Exoplanet atmospheres Characterization Observatory Payload Short-Wave infraRed channel: EChO SWiR

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ABSTRACT

EChO (Exoplanet atmospheres Characterization Observatory), a proposal for exoplanets exploration space mission, is considered the next step for planetary atmospheres characterization. It would be a dedicated observatory to uncover a large selected sample of planets spanning a wide range of masses (from gas giants to super-Earths) and orbital temperatures (from hot to habitable). All targets move around stars of spectral types F, G, K, and M. EChO would provide an unprecedented view of the atmospheres of planets in the solar neighbourhood.

The consortium formed by various institutions of different countries proposed as ESA M3 an integrated spectrometer payload for EChO covering the wavelength interval 0.4 to 16 µm. This instrument is subdivided into 4 channels: a visible channel, which includes a fine guidance system (FGS) and a VIS spectrometer, a near infrared channel (SWiR), a middle infrared channel (MWiR), and a long wave infrared module (LWiR). In addition, it contains a common set of optics spectrally dividing the wavelength coverage and injecting the combined light of parent stars and their exoplanets into the different channels. The proposed payload meets all of the key performance requirements detailed in the ESA call for proposals as well as all scientific goals.

EChO payload is based on different spectrometers covering the spectral range mentioned above. Among them, SWiR spectrometer would work from 2.45 microns to 5.45 microns. In this paper, the optical and mechanical designs of the SWiR channel instrument are reported on.

Key words: Exoplanets, Atmospheres, Payload, Infrared, Spectrometer.

1. INTRODUCTION

The Exoplanet Characterizaton Observatory (EChO) was one out of four ESA M-class (M3) candidate missions for the Cosmic Vision 2015-2025 program, with a launch anticipated in the 2020-2022 time frame. EChO was though to explore the atmospheres of a significant sample of planets orbiting Galactic stars other than the Sun, the so-called exoplanets. EChO was going to enable the first comparative physical and chemical study of these "exoworlds" by delivering spectroscopic data in the wavelength interval 0.6-11 µm (goal 0.4-16 µm), thus covering the optical, near-, and mid-infrared regimes.

Planet targets of EChO included a few super-Earths (large terrestrial planets with masses above 5 M_{earth}), and many gas and ice giant planets, all in orbits close to their parent stars and with a star-planet orbital geometry aligned with our line of sight. As seen from EChO, planet targets transit in front of and behind their

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parent stars, enabling the measurement of the planet atmospheric transmission, reflection and emission spectra over a continuous wavelength range that spans the optical to thermal infrared. EChO would observe both the host star and the unresolved planet simultaneously and would exploit small differences in the light originated at different points in the planetary orbit: during the primary eclipse (the planet passes in front of its parent star), the combined signal consists of the stellar contribution and the transmission spectrum of the planet atmosphere; before or immediately after the secondary eclipse (the planet goes behind its star), the emission spectrum from the planet adds to the stellar energy; and on either side of the eclipse, light reflected by the planet as well as some emission from the day- and night-sides of the planet contributes to the signal. The majority of the planet targets was going to be revisited by EChO over the course of the mission (5 yr) aimed at obtaining the transmission and emission energy distribution of the planet atmospheres with sufficient signal-to-noise quality. This was indeed challenging since the flux contrast between exoplanets and parent stars is typically 10^{-3} to 10^{-5}. EChO needed to be designed and built to guarantee this contrast ratio over a wide spectral range and over the duration of the mission.

