An improved version of the Visible and Near Infrared (VNIR) spectrometer of EChO

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ABSTRACT

The Visible and Near Infrared (VNIR) is one of the modules of EChO, the Exoplanets Characterization Observatory proposed to ESA for an M-class mission. EChO is aimed to observe planets while transiting by their suns. Then the instrument has be designed to assure a high efficiency over the whole spectral range. In fact, it has to be able to observe stars with an apparent magnitude M_v= 9÷12 and able to see contrasts of $10^{-4}÷10^{-5}$ in order to reveal the characteristics of the atmospheres of the exoplanets under investigation.

VNIR was originally designed for covering the spectral range from 0.4 to 1.0 µm [1] but now the design has been reviewed and its spectral range has been extended up to 2.5 µm. It is a spectrometer in a cross-dispersed configuration that, then, uses the combination of a diffraction grating and a prism to spread the light in different wavelengths and in a useful number of orders of diffraction. Its resolving power is about 330 over the entire spectral range and its field of view is approximately 2 arcsec.

The spectrometer is functionally split into two channels respectively working in the 0.4-1.0 µm and 1.0-2.5 µm spectral ranges. Such a solution is imposed by the fact the light at low wavelengths has to be shared with the EChO Fine Guiding System (FGS) devoted to the pointing of the stars under observation. The instrument works at 45K and its weight is 6 kg.

Keywords: Spectroscopy, Exoplanets, Planetary atmospheres, Space telescopes

1. INTRODUCTION

The EChO mission [2] will take up the challenge to explain the diversity in terms of formation, evolution, internal structure and atmospheric composition of exoplanets. This requires in-depth spectroscopic knowledge of the atmospheres of a large and well-defined planet sample for which precise physical, chemical and dynamical information can be obtained.

EChO will carry a single, high stability, spectrometer instrument. The baseline instrument for EChO is a modular, three-channel, highly integrated, common field of view, spectrometer that covers the full EChO required wavelength range of 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 to the goal wavelength of 16.0 µm. Also included in the payload instrument is the Fine Guidance System (FGS), necessary to provide closed-loop feedback to the high stability spacecraft pointing. The required spectral resolving powers of 300 and 30 are achieved or exceeded throughout the band. The baseline design largely uses technologies with a high degree of technical maturity.

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The spectrometer channels share a common field of view, with the spectral division achieved using a dichroic chain operating in long-pass mode. The core science channels are a cross-dispersed spectrometer VNIR module covering from 0.4 to ~2.5 µm, a grism spectrometer SWIR module covering from 2.5 to 5.3 µm, and a prism spectrometer MWIR module covering from 5.3 to 11 µm. All science modules and the FGS are accommodated on a common Instrument Optical Bench. The payload instrumentation operates passively cooled at ~45K 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 wavelength channels. In the following, the characteristics of the VNIR module are described in detail.

The VNIR design must fulfill both scientific and technical requirements imposed by the EChO mission. Spectroscopy of planetary transits of a large variety of exoplanets requires the use of a multichannel spectrometer to cover the wide wavelength range. Moreover, a quite low operational temperature is needed to operate both SWIR and MWIR detectors and to reduce the background noise. Photometric stability and SNR are also crucial parameters in order to assure the scientific objectives of the mission.

2. MODULE DESIGN

2.1 Optical layout

The system covers the spectral range between 0.4 and 2.5 µm without gaps and the resulting resolving power is nearly constant, R≈330. The wide spectral range is achieved through the combined use of a grating with a ruling of 14.3 grooves/mm and blaze angle of 3.3° for wavelength dispersion in horizontal direction and an order sorting calcium fluoride prism (angle 22°), which separates the orders along the vertical direction. The collimator (M1) and the prism are used in double pass (see figure 1). The prism is the only optical element used in transmission. All other optics are made of reflecting surfaces: 2 off-axis conic mirrors, 1 spherical mirror, 1 flat mirror and 1 grating. All reflecting elements will be made of the same aluminium alloy as the optical bench. This simplifies the mechanical mount and alignment of the system.

