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ELT -HIRES the High Resolution Spectrograph for the ELT: End to End simulator. Design approach and results.

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ABSTRACT

We present the updated design and architecture of the End-to-End simulator model of the high resolution spectrograph HIRES for the future Extremely Large Telescope (ELT). The model allows to simulate the propagation of photons starting from the scientific object of interest up to the detector, allowing to evaluate the performance impact of the different parameters in the spectrograph design. The model also includes a calibration light module, suitable to evaluate data reduction requirements. In this paper, we will detail the architecture of the simulator and the computational model which are strongly characterized by modularity and flexibility that will be crucial in the next generation instrumentation for projects such as the ELT due to of the high complexity and long-time design and development. We also highlight the Cloud Computing Architecture adopted for this software based on Amazon Web Services (AWS). We also present synthetic images obtained with the current version of the End-to-End simulator based on the requirements for ELT-HIRES (especially high radial velocity accuracy) that are then ingested in the Data reduction Software (DRS) of CRIRES+ as case study.

Keywords: End-to-End simulators – Instrument modeling – Parallel computing – Cloud Computing Architecture – HIgh REsolution Spectrograph (ELT-HIRES) – ELT telescope.

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1. INTRODUCTION

Front line researches in different fields of astrophysics are entering a new era, where the signal detection capabilities will be pushed to unprecedented sensitivity. In the context of exoplanetary science, the atmospheric characterization through high resolution spectroscopy, with the ultimate goal of detecting the few ppm amplitude signal of an Exo-Earth orbiting Solar-like star, and furthermore the possible detection of life bio-signature on exoplanets are only two of the most fascinating examples.

However, the measurement of these properties is challenging both for the physics behind them and for the precise design, optimization, characterization and complexity of the required instrumentation. This unprecedented sensitivity, in fact, will be achieved thanks to more and more complex observation facilities in term of technologies, instrumentations, operative modes and procedures. This arises both from the infrastructure required by large aperture telescope and even more heterogeneous and complex instrumentation. In order to assess the impact of design architecture on the instruments behavior and to accurately predict instruments performances, end-to-end simulators have become key tools[2,3].

End-to-End instrument models (E2E) are simulators which allow physical modeling of the whole system: from the light source to the raw-frame data. Synthetic raw-frames are the output, ingested by the Data Reduction Software (DRS), to be analyzed in order to assess if the scientific requirements (in terms of spectral resolution, SNR, Radial Velocity accuracy and precision, etc.), related to the specific science drivers, are satisfied with the specific instrument design and architecture. Moreover, E2E are valuable tools to be exploited to optimize performances, calibration procedures and observation plans, with the ultimate goal of maximizing the scientific return, before the on sky operations.

In this paper we present the current design and development status of the E2E simulator for ELT-HIRES, the high resolution spectrograph for the ELT. The development of the simulator directly during the design phase will benefit the whole ELT-HIRES project, in addition to the aspects mentioned before, giving reliable simulations to gain a deep understanding of the instrument design, improving the capability of early identification of system level problems. This is fundamental to properly characterize error budget and systematic effects at system engineering level.

2. ELT-HIRES OVERVIEW

The huge photon collecting power of the 39 m primary mirror diameter ELT coupled with a High Resolution Spectrograph (ELT-HIRES) will allow to make fundamental discoveries in a wide range of astrophysical areas, outlined by the Science Team of the ELT HIRES consortium[4,5,6,8]:

- The study of Exo-planetary atmospheres and the detection of signatures of life on rocky exo-planets.
- The chemical composition, atmospheres, structures and oscillations of stars.
- The spectroscopic study of the galaxies evolution as well as the three dimensional IGM reconstruction at high redshift.
- Fundamental constants (such as the fine-structure constant α and the proton-to-electron mass ratio μ) variation and the related cosmology.

The E-ELT will be the largest telescope to observe in visible and infra-red light; the baseline of the optical design (see Figure 1) is five mirror solution[1]: aspherical (almost paraboloid) primary mirror M1, a convex secondary mirror M2 with 4 m diameter, concave tertiary mirror M3 with 3.75 m diameter, and two flat mirrors (called M4 and M5). These two latter mirrors have the purpose to feed two Nasmyth focal stations and for adaptive optics; below each Nasmyth platform a Gravity Invariant focal station, fed by a steerable and removable mirror (M6), will be located (see Figure 1). In addition the M6 mirror and a Coudè-train relay optics will allow to feed a Coudè focal station, which will be specialized to host instruments requiring very high long term stability in terms of thermal and mechanical perturbations. The telescope structure will be alt-azimuth type.

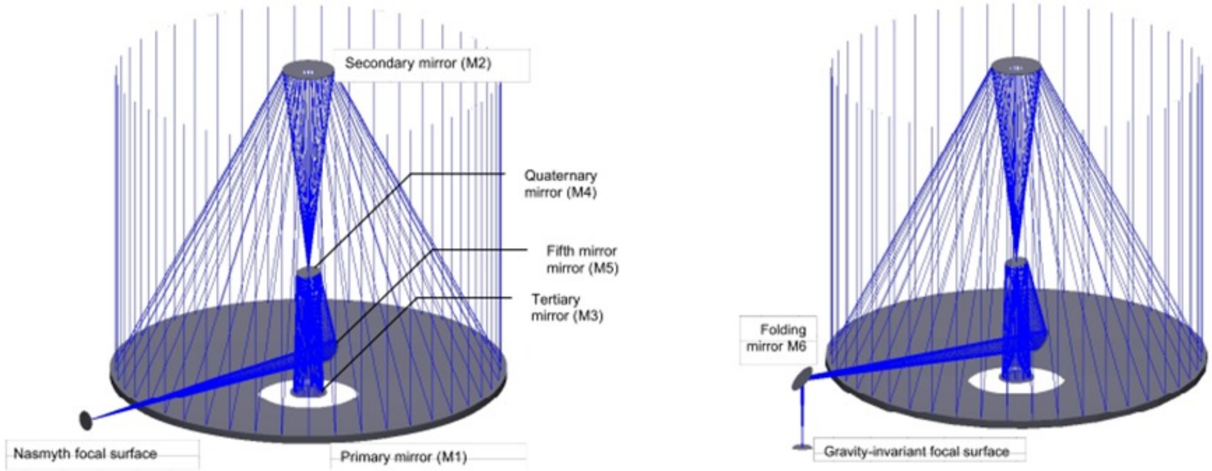


Figure 1. E-ELT optical layout: Nasmyth focus (left) and Gravity invariant focus (right), taken from [1]

HIRES is a modular fiber-fed cross-dispersed echelle spectrograph that will operate both at a Nasmyth and at Coudé focus of the ELT. The baseline architecture, defined in the Phase A of the project, consists of two separate spectrographs operating in the visible (BVRI) and infrared (ZYJH) bands, (see Figure 2, and for details reference[21]). A more complete solution consisting of four separate spectrographs with the addition of the U and K bands respectively is also taken into account in the instrument design (and handled by the software, described in reference[7]) even though this solution due to the cost cap is currently termed as "*add-on*".

