Reason behind the walking noise and how to minimize it.

Foreword

An astrophotographer who is familiar with the basics and knows that it is important to combine multiple images to get better shots of faint subjects often faces difficulties along the way. One of them is the so-called walking noise. It's a pesky beast that's hard to get rid of, and it significantly affects the final image. Here are some examples of this problem:

Figure 1 A photo of my hiking setup taken with a Galaxy S8 smartphone. 12 shots of 10 seconds each.

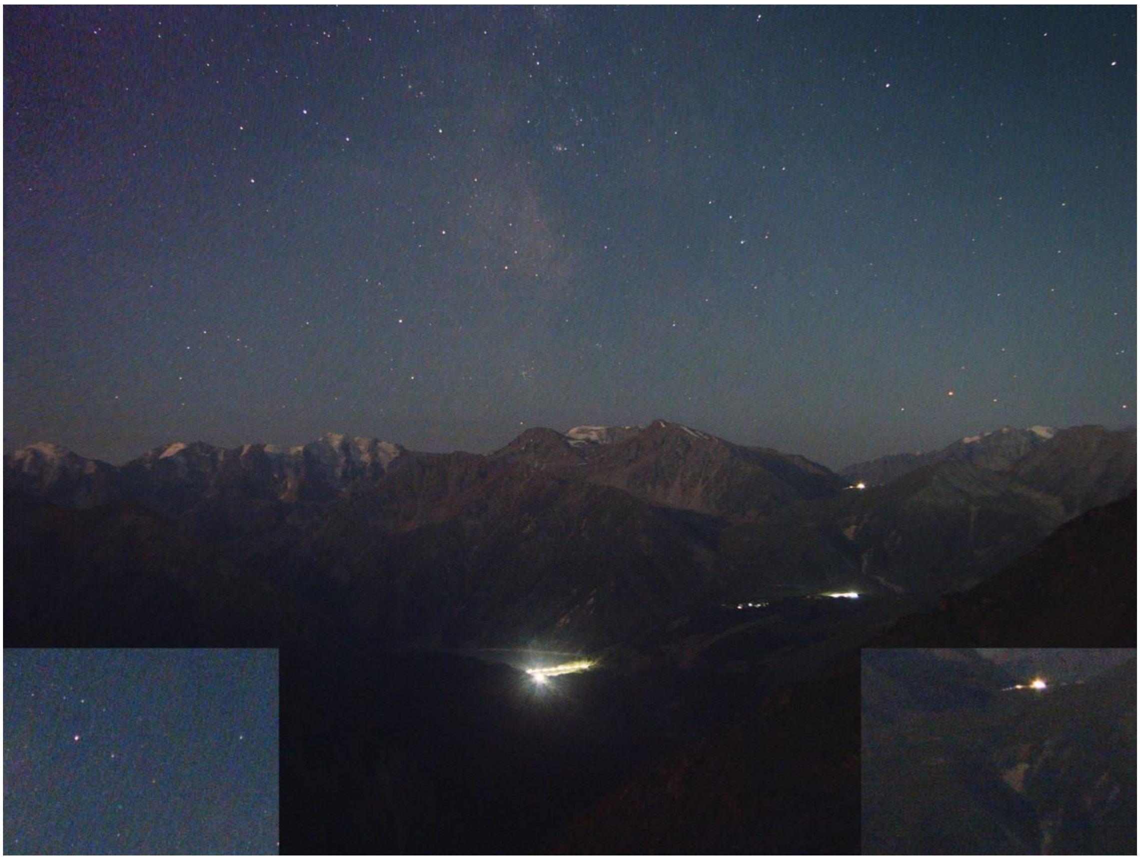

Figure 2 A composite photo taken from time-lapse footage taken with a Canon S5IS camera. 16 shots of 15 seconds each.

You can clearly see that the noise forms predictable trajectories when several images taken with a stationary camera are aligned with respect to the sky. And even full calibration often does not help. Here we will try to understand the reason for this and the possible ways to avoid or at least mitigate the consequences.

Theory

There is a well-known formula for calibrating astronomical images

$$signal = \frac{light - offset_{master} - dark_{master}}{flat_{master}} \qquad 1$$

Where master frames are obtained by averaging individual offset, dark and flat shots, the procedures for obtaining which, I believe, are known to everyone. It is desirable to have the larger the number of calibration frames, the better.

The starting formula arises due to the fact that the light entering the camera passes through various optical elements and first of all some of it is absorbed by the lens/light filters, then the charge accumulated in the cells is multiplied by a certain coefficient set by the user aka ISO/gain. And in the end, digitization takes place. And in order to get the initial signal we reverse this chain back:

$$ADU_{light} = photoelectrons_{light} \cdot transmission \cdot gain + offset \qquad 2$$

I excluded the dark current from consideration, because it will not add anything fundamentally new to us, but will increase the calculations.