The light is fed to the spectrometer via two fibres positioned on the side of the M2 mirror. The fibres are commercial, radiation resistant, space qualified, fused-silica with ultra-low OH content and core diameter of 50 µm. Their internal absorption is lower than 1 db/m up to 2.4 µm, and reaches 2 db/m at 2.5 µm. Therefore, by limiting their length to 0.2 m, we can achieve an internal transmission >90% over the full wavelength range. The fibres are separately fed by two identical off-axis parabolic mirrors (M0) which intercept the collimated light transmitted from the first dichroic (D1b), IR, and reflected by the beam-splitter, VIS. The use of an optical fiber coupling gives a larger flexibility in the location of the VNIR spectrometer within the EChO payload module. The VNIR characteristics are summarized in Table 1.

A Mercury Cadmium Telluride (MCT, HgCdTe) detector has been considered for VNIR. Figure 2 shows the observable spectral orders, m, projected on the MCT array, starting from m = 3 at the bottom (near infrared spectral range) to m = 20 on the top (visual spectral range). Namely, the figure shows the distribution of the light on the array between 2500 nm (m = 3) and 400 nm (m = 20). The central wavelength in each order m, positioned at the blaze angle of the grating, is given by the relationship $\lambda = 8.1/m$ µm. The VIS and IR spectral ranges are separated on the detector because the fibres are placed at the spectrometer entrance are separated by 1 mm. In general, most wavelengths are sampled twice on different orders, i.e. in different areas of the detector, as shown in figure 2. The spectrum in each order is spread across several pixels in the vertical direction. Thus, a sum over 5 pixels will be done to increase the sensitivity of the system in order to provide a so-called spectral channel.

The last two instrumental features, about wavelength sampling, also have the advantage to reduce systematic errors in the measurements once properly exploited. As previously said, the coupling of the VNIR module to the telescope will be done through the use of a dichroic element that will select and direct the visible and near infrared light towards the combined system VNIR and FGS. A beam-splitter is foreseen to further divide the light beam between FGS and VNIR. The balance of this beam-splitter will need to be studied in conjunction with the FGS team to maximize the science return while maintaining sufficient signal for the guider system. As the performance of the module optics should be very good to assure the observations of planets in transit or in occultation of a star, the detector is going to be a key element in the system.

In order to meet the EChO visible channel performance requirements, it is possible to pursue different ways, based on different detectors and readout electronics as well as on the optical spectrometer design characteristics. In addition all these system features must be coupled with the best data collection technique; the electronic design together with the processing algorithm allows to identify cosmic ray and other glitches and to optimize the signal to noise ratio [3].

Table 1. Main EChO VNIR module scientific and technical requirements. ΔN is the noise increase due to pointing inaccuracy and post-processing. N is the fundamental white noise floor (i.e. photon noise from the target and zodiacal background).

Parameter	Value
Spectral Range	0.4-2.5 μm
Resolving power	≈ 330
FOV	2 arcsec
SNR	25 @1.5 μm for 1 sec exposure, star Mv = 9
Detector Type	HgCdTe
Detector size	512 x 512 pixels
Pixel size	18 μm square
Pixel binning	5x5
Signal digitalization	16 bits
Working Temperature	40-45K

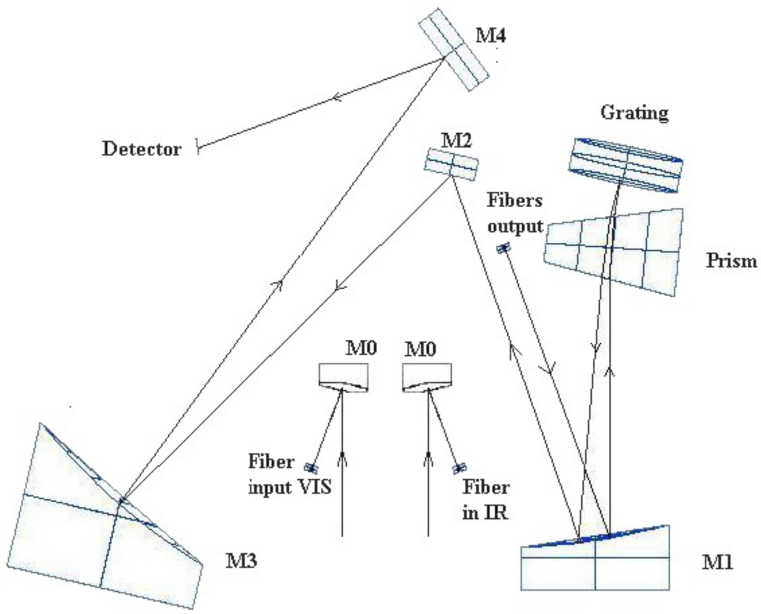

Figure 1. Optical layout of the VNIR spectrometer.

