Preliminary study of the EChO data sampling and processing

M. Farina[*a,b], A. M. Di Giorgio[b], M. Focardi[c], E. Pace[d], G. Micela[a], E. Galli[b], G. Giusi[b], S. J. Liu[b], S. Pezzuto[b]

[a]INAF-Osservatorio Astronomico di Palermo “Giuseppe S. Vaiana”, Piazza Del Parlamento 1, 90134 Palermo, Italy; [b]INAF-Istituto di Astrofisica e Planetologia Spaziali, via Del Fosso del Cavaliere 100, 00133 Roma, Italy; [c]INAF-Osservatorio Astrofisico di Arcetri, Via della Torre del Gallo 5, 50125 Firenze, Italy; [d]Università degli studi di Firenze, Dipartimento di Fisica e Astronomia, largo E. Fermi 2, 50125 Firenze, Italy.

ABSTRACT

The EChO Payload is an integrated spectrometer with six different channels covering the spectral range from the visible up to the thermal infrared. A common Instrument Control Unit (ICU) implements all the instrument control and health monitoring functionalities as well as all the onboard science data processing. To implement an efficient design of the ICU on board software, separate analysis of the unit requirements are needed for the commanding and housekeeping collection as well as for the data acquisition, sampling and compression. In this work we present the results of the analysis carried out to optimize the EChO data acquisition and processing chain.

The HgCdTe detectors used for EChO mission allow for non-destructive readout modes, such that the charge may be read without removing it after reading out. These modes can reduce the equivalent readout noise and the gain in signal to noise ratio can be computed using well known relations based on fundamental principles. In particular, we considered a multiaccumulation approach based on non-destructive reading of detector samples taken at equal time intervals. All detectors are periodically reset after a certain number of samples have been acquired and the length of the reset interval, as well as the number of samples and the sampling rate can be adapted to the brightness of the considered source.

The estimation of the best set of parameters for the signal to noise ratio optimization and of the best sampling technique has been done by taking into account also the needs of mitigating the expected radiation effects on the acquired data. Cosmic rays can indeed be one of the major sources of data loss for a space observatory, and the studies made for the JWST mission allowed us to evaluate the actual need of the implementation of a dedicated deglitching procedure on board EChO.

Keywords: Exoplanets, MCT detectors, EChO

1. INTRODUCTION

EChO (Exoplanet Characterization Observatory) is a medium class space mission, dedicated to the characterization of the atmospheres of exoplanets transiting nearby stars. It has been designed to study the chemical composition and abundances, the thermal structure and the spatial and temporal variation of the atmospheric structure of ~100 exoplanets, spanning a planets mass range from the gas giants (hot Jupiters) down to super Earths, around host stars with spectral types spanning from F-type up to M-type stars. The ultimate aim of the mission will be to determine the mechanisms that drive the formation of exoplanets themselves, see Tinetti et al 2014[1].

EChO is equipped with an integrated spectrometer that covers the wavelength range between 0.4 and 16 µm with a spectral resolving power ~300 up to 5 µm and ≥ 30 up to 16 micron, sufficient to resolve the spectral features of the main molecular species. The spectrometer consists of six channels grouped into four spectrometer modules as described in Swinyard et al. 2012 [2], Focardi et al. 2012 [3] and summarized hereafter:

- VNIR, covering the wavelengths range from 0.4 µm to 2.47, internally divided into two channels, the first one from 0.4 µm to 0.8 µm and the second one from 0.8 µm to 2.47 µm;
- SWIR, covering the wavelengths range from 2.47 µm to 5.55 µm;

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- MWIR, covering the wavelengths range from 5.3 µm to 11.25 µm, internally divided into two channels, the first one from 5.3 µm to 8.45 µm and the second from 8.45 µm to 11.25 µm;
- LWIR, covering the wavelengths range from 11.25 µm to 16 µm. This channel is actually an extension of the baseline design, which includes only the first four modules. Being particularly suited for the detection of the CO_2 band at 15 µm, this range has been added to improve the payload capabilities to retrieve the thermal profile in terrestrial atmospheres, especially for planets in the habitable zone (see Tinetti et al. 2012[1]).