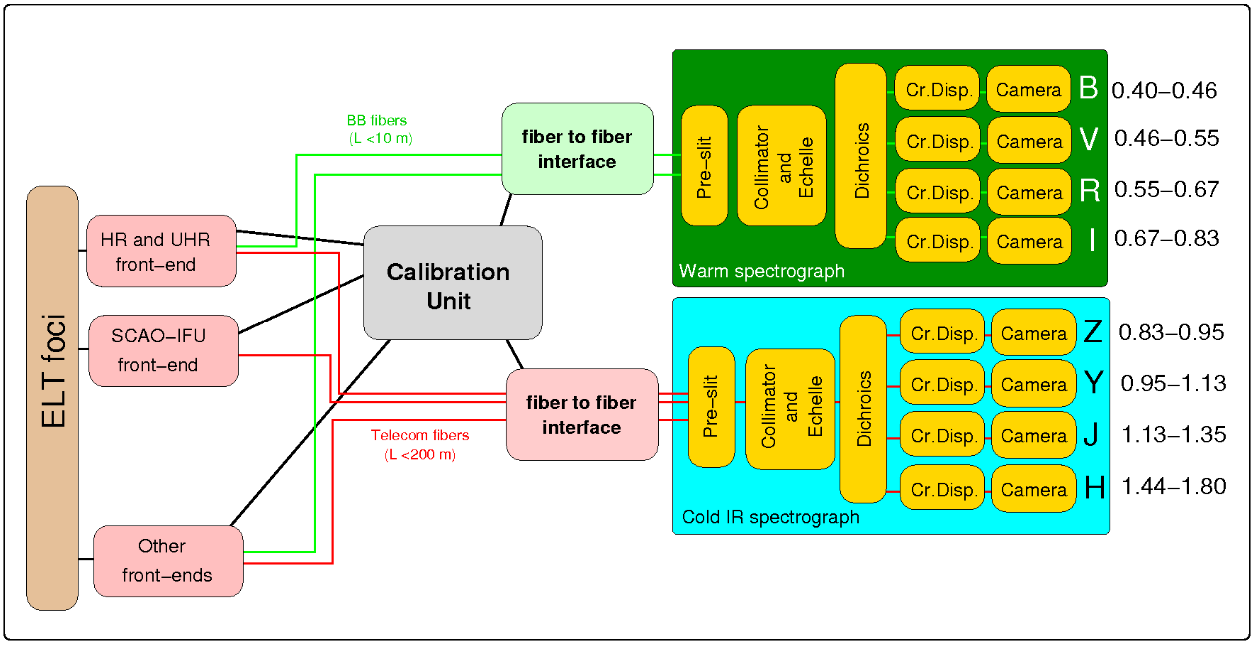


Figure 2. Schematic of the proposed ELT-HIRES functional architecture concept. The different sub-systems of the instrument (front-end, fiber link, calibration unit, spectrometers) are indicated, as well as the possible length of the fiber bundles, according to the specific wave-band. The wavelength splitting in the different spectrograph modules is reported (in µm).

The light from the telescope is split, via dichroics in the Front-End (FE), in the two wavelength channels. The FE sub-system also provides: atmospheric dispersion correction, field stabilization and guiding. Each wavelength channel interfaces with several fiber bundles that feed the corresponding spectrograph module (VIS and NIR). Each fiber-bundle corresponds to an observing mode. All spectrometer modules have a fixed configuration, i.e. no moving parts. They include a series of parallel entrance slits consisting of linear micro-lenses arrays each glued to the fiber bundles. In order to accomplish the specific scientific goals (see refrence[8], as well as for a description of the observing modes), for the different main observing modes two possible resolution capabilities (HR with R = 100000 and UHR with R = 150000, see Figure 2) are foreseen, which can be implemented by feeding the spectrograph modules with different fibers bundles. The technique used by the Front-End and Fiber-Link sub-systems to feed the huge AΩ-product at the spectrograph entrance in the selected architecture is the field dicing (see for details reference[9]), in which each fiber of the bundle is looking at a slightly different part of the object.

The spectrometers can be ideally divided according to their specific function into two units: the pre-slit unit, a re-imaging system which collects the light from the fiber optics and feeds the spectrometer unit, which has the usual purpose of separate the light into its constitutive wavelengths and then refocus them onto the detector surface. The spectrometer units' optical configuration (see for details[21]) is the white pupil layout with an off-plane echelle grating; while the current camera optical configuration is the Schmidt camera.

The Calibration Unit, located in the Coudé room, is connected via fibres to the Front End and to the Fibre Links. The foreseen calibration sources are intensity calibration sources (laser driven light source, halogen lamps, light emitting diodes, light bulbs) and spectral sources for simultaneous calibration (AstroComb, Faby-Perot, single wavelength laser, hollow-cathode lamps).

ELT-HIRES has a Polarimeter arm, which is composed by two modules: Intermediate Focus Polarimetric Module (IFPM) and Front End Polarimetric Module (FEPM). The IFPM is located in the Adaptive Optics Tower of the telescope and is in charge of splitting the incoming beam into the ordinary and extraordinary beams via a birefringent prism (double Wollaston). This module uses also the calibration light via a fiber bundle coming from the Calibration Unit. The FEPM splits, via dichroics, the ordinary and extraordinary beams in the two wavelength channels (VIS and NIR) and provides usual Front-End functionalities listed above.

3. END-TO-END SIMULATOR DESIGN PHILOSOPHY AND ARCHITECTURE

The design philosophy of the E2E simulator is characterized by three fundamental aspects:

- Modularity: the system is organized in Modules and Units, each in charge of its own responsibility, with specified interfaces and possibly with the maximum degree of independence. Since the instrument is itself complex (telescope, fiber-link, spectrograph, detectors) one of the key step is to identify and define the different Modules (and Units) and their interfaces. This allows to well characterize the behavior and the functionalities of each of them;
- Flexibility: Since Units and Modules are, at first level of approximation, independent the system should allow to choose what to simulate or not, or to by-pass some units (e.g. simulate only emission from the object without atmospheric contamination or, instead, simulate the echellogram without taking into account PSF diffraction);
- Speed: It is straightforward to expect that a certain amount of simulations will be performed during the whole design phase of the instrument. For this reason, it is crucial to design a solution that could achieve a fast computational time by adopting the proper state-of-the-art technologies. For this reason, the system has been design by the adoption of Cloud-Computing that allow to speed up by various orders of magnitude the computational time.

The End-to-End simulator architecture, shown in the schematic of Figure 3, is highly modular, composed by different modules each one with specific tasks, units-functionalities and interfaces. In details, a Unit is a piece of software, function or interface of a part of the HIRES spectrograph and could be considered as a black-box that exchanges data both with other units of the same module, and even with other modules (as represented in Figure 3). Modules are piece of software that model either an external component (w.r.t. the HIRES spectrograph) such as Telescope, or the Spectral Energy distribution of the object to simulate, or a piece of software that has not a counterpart on the actual hardware (e.g. the Image Simulator module). Each module or unit is identified and characterized by: main tasks, inputs required and the expected outputs in the expected format (like tfits table, image, etc.).

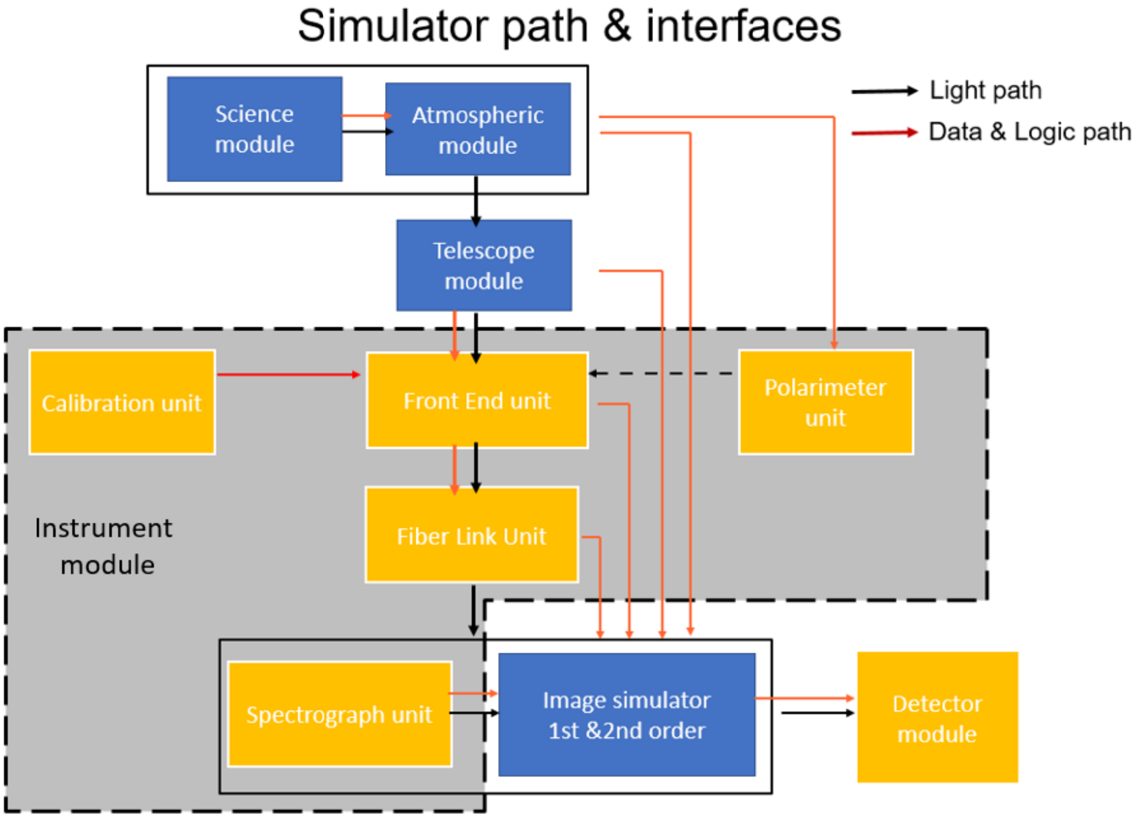


Figure 3. General schematic diagram of the End-to-End simulator modules, with the related interfaces. The light path and data-&-logic path through the different units are shown. Instrument related units of the End-to-End simulator are colored in orange, while in blue other units simulated by the End-to-End model but independent from ELT-HIRES Spectrograph. The units which compose the Instrument Module are grouped by the grey box.