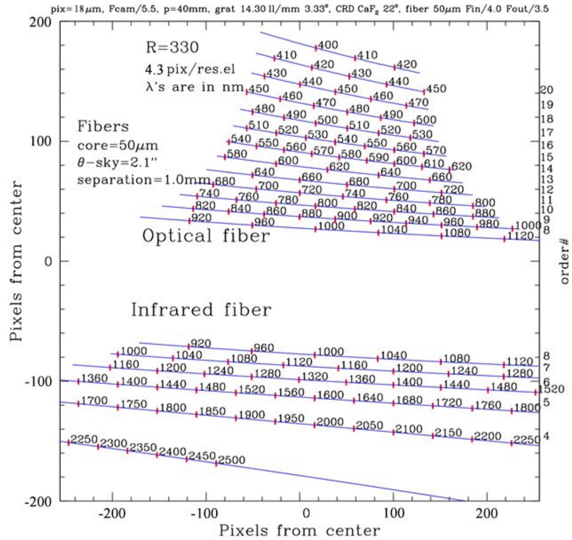

Figure 2. Grating diffraction orders projected on the VNIR detector, starting from m = 3 at the bottom (near infrared spectral range) to m = 20 on the top (visual spectral range). The wavelengths in nanometers are also indicated.

The instrument calibration is going to be performed looking at a known reference star before and after any target observation. The star calibration is meant to verify mainly the position of the spectral lines but also the radiometric response. A very high level of radiometric accuracy, better than 10^{-4}, is assured by the continuous monitoring of the parent star during the transit observations. The observation session is supposed to vary from minutes to about 10 hours depending on the characteristic of the target itself. However, as standalone procedure regardless any request for a star pointing, it is important to monitor also the stability of the instrument and, in particular, of the detector along the mission. For this purpose, a less demanding accuracy and stability is needed, of the order of a few percent. The calibration unit will be equipped with two Halogen-Tungsten lamps for redundancy.

These kinds of lamps are currently used as spectral calibration sources of optical systems [4, 5] and they are the baseline for the development of the VNIR calibration unit too. The calibration lamps will be equipped with a close loop control system to assure the requested stability over the observation time. The lamps will have color temperature higher that 3000K and they will be operating for very short times during the observation sessions.

The signal coming from one of the two lamps, can be used to perform several instrumental checks during the development of the mission: to verify the in-flight stability of the instrumental spectral response and registration; to perform a check on the relative radiometric response of the instrument; to monitor the evolution of possible defective pixels. The lamps inject their light into an integration sphere, which will have two output fibers that will feed the two input fibers to the spectrometer (ranges 0.4-1.0 µm and 1.0-2.5 µm respectively).

2.3 Mechanical and thermal design

VNIR instrument is housed in a mechanical structure, that will be flat-mounted on the spacecraft interface (an alternative isostatic mounting could be evaluated if needed to reduce optical bench distortions). The lower part of the VNIR optical bench will be dedicated to the services to spectrometer: the input box where the mirrors concentrate the light on the optical fibers and the calibration unit in two separated box in order to minimize light and thermal contamination of the rest of the instrument.

The VNIR calibration unit switches on/off and overall control will be performed by the EChO Instrument Control Unit (ICU) [6]. The mass of the instrument is estimated to be about 6.62 kg (20% margin included). The overall dimensions are: 342 x 325 x 190 mm as. The VNIR First Resonant Frequency is planned to be larger than 150Hz. VNIR CFEE (Cold Front End Electronics – SIDECAR ASIC as baseline) will be located on the telescope optical bench; these are supposed to be at temperatures lower than 50K; the detector is planned to work at a temperature in a range of 40 - 45K, dissipating about 30 mW. In order to minimize the thermo elastic deformations and assure a good performance also at low temperatures, the instrument (optical bench, optical supports and mirrors substrates) will be realized in the same material of the payload optical bench (aluminium) and the box will be thermally linked through its feet to it.