EChO would explore about 100 exoplanets with masses spanning from super-Earths to Jupiter-size planets, atmospheric temperatures above 300 K, and orbiting stars of spectral types F, G, K, and M up to distances of about 75 pc from us (depending on the star). The resolving power given by EChO (>300 for wavelengths <5 µm, >30 for wavelengths >5 µm) would be sufficient to separate spectroscopic features due to different molecular species, to retrieve chemical abundances and atmospheric composition, to measure atmospheric temperature, albedo, thermal structure and temporal variations, and to constrain the atmospheric theoretical models that best reproduce the observations. Expected molecular species are water (H_2O), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and ammonia (NH_3) for warm to hot planets, and ozone (O_3), sulphur dioxide (SO_2), ethylene (C_2H_4) and nitrogen dioxide (NO_2) can appear at low temperatures. Additional science objectives, like star-planet interaction, planet formation, etc., may be also addressed by EChO, which made this mission a very attractive planetary exploration laboratory.

The consortium formed by several institutions (UCL, Oxford University, INTA,…) of various countries (England, Spain,…) proposed an integrated spectrometer payload for EChO covering the wavelength interval 0.4 to 16 µm. Basically, and although a deeper description is presented elsewhere,[1] this instrument was subdivided into 4 channels: one visible module (0.4 or 0.6 to 2.47µm), which includes a fine guidance system (FGS) and a VIS spectrometer, a near infrared channel (SWiR, 2.45 to 5.45µm), a middle infrared channel (MWiR, 5.2-11.5µm), and a long wave infrared module (LWiR, 11.5-16µm). In addition, it contained a common set of optics (collimator and a set of dichroics) collimating and spectrally dividing the wavelength coverage and injecting the incoming light into the different channels. The proposed payload met all of the key performance requirements detailed in the ESA call for proposals as well as all scientific goals.[2]

The SWiR spectrometer, under the INTA-CAB group responsibility, was in charge of the information contained in the spectral range 2.45 through 5.45 µm analysis. The original spectral division of the EChO payload instrument assigned a larger spectral coverage to the SWiR channel (0.9-5.2 µm,[2]), consisting of two submodules (0.9-2.5 µm, and 2.5-5.2 µm), thus including two detectors. Based on a recent study on economical and technical feasibility aspects and on the availability of state-of-the-art visible and infrared detectors, the consortium finally decided to have a SWiR channel with shorter wavelength coverage and one single detector. This decision was taken in compliance with the scientific requirements of the EChO space mission. Here, the on-going study of the SWiR channel, focusing on the one-detector concept and including the evolution of the different trades up to date and the current identification of critical aspects are reported on.

2. SWiR SPECTROMETER DESCRIPTION

As was mentioned in the introduction, the SWiR design philosophy was changed as a result of the wavelength range coverage and other system level decisions. In the EChO Payload assessment phase framework, different trades were hence developed in order to satisfy the scientific requirements of the mission.

Briefly, the optical design evolved from a two instruments (and two detectors) concept, covering the spectral range from 900nm to 5200nm, to a single instrument concept that would cover the spectral range from 2450nm to 5450nm. In **Figure 1**, some images of the different trades are summarized.

