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Authors	Genoni, Matteo, LANDONI, Marco, Riva, M., PARIANI, Giorgio, MASON, Elena, DI MARCANTONIO, Paolo, Disseau, K., Di Varano, I., Gonzalez, O., Huke, P., Korhonen, H., LI CAUSI, Gianluca
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The end-to-end simulator for the E-ELT HIRES high resolution spectrograph

M. Genoni*[ab], M. Landoni[b], M. Riva[b], G. Pariani[b], E. Mason[c], P. Di Marcantonio[c], K. Disseau[d], I. DiVarano[e], O. Gonzalez[f], P. Huke[d], H. Korhonen[g], Gianluca Li Causi[h]

[a]Univeristà degli Studi dell' Insubria, Dipartimento di Scienza ed Alta Tecnologia, via Valleggio 11, I-22100 Como, Italy;

[b]Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Brera-Merate, via E. Bianchi 46, I-23807 Merate (LC), Italy

[c]Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Trieste, via Tiepolo 22, I-34131 Trieste

[d]Georg-August-Univ. Göttingen, Institute for Astrophysics, Friedrich-Hundplatz 1, 37077 Göttingen
[e]Leibniz-Institut für Astrophysik (AIP) , An der Sternwarte 16, 14482 Potsdam, Germania Germany

[f]UK Astronomy Technology Center (ATC) - Royal Observatory, Edinburgh, Blackford Hill – Edinburgh

[g] Niels Bohr Institute – Dark Cosmology Center Juliane Maries Vej 30, 2100 København Ø

[h]Istituto Nazionale di Astrofisica – Istituto di Astrofisica e Planetologia Spaziali, via Fosso del Cavaliere 100, Roma

ABSTRACT

We present the design, architecture and results of the End-to-End simulator model of the high resolution spectrograph HIRES for the European Extremely Large Telescope (E-ELT). This system can be used as a tool to characterize the spectrograph both by engineers and scientists. The model allows to simulate the behavior of photons starting from the scientific object (modeled bearing in mind the main science drivers) to the detector, considering also calibration light sources, and allowing to perform evaluation of the different parameters of the spectrograph design. 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 astronomical observation projects like E-ELT due to of the high complexity and long-time design and development. Finally, we present synthetic images obtained with the current version of the End-to-End simulator based on the E-ELT HIRES requirements (especially high radial velocity accuracy**)**. Once ingested in the Data reduction Software (DRS), they will allow to verify that the instrument design can achieve the radial velocity accuracy needed by the HIRES science cases.

Keywords: End-to-End model – End-to-End modular modeling – End-to-End flexible modeling – Spectrograph parametric model – High resolution spectrograph – E-ELT telescope.

INTRODUCTION: MOTIVATION AND MAIN GOALS

In the last decades astronomical observation projects have become more and more complex both 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.

*matteo.genoni@brera.inaf.it;

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In order to overcome and mitigate this situation it became necessary to develop End-to-End instrument models[2,3], i.e. simulators which allow physical modeling of the whole system from the light source to the reduced data.

The aim of our work is to design and develop the physical model of the different modules, which compose the entire End-to-End system, directly during the project design phase. This approach will benefit the entire project since it allows to:

- generate synthetic detector images starting from starlight or calibration light that closely represent the expected ones from the commissioned instrumentation, that will serve for detailed scientific verifications of the proposed observations;
- exploit the generated detector images for the development of the data reduction software in parallel to the instrument design, or alternatively, for test and verification purposes of existing data reduction pipelines, exploring the possibility of reusing existing pipeline code;
- keep the whole system and its different modules efficiently under control during every phase of the project (both design and assembly-integration phases) allowing to test directly the chosen design from simulated frames to data reduction and analyses.
- exploit reliable tools (the different operative modes of the simulator) at a system engineering level to evaluate the effect of the main instrument parameters directly on the final performance.
- evaluate the effects on the final performance of the different instrument architectures and technologies;
- achieve a deep understanding of the design as well as design optimization and improvements exploiting the capability of early identification of system level problems;
- gather an early performance verification purposes ensuring design requirements are met;
- give reliable inputs for calibration procedures;
- improve the effectively achievable scientific goals, through the observation performance optimization during simulation, long before it is carried out in practice;
- plan efficiently the observation proposals and programs that will be run on the actual instrument;

Fundamental general aspects which characterize the simulator are its modularity and flexibility. They will be extremely important in the next generation telescopes and their related instruments like the E-ELT (European Extremely Large Telescope) because of the high complexity and long-time design and realization. Moreover these aspects will help an efficient evaluation of the effects of new technologies (e.g. instrumentations) and procedure (e .g. data reduction software). Modularity and flexibility will be of relevant importance in the design and building of an End-to-End simulator, which foresees the integration of different software packages that are aimed to allow a successful cooperation of a wide range of users: from project manager and engineers to instrument scientist and astronomers.