We only have access to the Analog-Digital Units values created by the analog-to-digital converter (ADC). To determine what number of photoelectrons (hereinafter, I'll refer to them as e^-) they correspond to is our job. For example, in order to obtain the number of registered electrons e^-_{light}, we need to take a frame without illumination of the matrix, otherwise we cannot determine the value ADU_{offset}. This means that we cannot calculate the value.ADU_{offset}

In the formula 2 the $transmission$ coefficient is the transmittance of the optical system (including the sensitivity of individual pixels and the overall vignetting of the system). I will not separate these two parameters here, because this does not affect the fundamental conclusions.

First, let's look at the master offset.

Even in the complete absence of light, the senor generates a certain responce, simply due to thermal fluctuations (plus the ADC itself is noisy). Moreover, all these fluctuations are added to our recorded signal. In order to determine, firstly, the magnitude of this "parasitic signal", and secondly, in order not to introduce unnecessary noise when subtracting the master-offset from single lights, a lot of such shots are made. Then random noises have the opportunity to be averaged, and systematic noises, repeated from frame to frame, remain at the final sum. In theory, if all pixels are the same, then the noise structure in them will be absolutely identical, but in reality, in addition to photon and read noise, there are also spatial inhomogeneities.

Example 1 is fixed pattern noise. When the $offset$ value is slightly different for different pixels.

Example 2 is PRNU (pixel response non-uniformity), in simple terms, slightly different gain factors for different pixels.

For CMOS, such internal noise is a natural occurrence, since each pixel has its own amplifiers.

How to determine the strength of this first type of noise inherent to your sensor? You need to create master-bias, approaching the number of frames to infinity. If with increasing n (the number of offset-frames) the $offset_{master}$ will rapidly approach to an even field that would indicate low pattern noise. If, with increasing n, the master-bias frame moves to a clear, stable pattern, this indicates non-uniformity of the bias current.

The second noise — is the same, but you will have to analyze the frames of a flat-field.

At the same time, if we calculate statistics for the entire frame, then in the case of ideal pixels, the variance of their signals will tend to zero as we average more and more frames. But if the offsets are unique to each frame, we will hit a certain limit determined by the sensor, and we won't be able to go any lower. Although there is nothing wrong with this; with proper calibration, all these inhomogeneities are removed quite well.

Suppose we made 25 frames for a master-offset, then its total noise for an ideal sensor will be ~5 times less than on a single offset. Or a little more, if there is a pedestal spread for individual pixels. One way or another, the characteristic values of offsets on modern DSLRs lie in the region of ADU_{offset}~$1000 \div 2000$, and after averaging 20-40 frames, the dispersion of the offset usually does not exceed several units $\Delta ADU_{moffset} \sim 1 \div 5$. For example, for the Canon 450D at ISO 400 (Gain ~ 2) the value itself $ADU_{moffset} = 1024$, and $\Delta\ ADU_{offset} \sim 12$ on a single frame and for 25 frames $\Delta ADU_{moffset} = 3.3 \div 3.5$, depending on whether we add the median or the arithmetic mean. In any case, the value is slightly higher than the theoretical value ($\frac{12}{\sqrt{25}} = 2.4$), which indicates the effects mentioned above. In the future, when subtracting the master-offset, this is the noise value we will bring to each single frame during calibration.

If we exclude the dark current from consideration, as I have already said, assuming that we shoot with relatively small shutter speeds, then the formula 1 considering 2 can be rewritten as:

$$e^-_{light} = \frac{ADU_{light} - offset_{master}}{transmission \cdot gain} \tag{3}$$

From here onwards the indices $light$, $flat$, $master$ are redesignated respectively as l, f, m.

The formula for the error on Δe^-_l considering the calculations for indirect measurements will be written as:

$$\Delta e^-_l = \frac{ADU_l - offset_m}{transmission \cdot gain}\sqrt{\left(\frac{\Delta transmission}{transmission}\right)^2 + \left(\frac{\Delta ADU_l}{ADU_l - offset_m}\right)^2 + \left(\frac{\Delta offset_m}{ADU_l - offset_m}\right)^2} \tag{4}$$

Derivation assumes that there is no error on $gain$.