4. END-TO-END SIMULATOR BREAK-DOWN

In this section, the description of each block reported in the schematic view of Figure 3 is reported.

4.1 Science Module

In the science module, a synthetic spectrum is created from a set of input parameters related to a specific science case, or source. Currently the module is set for stellar science cases, for which the input parameters are: the spectral type (with specified effective temperature and surface gravity), magnitude, radial velocity and exposure time. For each stellar source, when the magnitude is provided in a given photometric band, the observed energy density is converted to photon-flux and the spectrum is normalized at the reference wavelength of the provided magnitude pass-band and then re-scaled accordingly. This module provides an output file, a FITS table, composed by two columns: the first one is the wavelength, in Angstroms, and the second one is the flux, in CGS units, or photon flux. The resolution can be set as an output-simulation parameter, and currently it is such that the resolving power is R=550000. An example of a synthetic 1D spectrum is reported in Figure 4.

The module will also be set for both to stellar populations and extragalactic science (QSO, etc.). In fact, adopting the same strategy, it can be extended for the whole science cases of HIRES whenever the theoretical spectrum is known (e.g. for QSO and Ly-α forest for the Sandage Tests simulations).

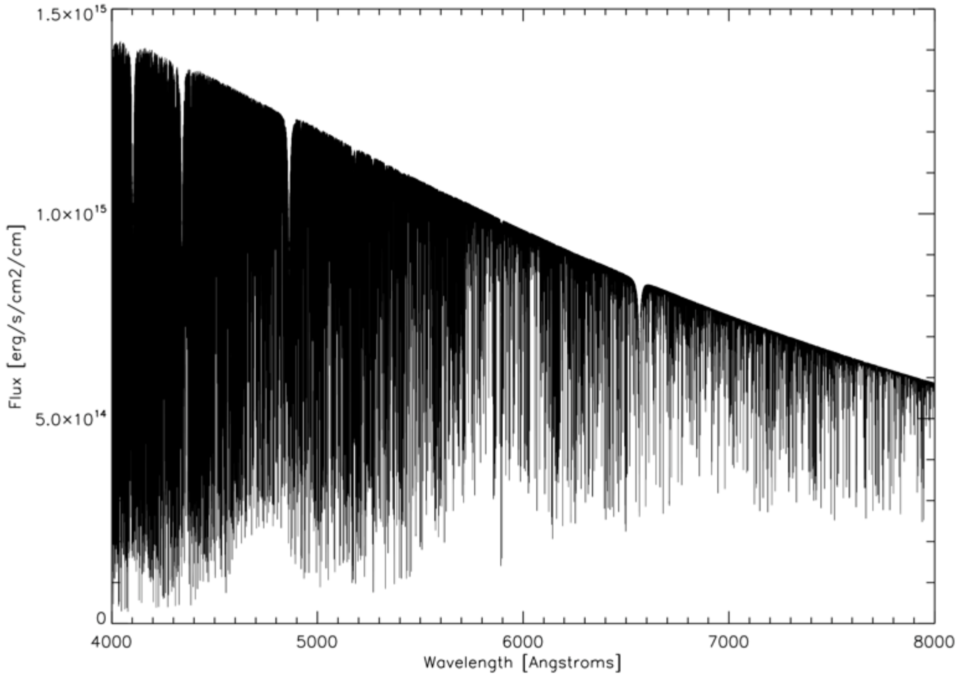


Figure 4. Synthetic emission spectrum from a G2V star obtained by the science module. Typical main sequence star of e□ective temperature 5000 K, surface gravity log(g)=4.5 and solar metallicity.

4.2 Atmospheric Module

The main aim of this module is to model the scattering, absorption and emission occurring in the Earth's atmosphere, and introduce it to the simulated science observations. This is done by using the ESO SkyCalc tool (available at the web page[11]), which is based on the Cerro Paranal Advanced Sky Model. The SkyCalc is queried using resolution step of 0.006 Angstroms, corresponding to at least spectral resolving power of about 550000 with the wavelengths range of ELT-HIRES. The sky spectrum obtained from SkyCalc is re-binned to the same wavelength scale as is used in the synthetic spectrum.

SkyCalc gives two different outputs: sky radiance (in photons/(s m^2 μm $arcsec^2$)) and sky transmission (in transmission fraction) at Paranal. For the End-to-end simulation purposes the sky transmission is divided into two components, general extinction curve, and telluric absorption lines (see Figure 5). Extinction curve, shown in the example of Figure 6, is obtained by a spline fit to the data, from which the saturated absorption lines are excluded. The absorption lines component, on the other hand, is given by removing the extinction from the total sky transmission spectrum.

The sky radiance is calculated at the area of one individual HIRES fiber (0.17 arcsec diameter of sky projection) and then the units are converted in photons/(s m^2 μm).

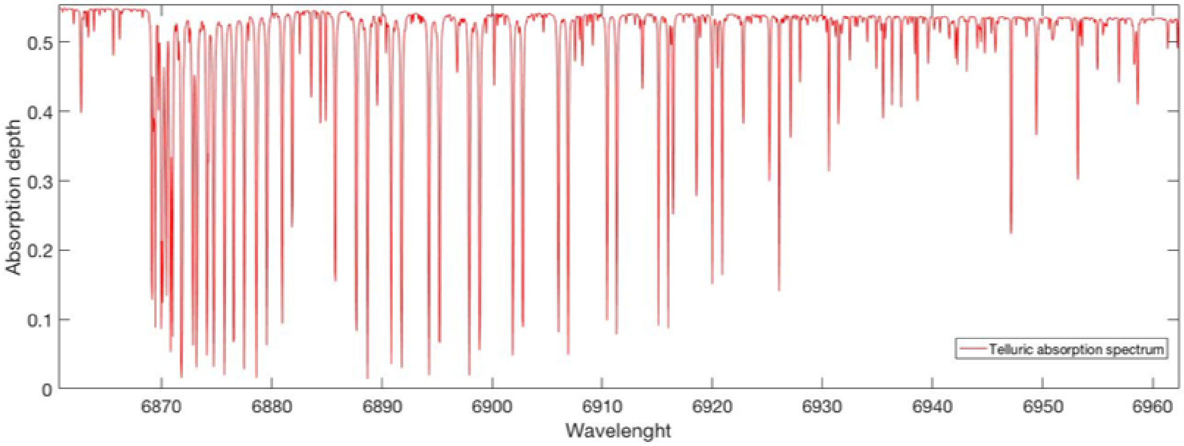


Figure 5. Example of telluric spectrum recovered adopting the procedure reported in the text (y axis is in relative units).

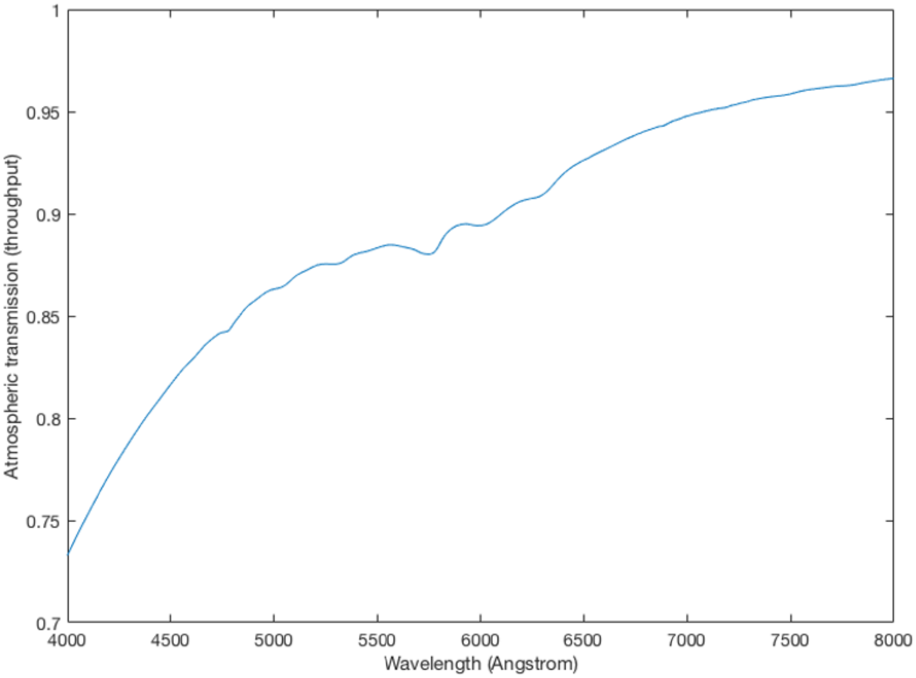


Figure 6. Atmospheric extinction curve adopted.