MAIN CAPABILITIES

In order to design and develop the End-to-End instrument simulator the following main tasks have been identified:

- to evaluate the spectral energy distribution of different targets like star, QSO or galaxies (these are of course related to the specific observation program);
- to account for the effects of the atmosphere;
- to perform a simulation of the complete optical train of the instrument; in particular for all the possible operative modes (e.g. different resolutions) of the instrument and all possible operation phases;
- to take into account both optical aberrations and diffraction effects;

- to take into account both mechanical and thermal effects;
- to perform high accuracy image reconstruction to be provided to data reduction pipeline;
- to include a simulation of the detector properties and of the impact of cosmic rays.

END-TO-END MODEL STUDY CASE: THE E-ELT HIRES

We present in this section the specific study case we have focused on for the design and development of the simulator, which is the High Resolution Spectrograph at the European Extremely Large Telescope (this is for the moment called E-ELT HIRES in order to avoid wrong association with the HIRES spectrograph at Keck telescope). We give an overview of the E-ELT design and of the spectrograph proposed architecture concept.

E-ELT HIRES overview

The huge photon collecting power of the 39 m primary mirror diameter E-ELT (see Figure 1 and 2) coupled with a High Resolution Spectrograph (E-ELT HIRES) will allow the European high resolution community to make fundamental discoveries in a wide range of astrophysical areas, outlined by the Science Team of the E-ELT HIRES Initiative[4,5,6]:

- 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 Fig. 1) is a 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 Fig. 2). 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 (rendering shown in Fig. 3) will be alt-azimuth type.

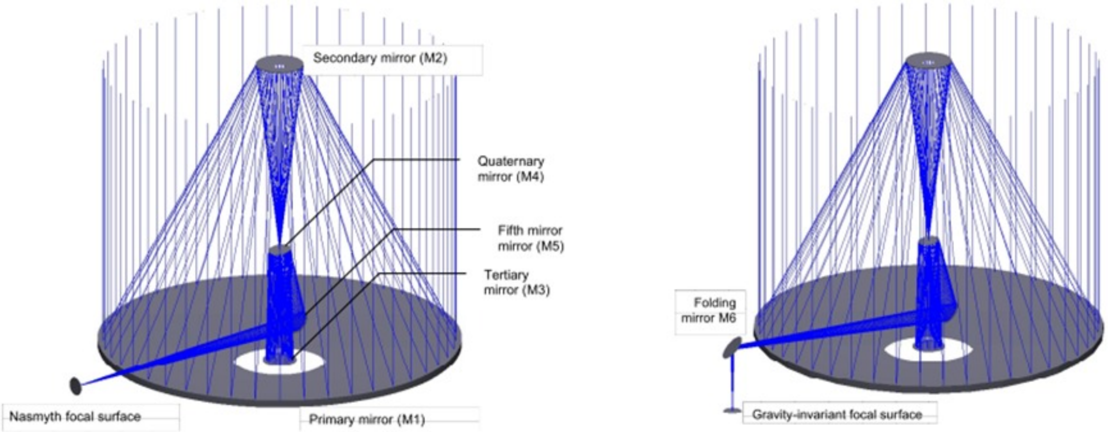

Figure 1. E-ELT optical layout: Nasmyth focus (left) and Gravity invariant focus (right), taken from [1].

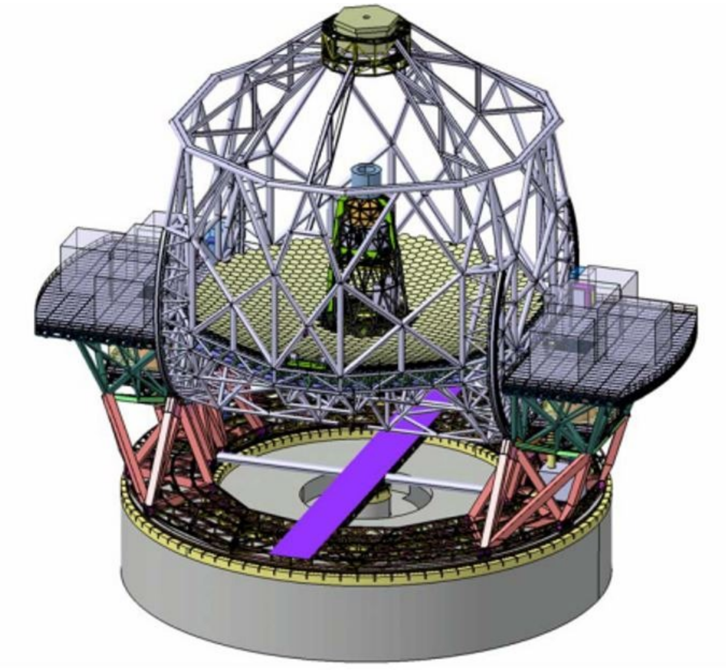

Figure 2. E-ELT structure, rendering, taken from [1].

The E-ELT spectrograph preliminary architecture concept, proposed by the E-ELT HIRES Initiative working group and at the moment in the phase A of the project, is highly modular. It foresees different independent fiber-fed echelle cross-dispersed spectrographs optimized for different wavelength bands of the whole spectral coverage of the instrument 370 nm to 2400 nm (see Figure 3 for details).

