Exoplanet Characterisation Observatory (EChO)

Assessment Phase Payload Study

Noise Evaluation for EChO VNIR Detectors

ECHO-TN-0002-INAF

Issue 0.3

Prepared by:	*M. Farina, A.M. Di Giorgio, M. Focardi*	Date:	2013, Dec, 03
Checked / Approved by:	*Anna Maria Di Giorgio*	Date:	2013, Dec, 03

DOCUMENT CHANGE DETAILS

Issue	Date	Contents	Description Of Change	Comment
0.1	‘13/09/15	All	Preliminary results	Draft version
0.2	‘13/10/20	All	Different sampling rate and optimization	First release
0.3	‘13/12/03	All	Doc Ref Change	

Contents

Sampling Methods

HgCdTe detectors used for ECHO mission allow for non-destructive (or multiaccumulation) readout modes, such that the charge may be read without removing it after reading out.

Multi-accumulate and sample Up-The-Ramp readouts are quite general terms and they are often used for all non-destructive readout modes such as Correlated Double Sampling (CDS), Multiple CDS (MCDS, also known as Fowler-M), sample Up-The-Ramp (UTR), Multi-Accumulate (MACC) and Differential Multi-Accumulate (DMACC).

All these sampling methods are graphically represented in Figure 1, following Hale et al. (slides: DfAGarching 2009-10-14). In all sections m is the number of scans to coadd and store after coaddition, p is the number of dummy scans between coadded groups and k is the number of stored cycles per exposure. In case of multi-accumulate modes, the number r of reset scans between exposures is indicated as well.

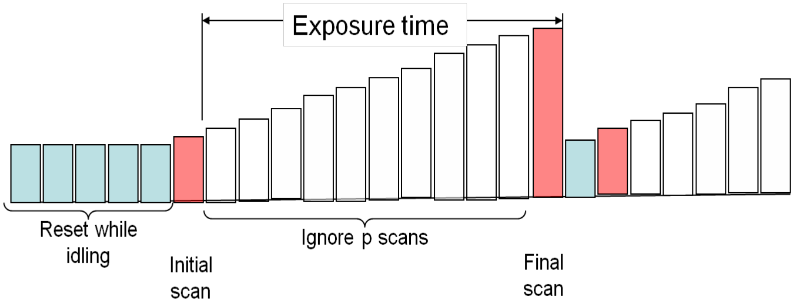
Correlated Double Sampling, reported in figure 1.a, is fully equivalent to Fowler sampling (figure1.b) with m=1. In this method the first frame shall be subtracted from last frame, while in Fowler-M, the mean of the first group of m frames shall be subtracted from the mean of the last group.

In Sample Up-The-Ramp (Figure 1.c), it is assumed that every scan is independently stored (no real-time coaddition is foreseen) and a least square fit of the ramp is used to measure its slope. This method is substantially equivalent to Multi-Accumulate with m=1. One advantage of UTR sampled data for space applications is that cosmic rays can potentially be rejected with minimal data loss. Cosmic rays hits, in fact, will appear as discontinuous steps in the acquired ramps. These steps can be identified and samples on either sides of the hit can be used to recover the slope.

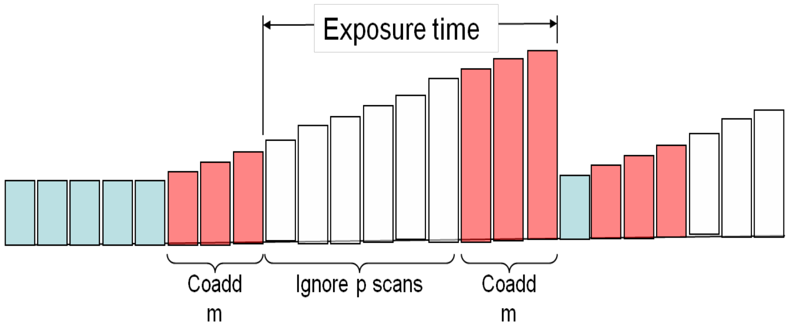
In Multi-Accumulate the detector readouts are grouped in contiguous sets of m readouts, coadded in real time and stored. The total exposure duration is a multiple of m scan times. The least square fit of stored (coadded) scans is then used to estimate the noise. One or more reset scans between exposures shall be included.

In Figure 1-e, the Differential multi-accumulate method is represented, where continuous non-destructive readout is employed, resetting the windows only when the integrated signal approaches the pixel capacity. Groups of samples are coadded and then subtracted to synthesize the frame rate desired with minimal noise.

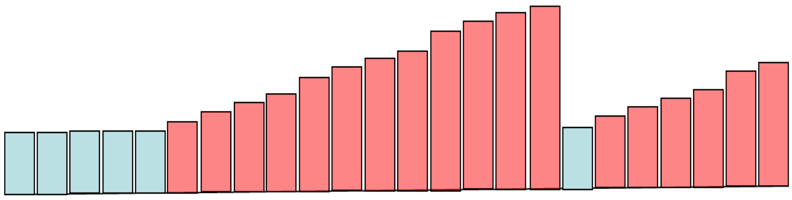
In the absence of cosmic rays, Up-the-Ramp sampling provides modestly (6%) higher signal-to-noise than does Fowler Sampling (Garnett & Forrest 1993). The fact that an Up-the-Ramp sequence can be screened for cosmic rays and other glitches improves this result. Furthermore, on-the-fly cosmic ray rejection allows longer integration times which also improves the signal-to-noise in the faint limit (Offenberg et al. 2001).



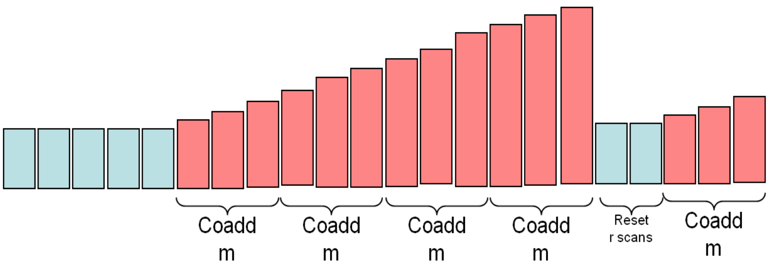
a. Correlated Double Sampli
m =1; p=10; k=2.



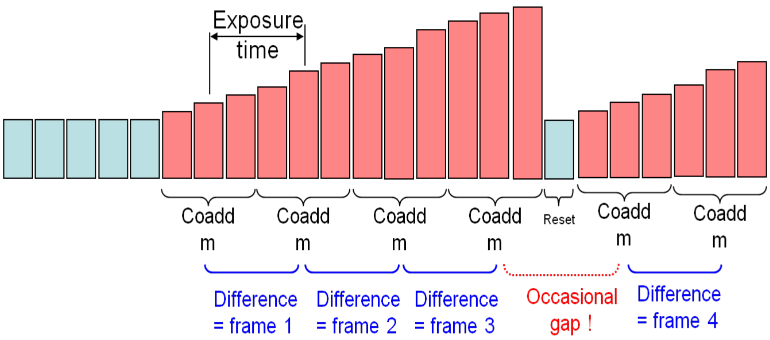
b. Fowler "m"
m =3; p=6; k=2.



c. Sample up the ramp
m=1; p=0; k=12.



d. Multi-accumulate
m=3; p=0; k=4;r=2.



e. Differential
Multi-accumulate

Figure 1 - Non-destructive readout modes.