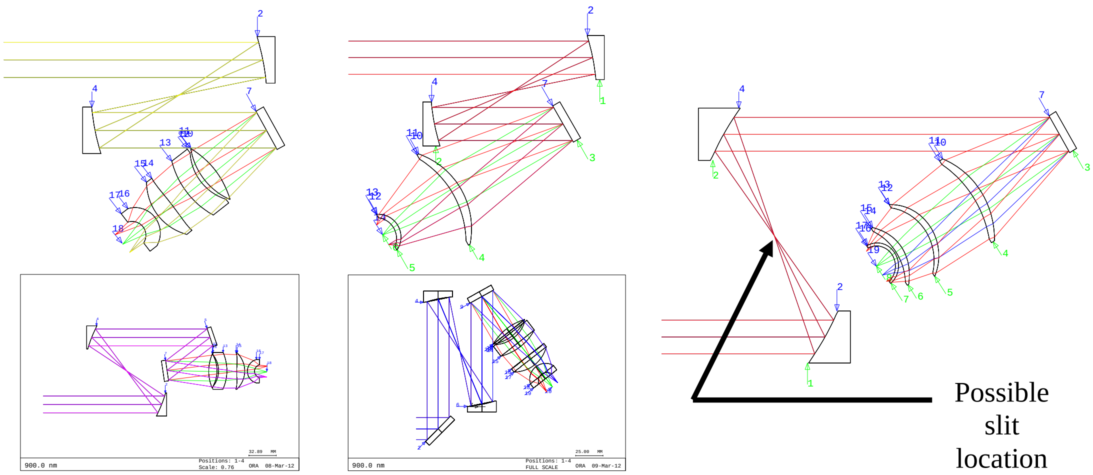


Figure 1 Different optical design trades. Left side: up, SWiR 1& 2 corresponding to trade A; down, from left to right, SWiR 1 trades B & C corresponding to a folding mirror inclusion. Right side: trade D (single detector concept covering from 1800nm to 5300nm)

As in the case of the optical design, the mechanical design also evolved from a two instruments concept to a single instrument concept. In **Figure 2,** some images of the different trades are shown.

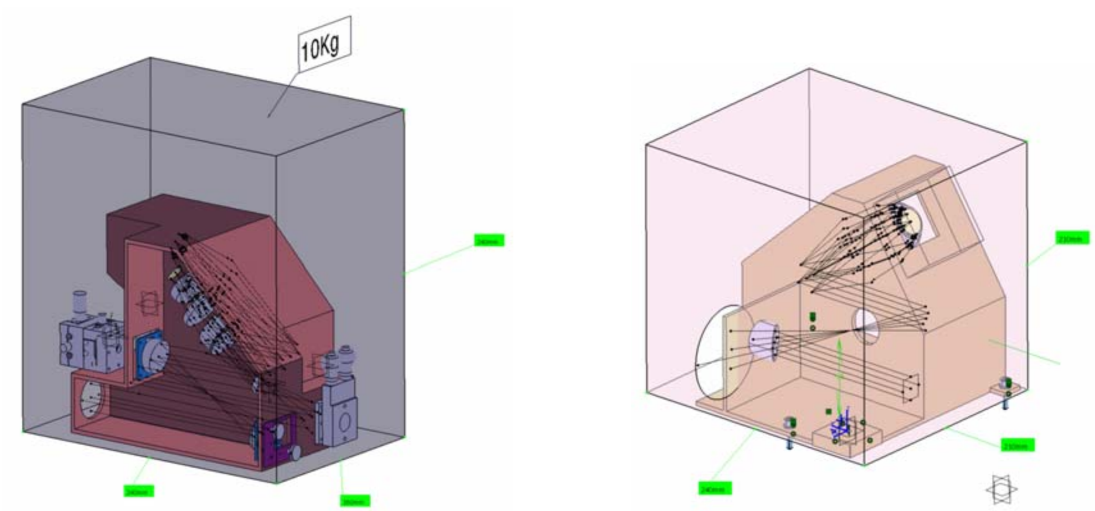


Figure 2 Different mechanical design trades. Left side: SWiR 1& 2 corresponding to trade A. Right side: trade D (single detector concept covering from 1800nm to 5300nm).

Final optical design.

A single detector version satisfying most of the requirements established for the EChO scientific team was presented previously.[3] However, such a design did not fit for two requirements: one related to the spectral resolution (that should be around or higher than 300 in all the spectral range) and the detector size, and other related to the constancy of the PSF (Point Spread Function) samplinq in all the covered spectral range.

In order to solve the first discrepancy, a combination of a prism and a grism (prism with a diffraction grating) was though to be included. In order to solve the other one, the design was properly adapted in terms of the f/# evolution with the wavelength.

The spectrometer baseline design covering from 2450 to 5450nm is based on the use of a badel, in order to adapt the beam diameter and the effective focal length (EFL), a prism (10º) and a grism (24.2º) for spectral separation and camera optics for light collection into the detector (elements ordered following the optical path). The optical layout and CAD diagrams are presented in **Figures 3** and **4**.

