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AN UNCONVENTIONAL REVIEW

A review of the astronomical camera manufactured by QHYCCD
from the point of view of a DSLR user

A DIFFERENT PERSPECTIVE

If you started deep sky astrophotography with a DSLR, you might well be tempted to move to a dedicated astronomical camera to improve sensitivity to H-alpha line and to reduce thermal noise. But when you leave your DSLR for a new astro-toy, you're also leaving your comfort zone. How are you supposed to handle those fancy things named *gain* and *offset*? How do they relate with what you used to know as ISO speed, with your chosen exposure time and with noise?

This is a rather unconventional review. While I covered all the basics of the QHY163 camera, I force myself to stand in the viewpoint of a DSLR owner, to answer such questions as:

- How should I change the *Gain* to obtain the same exposure in half the time?
- With a DSLR I can trade-off read noise for dynamic range. Is this still true with an astronomical camera?
- How is *offset* affecting the exposure? How do I set it in relationship with *Gain*?
- What's the magnitude of read noise? Or better, what's the minimum exposure time to be sky-limited?

ABOUT THE AUTHOR

My name is Alessio Beltrame and I live in North-Eastern Italy where I was born in 1966. My education includes a 5-year Engineering degree (MS equivalent) with a thesis on artificial intelligence applied to electronic design, but I was always fascinated by physics and astronomy, even before attending the elementary school.

I'm also attracted by photography, with a special interest in soccer. This is one of the genres where technical knowledge of cameras and the physics behind their operation is just as important as the artistic aspects. In the last two years I finally found the time and motivation to combine photography and science in one of my childhood passions: the astronomy. With a deep scientific/technical background, I just can't resist to look inside my cameras to find out what happens inside the box the shutter clicks.

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Release history:

- *Release 1.1 – November 2017: new dark current measurement method and results; typos fixing.*
- *Release 1.0 – October 2017: first release*

INTRODUCTION

HOW I CAME TO THE QHY163M

With less than two-year experience in this fields, I'm relatively new to astrophotography. As most amateurs, I started imaging with my Canon 7D Mark II (7D2), which is a very good performer if compared to its peers. However, I'm mainly interested in deep sky objects, emission nebulae being my favorite target. Unfortunately, this is exactly where the 7D2 falls short when compared to astronomical cameras, due to its low sensitivity to H-alpha and to thermal noise (with 25-27°C ambient temperature even at midnight, in the hot Italian summers you are lucky if you can keep your sensor's temperature below 35°C). Add to that the nasty light pollution of northern Italy's sky, and you're set to move to a CCD camera[1]. Or not?

Well, there's a new kid on the block in DSO imaging. QHYCCD and ZWO now offer cooled CMOS cameras which are designed from the ground up for DSO imaging. I found the idea quite intriguing. After some online research and a very fruitful talk with Mauro Narduzzi at SkyPoint (see References), I purchased a QHY163M mono CMOS camera.

As soon as I carried it home, weather changed from sunny to rainy (no surprise at all in that). But, Hey, what a fabulous chance to put the new camera to the test and to learn something from it!

Before my purchase I browsed the net and found some measurements on the QHY163M. I wanted to check those reports and to verify the specs provided by the manufacturer. But more than anything else, I wanted to learn how to use it on the field and how it compares to my 7D2. As an amateur (daytime) photographer, I feel at home with such things as apertures, shutter speeds and ISO settings. After years of photography, they have become second nature.

But how those numbers relate with those fancy things named GAIN and Offset? Don't get me wrong: I perfectly understand the physical meaning of the sensor gain and the offset, I even wrote a booklet on that topic (sorry, Italian only). The GAIN of a CMOS camera and the ISO of a DSLR are both an expression of the electrical amplification of signal in the sensor. However, GAIN and ISO affect the amplification in different ways.

When you're used to DSLRs, you know that you can double the exposure time by halving the ISO and vice-versa. But the GAIN of a QHY163M works in a different way and to double the exposure time you have to **decrease** the GAIN by 60.

This is one of the lessons I learned during my test of the QHY163M. I decided to share what I learned with all amateur astronomers that own or are interested in a QHY163M or similar cameras such as the ZWO ASI1600M.

This is what this document is all about and it should be particularly appealing to those astro-imagers that make the jump from DSLR to astro-cameras.

I hope you will find it useful. Enjoy.

[1] *Of course, one can mod its DSLR to improve H-alpha sensitivity. It's also possible to install a cooling system. To me this is total nonsense, particularly when applied to a pro or semi-pro DSLR such as the 7D Mark II. But even if you are ready to trade-off your daytime color balance and the ability to use the display of your 2,000$ camera, you have to consider that a full modding would be as expensive as a new QHY163M. Also, unless your modification includes the removal of the Bayer filter, your OSC (One Shot Color) DSLR won't be able to compete with a monochrome camera in terms of signal to noise ratio, not even in LRGB mode, let alone narrow band.*

TEST PROCEDURE

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THE SPECS AND THE TEST

The QHY163M is an astronomical cooled camera that belongs to the COLDMOS line of CMOS cameras by QHYCCD. In a market segment where lifespan is longer than typical consumer products, the QHY163M is quite a new product, which is on the market since 2016.

Contrary to the common trend in astronomical cameras, where CCD takes lion's share of sensor technology, the QHY163M is based on the Panasonic MN34230 CMOS sensor, a 4/3" chip featuring 3.8μ pixels and a 16-megapixel resolution. Cooling down to -40°C with respect to ambient temperature is achieved through a thermoelectric cooling system (TEC) based on a two-stage Peltier cell system.

The drivers provided by QHYCCD allow to set several parameters, including:

- *GAIN*: it allows to set the sensor's gain, i.e. the ratio between electrons and ADUs;
- *Offset*: basically, this is a constant that is added to the readout of each pixel in order to avoid clipping to zero due to noise; this constant is also referred to as the *pedestal* or *bias*;
- *USB Traffic*: it allows to adjust the data transmission rate through the USB port (after the latest SDK update, this is applicable only to video acquisition, where the maximum frame rate is important - mainly high-resolution imaging, such as moon and planetary).

I tested the following characteristics of the sensor:

- Linearity
- Read out noise (RON)
- Thermal noise (dark current)
- Full Well Capacity (FWC), i.e. the maximum number of electrons that can "fit" into a pixel at a given gain
- Dynamic range, i.e. the ratio between the maximum signal and the noise floor
- The gain, i.e. the ratio between the electrons collected in a pixel's well and the corresponding readout in ADU (analog-to-digital units, also referred to as DN - Data Numbers).

NOTE: Please do not confuse the gain with the corresponding Gain parameter in the camera driver. For the sake of clarity, I will write in lower case the electrical conversion rate (gain) and in upper case the driver parameter (GAIN).

The above physical quantities have been measured for different combinations of GAIN and Offset.

TEST CONDITIONS

I carried out all tests connecting the QHY163M to a QHYFCW2-M filter wheel and to a Takahashi FSQ-85EDX refractor (f/5.3). I aimed the Tak to a white, uniform surface illuminated by a constant light source. For all exposures I used an Astronomik L-2 Luminance filter (36 mm).

I performed the same tests with my Canon EOS 7D Mark II connected to an EF 70-200L f/2.8 USM IS II tele-zoom set at f/4 and aimed to the same surface, in the same conditions of illumination.

TEST REPORT - 1

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LINEARITY

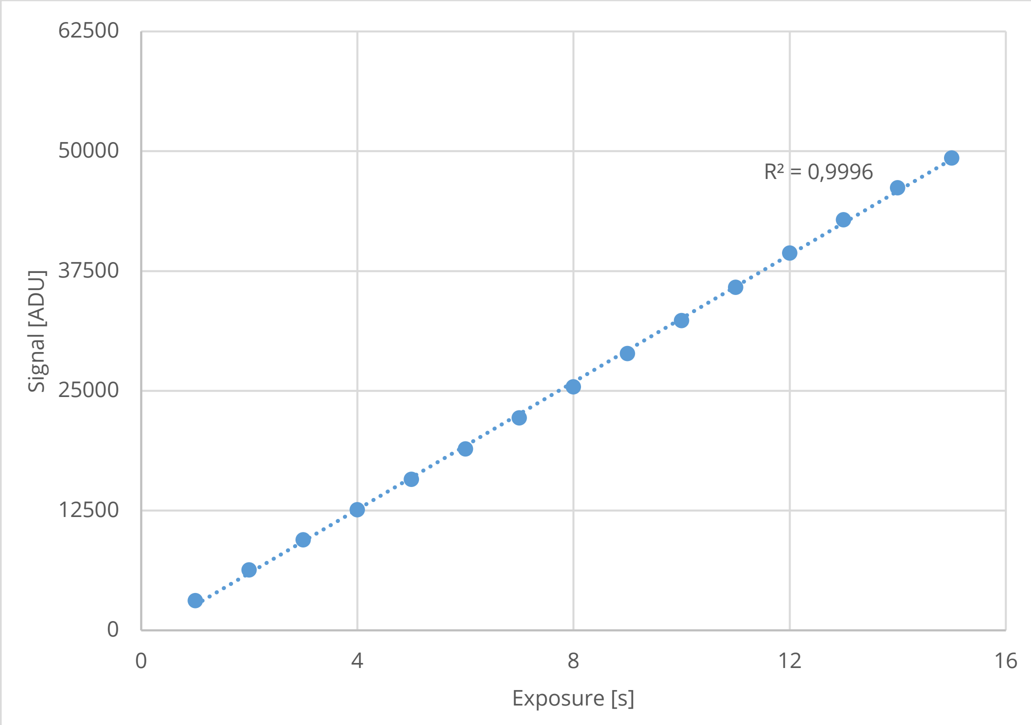
To evaluate linearity, I took 15 exposures of increasing time, in order to cover the entire output range of the sensor (ADU output is expressed in 16 bits, so the actual output range is 0 ÷ 65535 - nonetheless, the ADC of the sensor is 12-bit only. Please refer to 12-bit ADC, 16-bit readouts to find how the 12-bit output of the ADC is mapped to 16-bit ADU values). Each sequence of 15 exposures has been programed through Sequence Generator Pro, in order to minimize the delay between the exposures and to reduce any error due to the variation of the target's light source). If the sensor is linear, we expect the mean value to be proportional to the exposure time.

