Thermal architecture of the Exoplanet Characterisation Observatory payload

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ABSTRACT

The Exoplanet Characterisation Observatory (EChO) is a space project currently under study by ESA in the context of a medium class mission within the Cosmic Vision programme for launch post 2020. The EChO main scientific objectives are based on spectroscopy of transiting exoplanets over a wide range of wavelengths, from visible to mid-infrared. The high sensitivity requirements of the mission need an extremely stable thermo-mechanical platform. In this paper we describe the thermal architecture of the payload and discuss the main requirements that drive the design. The instrument is passively cooled to a temperature close to 45K, together with the telescope, to achieve the required sensitivity and photometric stability. Passive cooling is achieved by a V-Groove based design that exploits the L2 orbit favorable thermal conditions. The Visible and short-IR wavelength detectors are maintained at the operating temperature of 40K by a dedicated radiator coupled to cold space. The mid-IR channels require lower temperature references for both the detectors and part of the optical units. These colder stages are provided by an active cooling system based on a Neon Joule-Thomson cold end, fed by a mechanical compressor, able to reach temperatures <30K.

The design has to be compliant with the severe requirements on thermal stability of the optical and detector units. The periodical perturbations due to orbital changes, to the cooling chain or to other internal instabilities make the temperature control one of the most critical issues of the whole architecture. The thermal control system design, based on a combination of passive and active solutions needed to maintain the required stability at the detector stages level is described.

We report here about the baseline thermal architecture at the end of the Study Phase, together with the main trade-offs needed to enable the EChO exciting science in a technically feasible payload design. Thermal modeling results and preliminary performance predictions in terms of steady state and transient behavior are also discussed.

This paper is presented on behalf of the EChO Consortium.

Keywords: Space instrumentation, thermal control, cryogenics, infrared, spectroscopy, exoplanets

1. INTRODUCTION

The Exoplanet Characterisation Observatory (EChO) is a space mission proposed in 2014 as a candidate for the Medium Class M3 opportunity of the ESA Cosmic Vision 2015-2025 programme.

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, 91433C · © 2014 SPIE
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Observations of the increasing number of exoplanets by space and ground telescopes show an incredible variety of characteristics (orbits, dimensions, temperature, composition, atmosphere, etc.) indicating that planetary systems appear much more diverse than expected. EChO[1] is the first dedicated mission to investigate exoplanetary atmospheres and to take up the challenge to explain this diversity, providing fundamental information on formation, evolution, internal structure and planet and atmospheric composition at a level never previously achieved.

The mission is aimed at undertaking spectroscopy of transiting exoplanets over the widest wavelength range possible, providing high resolution, multi-wavelength spectroscopic observations on the atmospheres of a large and representative selected sample of known exoplanets. EChO results could constrain models of the planets internal structure and improve our understanding of how they form and evolve, addressing their suitability for life and placing our Solar System in context.

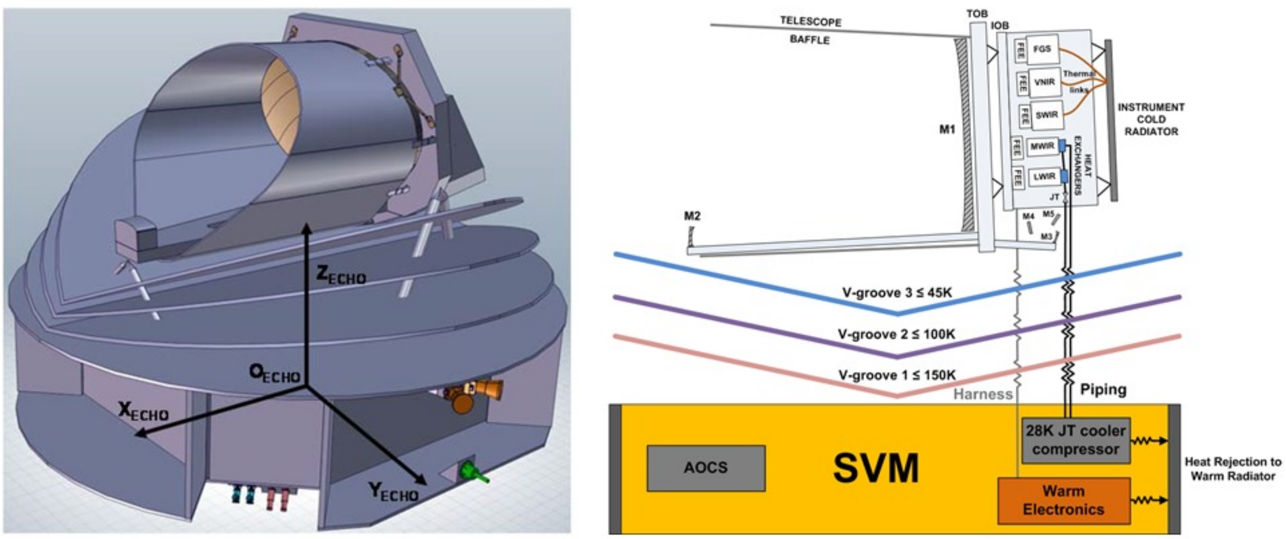

Figure 1. Pictorial view (left) and block diagram (right) of the EChO spacecraft

1.1 Payload baseline architecture

EChO is designed as a dedicated survey mission for transit and eclipse spectroscopy capable of observing a large planet sample within its four-year mission lifetime[2]. EChO will be launched on board the Soyuz launcher from the *Centre Spatial Guyanais* in Kourou (French Guiana), into a direct transfer leading to a large amplitude orbit around the Sun-Earth L2 point. This science operations orbit is key to meeting two of the most important requirements: it offers a very stable environment (for thermal, power and communication purposes), combined with a very large instantaneous field of regard.

In Figure 1 is represented a block diagram showing the basic mission concept: a cold Payload Module (PLM) mounted on a warm Service Module (SVM)[3]. The SVM contains all the units required to support the payload in operating conditions (the Warm Electronic System[4]) and to keep the spacecraft (S/C) operational. The PLM, supported on the SVM by three glass-fibre reinforced plastic (GFRP) bi-pods, includes the thermal shielding system: three V-Grooves[5] that, in sequence, are used to passively cool the telescope assembly and the instrument to < 50 K. This configuration allows to minimise the thermal background fluctuations and the noise of the focal plane detectors. The telescope assembly (Figure 1) is composed by an optical bench, the mirrors (M1 – M3) and the baffle. The observation sequence consists of staring mode spectroscopic observations taken over the various phases of the target light curve[2]: the spectrum of the planet is seen 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). For this reason, there is no need for a large field of view, nor for high angular resolution. A 1 m^2 class telescope is sufficiently large to achieve the necessary spectrophotometric precision: in practice, the selected telescope is a three mirror elliptical off-axis Korsch design[3] providing an effective collecting area of 1.131 m^2 and a small collimated input beam to the instrument, diffraction limited at 3 μm.