4.3 Telescope Module

The aim of this module is to predict the telescope point spread function (PSF) with and without adaptive optics (AO) system corrections, the image at the telescope focal plane and the telescope throughput. This module relies on the PASSATA software[11], developed by the Adaptive Optics group of the Arcetri observatory for Monte-Carlo end-to-end adaptive optics simulations and managed by the Telescope Simulation and AO group in the framework of the ELT-

HIRES project. The interaction with this work-package has been set for the definition of the interfaces between the simulations of this independent software and the E2E simulator.

The input parameters are: zenith angle, seeing, the estimated average wind speed (from wind profiles of different atmospheric layers), telescope wave-front error matrices (WFEM), the AO system parameters and telescope coatings reflectivity profile. The WFEM and telescope transmission profiles are gathered from ESO, while the set AO system parameters (like actuators number and frequency, number of wave-front modes to be controlled and system acquisition frequency) are internal parameters used by the PASSATA software. The output interfaces are with Instrument Module, for what concern the telescope PSF (both with and without the AO correction), and Image Simulation Module for what concern transmission. The output telescope PSF is given with a sampling of 0.008 arcsec/pixel.

An example of the PSF profile (non-normalized) simulated by the Telescope Module, both in seeing limited and SCAO (Single Conjugate Adaptive Optic) operative mode for ELT-HIRES is shown in Figure 7. The SCAO correction performance is simulated in different conditions of seeing (best seeing = 0.47 arcsec; median seeing = 0.8 arcsec) and source magnitude, for zenith distance = 0 at λ =1000 nm.

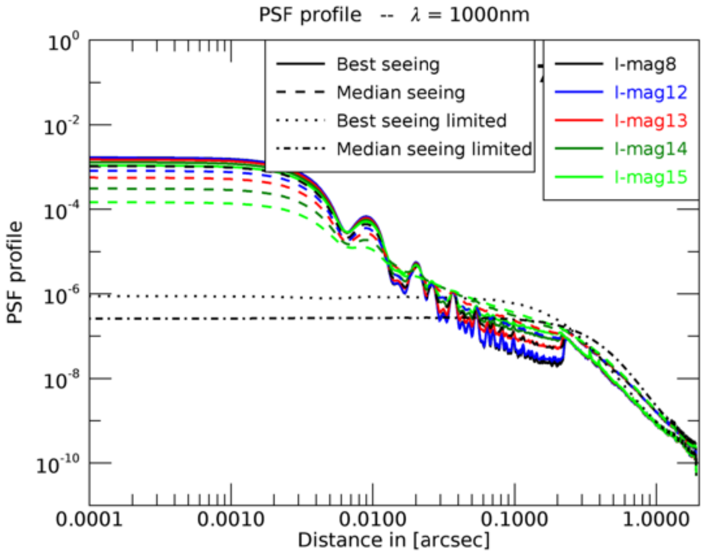


Figure 7. Mean profiles of the non-normalized PSFs under different seeing conditions and source magnitude, for zenith distance = 0 at λ = 1000 nm. The comparison between the AO correction and seeing limited case shows that the PSF profiles, at a certain distance from central core, drop to the seeing limited case because not corrected.

4.4 Instrument Module

This module is in charge to generate data for rendering the geometrical images of the instrument focal plane, to evaluate the instrument PSF and instrument throughput. The module is organized in units:

- The Front End (FE) Unit and Fiber Link (FL) Unit models the link between the telescope and instrument.
- The Calibration Unit produces the SED of the selected calibration sources.
- The Spectrograph Unit models the optical path along the optical train taking into account distortion, the effects of dispersive elements and the optical quality in different conditions are evaluated in order to compute the whole point spread function for different wavelengths and positions on the instrument image plane. The transmissivity and reflectivity of the different optical components as well as the echelle grating blaze function and cross disperser diffraction efficiency are modeled for the instrument throughput calculation.

- The Polarimeter Unit is aimed at evaluating the telescope polarization effects and the final odd and even flux at the polarimetry arm output.

4.4.1 Front-End Unit

The task of this unit is to predict the light distribution at the FE focal plane and to predict the FE throughput. The required inputs are: telescope focal plane image (internal interface in the E2E simulator), the Front-End optical design and optical parameters like the proposed glasses and coatings in order to estimate the FE point spread function (and the FE throughput). The FE focal plane is the plane where the dicing-unit samples the field (in case of field-dicing technique selected) with a micro-lens array and separates the different parts of the field feeding the corresponding fibers in the fiber bundle (part of the Fiber-Link unit).

In order to predict the light distribution at the FE focal plane (see Figure 8) the telescope focal plane image is convolved with the estimated PSF of the Front-End (2D image FITS). The telescope image in input is sampled with a defined resolution of 0.008"/pixel (see Telescope Module section). The FE estimated PSF size is 0.025 arcsec.

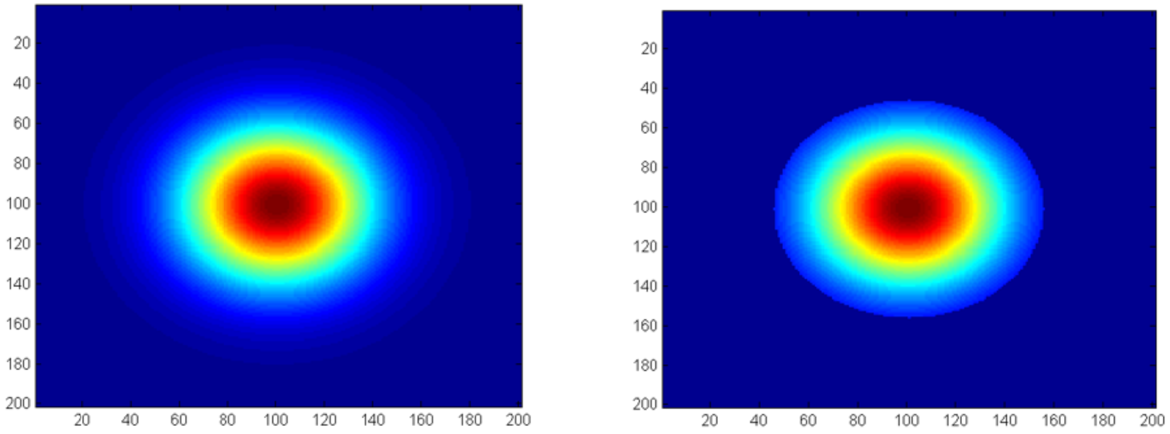


Figure 8. Front-End focal plane. *Left panel:* the telescope focal plane image is convolved with the estimated FE PSF of 0.025 arcsec. *Right panel:* Portion of the FE unit focal plane light distribution that feeds the dicing unit aperture.

The dicing-unit micro-lens array has been modeled by simulating the different micro-lenses as sub-circles placed in the FE focal plane according to a hexagonal packing. An example with 30 fibers is reported in Figure 9. The amount of flux taken by each micro-lens is computed by evaluating how much of light with respect to the total is captured by each fiber, so that it is possible to estimate the amount of light processed by each of them. Finally the FE throughput is calculated by the modeling of the different glasses and coatings transmissivity and reflectivity. The output tables with amount of light and related fibers, and FE throughput as function of wavelength are transmitted to the Image Simulator Module.

