The instrument control unit of the EChO space mission: electrical architecture and processing requirements

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ABSTRACT

The Exoplanet Characterization Observatory (EChO) is conceived for the spectrophotometric study from space of the atmospheres of a selected target sample of transiting extra-solar planets. It has been designed to run as a candidate for the M3 launch opportunity of the ESA Cosmic Vision program and can be considered as the next step towards the fully characterization of a representative sample of the already discovered transiting exoplanets.

The EChO payload is based on a single highly thermo-mechanical stabilized remote-sensing instrument hosting a dispersive spectrograph. It is able to perform time-resolved spectroscopy exploiting the temporal and spectral variations of the measured signal due to the primary and secondary occultations occurring between the exoplanet and its parent star. The adopted technique allows the extraction of the planet spectral signature and to probe the physical and chemical properties of its atmosphere.

EChO is composed by four scientific modules, all suited on a common Instrument Optical Bench (IOB). Each module is operated by a unique control and processing electronics, the Instrument Control Unit (ICU), acting as interface between the payload and the spacecraft (S/C) Data Management Subsystem (DMS) and Power Control and Distribution Unit (PCDU).

The main ICU tasks concern the instrument commanding, based on the received and interpreted TC & TM; instrument monitoring and control by means of the housekeeping (HK) data acquired from the focal plane units; synchronization of all the scientific payload activities; detectors readout and data acquisition, pre-processing, lossless compression and formatting before downloading the TM science data and HK to the spacecraft mass memory.

As far as the software is concerned, these activities can be basically grouped and managed by the *Instrument Control* software and *Data Processing* software; both will constitute the On Board Software of the overall payload designed to address all the processing requirements as driven by the EChO science case [1, 2].

This paper is conceived as a memory for an EChO-like payload electrical architecture with processing capabilities mainly driven by the scientific requirements as defined and frozen at the end of both the Payload Assessment Phase and the M3 mission selection process, held by ESA at the beginning of February 2014.

Keywords: Exoplanets atmospheres, spectrophotometer, Instrument Control Unit, processing requirements, data processing, On Board Software.

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Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, edited by Jacobus M. Oschmann, Jr., Mark Clampin, Giovanni G. Fazio, Howard A. MacEwen, Proc. of SPIE Vol. 9143, 91434H · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2055443

1. INTRODUCTION

The EChO instrument basic concept [3] consists of a 1.2 m class telescope passively cooled down to 50 K on a spacecraft in orbit around the second Lagrangian point (L2) of the Sun-Earth system. The observation sequence is characterized by staring-mode spectroscopic acquisitions taken over the various phases of the target light curve as the planet transits in front and behind the host star. The spectrum of the planet can be recorded either in absorption against the stellar spectrum (primary transit) or in emission together with that of the star. The stellar spectrum is observed in the absence of the planet as the planet transits behind the star (secondary eclipse). The signal from the planet is thus isolated from the star by properly fitting a light curve to each observation.

The contrast between the star and the planet spectra is a function of the stellar type and the size and temperature of the planet and varies strongly with wavelength. Typical values range from 10^{-3} for "hot Jupiters" in orbit around G stars to 10^{-5} for "temperate super-Earths" around late-type M stars [4]. Extracting the spectrum of the planet therefore requires the co-addition of many transit observations (defining the overall observing time) in order to build up the total signal to noise ratio in the measurement. To achieve this to the requested level demands a high level of stability in the detection system, requiring, in turn, a payload design with a high degree of integration between the various components and with the satellite subsystems.

All aspects of the system and payload design need careful attention, especially with regard to factors that can affect the photometric stability of the system and/or provide spurious signals that might mimic the light curve signature from the target planetary systems (i.e. the stellar activity).

1.1 The EChO payload

The basic instrument configuration is represented by a three modules (VNIR, SWIR, MWIR)[1] highly integrated, common field of view, spectrometer that covers the full mission-required wavelength range from 0.55 µm to 11.0 µm. The baseline design includes the goal wavelength extension to 0.4 µm while an optional LWIR channel extends the range up to the wavelength of 16.0 µm. In this way the full payload can incorporate up to six channels divided into four modules mounted on the same IOB and fed by a series of dichroics operating in long-pass mode splitting the incoming light into the different channels.

