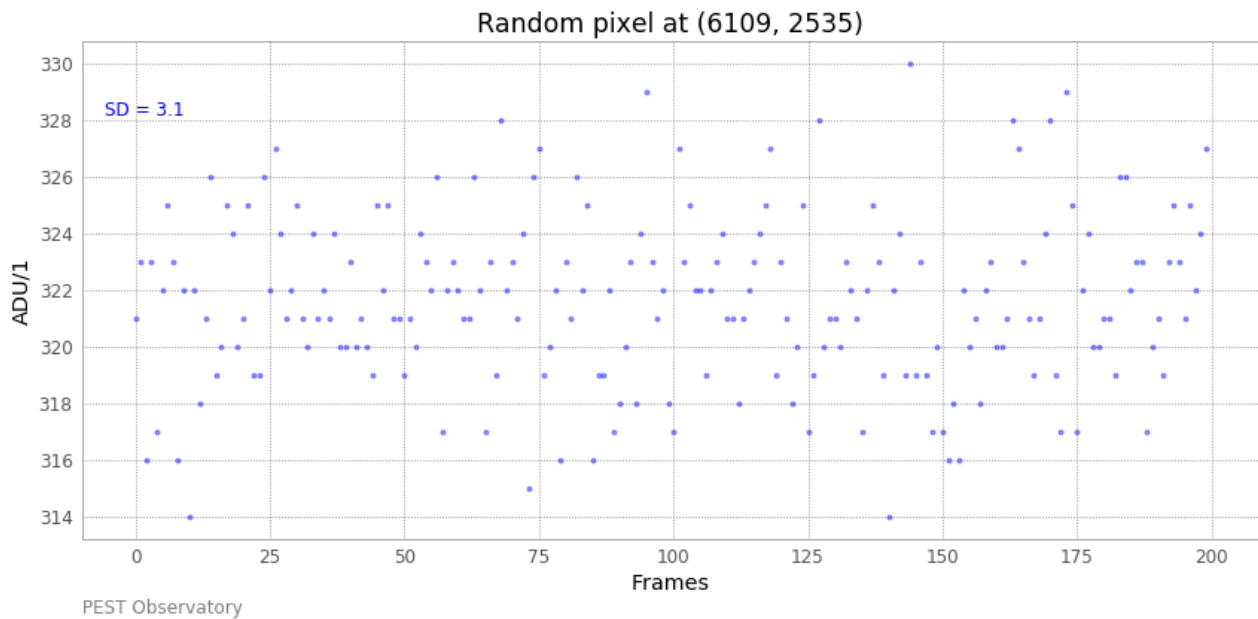
PEST Observatory

Mode5 RTS Pixel at (2500, 14)



PEST Observatory

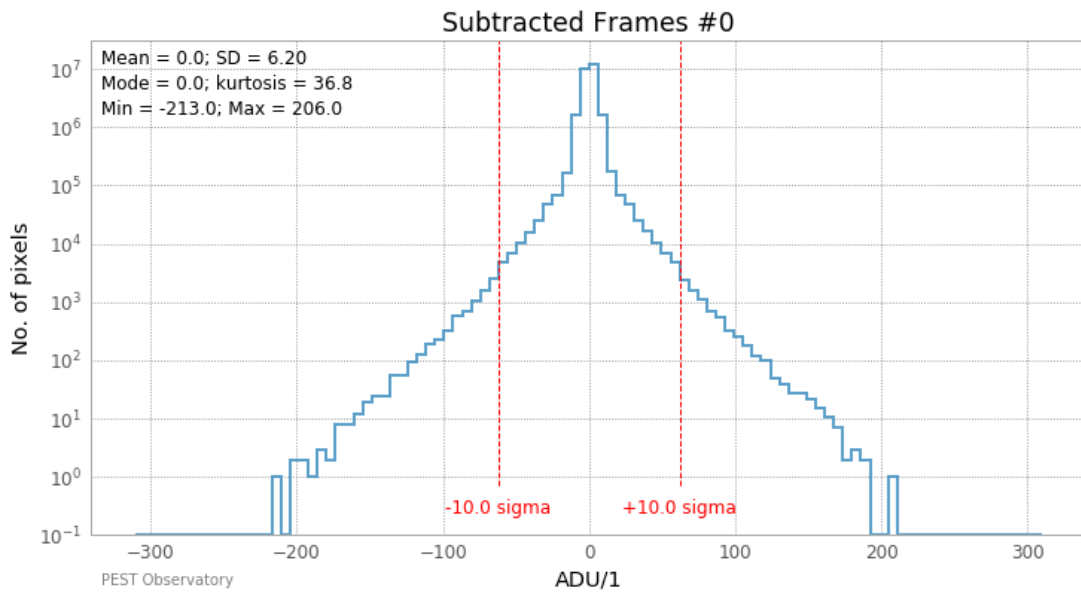
The first 2 above are not clearly RTS, but the bottom 2 are, albeit with much less frequent jumps up or down. But the first 2 do have elevated scatter. To make this clearer here are a couple of randomly chosen pixels.



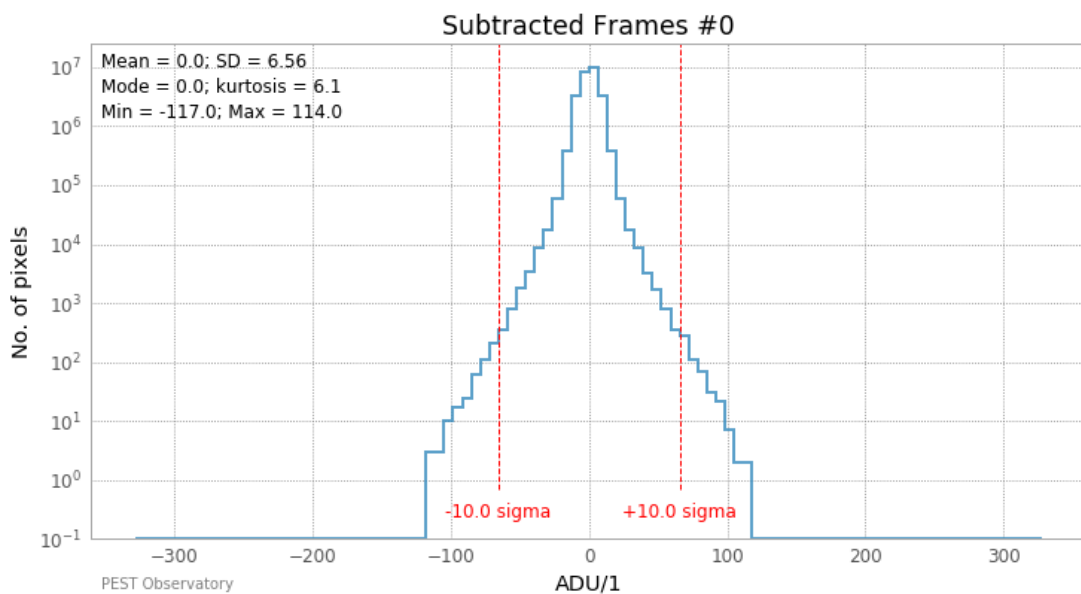
They have  $SD \sim 3$  ADU vs the 2 'least bad' pixels of  $\sim 20$  ADU. Incidentally  $SD = 3$  ADU implies read noise of  $3 \times 0.8 = 2.4$  e- which is lower than the read noise of 3.5 e- measured 'in the bulk'.