The signal from the planet is isolated from the star by fitting a light curve to each observation as the planet transits in front and behind the host star. To extract the spectrum of the planet therefore requires the co-addition of many transit observations in order to build up the total signal to noise ratio in the measurement. To achieve this to the level required demands a high level of stability in the detection system, requiring, in turn, a very careful payload design especially with regard to factors that can affect the photometric stability of the system and/or generate spurious signals. In this framework, thermal design is one of the key element of systematic errors control.

The payload is completed by the Instrument Focal Plane Unit (Figure 2): the Instrument Optical Bench (IOB), and the relative shroud, that supports the instrument module channels, the instrument radiator and the cryogenic system cold ends for detectors cooling and the fine guidance sensor (FGS) needed to achieve the fine pointing stability required[3].

1.2 Instrument

The scientific objectives of the mission require a broad instantaneous wavelength coverage to detect as many molecular species as possible, to probe the thermal structure of the planetary atmospheres and to correct for the contaminating effects of the stellar photosphere. The baseline instrument for EChO (Figure 2) is a single but modular, three channel (plus an optional one), high stability, highly integrated, spectrometer that covers the full EChO required wavelength range of 0.55 µm to 11.0 µm. The design is optimized to maintain a high level of modularity, to allow for simple technical and programmatic interfaces between units. A common Instrument Optical Bench supports a set of common optics (a dichroic chain) that splits the wavelengths of the incoming radiation from the telescope to the different modules at the band cuts as shown in Figure 2. The instrument design includes a cross-dispersed spectrometer VNIR (Visible and Near InfraRed) module with two fibre-fed channels covering from 0.55 to ~2.5 µm (with the goal of extending the range down to 0.4 µm), a grism spectrometer SWIR (Short Wavelength IR) module covering from 2.5 to 5.3 µm; and a prism spectrometer module with two MWIR (Mid Wavelength IR) channels, imaged on a single focal plane, covering the 5.05-11.5µm range (5.05-8.65µm and 8.25-11.5µm). An extra Long Wavelength IR (LWIR) channel covering the 11–16µm range is part of the general design as a goal. The channel boundaries were chosen to ensure overlapping of spectral ranges between modules for full wavelength coverage and cross-calibration. The spectral resolving power needed, R~300 for wavelengths less than 5 µm and R~30 for wavelengths greater than this, are achieved or exceeded throughout the band.

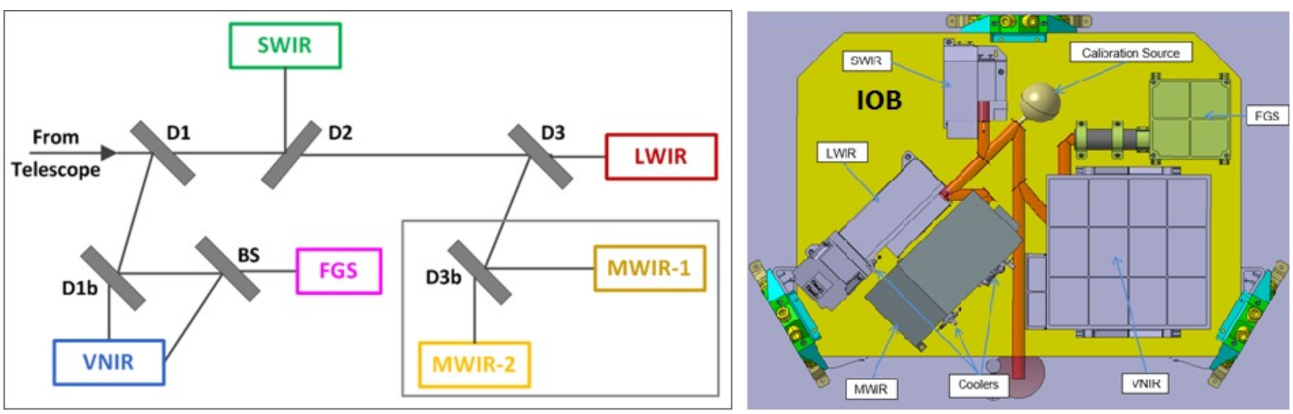

Figure 2. Instrument channels configuration (left) and mechanical layout on optical bench (right)

The baseline selection of detectors for all channels is MCT (Mercury Cadmium Telluride) coupled to SIDECAR ASIC-type Front End Electronics (FEE)[3]. The FGS, VNIR and SWIR channels are based on Teledyne H2RG devices, operating at a temperature of about ~40K. This is achieved passively with a dedicated instrument cold radiator. The M/LWIR detectors reach the required dark current and detector noise level at a temperature of ~28K, that is provided by an active cooler system based on a Neon Joule-Thomson refrigerator[3].

2. THERMAL ARCHITECTURE

The spacecraft thermal design (Figure 3) is based on a cold Payload Module (PLM) sitting on the top of a warm Service Module (SVM). The mission thermal control is ensured by a combination of passive and active cooling systems. The SVM is thermally controlled in the 260K-280K range for nominal operations of all the S/C subsystem units. This is achieved through panel radiators on the module sides that constantly face the cold sky and dedicated heaters where required. Thermal uniformity across the warm radiators can be achieved by heat pipes.

The cold payload is passively cooled by a high efficiency thermal shielding system. The SVM top floor, covered with low emissivity Kapton MLI, acts as the first main barrier between the PLM and the Sun (and the warm units in the service module). A set of 3 thermal shields in a V-Groove (VG) assembly, similar to the configuration in the Planck ESA satellite[5], provides the first three cold reference stages exploiting the favorable conditions of the L2 thermal environment. The V-Groove1, 2 and 3 temperature stages at around 150 K, 90 K and 50K respectively are used for intercepting parasitic heat leaks (harness, struts, piping, radiation, pre-amplifiers) and for cryochain pre-cooling. The Telescope Assembly, operating in the cold environment prepared by the last V-groove, acts as an extra radiative stage using its large baffle and bench as radiating surfaces, reaching temperatures below 47 K by passive means only.

