Publication Year	2016
Acceptance in OA	2020-07-17T10:45:48Z
Title	End-to-end modeling: a new modular and flexible approach
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Publisher's version (DOI)	10.1117/12.2233531
Handle	http://hdl.handle.net/20.500.12386/26478
Serie	PROCEEDINGS OF SPIE
Volume	9911

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M. Genoni, M. Riva, M. Landoni, G. Pariani, "End-to-end modeling: a new modular and flexible approach," Proc. SPIE 9911, Modeling, Systems Engineering, and Project Management for Astronomy VI, 99112G (8 August 2016); doi: 10.1117/12.2233531

Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

End-to-End modeling: a new modular and flexible approach

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ABSTRACT

In this paper we present an innovative philosophy to develop the End-to-End model for astronomical observation projects, i.e. the architecture which allows physical modeling of the whole system from the light source to the reduced data. This alternative philosophy foresees the development of the physical model of the different modules, which compose the entire End-to-End system, directly during the project design phase. This approach is strongly characterized by modularity and flexibility; these aspects will be of relevant importance in the next generation astronomical observation projects like E-ELT (European Extremely Large Telescope) because of the high complexity and long-time design and development. With this approach it will be possible to keep the whole system and its different modules efficiently under control during every project phase and to exploit a reliable tool at a system engineering level to evaluate the effects on the final performance both of the main parameters and of different instrument architectures and technologies. This philosophy will be important to allow scientific community to perform in advance simulations and tests on the scientific drivers. This will translate in a continuous feedback to the (system) design process with a resulting improvement in the effectively achievable scientific goals and consistent tool for efficiently planning observation proposals and programs. We present the application case for this End-to-End modeling technique, which is the high resolution spectrograph at the E-ELT (E-ELT HIRES). In particular we present the definition of the system modular architecture, describing the interface parameters of the modules.

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

1. INTRODUCTION: MOTIVATION AND MAIN GOALS

In the last decades astronomical observation projects have become more and more complex both in term of technologies, instrumentations and operative modes and procedures. This high level of complexity has been required to achieve a wide range of more and more detailed scientific discoveries. Because of the high level of complexity it was found 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.

In the past End-to-End simulators have been realized specifically for single instruments (more generally for system composed by telescope and instrument + detector); the aim and innovative approach 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 philosophy will benefit the entire project for the following reasons:

- keeping the whole system and its different modules efficiently under control during every project phase (both design and assembly-integration phases);
- exploiting reliable tool at a system engineering level to evaluate the effects on the final performance of the main parameters;

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Modeling, Systems Engineering, and Project Management for Astronomy VII,
edited by George Z. Angeli, Philippe Dierickx, Proc. of SPIE Vol. 9911, 99112G
· doi: 10.1117/12.2233531

- evaluate the effects on the final performance of the different instrument architectures and technologies;
- understanding the design;
- design optimization and improvements;
- early performance verification purposes ensuring design requirements are met;
- early identification of system level problems;
- generation of synthetic detector images for the development of the data reduction software, or alternatively synthetic images used for testing and verification of existing data reduction pipelines, exploring the possibility of reusing existing pipeline code;
- giving reliable inputs for calibration procedures;
- allowing scientific community to perform in advance simulations and tests on the scientific drivers;
- generation of synthetic detector images closely representing the expected one from the commissioned instrumentation will serve for detailed scientific verifications of the proposed observations;
- improvement in the effectively achievable scientific goals, through the observation performance optimization during simulation, long before it is carried out in practice;
- efficient planning of observation proposals and programs;

Fundamental general aspects which characterize the simulator are modularity and flexibility. They will be extremely required 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 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 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.

2. MAIN CAPABILITIES

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

- simulate the radiation emitted by the different target celestial objects (these are of course related to the specific observation program);
- accounting for the effects of the atmosphere;
- 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;
- take into account both optical aberrations and diffraction effects;
- take into account both mechanical and thermal effects;
- perform high accuracy image reconstruction to be provided to data reduction pipeline;
- include a simulation of the CCD properties and of the impact of cosmic rays.

3. 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; this is practically referred to the possible different scripts or functions which could model single components of each module. A diagram of the simulator architecture and modules is shown in Figure 1. In the following a brief definition and description of the main modules is given, focusing on their functionalities and interfaces.

3.1 Science Object Module

This module simulates the light radiated from a selected kind of target object 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 stellar/object noises are taken into account. The module interfaces are the Telescope Module and Image Simulation Module.