#### 5.4 What effect does a different Mode have?

First, for ease of comparison I repeat here the Mode #5 subtraction shown in 5.1 above.



Then a histogram of 2 bias frames in Mode #4 subtracted from each other.



The shapes are similar but the distribution seems narrower with Mode #4. In particular the kurtosis = 6.1 vs 36.8 with Mode #5, indicating that there are many fewer points in the wings of the distribution.

Is RTS less severe under Mode #4?

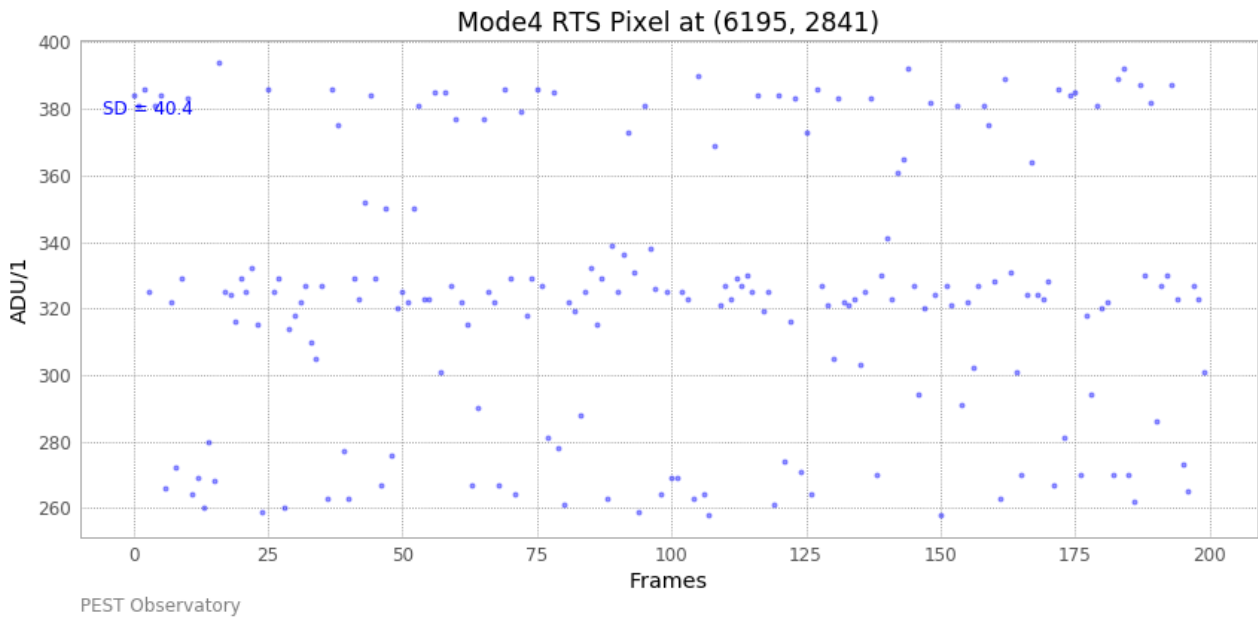
No. Look at the edges of the distribution. Under Mode #4 these are at +/- 120 ADU. This is equivalent to +/- 120 x 1.33 = +/- 160 e-. Under Mode #5 the +/- 200 ADU edges are equivalent to +/- 200 x 0.8 = +/- 160 e-. They are the same.

My interpretation is that across the 2 different Modes the read noise and gain changed for the bulk of the sensor but the population of 'RTS affected' pixels in the wings are the same and behave the same in terms of excess electrons emitted. The Mode #4 distribution only appears to be narrower

because read noise is higher than Mode #5 (6.2 vs 3.5 e-) so the distribution of 'normal' pixels is wider.

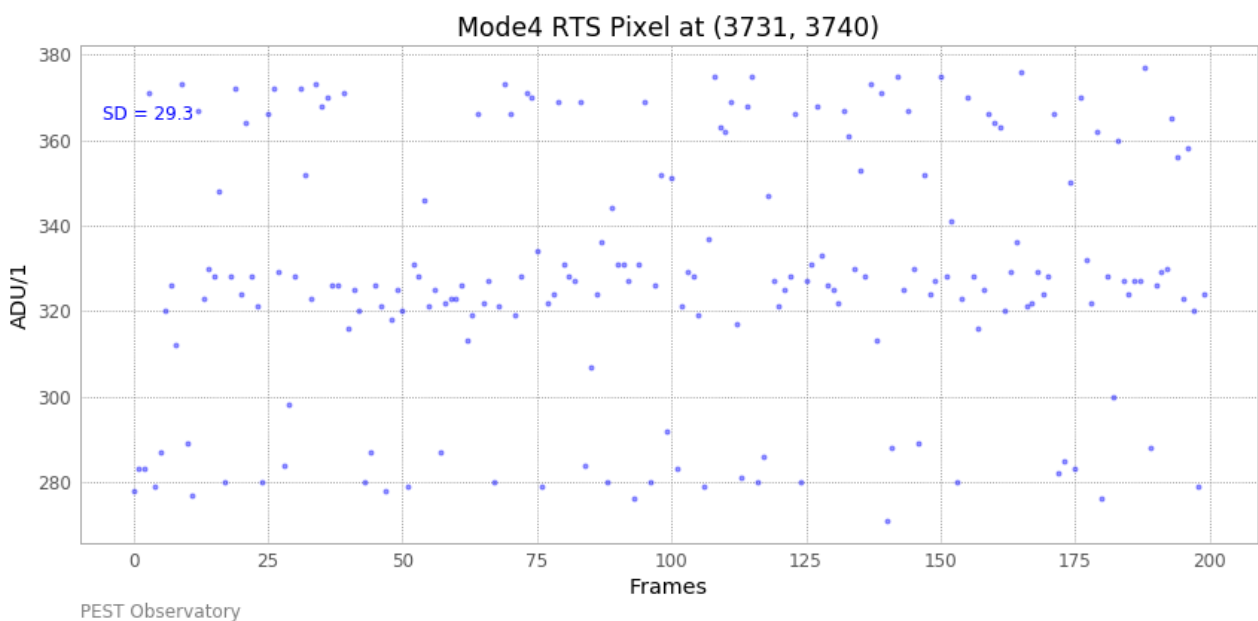
It appears there are 2 populations of pixels – 'normal' and 'RTS affected'. The former with lower noise which can change with the Mode selected, and the latter with higher e- scatter (either multi-modal or just random high scatter) unaffected by Mode, or indeed by exposure length or light flux (see 5.6). When we measure 'Read Noise' the result is a composite of these 2 populations (normal pixels are 2.4 e- but we measure Read Noise of 3.5 e-).

Can we find evidence in the behaviour of individual pixels in support of this? Here's one of the 'RTS affected' pixels we met earlier – at (6195, 2841) but this time under Mode #4.



Qualitatively the behaviour looks the same and that is the case quantitatively as well. The alternate levels are now +/- 60 ADU or +/- 80 e-. In Mode #5 they were +/- 100 ADU i.e. +/-80 e- as well.