The different spectrometers can be 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. A fore-optics system in combination with a lens-let array is used to couple the telescope focal plane and the fiber optics[6], which are vertically re-arranged to feed the pre-slit unit.

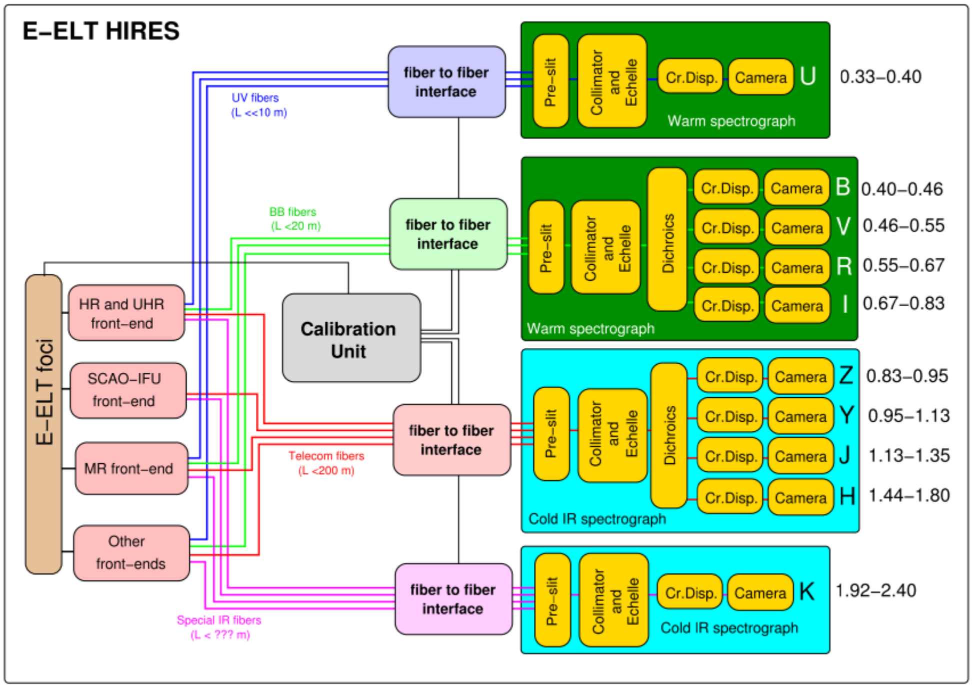

Figure 3. E-ELT HIRES preliminary architecture concept.

The proposed architecture also allow different main observing modes, depending on resolving power and different fiber-slit arrangements:

- High Resolution (HR) mode: R = 100000, 2 apertures (with one object and one sky bundle of fibers) each one subtending a size ≥ 0.87” on sky;
- Ultra-High Resolution (UHR) mode: R = 150000, 2 apertures (with one object and one sky bundle of fibers) each one subtending a size ≥ 0.75” on sky;
- MOS Medium Resolution (MR) mode: R ≥ 10000, 10 fibers each looking at a different object subtending 0.86” on sky.

In order to better accomplish the specific scientific goals, high radial velocity accuracy, high throughput and IFU capabilities are foreseen for both the high resolution mode and ultra-high resolution mode. This means that for HR and UHR modes there will be specific sub-modes (optimized for specific science cases) which will be implemented by feeding the spectrograph modules with different fibers systems. The technique used to feed the spectrograph entrance in the selected architecture is, at the moment, the field dicing (see for details reference[7]), in which each fiber of the bundle is looking at a slightly different part of the object. Moreover in this way the spectrometers entrance slit width is reduced allowing high resolving power performance keeping the components size within manufacturing capabilities. Anamorphic effects are also exploited in both the pre-slit and spectrometer units of each module.

In addition to the Resolving power and wavelength coverage requirements, two other relevant design drivers derived by the E-ELT HIRES Initiative working group involve the accuracy on radial velocity measurement of < 10 cm/s (related in particular to the exoplanets science) and gather spectra with signal-to-noise ratio ≥ 100 for faint object that is prohibitive at the moment with 10 m class telescope like the VLT.

END-TO-END MODEL ARCHITECTURE

The required capabilities described above are translated in different modules, each one with specific units-functionalities and interfaces. We underlined once more that modularity and flexibility will be continuously taken into consideration in the definition of interfaces among different modules and among different module units or elements (see Figure 4 for a schematic overview).

