Canon 60Da Linearity Testing

Canon DSLR cameras are very popular among astrophotographers and for good reason with features like dark current suppression, low noise sensors and very good linearity with varying illumination. In fact the linearity of the 60Da is as good as several dedicated CCD cameras I've used in the past. There are a great many rules of thumb surrounding acquiring flats, perhaps more than any other type of calibration frame. Most of these rules seem to be concerned with ISO setting or with camera linearity; for some strange reason many seem to think that DSLR's have problems with linearity. Recently I've attempted to test my 60Da for linearity and its effect on flat calibration in an effort to determine if these rules of thumb are valid. This paper presents both the test method and the results.

Test method

The camera was tested for linearity under both varying illumination and varying ISO conditions. Ideally the linearity could be directly tested using a light source that could be varied and set to a controlled level for each measurement and the average value measured by the sensor would be plotted against the light level. Since I did not have access to a controlled light source with sufficient accuracy, varying illumination was achieved with a constant light source and varying exposure time with fixed ISO and f-stop settings. All images were converted using the *Bayer Basic Raw* setting of the *Digital Camera Raw Conversion* function in Images Plus. The Bayer Basic Raw setting does not de-Bayer the image and simply converts the raw file to some other format, fits in this case, with no other processing. Images Plus was used to determine the average pixel luminance value using the histogram function.

The camera, with an eighteen millimeter lens was placed on a tripod and pointed at a wall in a dark room. The wall was illuminated with a lamp and the focus manually set to infinity. By setting the focus to infinity any details of the wall were blurred and only its average illumination was visible to the sensor. The focal ratio was set at f/9 and the exposure was varied from 1/200 of a second to 3.2 seconds with the last several shots pushing the camera into saturation. The average image level was recorded as well as the exposure time for each image.

To test the linearity with ISO the exposure was fixed at 0.8 seconds at f/9 and the ISO was varied from 100 to 1600. Again the image level was measured using Images Plus. The test setup is shown in the figure below.

Figure 1 - Test setup

Results

The results, when the average pixel value is plotted against exposure time, are shown below.

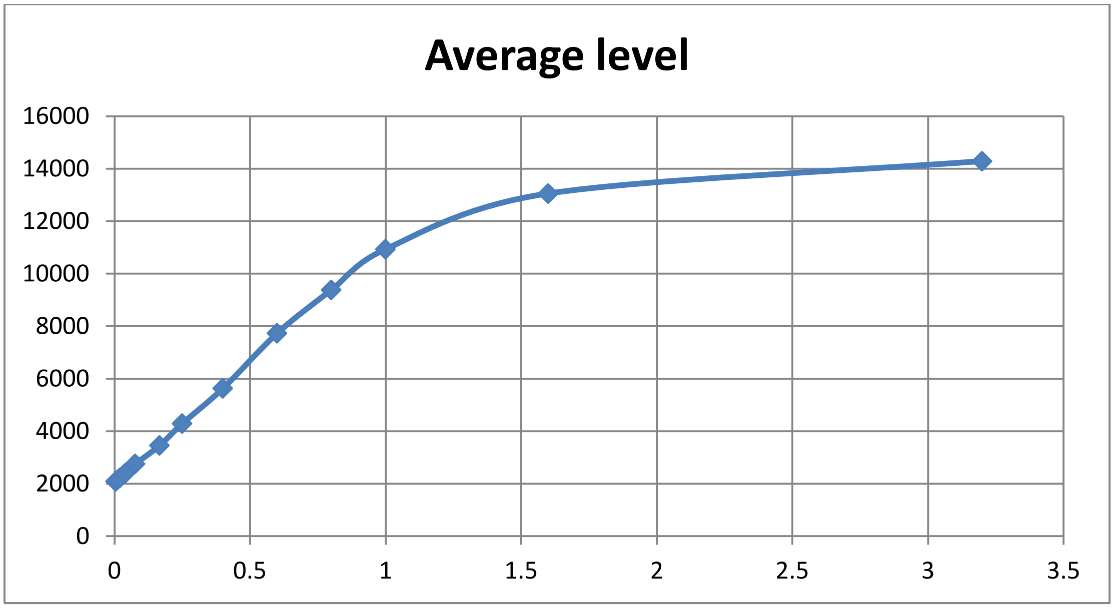

Figure 2 - Exposure linearity

As can be seen from the plot, from short exposures to about one second the camera response is quite linear and then saturates normally. A blow-up of the linear region along with the line of best fit is shown below.

