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Contents

This document explores different sets of on-board calibration procedures for the NISP dark current map measurement, based on possible implementations in the mission and identifies the corresponding calibration modes and the impact on the mission time. We derive advantages and drawbacks of the different solutions. This comparison will help for the preparation of the calibration and characterization plans of the detectors.

1 Introduction and goal

In this paper, we study what is the best strategy to correct and calibrate the dark current noise in the NISP science images. The required dark current correction must be performed to an accuracy of 0.4% for photometry and 7% for spectroscopy which is equivalent to a 0.5 e^- and 1 e^- calibration error for typical low flux in science images.

Traditionally, long dark images are taken during the mission monthly using the same readout and exposure scheme than science images. The dark should be also long enough to not be dominated by the readout mode and required to have a closed shutter.

A possibility to save calibration time is to take shorter dark images using slews of the satellite. Typically, slew will take 150 to 300s, a time significantly shorter than the spectroscopic exposure time, currently set to 560s. Then, as it is not a typical implementation, we have explored the impact of using short dark images for the spectroscopic mode on both readout mode and needed mission time.

2 Overview of readout mode definitions

The readout strategy for the NISP detector is based on particular readout modes: the photometry channel uses a *Fowler-16* mode with typical exposure time below 100s and the spectroscopic mode use a *multi-4×37* mode in 560s. In this section, we recall basic detector readout mode definitions. Table 1 recalls the definition of the terms that will be used throughout this document.

2.1 Multiaccum, Up The Ramp and Fowler modes

The NISP baseline readout mode is the so-called *multiaccum* scheme in which m frames are averaged in each of the n groups of an exposure.

Figure 1 displays typical sampling modes. Each group is the result of averaging frames. The *multi-*$m \times n$ notation is used to designate a readout mode made with n groups, each containing m averaged frames. The time difference between frames is called dt_{frame} while the time difference between groups is set to dt_{group}.

The integration time is $m \times dt_{frame}$ higher than the exposition time and depends on the size of the group. In an UTR mode, integration time and the exposure time are quite identical. It will not be the case in a *Fowler* one or in a *multiaccum* where the number of frames per group m is large (m¿10). For this case, we use the integration time of 565s as a limitation.

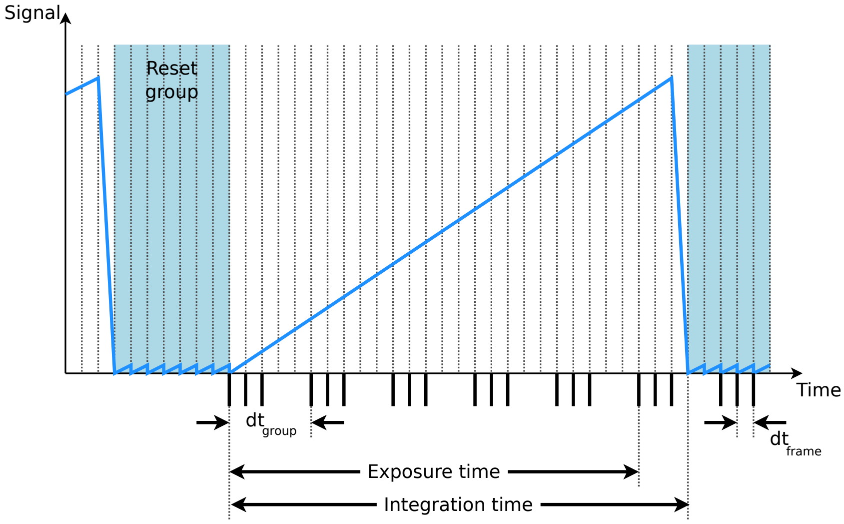
Then, the *multiaccum* parameters are set to satisfy the condition

$$n \times m < \frac{t_{expo}}{dt_{sample}}$$

Table 1: Usefull definitions

Term	Definition
frame	the result of clocking and digitizing all pixels in a rectangular area of the SCA.
group	one or more consecutively read frames. There are no interleaving resets. Frames may be averaged to form a group.
exposure	the final result of a given period of time during which the signal is non-destructively sampled after a reset. An exposure is defined by a proper integration time and exposure time.
integration time	the total time to take all frames (from first one to last one).
exposure time	the time during an exposure spent accumulating the signal from a source. The exposure time is the time difference between the first sample in the 0th group and the first sample in the last group (overhead associated with finishing last group is excluded).
read	the act of clocking and digitizing pixels in a detector.
readout noise by pixel	read noise is the uncertainty in the measurement of charge in a pixel. Contributions to read noise include: shot noise in FETs, Johnson noise, (resistive elements), drifts in references (ground) voltages, settling effects...
dark by pixel	the portion of the signal that accumulates in the absence of exposure to light.
total noise by pixel	total noise per pixel is the uncertainty in measuring the charge in a pixel. It is the variance of n measurements taken on a given pixel during n different *dark* exposures. Each of the n measurements is the result of least square fitting m samples taken in *multi-*$m \times n$. The contributions to the total noise include multiple components such as read noise, shot noise on integrated dark current, shot noise from amplifier glow, 1/f variations, electronics and cable noise, clocks and bias stability, etc..
CDS by pixel	the "Correlated Double Sampling" readout mode provides straightforward removal of chip bias effects, due to the fact that the array is typically read once at the start of an exposure and again at the end of an exposure. The single read noise is then the noise of one frame.