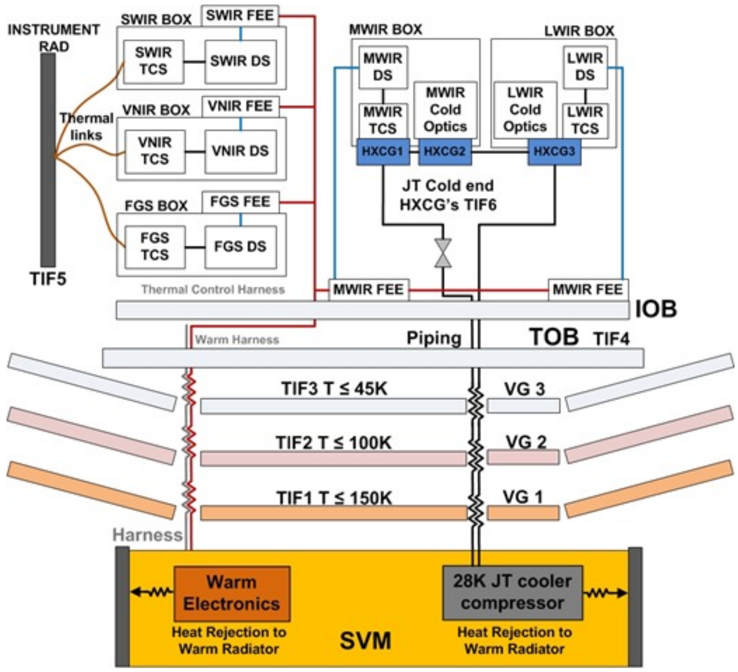

Figure 3. EChO spacecraft thermal architecture

Instrument modules cooling is achieved in two different ways. The detectors of two channels (VNIR and SWIR) and of the FGS will be cooled in the 40 – 45 K range by a dedicated radiator that will benefit of the cold radiative environment set by the last V-Groove. The science channels operating above 5 μm (MWIR1 and 2 and, in case, the LWIR) need to operate at lower temperatures, around 28K (see Table 1), to minimise both the detector noise and the thermal background noise of the internal optical elements. This requires the implementation of an active cooling chain down to ~28 K: this is based on a Neon JT cooler designed and provided by Rutherford Appleton Laboratory (RAL) in the UK.

Detectors temperature stability is one of the most important requirements issue for scientific performance and is ensured by active control stages based on a closed loop circuit.

2.1 Thermal requirements

The EChO instrument main thermal requirements in terms of operating temperature and stability are set by the baseline detectors/optical modules selection, derived from the basic scientific requirements[2], and can be summarized in the following table:

Table 1 Main thermal requirements for the EChO Instrument and expected dissipation from cold active units

Channel	Optical Modules		Detectors			T Control Stage	FEE		
	Op T (K)	ΔT [a] (K)	Op T (K)	ΔT [a] (K)	Load [b] (mW)	Load [b] (mW)	Op T (K)	ΔT [a] (K)	Load [b] (mW)
FGS	≤50	0.5	≤45	± 0.05	10	5	≤55	2	20
VNIR	≤50	0.5	≤45	± 0.05	10	5	≤55	2	20
SWIR	≤50	0.5	≤45	± 0.05	8	5	≤55	2	20
MWIR	≤32	0.5	≤28	± 0.005	5	5	≤55	2	20
LWIR	≤28	0.5	≤28	± 0.005	5	5	≤55	2	20

Notes: [a] *Peak to peak value over a typical observation cycle time (10 hours)*
[b] *50% margin is assumed at this stage of the study*

The detectors and front-end electronics load reported in table is evaluated on the basis of the present design trade-off study of the channels detecting chain. The control stages power is a maximum average allocation for the predicted dissipation of the closed loop circuit when assumptions on the expected instabilities at the relevant thermal interfaces are made (see 4).

2.2 PLM thermal design

From a simplified thermo-mechanical point of view, each channel module can be considered as composed by a box, made of an Al alloy to minimize thermal gradients, that includes an Optical Module (OM) and a Detector System (DS). Each DS consists of a Focal Plane Assembly (FPA) with its Temperature Control Stage (TCS). Due to FPA electrical performance issues the cryo-harness connecting the FEE to their detectors cannot be longer than 10 - 20 cm. From this follows that the cold electronics must be mounted in proximity of the detectors. For the three warmer channels the cold driving electronics is installed on the module box nearby the detectors stage. For the L/MWIR modules, in order not to over load the cooler cold end, the FEE box is mounted on the Instrument Optical Bench (IOB). The FEE thermal coupling to the modules boxes, or to the IOB, is optimized to allow a fast heat transfer to the Telescope Optical Bench via the IOB itself. If the warm harness is thermally anchored to the TOB, a possibility may be offered by using the cables as conductive links to efficiently transfer heat from the cold electronics towards the telescope assembly.

The general scheme of the EChO thermal architecture[6], with the six main thermal interfaces identified in the study, is shown in Figure 4. The FGS, VNIR and SWIR Modules share the same thermal design. The detectors operate at T ≤ 45K, cooled by a dedicated passive radiator stage (the instrument radiator see 2.3) located inside the cold environment set by the third V-groove and the Telescope Optical Bench. This radiator is mechanically supported on the Instrument Bench by means of insulating struts and is considered a part of the instrument. High conductive links connect the FGS, VNIR and SWIR detectors, through their thermal control stage, to the radiator. The Module Box of the FGS, VNIR and SWIR channels is mechanically supported on the Instrument Optical Bench and thermally linked to the bench by using conductive mechanical supports. In this configuration, at steady state, the FGS/VNIR/SWIR optical units are expected to thermally equilibrate with the IOB. The MWIR and LWIR detectors technology baseline requires lower operating temperatures, on the order of 30K, to achieve the required sensitivity and noise level. This temperature, when a load of tens of mW is dissipated, can be reached only by using an active cryogenic system that exploits the V-Groove radiators as pre-coolers to improve efficiency and performance. The baseline for the active cryogenic system is described in 2.4. The MWIR and LWIR module optics shall operate at low temperature, to minimize thermal background noise on the detectors. For this reason the modules boxes and part of the internal optical units needs to be thermally decoupled from the optical bench, to limit the heat load on the cooler heat exchangers. The optimization of the longer wavelength channels cooling requires that the MWIR and LWIR modules and the cooler cold ends are located in a compact mechanical arrangement to minimize the thermal path. The JT cooler cold tip is split in three heat exchangers (HXCG 1, 2 and 3) mounted at a convenient position on the modules by insulating supports. Detectors and cold optics connect to these cold references by high conductivity thermal links. Since the LWIR channel cold optics and detectors share the same temperature requirements a single heat exchanger serves the whole module. Two separate heat exchangers are dedicated to the MWIR optics and detectors, since they should work at different temperatures.