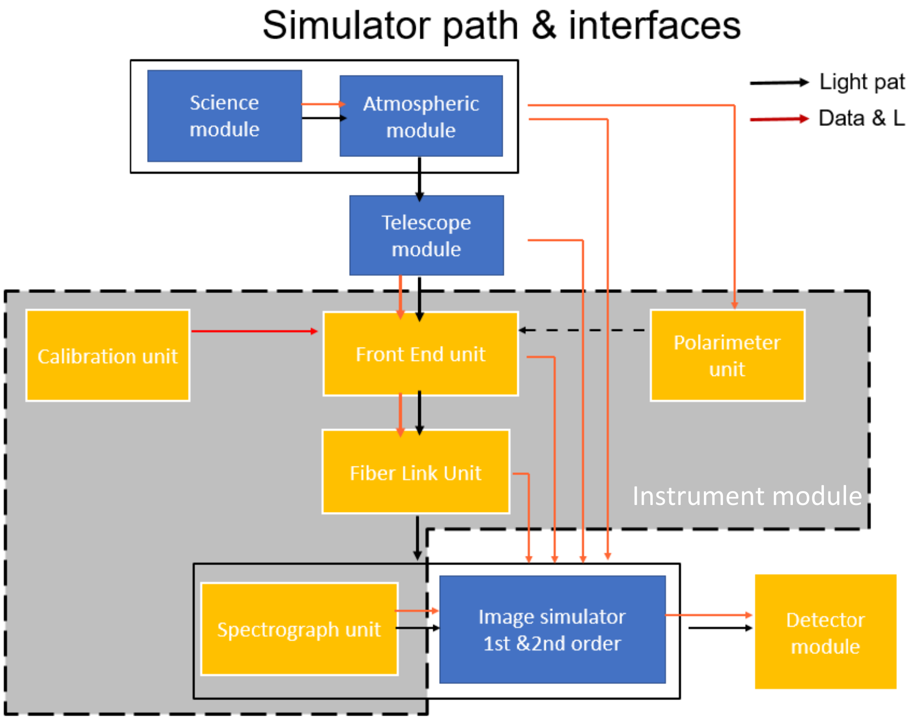

Figure 4. General schematic diagram of the End-to-End simulator modules, with the related interfaces. The light path and data & logic path through the different units are shown. Instrument related units of the End-to-End simulator are colored in orange, while in blue other units simulated by the End-to-End model but independent from E-ELT HIRES Spectrograph. The units which compose the Instrument Module are grouped by the grey box.

In the following a brief definition and description of the main modules is given, focusing on their functionalities and interfaces.

Science Object Module

This module simulates the theoretical spectral energy distribution (SED) for a selected kind of target object, or specific science case, by loading an input spectral template, which is rescaled on the basis of the object magnitude in order to give the number of photons; according to the target object different noises are taken into account. The module interface is with the Atmospheric Module.

Atmospheric Module

It generates the sky emission lines spectrum, at a given high resolution, and the atmospheric transmission profile (the telluric spectrum, see Figure 5) based on the sky condition and standard atmospheric parameters of the specific observatory site by the adoption of the ESO tool Molecfit[8]. At the moment a mean airmass value has been considered. This module then combines the sky spectrum with the science one and filters the resultant spectrum with the atmospheric transmission profile (see an example in Fig. 5) and considering the Atmosphere Dispersion at given zenith angle (or ADC residuals if ADCs are present). The output interfaces are with Instrument Module, Polarimeter Unit and Image Simulation Module.

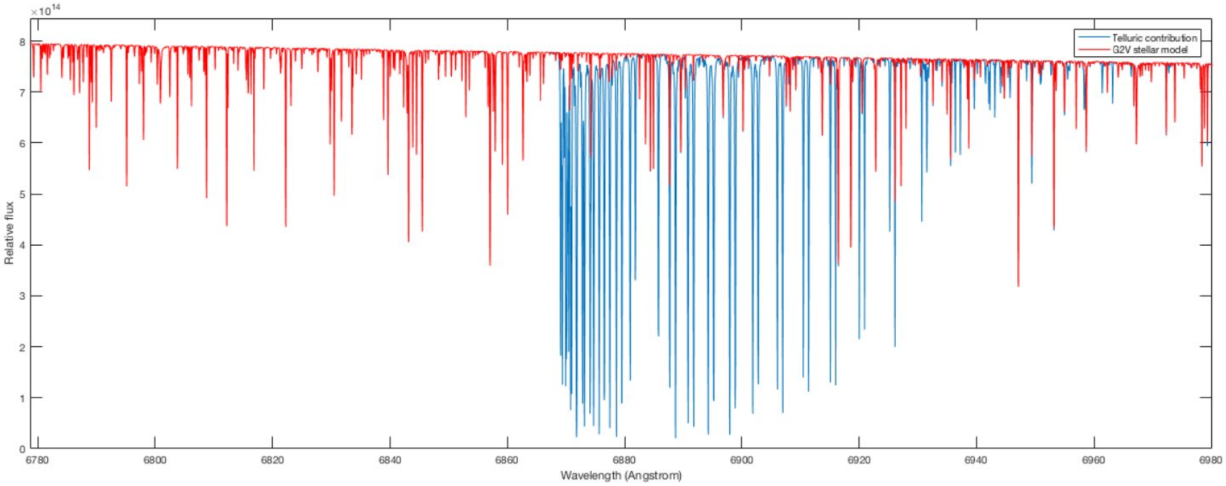

Figure 5. Example of part of simulated spectrum in output from the Atmospheric Module; in red a G2V stellar model and in blue the telluric spectrum. Both are computed at a resolution 3 times higher than the main observing mode resolution.