Now we would like to understand the values of each term in the formula. Let's start with the first one, determining error in transmission: $\Delta transmission$

From the formula:

$$ADU_f = e_f^- \cdot transmission \cdot gain + offset \qquad 5$$

$$transmission = \frac{ADU_f - offset}{e_f^- \cdot gain} \qquad 6$$

Similar to the formula 4:**Ошибка! Источник ссылки не найден.**

$$\Delta transmission = \frac{ADU_f - offset_m}{e_f^- \cdot gain}\sqrt{\left(\frac{\Delta e_f^-}{e_f^-}\right)^2 + \left(\frac{\Delta ADU_f}{ADU_f - offset_m}\right)^2 + \left(\frac{\Delta offset_m}{ADU_f - offset_m}\right)^2} \qquad 7$$

A typical DSLR has a 14-bit ADC. Which means that we have ~16000 samples at our disposal. Even if we exposed our frame of a flat field quite weakly, not in 2/3 of the available range, but in such a way that after subtracting the master-offset we have a signal of only $ADU_f - offset_m = 1000$, then, assuming, for example, a unit gain, the measurement error in $\Delta transmission$ will be equal to:

$$\Delta transmission = transmission\sqrt{\left(\frac{\sqrt{1000}}{1000}\right)^2 + \left(\frac{\sim\sqrt{1000}}{1000}\right)^2 + \left(\frac{\sim 2 \div 3}{1000}\right)^2} \sim \sqrt{\frac{2}{ADU_f - offset_m}} \qquad 8$$

Where the magnitude Δe_f^- was estimated according to the Poisson distribution, as $\sqrt{e_f^-}$, and since we assumed gain to be close to unity, then $e_f^- \sim ADU_f - offset_m$.

By substituting 8 in 4 we get:

$$\Delta e_l^- = e^-\sqrt{\left(\frac{\Delta e_f^-}{e_f^-}\right)^2 + \left(\frac{\Delta ADU_f}{ADU_f - offset_m}\right)^2 + \left(\frac{\Delta offset_m}{ADU_f - offset_m}\right)^2 + \left(\frac{\Delta ADU_l}{ADU_f - offset_m}\right)^2 + \left(\frac{\Delta offset_m}{ADU_l - offset_m}\right)^2} \qquad 9$$

From this we can see that if we expose flats in the same way as we have lights, then we actually increase the final relative error by a factor of square root two. Worsening the total result by the same number of times. Of course, provided that you shot exactly as many flats as lights. If we took them 8 times more (or fill the histogram with three stops more), then the final deterioration will no longer be a root of two times more, but only a factor of $snr\frac{\sqrt{8+1}}{\sqrt{8}} = 1.06$. Or by 6%.

Practical test

Now that we are done with the theory, it is up to us to test it in practice. What was done:

Frames of a flat field were taken, simulating both the useful signal and also used to calibrate this signal.

2 sequences were captured:

1) 8 Flats of 1/6 second at ISO 400 and f/11 aperture (so that the shutter speed is longer and the dust appears better). These frames were inspected in Iris for overexposure and the average of the pixels in the green channel ~ 7935 with dispersion 130 was obtained. In the end, only 4 of them were taken. Further it will be explained why, but the final "integration time" is ~ 2/3 of a second.

2) The 64 flats that are three stops dimmer than the first ones, i.e. 8 times less light fell on the sensor, which corresponded to a shutter speed of 1/50 of a second. The average value of the pixels in the green channel was 976 with a variance 44.4.

First, let's do a sanity check. ISO 400 in my earlier experiments gave the Canon 450D a conversion factor $0.52\frac{e^-}{ADU}$. Which corresponds to about a double gain (1.91). This means that for a long flat 7935, there are half as many photoelectrons ~ 3966. Dispersion, according to the Poisson distribution, is the root of this: 63. And, since we have doubled each count, the variance for $\Delta ADU = 2 \cdot 63 = 126$. That is, the numbers are fitting. For a short flat, it’s similar deal — you can check. At the same time, both for a long and for a short flat, the photon noise is many times higher than the read noise in the 12 ADU (10.5 and 3.7 times, respectively), so there is an almost complete coincidence of the calculated and experimental noises: the offset contributes practically nothing here.

Next, we create a master-flat from the first half of those short flats. To make sure if the walking noise appears on a final picture due to the lack of linearity of the response of each pixel, or because of something else. To do this, of course, we need to subtract the master-offset from each frame. This will make the noise situation a little worse for us, but let's check on paper and compare. To do this, I uploaded the first file in the series and measured the variance. It turned out to be equal to 43.9. The variance on the master offset is, as I said, 3.5:

$$\sqrt{43.9^2 + 3.5^2} = 44.04$$

After the operation, I get a result of 44.0. So far, everything is according to textbooks. So there is not much point in shooting offsets more than 25-30. At least if you're shooting in a light-polluted area, or you can set the shutter speed so that you have a background of ~1000 counts from 16k.