"RAMPs" Simulation

The up-the-ramp approach is based on nondestructive reading of detector samples taken at equal time intervals. Nevertheless, as we saw in the previous section, there are different ways to build up the ramp.

Simulations, using UTR and MACC sampling method, are shown; the aim of this work is improving signal to noise ratio and identifying Comic ray and other glitches.

The variables are:

n= numbers of stores per exposure (groups)

m=numbers of scans to coadd per group.

For example in Figure 2 we adopted n=6 and m=4. The integration time t_{int} is the time between digitizing pixel [0,0] in the first frame of the first group and digitizing the same pixel in the first frame of the last group. The frame time t_f is the time interval between reading pixel [0, 0] in one frame and reading the same pixel in the next frame within the same group (sampling frequency). The group time t_g is the time interval between reading pixel [0, 0] in the first frame of one group and reading the same pixel in the first frame of the next group [B. J. Rauscher et al., PASP, 119, 768, 2007].

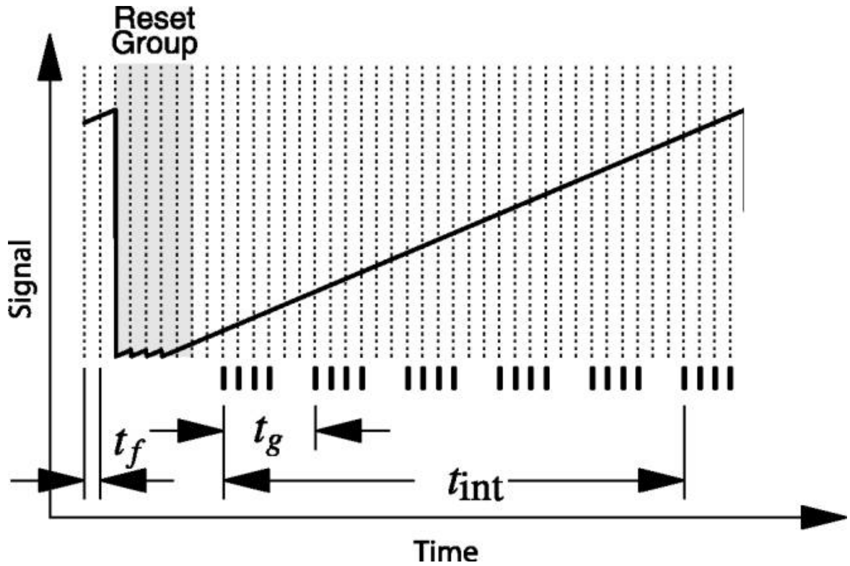


Figure 2 - Diagram of a detector readout scheme. The detector is readout at a constant rate. Although frames are clocked and digitized at a constant rate, to conserve data volume, not all frames are saved. In the figure, taken from Rauscher et al. 2007 and

referred to the JWST NIRSpec detector readout scheme, saved frames are indicated by short, double-width lines. Saved frames are coadded and averaged, resulting in only one averaged group of data being saved every t_g sec. The resulting stored dataset is essentially an up-the-ramp sampled data cube with points spaced at t_g intervals.

The general expression for total noise variance in case of UTR/MULTIACC readout modes is:

$$\sigma^2 = \frac{12(n-1)}{nm(n+1)}\mathrm{R}^2 + \frac{6(n^2+1)}{5n(n+1)}(n-1)(t_g)f - \frac{2(2m^2-1)(n-1)}{mn(n+1)}(m-1)(t_f)f$$

Where R is the readout noise and f is the flux, including photonic and dark currents. R is in unit of e^- *rms* per read and f is in unit of $e^- s^{-1} spaxel^{-1}$ (note[1]); n, m, t_g and t_f have been defined above.

The noise model described above includes read noise and shot noise on integrated flux, which is correlated across the multiple nondestructive reads sampling up the ramp. Refer to Rauscher et al. 2007 section 3.3 for a detailed description of the method used to derive the noise equation.

We used the noise model, for three different kinds of detectors, to simulate the expected noise levels for the ECHO VNIR; sensors are from SELEX, TELEDYNE and RAYTHEON. The used input data (as example faint photocurrent) have been taken fromthe EChO Detectors WG spreadsheet *"Detectors v Noise Budget v4.xls"* while readout noises and SCDA dark currents are from industry; the results are per spaxel. The expected noise curves have been reported by using the different sets of symbols indicated directly on the plots.

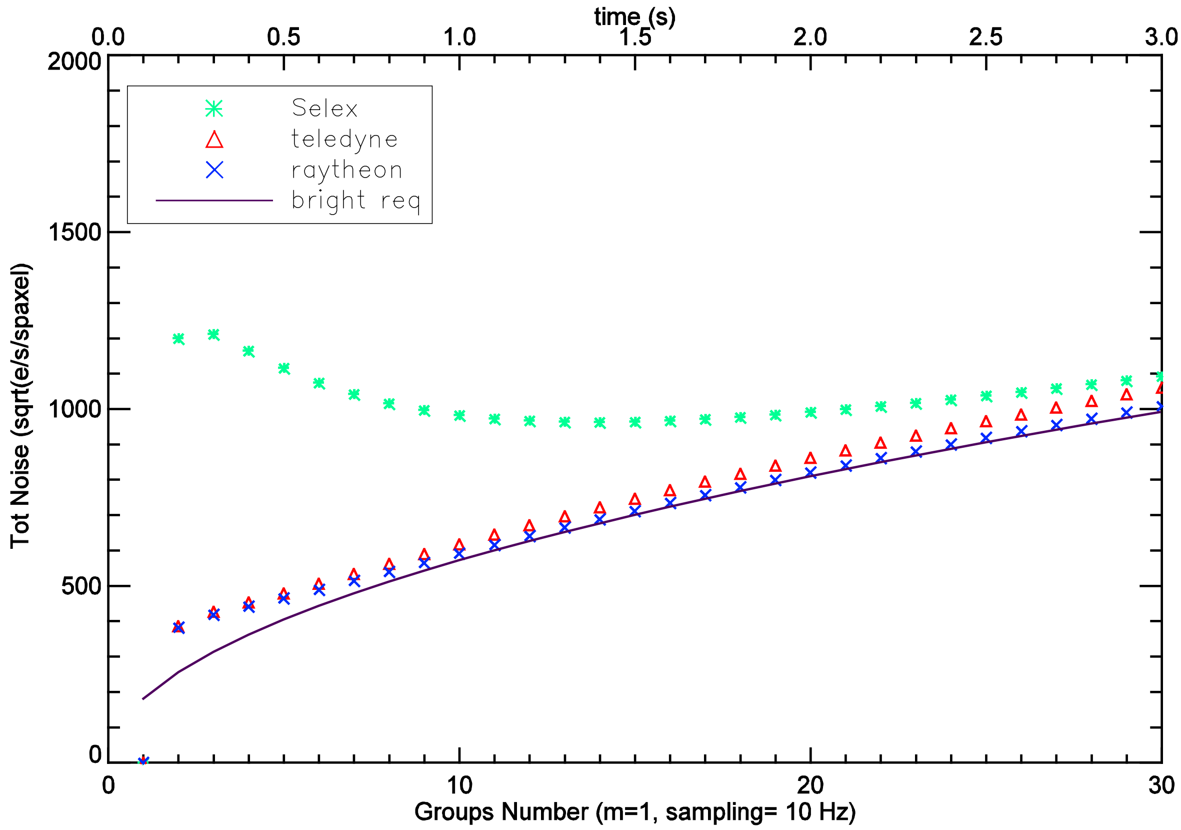
For a comparison with the system requirements, the noise requirement curves have been used following the Detectors WG calculations. In particular, for this study, only the values at at 1.5 µm have been taken and integrated over exposure time. The values are referred to one spectral bin and shall therefore be compared with the noise per spaxel values (not noise per pixel).