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. The module can run in two alternative operative ways. The first one is a simplified telescope version that simulate the optical path taking into account distortion and optical quality as the spatial, wavelength and time variation of the telescope PSF in different conditions aimed to obtain the telescope PSF at the level of telescope focal plane. This approach could be used when parameter from the telescope are not fully defined and allows to perform simulation also under simplified assumptions. The second one, instead, relies on fully computation of PSF from the E-ELT as illustrated in the paper of Basden 2014[9]. The output interfaces (for both implementation) are with Instrument Module and Image Simulation Module.

Instrument Module

This module has the purpose to generate geometrical images of the instrument focal plane, to evaluate the instrument PSF and instrument throughput. In addition it models also the link between telescope and instrument (optics train or optical fiber according to the specific case) and it produces the spectral energy distribution of the selected calibration sources at a given resolution for flat-field and/or wavelength calibration. The module is organized in units: the Front End Unit and Fiber Link Unit models the link between the telescope and instrument (see paper of Disseu et al. in this proceeding for details), the Calibration Unit produces the SED of the selected calibration sources (see for details of calibration sources and strategy the paper from Huke at al. in this proceeding). 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 is evaluated in order to compute the whole point spread function (PSF) 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[11] Unit aim to simulate the induced telescope polarization effects and the final odd and even flux at the polarimetry arm output. It is foreseen the simulation of the physical operative conditions in terms of ambient, mechanical and thermal effects. The module interfaces with Atmospheric Module, Telescope Module, the Image Simulation Module and Detector module.

Image Simulation Module

It simulates the image on the detector surface by generating low resolution spectra or high resolution echellograms according to the user required observing mode; synthetic frames are obtained by convolving the ideal image of a specific object or entrance slit at a specific wavelength (optical fiber at a specific wavelength in the case of fiber fed instruments) with the resulting PSF of the whole instrument. The module is split into two units: one, the First Order Unit, takes into account first order diffraction and optical blurring effects in the PSF to be used in the convolution with the ideal image; the other, called Second Order Unit, estimates second order effects on the PSF halo due to pupil obscurations and non-uniform illumination (as also deeply described in Li Causi et al 2014[13]). This module also combined the efficiencies/throughput computed by other modules to simulate the number of photons hitting each pixel of the detector. Interfaces are with all other modules. Optical defocusing effects due to both flatness deviation of detector surface and beam divergence across the thickness of detector substrate (especially for thick full-depleted CCDs) are also taken into account by this module.

Detector Module

This module simulates the real final detector outputs, modeling the photon noise (due to the quantum nature of light) and all the detector physical effects: quantum efficiency, charge diffusion, charge transfer efficiency (CTE), read-out noise, conversion into ADU, detector bias, dark current, non-linearity, defects like bad pixel/column and contaminants like cosmic rays; it is interfaced with Image Simulation Module and DRS pipeline (which is not part of the End-to-End simulator).

Control program of the whole simulator architecture

The whole End-to-End simulator architecture is planned to be controlled and managed by a high level program, external to the different modules listed above. This high level program integrates all the modules by setting the input data, parameters and passing data between them; moreover it will also call the different modules at appropriate times, managing the data flow and it will determine the times at which a module must be run again to account for a change in its input data or parameters. At the current version most of the functions and operations that coordinate the different modules are implemented in MATLAB. A possible different implementation could be considered (e.g. C++) on the basis of the optimization of the performance in modularity and flexibility managing as well as the maximization of the End-to-End simulator usability by the wide range of users for which it is developed.

PRELIMINARY RESULTS: INSTRUMENT AND IMAGE SIMULATION MODULES

Instrument Module: Spectrograph Unit

The purpose of the Instrument Module is to simulate the physical aspects of the different optical components of the instrument, taking into account aberrations, distortion and diffraction effects as well as the physical operative conditions of the instrument in term of ambient, mechanical and thermal effects. Here we present the results concerning the spectrograph which can be modeled using two different alternative versions: the Parametric Version and Ray-Tracing Version. The former is based on a physical parametric model 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). Dispersion and diffraction effects as well as optical component efficiency have been already taken into account, while ambient, mechanical and thermal effects will be introduced in the future versions. A detailed description and verification of the paraxial parametric model can be found in a previous proceeding[14]. Below we list the main parameters related to the spectrograph physical model, while in figure 6 we show a schematic representation of them.

Inputs Parameters form other modules: telescope primary mirror diameter, angular aperture diameter of the object image on the telescope focal plane (which is actually related to the seeing condition) and pixel size.

Input variable parameters: number of optical fibers and their working F-ratio; main collimator F-ratios (which could be different in the x, spectral, and y, spatial, directions), echelle grating blaze angle, groove density and tile size (normally high resolution performances require a mosaic made by more than one echelle grating), cross disperser working angle and groove density, various different possible anamorphic effects generated by the spectrograph optical components.

Top level requirements and input performance data: resolving power, wavelength coverage and band division, spectral and spatial sampling values, inter-order separation (separation of the different diffracted orders projected onto the detector surface).

The critical output parameters for the instrument design, mainly related to technical complexity and cost issues which characterize the proposed architecture concept and/or involved or assessed technologies, are: echelle grating numbers to form the mosaic, spectrograph camera size and optics working F-ratios, number of detectors required the collect the whole echellogram.