I ran 3 series of test, using different combinations of GAIN and Offset:

- Gain = 0; Offset = 10
- Gain = 120; Offset = 40
- Gain = 300; Offset = 60

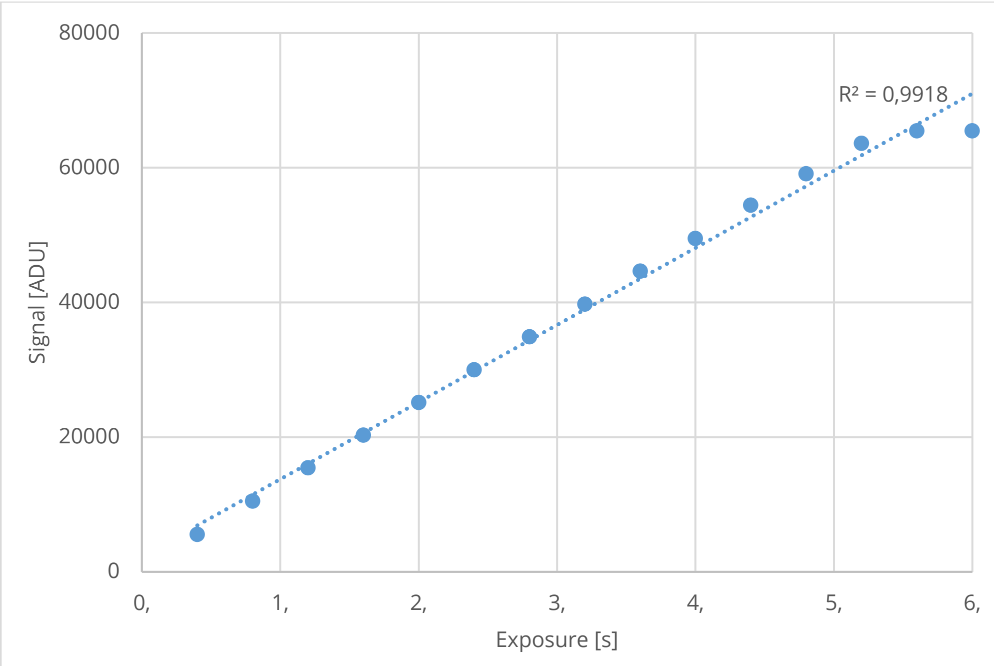
RUN 1: GAIN 0 - OFFSET 10

Exposure [s]	Mean [ADU]	Median [ADU]	Minimum [ADU]
1	3100	3104	160
2	6299	6320	160
3	9424	9456	160
4	12569	12608	160
5	15700	15760	160
6	18871	18944	160
7	22086	22176	160
8	25332	25440	160
9	28726	28886	160
10	32175	32336	160
11	35651	35824	160
12	39136	39376	160
13	42636	42864	160
14	45945	46192	160
15	49302	49296	160



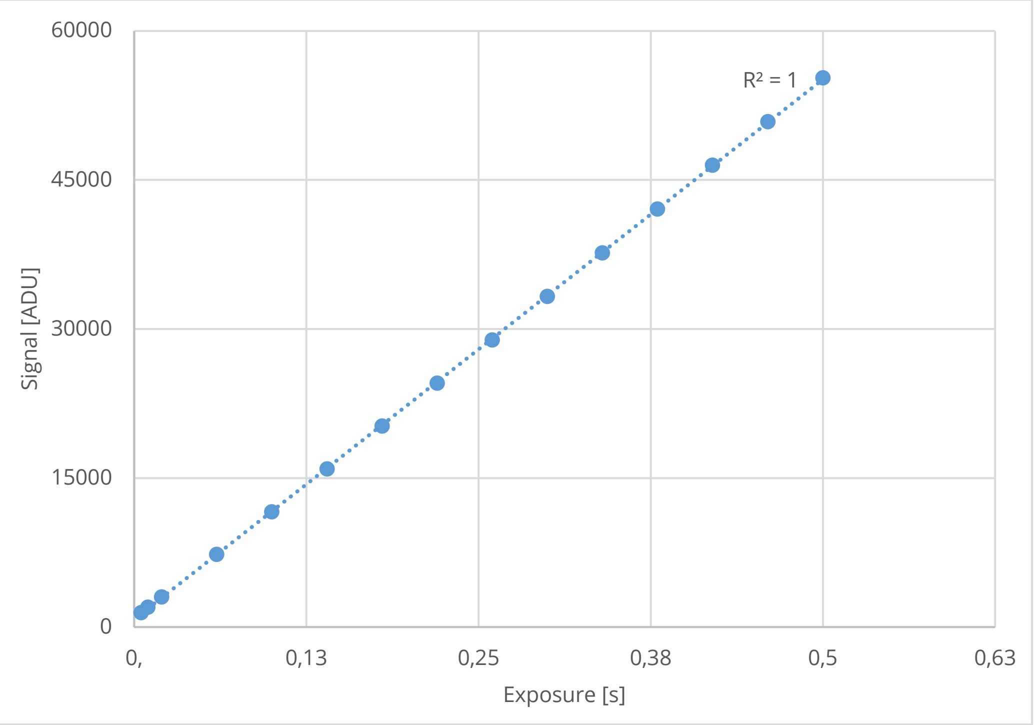
RUN2: GAIN 100 - OFFSET 40

Exposure [s]	Mean [ADU]	Median [ADU]	Minimum [ADU]
0,4	5554	5552	640
0,8	10492	10512	640
1,2	15419	15456	640
1,6	20259	20304	640
2	25085	25152	640
2,4	29952	30032	640
2,8	34793	34912	640
3,2	39629	39760	640
3,6	44501	44656	640
4	49342	49520	640
4,4	54118	54436	640
4,8	58890	59136	640
5,2	63345	63648	640
5,6	65397	65504	640
6	65485	65504	640



RUN 3: GAIN 300 - OFFSET 60

Exposure [s]	Mean [ADU]	Median [ADU]	Minimum [ADU]
0,005	1491	1472	16
0,01	2088	2000	16
0,02	3060	3040	16
0,06	7322	7312	960
0,1	11616	11600	960
0,14	15943	15920	960
0,18	20262	20256	960
0,22	24575	24560	960
0,26	28923	28912	960
0,3	33279	33280	960
0,34	37688	37680	960
0,38	42071	42080	960
0,42	46671	46480	960
0,46	50859	50880	960
0,5	55262	55280	960

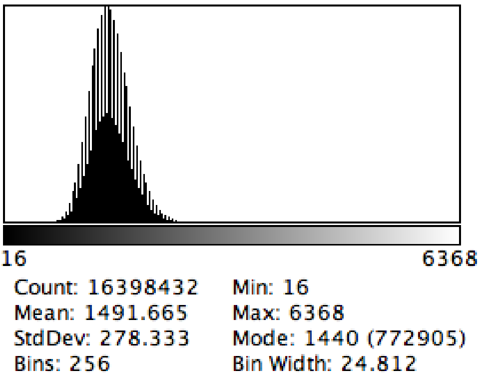


EVALUATION OF RESULTS

Sensor's linearity appears to be excellent, no matter the choice of GAIN and Offset. A confirmation comes from the linear regression analysis, which returns a regression coefficient R substantially equal to 1 (meaning perfect correspondence between the data sample and the hypothesis of linearity).

There's only one anomalous data point (GAIN 100 - Offset 40 - Exposure of 6 seconds), but it is clearly due to the Full Well Capacity limit (saturation of sensor).

It's interesting to note that 3 data points in Run 3 (GAIN 300 - Offset 60) return a minimum value of 16 ADU (it applies to 300 - 500 pixels, which can be considered cold pixels). This is an anomalous behavior for which I couldn't find a completely convincing explanation, given the relation between electrons and ADUs that I will present in a moment. In addition, the histogram appears to be clearly separated from the origin and it is not truncated to the left, so this is not apparently related to a low offset value.



My guess is that there is something weird happening at ultra-short exposures (read: inaccurate exposure timing). Browsing the QHYCCD forum you may find the recommendation to use an exposure time of 0.3 seconds for Bias frames. See also Sensor fundamentals below.

TEST REPORT - 2

HOW OFFSET TRANSLATES IN ADU

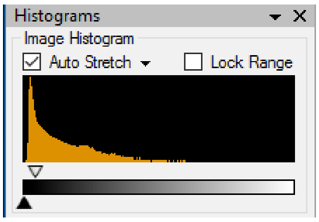
The net effect of the *Offset* regulation is to add a constant value to each pixel reading expressed in ADU. This value is useful to prevent zero-clipping (and consequent data loss) when signal and total noise have comparable magnitudes. If you look carefully to the above data tables, it is easy to see that the minimum value of each exposure does not depend on the exposure time. This is where Offset kicks in and it is clear that the minimum value in each exposure is given by 16 * *Offset*. We can summarize this rule in the following table:

Offset	ADUs added to signal
10	160
40	640
60	960

At higher gain values, the variance of data is also higher, so negative values are more likely. This is why you should increase the *Offset* as you increase the GAIN. On the other hand, a higher value of Offset leaves less room for data within the 16-bit resolution (at Offset=256 you "steal" 4096 levels out of 65536), so it's not a good idea to set a very high Offset in each and every situation.

As a general rule of the thumb, you should set the Offset at approximately 40% to 50% the value of GAIN. For instance, for GAIN=300 set the Offset anywhere between 120 and 150.

To double check, just make sure that your light frames' histogram is clearly detached on the left, just like the following picture.



12-BIT ADC, 16-BIT READOUTS

While the analog-to-digital converter (ADC) of the sensor has a resolution of 12 bits (which can represent the range 0 ÷ 4095), pixel values in ADU are given in the 0 ÷ 65535 ADU, i.e. using 16 bits.

If you read between the lines of manufacturer's documentation, you can find that the ADC output is shifted to the left by 4 pixels (padding with 0's), which corresponds to multiplying it by 16. The check that I wrote a very simple python script:

```
# REQUIRES AstroPy & NumPy
from astropy.io import fits
# Open FITS fils - change filename as needed
hdulist=fits.open("test.fit")
hdu=hdulist[0]
# Scanning actual data
# Data is stored as an array (rows) of arrays (columns)
# Pixel at raw r and column c is stored in hdu.data[r][c]
```

```
# n = number of anomalous bits found
n = 0
for row in range(0,len(hdu.data)):
  print("Scanning sensor line #%s out of %s" % (row,len(hdu.data)))
  for col in range(0,len(hdu.data[row])):
    if (hdu.data[row][col] & 0x000F) != 0:
      print("Pixel value not multiple of 16 at %s, %s" % (row,col))
      n = n + 1
print ("A total of %s pixels with non zero value in the 4 least significant
bits have been found" % n)
```

This script scans the entire FITS image, looking at the least significant 4 bits of each pixel and incrementing a counter if any of those bits is not 0. On each image I ran this script against, no such pixels where found. The ADC readings are indeed multiplied by 16.