An Instrument Control Unit (ICU) is foreseen as the main electronic subsystem of the EChO scientific payload, interfacing the spacecraft and collecting data from all the payload spectrometers modules. ICU is in charge of two main tasks: the overall payload control and the housekeeping and scientific data digital processing, including the lossless compression prior to store the science data to the spacecraft mass memory. These two main tasks are accomplished thanks to the payload on board software (OBS) running on the ICU CPUs.

To implement an efficient design of the OBS, separate analysis of the unit requirements are needed for the instrument control functionalities and for the data acquisition, sampling and compression. In this work we present the results of the analysis carried out to optimize the EChO data acquisition and processing chain for the VNIR channel, which will host the largest focal plane arrays. The results of the analysis will be used to derive the requirements on processing power and memory needs for the CPU board in the EChO ICU.

2. THE CONSIDERED DETECTORS

During the assessment study, the possibility to adopt a European HgCdTe (Mercury Cadmium Telluride, MCT) detector system for all baseline channels has been investigated. In the recent years both ESA and ESO invested on the development of Near IR (0.9 to 2 µm) arrays, with an ongoing investment also in the development of an European equivalent to the SIDECAR ASIC used to readout the US Teledyne MCT sensors.

Within the EChO Consortium, therefore, an effort has been put on evaluating the performances of detector arrays and readout electronics systems produced by various potential European and US providers, with a comparative analysis aimed at checking their capability to fulfill the mission scientific and technical requirements. More in detail, the criteria used in the assessment study have been the noise performance, the compatibility of optical and thermal interfaces, the complexity of electrical interface to front end electronics, the TRL requirement and the operability in terms of read out modes and rates, handling cosmic ray events and quantum efficiency.

The final result of the study was to adopt the Teledyne Hawaii-2RG (H2RG) device as the baseline for the Fine Guidance Sensor (FGS) and the VNIR and SWIR channels. The European SELEX ES devices were also potential candidates for these three channels, however their current TRL is relatively low when compared to Teledyne's devices. Also for the MWIR channel the Teledyne NEOCAM device has been selected as the baseline, because there isn't any immediate European solution. For what concerns the LWIR channel, the best option currently available is the 7K Raytheon SiAs device. An alternative SiGa based device is currently under investigation, but the related technology has not been considered mature enough for their utilization in the mission.

The Teledyne baseline detectors are hybrid CMOS arrays which use HgCdTe 2K×2K 18 µm pixel pitch sensors for light detection and a silicon integrated circuit for signal readout. Similar detectors have been already used at the focal plane of astronomical instrumentation, designed both for space mission and for on ground facilities [4], see Table 1.

Table 1: List of instrumentation using Teledyne MCT sensors.

Mission/Facility	**Istrument**
Hubble Space Telescope (HST)	Wide Field Camera 3 (imager)
James Webb Space Telescope (JWST)	Near Infrared Spectrograph (NIRSpec) Near Infrared Camera (NIRCam) Fine Guidance Sensor (FGS) (imagers and spectrograph), NIRISS
Carnegie Observatory	Four Star (imager)
European Southern Observatory	X-Shooter (spectrograph)
Euclid	NISP

The Teledyne detectors have a low dark current (<0.01 e-/pix/s) and a high quantum efficiency (>80%). They support a non-destructive pixel readout and therefore it is possible to reduce the readout noise by taking many samples during the exposure. Our contribution to the detectors trade-off study has been to check if it was possible to find, for all the considered arrays, a readout strategy able to satisfy the noise requirements expected for the VNIR channel, even taking into account the noise introduced by the readout electronics.