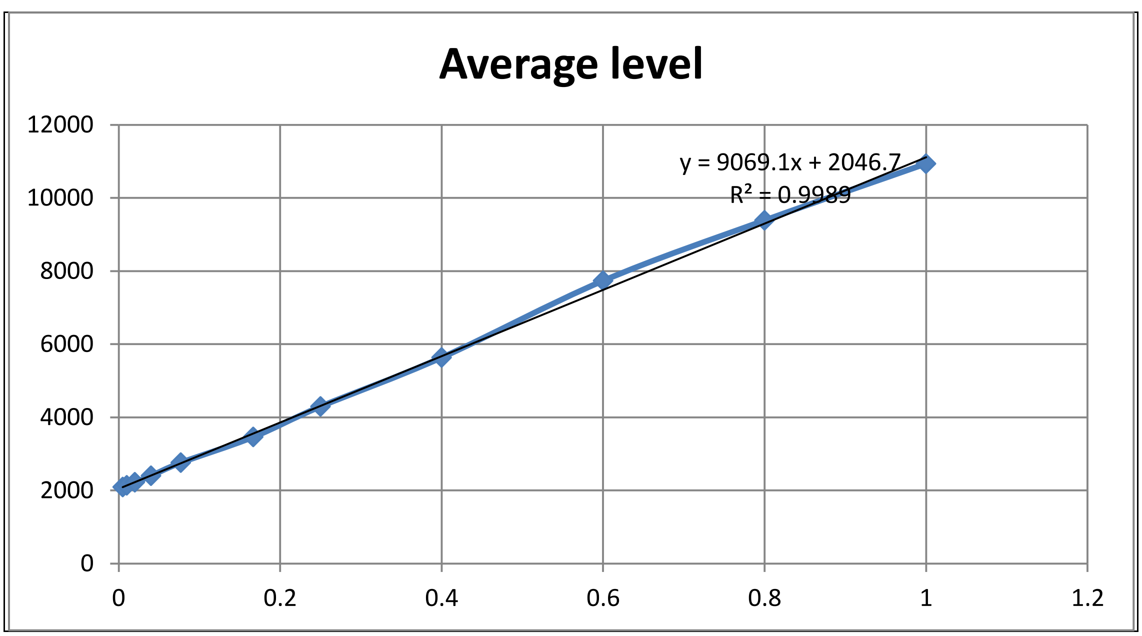

Figure 3 - Linear range

For reference the histogram for the shortest exposure used to produce the plot in Figure 3 peaked just above zero and the histogram for the longest exposure shows signs of saturation. Both histograms are shown in the figures below. It should be noted that the Images Plus histogram tool uses a log scale so they look substantially different than those displayed in Photoshop.