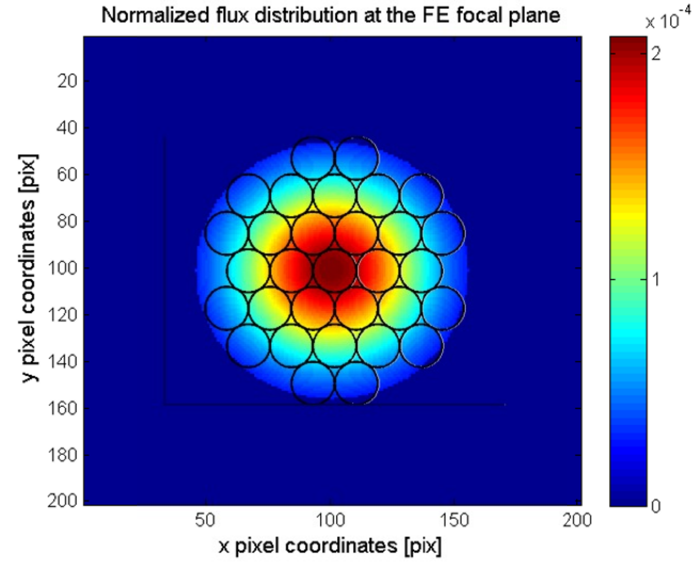


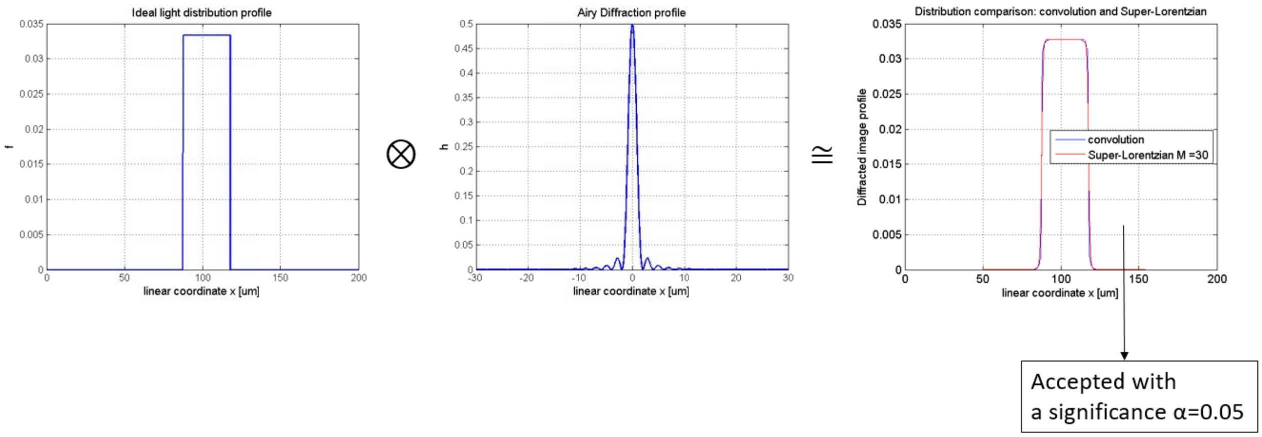
Figure 9. Dicing unit array example: 30 micro-lenses modeled as circles and packed in hexagonal layout.

4.4.2 Fiber-Link Unit

This unit has the purpose to predict the light distribution at the end of the fibers by taking into account all the possible effects that could occurs while light passes through the fiber (like modal noise and non-uniform illumination). In the current version of the simulator, a perfect scrambling system is assumed so that the output end of each fiber is expected to be a top-hat function. Nevertheless, the whole set of physical parameters foreseen to be considered for a more detailed simulation (which will be part of the next E2E simulator versions) are: fibers-bundles layout, fibers type and geometry and the operative conditions in term of temperature and mechanical stresses. According to physical optics, diffraction should be taken into account so this profile could be safely approximated by a top-hat function plus the Airy diffraction disk. The most straightforward equation that is able to capture these effects is the so-called Super-Lorentian function (see reference[15] for details):

$$I_{SL}(r) = \frac{I_0(R_{SL}, M)}{\left(1 + \left(\frac{r}{R_L}\right)^M\right)} \quad \text{with} \quad I_0\left(R_{SL},\ M\right) = \frac{M \sin(2\pi/M)}{2\pi^2 {R_{SL}}^2}$$

The free shape parameter M was tuned to M=30, as shown in Figure 10, in order to recover the proper dimension and the amount of diffraction effect coming from the finite aperture of the system. With this set, this function fits the physical model with the confidence level of 0.05. In the next versions of the simulator, this module should be able to reproduce physical effects observed in optical fibers, like the modal noise, taking into account the set of input parameters mentioned before.



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a significance α=0.05

Figure 10. *Left panel*: top hat function that model the output of a perfect optical fiber. *Center panel*: diffraction pattern from the output fiber. *Right panel*: comparison between the top-hat function convolved with the Airy disk and the Super-Lorentian function.

4.4.3 Calibration Unit

The calibration unit is in charge to simulate the Spectral Energy Distribution (SED) of the calibration sources acting in the same way of the Science module. Both arc lamp and flat field are simulated. This unit requires to know which kind of lamps are to be simulated (flat field, ThAr, Fabry Perot, etc.), the instrument maximum resolution and returns a tfits table that contains the spectral energy distribution of the required source in the proper units. An example of this is reported in Figure 11, where it is shown a portion of a Fabry-Perot etalon used as a wavelength calibration source.

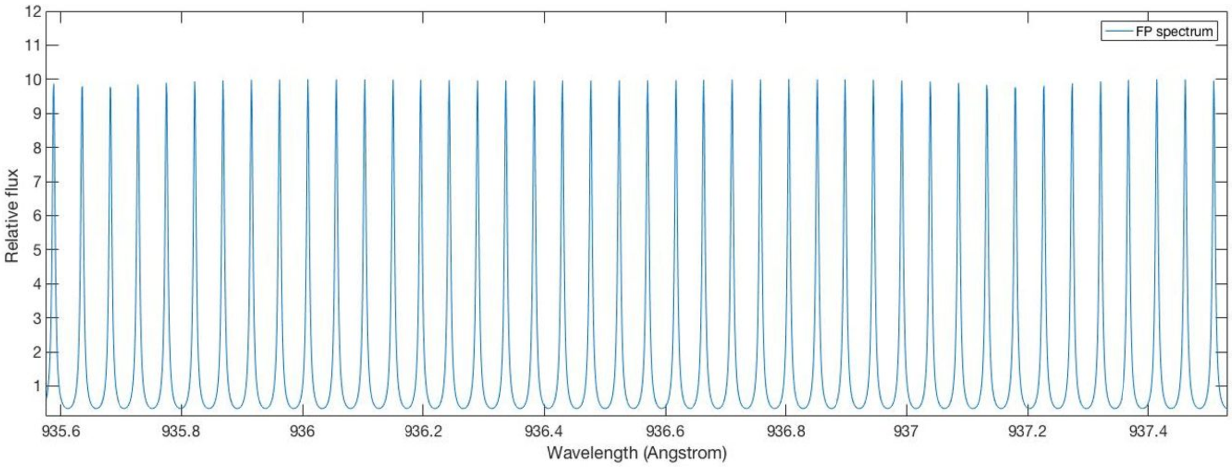

Figure 11. Example of SED produced by the calibration unit (Fabry-Perot etalon).

4.4.4 Polarimeter Unit

The Polarimeter Unit is aimed at evaluating the telescope polarization effects and to give the final ordinary and extraordinary flux at the polarimetry arm output, as well as PSFs and overall efficiency. In the current version of the E2E simulator no modeling is implemented for this Unit.

4.4.5 Spectrograph Unit

The purpose of this Unit is to simulate the physical effects of the different optical components of the spectrometer with the final aim of predict the echellogram (spectral format) at instrument focal plane, the throughput and the light distribution of the camera entrance pupil (this is exploited to simulate/estimate the second order effects on the object spectrum due to pupil obstruction and non-uniform illumination). Aberrations, distortion and diffraction effects have already been taken into account at this current simulator version, while the physical operative conditions of the instrument in term of ambient, mechanical and thermal effects will be introduced in the future versions.

The spectrograph can be modeled using two different alternative approaches: the Parametric Version and Ray-Tracing Version. The former is based on a physical parametric model (see for example refrence[14]), built with the physical equations and relations which characterize the optical elements, while the latter is a ray-tracing version built with commercial optical design software (e.g. Zemax). The Parametric Version is a useful tool which can be exploited to have a complete run of the simulator, even if the optical design of the instrument is only at a preliminary phase and the detailed optical ray-tracing files and documentation are not already complete and available, with the purpose of doing considerations regarding the orders curvature, lines tilt, fibers alignment which are relevant aspects for the data reduction software. In addition this approach allows for quick parametric evaluations and analyses concerning different possible spectrograph design choices and architectures.

While the Ray-Tracing Version takes as input directly the ray-tracing optical design files, built in the commercial software package Zemax, and uses some specific software tools to extract the required outputs (spectral format at instrument focal plane, the throughput and the light distribution of the camera entrance pupil), the Parametric Version needs some input parameters to model the spectrograph; these parameters are the same parameters which the optical designer takes into account in the design and optimization of the spectrograph with the ray-tracing software. In the frame of the End-to-End simulator architecture the inputs have been divided in the following types: top level requirements (e.g. resolving power, wavelength coverage and sampling), inputs parameters form other modules (e.g. telescope size, Detector pixel size) and Input variable parameters (e.g. number of optical fibers, optical elements F-ratio, dispersing elements working angle and line density, glasses and coatings properties and operative conditions in term of temperature and pressure).