3. DATA COLLECTION TECNIQUES DESCRIPTION

As stated above, HgCdTe detectors allow for non-destructive (or multi-accumulate) readout modes, such that the charge may be read without removing it after reading out. Hereafter the most used data collection techniques for such kind of detectors are briefly described. In all of them at the beginning of an exposure a detector reset leads the signal to the initial value, which increases linearly with time as the charge increases and accumulates on the detector. This process goes on until the detector is reset to its original value at the end of the integration. The measurement result comes from a linear fit through the signal reads executed at different times during the exposure. One or more reset scans between exposures shall be included when the integrated signal approaches the pixel capacity.

The considered data collection techniques are 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). They differ from each other in the way the signal samples, i.e. the signal non destructive readouts, are grouped and coadded before the fit. All sampling methods are graphically represented in Figure 1, where the number of scans to coadd has been indicated with m.

The CDS method, reported in Figure 1A, is the simplest one and essentially consists of subtracting the first sample from the last sample of the exposure. All samples in between the first and the last readouts are discarded. Since no sample coaddition is implemented in this method, it has been characterized with $m = 1$. An example of the Fowler-M method is reported Figure 1B, where the $m = 3$ case is represented. More in general, the method consists of taking m non-destructive readouts immediately after the initial reset (Pedestal Samples) and another m non-destructive reads at the end of the integration (often indicated as Signal Samples); the average of the Pedestal Samples are then subtracted from the average of the Signal Samples to obtain the slope of the measured ramp. The UTR method shown in Figure 1C assumes that every scan is independently stored, i.e. no real-time coaddition is implemented, and a least square fit through all the acquired samples is used to estimate the ramp slope. In MACC (Figure 1D) the detector readouts are grouped in contiguous sets of m readouts, coadded and averaged in real time and stored. The total exposure duration is a multiple of the time needed to acquire m samples. It can be seen that the UTR method can be considered to be equivalent to the MACC method with $m = 1$. Finally, in Figure 1E a representation of the DMAC method is provided. Analogously to what happens in MACC, detector readouts are grouped in contiguous sets of m samples. The averaged value of each group is then subtracted from the value of the previous adjacent group.

Which one of these sampling techniques gives the best signal to noise ratio (S/N) depends both on whether the observation is background or readout-noise limited and on the need to identify distortions of the ramp shape due, for example, to the effects of Cosmic Rays (CR) hits on the detectors.

Fowler-M and UTR methods behave better than CDS in case of readout-noise limited measurements. The Fowler sampling performance depends on the exposure duty cycle, that is the percentage of time spent only in the first and last m sampling intervals with respect to the total observing time. Garnett & Forrest 1993[5] report that this method provides the best result for a duty cycle of 2/3 (1/3 at the beginning and 1/3 at the end of the total observing time). In this case the S/N obtained with the UTR method is approximately 6% better than that obtained with Fowler-M. On the other hand, in case of background limited performance, in which the photon noise is the dominant contributor to the overall noise, the best theoretical S/N is achieved with the CDS method. In this case, the S/N for UTR is approximately 9% lower than that obtained for CDS[5].

The UTR method is the most suitable also when it is necessary to detect distortions of the ramp shape due to the effects of CR hits on the detectors. Furthermore, on-the-fly cosmic ray rejection allows longer integration times, thus improving the S/N (Offenberg et al. 2001[6]. As demonstrated by Anderson and Gordon (2011[7], the best methods to correct for cosmic rays in the ramps are the two-point difference method and the y-intercept method. In particular, this last method is optimal in the read-noise dominated regime, while both the methods result to be efficient in the glitches detection and removal in the photon noise dominated regime. For the mathematical details see Anderson and Gordon (2011) [7]).