Figure 1: Diagram example of the *multiaccum* readout mode sampling (multi-3×6)



where t_{expo} is the exposure time, which does not depend on the size of the group.

The *Up The Ramp* readout mode (UTR) is a particular case of the *multiaccum* readout mode, where the number of frames per group is set to one. Then, the time difference between two successive frames (dt_{frame}) depends of the number of reads per exposure. It can not be lower than the time required to read out the array continuously which is $\mathrm{dt}_{sample} = 1.31$s for the NISP instrument using a 100kHz clock.

3 Noise simulation in an UTR mode

3.1 Simulation method

To evaluate the impact of the readout and dark noise on different exposures, we use a simplified simulation where exposures are generated with Up The Ramp reads in the adequate number (typically $\sim 80 - 250$). For that, we need to introduce the concept of single read noise: the single read noise will be derived from the observed *Fowler* noise in the maps provided by Teledyne, as this takes into account implicitly the 1/f effects for similar exposure times (2 groups of 16 samples, 339 seconds apart, 10.6 s/frame in the Teledyne data).

The single read noise is then assumed to be given by:

$$\sigma_{1read} = \frac{4. \times \sigma_{Fowler-16}}{\sqrt{2}}$$

The read noise is then expected to decrease as the squared root of the number of reads. Then, the CDS readout mode being composed of two groups of one frame each:

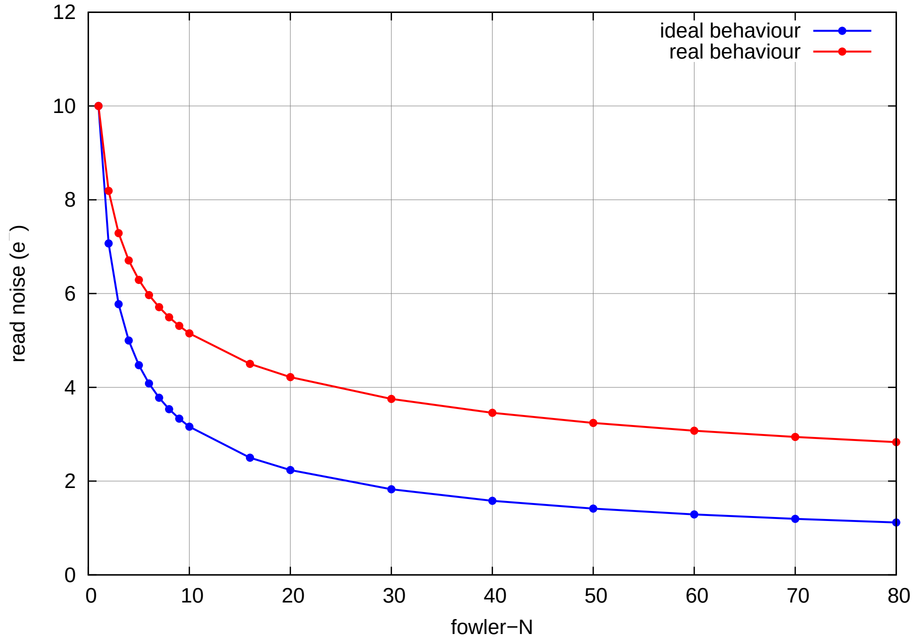
$$\sigma_{1read} = \frac{\sigma_{CDS}}{\sqrt{2}}$$

In fact, this ideal behaviour is degraded by an interread periodicity dependant noise. To take into account this so called 1/f noise effect, we derive the single read noise to be given by:

$$\sigma_{1read} = \frac{1.8 \times \sigma_{CDS}}{\sqrt{2}}$$

where the 1.8 factor is obtained by scaling the noise spectrum of a detector. For example, a real detector with a CDS noise of 10 electrons and a 1/f noise is equivalent to an ideal one with a CDS noise of 18 electrons and no 1/f noise. This more realistic behaviour is then normalized to 10 electrons of CDS noise, as shown in figure 2, and simulated like that.

Figure 2: 1/f effects on the single read noise: read noise σ_{1read} input of the number of frames in a *Fowler-N* mode



For each simulated exposure, the set of measured values is adjusted with a straight line, which slope a is expressed in electron/s. The standard deviation δa over all straight lines is evaluated from the 10000 ramps and the measurement noise over the exposure is defined as:

$$N_{noise} = T_{expo} \times \delta a$$

δa depends on the readout mode. The number of reads is then adjusted to the exposure time, without trying at this stage to mimic the actual multiaccumulation ramp of EUCLID. Some examples of the number of reads as a function of the exposure time are given in table 2, for a *Up The Ramp* readout mode.

While the minimal time between successive read frames is $\mathrm{dt}_{sample} = 1.31\mathrm{s}$ for the NISP instrument, the number of reads is also constrained by the frame processing time, which justifies this table.

Table 2: Exposure times and number of reads

Exposure time T_{expo}(s)	Nb of reads (UTR)
300	80
560	150
1000	250
1500	400

The dark current variation is simulated by superposing a stochastic fluctuation between each consecutive read to the expected dark current. In order to save computing time, an uniform distribution has been substituted to the actual Poisson distribution, ensuring that both have the same standard deviation.