There are two fibre-fed VNIR channels (one visible and one near-infrared) covering the 0.4 µm - 2.47 µm wavelength range [5, 6, 7, 8], one SWIR channel covering the 2.42 µm - 5.45 µm range, two MWIR channels covering the 5.05 µm - 11.5 µm range (5.05 µm - 8.65 µm and 8.25 µm - 11.5 µm) and the optional LWIR channel covering the 11 µm - 16 µm interval. The two MWIR channels, as well as the VNIR ones, are imaged on a single focal plane.

The channel boundaries were chosen in such a way as to avoid potential weaknesses in the optical performances of the dichroic elements, and to ensure overlapping of spectral ranges between modules for full wavelength coverage and cross-calibration purposes.

The payload also includes a Fine Guidance System (FGS), necessary to provide a closed-loop feedback to the high stability spacecraft pointing. The required spectral resolving powers of 300 (VNIR, SWIR) or 30 (MWIR, LWIR) are achieved or exceeded throughout the band. The baseline design largely uses technologies with a high degree of technical maturity (TRL > 5).

The payload instrumentation and the detectors proximity electronics are passively cooled at ~ 45 K with a dedicated instrument radiator for cooling the FGS, VNIR and SWIR detectors to 40 K. An Active Cooler System based on a Neon Joule-Thomson Cooler provides the additional cooling to ~ 28 K which is required for the longer wavelengths channels (MWIR, LWIR).

In the present baseline payload design the detectors for the VNIR, SWIR and FGS modules are represented by the Teledyne HgCdTe (MCT) arrays with 512 x 512 - 18 µm pixel pitch (HxRG devices). These arrays are produced in US and are presently the only ones at the required TRL level with an expected noise within the EChO requirements as well as the Teledyne NEOCam device, selected as the baseline for the MWIR channel.

The advantage of this configuration is the simplification of the payload cooler by avoiding the use of an active two-stage cooler otherwise required to operate the alternative Raytheon Si:As detectors down to 7 K to achieve the desired dark current level at longest wavelengths.

Following these considerations, the baseline payload design (without the LWIR module) relies on spectrometer modules

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[1] VNIR: Visible and Near Infrared; SWIR: Short Wavelength Infrared; MWIR: Medium Wavelength Infrared; LWIR: Long Wavelength Infrared.

hosting only MCT-type detectors from Teledyne operating at temperatures no lower than 28 K and electrically and mechanically bonded with their ROICs (readout integrated circuits).
All the ROICs have at least four or more analogue outputs, amplified and interfaced with their own cold front-end electronics CFEEs (i.e. the Teledyne Sidecar ASICs) where detector clocking, wave shaping, signal filtering and analogue to digital conversion are managed. Digital data are then transferred to the Warm Front End Electronics (WFEEs) hosting a digital logic (mainly a FPGA and/or a microcontroller) to produce command and control signals and digital clocks (mainly the Master Clock and Sync signals) to drive the detectors ROICs and the Sidecar ASICs.
The pre-processing operations on the acquired spectra (e.g. digital masking and image cropping) as well as HK management and A/D conversion are implemented on board the WFEE by means of a suitable FPGA, as a support to the overall ICU processing.