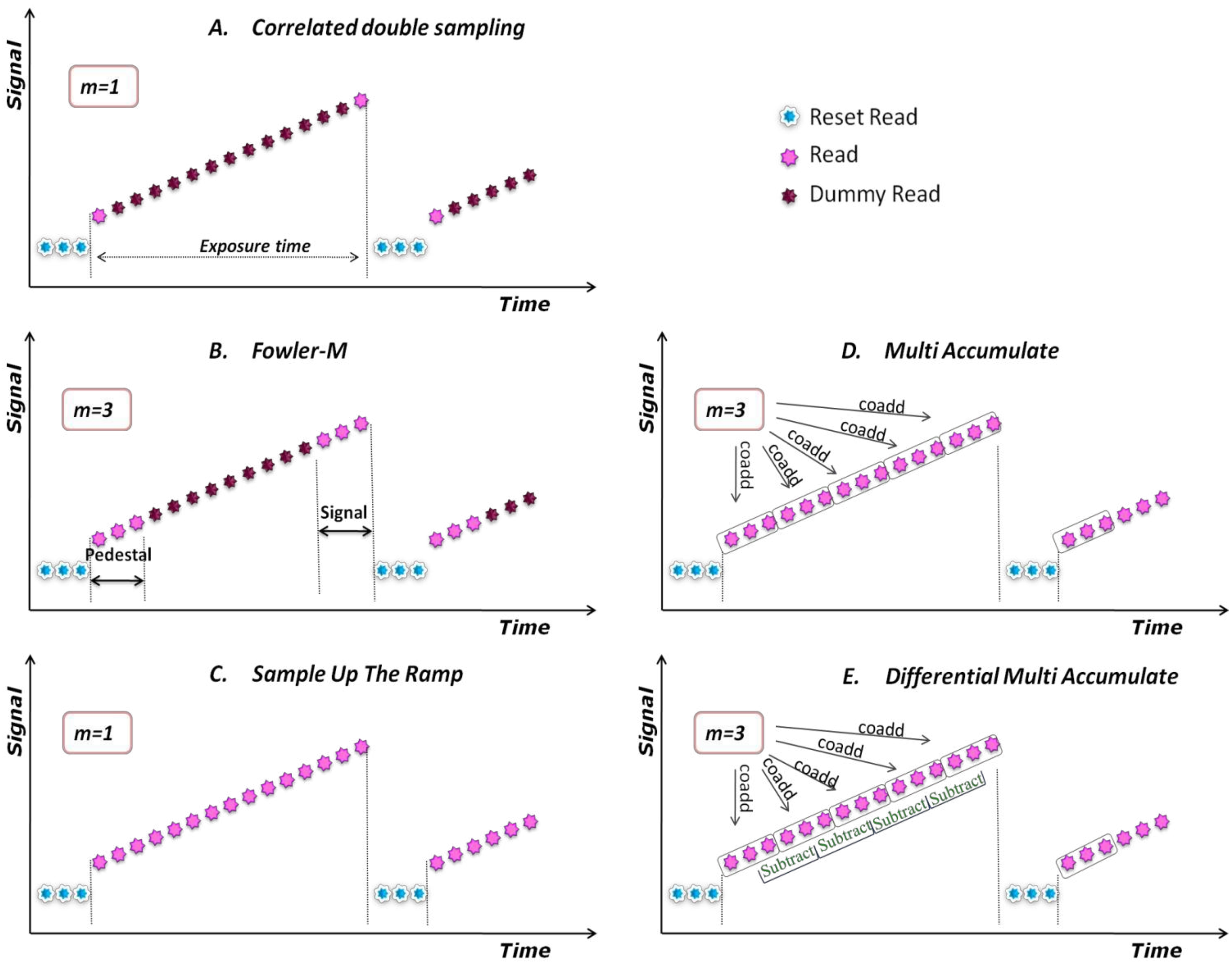

Figure 1 MCT detectors readout schemes. See text for a detailed description of the five different schemes.

4. VNIR DETECTORS BEST READOUT MODE EVALUATION

The VNIR focal plane array is a HgCdTe array of 512×512 pixels with 18 µm pixel pitch. It is the most demanding module of the EChO payload from the point of view of the necessary onboard digital processing (see Focardi et al. 2014[8] for a description of the digital processing unit and Adriani et al. 2014[9] for a description of the overall VNIR module). For this reason the first analysis of the effects of the readout noise on the overall noise budget as a function of the readout mode has been done for the VNIR detectors.