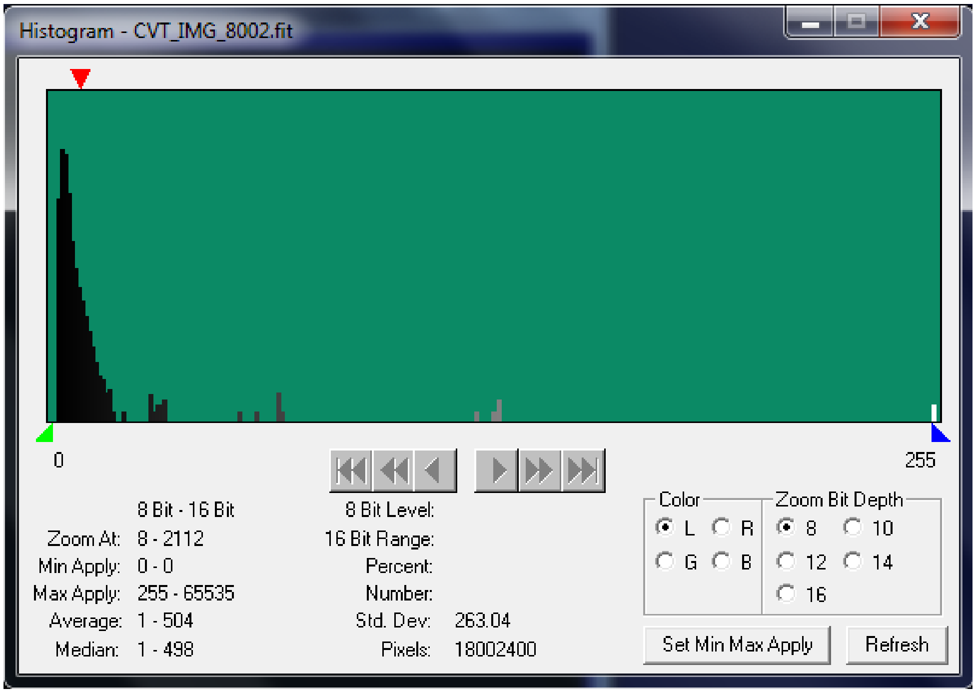

Figure 4 - Histogram for shortest exposure

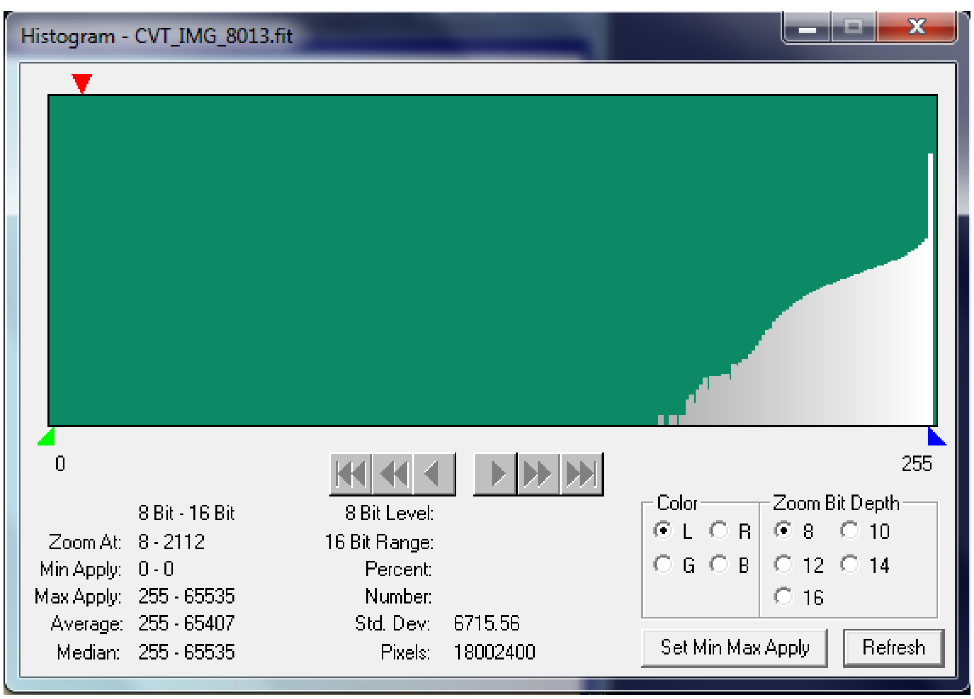

Figure 5 - Histogram for one second exposure

This range encompasses the entire dynamic range of the camera.

If we remove the curve of best fit from the data we can see the actual error and the table below gives the error as a percentage of the full scale value.

Exposure time	Percent error
0.005	0.00%
0.01	0.00%
0.02	0.03%
0.04	0.05%
0.08	0.10%
0.17	0.59%
0.25	0.11%
0.4	0.24%
0.6	1.51%
0.8	0.51%
1	1.10%

Figure 6 - Linearity error

The percent error is calculated against the maximum value of 2^{14} or 16384. If we plot the residual error, anything that is not on the horizontal axis (y-value of zero) represents a linearity error giving the plot below.