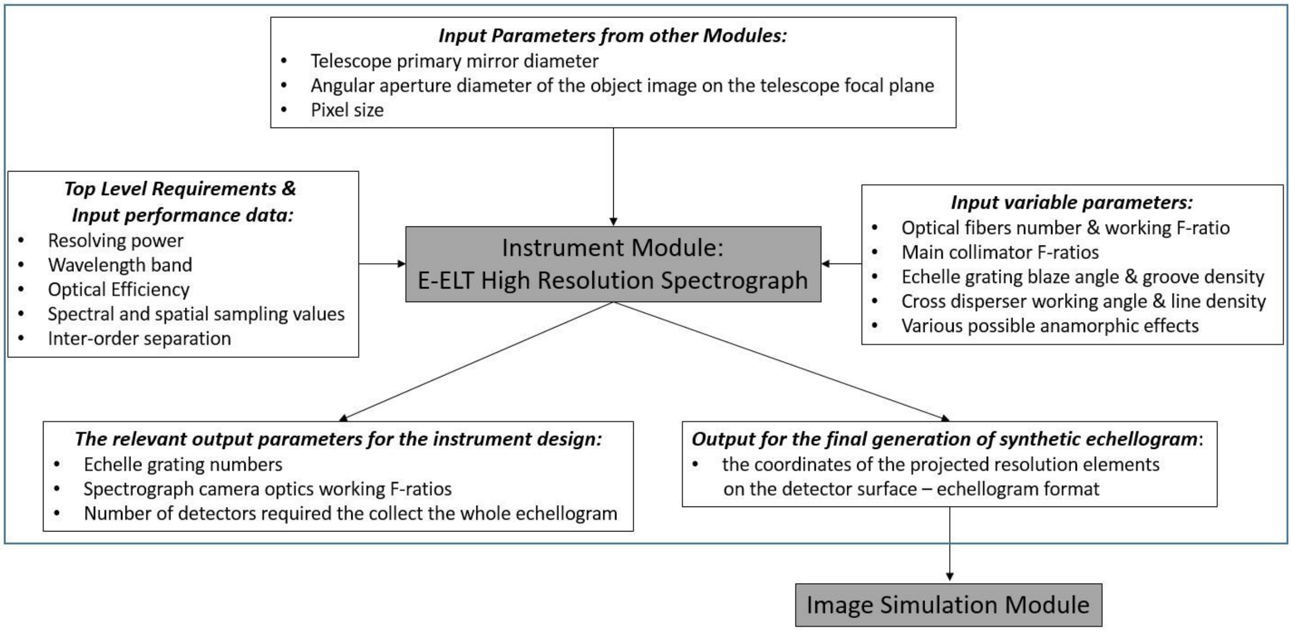

Figure 6. Schematic of the Instrument Module for the E-ELT high resolution spectrograph main input and output (for both the instrument design at a system engineering level and for the final generation of synthetic echellogram) parameters.

The other relevant outputs which come out from this model are the coordinates of the projected resolution elements on the detector surface (in particular the coordinates the projected image of the central point of the spectrograph entrance slit is calculated in the paraxial parametric model); these are passed as input to the Image Simulation Module for the generation of synthetic diffracted spectra. An example of the echellogram format retrieved by the Instrument Module is shown in figure 7.