The choice of the best sampling strategy for this array depends on two main aspects: the need to maximize the S/N in the measurements of both bright and faint sources and the need to identify Cosmic Rays and other glitches. It is therefore important to provide an estimation of the total noise expected for the different readout samplings and strategies.

The general expression for the total noise variance, in case of UTR/MACC readout modes, has been provided by Rauscher et al. 2007[10] and is reported hereafter:

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

where R is the readout noise and f is the flux, including both photonic flux and dark current. R is in units of e- rms and f is in units of e-s^{-1}spaxel^{-1}; m is the number of samples per group (see section 3) and n is the number of groups per exposure. If m = 1 the group is made by a single read (or sample) and the number of readouts is equal to the number of groups. The frame time t_f is the time interval between the acquisition of two consecutive frames (frame sampling time). The group time t_g is the time interval between the acquisition time of the first frame of one group and the first frame of the next group. The sampling approach is based on nondestructive reading at equal intervals t_f.

We used the previous relation to evaluate the noise expected for the VNIR detectors when read out using the sample up-the-ramp or multi-accumulate methods. The results have then been compared with the system requirements for the two different detector arrays mentioned in section 2, i.e. Teledyne H2RG arrays and SELEX ES devices. We compared different data collection techniques by analyzing the expected total noise as a function of the different measurement parameters for both bright and faint sources. The brightest and the faintest targets to be observed by the EChO payload are defined in the EChO Mission Requirements Document[11].The brightest is a K0V star of K magnitude 4.0, corresponding to an object with a surface temperature of 5250 K , a radius of 0.8 r_{sun} at a distance of 12.3 pc. The faintest considered object is a function of the wavelength, as shown in Table 2. To calculate the expected fluxes, therefore, different spectral energy distributions shall be considered in the three regimes.

Table 2 Characteristics of the faintest star that will be observed by EChO in the three different λranges reported in the first column

	Type	**K Magnitude**	**T [K]**	**Radius [r_{sun}]**	**Distance [pc]**
Under 3 microns	M5V	8.8	3200	0.19	20.6
From 3 to 8 microns	G0V	9.0	6030	1.05	238
Above 8 microns	G0V	8.0	6030	1.05	150

We considered integration times of 3s for bright sources and 600s for faint sources, to be compatible with the full well depth capacity of the detectors given the expected fluxes of the two types of sources.

4.1 Expected noise signal for Bright and Faint sources

Figure 2 and Figure 3 show the total noise variance versus the number of groups as obtained by applying the UTR and MACC sampling methods to the expected ramps for bright and faint sources respectively. The sampling rate $1/t_f$ and the number m of scans to coadd per group used to provide the curves are reported in each plot. The noise requirement at 1.5 µm is plotted for comparison. We assumed to use the same readout mode for all wavelengths in the range covered by the VNIR channels. This assumption is correct for the wavelengths in the range 0.6µm-2.5µm, where the focal plane intensities obtained by considering the spectral types of the sources that will be observed by EChO, and convolving their flux in the various spectral elements with the related bandpass and all other instrumental effects, show a regular behavior with similar values in all considered spaxels (it is worth remembering that different pixels in the VNIR focal plane will be interested by different spectrum wavelengths and orders and, consequently, by different input flux levels). In the range 0.4µm-0.6µm the expected flux is considerably lower. Given the early phase of the mission and the status of the design of the overall detectors data acquisition chain, we decided to use the same readout mode also in this range. This assumption does not allow to optimize the results for the shorter wavelengths, but shall be considered as the first step of a more detailed investigation that will be performed in the next phases of the work

The adopted sampling rate is 8 Hz for bright sources and 1/16 Hz for faint sources, see Focardi et al. 2014[12]. In all plots of Figures 2 and 3 the black line represents the noise requirement, the triangles the expected total noise obtained considering the readout noise of the Teledyne detectors and the stars the total noise expected with the SELEX ES arrays.

