

NOTCam Hawaii readout modes for the new controller

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1 Introduction

Some extra functionality is desired from the new CUO array controller to improve the performance of NOTCam and optimise the readout performance of the Hawaii-1 detector. These requests are as a result of reading the literature and from experience gained from using NOTCam. Some new commands are asked for to provide a more versatile operation, though they typically only require making the existing readout modes used in the present controller more flexible. In all cases what is needed is either the splitting up of the normal readout commands or the rearrangements of a command, rather than the development of new features.

2 Current status

There are two basically different readout modes available in NOTCam at present: the *reset-read-read* mode and the *ramp-sampling* mode (see Fig. 1). Both of these are simple versions of the more general Fowler sampling mode, see [2]. The NOTCam data acquisition system, described in detail by [3], currently consists of three main exposure commands:

- **exp, dark**

These take one argument which is the exposure time t in seconds. They use the so-called *reset-read-read* readout mode. The only difference between the two is the opening of the shutter for **exp**. As the name of the mode indicates, the array is reset, immediately read, then waits t seconds, then reads again. The difference between the two raw readouts gives the resulting image. Currently, what is stored in a file is the following: 1) the “reset-subtracted end-of-integration” readout and 2) the reset readout.

- **mexp, mdark**

These are multiple versions of the above mode. They take the two arguments time t and number N . For each of the N multiple exposures an

image file is made to contain, as above: 1) the “reset-subtracted end-of-integration” readout and 2) the reset readout. In addition, an average image of all the N images is stored in an additional file.

- **frame, dframe**

These commands use the *ramp-sampling* mode, a mode that takes advantage of the non-destructive read of infrared arrays and reads the array multiple times while integrating, see Fig. 1. Again the two arguments are t and N , and the command starts by resetting the array and reading the reset image. But now t is the time between each readout (required to be larger than the readout time) and N refers to the number of readouts, such that the total exposure time is $t \times N$. A linear regression analysis is made (per pixel) through all raw images (also the reset image) and the resulting image (i.e. the slope multiplied by the exposure time) is stored as the first image in the data file. Then all the individual readouts (but now reset-subtracted) are stored, and at last, as the $N + 2$ nd image the reset readout is stored.

These commands have been in use since June 2001, only slightly upgraded with bug fixes and improved user-friendliness in March 2002, as well as the addition of a **clear** command plus documentation in 2006. Some problems and undesirable features with the NOTCam have been pointed out. It is expected that all of the following short-comings will be solved with the new controller:

- The lack of a functioning **abort** command to interrupt an ongoing exposure.
- The long readout time of 3.6 sec per frame leading to a minimum of **7.2 sec** per useful image, to be compared with **1.68 sec** for Omega-Cass/CalarAlto, or **2 sec** for LIRIS/WHT.
- The first column of each quadrant being unreadable by the controller, leading to the appearance of a **dead column** across the whole center of the array (plus one at the edge, of less importance).

In addition to this, infrared arrays have inherent features that are different to CCDs, and there is room for improvement both in terms of noise and systematics (such as for instance the Reset Anomaly), as well as in the data saving philosophy. In the following we describe current weaknesses and some suggested ways to make improvement. This requires only very minor modifications at the controller end, mainly consisting in splitting up currently available commands in smaller subunits, and thereby allow for composing exposure commands. In addition, more flexible data saving options will be needed as the short readout time with the new controller in principle will allow for much higher data rates.

3 Noise reduction

Ramp sampling (see Fig. 1) would usually be used for ‘short’ integrations of up to a few minutes, but for integrations of typically 600 seconds or more the so-called Fowler sampling (see Fig. 2) is preferred, where you take many samples

only at the beginning and end of the integration. The slope for the Fowler sampling is calculated from the average of all the Fowler pairs, i.e. assuming 64 samples 1st and 33rd pair, 2nd and 34th pair etc. The integration time is then the separation of the pairs rather than the total period.