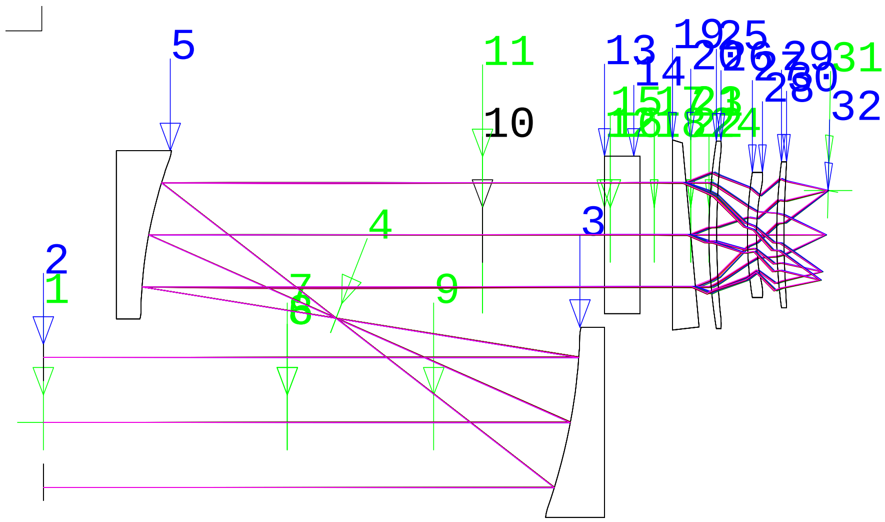


Figure 3. EChO SWiR channel optical layout.

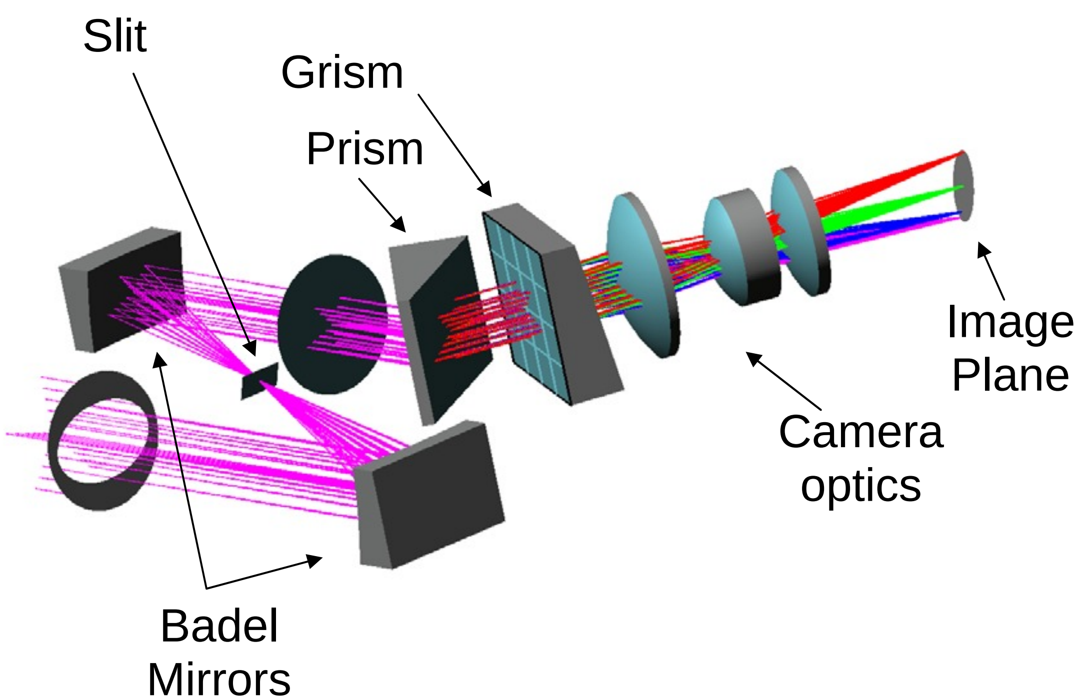


Figure 4. EChO SWiR CAD diagram.