EXPRESSION OF PIXEL VALUES IN ADU

If we combine what I found for Offset and pixel values, we can express the readings in ADU using the following formula:

$P(r,c) = 16 * (P_e(r,c) / g + Offset)$

where:

- P(r,c) is the pixel value at row r and column c, expressed in ADU
- P_e(r,c) is the detected signal value (in electrons) for the pixel value at row r and column c
- g is the gain of the signal amplifier, expressed in electrons/ADU. This value depends on the GAIN parameter (as set in the camera driver) in a way that I'll show in a moment
- Offset is the value of the homonymous driver parameter

DSLR COMPARISON

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GAIN VS EXPOSURE TIME

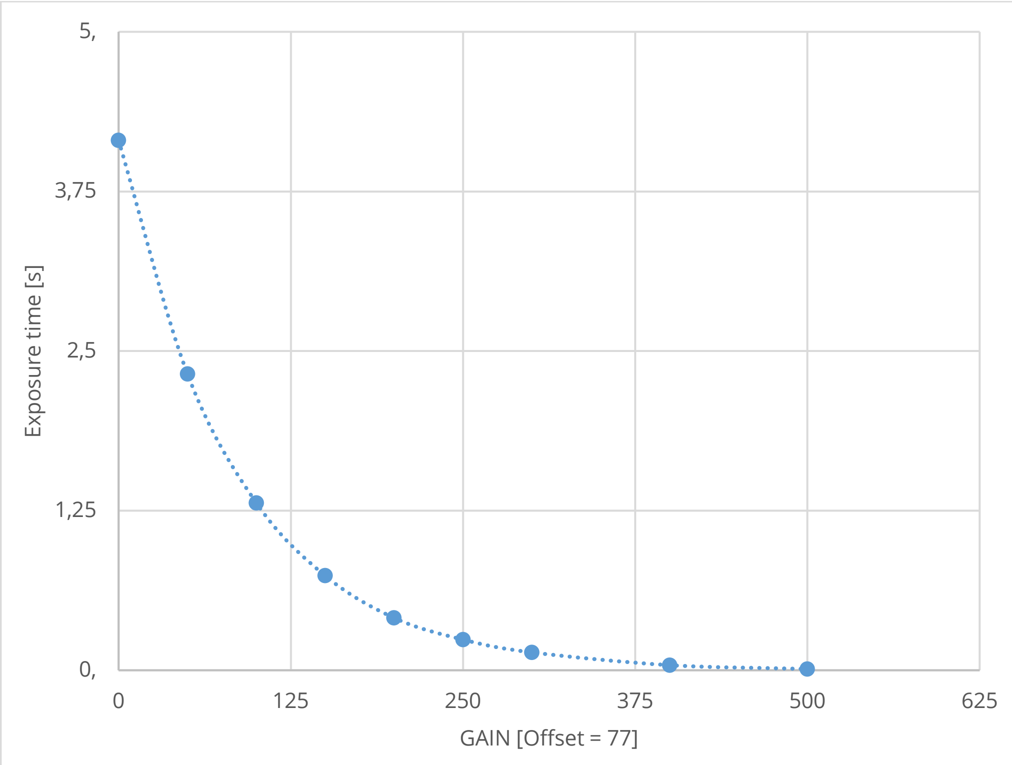
The next test was targeted to finding out the relation between the GAIN and the exposure time, in order to obtain a given ADU value in the output image. Again, I shoot a series of images with a constant illumination surface as a target and I measured the time to reach a pre-determined average value in ADUs (in this test I used 40,000 ± 500 ADUs, but you can use any other value as long as it is the same for all images).

For each image I used a different value of GAIN, but the same value of Offset in order to simplify the comparison among the images (otherwise, you should subtract the Offset from the mean).

You can proceed by trial and error, but a simpler way to run this test is to use the Flat Calibration Tool of Sequence Generator Pro. Just set your desired target value in ADU (in this case 40000) and let it find the corresponding exposure duration.

Here are the results:

GAIN	Offset	Exposure time [s]
0	77	4,15
50	77	2,32
100	77	1,31
150	77	0,74
200	77	0,41
250	77	0,24
300	77	0,14
400	77	0,04
500	77	0,01



The curve is very similar to what you can expect from an exponential low. As a DSLR user I'm accustomed to think in terms of stops, so I asked myself if I could model this curve in terms of powers of 2.

The answer is positive. If we indicate with T_0 the exposure time with GAIN=0 and with G the current GAIN level, we can express the exposure time T like this:

$T = T_0 * 2^{G/60}$

In the following table I listed again the previous results along with the prediction of the above equation. As you can see, the data are a perfect fit for the model.

Gain	Offset	Exposure [s]	Model[s]
0	77	4,15	4,15
50	77	2,32	2,33
100	77	1,31	1,31
150	77	0,74	0,73
200	77	0,41	0,41
250	77	0,24	0,23
300	77	0,14	0,13
400	77	0,04	0,04
500	77	0,01	0,01

But how do you use the above equation? It's really simple and you don't need to face any fancy calculation. Just a simple rule:

If you add (subtract) 60 to the GAIN, your exposure time halves (doubles).

Are you really bound to think in terms of ISO? Don't worry, here is another simple rule:

To add the equivalent of an ISO stop, increase the GAIN by 60; to reduce the equivalent of an ISO by one stop, decrease the GAIN by 60.

Don't get me wrong. This only applies to signal amplification (read ahead for readout noise), yet it's a nice starting point to determine how long you should expose at a given GAIN.

Let's say that you got a nice histogram at GAIN = 30 with a 600-second exposure. How should you change the GAIN to obtain an equivalent image with an exposure of 300 seconds only? With a DSLR you would double the ISO (e.g. from 800 to 1600), but this is the wrong answer with the QHY163M: you need to add 60 to your previous GAIN, so you rise up to 90 instead of doubling it to 60!

GAIN - ISO EQUIVALENCE

The next logical step consists in determining an ISO equivalence for the QHY163M. To find this out I ran a series of exposures using both the QHY163M and the Canon 7D Mark II. The procedure is basically the same of the Linearity test: shooting a white surface with an exposure time to be determined, in order to obtain a preset mean value in the output image (this time I chose 12000 ADU).

With the 7D2 I used an f/4 aperture and I ran the test at 5 different ISO speeds from ISO 100 to ISO 6400. With the QHY163M I used again the Takahashi FSQ-85 EDX, thus with an aperture of f/5.3, and I used a GAIN value of 0, 100 and 300; I always set Offset at 77. The results are listed below.

Configuration	Exposure [s]
Canon 7D Mark II @ ISO 100	4,00
Canon 7D Mark II @ ISO 400	1,00
Canon 7D Mark II @ ISO 1600	0,25
Canon 7D Mark II @ ISO 6400	0,07
QHYCCD QHY163M @ GAIN 0 Offset 10	3,80
QHYCCD QHY163M @ GAIN 100 Offset 40	0.85
QHYCCD QHY163M @ GAIN 300 Offset 60	0,10

You may find that ISO 100 and GAIN 0 look quite similar, but wait a moment: we have to take into consideration the fact that I used two different focal ratios. To compare apples with apples we need to divide the exposure times of the QHY163M by a factor given by $(5.3/4)^2$, i.e. the square of focal ratios.

After applying this correction, the table looks like this:

Configuration	Exposure [s]
Canon 7D Mark II @ ISO 100	4,00
Canon 7D Mark II @ ISO 400	1,00
Canon 7D Mark II @ ISO 1600	0,25
Canon 7D Mark II @ ISO 6400	0,07
QHYCCD QHY163M @ Gain 0 Offset 10	2,16
QHYCCD QHY163M @ Gain 100 Offset 40	0,48
QHYCCD QHY163M @ Gain 300 Offset 60	0,06

Now you may note that the exposure time for the QHY163M is about one half of the exposure time for the 7D Mark II at ISO 100. **We can then infer that the setting GAIN = 0 can be associated with the ISO 200 setting of a DSLR**. To be fair, if we use a one-third stop scale, the data point at GAIN = 0 is nearer to ISO 160 than it is to ISO 200. Anyway, for the sake of simplicity, I'll stick with ISO 200.

Remember from the previous paragraph that an increment of 60 units of GAIN corresponds to halving the exposure time. Now we have all that we need to list a full-scale equivalence between GAIN and ISO.

ISO	Gain
200	0
400	60
800	120
1600	180
3200	240
6400	300
12800	360
25600	420
51200	480
102400	560

As an additional confirmation, you may see that the exposure time for the QHY163M at GAIN = 300 is substantially identical to the exposure for the 7D Mark II at ISO 6400, as predicted in the above table.

By the way, this means that the DSO preset in QHYCCD ASCOM driver (Gain = 174, Offset = 74) is more or less equivalent to ISO 1600 on a DSLR.

Note: in the latest releases of its ASCOM driver, QHYCCD changed the GAIN scale (from 0 ÷ 58 to 0 ÷ 580, i.e. it was multiplied by 10). It also introduced the possibility to save 9 named GAIN/Offset presets. Two presets are available by default, Deep Sky Objects and Planetary).

TEST REPORT - 3

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SENSOR FUNDAMENTALS

After comparing the QHY163M, I measured the fundamentals of its sensors: gain, readout noise, dark current, full well capacity and dynamic range.

Test exposure were takes at -10°C (-35°C with respect to ambient temperature). For each test configuration I took two bias frames, two dark frames and two flat frames. To avoid calculations by hand, I used those frames to feed the **BasicCCDParameters** script of PixInsight.

Note: some reports by Jon Rista for a camera with the same sensor (ASI1600 - https://www.cloudynights.com/topic/579728-flat-frames-what-is-the-ideal-adu-value/#entry7920805) seem to suggest anomalous fluctuations for Bias frames below 0,2-second exposure. I believe those fluctuations may be related to inaccurate timing during the exposure (the QHY163M and the ASI1600 have no mechanical shutter). See also Evaluation of results above.

The following table show the test reports. Please remember that the ADC value in each pixel is shifted by 4 bits (see 12-bit ADC, 16-bit readouts), so the reported gain value is 16 times lower than the real value. For instance, the gain reported for GAIN=0; Offset=10 is 0.302, so the real gain is 0.302 * 16 = 4.832 e-/ADU).