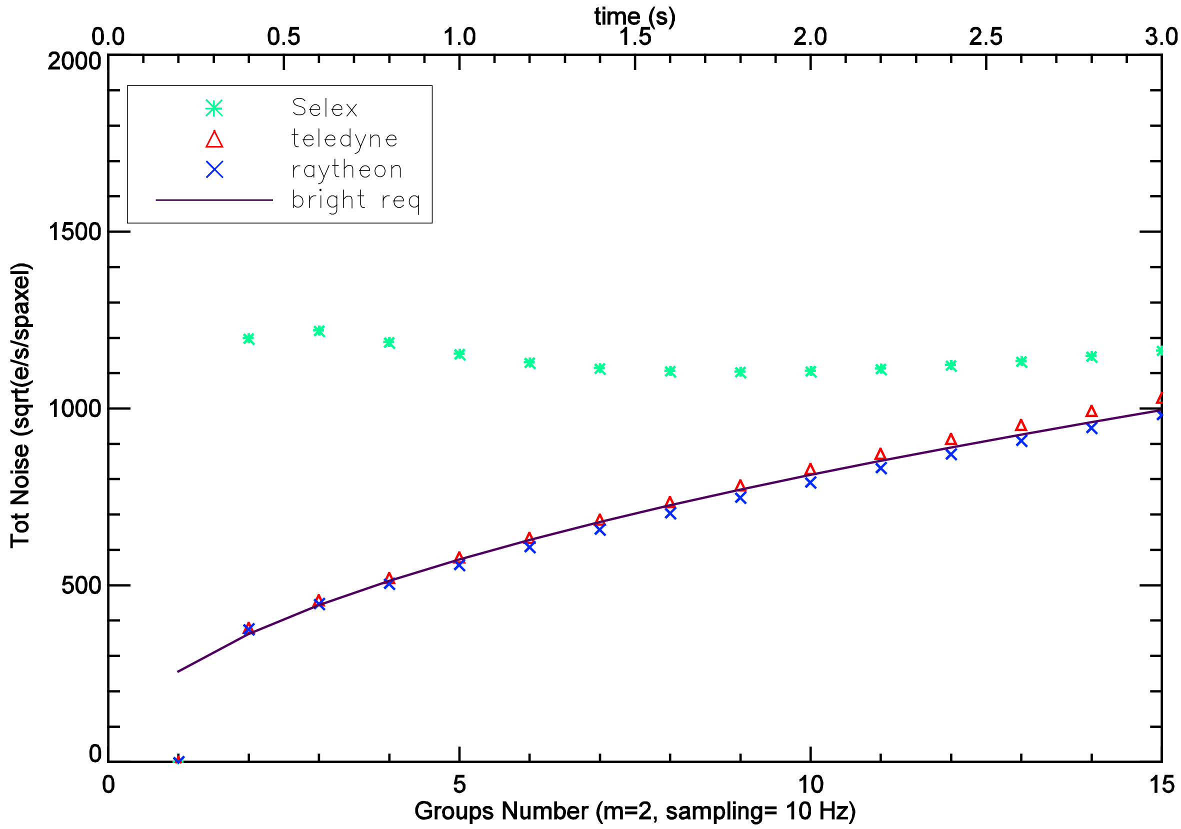
The adopted integration times are 3s for bright sources and 600s for faint sources, in order to be comparable with the Detectors WG results; all comparisons are made at 1.5 µm and at 40 K.

[1]Spaxels are pixels bins of *n×m* pixels, *n* along the spectral direction and *m* along the spatial direction.

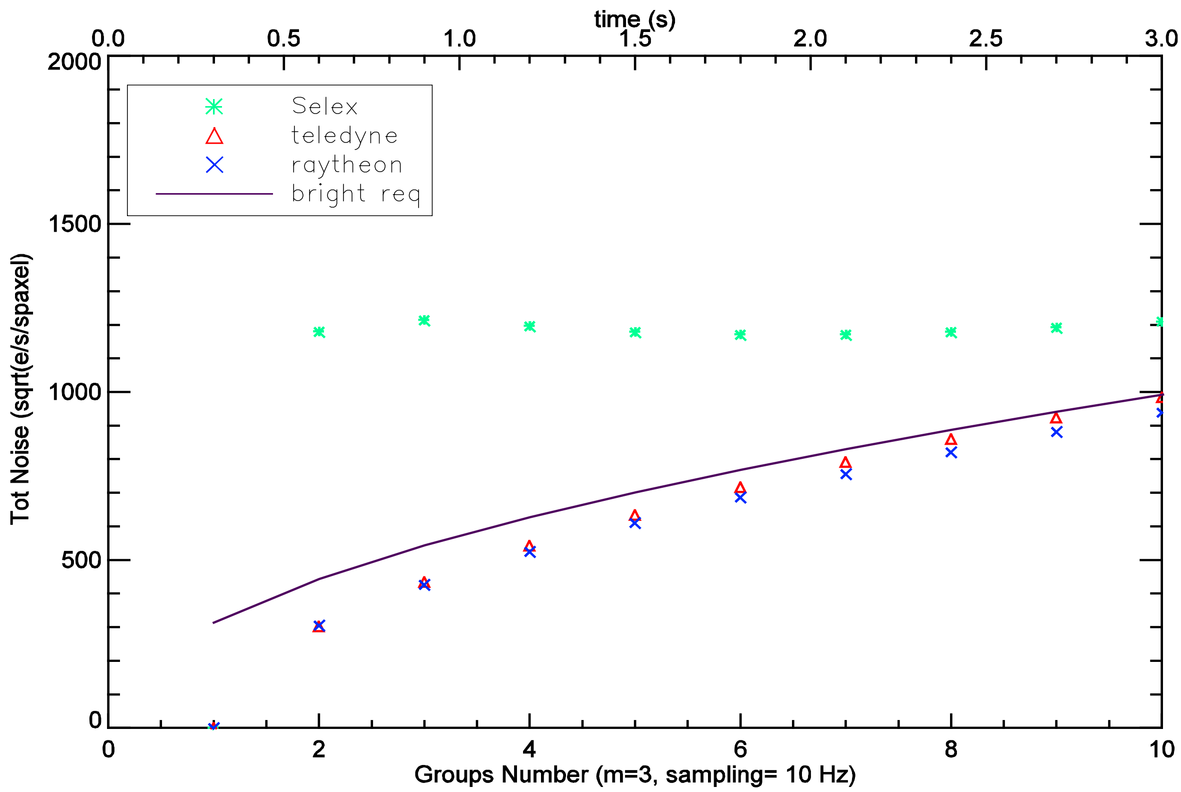
Noise Simulations For Bright Sources

The following plots show the noise simulations for bright sources, using UTR and MACC sampling method. Each plot represents groups number (or frame scans if *m=1*) with time on the horizontal axes and noise signal on the vertical axis; the maximum integration time considered for bright sources is *3s*. The sampling frequency t_f and the numbers of scans to coadd per group *m* are fixed for each plot. The results are for SELEX, TELEDYNE and RAYTHEONdetectors: the comparison with system requirement is done at 1.5µm.