In both cases the maximum considered number of scans to coadd per group is m = 3 (plot "C" in the two Figures). This because for greater m numbers the total groups number per exposure would not be sufficient to perform the linear fit of the ramps and ultimately to allow for CR detections and correction.

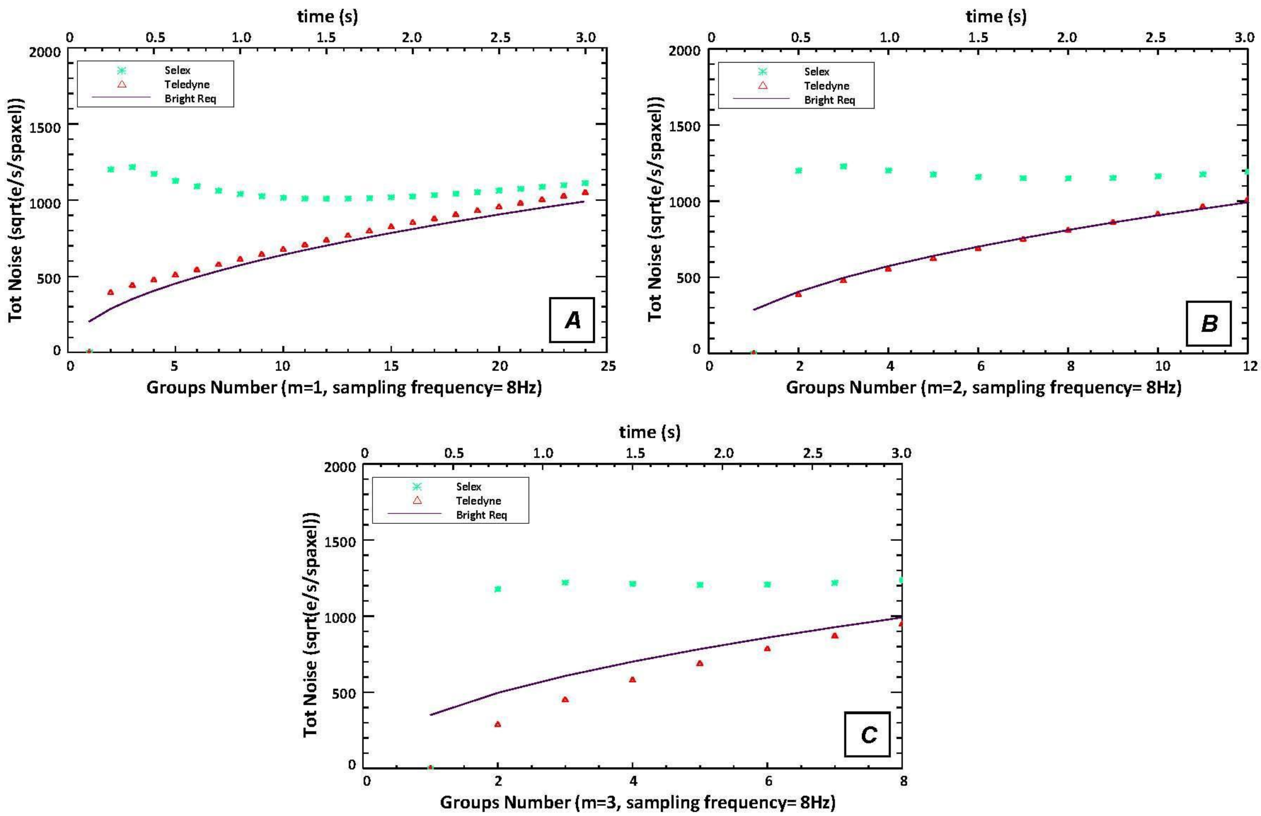

Figure 2 Comparison between noise requirement and expected noise for bright sources with different *m*.