As mentioned before, it was required a similar PSF sampling for the whole covered spectral range. Using the paraxial optics approach (**Figure 5**) and the corresponding expression for the diameter of the Airy disc:

$$\phi_{Airy} = 2 \times 1.22 \times \lambda \times \frac{f_{tel}}{\phi_{EP_{Tel}}} = \ldots = 2 \times 1.22 \times \lambda \times \frac{f_{\lambda}}{\phi_{ExP_{Tel}}}$$

the PSF sizes for the wavelengths covering the spectral range of interest were obtained. (**Table 1**) In this table, the PSF sizes (spectral × spatial) corresponding to the 88 μm defocused design can be also found. As can be observed, such a defocus was needed in order to assured not only the homogeneity of the PSF size with the wavelength, but also the condition to have a PSF equal or higher than 2 pixel in the whole covered spectral range.

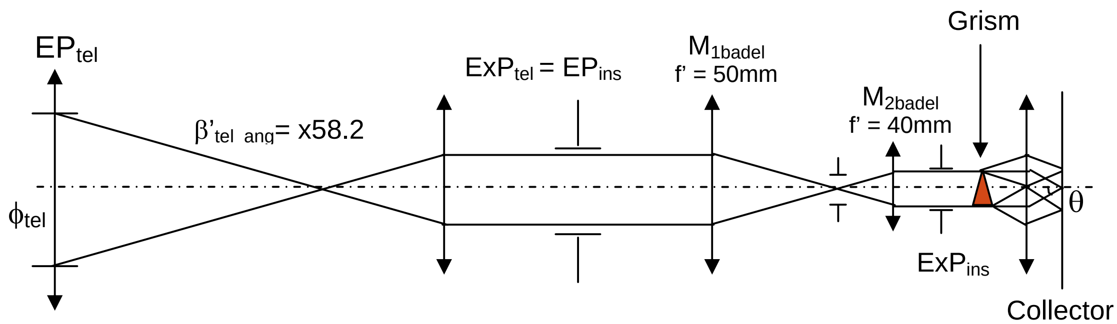
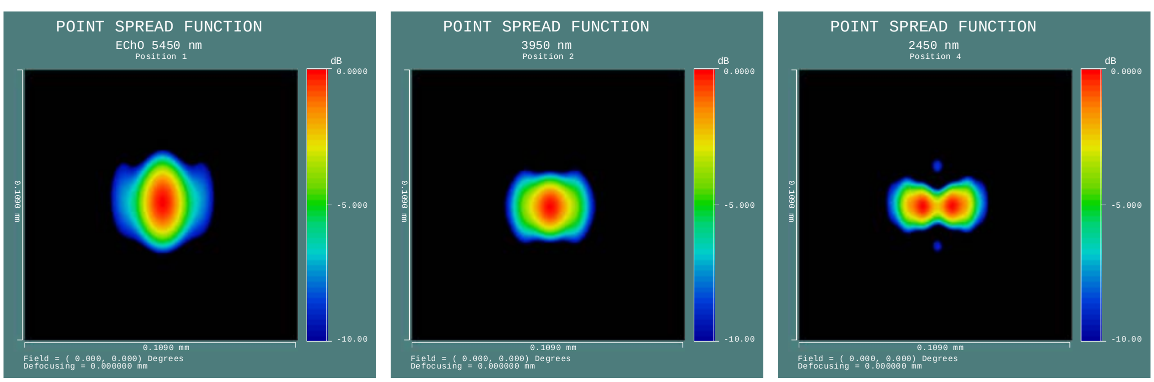


Figure 5. EChO SWiR optical simplification (paraxial optics) diagram.