3. INSTRUMENT PERFORMANCES

The grating's orders of diffraction, as shown in figure 2, on the detector would not be equally illuminated if the input light would have a constant intensity over the entire spectrum because the grating's efficiency changes along the order. The maximum efficiency is around the center of the blue curves in figure 2. In this spectrometer configuration some wavelengths can be observed on two adjacent diffraction orders. To completely recover the light at those wavelengths the signal coming from the adjacent order has to be summed. The sum has to be done to maximize the result and keep the highest feasible signal to noise ratio.

A reasonable compromise has been found in summing the adjacent orders when the grating efficiency is higher than 80% with respect to the maximum. The result is a component of the Instrument Transfer Function (ITF) that will be given as result of the on-ground instrumental calibrations by measuring and combining the optical efficiency of the spectrometer and the detector performances. The photometric stability is a key factor in the noise budget of the observations. The photometric stability of the instrument throughout consecutive observations lasting up to tens of hours (to cover the goal of phase curve observations) is mainly governed by the following factors:

a) Pointing stability of the telescope quantified in terms of Mean Performance Error (MPE), Pointing Drift Error (PDE) and Relative Performance Error (RPE), see below for details;

b) Thermal stability of the optical-bench and mirrors: thermal emission of the instrument can be regarded as negligible for most wavelengths, but become observable at wavelengths beyond 12 μm. The stability of payload module (instrument and telescope) is therefore an important factor for the photometric stability in MWIR and LWIR channels.

c) Stellar noise and other temporal noise sources: whilst beyond the control of the instrument design, noise is an important source of temporal instability in exoplanetary time series measurements. This is particularly true for M dwarf host stars as well as many non-main sequence stars. Correction mechanisms of said fluctuations must and will be an integral part of the data analysis of EChO [7]. As mentioned above, the pointing stability is affected by the following jitter types:

- Relative Performance Error (RPE), defining the high frequency (> 1 Hz), unresolved jitter component;
- Performance Reproducibility Error (PRE), defining the low frequency (< 1 Hz), resolved PSF drifting due to pointing jitter;
- Mean Performance Error (MPE) which is the overall offset (in time series, the flux offset) between two or more observation windows.

The effect of the relative performance error (RPE) is a photometric error within an observation while the effect of the mean performance error (MPE) is a loss of efficiency from observation to observation. To quantify the effects of jitter on the observations, a simulation has been performed at two representative wavelengths (0.8 and 2.5μm). The illumination pattern of the telescope is obtained from optical modeling. The energy collected by the fiber is then studied as a function of MPE, RPE and PRE. The impact of three different RPEs is studied:

i) RPE1 = 30 mas-rms from 1 to 10Hz;

ii) RPE2 = 50 mas-rms from 1 to 300Hz;

iii) RPE3 = 130 mas-rms from 1 to 300Hz.

These three cases correspond to three different AOCS (Attitude and Orbit Control Systems) solutions. A fixed PRE = 20 mas-rms from 0.020 to 4 mHz is used in this simulation. The results of the simulations are discussed in [8] and are here briefly summarized. The effect of the MPE on the normalized transmitted energy is shown in figure 3. The combined effect of the RPE and PRE on the photometric error is shown in figure 4.

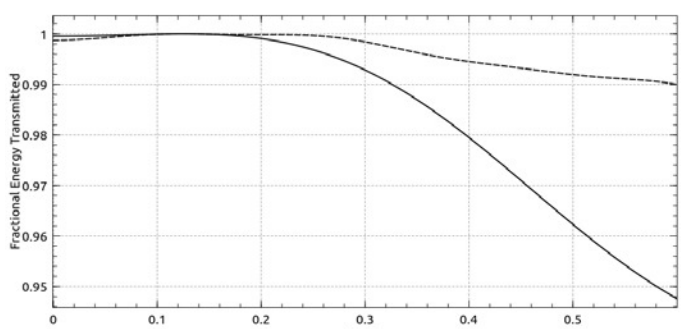

Figure 3. Normalized energy loss vs MPE at 0.8 μm (dashed line) and 2.5 μm (solid line).

The worst case photometric error is obtained when observing a bright target (a star with visual magnitude Mv = 4) with the RPE3 option and results in 10% of the total allowed system noise variance in one second of integration for this channel.

The analysed optical system is the EChO telescope and the concentrating system (f#4) in input of fibre. The configuration optimized consists in primary mirror telescope distance M_{T1}-M_{T2}=1.500 mm, the configuration defocused determines WFE 250 rms with shift M1-M2 position of 87 micron (WFE calculated at 1 µm wavelength).