Let's look at another pixel.

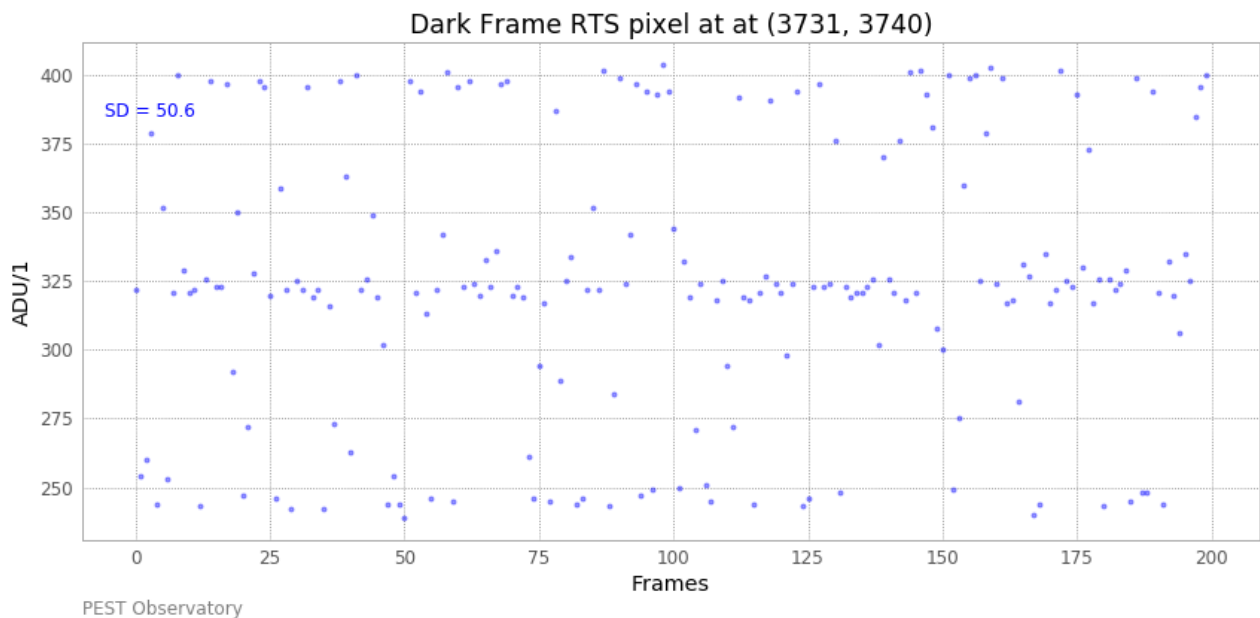
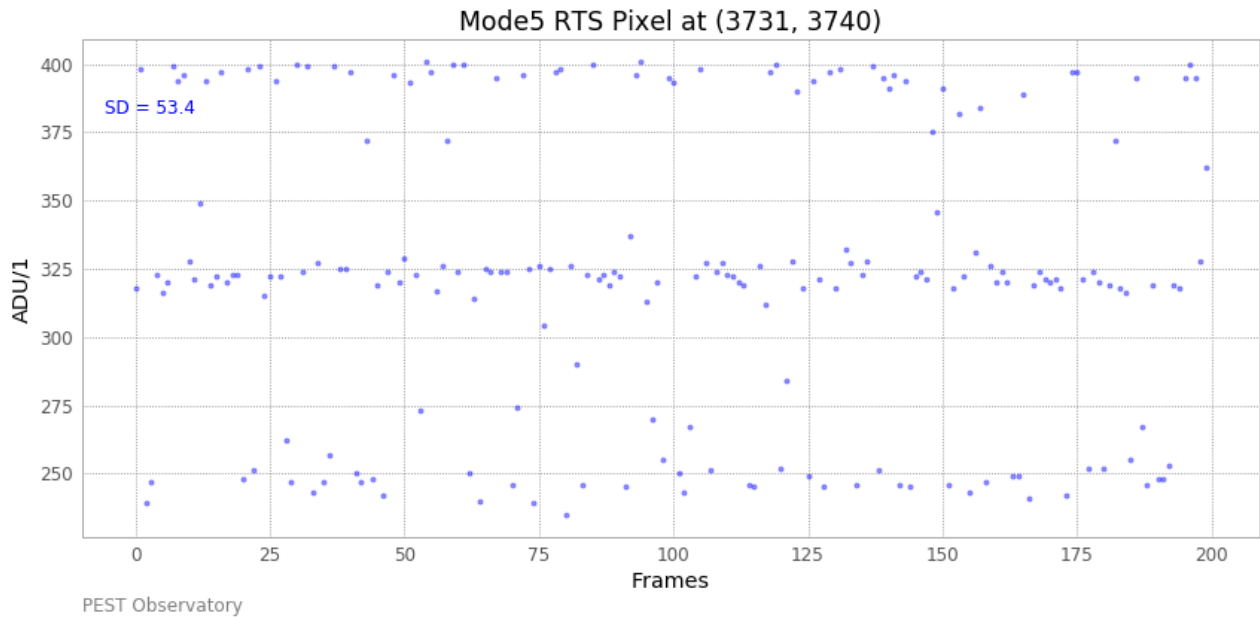


The alternate levels in Mode #4 are +/- 45 ADU or +/- 60 e-. In Mode #5 they were +/- 75 ADU, also +/- 60 e-.

### 5.5 RTS pixel behaviour in dark frames

Does an RTS pixel's behaviour change with longer dark exposures? Do the magnitude of the ADU jumps change?

For convenience this is the RTS pixel at (3731, 3740) that we saw before, under Mode #5 and 0.001s exposure. And below it is the same pixel with 6s exposure.



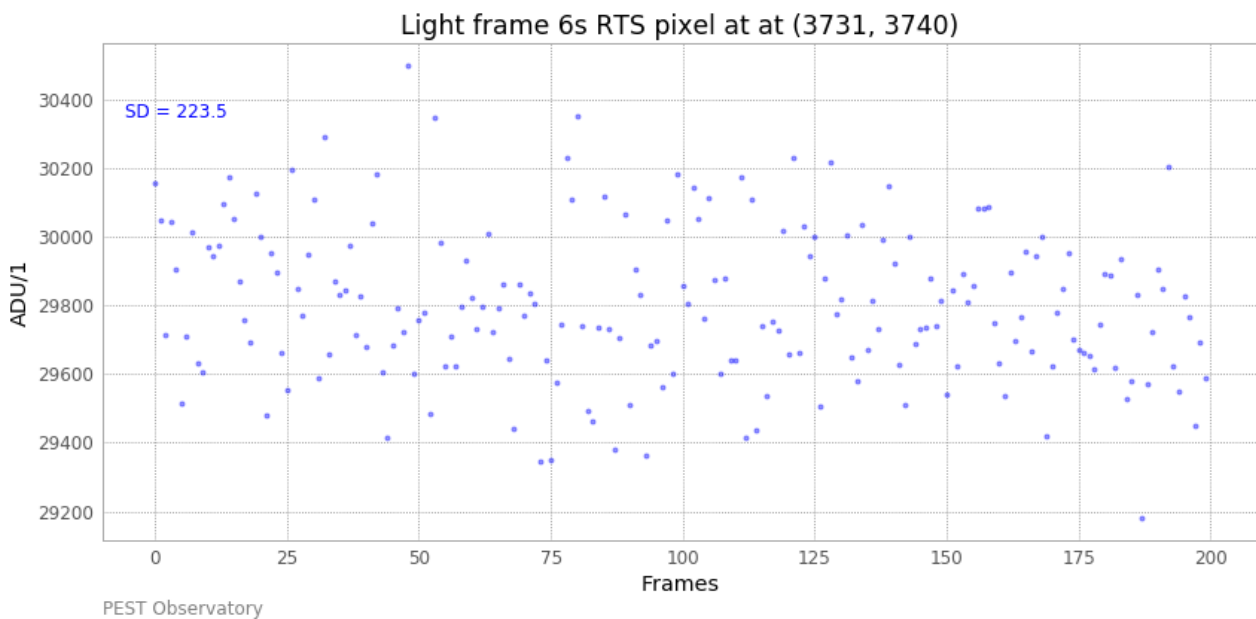
They are very similar with jumps of +/- 75 ADU. I confirmed that other RTS pixels behave the same way.