λ (nm)	PSF spect × spat (μm²)	PSF spect × spat (px²)	90% encircled energy spect × spat (px²) after 88μm defocus
5450	40.5 × 59.6	2.3 × 3.3	2.3 × 2.3
3950	29.2 × 42.9	1.6 × 2.4	2.2 × 1.8
2450	17.7 × 26.1	1.0 × 1.4	2.3 × 2.5

Table 1. EChO SWiR channel general optical features and performance characteristics.

The resultant PSF obtained are shown in **Figure 6** for three different wavelengths (5450, 3950, and 2450nm). In fact, it was considered in the design -10dB condition for the energy decrement (90% of the encircled energy), condition close to the Airy disc (≈86%).



42 x 42 μm² (2.3 x 2.3 px²)   39 x 31.5 μm² (2.2 x 1.8 px²)   42 x 45 μm² (2.3 x 2.5 px²)

Figure 6. EChO SWiR 90% encircled energy for different wavelentghs.

All the optical features and performance main characteristics of the SWiR instrument are summarized in **table 2**.

λ Range	2450 – 5450 nm
SWiR Dichroic (common optics)	R > 90% (TBC) for λ ∈ (2450 – 5450) nm
	T > 90% (TBC) for λ ∈ (5450 – 16000) nm
EFL	4439.94 mm for 5450 nm
	4416.03 mm for 3950 nm
	4349.61 mm for 2450 nm
SWiR Grism Grating	≈ 90 l/mm (-1st order)
SWiR Optics	Ge (except for the grism, ZnSe)
SWiR FPA	Teledyne H1RG, and Europeans MCT: (TBD) as back-up solution
	Pixel size: 18 μm (TBC)
Spectrum Length	≈ 17.3 mm, 962 px
R (λ/Δλ)	401 & 268 @ 2450 nm (2 & 3px as resolution element respectively)
	627 & 420 @ 3950 nm (2 & 3px as resolution element respectively)
	852 & 568 @ 5450 nm (2 & 3px as resolution element respectively)
T (Transmittance)	45% of averaged in-band T (TBD pending on coatings)

Table 2. EChO SWiR channel general optical features and performance characteristics.

Final thermo-mechanical design.

As in the case of the optical design, only the thermo-mechanical details corresponding to the final design ('one instrument or detector') are presented.

1. Mechanical design.

In the current situation, a resume of the design baseline (**Figures 7** and **8**) is as follow:

- Mass: 6kg (20% of margin included) for all SWiR hardware (TBC, To Be Confirmed).
- First frequency: TBD (To Be Defined).
- Volume: Current design volume is 210x240x240 mm (**Figures 7** and **8**).
- The reference system used on SWiR is defined through a rectified plane parallel to the iOB plane, where an optical reference (a polished cube, TBD) will be located for AIV purposes (**Figure 9**). One of the axes is parallel to the entrance beam and contained in the plane, while another axis is perpendicular to such a plane. The third axis forms a Cartesian right-handed coordinate system.

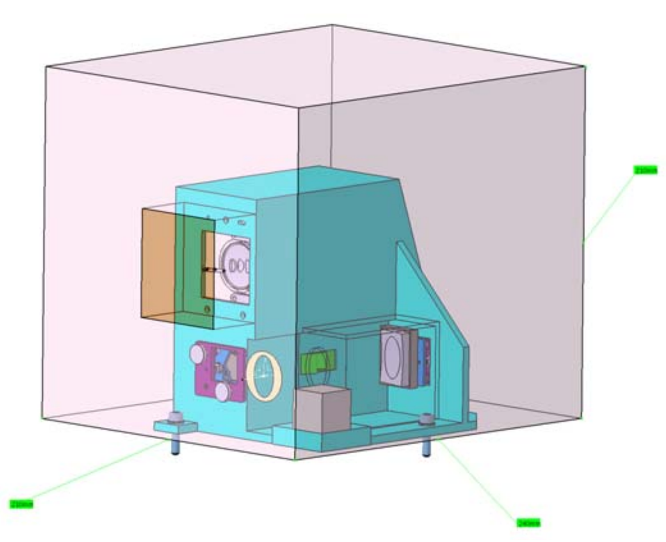


Figure 7. EChO SWiR channel mechanical layout (current envelope and envelope including in the ICD).