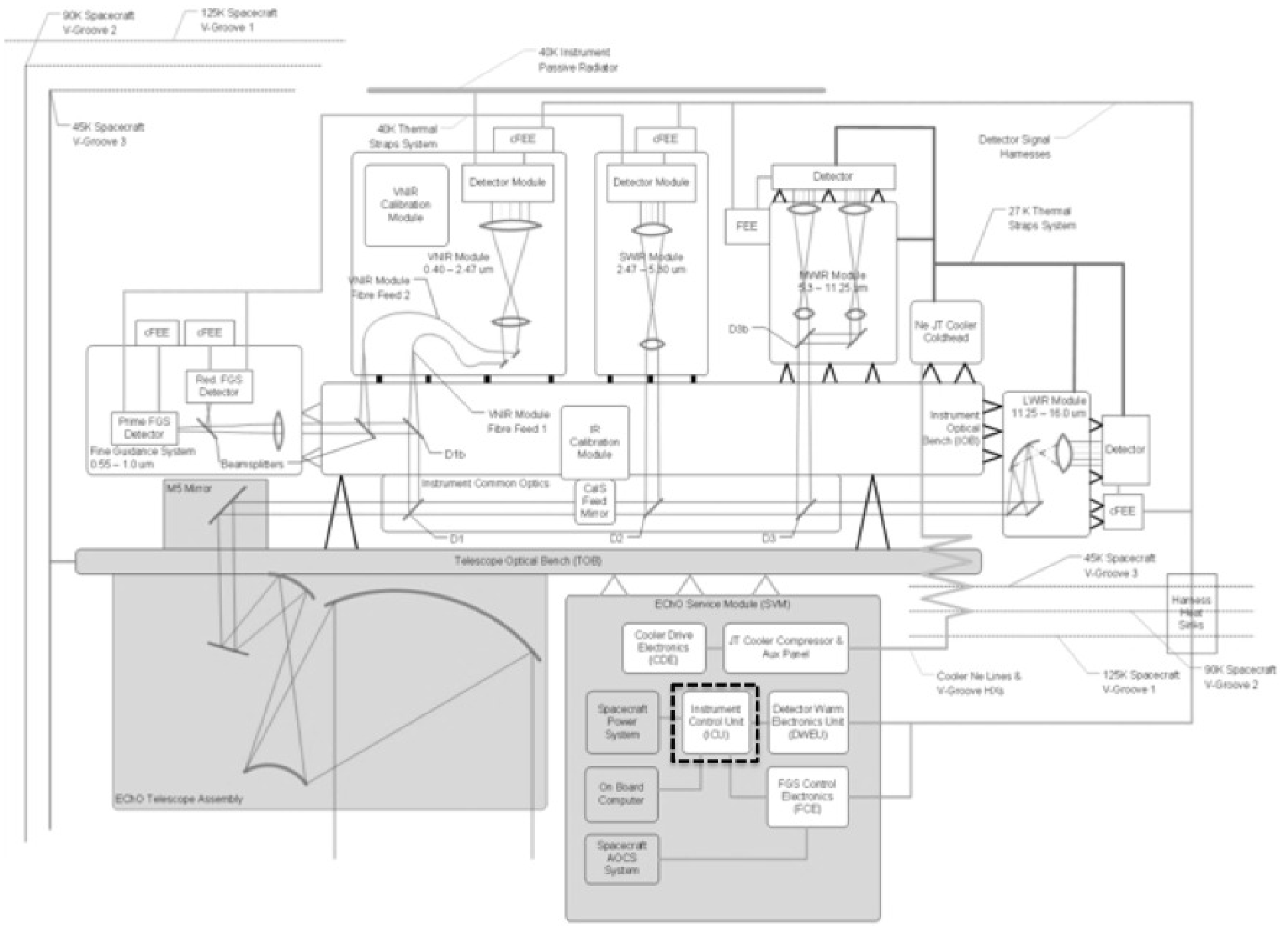

Figure 1. EChO Payload functional block diagram. Due to the severe thermal requirements, the instrument is split into cold and warm parts. The ICU, operating at 273K - 300 K, is located in the warm Service Vehicle Module (SVM) part. Courtesy EChO Consortium.

2. ICU BUDGETS AND PROCESSING REQUIREMENTS

The ICU design process, as well as the overall payload design, originates from the basic requirements and environmental constraints reported in the ESA EChO governing documents data pack. In particular the Experiment Interface Document - part A (EID-A) [9] provides the mechanical, thermal and electrical budgets as well as the assessment of the overall payload interfaces to the Spacecraft.

These budgets and constraints have been collected and resumed in the EChO Requirements Specification documents by the Consortium and addressed by the EID-B document [10] and by the overall Assessment Study Report documentation provided to ESA.
In the following we provide only the main requirements useful for the scientific data processing definition and the ICU electrical and electronic design supporting the data processing and the instrument management tasks. ICU power, mass and volume identified at the end of the design process (Tab. 1), have been demonstrated within the limits pointed out in the EID-A. The main constrain limiting the design choices and the science planning is the overall data volume produced weekly by the instrument and transmitted, as formatted telemetry (TM), to the S/C. This data volume is fixed in less than 35 Gbits/week.

Budgets	*Basic*	*Nominal (20% cont.)*	*Margin*
Power (W)	20	24	4 (cont.)
Mass (Kg)	7.5	9	< 25 (total electronics)
Volume (mm^3)	250 x 240 x 150	-	0 x 0 x 30

Tab. 1. ICU power, mass and volume budgets.