RUN 1: GAIN 0 - OFFSET 10

Measurement	R/C0	G/C1	B/C2	-/C3	Units
mean B1	148.119	---	---	---	ADU
stddev B1	11.529	---	---	---	ADU
mean D1	149.055	---	---	---	ADU
stddev D1	17.217	---	---	---	ADU
mean D2	133.844	---	---	---	ADU
stddev D2	90.849	---	---	---	ADU
mean F1+F2	64712.932	---	---	---	ADU
stddev F1-F2	462.256	---	---	---	ADU
mean B1+B2	296.127	---	---	---	ADU
stddev B1-B2	16.240	---	---	---	ADU
mean D1-B1	0.935	---	---	---	ADU
gain	0.302	---	---	---	e/ADU
readout noise	3.466	---	---	---	e
readout noise	11.483	---	---	---	ADU
dark current	0.028	---	---	---	e/sec
fullwell cap.	19780.793	---	---	---	e
dynamic range	5706.995	---	---	---	steps

RUN 2: GAIN 120 - OFFSET 60

Measurement	R/C0	G/C1	B/C2	-/C3	Units
mean B1	952.855	---	---	---	ADU
stddev B1	21.426	---	---	---	ADU
mean D1	958.763	---	---	---	ADU
stddev D1	59.014	---	---	---	ADU
mean D2	1005.679	---	---	---	ADU
stddev D2	297.159	---	---	---	ADU
mean F1+F2	70899.485	---	---	---	ADU
stddev F1-F2	973.186	---	---	---	ADU
mean B1+B2	1905.543	---	---	---	ADU
stddev B1-B2	29.825	---	---	---	ADU
mean D1-B1	5.908	---	---	---	ADU
gain	0.073	---	---	---	e/ADU
readout noise	1.538	---	---	---	e
readout noise	21.089	---	---	---	ADU
dark current	0.004	---	---	---	e/sec
fullwell cap.	4778.602	---	---	---	e
dynamic range	3107.489	---	---	---	steps

RUN 3: GAIN 174 - OFFSET 77

Measurement	R/C0	G/C1	B/C2	-/C3	Units
mean B1	1228.049	---	---	---	ADU
stddev B1	33.851	---	---	---	ADU
mean D1	1202.522	---	---	---	ADU
stddev D1	100.643	---	---	---	ADU
mean D2	987.622	---	---	---	ADU
stddev D2	512.542	---	---	---	ADU
mean F1+F2	64908.739	---	---	---	ADU
stddev F1-F2	1261.937	---	---	---	ADU
mean B1+B2	2456.284	---	---	---	ADU
stddev B1-B2	46.678	---	---	---	ADU
mean D1-B1	-25.528	---	---	---	ADU
gain	0.039	---	---	---	e/ADU
readout noise	1.296	---	---	---	e
readout noise	33.006	---	---	---	ADU
dark current	0.002	---	---	---	e/sec
fullwell cap.	2573.605	---	---	---	e
dynamic range	1985.549	---	---	---	steps

RUN 4: GAIN 300 - OFFSET 150

Measurement	R/C0	G/C1	B/C2	-/C3	Units
mean B1	2388.946	---	---	---	ADU
stddev B1	119.661	---	---	---	ADU
mean D1	2447.470	---	---	---	ADU
stddev D1	316.169	---	---	---	ADU
mean D2	2810.659	---	---	---	ADU
stddev D2	1209.323	---	---	---	ADU
mean F1+F2	73496.307	---	---	---	ADU
stddev F1-F2	2765.222	---	---	---	ADU
mean B1+B2	4777.133	---	---	---	ADU
stddev B1-B2	166.170	---	---	---	ADU
mean D1-B1	58.524	---	---	---	ADU
gain	0.009	---	---	---	e/ADU
readout noise	1.060	---	---	---	e
readout noise	117.500	---	---	---	ADU
dark current	0.000	---	---	---	e/sec
fullwell cap.	591.102	---	---	---	e
dynamic range	557.745	---	---	---	steps

COMPARISON WITH THE CANON 7D MARK II

To compare the QHY163M with a DSLR, you can look for online resources, for instance http://www.sensorgen.info. I was particularly interested in comparing the QHY163M with my DSLR, the Canon 7D Mark II (7D2). The 7D2 is basically a sports camera, but it features one of the best sensors in Canon's lineup (but if falls short in many ways when compared to Sony sensors in Sony and Nikon cameras, particularly in dynamic range).

The 7D2 is an excellent performer in terms of dark current, if compared to other uncooled DSLR's. H-alpha sensitivity is good in DLSR's terms, yet monochrome, cooled astronomical cameras play in different league in this respect.

Some reports for the 7D2 are available at http://www.sensorgen.info/CanonEOS-7D-Mark-II.html or http://www.clarkvision.com/reviews/evaluation-canon-7dii/.

The most important parameters are listed here:

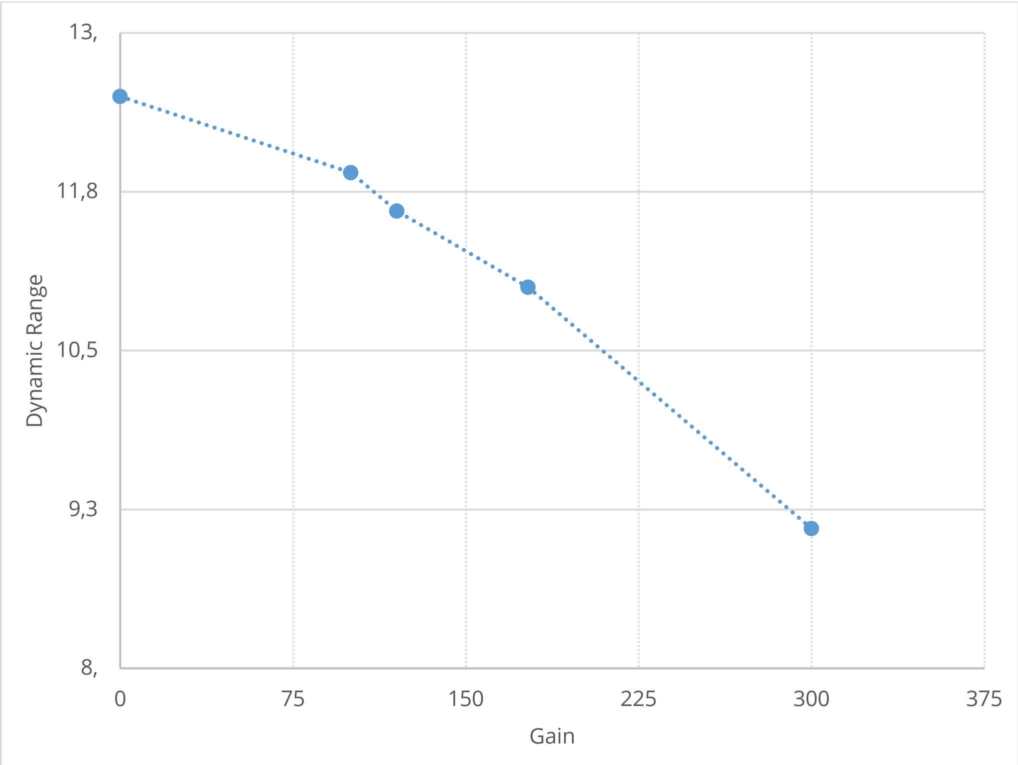
Sensorgen	Readout noise [e-]	FWC [e-]	Dynamic range [stops]
ISO100	12,9	29544	11,2
ISO200	8,0	18552	11,2
ISO400	5,2	9724	10,9
ISO800	4,0	4866	10,2
ISO1600	2,8	2509	9,8
ISO3200	2,1	1236	9,2
ISO6400	2,2	626	8,1
ISO12800	2,0	320	7,3

Clark	Gain [e-/ADU]	Readout noise [e-]	FWC [e-]	Dynamic range [stops]
ISO100	2,74	15,0	31800	11,0
ISO200	1,34	7,8	17800	11,2
ISO400	0,67	4,6	8910	10,9
ISO800	0,34	3,2	4520	10,5
ISO1600	0,168	2,4	2230	9,9
ISO3200	0,084	1,9	1110	9,2
ISO6400	0,042	1,7	560	8,4
ISO12800	0,021	1,6	279	7,4

DYNAMIC RANGE

In agreement with manufacturer's claims, **the Dynamic Range (DR) tops out at 12.5 stops at GAIN = 0** and it stays on excellent levels (11 stops) up to the midrange GAIN of 180 approx. Even at higher GAIN levels you still get a very good DR value of 9+.

Gain	Dynamic range [stops]
0	12,5
120	11,6
174	11,0
300	9,1



The comparison with the 7D2 puts it into the shame. In "equivalent" use conditions (from the point of view of gain - ISO 1600 for the 7D2, GAIN = 174 for the QHY163M), the QHY163M shines with a DR reaching 11 stops, while the 7D2 lags behind with only 9.8-9.9 stops.

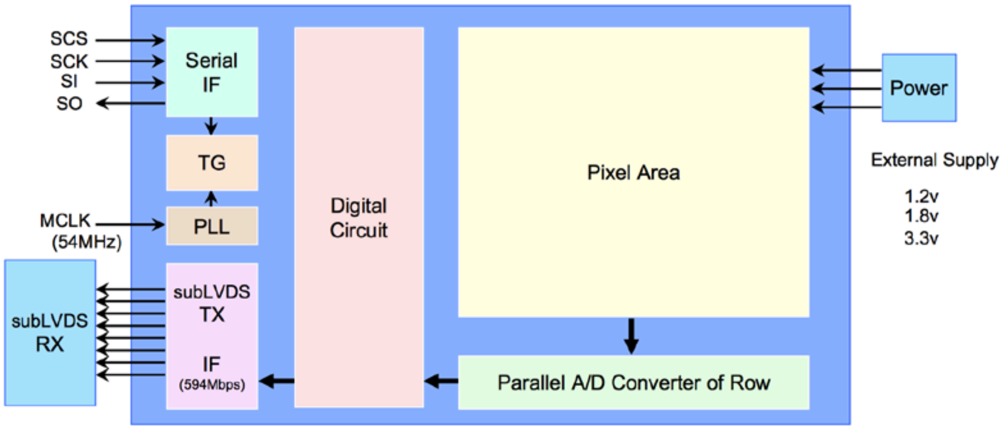
The advantage offered by the QHY163M is even more evident at lower GAIN. While the 7D2 is limited to 11 stops at ISO 100, the QHY163M goes up to 12.5 stops at GAIN 0.

This is the only situation where the relatively low resolution of the ADC can be a limit (12-bit resolution for a 12.5-stop dynamic range). With a **single exposure** the quantization noise is no more negligible. However, we usually stack multiple exposures and a handful of them is more than enough to forget about quantization noise.