Conclusion: RTS behaviour is a read-related noise rather than being akin to dark current. It is not exposure time related. [Caveat: There is a tiny number of RTS pixels where ADU does increase with exposure time – see 6.3].

## 5.6 RTS Pixel in Light Frame

How do RTS pixels behave with light? Do their noise contribution remain about the same in absolute terms, or does the noise scale with light?

I acquired 200 light frames, also 6s exposures but with a light level enough to give about half full well, or about 29,800 ADU. Below is the same pixel as above but with light;



If there is any RTS behaviour it is not apparent by eye so let's see if the measured scatter is higher than non-RTS pixels. The average scatter of the worst 10 RTS pixels was 223 ADU. That for 10 random pixels (i.e. likely to be non-RTS) was 215 ADU. The 'excess noise' equals 59 ADU (subtraction in quadrature).

I measured the average scatter of the worst 10 RTS pixels in 0.001s dark frames to be also 59 ADU. The same was found for 6s dark frames.

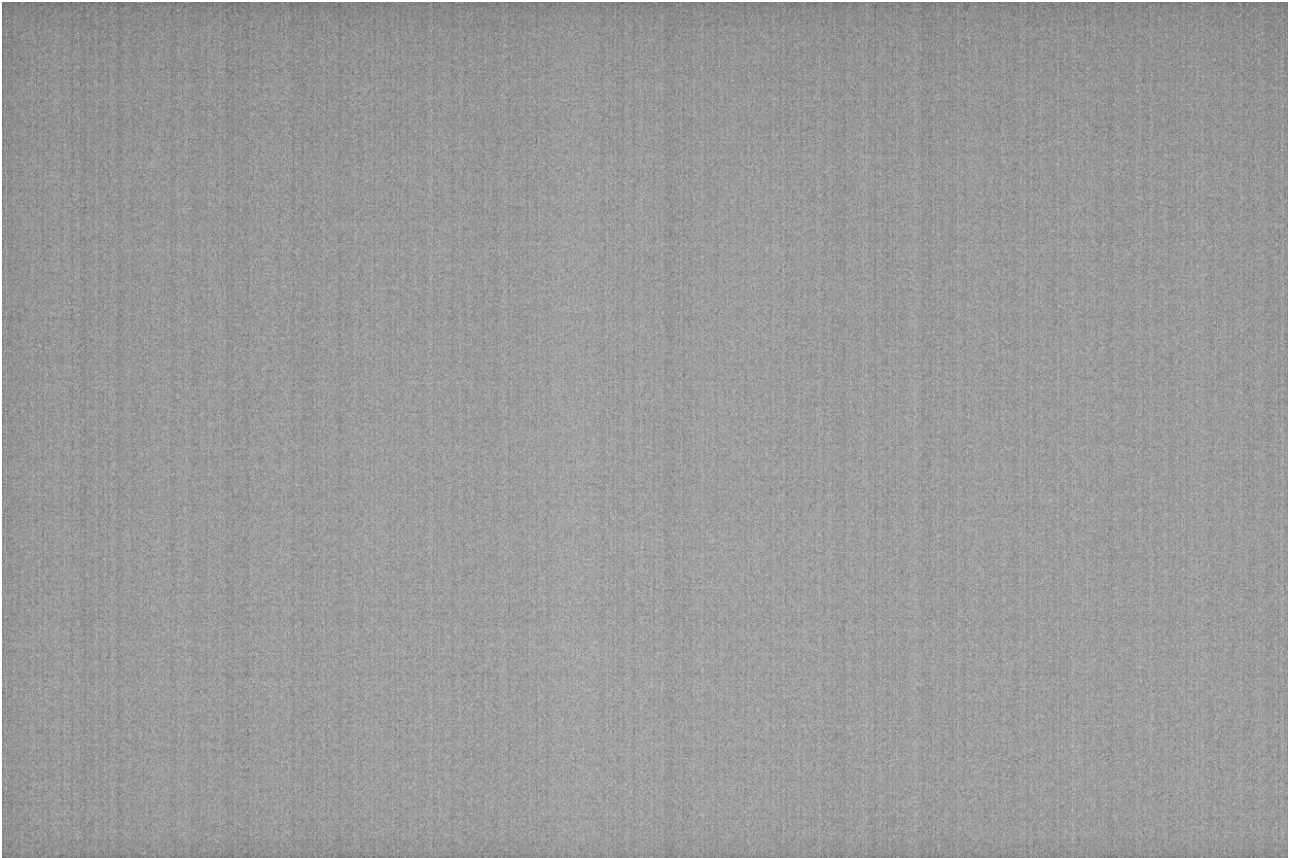
I conclude that RTS behaviour remains the same with different exposure times and light levels. This reinforces the point that RTS can be considered a form of read noise. Its contribution to photometric error will already be included when using our normal procedures because the measurement of read noise described above also includes RTS pixels. There is no evidence that RTS pixels might skew photometry measurements systematically higher or lower.

## 6 Dark Frames

I will now look at dark frames from the QHY268M. Is there amp glow? Do the hot pixels subtract out? Spoiler: 'No' and 'Mostly'.

### 6.1 *Amp glow*

In short, there isn't any! Here's a master dark frame created using C-Munipack from 20 x 120s darks.



There is some weak horizontal and vertical banding but a profile through the dark vertical band in the middle of the image shows that it's only about 1 ADU higher.