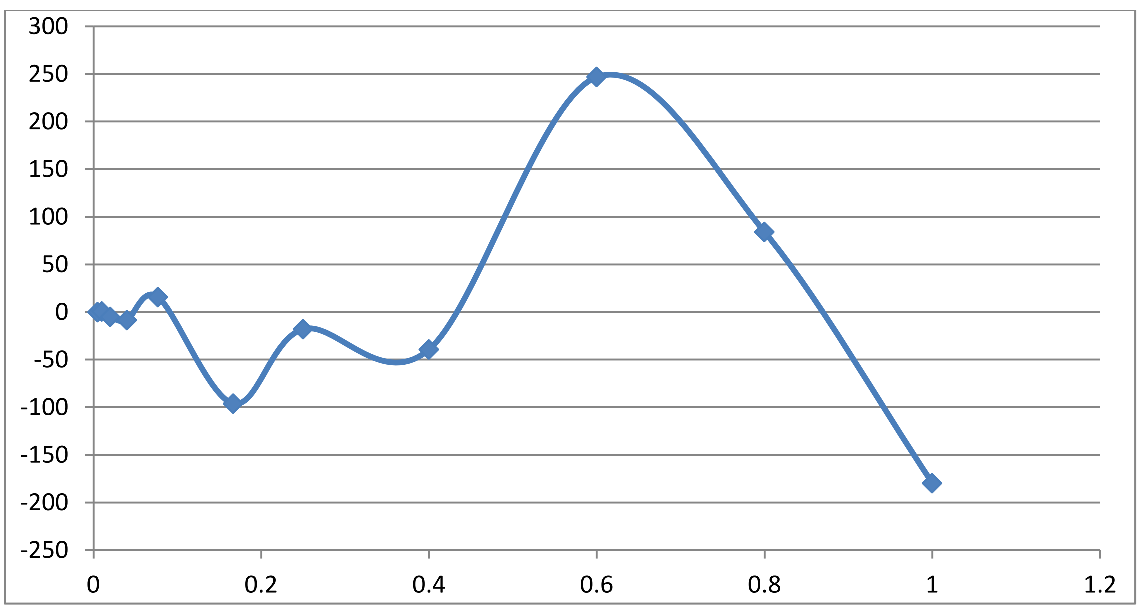

Figure 7 - Residual error

The histogram shown in Figure 5 shows that there is some saturation showing up in the one second exposure which accounts for some of the error. If the data is limited to those points with absolutely no saturation we have to ignore everything above 0.8 seconds. The histogram for the 0.8 second exposure is shown below and is free of any saturation.

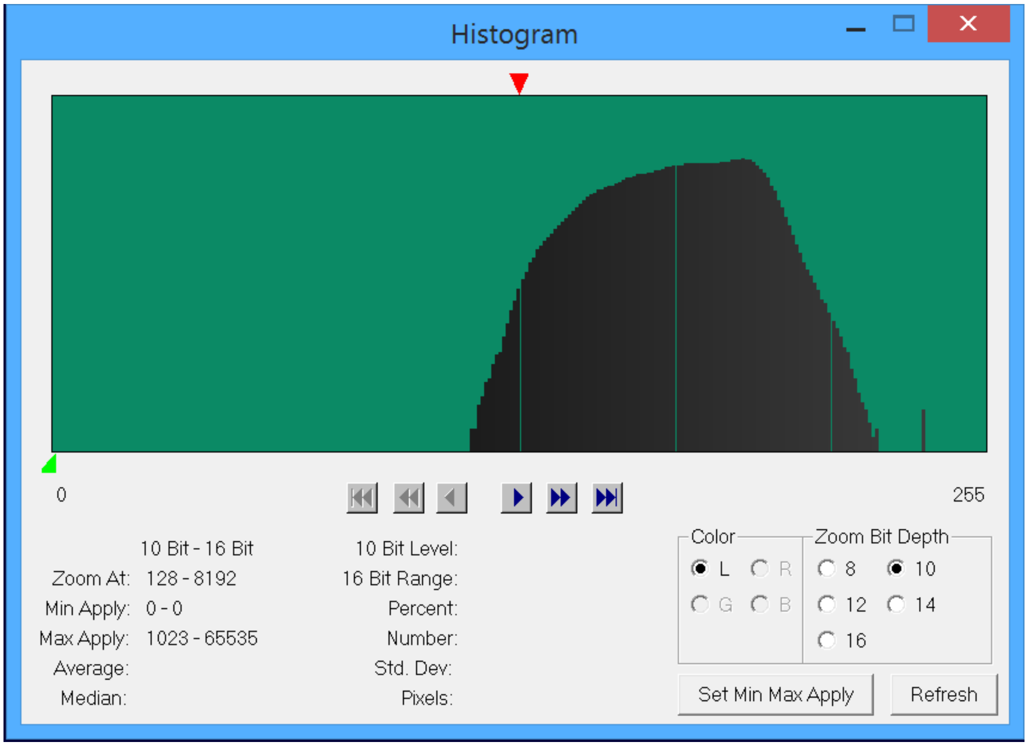

Figure 8 - 0.8 second exposure histogram

If the residual error is plotted over this range, the situation improves further as shown below.