READOUT NOISE

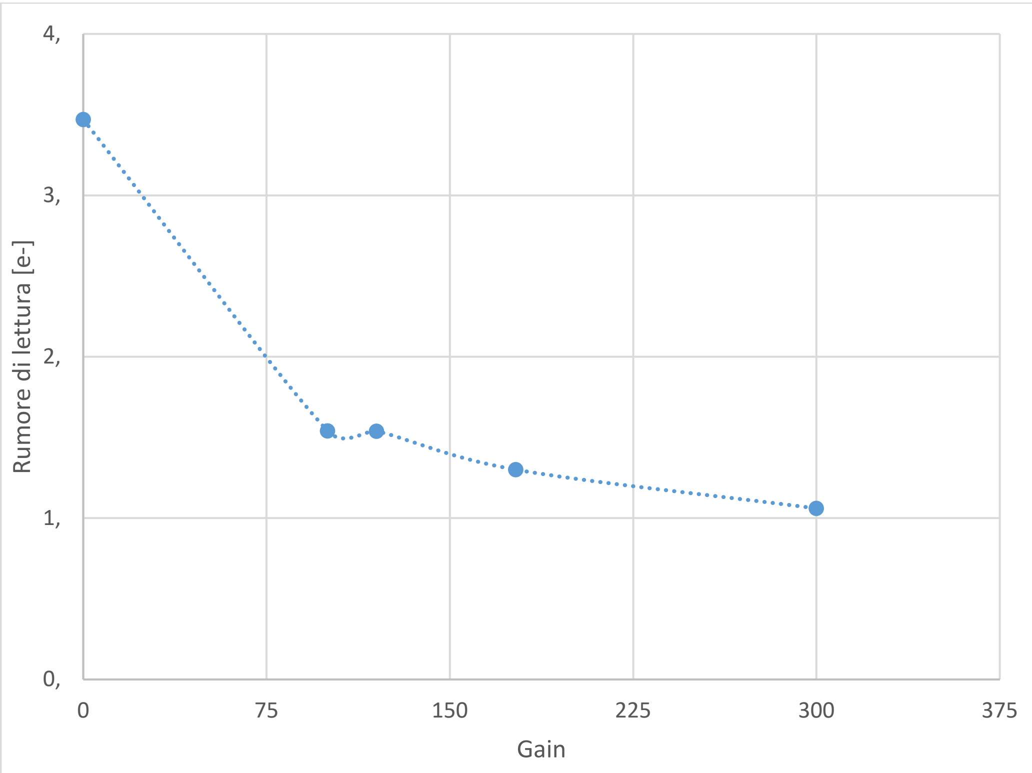
Just like last generation Sony sensors (and contrary to most Canon sensors), the Panasonic sensor mounted on the QHY163M shows a very low readout noise, even at lowest gain settings. The readout noise curve flattens quickly towards the minimum value of 1 electron.

This is a distinctive feature of sensors featuring **a very low downstream noise, thus rather insensitive to the gain settings** (in the DSLR world these sensors are said to be ISO-invariant). As confirmed by the its data sheet, the Panasonic MN34230 features a built-in ADC: the short path from the signal amplifier to the ADC helps a lot in reducing downstream noise, as opposed to camera designs where the ADC is external to the chip sensor (CCD cameras and Canon DSLRs).



In good measure, from GAIN = 100 you get diminishing returns in terms of readout noise, so raising the GAIN over 300 appears to be questionable (since at higher GAIN you also loose dynamic range).

Gain	Readout noise [e-]
0	3,47
100	1,54
177	1,30
300	1,06



Again, the comparison with the 7D2 shows that the QHY163M is a clear winner. But it is also superior to Sony-equipped DSLR's, including Nikon and the same Sony. There's no comparison with cameras featuring CCD sensors: the best ones are far away with 5-6 electrons, but on average a CCD sensor has a readout noise of no less than 8 electrons.

DSLR COMPARISON PART 2

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USE IT LIKE A DSLR

It should come at no surprise at all, as both are based on CMOS technology. The QHY163M may be used much like a DSLR camera. With a DSLR you can improve readout noise by raising the ISO speed. The same applies with the QHY163M: you can reduce readout noise by raising the GAIN. In both cases you will get diminishing returns as you raise the ISO/GAIN and after a certain point the advantage of increasing ISO/GAIN becomes negligible.

On the other hand, a DSLR shows the best performance in dynamic range at base ISO. The same happens with the QHY163M, which offers the best dynamic range at GAIN 0.

FULL WELL CAPACITY

The Full Well Capacity (FWC) measures in at approx. 19.800 electrons at GAIN=0, in line with the value provided by QHYCCD. It's still far from the theoretical limit of approx. 2000 electrons per square micron (or 29000 electrons for the 3.8 μ^2 pixels of the QHY163M). Probably this is due to the on-chip read and conversion circuitry (less space for the pixel's active surface, less space for the electron well).

The FWC, along with the read noise floor, determines the dynamic range. As the DR is excellent, you shouldn't worry too much about the FWC value.

TEST REPORT - 4

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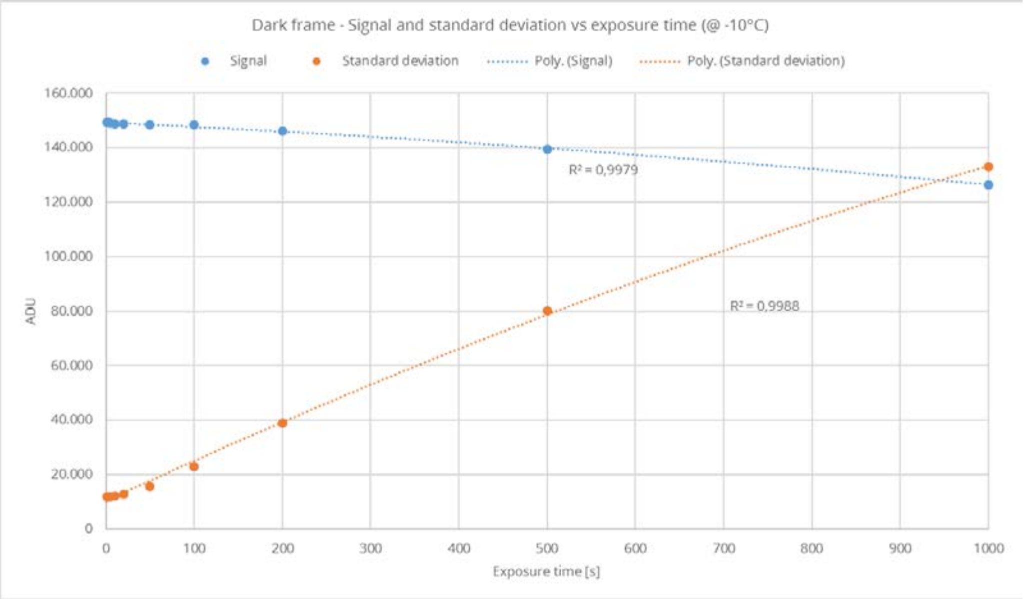
DARK CURRENT

One of the weird things about this camera is that the mean of a Dark frame is typically lower than the mean of a corresponding Bias frame. The longer the exposure duration of the Dark, the lower is the mean, while the standard deviation rises as expected.



It turns out that this effect is due to the optical black calibration of the sensor. The purpose of this area of the sensor (which is shielded from light) is to set the black point of the output frame, but for long exposures the amp glow causes an increase of temperature, which in turn causes an overcorrection of the black point, resulting in the slight decrease of the mean observed in the above graph.

There are no detrimental consequences on your images, as long as you're careful with the calibration. In datail, you must ensure that:

- **Dark frames are taken with the same identical exposure and temperature of your light frames. Needless to say, you must also you the same GAIN and Offset.**
- **Don't use Master Dark scaling when calibrating. If you use PixInsight, disable the Optimize option for the Master Dark in ImageCalibration process.**
- **If you calibrate Darks with a Master Bias frames too, you should also add a pedestal to avoid black clipping when subtracting the bias from the darks.**

Due to the overcorrection, the short way to measure dark current is not viable, as it would lead to unpredictable results.

I learned a possible workaround to get a more reliable measure of dark current from Christian Buil (see references). The method consists in taking two dark frames **with the same duration and the same temperature**, let's call them D1 and D2. Then, you subtract D2 from D1 (in PixInsight use PixelMath – in ImageJ you use Image operations – Subtract). As the fixed pattern noise (and amp glow!) is the same in both images, by subtracting one from the other we eliminated its contribution to total noise and we are left with thermal noise (due to dark current random nature) with readout noise and with random telegraph signal (signal shot noise is obviously zero, as we are using dark frames).

Now, for the property of Poisson distribution we may calculate the total noise of the difference image as its standard deviation σ(D1-D2), that is:

$$\sigma_{1-2} = \sigma(\mathrm{D1} - \mathrm{D2}) = \sqrt{\sigma(\mathrm{D1}) + \sigma(\mathrm{D2})} = \sqrt{2}\,\sigma'$$

$$\sigma' = \frac{\sigma_{1-2}}{\sqrt{2}}$$

Where I assumed that:

$$\sigma' \cong \sigma(\mathrm{D1}) \cong \sigma(\mathrm{D2})$$

In other words, the standard deviation of the two dark frames is approximately the same and equal to σ'. This is very reasonable, because two darks taken in the same conditions should be (on average) very similar (of course, individual pixels may assume radically different values).

Now, for a dark frame we may write:

$$\sigma = \sqrt{\mathrm{D_c t} + \mathrm{RON}^2 + FPNU^2 + RTS^2}$$

Where Dc*t is the dark signal (do not confuse it with dark noise, which is the square root of dark signal!), given by the product of dark current D_c times exposure time; RON is the readout noise; FPNU is the fixed pattern noise. We can also rewrite the above equation as:

$$\sigma^2 = \mathrm{D_c t} + \mathrm{RON}^2 + FPNU^2 + RTS^2$$

$$\mathrm{D_c t} + \mathrm{RTS}^2 = \sigma^2 - \mathrm{RON}^2 - FPNU^2$$

We may find the value of RON from the sensor's datasheet (there are also several simple ways to measure it from flat and bias frames, but I will not cover that topic in this paper) and we can calculate σ for any given dark frame, but we cannot discriminate the contribution of dark current and RTS from the contribution of fixed pattern noise. However, if we subtract a dark frame from another dark frame, the fixed pattern noise cancels out while the standard deviation is given by the formula we find above, so we are left with:

$$\mathrm{D_c t + RTS^2 = (\frac{\sigma_{1-2}}{\sqrt{2}})^2 - RON^2}$$

The contribution of RTS to the total noise is generally small and we may decide to ignore it by putting:

$$\mathrm{RTS \cong 0}$$

Finally, if we solve for D_c we find out that:

$$\mathrm{D_c} = \frac{(\frac{\sigma_{1-2}}{\sqrt{2}})^2 - \mathrm{RON}^2}{t}$$

If we decide to disregard the approximation regarding the RTS, we may still note that RTS^2 is necessarily zero or greater than zero, which allows us to rewrite the above formula as an inequality:

$$\mathrm{D_c} \leq \frac{(\frac{\sigma_{1-2}}{\sqrt{2}})^2 - \mathrm{RON}^2}{t}$$

Here I'm expressing all variables in ADU instead of electrons. If you want to find dark current in electrons per second, simply multiply the dark current D_c by the square of the gain. Otherwise, in the above formula you can multiply the standard deviation σ_{1-2} by the gain G and enter the readout noise in electrons:

$$\mathrm{D_c} \leq \frac{\frac{(G\,\sigma_{1-2})^2}{2} - \mathrm{RON}_{e-}^2}{t}$$

I though it is possible to extend Buil's formula by taking several darks and more precisely an even number, let's call them D_1, D_2, D_3, … D_n. Then, we construct a composite image D as:

$$\mathrm{D = D_1} - D_2 + D_3 - D_4 + \cdots + D_{n-1} - D_n$$

$$\sigma(\mathrm{D}) = \sqrt{n}\,\sigma'$$

where again:

$$\sigma' \cong \sigma(\mathrm{D_1}) \cong \sigma(\mathrm{D_2}) \cong \cdots \cong \sigma(\mathrm{D_n})$$

By repeating the same steps above, we find that

$$\mathrm{D_c} \leq \frac{\frac{(G\,\sigma(D))^2}{n} - \mathrm{RON}_{e-}^2}{t}$$

with the relevant difference that we are now working on several frames, so statistical fluctuations and the influence of measurement errors on single frames should be considerably reduced.