Feel free to calibrate our sources and now put them into a master-flat. For the first half, after averaging, we get 975.2 ± 10.1. For the second half — 972.6 ± 10.2. Which, as it were, is not very consistent with the complete independence of pixel samples, because if it were, the dispersion value should be in the region of $\frac{44}{\sqrt{32}} = 7.78$.

So we came to what we suspected:

> *The second noise is the same, but you will have to look at the frames of a flat field.*

So, we found out. Those pesky noises DO there. So, yes, dithering is our everything. Which flats are better though? Who is best at removing the amplification inhomogeneities that we have run into: long ones or those that are taken with the same histogram filling as our lights? To do this, let's take the second half of our short shots (33-64) and make a short master-flat out of them, which, although it will be noisier than the long one, will probably be better at fighting walking noise than a long one (after all, the pixels are exposed in the same way).

Therefore, next, take the first half of the images and calibrate it with the flat resulting from the second half. Translate into color and add using three different ways:

1) Addition without displacements at all, as if we had a perfect polar alignment.

2) Addition with a stable offset of 2 pixels horizontally and vertically, simulating drift.

3) Addition with a stable offset of 2 pixels horizontally and vertically, plus random shifts dispersed according to an even distribution in the range [-8, +8].

Then repeat all the same manipulations, using a long flat. Since for the first part only half of the frames went into the final sum, so for the long master flat I used only 4 frames, not 8.

The results are shown in the picture below. Main conclusion here is that exposure of the master-flat has little effect on its ability to eliminate the walking noise. As well as the fact that underexposed flats allegedly do not work. The worst they can do is to add unnecessary noise in the source code.

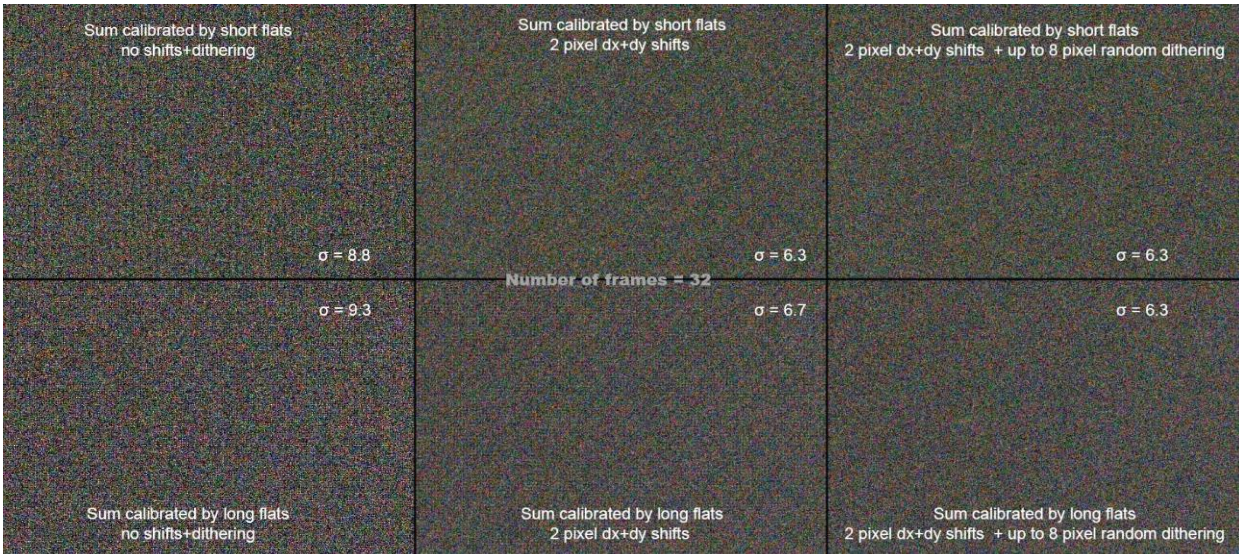

Figure 3 The results of testing the algorithms, which one fights the broom best.

It can be seen that the randomization of the frame positions to the ±8 pixels completely killed the walking noise. This means that in order not to lose the working area of the frame, large movements are not required. Plus, in order not to overload the already quite voluminous text, I will say without proof that you can shoot in series without moving, and then align all the frames with the reference one. And noise will also be quite effectively eliminated. On average, it turns out that if you take the entire session, divide it into 10-15 equal intervals and make a single movement at the end of each interval, the walking nise goes away almost as efficiently as when moving through each frame. But it takes much less time to "settle" the setup. This is the conclusion.

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2026.03.23
Translated in English 2026.03.23