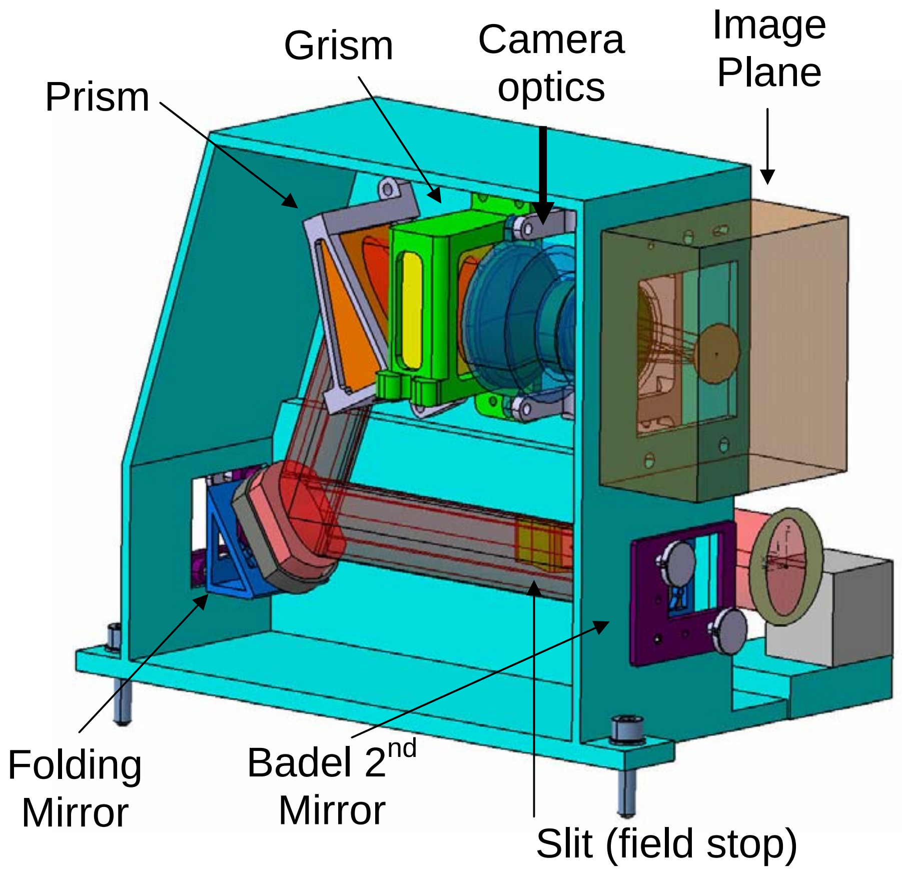


Figure 8. EChO SWiR channel detailed mechanical layout.

2. Thermal aspects.

Thermal studies are in progress with respect to thermal interfaces definition. The currently assumed thermal operating temperature of both the IOB (Instrument Optical Bench) and the SWIR detector is 45 – 50 K.

3. Interfaces.

There is also an interfaces proposal (**Figure 9**) and although not all the interfaces can be fixed due to the pending final definition of the instrumentation optical bench, they can be summarized as follow:

- 3xM5 screws (A286 steel, TBC) of 20mm length for the assembly to IOB.
- In order to maintain a certain level of preload during the mission, 1.5mm Invar washers will be used.
- Al 6061-T6 will be used for most of SWiR mechanical elements. Particularly, the box plate will be a 5mm plate of such Al.
- Positioning through two 5mm diameter pins: a dowel-pin, and a slotted dowel-pin (linear slot parallel to the entrance beam).
- Top surface polished for optical cube positioning.
- Reference system: reference hole (main dowel-pin) at the top surface (although also possible at bottom surface)
- Bottom surface (in contact to IOB) also polished
- For the FPA: two pins of 2mm of diameter will be used, one fixed and the other situated on a linear slot parallel to Y axis, and perpendicular to the entrance beam (X). The mounting pattern consists of a bolt fitting, three M4 bolts (**Figure 10**).