I performed the measurement using up to 14 dark frames taken at -20°C, obtaining the following results:

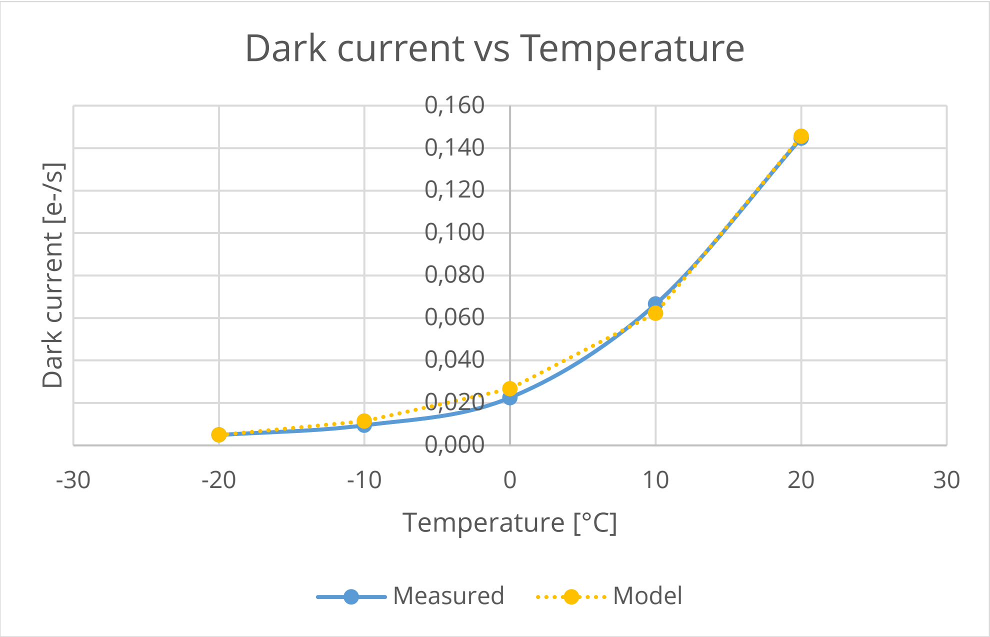
Frames	Dark current [e-/s/pixel]
2	0,0047
4	0,0054
6	0,0051
8	0,0047
10	0,0052
12	0,0053
14	0,0051

As you can see, there is an initial fluctuation, then the measured value seems to settle around 0.005 electrons per second per pixel, which is my best estimation for the dark current at -20°C.

Dark current is reasonably low, and you can expect it to be less than **0.01 electrons per pixel per second** at typical operating conditions (with a cooling system capable to go up to 40°C below ambient temperature, you're likely to operate at -10°C or lower even in summer).

Temperature [°C]	Measured dark current [e-/s]	Predicted dark current [e-/s]
-20	0,005	0,005
-10	0,009	0,011
0	0,022	0,025
10	0,067	0,062
20	0,145	0,148

The Predicted dark current column refer to a mathematical model for dark current. It is generally assumed that dark current doubles for every increase of T_k degrees in temperature, where T_k is a constant that depends on the specific sensor and generally assumes a value around 5 ÷ 6 °C. For this camera I found this constant to be a little higher, around 8.2 °C and I used this value to populate the Predicted column. The following graph shows that the model is a good fit for data:



Compared with a standard CCD camera, with the QHY163M you get less when pushing down the temperature. The other side of the coin is that you pay a smaller penalty when a high ambient temperature prevents the camera to operate at very low temperatures.

In terms of absolute value of noise, and to put things in perspective, in a 15-minute exposure at -20°C you're going to get a little less than 5 electrons worth of thermal noise, which add up to the read noise of 1 ÷ 1.5 electrons for a total noise of 6 electrons. By contrast, the most popular of CCD sensors, the KAF-8300, starts at 8 ÷ 10 electrons for read noise only.

Quick note: it seems that the minimum operational temperature of this camera is -30°C. I wasn't able to test this assertion, as the ambient temperature never drops below 10°C while I'm writing this review.

TEST REPORT - 5

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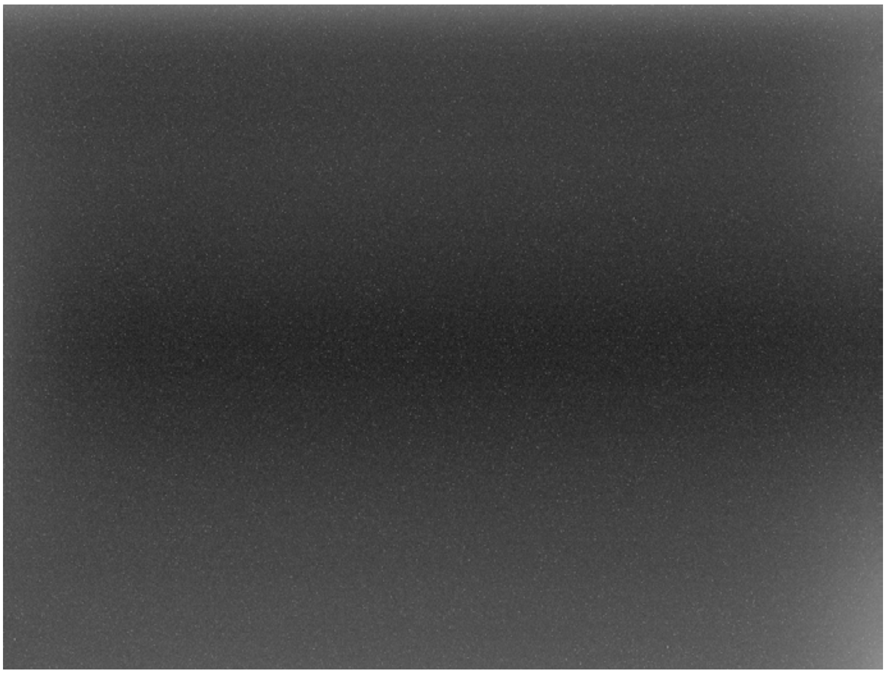
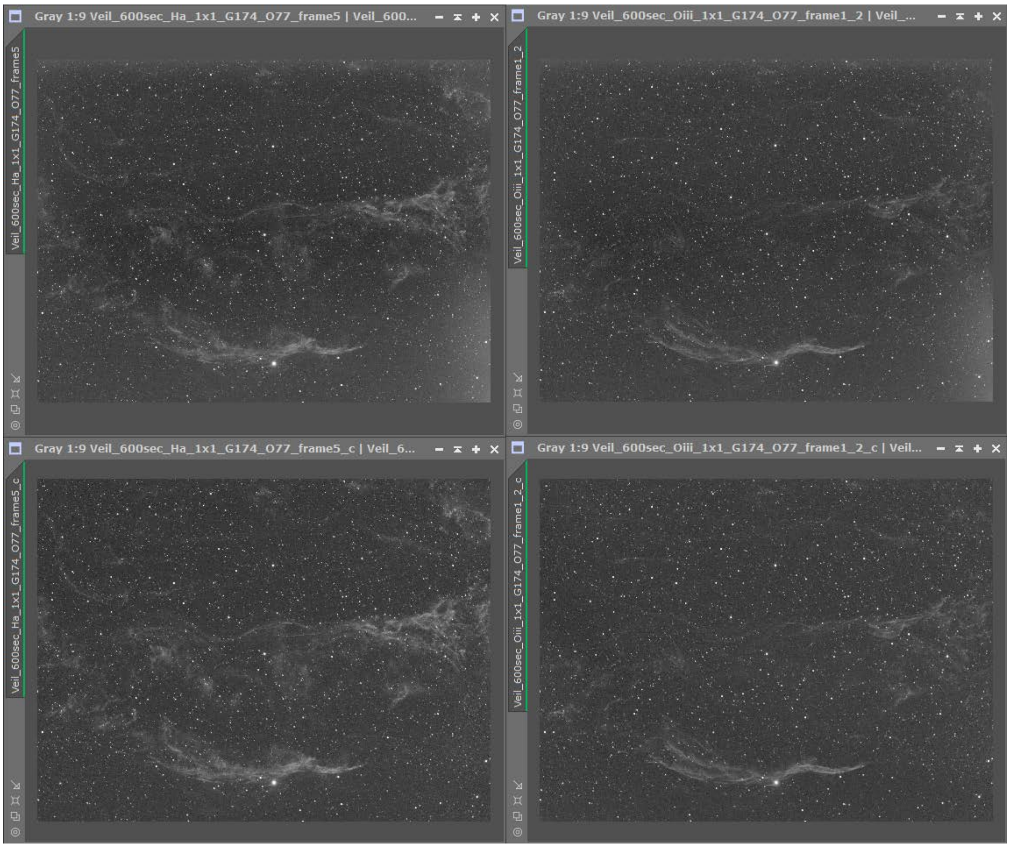
AMP GLOW

As regards amplifier glow, it shows only for exposure times exceeding some minute. It is more prominent in the bottom right and top right corners, but for very long exposures (10 minutes and more) you will start to notice it even in the top and bottom bands.



Amp Glow for an exposure of 600 secondi @ -10°C (STF stretch with PixInsight)

For short exposures, like a minute or less, amplifier glow is not a factor. **In any case, a good image calibration removes all the effects of amplifier glow**, as shown in the following pictures (calibration in PixInsight using 100 Bias frames, 16 Dark frames and 20 Flat frames).