The plots have been obtained assuming a detectors readout at constant rate and the processing of all acquisitions. The readings when grouped are coadded and averaged, resulting in only one average value being saved every $t_g = m \times t_f$ seconds. As described in section 3, it should be also possible to discard some readings between the groups in order to minimize the overall data volume. In this case, the time between adjacent saved groups is given by $t_g=(m+d)$ sec, where d is the number of dummy readouts.

For bright sources, it was possible to obtain an optimized set of readout mode parameters only in the case of the Teledyne detectors, which provided an expected total noise below the scientific requirement for $m>1$. The estimated noise for the SELEX ES detectors was always well above the noise requirement and the obtained trend was not decreasing with the increase of the integration time. In addition, in the case of the Teledyne detectors, for $m\geq2$, the minimum number of groups to satisfy the requirement was always very low. This situation will allow 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.

In case of faint sources the results obtained for the 1/16Hz sampling rate were similar to the previous ones, even if in this case the considered SELEX ES detectors were able to meet the noise requirements in at least one case, with $m=3$ and the minimum groups number equal to 7.

Considering these preliminary results it was shown that with Teledyne sensors it is possible to better combine bright and faint sources results, while SELEX ES detectors performances in terms of the overall noise obtainable with different readout strategies need to be better investigated.

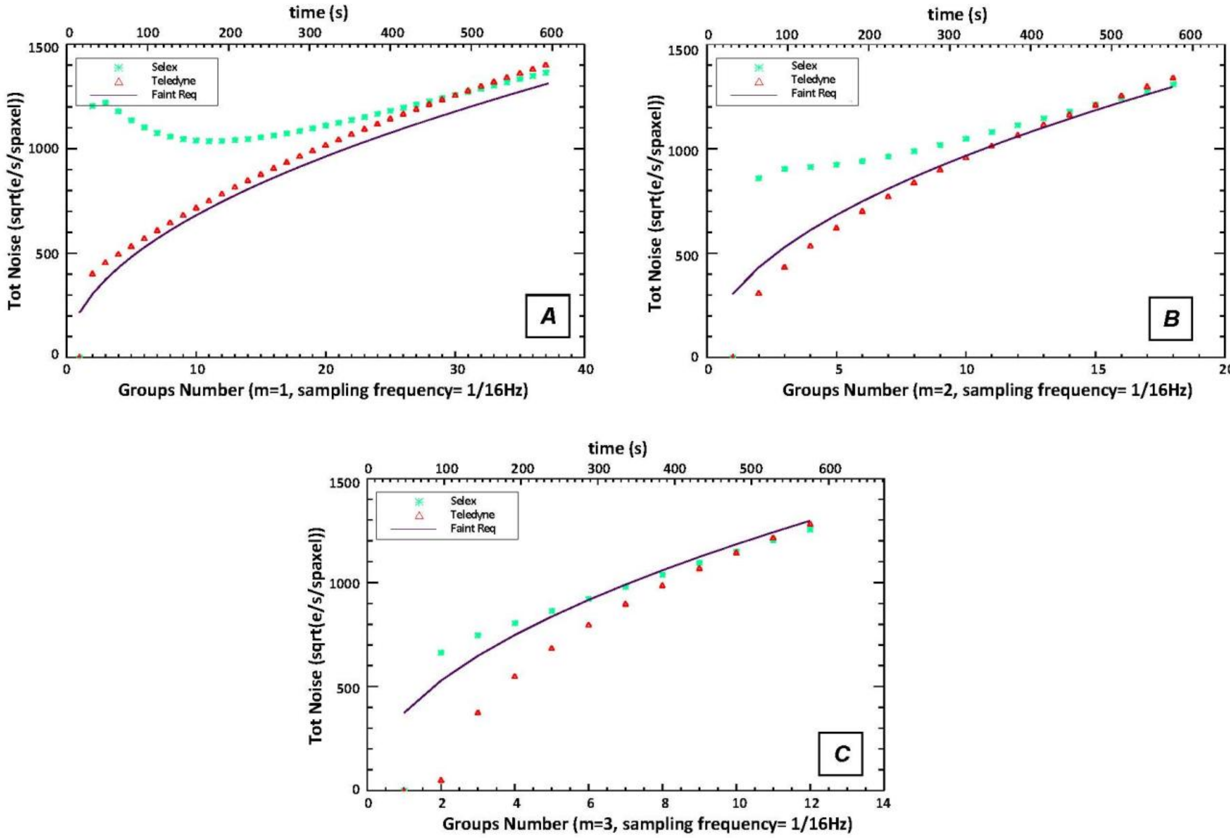

Figure 3 Comparison between noise requirement and expected noise for faint sources with different *m*.