Then the number of exposures N_{expo} needed to achieve a calibration level from the standard noise is given simply by:

$$N_{expo} = \frac{N^2_{noise}(560s)}{\sigma^2_{calib}}$$

where σ_{calib} is here chosen to be 0.5 or 1 electron and $N_{noise}(560s)$ is the expected noise, scaled to a 560s science exposure.

Using this method, we can provide at the same time:
- the noise affecting a single exposure,
- the calibration error on the dark in a single calibration exposure with the standard deviation as defined by the quoted parameters.

The current requirement is of $N_{noise} = 9$ e$^-$ total noise on spectroscopic mode (in 560s) with a typical dark current < 0.1 e$^-$/s but these are *mean* values and more realistic experimental conditions are needed to really assess the impact on calibration.

We will then do studies to define the total number of 300s calibration exposures in different detector conditions:
- simple UTR cases and fixed mean noises (total, CDS and dark current),
- simple UTR and more realistic detector noise parameters.

In the next section we will also study a realistic *multiaccum* simulation.

3.2 Simulation results for simple UTR

First, typical noise values will be taken. We make simple simulation using a dark value of 0.1 e$^-$/s and different CDS noise values with 560s exposure time (UTR150) for a calibration at the 1 e$^-$ level. Results are reported on table 3.

Table 3: Measurement error in a single 560s exposure (UTR150) with a dark current of 0.1 e^-/pix/s

CDS noise σ_{CDS} (e)	*Fowler* noise σ_{Fowler} (e)	Single read σ_{1read} (e)	Total dark N_{dark} (e)	N_{noise}(560s) 1 exposure (e)	N_{expo} (σ_{calib}=1 e^-)	Total time (s)
8	3.6	10.18	56	8.756	76	42560
9	4.05	11.45	56	8.727	76	42560
10	4.5	12.72	56	8.854	78	43680
12	5.4	15.27	56	9.116	83	46480
15	6.75	19.09	56	9.705	94	52640
18	8.1	22.91	56	10.287	105	58800
22	9.9	28.00	56	11.335	128	71680
24	10.8	30.54	56	11.860	140	78400

If we want to stay in the $N_{noise} < 9$ e^- limit with a one electron error, we depend hardly of CDS value (because dark value is fixed).

Then we calculate the impact on a 300s exposure in table 4 for 300s exposures (adjusting an UTR80 readout). What is relevant in this case is the error scaled to the same image time of 560s, which is obtained using the following expression:

$$N_{noise}(560s) = \frac{560}{300} \times N_{noise}(300s)$$

Table 4: Measurement error in a single 300s exposure (UTR80) with a dark current of 0.1 e^-/pix/s

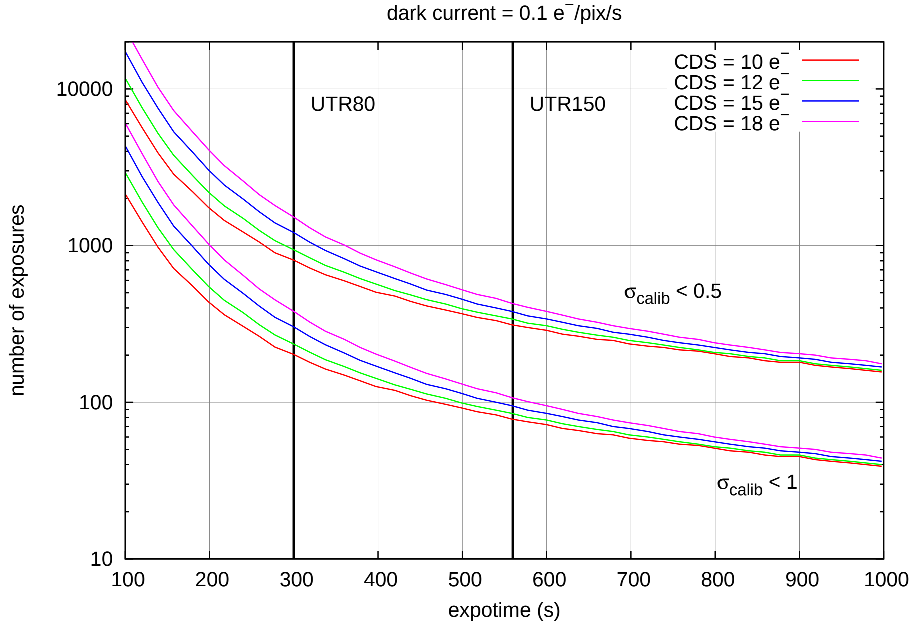
CDS noise σ_{CDS} (e)	Total dark N_{dark} (e)	N_{noise}(300s) 1 exposure (e)	N_{noise}(560s) (scaled) (e)	N_{expo}(300s) (σ_{calib}=1 e^-)	Total time (s)
8	30	7.08	13.22	174	52200
9	30	7.32	13.67	186	55800
10	30	7.60	14.19	201	60300
12	30	8.25	15.41	237	71100
15	30	9.33	17.42	303	90900
18	30	10.41	19.44	377	113100
22	30	11.99	22.39	501	150300
24	30	13.03	24.33	592	177600

With this simple exercise, we see that the cost in total time of 300s exposures is of a factor 2 (180000s instead of 78000s), having however the merit of fitting in the slewing time and not mission time.