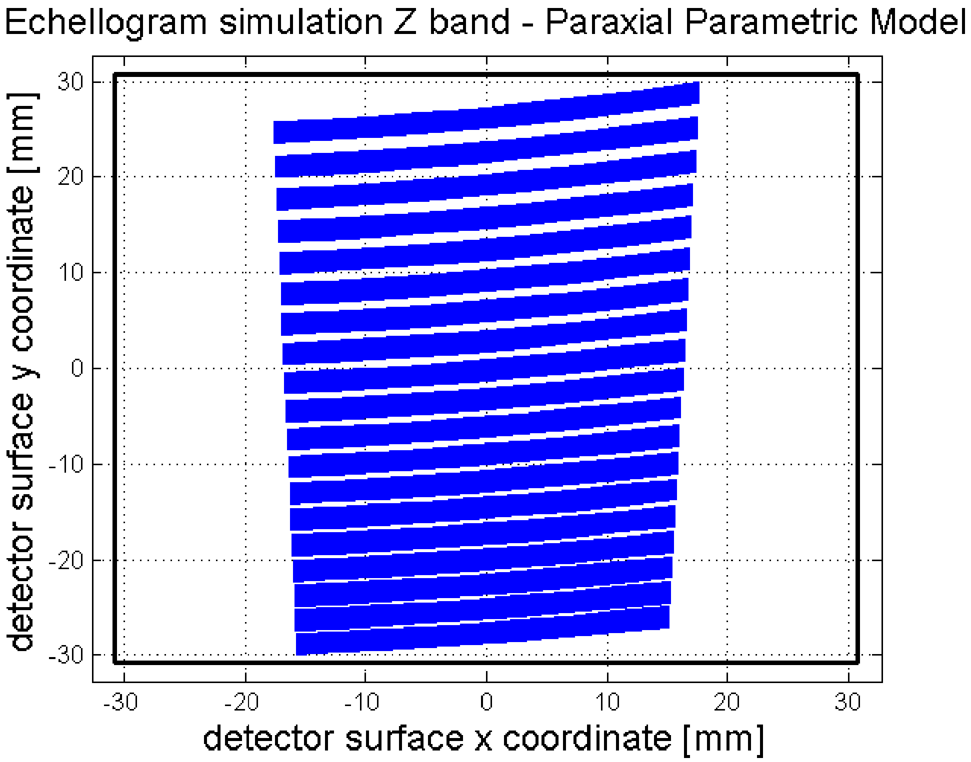

Figure 7. Echellogram format example from the Instrument Module *Paraxial Parametric Model* computation; note that all the fibers per each order are plotted, including the dark fibers which are exploited to separate the fibers dedicated to the sky and object in the High Resolution mode (i.e. the plot could be representative of the High Resolution IFU mode).

Image Simulation Module

The aim is to model the image on the detector surface by generating low resolution spectra or high resolution echellograms according to the user required simulation mode; the outputs format is a matrix which represents the flux on each single pixel. Synthetic frames are obtained by convolving the ideal image of a specific object or wavelength (spectral resolution element) with the resulting PSF of the whole instrument, which is taken as input from the Instrument Module (as well as the information of the ideal image position on the detector plane). In addition the information of instrument efficiency will be used to compute the number of photons incident on the detector surface per each object image or spectral resolution element. In practice this will be done by integrating the convolved signal in each pixel and imposing that the integral calculation result is equal to the number of photons received from the specific object or specific wavelength and from the sky. The accuracy of the output format can be checked by evaluating the barycenter of the different object images or spectral resolution elements. As before a list of the main parameters and a schematic are given.

Inputs parameters form other modules: object or wavelength image coordinate positions, size of the ideal image, PSF geometry and PSF parameters (parameters which describe and model the point spread function), number of science object and sky photons and efficiency of the whole instrument chain (from the telescope through the instrument image plane, taking into account also the detector quantum efficiency).

Input variable parameters: number of pixels and pixel size. Top level requirements and input performance data: for the case of high resolution spectrograph aimed to reach 10 cm/s of radial velocity precision and wavelength accuracy, the wavelength image barycenter reconstruction accuracy will be the primary performance of this module; to give an order of magnitude the spectral resolution element barycenter reconstruction accuracy should be better than ~ 1nm.

We have developed our own integral computation procedure using an innovative approached 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 ideal function and PSF for the point convolution evaluation. The adoption of parallel computing is crucial, since the simulations of synthetic spectra gathered by HIRES involve a huge amount of computational power. In particular, as explained in the previous sections, each resolution element (SRE) must be simulated with an accuracy of few nm on the detector and the number of SRE (including sampling anti-aliasing) is of the order of 7 x 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 ideal illumination profile that can be safely modeled as a Super-Lorentzian function with parameter M = 30 (see reference[15] for details, Equation and left panel of Figure 8) and a Gaussian Point Spread Function that represent the PSF of the spectrograph itself (right panel of Figure 8).

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

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 schema of Figure 9

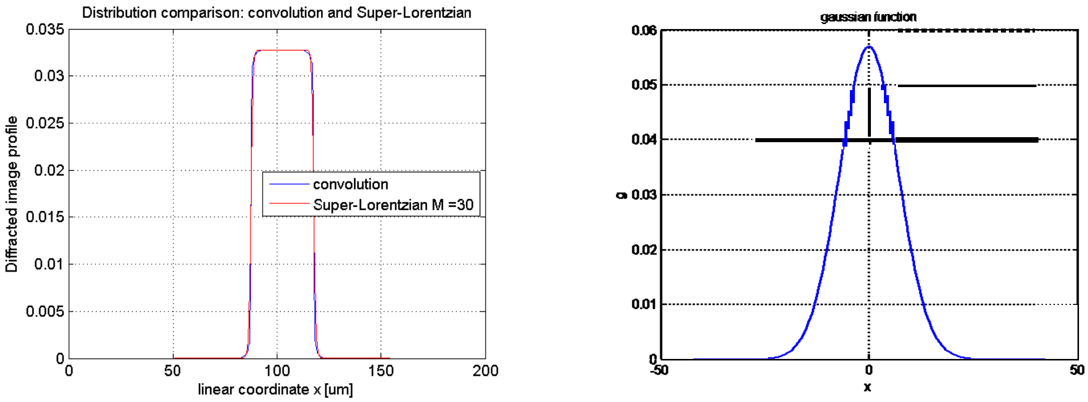

Figure 8. Left panel: fiber exit illumination profile assuming a Super-Lorentzian function. Right panel: Gaussian Point Spread Function that represent the PSF due to optical aberrations of the spectrograph itself.

In particular, for each pixel a Computation CUDA Block is assigned and, for each one of the 100 subpixel, a worker thread compute the value of surface integral 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 us for each SRE.