Fowler sampling would also be used if only a few samples are to be taken.

For the limiting cases, first for ramp sampling where the integration is completely filled with nondestructive readouts, i.e. $T_{int} = nT_{read}$ the signal to noise ratio is given by equation 2. The other limiting case is for $T_{int} \gg nT_{read}$ the signal to noise ratio for this is given by equation 3.

- T_{int} - the total integration time
- T_{read} - the readout time (typically 1s)
- n - number of NDRs

The general equation describing Fowler sampling is:

$$SNR_{sample} = SNR_{dc} \sqrt{\frac{n(n+1)}{6(n-1)}} \quad (1)$$

SNR_{dc} is the signal to noise ratio of a single double correlated read.

For ramp sampling:

$$SNR_{ramp} = SNR_{dc} \sqrt{\frac{n}{8}} \quad for \quad T_{int} = nT_{read} \quad (2)$$

and for Fowler sampling:

$$SNR_{fowler} = SNR_{dc} \sqrt{\frac{n}{2}} \quad for \quad T_{int} \gg nT_{read} \quad (3)$$

for $n \gg 1$ SNR_{ramp} is better by $\sqrt{8/6}$ than SNR_{fowler}
for $n \gtrsim 1$ SNR_{fowler} is better by $\sqrt{3}$ than SNR_{ramp}

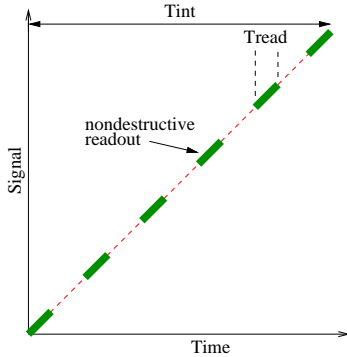


Figure 1: Ramp sampling

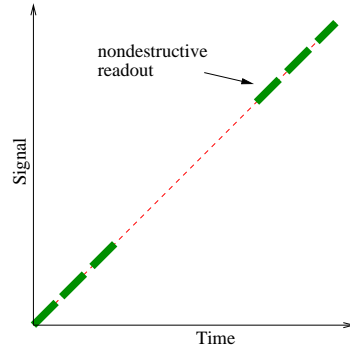


Figure 2: Fowler sampling

Due to serial shift register glow a maximum of 64 NDRs [1] will give a minimum readout noise (e.g. $6e^-$). For long integration (e.g. $>600s$) then $T_{int} \gg nT_{read}$ holds and Fowler sampling should be used. For the intermediate case of either *ramp-sampling* with a period between reads or an integration of $<600s$ for *fowler-sampling*, and depending on the amount of glow from the serial register we have, the preferred readout mode needs to be determined.

4 Sub-pixel sampling

Another method to reduce noise [1] is to take multiple samples of each video level of a single pixel read, with the resulting value being the average of all the sub-pixel readings. This will actually be done due to the way the new controller works!

5 Reset Anomaly

As a result of the detector reset, the signal from the array is very non-linear as a function of time. Two methods are suggested for reducing the Reset Anomaly. One proposed by Yanagisawa [4] is to do a modified read sequence which requires doing a number of resets or a single long reset, then a number of NDR without digitisation, integrate, do more NDR without digitisation, then the actual read. The other, described in [1] is to substrate a dark frame of equal length to the science frame. Alternatively, since this feature is related to resetting of the array, then simply do not reset if the signal is sufficiently low.

Just to clarify what an actual reset is, a line is reset then read, move to the next line reset and read etc, rather than reset whole array, read whole array. For the Hawaii array it is not possible to reset an individual pixel.

6 Shutter

With a fast readout you probably don't need a shutter. Some options are available to do this, one is simply to disconnect the shutter cable and leave the shutter open or more elegantly have a command to "disregard" the shutter (leaving it either open for exposures or closed for darks). For instance the command could be called **set-shutter** and take one argument that would be either **active**, **open** or **closed**, the first one being the default mode where the shutter is operated as normal, the latter two being the disregard shutter mode, where it is left passive either open or closed. Such a command should be sticky.