The fibre with 50 µm diameter corresponds to a Field of View (FOV) of 2 arcsec. The spot diagram and the encircled energy are simulated to verify the requirement. Simulation of encircled energy in 250 rms WFE generated by defocusing (M_{T1} back with respect to M_{T2}) of 0.087 mm (FOV/2= 1 arcsec).

The simulation considers only defocusing shift on optical axis. It is not a complete evaluation of efficiency because the tilt and lateral shift are not included. Figure 5 shows that the spot diagrams of the aberrated beam after defocusing is collected inside the fiber diameter.

Spot diagram inside the fibre diameter and collected Encircled Energy (96.75%) demonstrate that the introduction of a defocusing of 250 WFE rms in entrance beam of fibre. The efficiency of a fiber is the product of three effects, namely internal transmission (which is at most 95% in our case), reflection losses at the entrance/exit (which amount to 6%) and focal ratio degradation (FRD), which measures the fraction of light exiting from the fiber within a given solid angle.

The value of FRD depends on the aperture angle (i.e. the focal aperture F/#) by which the fiber is fed, and by the focal aperture accepted by the spectrometer. The VNIR fiber receives an F/4 input beam and feeds the spectrometer with an F/3.5 output beam. Therefore, the FRD losses are about 5% and total efficiency is about 85%.

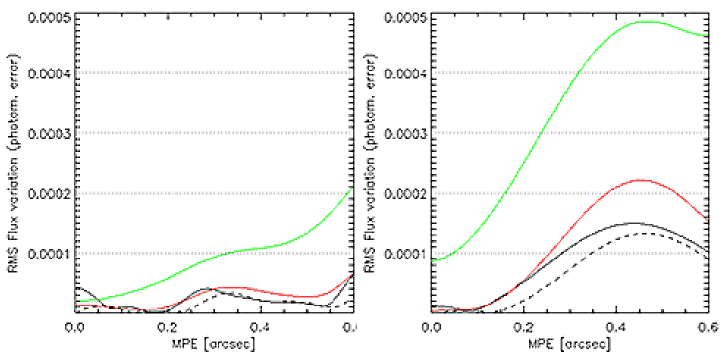

Figure 4. Photometric error induced by combine RPE/PRE at 0.8 µm (left) and 2.5 µm (right) in one second of integration. The solid lines correspond to the RPE1 (black), RPE2 (red) and RPE3 (green) cases discussed in the text.

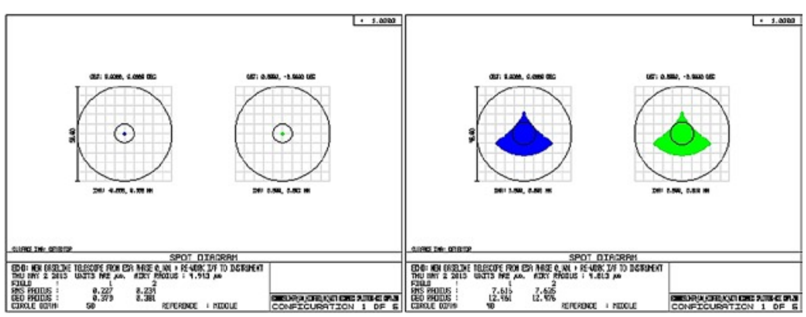

Figure 5. Spot diagrams of focused system in 50 micron at central field 0.0° in blue and marginal field 2.78°x10^{-6} in green colour (on left side) and Spot diagram of defocused system in 50 µm at central field 0.0° in blue and marginal field 2.78°x10^{-6} in green colour (right side).

The light from the telescope can be fed to the fiber on the image plane or on the pupil plane. The former solution is used in HARPS, the ultra-high precision astronomical spectrometer which has reached the highest accuracy in the detection of extra-solar planets. On the other hand, pupil-feeding are often used in fiber-fed astronomical instruments. In the case of

VNIR we can use both solutions, the only difference being the curvature of the input surface of the fiber, which is flat in case of image-feeding. For pupil-feeding, instead, the curvature is such that the first part of the fiber acts as a micro-lens adapter. We plan to test both solutions and select the one providing the best performances in terms of total efficiency and scrambling gain.

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