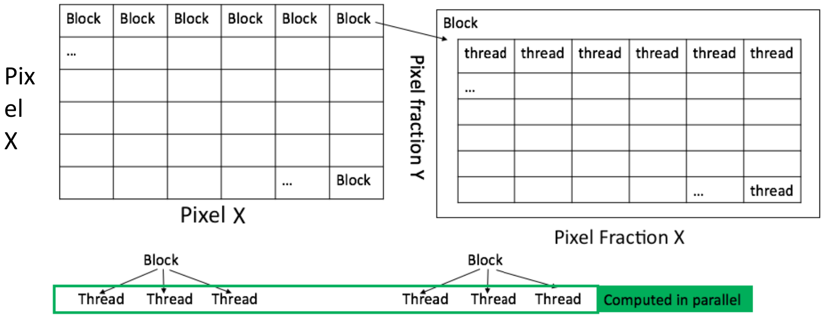

Figure 9. Schematic of CUDA Block and Worker Thread architecture for the computation of convolution and surface integral on each detector pixel.

Since the problem is, for definition, 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). In details, we compute each order of the echellogram with a different computer (namely "instance", equipped with NVDIA CUDA card) running on cloud allowing to further parallelization of the computation. Results are then stored in simple binary files automatically upload on Amazon S3 storage service. A sample result that we obtained with our approach is reported in Figure 10, where we simulated a G2V star spectrum with simultaneous Fabry-Perot spectrum and polarimetric observation (object odd and event PSFs falling on the two spectrograph apertures) gathered by the E-ELT HIRES Z-band spectrograph arm.
With our approached based on hybrid combination of CUDA and cloud computing, we obtained the image in 0.5 day of computation using a 5 g2x.large instances on AWS.

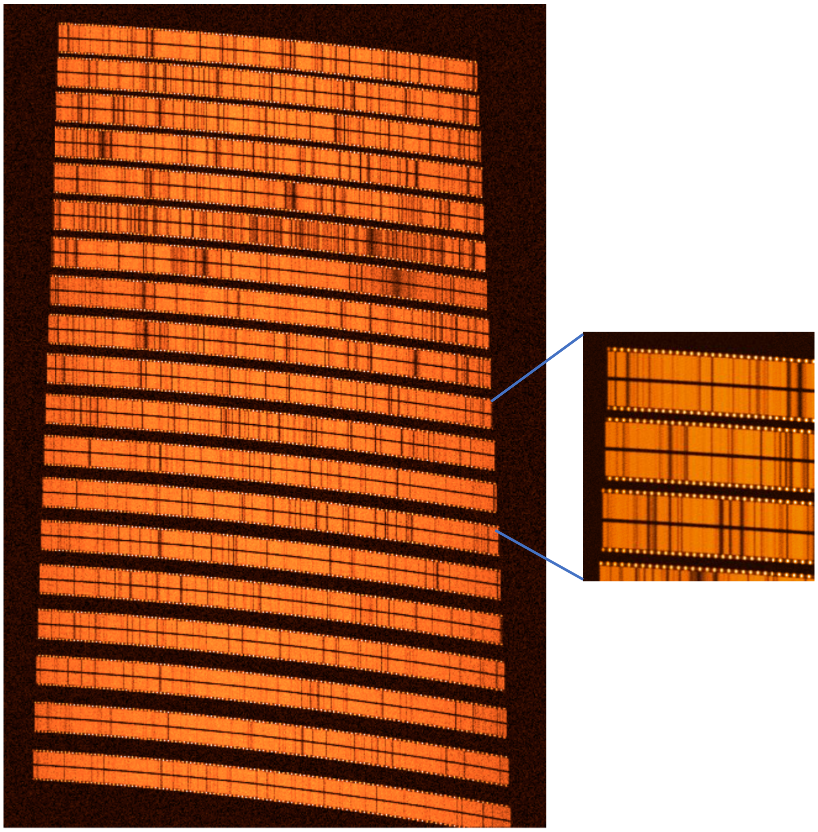

Figure 10. Synthetic echellogram of the E-ELT HIRES Z-band arm. The spectrum has been generated considering per each order the free spectral range increased by the 10%. In this case the dark fibers between the two aperture are not illuminated. Right inset: zoom on spectral order

CONCLUSIONS AND FUTURE DEVELOPMENTS

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 E-ELT (E-ELT HIRES). The simulator architecture is characterized by high modularity and flexibility. These aspects will be fundamental in the next generation astronomical observation projects like E-ELT (European Extremely Large Telescope) because of the high complexity and long-time design and realization. Moreover they are of relevant importance in the design and building of a simulator which foresees the integration of different software packages and which is aimed to allow a successful cooperation of a wide range of users: from project manager and engineers to instrument scientist and astronomers.

We have described the main functionalities and interfaces of the different modules which compose the simulator. In addition the preliminary results regarding two modules have been described; in particular the definition of the parameters and the implementation of Spectrograph Unit of the Instrument Module have been illustrated (referring to a previous paper for further details), showing an example of echellogram format simulation. For what concern the Image Simulation Module the key parameters for the pixel flux calculation have been defined and the innovative approach based on heavy parallel computing CUDA by NVIDIA and *cloud computing* architecture is described. In the future developments of the simulator the contribution of all the other modules will be integrated in order to run a complete end-to-end simulation.

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