We generalize these results in figure 3 by a set of curves showing the total time needed for reaching the two values of σ_{calib} of 1 e^- and 0.5 e^-, using a dark current of 0.1 electron/pixel/s and a

CDS noise from 10 to 18 electrons. This Figure includes the numerical values given in tables 3 and 4.

Figure 3: Total number of exposures versus one exposure time to obtain a given calibration error



We notice that in the case of 150s calibration exposures, the total number of exposures needed to obtain a given σ_{calib} is about five times larger than in the case of 300s exposures.

3.3 UTR Noise simulation results for typical detector noise

To be able to test the margin we have in these numbers, we have simulated a more realistic phase space of detector noise parameters from what we learnt from Teledyne distribution.

In the following, the UTR80 read mode (300s exposure time) is used as the calibration mode while the resulting calculated noise is extrapolated to a UTR150 mode (560s exposure time), the science one.

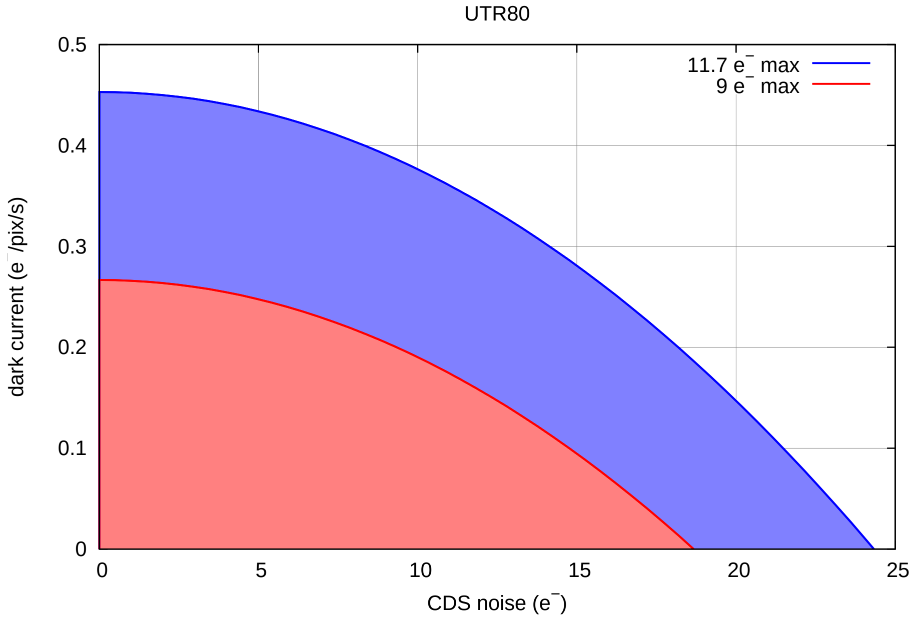
A phase space is defined from the Teledyne detectors specifications with the following assumption:
- the mean total noise of the pixels is 9 electrons,
- 98% of the pixels have a total noise lower than 130% of the mean value.

This translate in:
- 50% pixels will be borne out by $\sqrt{N_{dark} + RN^2 + \sigma_{calib}^2} < 9\ e^-$
- 98% of pixels will follow $\sqrt{N_{dark} + RN^2 + \sigma_{calib}^2} < 11.7\ e^-$

where RN is the read-noise, derived from the CDS one and depending of the number of reads per exposure.

This phase space is shown in figure 4.

Figure 4: Phase space definition for given total noises



Out of the area delimited by these curves, it is not possible to reach a total error lower than 9 or 11.7 electrons, regardless of the number of exposures. For example, if the CDS noise is equal to 15 electrons, the dark current has to be lower than 0.08 e^-/pix/s to obtain a total error lower than 9 electrons, after an adequate number of exposures.

At the border of the allowed phase-space, we can now estimate the number of exposures needed to reach a given value of σ_{calib} as a function of the values of the CDS noise and of the dark current. That is the purpose of figure 5 in which the CDS noise and the dark current are chosen such that the total noise is 9 electrons. Three curves are represented on this pictures:

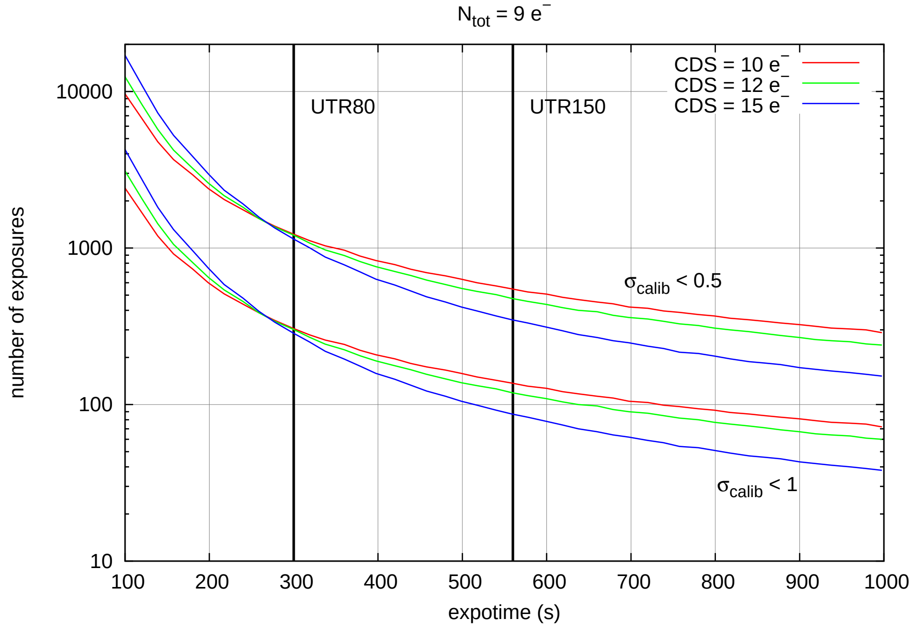
- $\sigma_{CDS} = 10$ e^- and dark current = 0.188 e^-/pix/s,
- $\sigma_{CDS} = 12$ e^- and dark current = 0.153 e^-/pix/s,
- $\sigma_{CDS} = 15$ e^- and dark current = 0.089 e^-/pix/s.