The echellogram in output from this Unit is composed by the coordinates of the projected resolution elements per each fiber/lens-let on the detector surface; these are passed as input to the Image Simulation Module for the generation of synthetic diffracted spectra (which will be commented in details in the Image Simulator Module). An example of the echellogram format retrieved by the Instrument Module is shown in Figure 12.

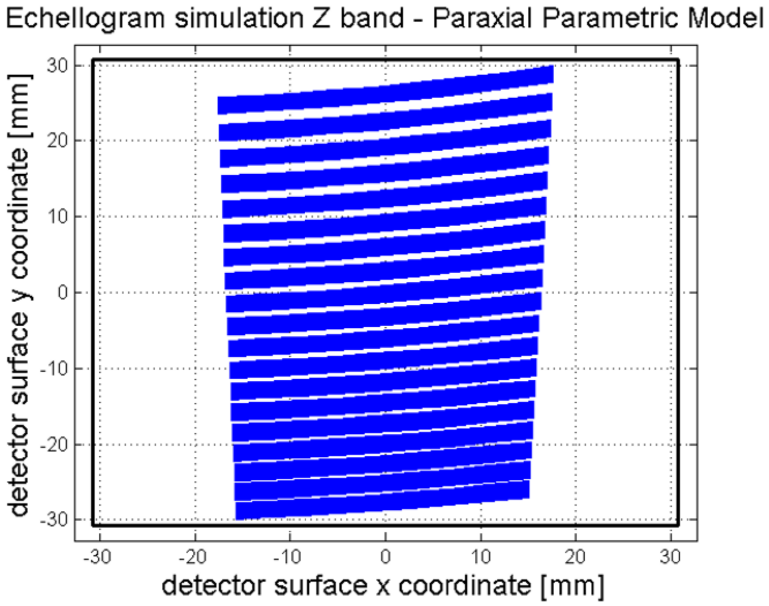

Figure 12. Echellogram format example from the Instrument Module Paraxial Parametric Model computation.

4.5 Detector Module

The task of this module is to simulate, on the rendered data, the effects produced by the detector. Besides the nominal Quantum Efficiency response and the usual noises (like photon noise, Read-Out-Noise, Dark Current, pixel non uniformity, etc.) that are well characterized and, in most cases, straightforward to simulate, this module will also have the aim to add other effects that could be relevant for high precision radial velocity measurement. In particular, additional blurring types of the Spectral Resolution Elements (SRE) caused by the detector itself, are planned to be taken into account in future versions of the E2E simulator; these are: defocusing due to the not ideal planarity of the detector surface, optical defocusing of the diverging beam after focal point and Gaussian blurring due to the dispersion of electrons across the sensitive material.

4.6 Image Simulator Module

This portion of the simulator is the kernel of the whole system. This piece of software, which runs heavily in parallel in a cloud distributed environment (see next section), is responsible for rendering the photons distribution of each resolution element for each fiber, for each order for each wavelength as should be detected at the level of the detector. A portion of this module, written in MATLAB, is also in charge to glue the different Units and Modules to produce the actual echellogram.

The perfect image of the fibers as seen at the level of the focal plane is estimated as explained in the Fiber-Link Unit subsection. Then, this distribution must be convolved with the PSF of the instrument that includes both aberration, diffraction and effects from the optics of the spectrograph. This is referred as *1st order PSF effect*, and it could be carried out in two ways:

- Analytically, using only the spectrograph paraxial model. In this scenario, the net effect is a Gaussian function whose FWHM represents the quality of the system.
- Using ray tracing, by polling Zemax to recover the map of the PSF that could be used as a kernel to be convolved with the light distribution coming from the fiber.

For the current version of the E2E simulator the first mode (analytically) has been adopted, although the whole architecture of the system is able to handle also the second one.

The actual PSFs are also affected by the diffraction coming from the obstruction present in Schmidt cameras proposed in the current spectrograph optical design. Diffraction spikes in the PSF are generated by the presence of sharp edges within the beam shape at pupil position. Each spike extends towards orthogonal direction with respect to the edge that produced it and its spatial distribution is broader than the Airy diffraction halo, as deeply described in reference[16]. The importance of simulating diffraction spikes for a spectrograph like ELT-HIRES is that, if a spike happens to extend along the spectral direction in the final image, it will spread the flux of any bright spectral line onto the adjacent spectral intervals, thus increasing the local stray light contamination. This effect is especially important around the narrow and intense sky emission lines (see again reference[16] for details). In this context, the Image Simulator Module (*2nd order PSF effect*) first computes an high resolution model of the beam obstruction, which depends on the beam shape, angle and position when the beam intersects the obstructing elements (different for each field and wavelength, and passed as inputs to this module, coming from the Spectrograph Unit of the Instrument Module). Then, it computes the diffraction component of the PSF shape by means of a Fast Fourier Transform of the obstruction model. The output of this module is a 2D image of the diffraction component computed on a sub-pixel sampling, combined with the 1st order optical aberration PSF (explained before). Finally, the Super-Lorentian illumination profile coming from fiber output end is convolved with the whole estimated PSF model, and the surface integral of the convolution is computed in each pixels to obtain the photons distribution for each SRE.

5. COMPUTATIONAL ARCHITECTURE

For a high resolution and high radial velocity precision spectrograph like ELT-HIRES, the wavelength image barycenter reconstruction accuracy will be the primary performance; to give an order of magnitude the spectral resolution element barycenter reconstruction accuracy should be better than $\sim$ 1nm. This requires, as expected, that the computation of the photons distribution for each SRE should be performed with high precision.

For this reason, we have developed our own integral computation procedure using an innovative approach based on heavy parallel computing CUDA by NVIDIA for the evaluation of single point convolution value.

The procedure is based on standard integration algorithm and, among others, foresees two different variable parameters exploited to directly control the computation accuracy and cost. These parameters are the single pixel partition for the integral calculation and the pitch scanning of the Fiber illumination profile and PSF for the point convolution evaluation (assuming only 1st PSF effect and analytical profile in the current version of the simulator).

The adoption of parallel computing is crucial, since the simulations of synthetic spectra gathered by ELT-HIRES involve a huge amount of computational power. In particular the number of SRE (including sampling anti-aliasing) to be computed is of the order of 7×10^9. It is thus clear that the complexity in time is a key factor in the design of our simulator. The image of single resolution element is obtained starting from the illumination profile, modeled as a Super-Lorentzian function with parameter $M = 30$ (see Fiber-Link Unit description for details), and a Gaussian that represents the PSF of the spectrograph itself (as described before).

The computation of each SRE image is performed on a grid of 10x10 pixels sampled in step of 0.1 pixels as depicted in the schematic of Figure 13. In particular, for each pixel a Computation CUDA Block is assigned and, for each one of the 100 sub-pixels, a worker thread compute the convolution value in that point. This kind of approach, allows to run in parallel 10.000 worker thread on a single GPU kernel allowing to decrease the time of computation up to 0.001 μs for each SRE. Since the problem is, as explained, parallelizable and SREs are independent of each other, we exploited the capability of cloud computing using the Elastic Computing 2 of Amazon Web Services (AWS) to increase the number of computer available to perform the whole simulation (see for details about cloud computing, the reference[18]). An additional key point of the computational architecture adopted is that the instrumental echellogram format computed is independent of the spectral energy distribution of the scientific scenario that can be simulated, as well as of the global throughput profile of the whole instrument (from telescope to detector QE). Thus the SED and throughput profile can be applied locally, once the illumination solution of the echellogram format is computed.

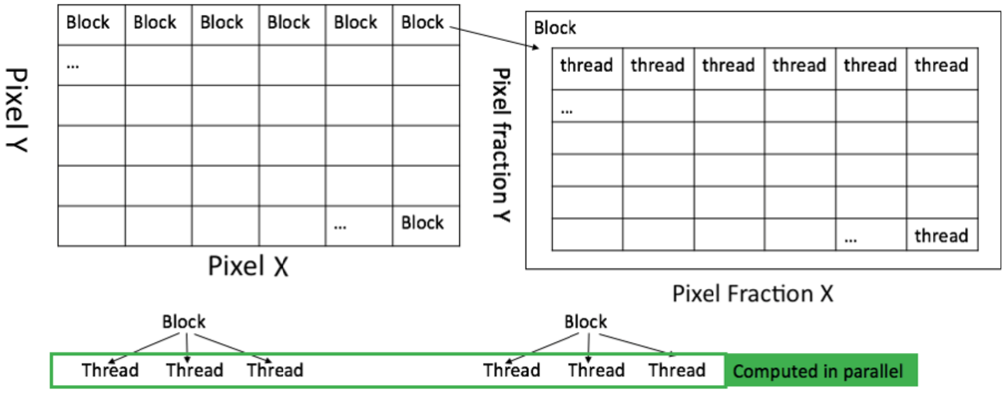

Figure 13. Schematic of CUDA Block and Worker Thread architecture for the computation of convolution and surface integral on each detector pixel.