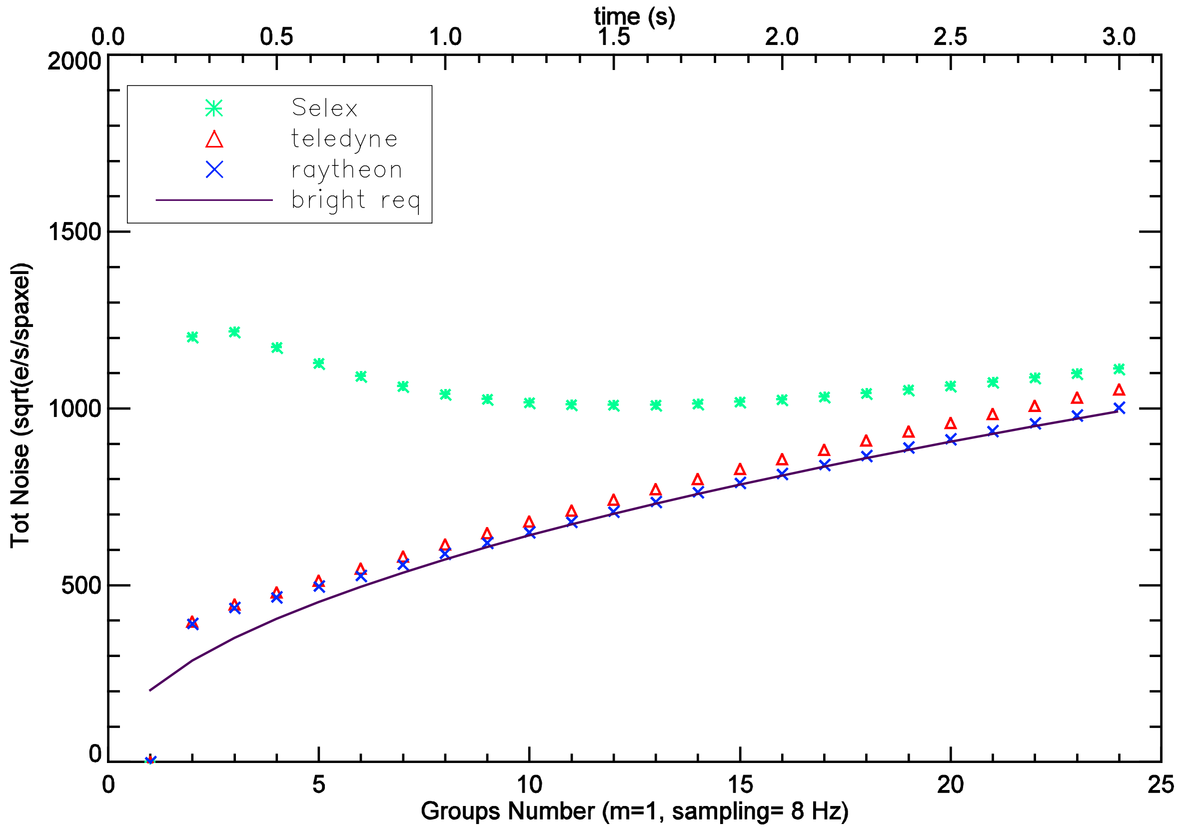


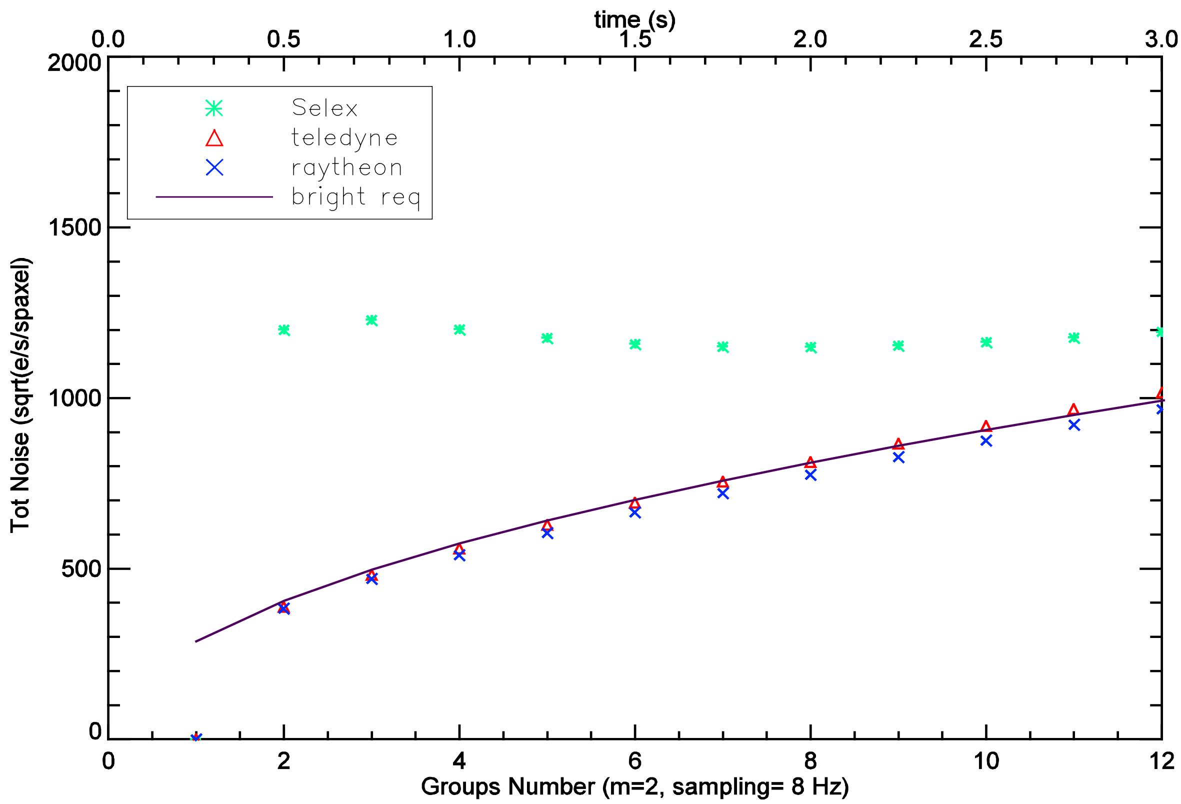


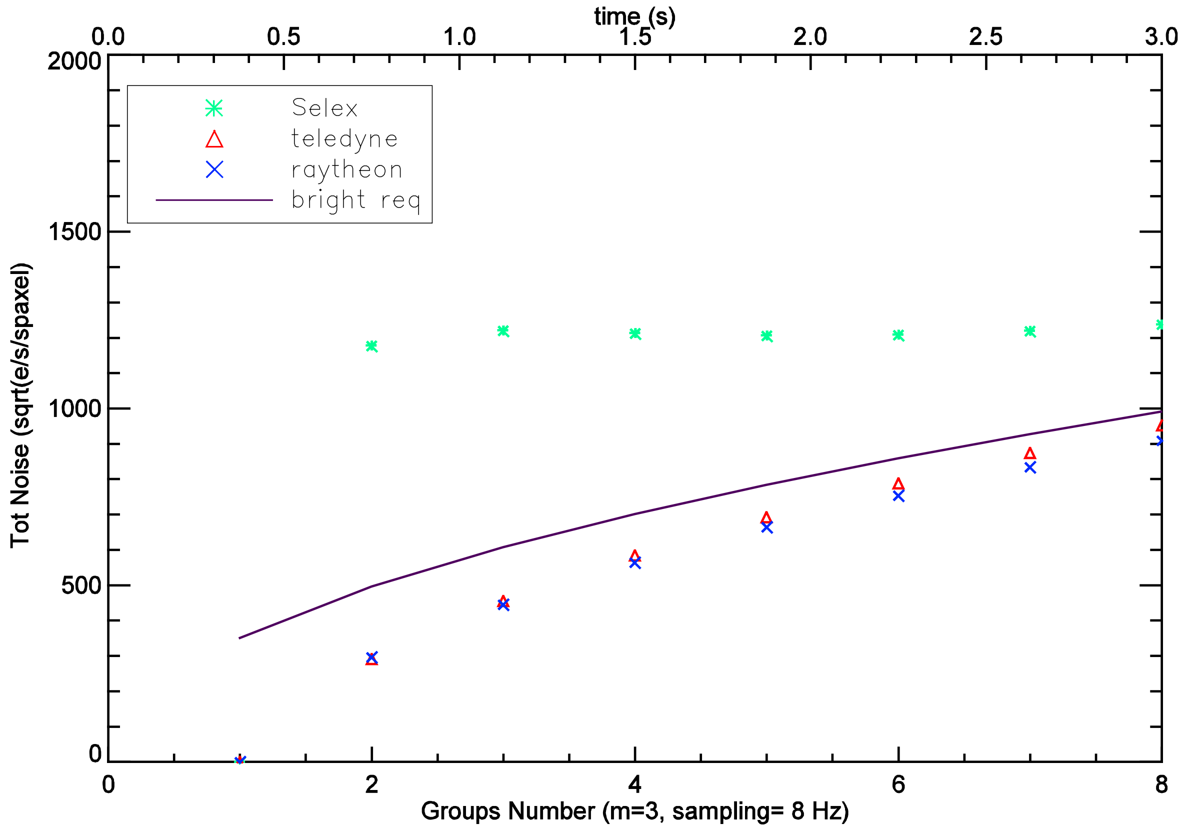
time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2000
1500
1000
500
0
Selex
teledyne
raytheon
bright req
Tot Noise (sqrt(e/s/spaxel))
0
5
10
15
Groups Number (m=2, sampling= 10 Hz)



time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2000