Removal of amp glow through calibration (with bias, dark and flat frames). Top row: uncalibrated light frames (left H-alpha, right O-III). Bottom row: the calibrated version of the same frames.

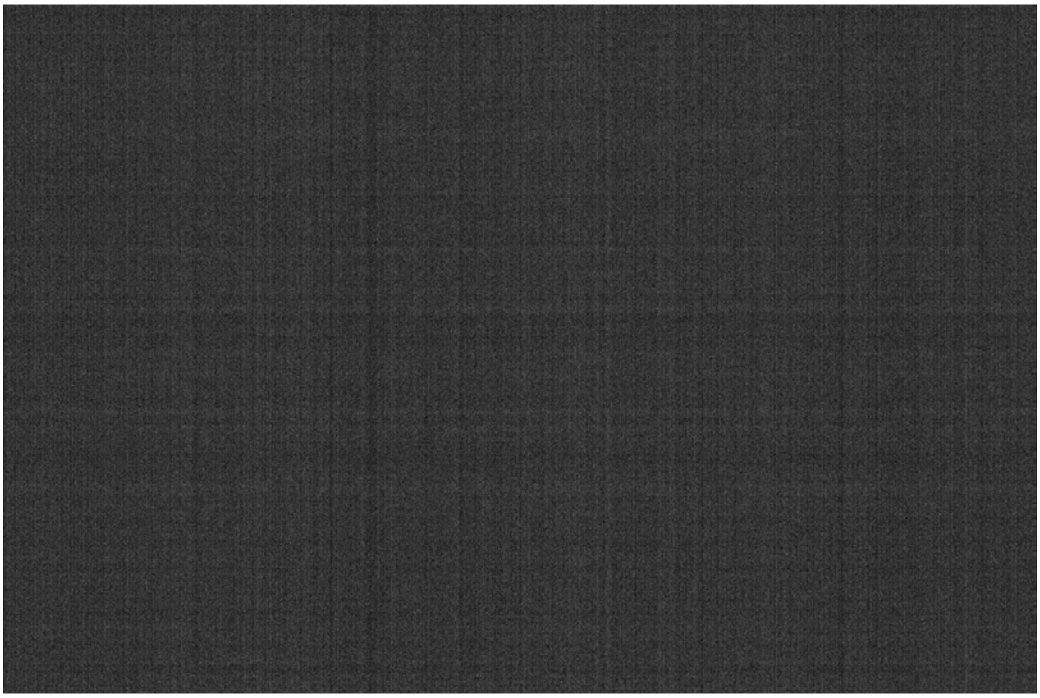
Again, I recommend to disable dark frame scaling during calibration (in PixInsight it's the Optimize option under the Master Dark tab of ImageCalibration process), in order to avoid undercorrection or overcorrection. Just use dark frames taken at the same temperature, exposure duration, GAIN and offset of your light frames.

Note: to reduce the amp glow, it was recommended to set the USB Traffic to zero (maximum transfer speed). Anyway, with the latest software release, the camera always works at USB Traffic = 0 when in single frame mode (not in video mode).

PIXEL RESPONSE NON-UNIFORMITY

Most noise sources are of **temporal** nature, meaning that their contribution to the reading of a given pixel changes with time in a random way. However, some noise sources tend to affect the same pixels in the same way over time. In addition, the noise on a given pixel is frequently related to the noise of neighboring pixels, thus forming a sort of pattern. Those noise sources are then of **spatial** nature and the most important examples are Fixed Pattern Noise, or **FPN**, which is independent from illumination and usually time-indipendent, and Pixel Response Non-Uniformity, or **PRNU**, which is basically a variation of the signal due to inhomogeneity of the sensor at pixel, column or row level.

While the magnitude of PRNU may be lower than or on par with the magnitude of readout noise, its effect is particularly nasty. In fact, the human brain is excellent at pattern recognition, so PRNU stands out. The most common form of PRNU is **banding**: an example of Bias frame of the Canon 7D (first release, or Mark I) is worth one thousand words:

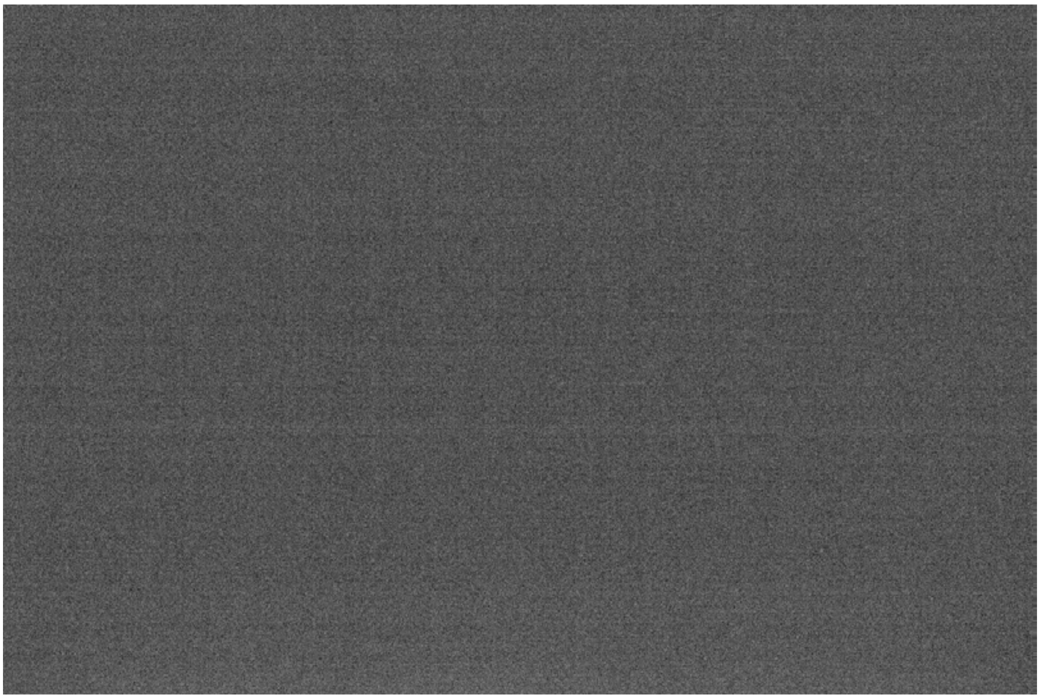


Bias frame of a Canon EOS 7D

Even though the image is resized to 25%, you may easily detect vertical and horizontal stripes. Banding has little impact on daytime photography, unless you need to recover shadows in underexposed areas (this is common for scenes with high dynamic range).

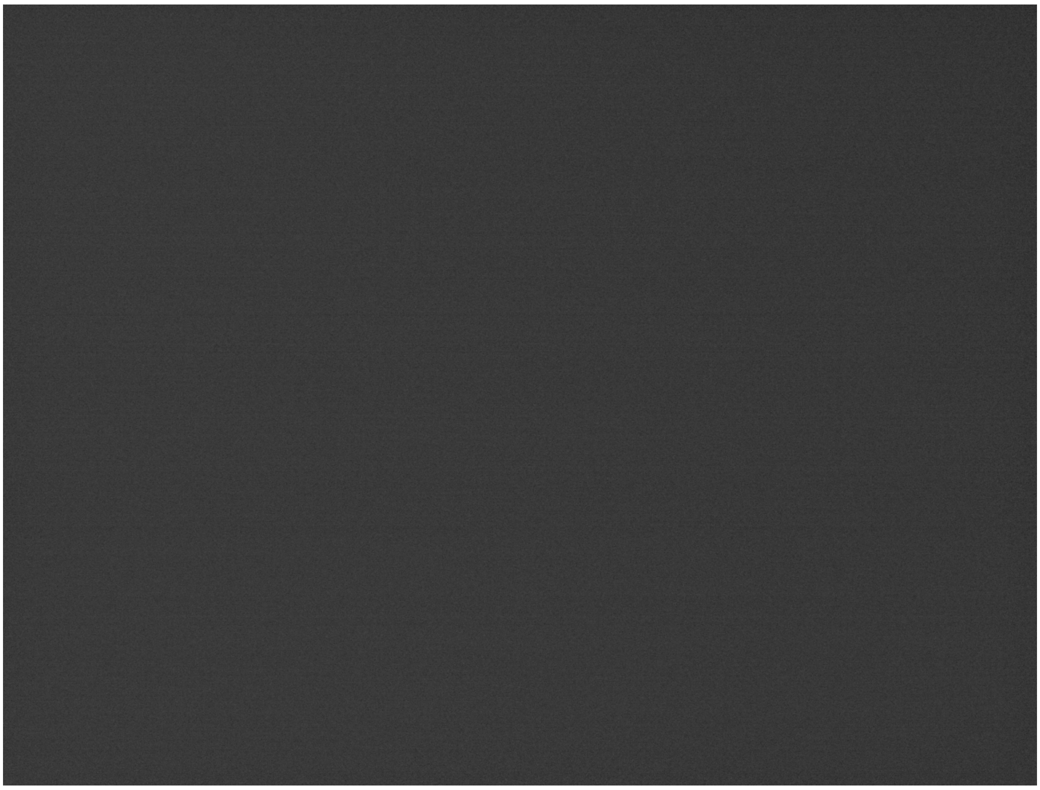
For astrophotography banding is an issue, because that all pictures need to receive an extreme stretch of the histogram. Due to fact that the **PRNU is not entirely random**, the usual calibration techniques with bias frames, and even dithering, can be ineffective. In fact, bands may appear in different positions on each frame.

CMOS sensors manufactured in the latest years (all Sony sensors and Canon sensors after 2014) show an improvement on PRNU. For instance, the Canon 7D Mark II shows to be light years ahead with respect to its previous version.



Bias frame of a Canon EOS 7D Mark II

The QHY163 is even better and shows no trace of banding after a quick inspection.