6. RESULTS

6.1 Performances

As stated in the previous section, one of the most important issue that should be investigated is the computational cost, especially in terms of complexity in time. This is the most critical point that could results in a showstopper. In particular, with the adoption of the Cloud Architecture (see reference[18]), the E2E is able to recover the echellogram format in approximately 0.5 days. This kind of computational time, which consider most of the effect needed to be simulated, allow to confirm that the current architecture is suitable for intensive simulation scenarios with large margin that could be used in the case of increased computational time required to add other effect (such as modal noise or the contribution of 2nd order PSF effects) which should be roughly of the same order. Moreover, as explained before, since the illumination solution of the echellogram format is independent on the spectral energy distribution of which is simulated (far all the scientific cases that can be considered), the number of required iterations on the cloud are order of magnitude less than the ones locally required to apply the SED.

6.2 Raw frames rendering and Data Reduction Software

One final activity required in the design of the E2E simulator is aimed at demonstrating the capability to close the loop with Data Reduction Software (DRS), since the delivered frames of the simulator will act as input for this pipeline. The strong link between the E2E and DRS is crucial especially in the next E2E simulator versions since this will allow to characterize the performances of the instrument by translating directly the optical and mechanical architecture in scientific terms, by simulating all the main ELT-HIRES science cases.

To demonstrate that this synergy is settled with proper interface and to see if the simulated echellograms can be handled by a DRS pipeline, the ELT-HIRES DRS working-group applied the beta recipes of the CRIRES+ DRS (Details on CRIRES+ Instrument and its DRS can be found here[19]), which is currently under development. In spite of HIRES being fiber-fed and CRIRES+ a true slit spectrograph, they share enough similarities in the echellograms being high-resolution, cross dispersed, tilted and inclined (pseudo-)slits, that the recipes could be applied without relevant modifications.

Two different raw frames (with exception of the BIAS trivial ones, not reported here) have been produced with the E2E simulator. The first on is a flat field frame in the Z Band as seen by HIRES (left panel of Figure 14) and the second one is a scientific frame of a G2V star with m V = 10 and exposure time = 50 s observed and seeing = 0.85 arcsec (that produces different illuminated slits) in the HIRES Z Band (see Figure 15) in polarimetric mode (both fiber-bundles illuminated by the same object) with simultaneous Fabry-Perot reference. These frames have been ingested by the DRS of CRIRES+.

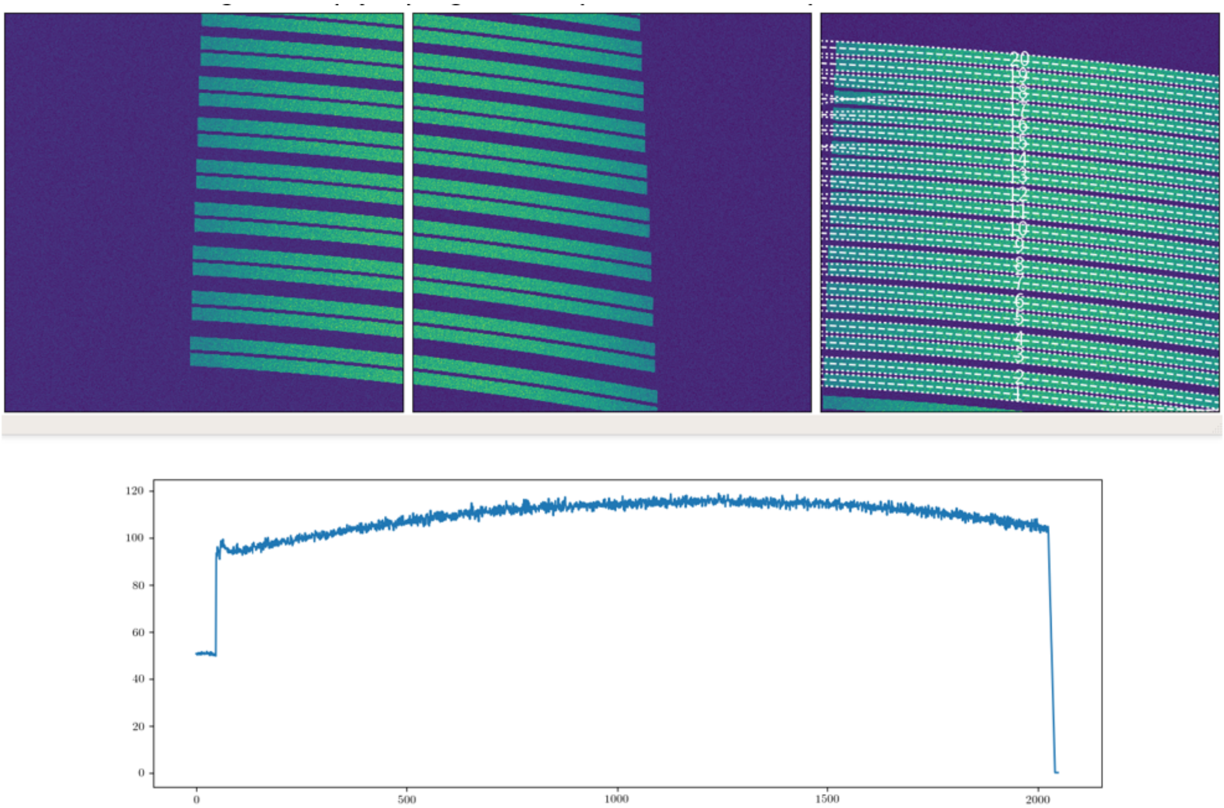

Figure 14. ELT-HIRES Z Band flat field frame produced with the E2E simulator. *Top-Left*: RAW data. *Top-Right*: order tracing from CRIRES2 pipeline. *Bottom*: recovered flat field 1D which shows the characteristic blaze function shape.

The order tracing, i.e. finding the spectral orders and fitting them with polynomials, was successful. A well-detected order was chosen for extraction. Perfectly vertical alignment of the fiber-slit to pixel columns was assumed, since this is how the simulations were made. An example of this, is reported on the right and bottom panel of Figure 14.

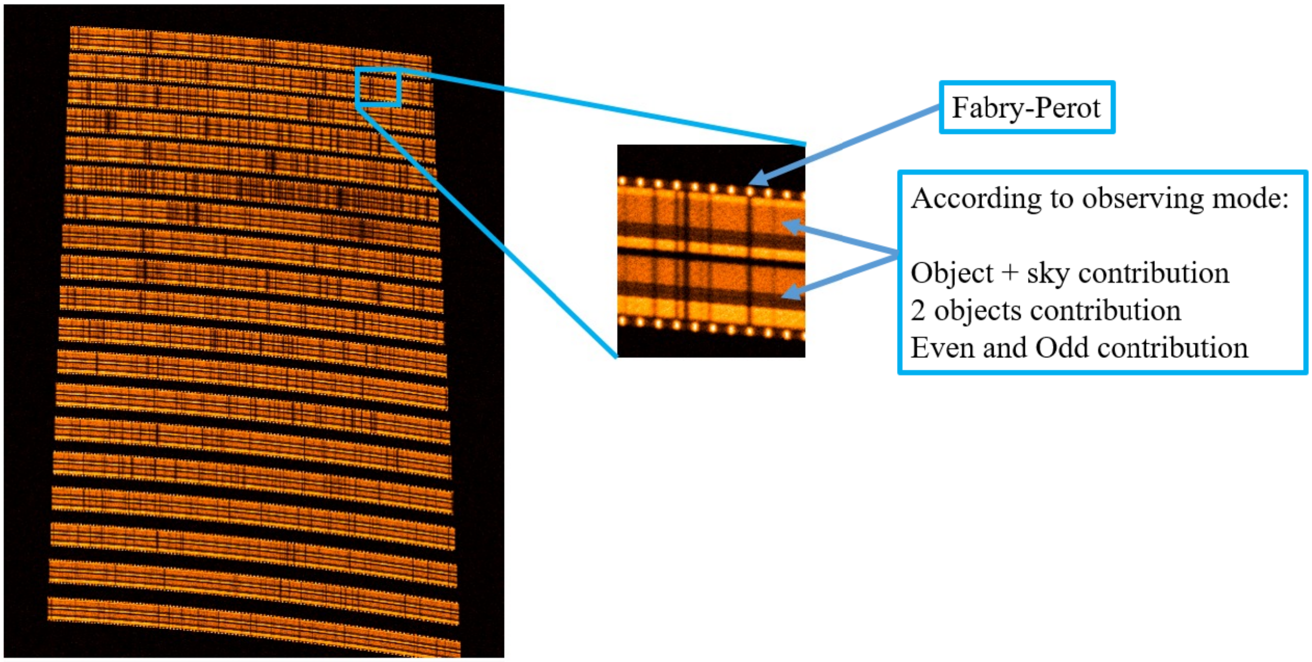

Figure 15. ELT-HIRES G2V star simulated raw frame (see text for details). The general possible fiber bundles flux according to the observing mode is recall in the figure. As explained in the text this simulation is for spectro-polarimetric mode.