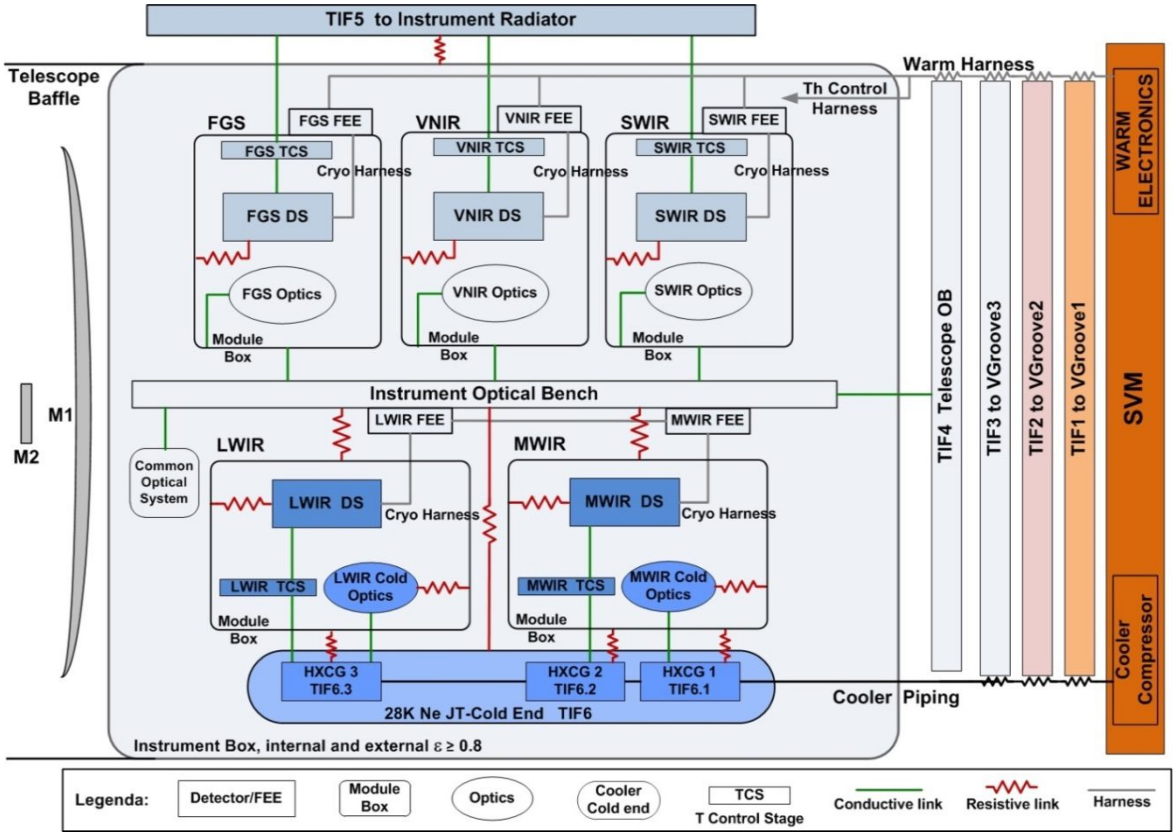

Figure 4. EChO PLM thermal architecture scheme with main thermal interfaces to S/C

In general, each detector stage is thermally decoupled from the relative module box or optics, to ensure optimal performances in terms of absolute temperature and stability. Coupling of the detectors to the temperature reference stage (cooler cold end or radiator) is achieved through high conductance links (high purity Al straps) that interface the focal plane Thermal Control Stage (TCS): this is the detector supporting flange that allocates an active closed loop thermal control system composed by a heater and thermistor couple driven by the warm electronics.

Instrument radiative thermal control is achieved by proper shielding and by the units IR emissivity. The radiative environment for the modules is set by the instrument enclosure, defined by the IOB and a MLI/SLI shroud that surrounds the channel modules and the common optics to shield them from the external environment. This blanket should have a very low emissivity on the external surface but requires high emissivity on the internal surface to limit straylight leaks. In this case, internally black coated MLI is used. The instrument cavity is passively maintained at a temperature ≤45 K by the radiative background set by the V-Grooves and Telescope Optical Bench. The radiative coupling between subsystems inside the box is defined by the high IR emissivity requirement ($\varepsilon \geq 0.8$) needed to minimize straylight radiation contamination in the optical paths of the channels. The mechanical units (boxes and surfaces) inside the instrument cavity shall be externally coated with black paint or anodizing.

The warm electronics is located in the SVM. All harness from SVM to Instrument channels should be thermally linked to all the passive stages (VG1, VG2, VG3 and TOB) for maximum parasitic interception. In this way the heat leaks due to wiring on the cooling stages are minimized. The cryo-harness heat leak to detectors is controlled by thermally optimizing the harness design with respect to the required electrical performances.

2.3 Cooling for 40-50K stage: instrument radiator

The V-Groove shields design provides a cold environment for the PLM units: telescope, instrument and cryocooler. The VNIR, SWIR and FGS channel requirements in terms of operating temperature, stability and dissipated loads need a colder and more stable reference, a dedicated smaller radiator for their detectors cooling only. The baseline for this extra passive stage in the EChO PLM, called Instrument Radiator, is to use a simple radiator facing the cold sky[6].

The V-Grooves heat rejection capacity is also used to intercept all parasitic leaks to the cold stage: harness, struts and radiation from warmer stages. In this way the Cold Radiator is fully devoted to channel detectors cooling, with parasitic leaks due only to its own supporting struts and thermal control harness. The expected active load due to detector dissipation is around 43 mW. Taking into account all worst case parasitic heat leaks due to struts, harness and radiation a total of 115 mW (including margin) is the expected load to the cold radiator.

The PLM configuration allows to fit a radiator of nearly 1 m^2 on the back of the Instrument Box. After several iteration in the EChO thermo-mechanical design process, a radiant surface of 0.96 m^2 (shape and position are shown in Figure 5) has been modeled, fully enclosed in the radiative environment defined by the last V-Groove and the Telescope Optical Bench. The orientation angle of the radiator inside the allocated volume is around 20° with respect to the vertical direction.

The radiator thermo-mechanical design is based on a sandwich of Al alloy layers (Figure 5 right panel). A honeycomb cells structure is packed between two Aluminum sheets. This simple thermo-mechanical design allows for low mass and volume while ensuring at the same time both mechanical rigidity and good thermal conductance in all three directions. The system is mechanically supported on the IOB with three insulating bipods.