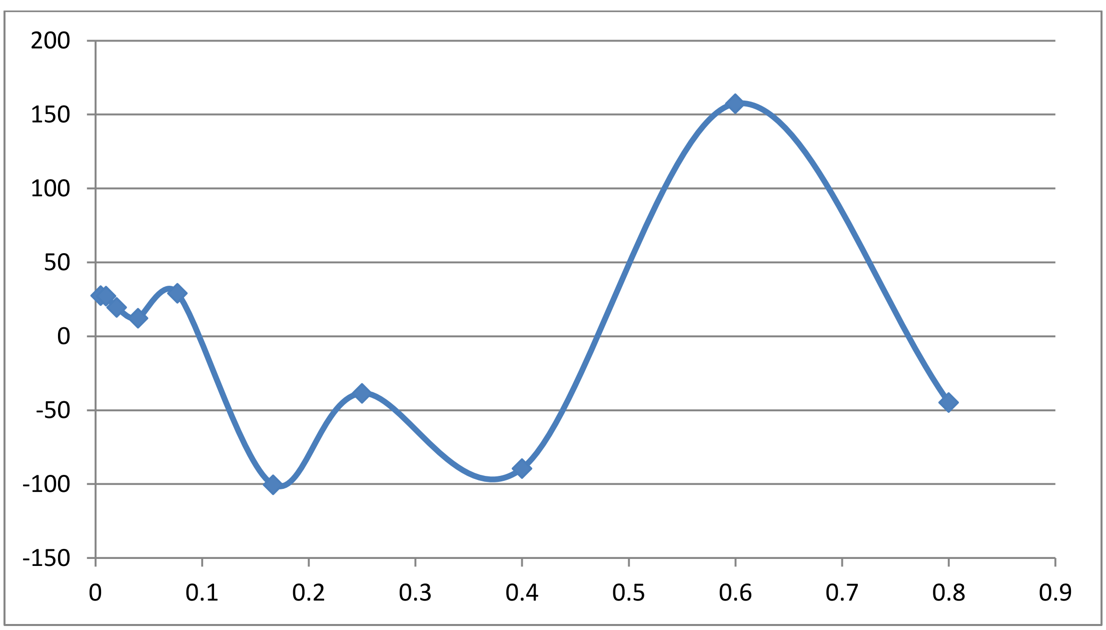

Figure 9 - Residual error to 0.8 seconds

This reduces the peak error from 250 to just over 150. Since the equation of best fit changes over this range, the percent error values are different as shown below.

Exposure time	Percent error
0.005	0.17%
0.01	0.17%
0.02	0.12%
0.04	0.07%
0.08	0.18%
0.17	0.61%
0.25	0.24%
0.4	0.55%
0.6	0.96%
0.8	0.27%

Table 1 - Percent error over linear range with no saturation

This gives a worst case error of just under one percent of full scale, a good value indeed. Now the remaining question is what is the effect of these small linearity errors on the final calibrated and stretched image?

Effect of ISO on linearity

Following a similar test method used to measure linearity with exposure, the effect of varying ISO from 100 to 1600 was tested. Images were taken with a fixed exposure time and focal ratio while ISO was varied. The result in the following plot shows virtually no error at any setting below saturation.