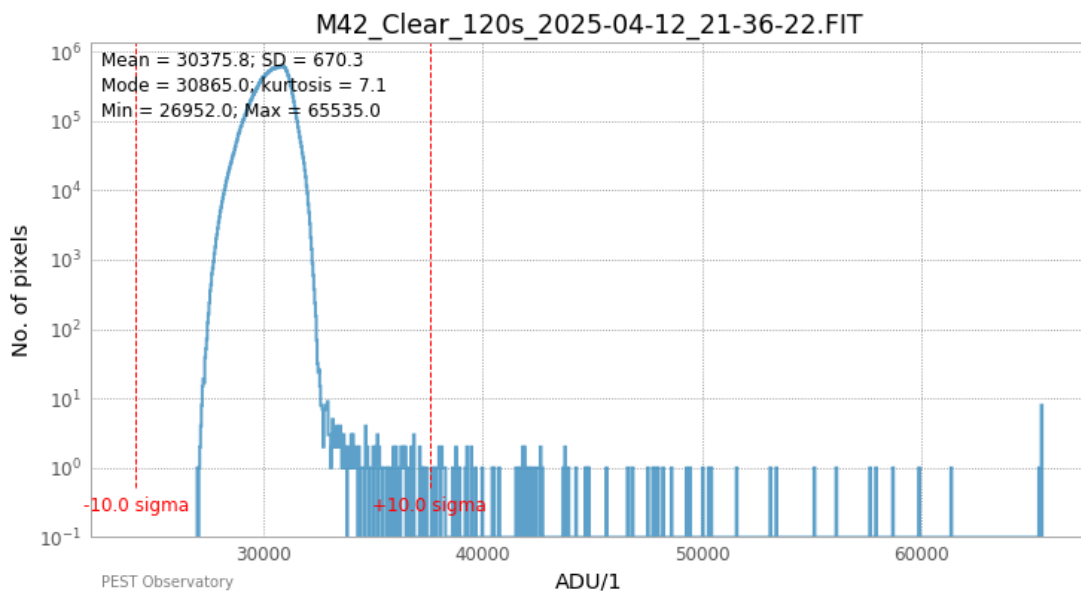
The dark frames are exceptionally clean.

### 6.2 *Dark subtraction*

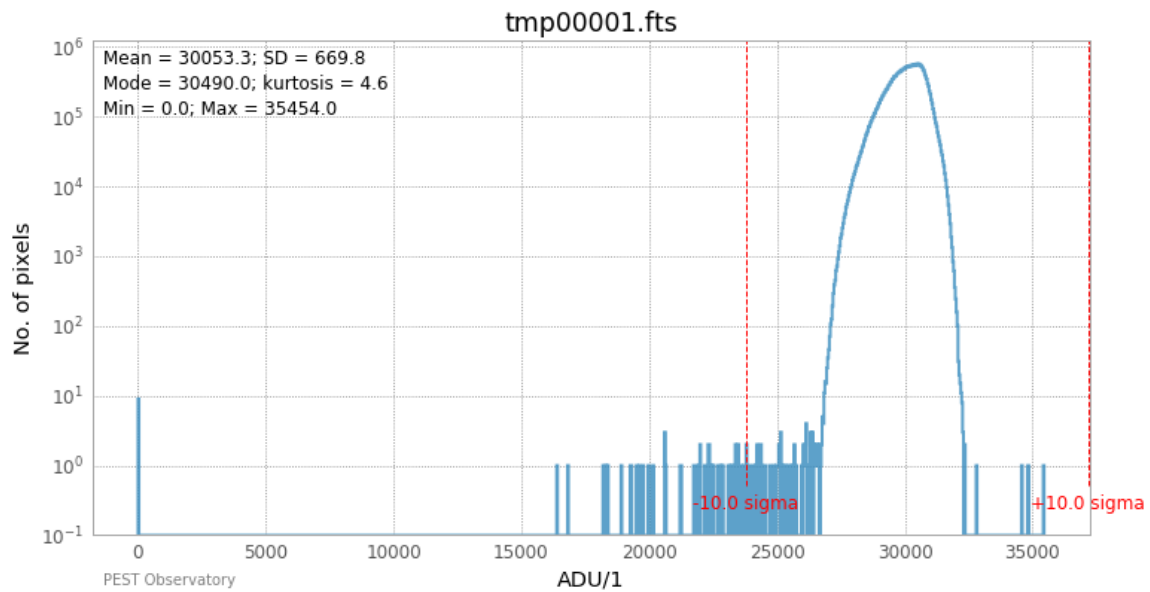
This is a single light frame of 120s exposure and about 30,000 ADU. Illumination was not very even but that doesn't matter for our purpose.



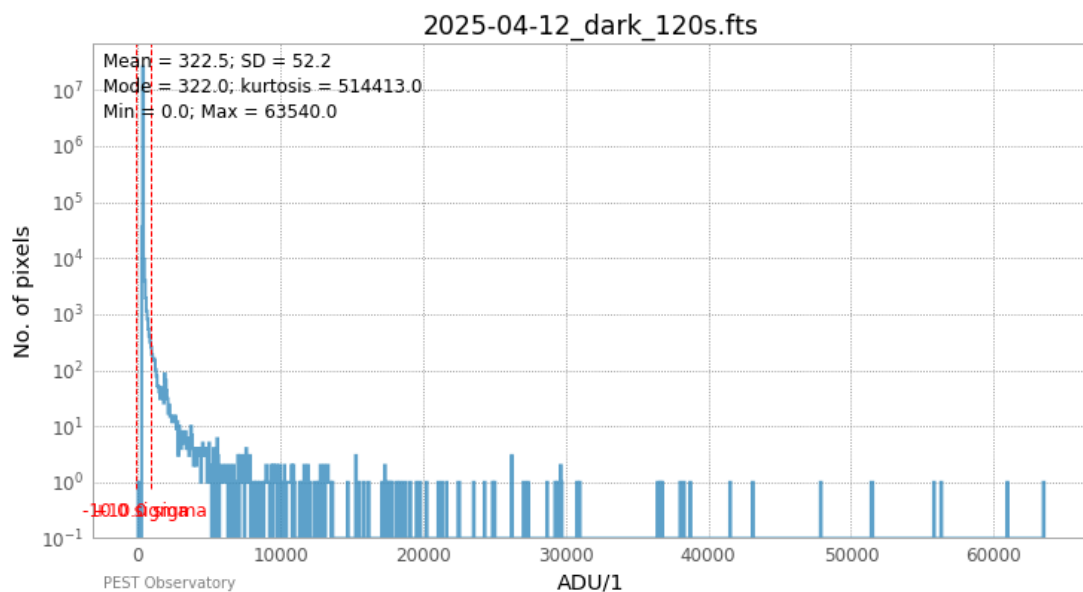
The histogram before dark subtraction shows a long tail of hot pixels out to the right with even some at saturation.



A master dark frame, created from 20 individual darks, was subtracted from this. The resulting histogram shows that most of the hot pixels have been subtracted out. But some pixels have been over-subtracted. The minimum ADU before was 26,952 but now there are some pixels at between 15,000 to 20,000. There are even some 10 pixels at 0.



This is evidence that there are some pixels that are saturated or 'hot' on the master dark but either 'not so hot' or 'also saturated' on the light frame. Can we see this on a histogram of the master dark (below)?



There are hot pixels but nothing obviously anomalous. Perhaps the 20 frames used for the master dark were not enough to average out RTS pixels? With a master dark of 40 frames the result was the same – the over-subtracted and '0' pixels were still there.