The radiator could be coated with white paint to avoid overheating due to a possible 10 min exposure to the Sun during launch. For this reason a conservative IR emissivity of 0.8 is assumed for this study even if white coatings with emissivity over 0.9 are available and regularly adopted for space applications. The radiator emissivity and efficiency could be increased by using standard solutions (special coatings, honeycomb cell structure etc.). On the internal surface facing the PLM, the radiator has a low emissivity coating (MLI or SLI, TBC) to limit radiation loads from the warmer parts of the spacecraft.

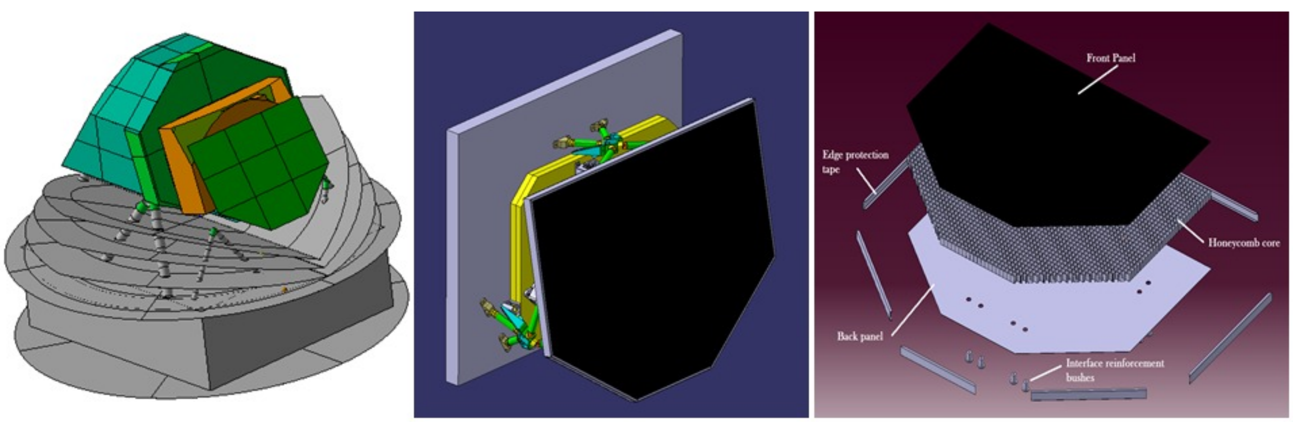

Figure 5. Instrument radiator: position in PLM (left), CAD views of the mounting on IOB (centre) and of the sandwich (right)

2.4 Cooling for the 28K stage: JT cryo-cooler

The EChO JT cryo-cooler has been designed by the RAL Cryogenics and Magnetics group in the UK[3]. The baseline configuration is a Joule-Thomson (JT) cooler making use of the cold heat exchangers (HXCG) developed for the Planck mission and the advanced compressor systems designed by RAL as part of the ESA 2K cooler development system. With a required operating temperature of 28K for the coldest stage it was decided to use Neon as the working cryogen.

A schematic view of the cooling system configuration is shown in Figure 6. The system incorporates a compressor stage that boosts the gas pressure from around 1.1 bar to 11 bar. The compressed gas then passes through an ancillary panel where the flow is measured and the gas is cleaned through a getter. The connecting pipework conveys the fluid through the heat exchangers for precooling and filters for cleaning on each of the passive stages. Enthalpy is recovered by means of a recuperative tube in tube piping that forces the warm high pressure and the cold low pressure streams to exchange heat. Finally the incoming gas enters the JT heat exchanger and one last filter before passing through the expansion orifice where liquid is formed. This liquid is contained in a sintered element to prevent sloshing and flash evaporation effects disturbing the temperature stability. On EChO there are several cooling point and these will be served by multiple heat exchangers. The cold gas then returns back to the compressors through the heat exchangers precooling the incoming gas.

The system has been currently sized to provide 200mW of cooling power at 27K. To achieve this performance approximately 35 mg/s of Ne flow is required at the planned operating pressure drop. This leads to a pre-cooling requirement of approximately 650 mW at the 100K V-Groove and ~550 mW on the 45K V-Groove. The input power required to provide this cooling is 130 W including electronics (30W) and margin.

The compressors are balanced in that they run in a head to head configuration. Vibration control is a key feature for a mission that requires such high level of stability during scientific observations. The exported vibration from balanced compressors on similar systems has been reduced to around 100mN with crude amplitude balancing. On the Planck mission, with active vibration control, levels of a few mN were achieved[5]. If required, algorithms that can be used to reduce the 100mN to lower levels are available and proven.

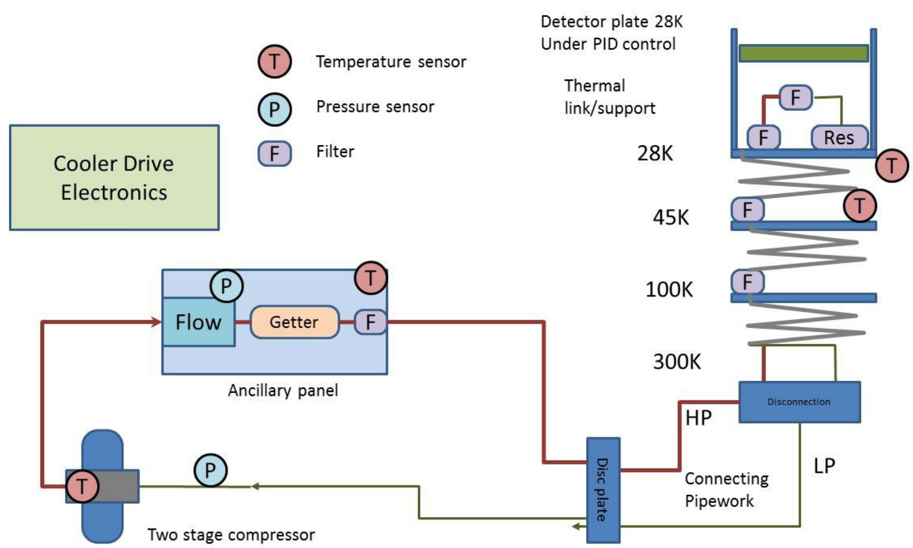

Figure 6. EChO Active Cooling System configuration scheme

3. ECHO THERMAL MODEL

EChO thermal architecture development is based on a set of Thermal Mathematical Models (TMM) used to verify and tune the design solutions. EChO thermal simulations have been carried out using two main models. First a reduced TMM was used to identify the best thermal configuration of each unit, simulating the instrument behavior with the PLM interfaces fixed as boundaries. Then the instrument model has been integrated into a geometrical and conductive model of the whole PLM. In this way it was possible to verify the instrument behavior (and design) in the general S/C thermal architecture studying the actual interaction with the rest of the PLM. Then the two models have been correlated and adjusted to optimize the design. All simulation have been developed in the ESATAN-TMS environment.