1500
1000
500
0
Selex
teledyne
raytheon
bright req
Tot Noise (sqrt(e/s/spaxel))
0
2
4
6
8
10
Groups Number (m=3, sampling= 10 Hz)

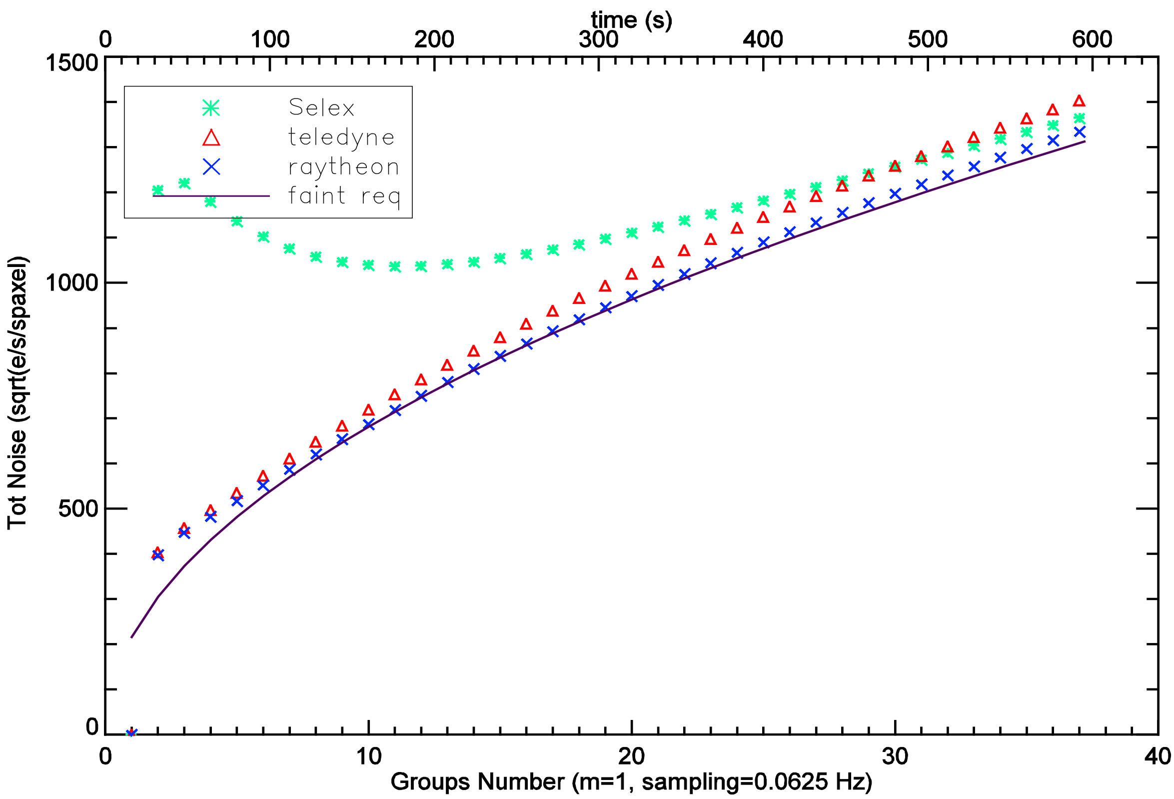

time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Selex
teledyne
raytheon
bright req
Tot Noise (sqrt(e/s/spaxel))
2000
1500
1000
500
0
0
5
10
15
20
25
Groups Number (m=1, sampling= 8 Hz)