The data flow across the sub-units and the timing of the processing tasks are mainly dictated by the star target brightness, the integration times and sampling rates required to collect spectra with a defined S/N ratio as well as by the spatial and spectral resolution adopted by each channel. The number of pixels used to properly acquire spectra and their digital representation (a grey scale depth of 16 bit/px), defines the overall data volume to be managed by the instrument.

2.1 Observational requirements

The main observational requirements concern both the observing efficiency of the EChO S/C during science operation phases, which shall be ≥ 85%, and the magnitude of the brightest and faintest stars to be observed by the payload, ranging from 2.9 (K magnitude, F9V-type star) for bright targets to 9.8 (K magnitude, M5V-type star) for the faintest ones. The fluxes from these targets are evaluated using the appropriate values from literature and libraries, and are based on the wavelengths of the emission peak of the target as a function of its temperature, the star radius and the distance from the Sun [11].

2.2 Data processing requirements

The expected data streams coming from the detectors assemblies are the main drivers to estimate the resources needed to perform the on-board data processing requested by science [11]. The most demanding modules from the point of view of digital processing are the VNIR and the SWIR ones. On the former module the VIS and NIR spectra are spread on the two detector halves, which are readout with a different output stage gain to collect signals with a proper S/N ratio. Therefore, the main design steps and the system processing needs have been performed and evaluated for these channels as a reference.
The detectors pixels will be digitally binned (on-chip binning is also possible, as baseline) to produce spaxels, i.e. n x n binned pixels along the spatial and spectral dimensions (n=5 in the baseline VNIR design).
In particular, in order to perform on board data processing and pixel deglitching from cosmic rays hitting the VNIR FPA, the two FPA halves (VIS and NIR ones) are digitally masked and cropped. This pre-processing task is adopted to reject all pixels not containing any useful information, reducing the overall pixels number to be processed to a factor of the order of 70% of the entire array. As baseline, digital masking and image cropping are processing tasks assigned to the WFEEs FPGAs, to reduce the overall computational load assigned to the ICU [12].
The basic data processing assumption is to sample up-the-ramp pixels in a non-destructive readout manner with a sampling rate up to 8 Hz (Tab. 2) [13]. This rate can be determined on-ground by simulations activities and in flight by dedicated calibration procedures. The maximum length of the ramp is determined by the saturation limit of the detectors for either target. Destructive readouts are considered after each exposure for bright, normal and faint sources for pixels resetting. The sampled ramps are fitted and the pixels photocurrent extracted. These data are then processed for pixels cosmic rays deglitching [14] (for the longest integration times), lossless compressed and transmitted to the S/C in

CCSDS format according to the instruments operating modes.

2.3 System performance requirements

The system level noise (after post-processing) has been assessed to be lower than X times the astrophysical noise, defined by the square sum of the stellar and zodiacal background shot noises.
The total noise shall then be less than:

$$Noise_{TOTAL} \leq \sqrt{(N_0 + zodi) \times (1 + X)}$$

Eq. 1. The total noise as a function of the stellar and zodiacal background shot noise.

Where N_0 is the flux by the target star being observed and the zodiacal background contribution (*zodi*) shall be evaluated using a worst FoV case (10”x10” - as baseline) and the averaged *zodi* value as defined by requirements. X represents a factor of noise increment that is a function of the wavelength (200% under 1 µm and 30% above 1 µm).
The square of the system level noise (after post-processing) is given as a function of the wavelength in Fig. 2 and shall be summed in RSS (root sum square) with the noise floor. The latter is defined by the noise introduced by the data acquisition system and the noise characteristics of the detector (mainly the readout noise introduced by the electronic chain up to the digital data output).
Once assessed the post-processing overall system noise level (astrophysical noise plus noise floor) it is possible to define the overall integration time to get a targeted S/N ratio aver a scientific observation, the ramps lengths (within the adopted sampling up-the-ramp or multi-accumulation method) and the number of the samples for a single ramp [13].