The reduced model, based on a relatively low number of nodes and conductors (see Figure 7), is used to study the thermal behavior of the instrument in steady state and its compliancy to the main requirements in terms of temperature, stability and heat fluxes once the external interfaces are fixed as boundaries. The model is based on the best up-to-date assumptions for detectors and electronics dissipations. Each channel module is composed by 5 nodes: the box, the optical system, the detectors, the thermal control stage and the proximity electronics. The instrument cold radiator is a single node coupled to space with properties that replicate the performance of a more detailed model dedicated to simulate the radiator behavior. In this reduced steady state model the harness has been simulated as conductive links between stages and units. The model has been run in the expected hot and cold thermal cases to bound the range of conductive and radiative environmental conditions.

The PLM geometrical model (Figure 8) is based on the coupling of a standard M-size SVM configuration with the EChO cold payload. The main radiative surfaces and representative supporting structures between the different stages are simulated on the basis of assumptions derived from the experience of previous successful missions (Planck, Herschel). The final thermal case simulation for the full PLM has been run by integrating the reduced model of the instrument and its radiator in the geometrical one. The instrument and radiator nodes definition in terms of bulk materials and properties is based on the reduced model assumptions but with a greater level of detail to deal with the full model interfaces definition. The cold-end at 28K is represented as a single boundary inside the instrument box. The instrument optical units and detectors are completely enclosed by the instrument bench and box that, at steady state, are basically isothermal. For this reason, the radiative exchange loads with the surroundings are negligible with respect to the conductive fluxes to/from the interfaces. Conductors representing the designed thermal passive links have been added between the instrument units and their respective temperature reference (the IOB, the cold Radiator, the JT cold end). The current version of the model is composed by nearly 1000 nodes. A more detailed description of the full model and its results is available in literature[7].

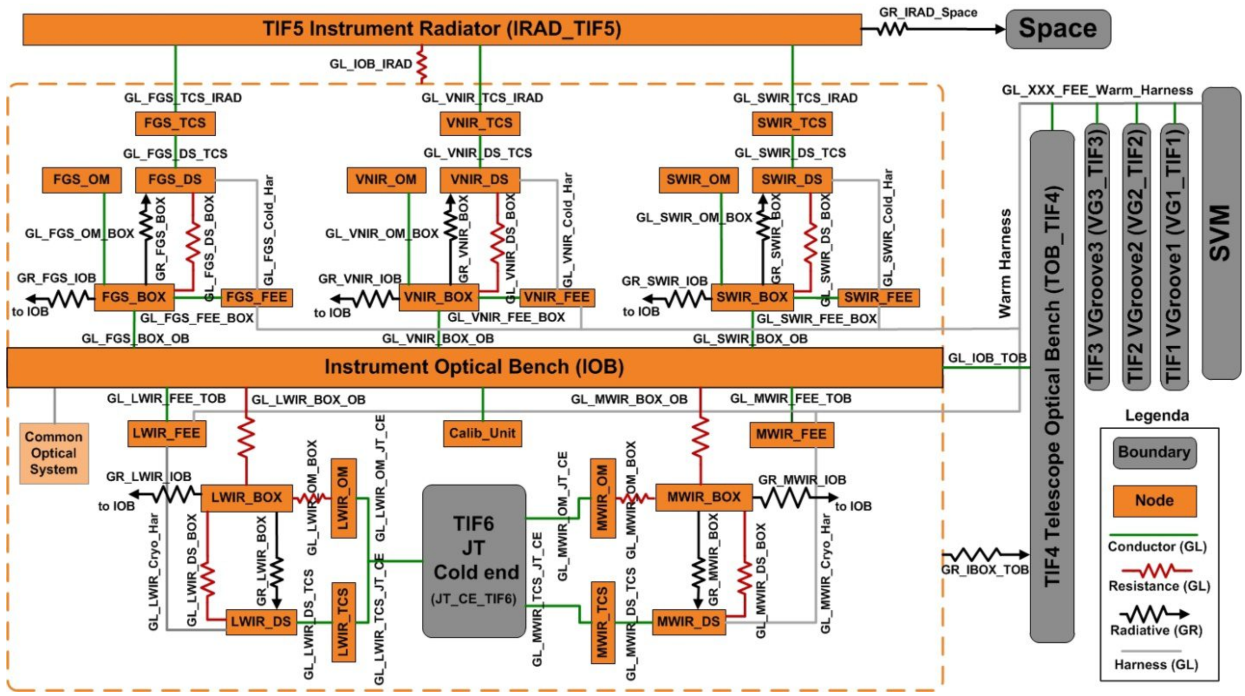

Figure 7. EChO reduced TMM scheme

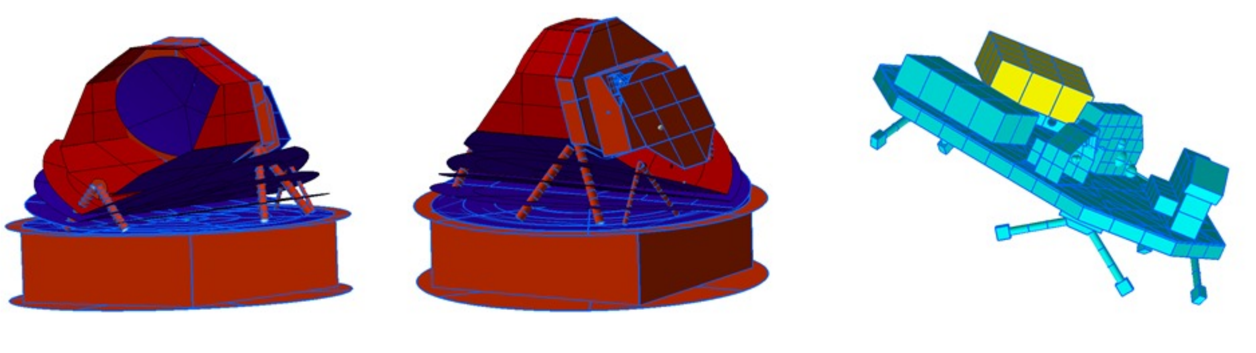

Figure 8. EChO geometric model views. Left: the EChO S/C geometrical model. Middle: rear view with the cold radiator on top of the instrument box. Right: a view of the instrument optical bench geometric model with the main units

The radiative case is run simulating one position in the solar L2 orbit at an average distance of 151.5 x 10^6 Km. The radiative exchange factors resulting from this analysis are used as the input for the thermal case definition. The final simulation is run with the same active loads assumptions of the reduced model. In the following tables are reported the average results in terms of temperatures and heat fluxes at steady state conditions. The main units temperature is graphically shown also in Figure 9.