As the curves are not superposed, the number of exposures depends not only on the total noise but also on the values of the dark current and CDS noise, individually. Note also that the curves are crossing for an exposure time of about 270s. That means that under this value, the total noise is dominated by the CDS one, while the dark current is dominant above it.

3.4 Number of 300s exposures for different dark currents and CDS noises

To explore all solutions, we fix now the exposure at 300s and we vary the CDS noise and dark current. The number of exposures needed needed to reach a calibration error of 1 e^- or 0.5 e^- on each pixel are shown in figure 6 as a function of the CDS noise (extrapolated to an UTR150 read mode). Similarly, the number of exposures for various CDS noises are also shown in figure 7 as a function of the dark current.

Figure 5: Total number of exposures versus one exposure time to obtain a given calibration error



The '+' signs give the limits below which the total noise is lower than 9 electrons. Similarly, the '×' signs give the limits below which the total noise is lower than 11.7 electrons.

As shown in these pictures, the number of exposures needed to reach a given total noise depends quadratically on the expected calibration error, but not so hardly on the dark current and CDS noise, since the signs representing each limit have about a same ordinate.

4 The *multiaccum* readout mode

In this section, we study the impact of the *multiaccum* mode to see what can be the best implementation for a calibration time of 300s.

Note that in the case of an exposure time of 300s, the integration time should now be adjusted to be:

$$t_{expo} = t_{integration} - m \times dt_{frame}$$

as illustrated by figure 1.

Of course the effect is negligible for previous UTR readout mode and that does not change any conclusion in the beginning of the document, but is higher when the number of frames per group is large, and has to be taken into account for all *multiaccum* readout mode. So, in what follows, the integration time is fixed and the exposue time can vary depending of the used readout mode.

Figure 6: Number of exposures of 300s for various dark currents as a function of CDS noise

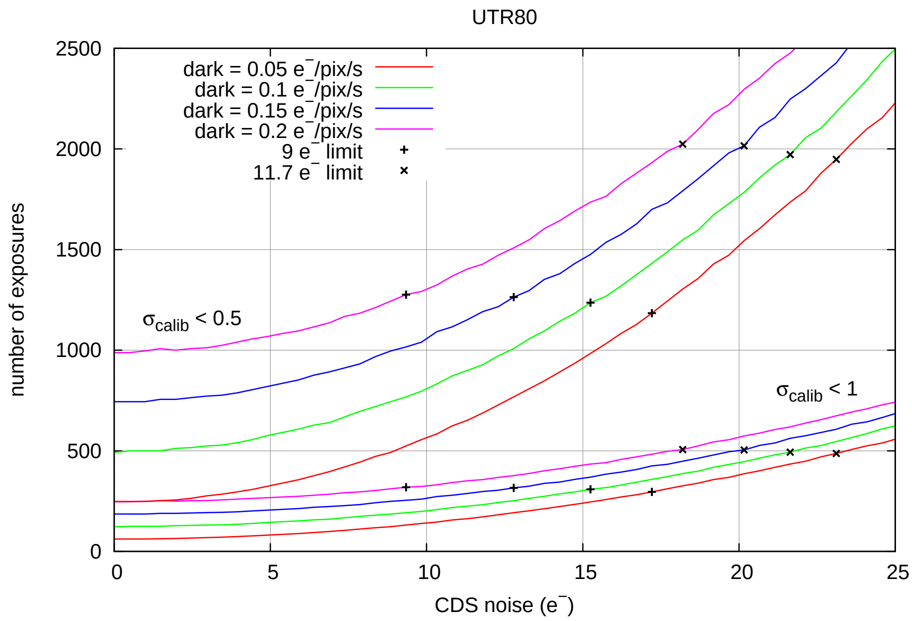
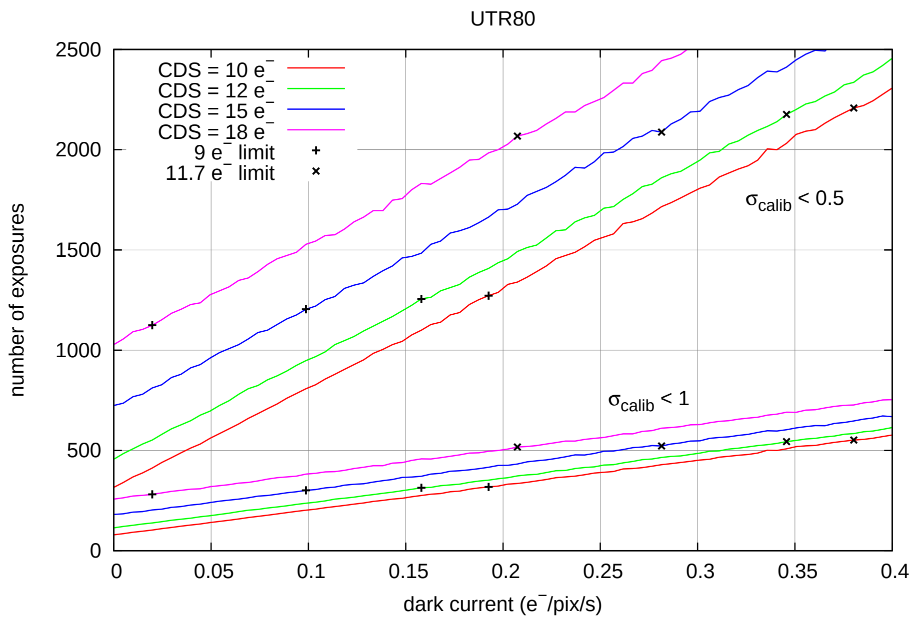