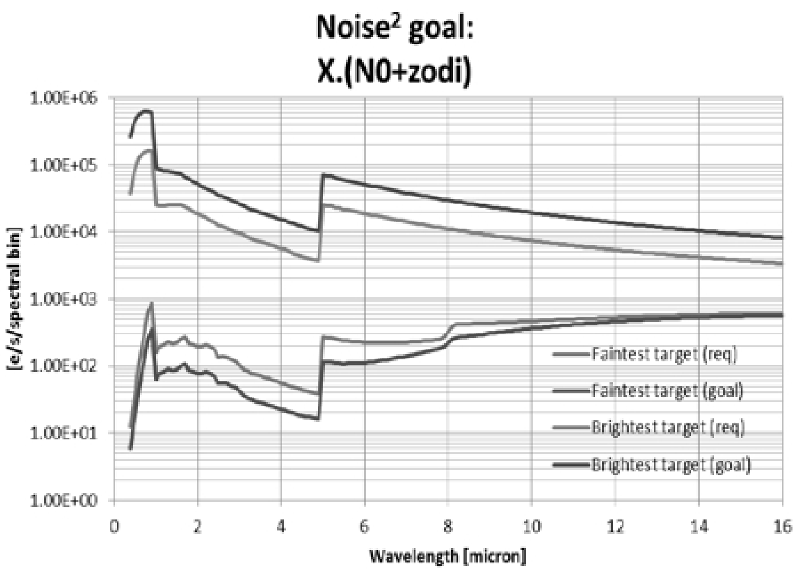

Figure 2. The square of the added (astrophysical) system level noise in *e/s/spectral bin* as a function of wavelength for the faintest and brightest star targets as defined by requirements and assessed by the chosen goals. Courtesy: EChO Consortium, Detectors WG.

The overall data flow (in bit/s) produced by all the scientific modules depends on the sampling rate, the number of involved pixels and their digital representation. These data shall be acquired, buffered and finally processed by the ICU electronics.
In order to evaluate the data rate budgets we defined three kinds of targets (bright, normal and faint) and the percentage of the mission time dedicated to each of them. For the bright mode observations we decided to transmit to the S/C (and from here to ground) only the on-board (ICU) evaluated ramp slopes plus a “goodness” of the fit for each ramp. For normal mode we foreseen to transmit the evaluated ramp slopes with no goodness of fit and, for the faint mode, all the raw data produced by the scientific modules.
The main parameters adopted for the scientific observations are resumed in Tab. 2.

Target type	*Primary sampling rate (Hz)*	*Ramp length (s)*	*ICU input Kspaxels/s (#)*	*Acquired ramps/s (#)*	*Scientific data daily rate (Gbit/day)*	*Assigned observing time (%)*
Bright	8	3	183.2	7634	21.1	7.5
Normal	1	32	23.2	1449	4.0	60
Faint	0.125	240	2.9	97	4.0	32.5

Tab. 2. Main parameters used to assess the ICU processing requirements (as a function of the star targets brightness) to guarantee a total uncompressed daily data volume (scientific data and HK TM) produced by ICU within 5 Gbits (35 Gbits/week max) with an assumed observing efficiency of 90%. Data compression factor is not considered here as it is used as a free parameter (ranging from 2 to 2.5) to fit the daily data volume varying the assigned observing time for a given star target.

2.4 The influence of cosmic rays pixel deglitching and data compression on ICU processing

Deglitching pixels arrays from cosmic rays hits is commonly an operation to be performed at pixel-level [13, 14]. Operating binning on-chip would lead to lose any pixel-based info on cosmic rays hits that would blur the spaxel integrated signal at the same time. Taking into consideration the predicted cosmic rays flux for an instrument located at L2, and an integration time from 1.5 to 3 seconds for bright targets, only less than 0.02% of pixels would be interested by cosmic rays hits, so an option to be considered could be avoiding any on-board deglitching operations based on pixels processing at least for bright targets.

The classical deglitching pixel-based procedure is a demanding processing task for the ICU CPU that would require the heavy use of the processor Floating Point Unit for the second derivative calculus needed for the glitches recognition and correction.

Deglitching could be operated at spaxel level by detecting cosmic rays hits and discarding them as outliers w.r.t. a median value reference as an operation performed on spaxel sub-arrays. This kind of simplified deglitching procedure has been considered for the implementation at FPGA level (HW-level). Pixels affected by cosmic rays hits should be flagged and not considered for the rest of the ramp production but properly replaced.