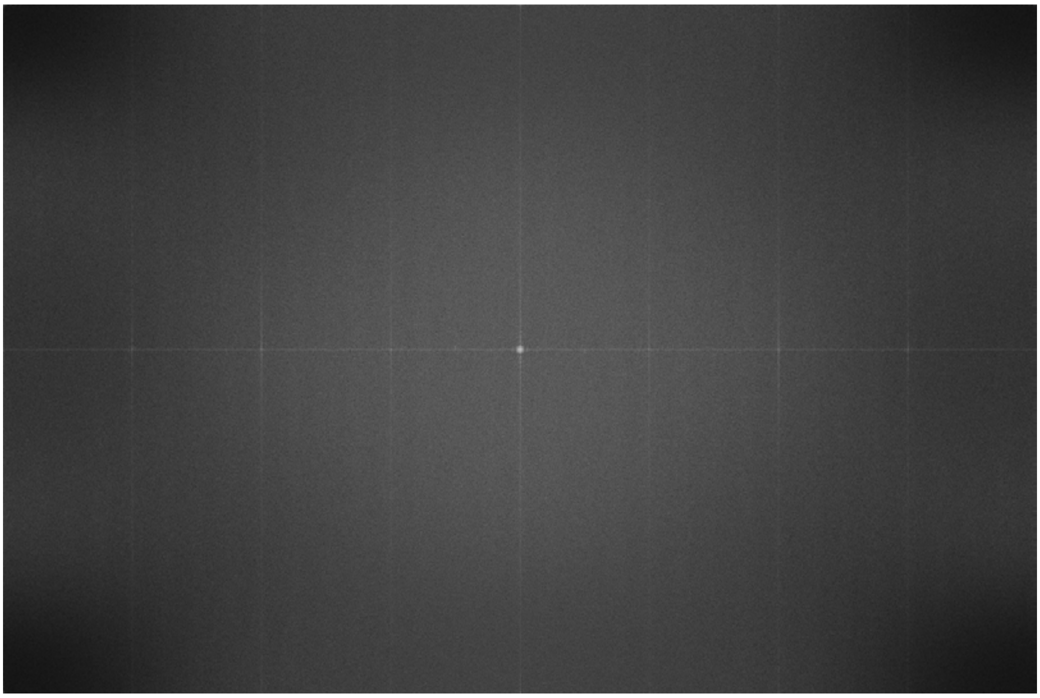


Bias frame of a QHY163M

All the above images have been stretched using the STF and HistogramTransformationTool of PixInsight.

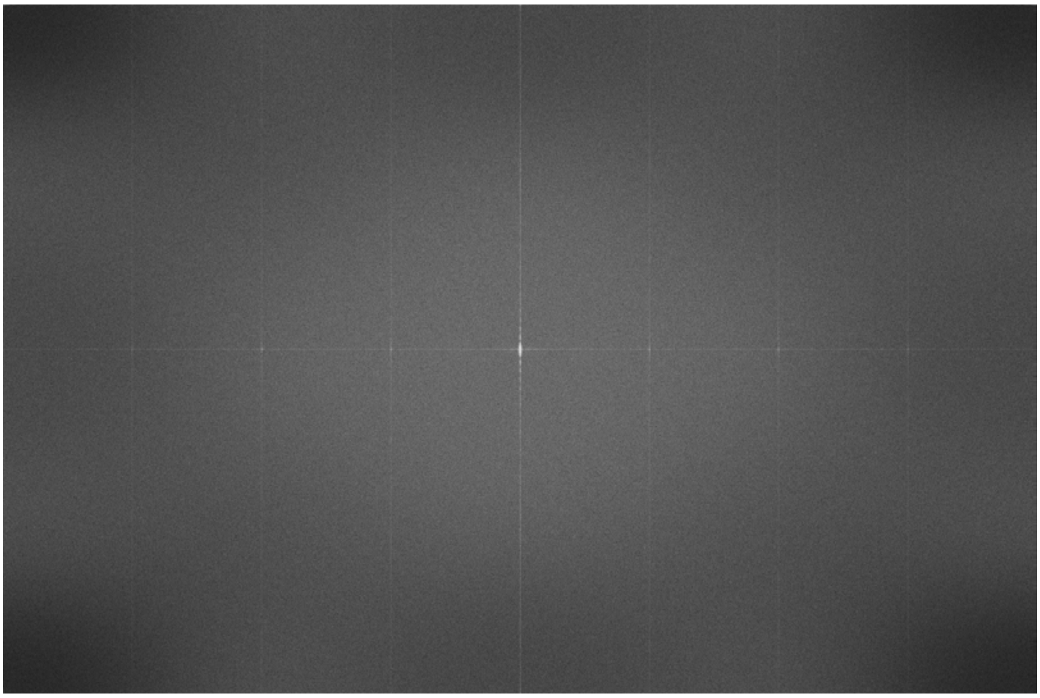
One of the best ways to evaluate the PRNU in an analytical way is to calculate a **DFT (Discrete Fourier Transform) of bias frames**.

For the Canon 7D, the DFT shows vertical and horizontal lines, that correspond respectively to horizontal and vertical banding. The presence of multiple lines means that there is banding at different frequencies, which means that there are bands of different width. The fact that DFT lines are horizontal and vertical confirms that the PRNU is related to rows and columns (rather than a "diagonal" direction).



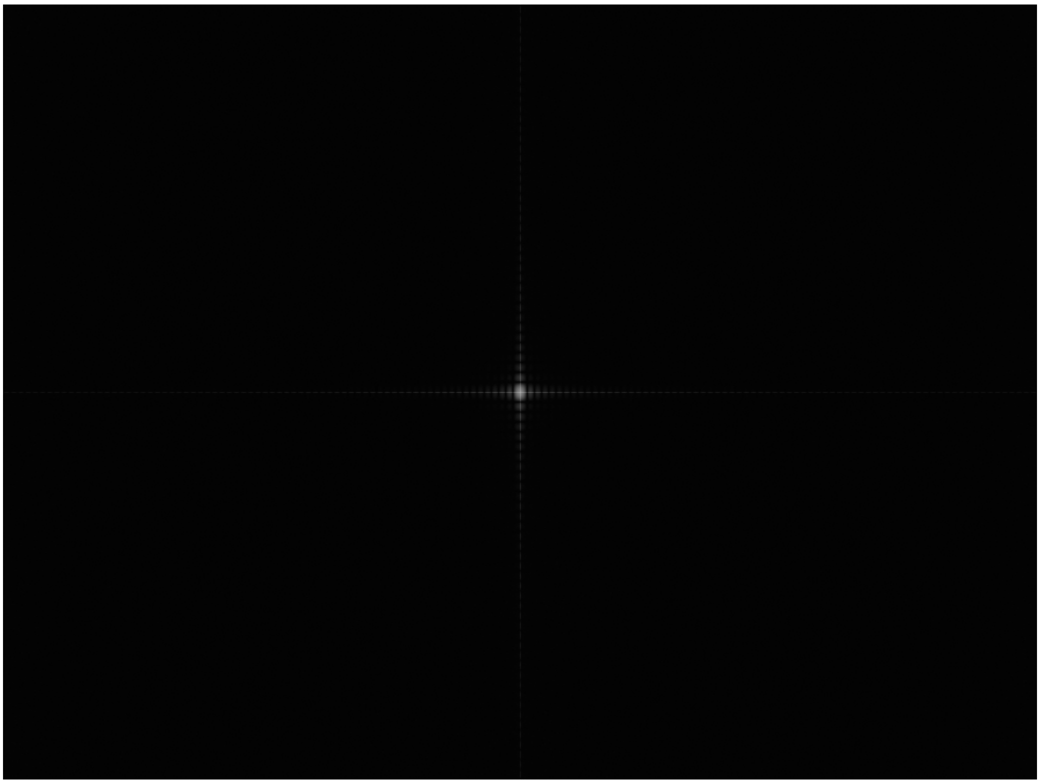
DFT of bias frame of a Canon EOS 7D

The DFT for the Canon 7D Mark II confirms that this camera is better than its predecessor in terms of PRNU. There's is more "energy" in the central spot, while lines are dimmer, meaning that the intensity of bands is lower. In addition, the central horizontal line is very dim, meaning that residual banding is mainly horizontal.



DFT of bias frame of a Canon EOS 7D Mark II

The DFT of the bias frame of the QHY163M confirms *in toto* the visual examination: the central spot is extremely lighter than its surroundings, as it should be in the ideal case where the bias is a pure constant.



DFT of bias frame of a QHY163M

In summary, the performance of the QHY163M appears to be excellent from the point of view of the PRNU, which should translate in an excellent calibration of light frames. In addition, the readout noise is so small that bias calibration could be unnecessary. Of course, this is a subjective consideration, that depends on the level of perfection you're looking for and how much time you are prepared to spend in post-production.

SUMMARY

FINAL VERDICT

Thirty pages and I only scratched the surface. There is much more to be said about the QHY163M, starting from the very good construction to the finest details, such as the heater on the glass window to prevent dew. Don't forget that this camera doubles as a planetary camera, that can reach very high frame rates, such as 100 fps at 800x600 pixels. But you can find that sort of information on QHYCCD website and in the several reviews that have been published thus far, along with some spectacular images shot with this camera.

The QHY163M and her CMOS sisters that are entering the market would deserve an in-depth discussion about how they could revolutionize astrophotography by allowing to apply high-res techniques to DSO imaging (a lot of short exposures instead of a few long exposures). But that would take too long for this document and you can find excellent discussions elsewhere (see also the links below).

The most important thing to say is that I fell in love with this camera after the first light frame (for the record, a 10-min Ha image of Veil nebula). All the specs are in line with the manufacturer's claims and with the results of other reviewers. Read noise, linearity and dynamic range are nothing less than excellent, an outstanding result for a camera that costs just 1,259 US$. Dark noise is not top of the notch, but it is fully under control. Amp glow is noticeable with long exposures, but it calibrates very well, and it is nothing to be concerned of.

The bottom line is that the QHY163M is a product that I don't hesitate to recommend to all astrophotographers looking for a mid-sized sensor and a perfect fit for all DSLR users which are tempted to move to a more performing camera. If you used a DSLR, you will feel at home with the QHY163M, as it works according to similar concepts. At such a low price, modding a DSLR instead of purchasing a QHY163M is non-sense.

RESOURCES

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REFERENCES

For a comparison between CMOS and CCD technology in astrophotography, including some test on the QHY163M:

★ Christian Buil
CMOS vs CCD
http://astrosurf.com/buil/CMOSvsCCD/index.html

For an in-depth look to sensor performance metrics and analysis some useful sources are:

★ Junichi Nakamura (Ed.)
Image sensors and signal processing for digital still cameras
2006 Taylor & Francis

★ Emil Martinec
Noise, Dynamic Range and Bit Depth in Digital SLRs
University of Chicago - http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/

★ QSI
Understanding CCD Read Noise
http://www.qsimaging.com/ccd_noise.html

★ R.I. Hornsey
Part III: Noise in Image Sensors
University of Waterloo

The following resource is available only in Italian language:

★ Mauro Narduzzi - Skypoint Srl
CMOS contro CCD. Fine di un'era?
https://www.skypoint.it/it/blog/20-cmos-contro-ccd-fine-di-un-era-pt-1

My free e-book about noise in image sensors, addressed to all photographers with some bonus for astrophotographers (Italian only, sorry):

★ Alessio Beltrame
Rumore e sensibilità ISO nei sensori di immagine
http://www.alessiobeltrame.com/il-negozio/

Finally, my first image with the QHY163M:

(view it on astrobin)