For the scientific frame, the optimal extraction was done by slit-decomposition (see for details[20]), a robust algorithm that is independent of the slit-illumination function, meaning that differently illuminated fibers (due to the seeing) along the pseudo-slit can be extracted together (see panels of Figure 16). The same flat-field frame that was used for order tracing was first extracted and recovered the blaze function along a single order.

An order, from the first available E2E science frame, was extracted with simultaneous etalon-calibration on either side of the fiber-slit. The etalon was extracted separately from the science, keeping identical pixel scales so that wavelength calibration is feasible. The one dimensional spectrum has been wavelength calibrated (using the extracted etalon spectra) with a simple fit computed in MATLAB and then the theoretical spectrum has been cross correlated using a CCF function with the recovered one (spectrum) by DRS. The overall dispersion and uncertainty (excluding obvious systematic effect stemming from the simplified wavelength solution) is roughly few m/s that is the expected accuracy for a SNR of about 40 in a single radial velocity measurement.

7. CONCLUSION

In this paper we have presented the development strategy and architecture of the current version of End-to-End simulator for the high resolution spectrograph at the ELT (ELT HIRES). The simulator architecture has been set up with the purpose (and ultimate goal for future developments) of modeling the full observation chain as much realistic as possible. The modular and flexible design philosophy as well as the physical modeling of the different Modules (and Units), which compose the entire tool have been described. Furthermore the computational architecture of the simulator has been detailed, highlighting its speed performance. The results concerning the synthetic echellogram (raw frame) produced and successfully processed by the beta recipes of the CRIRES+ instrument DRS have been presented, thus probing the full chain feasibility and consistency of the system. This is a key step for the future developments of both the E2E simulator and the DRS pipeline (the specific one for ELT-HIRES) which will help the future design and architecture development of the spectrograph and will enable astronomers and engineers to perform science verification as well as instrument optimization (or to overcome possible problems) well before the first light.

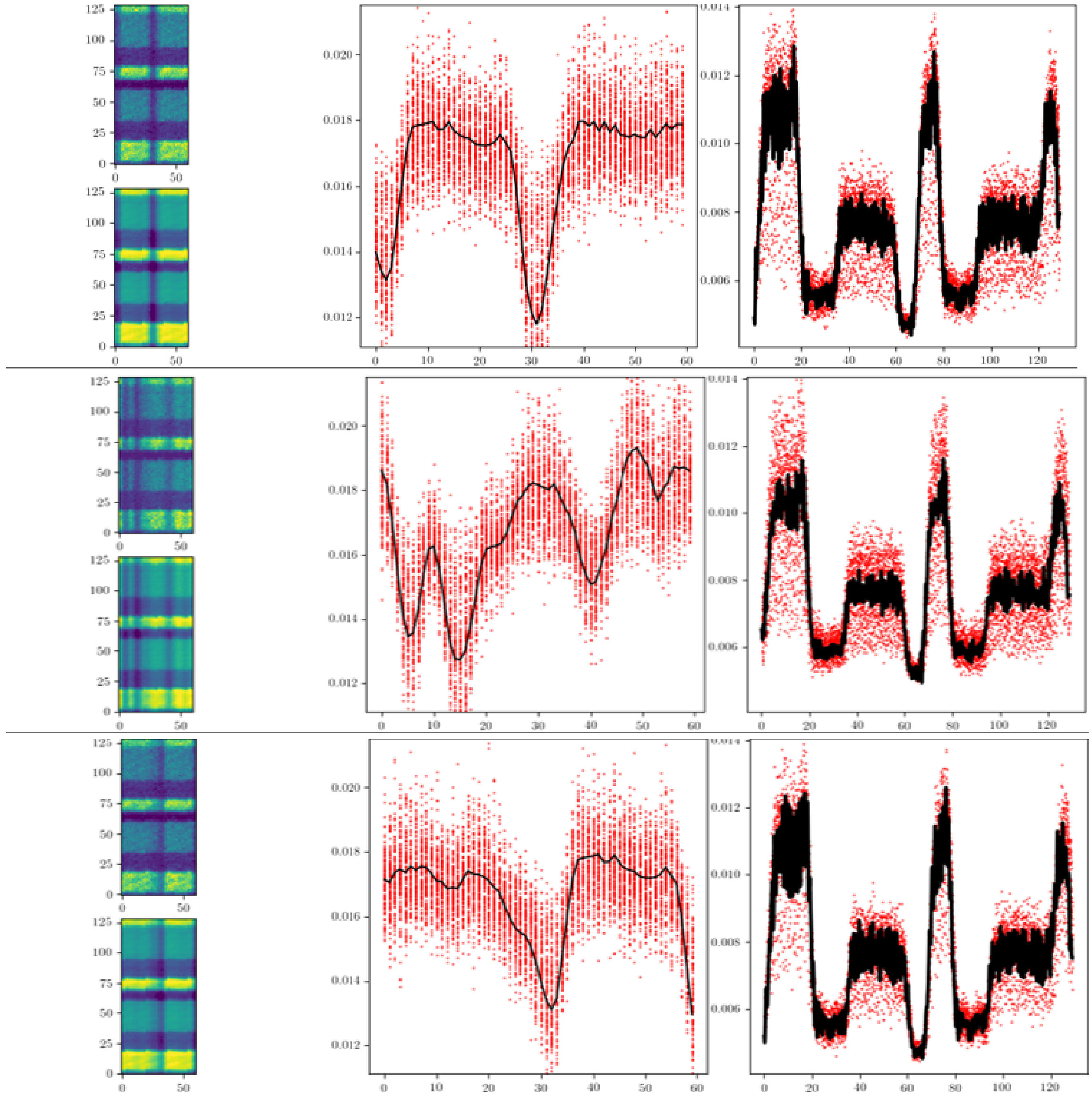

Figure 16. Order tracing along spectral direction of the order 146 of HIRES Z band. *Left upper panel*: RAW data. *Left bottom panel*: reconstructed surface. *Right panels*: Extracted scientific spectrum and illumination profile of the fiber-slit.

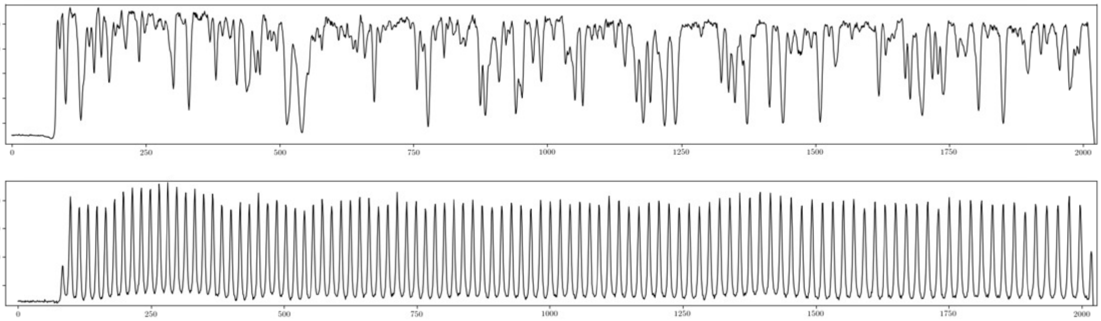

Figure 17. Extraction of the 146th order of the ELT-HIRES Z Band. *Upper panel*: scientific spectrum. *Lower panel*: simultaneous reference etalon.

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