Figure 7: Number of exposures of 300s for different CDS noises as a function of dark current



4.1 Influence of n and m, individually

In the case of an integration time $t_{integration} = 300$s and a sampling time $dt_{sample} = 1.31$s, n and m are constrained to $n \times m < 230$ to verify the equation:

$$n \times m < \frac{t_{integration}}{dt_{sample}}$$

Each of the two parameters is fixed in turn to a value varying from 2 to 15. The other parameter is then borne out by the previous equation.

A set of resulting simulations is shown in table 5. The number of required exposures is presented as a function of number of the groups and frames in table 5, as well as in figures 8 and 9.

Table 5: Measurement error in a single 300s exposure with a dark current of 0.1 e^-/pix/s and a CDS noise of 15 electrons

Groups n	Frames m	Total dark N_{dark} (e)	Noise (300s) 1 exposure (e)	Noise (560s) (scaled) (e)	N_{expo} (σ_{calib}=1 e^-)
2	2	30	17.47	32.61	1063
2	5	30	12.67	23.66	559
2	10	30	9.92	18.52	342
2	15	30	8.70	16.24	263
5	2	30	16.29	30.40	924
5	5	30	11.80	22.03	485
5	10	30	9.31	17.38	302
5	15	30	8.27	15.43	238
10	2	30	13.75	25.67	659
10	5	30	10.04	18.75	351
10	10	30	8.25	15.40	237
10	15	30	7.51	14.02	196
15	2	30	12.24	22.84	521
15	5	30	9.10	16.99	288
15	10	30	7.62	14.23	202
15	15	30	7.07	13.19	174

It is seen that (as expected) the calibration error decreases when the number of reads is increased. We will now have a look on the influence of the repartition of the number of groups and frames for a given total number of reads.

4.2 Defined number of reads

The goal of this section is now to fix the total number of reads to verify that the decrease of the noise is dominated by the increases of the number of frames per group, as suggested by pictures 8 and 9.

As shown in the previous section, the total noise decreases when the number of reads is higher. This effect is available both for a higher number of groups n or a higher number of frames per group

Figure 8: Number of exposures for different frames numbers m as a function of groups number n

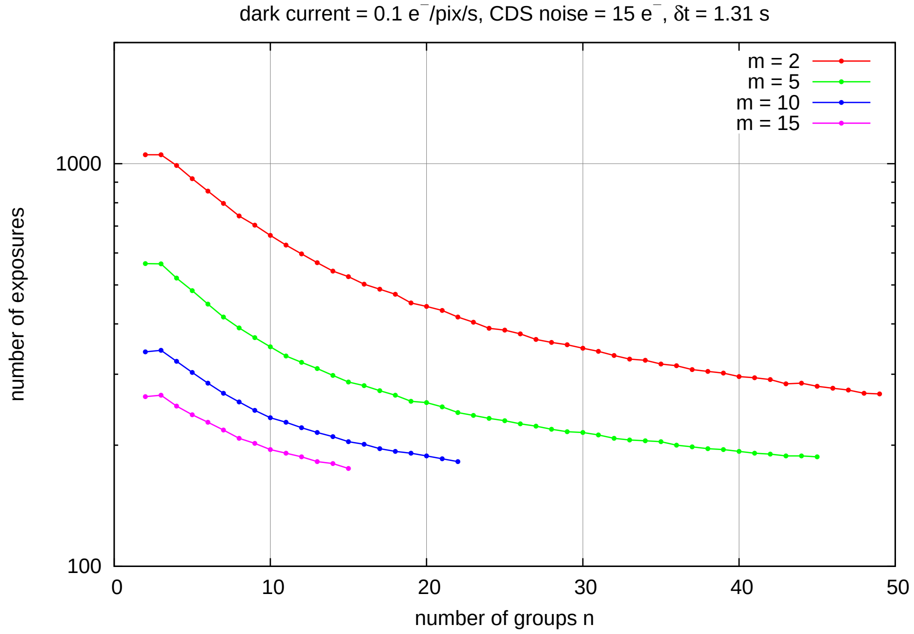
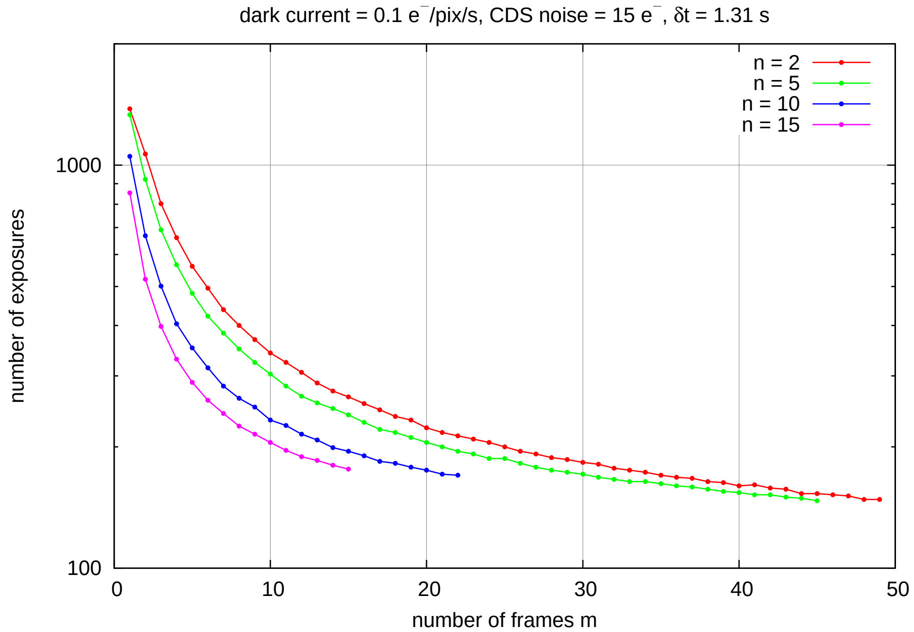