It should be mentioned that although one would like to be able to bypass the shutter, in principle, the shutter allows NOTCam users to use shorter exposures than the readout time, which is not normally the case for near-IR instruments.

7 The Commands requested

The two basic readout modes available with the present system, and asked for in the “Detector Controller User Requirements” document for the new controller, are *Reset-Read-Read* and *Ramp-Sample* (Frames). It is desirable to make both of these modes more flexible for the aim of obtaining lower read noise and cleaner images.

It is also requested that it is possible to implement “Fowler Sampling” [2], see Fig. 2, of which both *ramp-sampling* (**frames**, **dframes**), see Fig. 1 and *reset-read-read* mode **exp**, **dark**, **mexp**, **mdark** command are variants. The Fowler sampling readout mode is to take a number of samples during an integration but to concentrate them at the beginning and end of the exposure. This compares with the **frames**, **dframes** commands where the reads are evenly distributed over the integration or the *reset-read-read* mode (**exp/mexp**, **dark/mdark**) where only one sample at each end of the integration is made.

Other requested commands are **reset**, **mreset** to implement a proper **clear** command. The **fowler**, **reset**, **mreset** and/or **clear** commands should be Sequencer commands. Regarding the **reset** command it would be advantageous to make it with a length parameter, so its period can be changed.

In addition another controller level command is desired, non-destructive read (NDR) without digitisation. This would be a fast read since no data saving is done and would be used to investigate a proposed method [4] of reducing the so-called “Reset Anomaly”, see above, and is executed within a normal read without returning to Sequencer level. The idea is to do several NDR without digitisation after doing the resets but before reading the reset level and similarly more NDR without digitisation at the end of the integration, then the actual reading of the data. A sequencer command could be written to do all this.

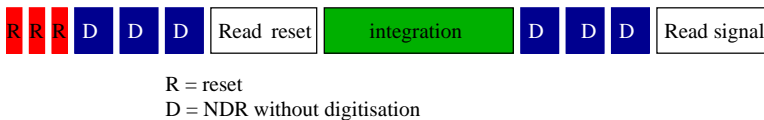


Figure 3: Example of ISLE [4] read scheme

It is hoped that with the new controller it will be possible to develop new features without the need to return to Copenhagen, i.e. we will be able to modify or even create commands if necessary. For example it could be desirable to implement the read without digitisation at the NOT since it is something extra requested and not essential for operational purposes.

8 Data storage

Some changes to the data saving and processing are also desired. As described in Sect. 2 for the basic *reset-read-read* mode only the reset readout and the

reset-subtracted end-of-integration image are currently stored. In very low-signal images, such as darks, the difference image between the two reads may occasionally have negative values. Because the images are stored as unsigned integers, the negative pixels in the difference image are wrapped around to very high values by having 65535 adu added to them. With the setup of the software for the new controller, we ask that for the basic *reset-read-read* mode the stored FITS file should consist of three extensions, the first being the the reset-subtracted image (as before), the second being the reset readout (as before) and the third being the raw end-of-integration readout. More specifically, for the **mexp**, **mdark** commands there is currently an average image made out of the N multiple exposures. Because the first exposure is usually quite noisy compared to the rest, it makes no practical sense to have this average image made, and we ask that it is taken away.

For the *ramp-sampling* readout, and the proposed *Fowler sampling* mode, it should be possible to save all the raw data frames.

As an example of the amount of data that can be obtained and consequently needs storing, for the limited case when the integration time is completely filled with reads and 64 samples are saved a 250 Mbyte file can potentially be taken in just over one minute! Though for normal use a period between reads will be used, to increase the integration time and probably not all the samples will be saved.