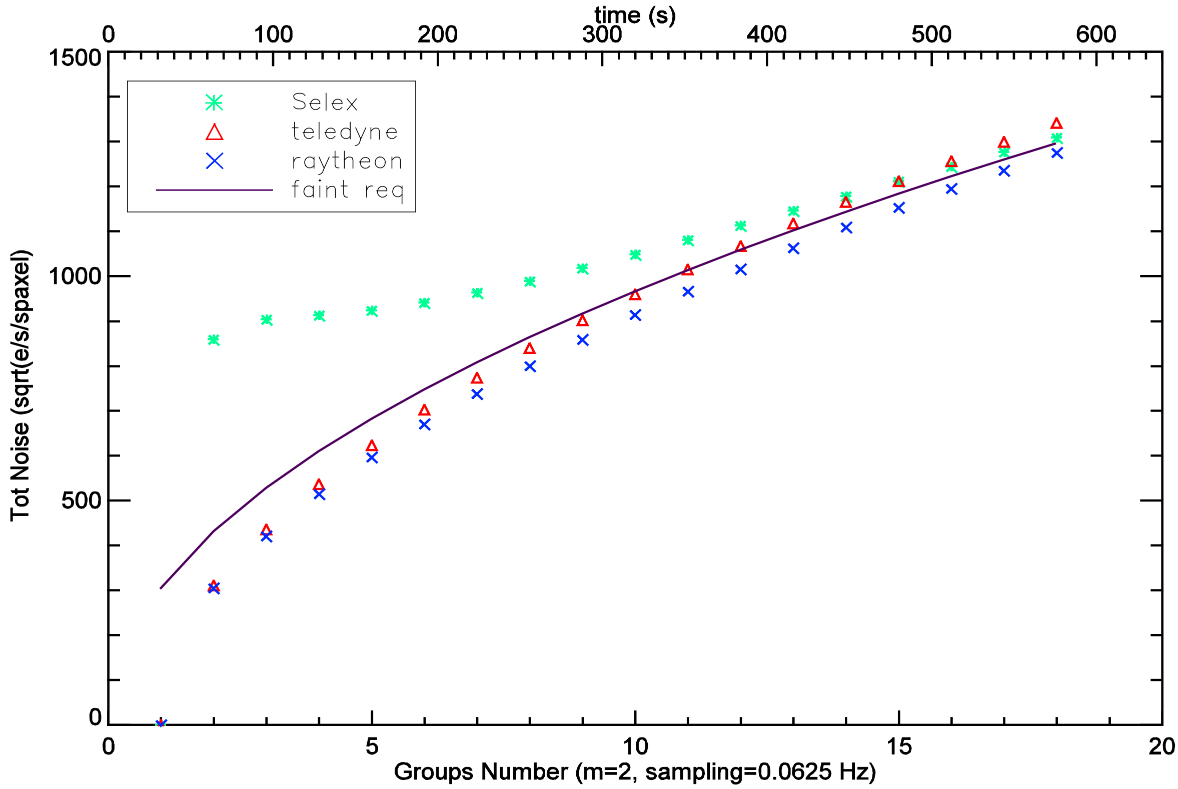

time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Selex
teledyne
raytheon
bright req
Tot Noise (sqrt(e/s/spaxel))
2000
1500
1000
500
0
0
2
4
6
8
10
12
Groups Number (m=2, sampling= 8 Hz)


time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2000
1500
1000
500
0
Selex
teledyne
raytheon
bright req
Tot Noise (sqrt(e/s/spaxel))
0
2
4
6
8
Groups Number (m=3, sampling= 8 Hz)

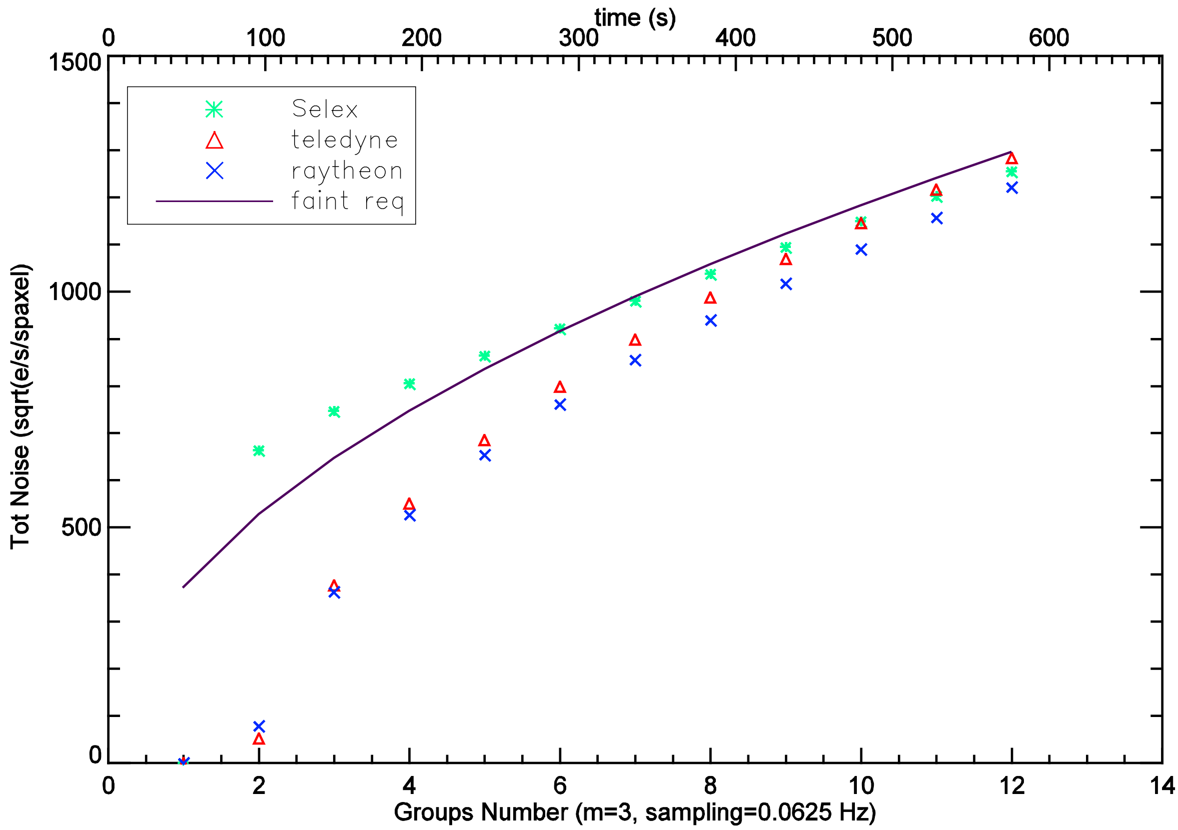
Noise Simulations For Faint Sources

All the following curves, showing noise contribution versus groups number, were obtained using UTR and MACC sampling methods; the simulations are for faint sources. The maximum integration time considered for faint sources is *600s*. Also those results are for SELEX, TELEDYNE and RAYTHEON detectors; the sampling frequency t_f and the numbers of scans to coadd per group m are fixed for each plot, moreover the comparison with system requirement is done at 1.5 μm.