The number of pixels belonging to a spaxel and affected by a cosmic ray hit can be determined by the hit geometry and particles energy. Adopting a proper detector shield only few pixels would be interested by a single cosmic ray hit and it should be possible to operate deglitching only for the faint targets (if needed) which require longer exposition times with a bigger and not neglecting hit likelihood [13].

Deglitching from cosmic rays hits has surely a big impact on the overall ICU processing architecture and should be carefully evaluated with respect to the overall system budgets. Deglitching is presently foreseen at CPU level in the ICU processing needs estimate.

Following the on-board pixels/spaxels processing all the scientific data representing spectra are compressed, packetized and sent to the S/C Solid State Mass Memory (SSMM). Lossless data compression techniques such as the extended-Rice and the small-Rice algorithms have been considered, leading to the baseline assumption of implementing a SW lossless compression.

Preliminary tests on very simple simulated spectra lead to lossless compression ratios (CR) above the needed factor of 2. As the processing time and the overall performance are strictly dependent on the target CPU we also took into consideration the possibility to adopt a HW compressor, where the implementation of the lossless compression algorithms is addressed at FPGA level exploiting a HDL language or using a dedicated ASIC.

2.5 Required baseline HW

Tab. 3 reports the expected ICU daily data volume, the data rates to the S/C, the CPUs expected processing power and memories usage. The following assumptions have been taken into account: the averaged number of clock cycles/elementary operation is 3 (1 MIPS = 3 Mega clock cycles); the number of elementary operations/pixel include the OS background activity overhead; digital data are stored in memory (SRAM and SDRAM/FLASH) before CPU processing; masking is performed by a FPGA aboard WFEEs before sending data to the ICU CPU; payload control refers to TC execution activity between ICU and the modules, including calibration units management.

Once pre-processed, scientific data are temporarily buffered and then sent to the DMS Solid State Mass Memory.

The main results shown in Tab. 3 are represented by the need to adopt two LEON-based CPUs, one for data processing and one for the overall instrument control. We also selected three Actel RTAX 2000-like FPGAs for pre-processing, memory management and auxiliary functions. The overall amount of different kind of memories is conceived for temporarily storage, buffering and processing purposes.
All the ICU processing and buffering capabilities are presently evaluated taking into account a 50% of margin, as usually adopted at the end of the Assessment Study (Phase A) and as required by EID-A.

	Scientific channels				
	VIS +NIR	*SWIR*	*MWIR-1*	*MWIR-2*	*LWIR (optional)*
Pixels covered by spectra	512x512	1024x13	63x13	87x13	50x6
Pixel pitch (μm)	18	18	25	25	25
Adopted binning	5x5	1x1	1x1	1x1	1x1
Digital masking	70%	100%	100%	100%	100%
# bits/pix	16	16	16	16	16
Primary rate (Hz) - (Bright targets case)	8	8	8	8	8
Ramp lenght (s) - (Bright targets case)	3	3	3	3	3
# Samples per ramp	24	24	24	24	24
Housekeeping TM (Gbit/day)	0.2				
Efficiency	85%				
Contingency	50%				
Available lossless compression factor (CR)	2÷2.5				
# CPUs (LEON-like running @ 60 MHz)	2 (Processing & Instrument Control)				
# FPGAs (RTAX 2000-like running @ 80 MHz)	3 (pre-processing, memory management and auxiliary functions)				
SRAM needed (MBytes)	16 (4 x 4 banks)				
SDRAM or FLASH needed (MBytes)	20				
EEPROM/PROM (MBytes) - BOOT SW, BIOS SW, ASW	8 (4 x 2 banks)				
Daily averaged data rate	< 60 kbit/s				
Peak data rate (burst mode, if needed)	< 10 Mbit/s				
Science TM (Gbit/day)	< 5				
TOT. expected daily data volume – science + HKs (Gbit/day)	< 5				

Tab. 3. Main HW components selected for the ICU design, based on processing requirements and system budgets.

Assuming a HK production rate of 0.2 Gbits/day, a realistic duty cycle of 85-90% and a lossless compression ratio of 2, then spending 10% of the mission in Bright targets mode, 80% in Normal targets mode and 10% in Faint targets mode gives a data rate of 4.72 Gbits/day, meeting the data rate requirement for the entire payload.
Values reported in Tab. 3 strongly depend on data processing required for onboard (ICU) deglitching procedures, compression task and pixels pre-processing, as discussed in the previous paragraph.