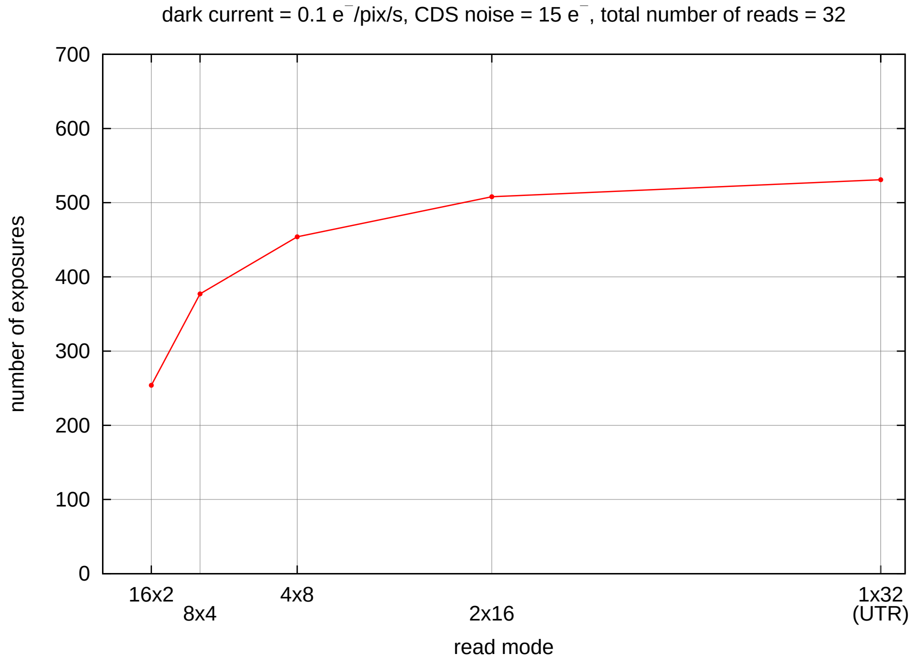
Figure 9: Number of exposures for different groups numbers n as a function of frames number m



m.

Thus, the total number of reads is set to a fixed value, chosen here to be 32, and the number of exposures needed to reach one electron of calibration error in different readout modes is drawn on figure 10. The 32×1 readout mode coresponds to a UTR32 one, while the 16×2 readout mode is equivalent to a *Fowler-16* one.

Figure 10: Number of exposures for different readout modes



This figure suggests that higher is the number of frames per group, lower is the resulting noise. This effect dominates the lower number of groups recorded in this case. Thus, for a total of 32 reads, the noise is lower with 16 frames per group.

That what is also illustrated by tables 6 and 7 and figures 11 and 12 corresponding to 300s and 560s exposures respectively.

The noise reduction is very powerful when the number of frames per group is large and increases slowly when the number of groups is large enough. Anyway, the *Fowler* mode has always a lower noise than the *UTR* one.

5 Conclusion

As shown in this document, it seems possible to implement a *Fowler-16* readout mode during the slew times to save calibration time, having the merit of being the same mode as the one used by the photometry channel.