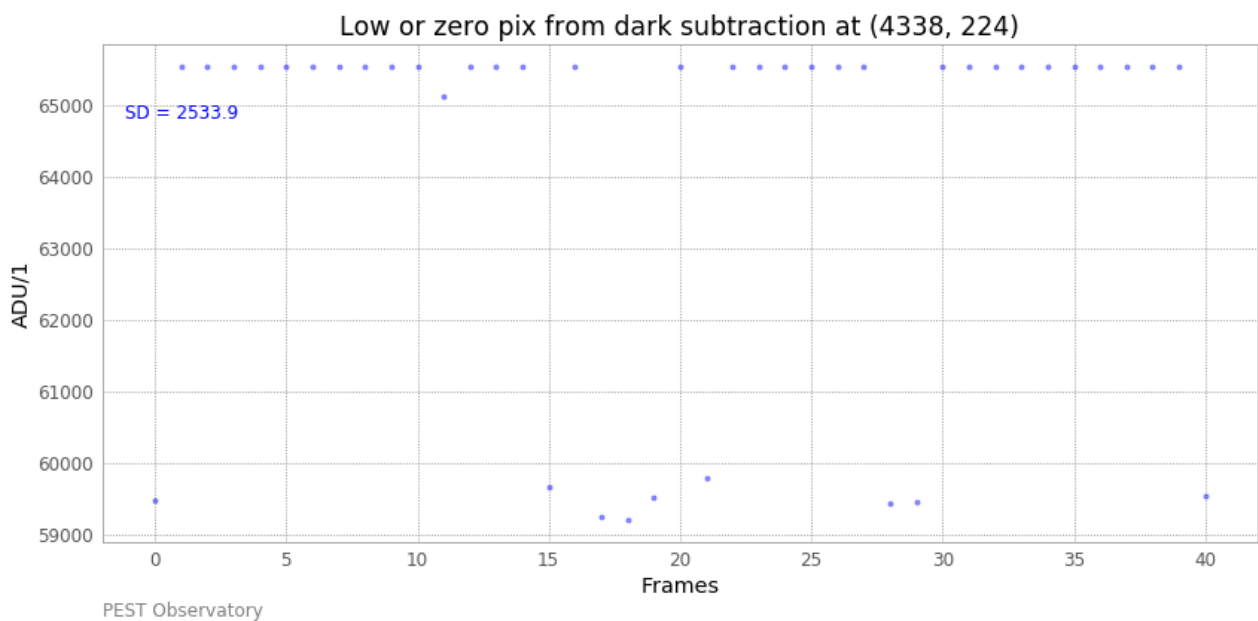
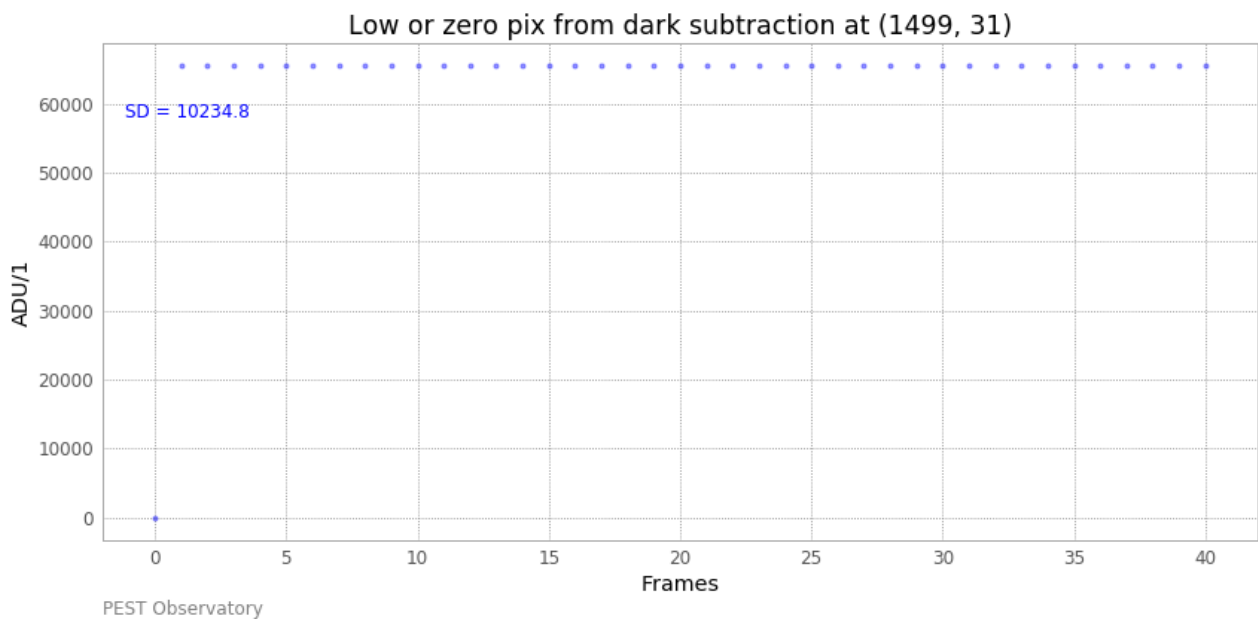
But are the '0' and 'over-subtracted' pixels concerning? An estimate of the number affected is <100 pixels out of 26m. This is 4 in a million. A typical photometry aperture of 7" radius has 1,700 pixels (0.3"/pix) so the chance that one of these pixels is within the aperture is only 1 in ~150. Even if the aperture had a '0' pixel its impact on flux measurement would only be 1 ppt (part per thousand), assuming all other pixels read 30,000 ADU.

I conclude that dark subtraction works well and no action is needed to correct for over-subtracted pixels.