5. COSMIC HITS RATE

The EChO observatory needs a cold and stable thermal environment as well as a large field of regard to allow efficient time-critical observation of targets randomly distributed over the sky. For these reasons, it has been planned to place the satellite in a large amplitude orbit around the L2 point, i.e. the second Lagrangian point. This position is one of the five solutions to the three-body problem provided by the mathematician Joseph-Louis Lagrange and in the Earth-Sun system it is located about 1.5million km from the Earth in the anti-Sun direction. In the past the WMAP, Planck and Herschel space missions orbited around this point. Presently the Gaia spacecraft is in L2 and in the future, the James Webb Space Telescope (JWST) will reach it before starting its observatory operations.

Near the Earth, the magnetic field offers a partial shielding to solar energetic particles and cosmic rays. This shielding capability decreases with the distance. The expected cosmic hits rate in L2 have been studied for JWST (Fixsen et al. 2000[13]; Rauscher et al., 2000[14]). According to these works, a rate confined between 5 and 30 events/s/cm^2 should be considered.

When a cosmic ray impacts a detector any unrecorded information stored in the focal plane at the impact location is lost. In order to understand which would be the volume of the data loss due to cosmic hits, the impacts rate estimation of JWST have been applied to the VNIR focal plane array. The result is shown in Table 3 together with the percentage of pixels affected by the impacts when considering the maximum integration times for bright (3s) and faint (600s) sources. The assumption is that five pixels are involved by each hit. The results are for the design of focal plane under study for EChO mission.

Table 3 Expected cosmic rate hits and data loss percentage assuming five pixel affected per cosmic ray hit.

Focal plane array (pixels)	512×512
Pixel size (µm)	18
Mean rate (events/s)	15
Events in 600 s	9000
Events in 3 s	45
Pixels affected in 600 s (%)	17.15
Pixels affected in 3 s (%)	0.10

The percentage of data loss is negligible in the case of bright sources. In this case, therefore, it will be not necessary to correct the ramps for the cosmic hits effects, but it will be sufficient to identify and discard the affected readouts (only a max 0.10% of the overall array will be affected by the cosmic hits in a 3 seconds exposure). On the other hand, for faint sources the percentage is quite high, and therefore a more detailed evaluation is needed, to assess the real need to implement a deglitching procedure onboard.

6. CONCLUSIONS

The total noise variance for the UTR and MACC readout modes has been provided for the VNIR focal plane detectors, as expected for the observation of the faintest and the brightest targets to be measured during the EChO mission.

The sampling rates of 8 Hz for bright sources and 1/16 Hz for faint sources have been considered. For bright sources only the Teledyne detectors provided an expected total noise below the scientific requirement. and in the case of $m \geq 2$, the minimum number of groups to satisfy the requirement is always very low. This situation allows to keep the maximum integration time as short as possible and to minimize the expected number of cosmic hits.

In case of faint sources both the considered types of detectors meet the noise requirements in at least one case, i.e. with $m=3$ and the minimum groups number equal to 7.

The main conclusion of our analysis is that two different readout rates and sampling methods are needed for bright sources and faint sources. With the noise performances considered for the Teledyne MCT detectors, it is possible to meet the noise requirements well within the maximum allowed integration times in both cases.

Future investigations are planned to improve the overall detector readout chain performances. The possibility to apply hardware coded ramps coaddition and to modify the detectors sampling rates will allow to explore a wider parameter space for the optimization of the readout mode procedures.

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