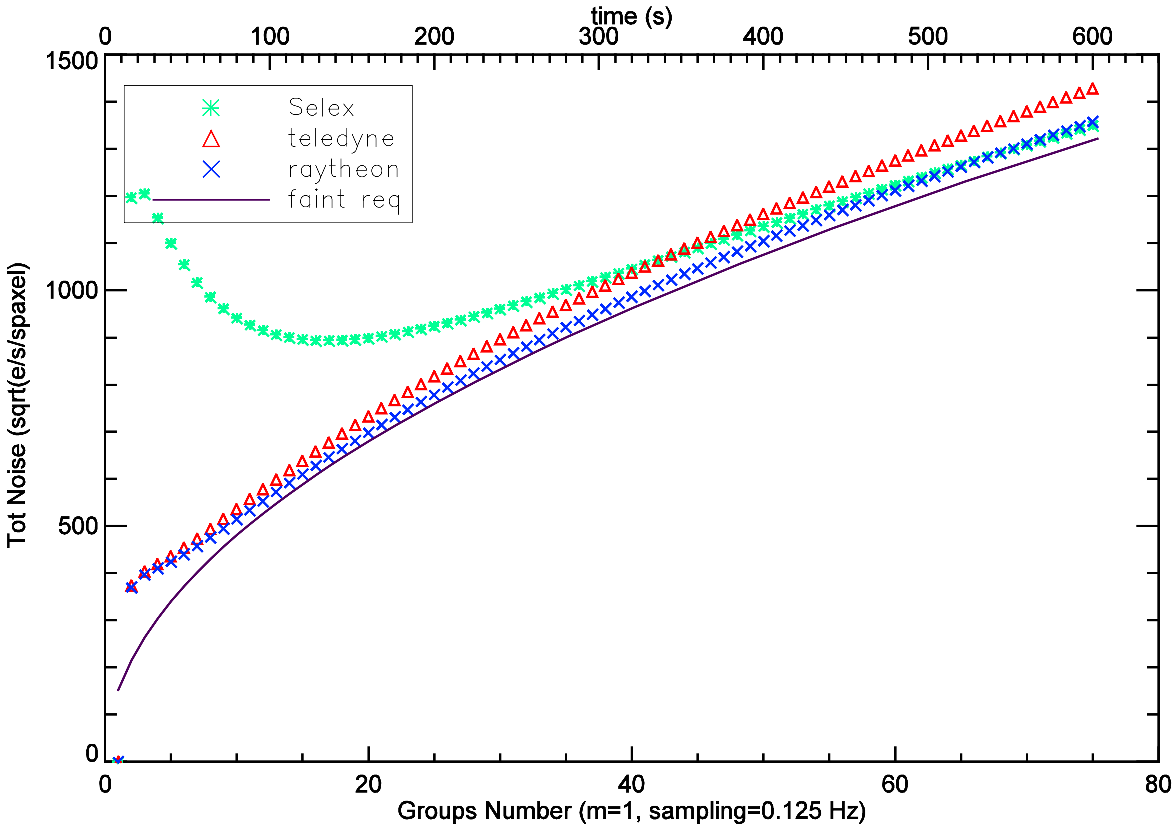


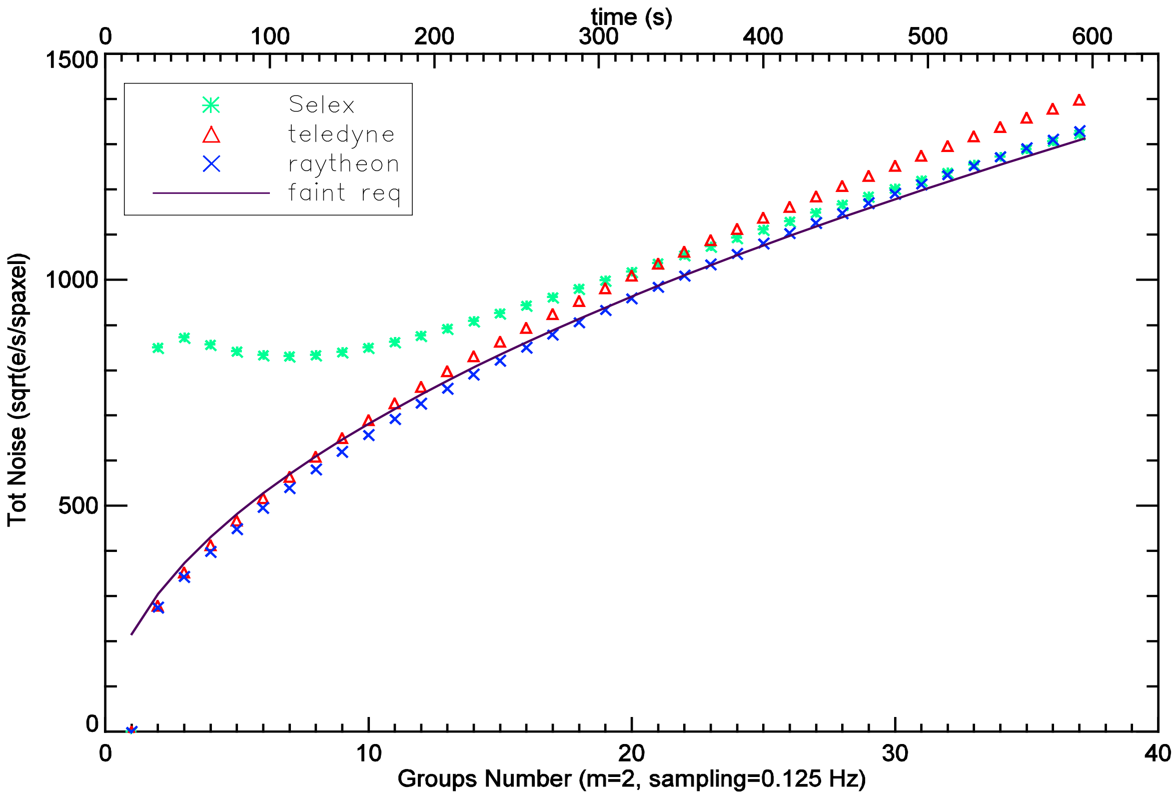


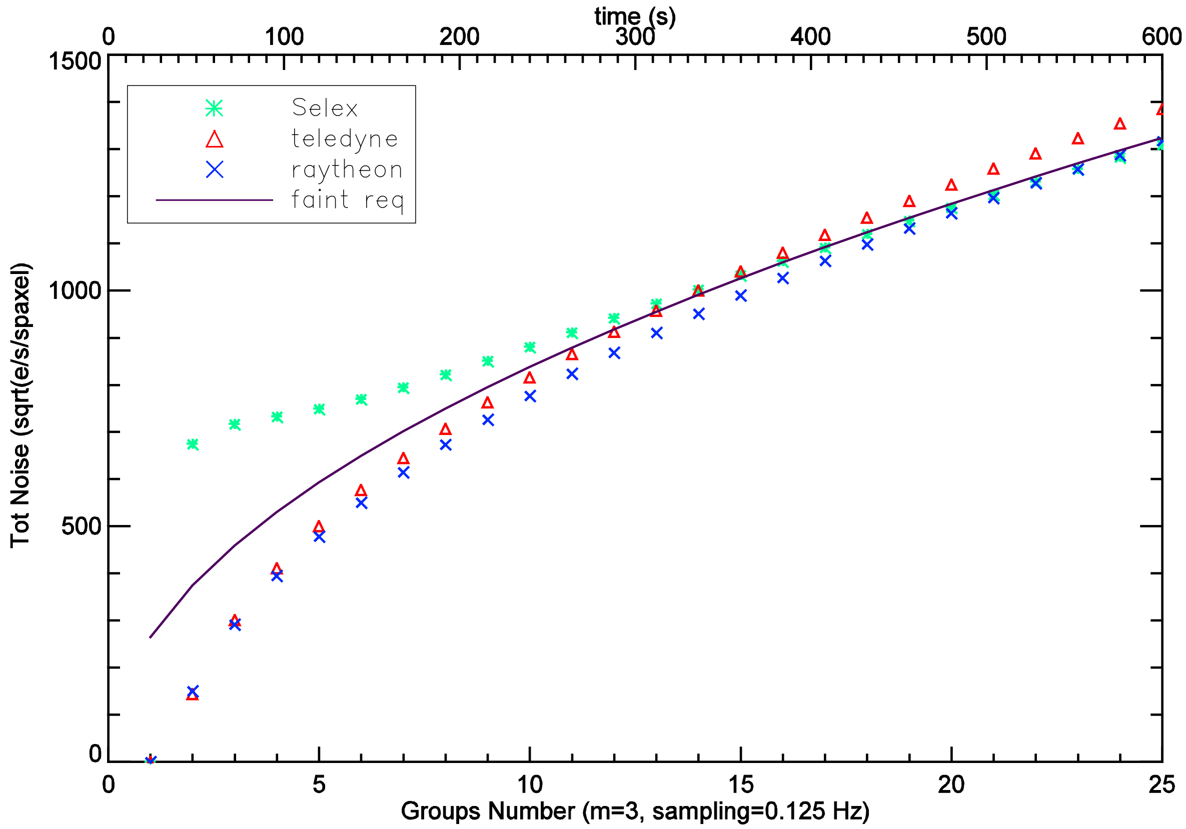
time (s)
Tot Noise (sqrt(e/s/spaxel))
Groups Number (m=2, sampling=0.0625 Hz)
Selex
teledyne
raytheon
faint req



time (s)
Tot Noise (sqrt(e/s/spaxel))
Groups Number (m=3, sampling=0.0625 Hz)
Selex
teledyne
raytheon
faint req


time (s)
0
100
200
300
400
500
600
1500
1000
500
0
Selex
teledyne
raytheon
faint req
Tot Noise (sqrt(e/s/spaxel))
0
20
40
60
80
Groups Number (m=1, sampling=0.125 Hz)


time (s)
0
100
200
300
400
500
600
1500
1000
500
0
Selex
teledyne
raytheon
faint req
Tot Noise (sqrt(e/s/spaxel))
0
10
20
30
40
Groups Number (m=2, sampling=0.125 Hz)


time (s)
0
100
200
300
400
500
600
1500
1000
500
0
Selex
teledyne
raytheon
faint req
Tot Noise (sqrt(e/s/s/spaxel))
0
5
10
15
20
25
Groups Number (m=3, sampling=0.125 Hz)