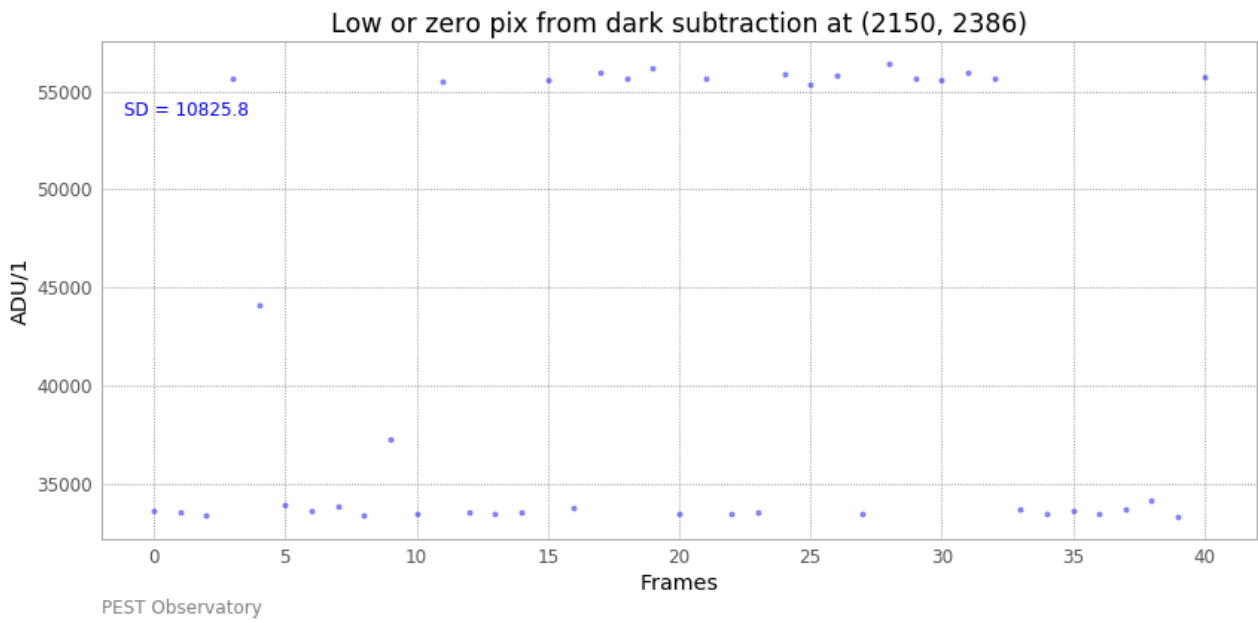
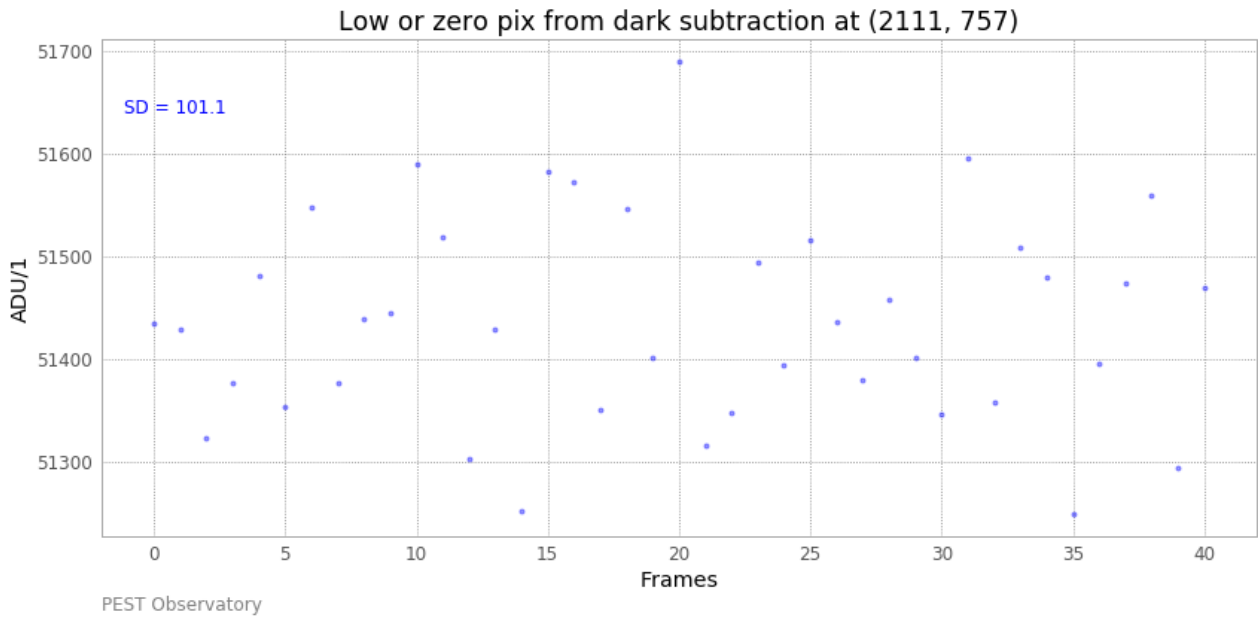
### 6.3 Investigation of 'over-subtracted' pixels

Nevertheless I want to understand what is happening so I identified the positions of all pixels in the dark subtracted frames more than 20-sigma away from the mode so that it included all the '0' pixels. There were just 10. I then plotted the values of these pixels in each of 40 nos. 120s dark frames in the master dark.

Two were predominantly at 16-bit saturation. These pixels in the master dark would have been at that level as well and so the corresponding light frame pixel would have dark subtracted to zero.

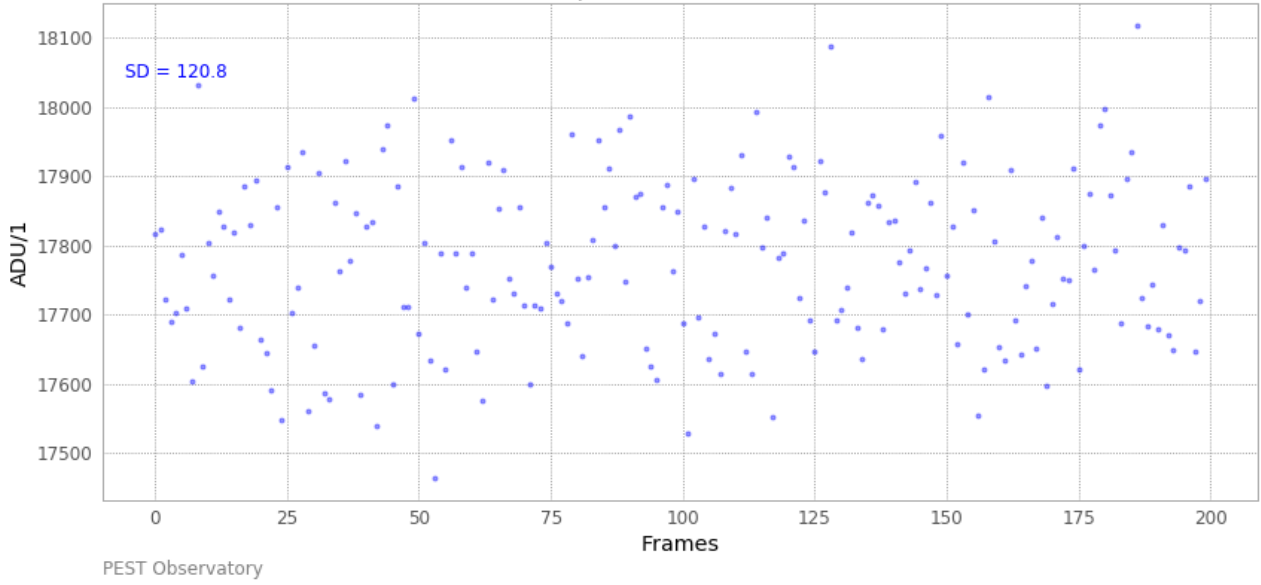


The rest were just very high. Remember the mode of the darks was just 322 ADU. These are over 30,000 ADU.