Table 2 PLM thermal model units average temperature

System	Sub-system	Unit	T (K)
SVM	Solar Array		312.95
	SVM average		249.30
VG1			148.81
VG2			93.05
VG3			48.30
Telescope	M1		33.34
	M2		33.42
	M3		33.34
	M4		33.34
	OB		33.34
	Baffle		32.89

System	Sub-system	Unit	T (K)
Instrument	Optical Bench		37.49
	FGS	Box	37.57
		Detectors	35.02
		FEE	37.72
	VNIR	Box	37.52
		Optics	37.52
		Detectors	35.01
		FEE	37.68
	SWIR	Box	37.57
		Optics	37.56
		Detectors	34.98
		FEE	37.74
	MWIR	Box	36.98
		Optics	28.01
		Detectors	28.19
		FEE	37.55
	LWIR	Box	35.98
		Optics	28.20
		Detectors	28.20
		FEE	37.55
	Radiator		34.72

The results in terms of temperature distribution are very encouraging: they show very small gradients between the units and the respective interfaces. This yields some extra margin for further optimization of the interfaces. The net heat load across the main thermal interfaces is reported in Table 3.

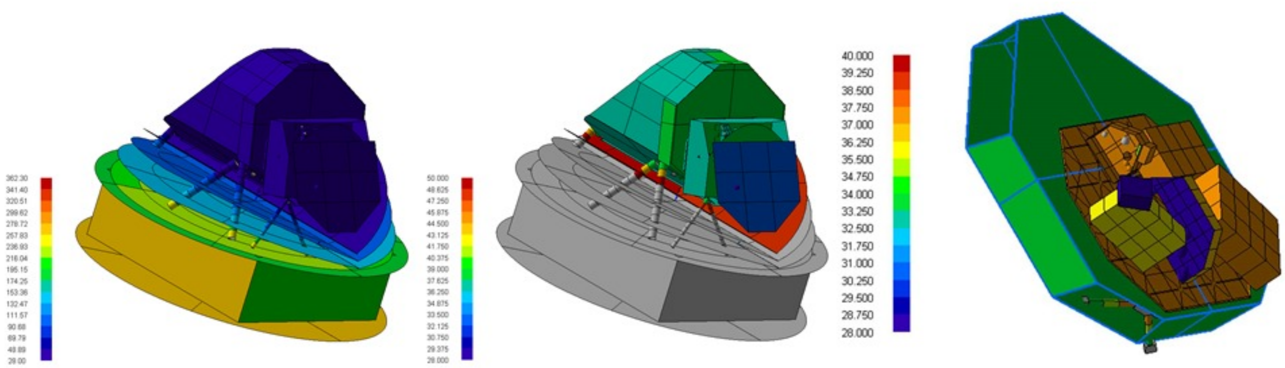

Figure 9. Spacecraft average temperatures (left). Cold PLM main units temperature (middle); Instrument Optical Bench and Module boxes (right)

The loads to the Instrument interfaces are evaluated by balancing the input/output heat fluxes to/from each node through all conductors. For the instrument internal thermal analysis the main interfaces are the Cold Radiator and the JT cooler cold-end. The resulting heat flux values, compared to the simplified model ones, are reported in the following table:

Table 3 PLM conductive and geometric model: heat fluxes at the instrument main internal thermal interfaces. An uncertainty of ±30% is assumed on all model results

Instrument Thermal Interface	Thermal Path	Heat fluxes (W)
Cold Radiator	Conductive heat leaks from spacecraft	0.0057
	Conductive load from detectors	0.0425
	Radiative load from warmer stages (VG3 and SVM)	0.0140
	Net heat flux rejected to Space	0.0627
JT Cold-end	Conductive links from L/MWIR modules	0.040

It is important to notice that even in the worst case of boundary conditions and parasitic leaks the total load on the JT cold end is well below the estimated heat lift capacity of the cooler (200mW). If this numbers will be confirmed in the next design steps, it will be possible to relax the heat load requirement to the cold end heat exchangers and optimize the cryochain performance in a narrower range. The cold radiator rejects more than 60 mW to space while, for the colder channels, almost 40 mW are loaded to the cooler cold heat exchanger.

The Geometrical Model most important results is to show how the whole spacecraft radiative design is really efficient in rejecting heat, taking full advantage of the L2 favourable thermal conditions. The Telescope Optical Bench, the Telescope Baffle and the Instrument Cold Radiator work together as a single large surface, representing the coldest radiative stages in the spacecraft, at a temperature lower than 40K, 10-15K colder than the last V-Groove.

4. THERMAL STABILITY ANALYSIS

Stable conditions during observations are a key requirement for the scientific objectives of EChO. For this reason, thermal stability is one of the key drivers of the mission design. There are two possible thermal noise sources in the EChO PLM: the radiators (V-Grooves and instrument radiator) and the cooler cold end. The main cause of fluctuations on a radiator facing the cold sky is due to orbital changes of the solar aspect angle related to flight dynamics following the mission scanning strategy (on timescales of 10 hours or so) or seasonal variations (typically on longer periods like weeks, months, years). Experience on previous missions[5] shows that such low frequency oscillations can be controlled under 200 mK over timeframes of 10 hours to avoid the thermal background stability becoming a major contributor in the instrument noise budget. The most significant temperature variation will happen when the Sun aspect angle changes while slewing to observe a new science target. Constraints on the maximum slew angle between successive targets are set to limit the induced temperature variation to less than 10K in the SVM top floor. This variation is further damped by more than 2 orders of magnitude at the PLM level, well below the temperature stability requirement as demonstrated by analysis and simulations. As a result, it is not anticipated that significant temperature regulation is needed for the units inside the SVM.

In a JT cooler, instabilities at the reference heat exchanger temperature are due to compressor modulation, with its typical high frequency spectrum (30-40Hz range), to cold-end internal mass flow 1- or 2-phase dynamics (on the order of tens of seconds) and to precooling stage variations (low frequency).