Cosmic Hits Rate

Assumption based on studies made for the JWST telescope gave an expected rate of cosmic events with impact on the detector confined between 5 and 30 *events/s/cm²* [Fixsen et al (2000); Rauscher et al. (2000)] which means that we expect on VNIR focal plane array the following hits:

Focal plane array (pixels)	256x256	512x512	512x512	512x512
Pixel size (μm)	30	15	18	20
Mean rate (events/s)	11	11	15	19
Eventsin 600s	6600	6600	9000	11400
Events in 3s	33	33	45	57

Table 1 - Expected cosmic rays hits rate for VNIR focal plane array.

When a cosmic ray impacts a detector any unrecorded information stored in the focal plane at that location is lost; thus if only one pixel per event were affected by the hit, the data loss would be as follow:

Focal plane array (pixels)	256x256	512x512	512x512	512x512
Pixel size (μm)	30	15	18	20
Pixels affected in 3s	0.05%	0.01%	0.02%	0.02%
Pixels affected in 600s	10.07%	2.52%	3.43%	4.32%

Table 2 - Expected data loss percentage, assuming one only pixel affected per cosmic ray hit.

Whereas, if a single event involves 5 pixels the data loss can be as high as the figures reported in the following table:

Focal plane array (pixels)	256x256	512x512	512x512	512x512
Pixel size (μm)	30	15	18	20
Pixels affected in 3s	0.25%	0.05%	0.10%	0.10%
Pixels affected in 600s	50.35%	12.60%	17.15%	21.60%

Table 3 - Expected data loss, assuming 5 pixels per hit.

Conclusions

The presented noise curves, coupled with the expected cosmic hits rates lead to the conclusion that two different readout rates and sampling methods are needed for bright sources and faint sources.

In case of bright sources, there is not much difference using both 8 Hz and 10 Hz sampling: Teledyne and Raytheon detectors types can reach the requirements with M≥2, on the contrary Selex sensors never satisfy the requirement, as shown in following tables:

	RAYTHEON	SELEX	TELEDYNE
M	*N minimum*		
1			
2	*4*		*4*
3	*2*		*2*

Table 4 – Minimum Number of sample groups for reaching a noise level below the requirement at a sampling frequency of 10Hz.

	RAYTHEON	SELEX	TELEDYNE
M	*N minimum*		
1			
2	*2*		*2*
3	*2*		*2*

Table 5 – Minimum Number of sample groups for reaching a noise level below the requirement at a sampling frequency of 8Hz.

N minimum is the minimum number of groups necessary to reach the noise requirement. Of course *N minimum* decreases with increasing the number of samples per group.

From Table 4 and Table 5 it can be seen that in case of M≥2 *N minimum* is always very low. This situation allows to tune the overall measurement duration (max integration time) based only on the deglitching procedure performances, keeping it as short as possible, thus minimizing the expected number of cosmic hits.

Additional considerations related to the maximum well depth should be taken into account when optimizing noise, acquisition rate and overall exposure time: using Teledyne detectors, for example, it is possible to acquire data for a longer integration time (up to 3 seconds for bright sources) due to their full well depth.

In case of faint sources at 1/8 Hz and 1/16 Hz sampling the sensors never satisfy the required noise conditions if M=1while with M=3 all the detectors types can reach the requirements, as shown in following tables:

	RAYTHEON	SELEX	TELEDYNE
M	*N minimum*		
1			
2	*6 to 21*		*2 to 9*
3	*2*	*16*	*2 to13*

Table 6 – Minimum Groups Number for reaching a noise level below the requirement at a sampling frequency of 0.125 Hz.

	RAYTHEON	SELEX	TELEDYNE
M	*N minimum*		
1			
2	*2*		*2 to12*
3	*2*	*7*	*2*

Table 7 – Minimum Groups Number for reaching a noise level below the requirement at a sampling frequency of 0.0625Hz.

For faint sources 1/16 Hz sampling frequency with different solutions of N and M seems to be slightly better than the results at 1/8 Hz sampling frequency, as reported in previous Table 6 and Table 7. In particular at 1/16 Hz sampling with M=3 and N=12 all the detectors can fall below the noise threshold; with M=2 and N=37 only Raytheon detector fall below and remain under the noise requirement along the ramp, while using Teledyne sensor it is necessary to stop the acquisition at N=12 and the maximum integration time is of the order of 300secs; Selex sensors don't reach the noise requirement.

Considering these preliminary results Teledyne and Raytheon sensors better combine bright and faint sources results, Selex detectors need to be better evaluated.

In the next phases this method will be validate by tests and more insights will be done. In particular, we are confident of reaching the noise requirement, for bright sources, using a lower data rate sampling than those reported previously and, for faint sources, falling below the noise threshold also with M=1: N=37 and M=1 is the best solution in order to simplify the data processing and make data fit. In fact, the maximum integration time allowed by detectors is much shorter than the time scale of sources observation and variability. Therefore many ramps could be coadded improving the signal to noise ratio.

About deglitching, the provided percentages allow us to conclude that it will be not necessary to correct for the cosmic hits effects in case of bright sources, where it will be sufficient to identify and discard the affected readouts (only a max 0.25% of the overall array will be affected by the cosmic hits in a 3 seconds exposure). In case of faint sources a more detailed evaluation will be performed in the future, to assess the real need to implement a deglitching procedure onboard.

Acknowledgement

We acknowledge the financial contribution by the Italian Space Agency in the framework of the ASI-INAF agreement I/022/12/0.

References

1. ‘Low-Noise IR Wavefront Sensing with a Teledyne HxRG’, D. Hale et al., slides: DfA Garching 2009-10-14.
2. ‘ Near-infrared arrays for SIRTF, the Space Infrared Telescope facility’, Garnett, J. D., & Forrest, W. J. 1993, Proc. SPIE, 1946, 395.
3. ‘Validation of Up-the-Ramp Sampling with Cosmic Ray Rejection on IR Detectors’,Offenberg, et al., 2001, PASP, 113, 240.
4. ‘Detectors for the JWST Near-IR Spectrograph. I. Readout Mode, Noise Model and Calibration Considerations’, B. Raucher et Al., 2007, PASP, 119, 768 and later errata corrige, 2010.
5. ‘Cosmic-Ray rejection and Readout Efficiency for Large-Area Arrays’, Fixsen et al. 2000, PASP 112, 1350-1359.
6. ‘Cosmic Ray Management on NGST 1: The effect of Cosmic Rays on Near Infrared Imaging Exposure Time, Rauscher et al. 2000, STScI-NGST-R-0003A.
7. EChO Mission Requirement Document, 14/09/2012, pp.20-21.