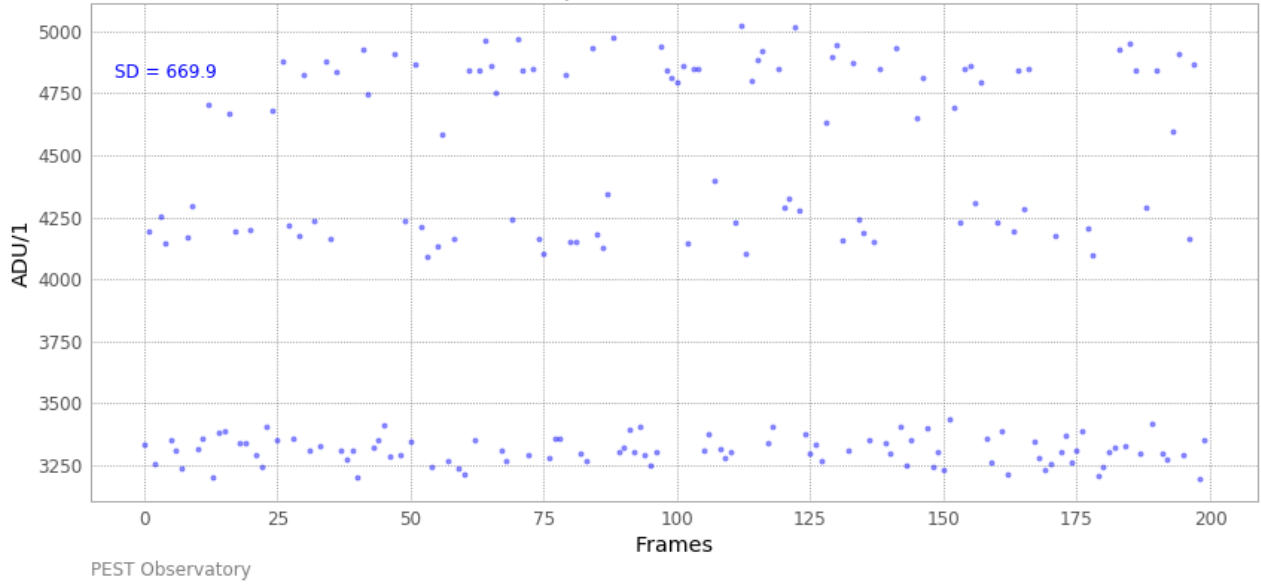


These were from 120s darks. Do these pixels behave the same in shorter exposure darks? I made the same plot using 6s darks over 200 frames. I show the same 4 pixels as above.

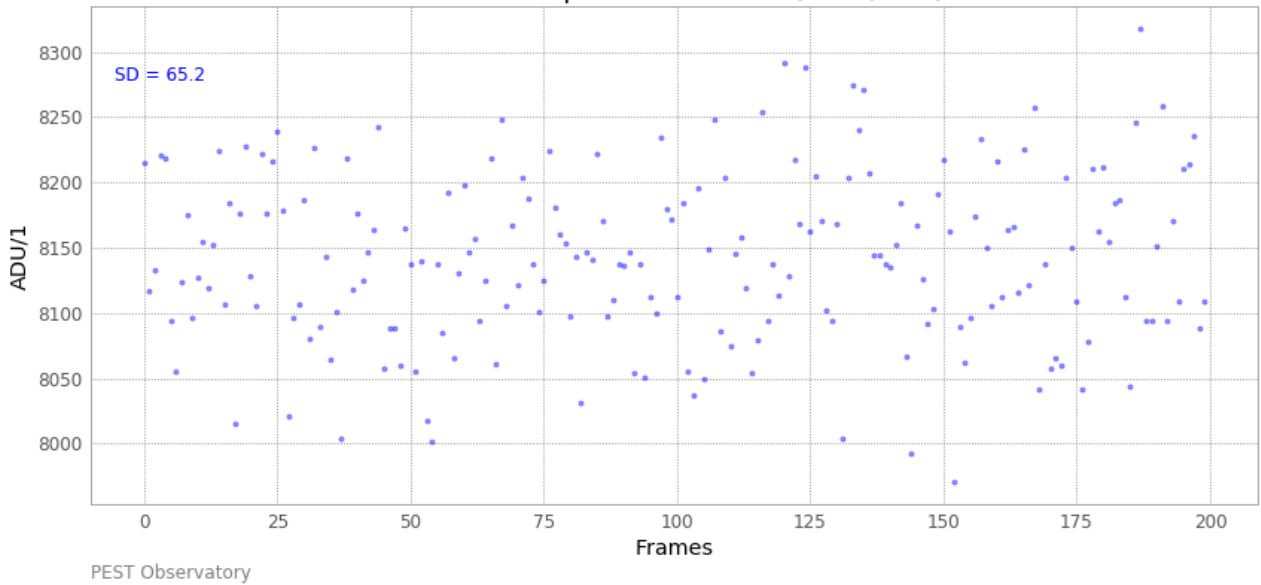
Low or zero pix in 6s darks at (1499, 31)

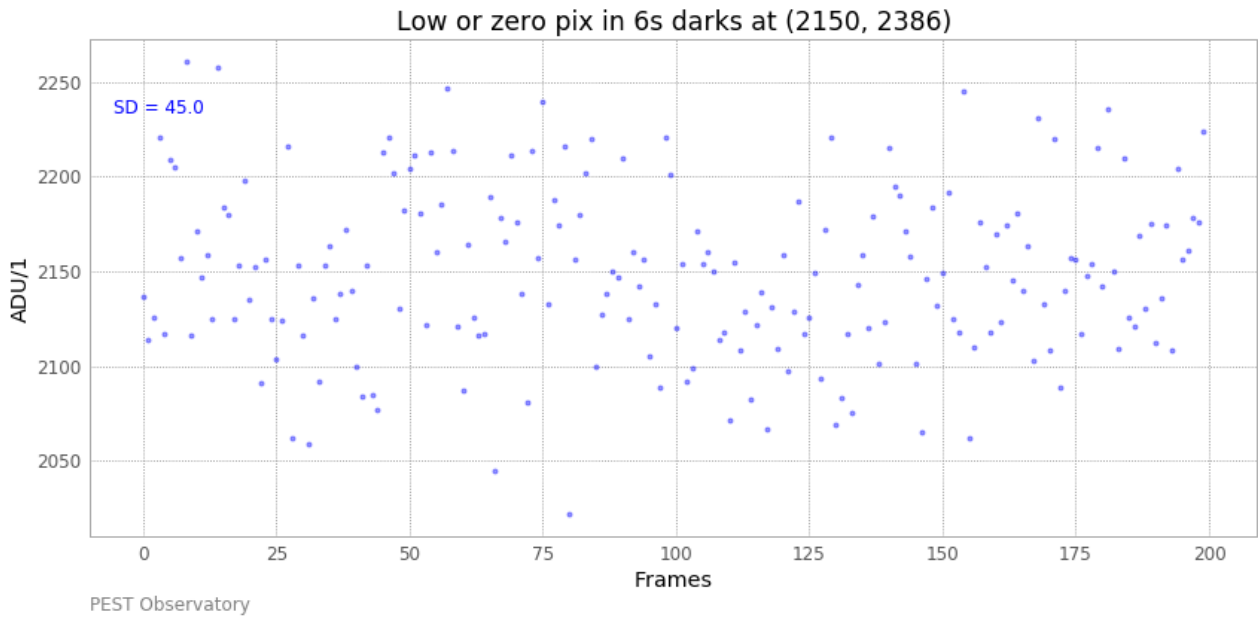


Low or zero pix in 6s darks at (4338, 224)



Low or zero pix in 6s darks at (2111, 757)





The mode of the pixels in these darks was 322 ADU. So these pixels still read high but this time they have changed with exposure. For example the mean of pixel (2150, 2386) was 2,150 with 6s exposure but ~45,000 at 120s. Interestingly this particular pixel changed from 'high scatter' at 6s to 'jumping between 2 levels' at 120s.

It appears there is a tiny (10's out of 26m) population of RTS pixels that do vary with exposure time. My assessment in 6.2 was that the impact on photometry will be negligible. But being able to identify these bad pixels keeps open the option to mask out these pixels as part of the photometry pipeline. For example the value of each of these pixels could be replaced with the mean of the 8 immediate neighbour pixels. I will leave a decision on this for later, once I get on-sky.