3. ICU ELECTRICAL ARCHITECTURE

This paragraph is dedicated to an overview of the ICU electrical architecture [15], as derived by the basic payload budgets and constraints coming from the EChO EID-A document as well as from the scientific data processing requirements previously defined. A more detailed description is reported on the Experimental Astronomy Journal, "*EChO Special Issue"*, edited by Springer in 2014 [16] and fully dedicated to the EChO science case.

3.1 ICU block diagram

ICU is structured in three main sub-units: DPU, HCU and PSU. The Data Processing Unit is a digital sub-unit with processing capabilities needed to implement the on-board data processing, the data storage and packetization, the telemetry and telecommand packets handling and the clock/synchronization operations.
The Housekeeping and Calibration source Unit is a sub-unit designed to provide the thermal control of the instrument subsystems and to manage the calibration source and the HK retrieval, while the Power Supply Unit manages the secondary voltages distribution to the instrument subsystems and ICU internal boards by means of DC/DC converters.
A single common TM/TC interface is foreseen at ICU level to minimize and simplify the number of interfaces towards the spacecraft. The ICU electronics reliability is based on a cold-strapped redundant architecture that removes or mitigates any electronics single-point failures. The tracks routing for the cold-strapping redundancy are foreseen on the back panel connecting all the electronics boards.

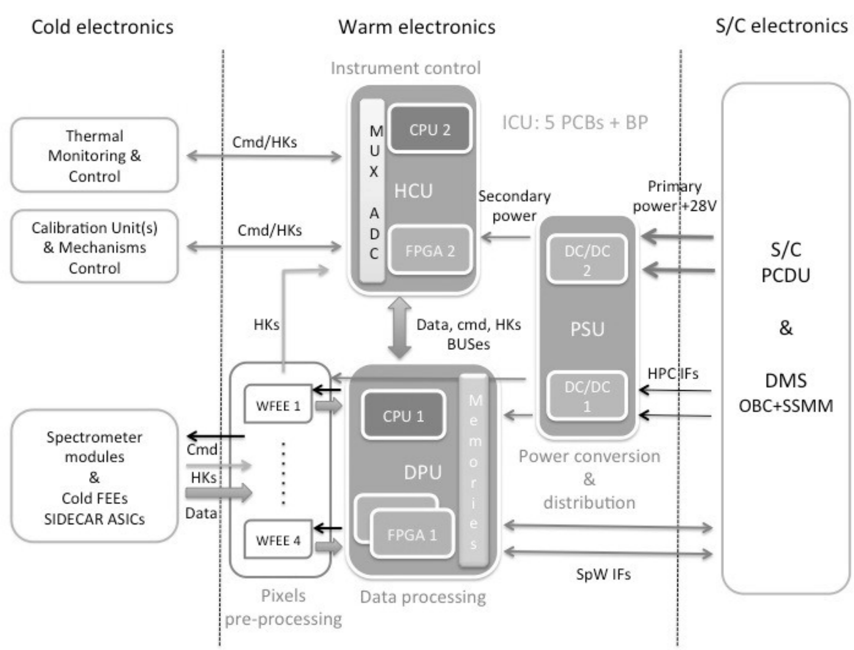

Figure 3. EChO baseline payload electronics block diagram. ICU is composed by 5 electronic boards plus a back panel and its subsystems are represented by light grey in the picture.

4. CONCLUSION

This paper has provided an overview on the EChO ICU electrical architecture as defined at the end of the M3 selection process. ICU has been designed following the processing requirements derived by a trade-off process between the scientific requirements and system budgets as dictated by the ESA EChO governing documents data pack and environmental constraints.

Although EChO has not been selected by ESA for the M3 launch slot the Consortium is still working with the same devotion in order to find a new and perhaps more exciting flying opportunity.

5. ACKNOWLEDGMENT

The Authors are grateful to the Italian Space Agency (ASI) for the support and the financial contribution "ASI-INAF agreement I/022/12/0" for the "Partecipazione Italiana allo Studio di Fattibilità della Missione EChO", to the overall partners of the EChO Consortium coordinated by the UK Rutherford Appleton Laboratory (RAL) and the EChO PI. Thanks also to the European Space Agency (ESA) for the support to the development of the mission Assessment Phase study.

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