Table 6: Measurement error in a single 300s exposure with a dark current of 0.1 e^-/pix/s and a CDS noise of 15 electrons

Groups n	Frames m	Noise (300s) 1 exposure (e)	N_{expo} (σ_{calib}=1 e^-)
2	40	6.39	142
4	20	7.68	205
5	16	8.01	223
8	10	8.51	252
10	8	8.68	262
16	5	8.92	277
20	4	9.04	284
40	2	9.24	297
80	1	9.33	303

Figure 11: Number of exposures for different readout modes (t_{expo} = 300s)

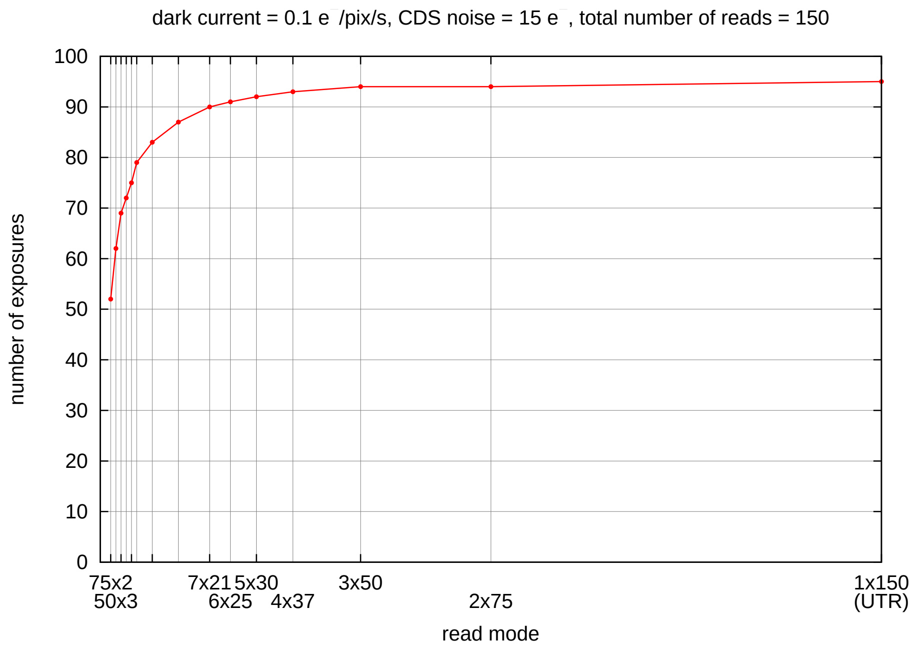
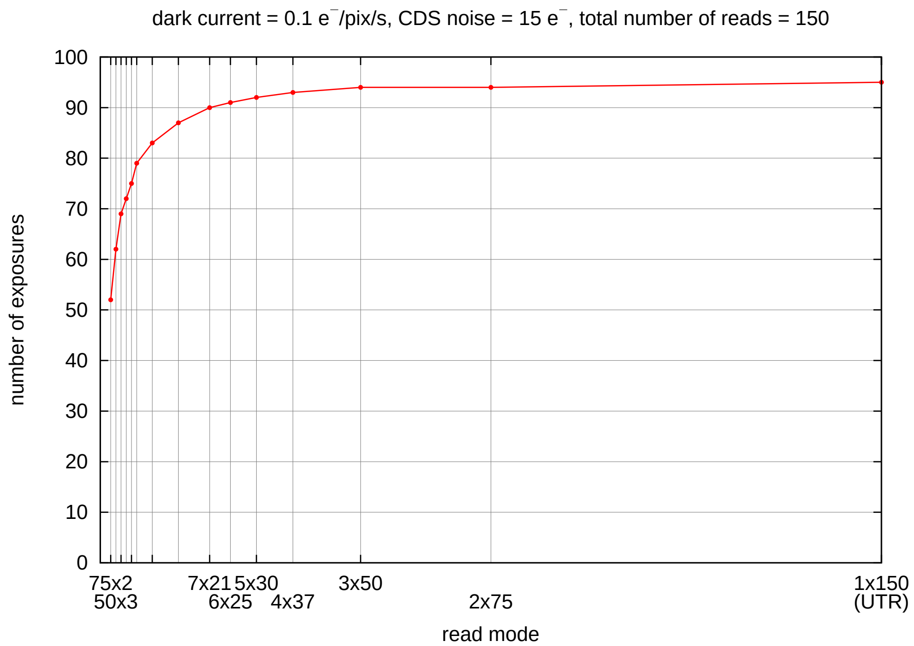


Table 7: Measurement error in a single 560s exposure with a dark current of 0.1 e^-/pix/s and a CDS noise of 15 electrons

Groups n	Frames m	Noise (560s) 1 exposure (e)	N_{expo} (σ_{calib}=1 e^-)
2	75	7.27	52
3	50	7.93	62
4	37	8.28	68
5	30	8.56	73
6	25	8.69	75
7	21	8.92	79
10	15	9.13	83
15	10	9.32	86
21	7	9.49	90
25	6	9.53	90
30	5	9.55	91
37	4	9.62	92
50	3	9.67	93
75	2	9.68	93
150	1	9.76	95

Figure 12: Number of exposures for different readout modes (t_{expo} = 560s)



This way, common dark exposures could be used both for photometry and spectroscopy images. However, to reach a calibration error lower than one electron for the spectrometry channel:

- 247 exposures of 300s are needed (corresponding to 74100s calibration time),
- 781 exposures of 150s are needed (corresponding to 117150s calibration time).

Note also that 1/f effects have been introduced here to realistically reproduce the real behaviour of the detector but are not exact, even if that should not have a large impact on these results.