It is clear that for practical purposes, a flexible saving option is desirable, although the default should be to save all. Because the *ramp-sampling* mode involves linear regression analysis on all readouts, this calculation needs to be done before the final file is stored. As before, the resulting image from the linear regression analysis should be stored as the first image/extension in the file. Contrary to the current situation, however, all the other images, depending on what the user wants to store, should be stored as raw untouched images. (Currently, these are reset-subtracted.) Again, to keep the files similar to before, the reset readout should be stored as the last image/extension in the file.

Flexible storing options could be incorporated into the exposure command such as:

frames t N -s [1] — storing only the linear regression analysis image
frames t N -s [1,10-15,45-50] — storing the 1st, the 10th-15th and the 45th-50th image extensions

where if no **-s** option is given, the default is to save all, or alternatively the saving options could be incorporated with arguments to the sticky command **autosave_on**. In any case, the flexible storing options are not meant to apply for the *reset-read-read* modes (i.e. **exp**, **mexp**, **dark**, **mdark** commands).

The linear fitting should be done only in pre-processing. Alternatively (or additionally) a real-time fit could be done during the integration c.f. ESO, but all raw data should still be optionally saved. pre-processing here means the processing done before the final file is stored.

9 Overheads

In the setup of the requested commands, especially the sub-units of new exposure commands such as **reset**, **NDR without digitisation**, **integrate** etc., it is vital that overheads are taken into account. It is therefore not requested that these are sequencer commands (which add 1-2 second overhead compared to what was the old BIAS level), but that new exposure commands on the sequencer level can be made by combining these sub-units.

10 Conclusion

None of the suggested "new" commands are actually new, they all exist at the low controller level in one form or another, already. e.g. the reset command exists but is always included with a read, and the NDR without digitisation exist but only with the saving of the data. The Fowler sampling mode, though similar to the *Frames* command and the Reset-Read-Read does require some additional thought but is similar in operation to both. The proposed extra functionality will improve the performance of NOTCam making it capable of returning data with lower read noise and cleaner images.

In summary the new commands that are requested are:

1. **reset t** - single reset with an optional period parameter
2. **mreset N** - multiple resets
3. **clear** - This is basically a mreset or long reset
4. **fowler t N** Fowler sampling readout, where **t** is the exposure time, or the separation between pairs, and **N** is the number of readout pairs (see Fig. 2). Possibly flexible data saving options should be included.
5. **read-without-digitisation** Read a pixel, but do not digitise
6. **set-shutter status** A sticky command to set the shutter to a given status, either "active", "passive-open", or "passive-closed". This in order to bypass the shutter, if wanted.
7. **integrate** Starting an independent integration (without reset).
8. **abort** Abort an on-going exposure.

We also summarize the old commands for which new storage options are requested:

1. **exp, dark** Every file should have 3 extensions, the first contains the processed image (reset-subtracted end-of-integration), the second contains the reset readout, and the 3rd contains the raw end-of-integration readout.
2. **mexp, mdark** As above, every file should have 3 extensions. The extra averaged image file is not required.

3. **frame, dframe** The linear regression analysis result should (as before) be stored in the 1st extension. The remaining images should be stored, according to the flexible saving options, in their raw (unprocessed) format, single readouts first and the reset readout as the last extension.

References

- [1] G. Finger, *Performance of large format HgCdTe and InSb arrays for low background applications. Optical and IR telescope Instrumentation and Detectors*, SPIE Vol 4008 (2000).
- [2] A. M. Fowler, *Demonstration of an algorithm for read-noise reduction in infrared arrays*, The Astrophysical Journal, Vol 353:L33-34, 1990 April 10.
- [3] J. Klougart, *Description of basic differences in BIAS and NOTCam BIAS*, www.not.iac.es/instruments/notcam/notcamBIAS.html (2006)
- [4] K. Yanagisawa, *ISLE: a general purpose near-infrared imager and medium-resolution spectrograph for the 1.88-m telescope at Okayama Astrophysical Observatory*, SPIE Vol 6269 (2006).