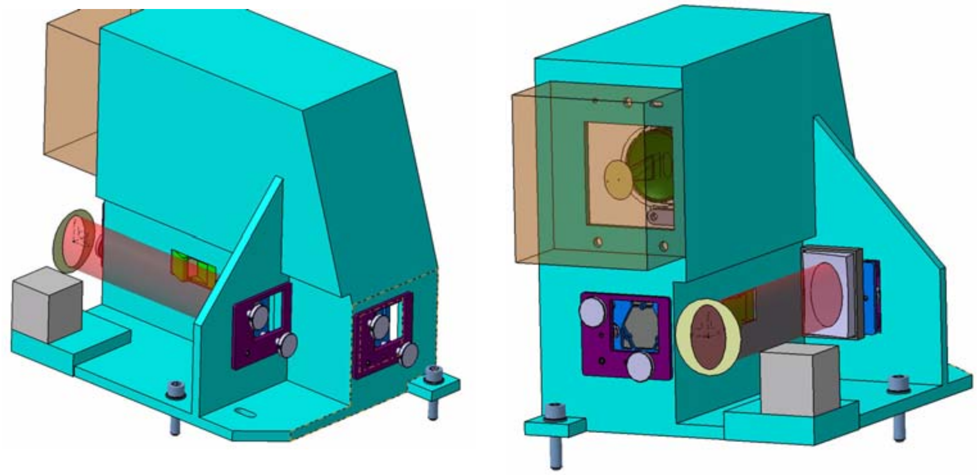


Figure 9. SWiR interfaces.

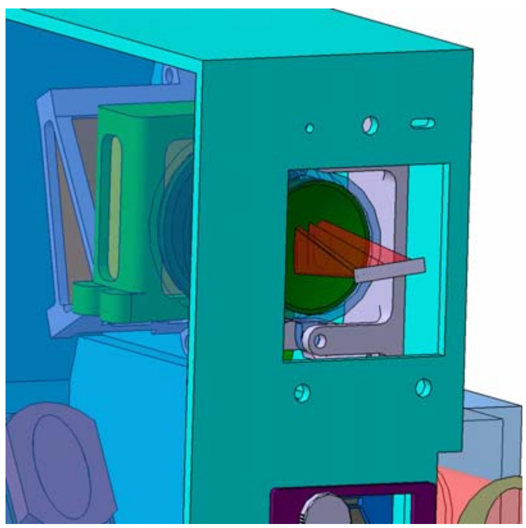


Figure 10. SWiR FPA interface detail.

3. CONCLUSIONS

The consortium in which INTA/CAB participate proposed as response to the ESA AO for the EChO payload, an integrated spectrometer payload for EChO covering the wavelength interval 0.4 to 16 μm. Among the 4 channels this instrument is subdivided into, INTA/CAB is in charge of the near infrared channel (SWiR) that covers from 2.45 microns to 5.45 microns. The SWiR spectrometer current optical and mechanical designs, including the evolution of the different trades followed, have been reported on.

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5. REFERENCES

[1] Swinyard, Bruce, et al., “An integrated payload for the Exoplanet Characterization Observatory”, Proceeding of SPIE 8442, doi: 10.1117/12.924688 (2012).
[2] EChO Response to Declaration of Interest in Science Instrumentation.
[3] Ramos, Gonzalo, et al., “EChO SWiR: exoplanet atmospheres characterization observatory sort-wave infrared channel of the EChO payload”, Proceeding of SPIE 8442, doi: 10.1117/12.925957 (2012).