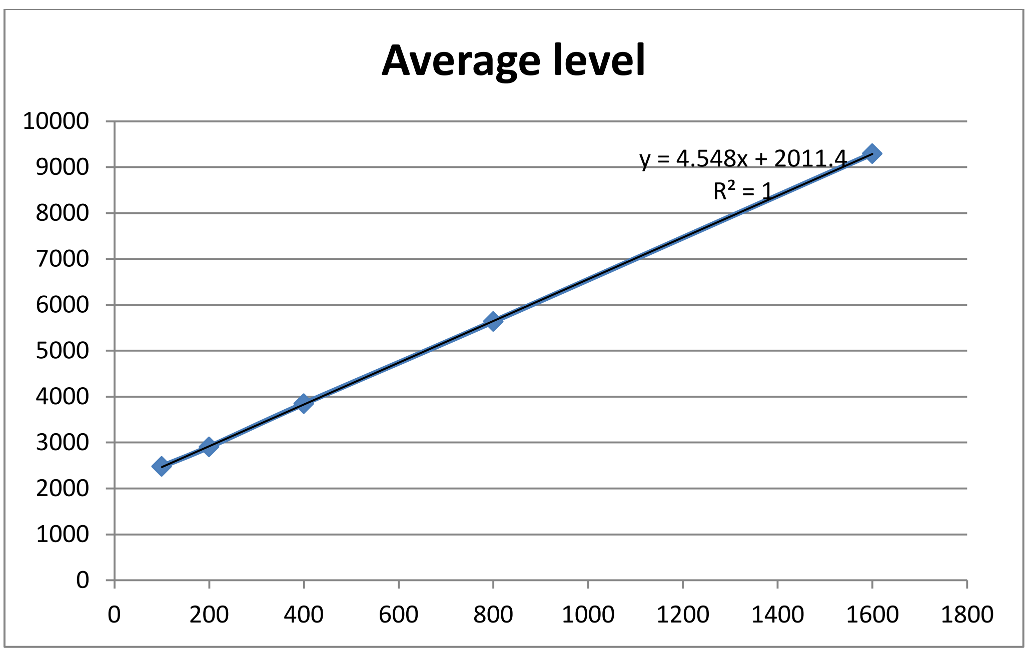

Figure 10 - Effect of ISO on linearity

As can be seen from the plot, there is no error over the entire test range.

Effect of small linearity error in flats

As interesting as these measurements are, the real question is what is the effect of calibrating an image with flats that have such small errors? In order to test this, an image of M8 was calibrated with flats, darks and bias frames to produce the image on the left of Figure 11. The same M8 image was then calibrated with the same dark and bias frames, but the flat was modified to have a one percent of full scale error by adding 165 to each pixel using a mask. The mask produced a gradient that was 165 higher at the center and the normal flat frame value at the edges. This image is shown on the right of Figure 11. Both images have had the same stretch applied.

Figure 11- Image comparison

As you can see from both images, there is not much difference!

Finally the image with the good flat calibration was subtracted from the image with the bad flat calibration and the result was stretched using histogram equalization. This clearly shows the difference between the two images, but an extreme stretch was required to make any difference visible.

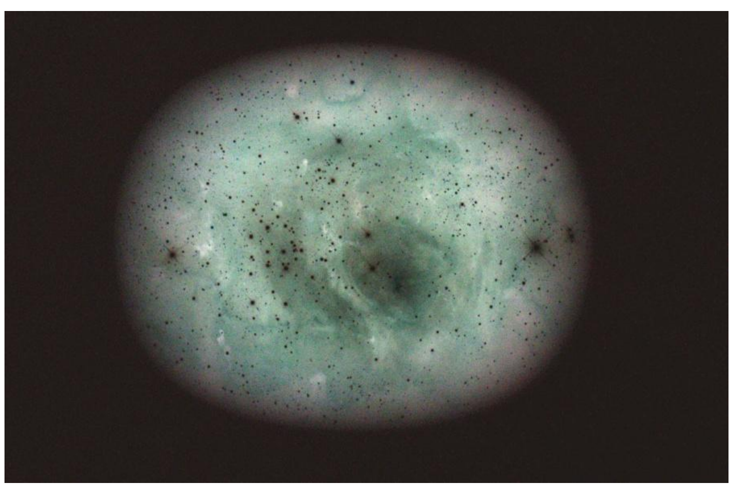

Figure 12 - Greatly stretched difference image

Conclusions

Modern DSLR's have very good performance in terms of linearity with exposure level. With peak errors just over one percent they compare favorably to high end CCD cameras. The testing detailed here shows that many of the rules of thumb surrounding flats are to some extent myths. In particular the rule that flats should be taken at the same ISO as the lights and that they should be exposed to half scale clearly is not supported by the data. While there is nothing wrong with this advice there is no evidence to support it either. At least the Canon 60Da remains linear up until saturation so flats may be exposed to any point in the histogram above the photon noise limit and below saturation. The effect of these small changes in linearity is very small on the final stretched image. Indeed, the data in Figure 3, shows that exposing at the half way point is actually the worst possible setting for linearity (not that a one percent error matters much). Much of the problems with flats stem from improper shielding from direct light and the failure to incorporate bias frames in image calibration. Incorporating bias frames is mandatory for proper flat calibration as the bias must be removed from both the light frames and the flats for calibration to work properly.