Thermal stability of the optical modules directly connected to the IOB (FGS, VNIR and SWIR) is not expected to be a major concern given the typical instabilities of passive radiators in L2 either on the timescales of EChO detectors average exposure or on the seasonal. Even in the case of few hundreds of mK peak to peak fluctuations every several hours (10000s time scales), the thermal mass and resistances of the instrument bench and modules can easily filter out well below the required 0.5 K peak to peak.

On the contrary, the detectors are directly connected to their temperature reference and the level of transmitted fluctuations could be at the limit of the required values. Since detectors stability is a key issue for instrumental performance, a careful design of a proper thermal control system is needed. This is achieved by a combination of passive and active systems. The passive component again uses the thermal inertia of the detector system components (struts and frames) to damp temperature oscillations during their propagation from the instability source (the 45K radiator or the 28K cold end) to the detectors. The finer active control is accomplished by a PID type controller on a stage thermally decoupled with a properly tuned resistance between the detectors and the source of temperature oscillations. The thermal break between the control stage and the temperature reference on one side and the detector on the other side, has to be properly designed on the basis of a trade-off that minimizes the detectors operating temperature and the power needed for active thermal control. Each detector is mounted on this supporting frame, designed to integrate the thermal link to the temperature reference and to accommodate the control system: a thermometer plus heater couple. Since active control on detectors stage is critical for instrument performance, a fully redundant system with two identical heater and sensor pairs is foreseen.

To verify the functionality of the active control stages design on the EChO modules, analytical studies correlated with a set of transient simulations have been carried out. If periodical thermal instabilities can be approximated with a sinusoidal function and imposed at the relevant interfaces, then the temperature fluctuations transmitted passively at the sensitive stages (the TCS for example) connected to the thermal noise source can be calculated.

In the next table are reported some conservative predictions of the possible fluctuations expected at the cold radiator interface and the cooler cold end heat exchangers on the basis of previous missions orbiting in L2 like Planck[5]. As this first analysis has the objective of providing safe and reliable figures for the thermal oscillations at various stages, it has been decided to assume conservative numbers in terms of the frequency components of the expected oscillations spectrum. These are reported in the first three columns of the following tables. The other columns show the level of the transmitted fluctuations evaluated at the Temperature Control Stages (TCS) and on the Detector Systems (DS) of the 45K and 28K focal planes.

Table 4. Preliminary analysis of worst case temperature fluctuation spectrum at 45K detectors stage

Time (s)	ν (Hz)	p-p ΔT (K) at radiator	ΔT at 45K TCS (K)	ΔT at 45K DS (K)	Control power max (W)	Control power ave (W)
10	0.1	0.002	3.181E-05	1.129E-06	0	0
100	0.01	0.005	0.0008	0.0003	4.550E-05	3.033E-05
1000	0.001	0.01	0.0048	0.0046	0.0003	0.0002
10000	0.0001	0.1	0.0500	0.0500	0.0030	0.0020

Table 5. Preliminary analysis of worst case temperature fluctuation spectrum at 28K detectors stage

Time (s)	ν (Hz)	p-p ΔT at cold end (K)	ΔT at 28K TCS (K)	ΔT at 28K DS (K)	ΔT at Cold Optics	Control power max (W)	Control power ave (W)
10	0.1	0.00002	0.00001	7.933E-07	1.768E-08	0	0
100	0.01	0.00005	0.000025	1.557E-05	4.420E-07	0	0
1000	0.001	0.0001	0.00005	4.961E-05	8.707E-06	0	0
10000	0.0001	0.001	0.0005	0.0005	0.0004	0.0004	0.0001

As expected, this preliminary analysis shows how the thermal design of the units allows for an efficient passive filtering of most of the higher frequency noise. From this follows that all possible oscillations generated in the cooler due to both compressor operations and cold end fluid dynamics (ν in the 10^{1} – 10^{-1} Hz range) are filtered out down to negligible levels by the thermal inertia and resistance of the systems. Only the slower oscillations, mainly due to changes related to flight dynamic issues pass through and need to be actively controlled. The last two columns in each table report the maximum and average proportional control power needed to control the transmitted fluctuations below the required level.

To verify the results of this analysis and to check the robustness of the EChO channels thermal design, a set of simple transient simulations have been run. Sinusoidal oscillations that include the frequency components reported in Table 4 and Table 5 have been imposed at the 45K and 28K channels detector interfaces. Dynamical simulations show that the active control system can effectively damp the residual oscillations well below the requirements (see Figure 10). The average power for thermal control on both stages is within the required 5 mW.

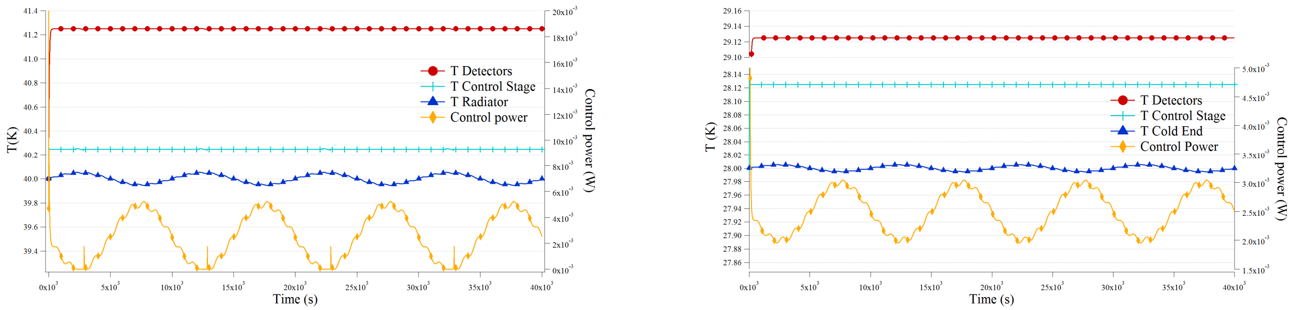

Figure 10. Simulation of transmitted oscillations to the 45K (left) and 28K (right) stage thermal control

5. CONCLUSIONS

We presented the baseline thermal architecture of the payload for the EChO mission at the time of the mission proposal for the down selection. From the basic thermal requirements of the instrument the whole design has been derived and the thermal interfaces to the Spacecraft have been identified. The general thermo-mechanical configuration of the units and the thermal interfaces has been described. The expected performances of the thermal control configuration have been analyzed on the basis of simulations in steady state and transient conditions. The results indicate that the present design is compliant to the instrument and interface requirements for temperature control and heat fluxes to the cooling stages. The thermal architecture here described provides a solid basis for a possible future design evolution.

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