3.2 Telescope and Instrument Modules

These two modules model two physically distinct but analogous optical systems: the telescope and the installed instrument. For this reason the conceptual architecture and structure of the two modules are the same. This foresees three main units to simulate and to evaluate the different physical effects: the Paraxial Unit, the Ray-Tracing Unit and the Throughput Unit. The Paraxial Unit models the optical path along the optical train taking into account distortion and the effects of dispersive element (at the moment the fore optics unit which link the telescope and instrument is modeled inside the Instrument Module itself). In the Ray-Tracing Unit the optical quality in different conditions is evaluated in order to compute the whole point spread function for different wavelengths and positions on the image plane (both the telescope and instrument focal plane) as well as the spatial, wavelength and time variation of the PSF itself. The transmissivity and reflectivity of the different optical components will be modeled and taken into account for the telescope and instrument efficiency calculation in the respective Throughput Units. In both modules it is foreseen the simulation of the physical operative conditions in terms of ambient, mechanical and thermal effects. The two modules interface with each other and also with the Science Object Module and Image Simulation Module; the specific interface flow is shown in Figure 1.

3.3 Image Simulation Module

It simulates the image on the detector surface by generating synthetic images, low resolution spectra or high resolution echellograms according to the user required simulation; synthetic frames are obtained by convolving the ideal image of a specific object or wavelength with the resulting PSF of the whole instrument. Interfaces are with: Instrument Module and Detector Module.

3.4 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).

3.5 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, outer with respect to the different modules listed above. This outer 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 of the different modules are implemented in MATLAB. This also could be the software for the development of the high level control code, even if the selection will be done 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.

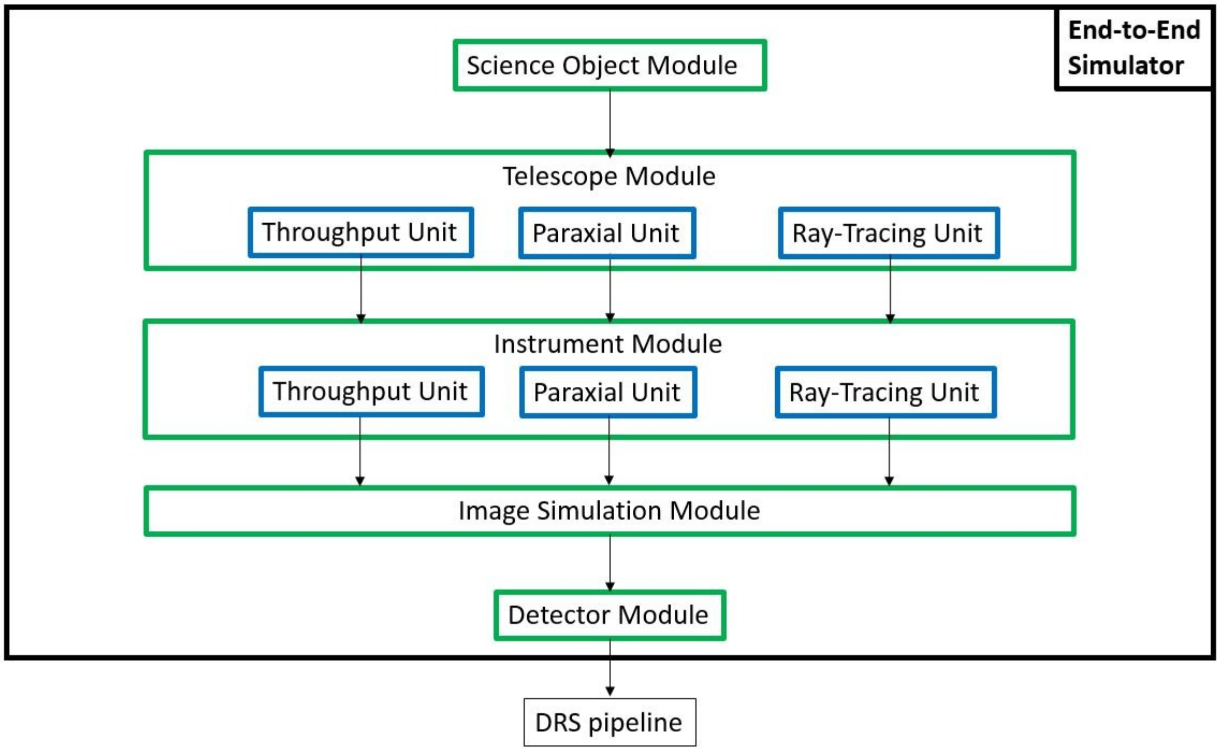

Figure 1. General schematic diagram of the End-to-End simulator modules, with the related interfaces. Note that in the current status the Telescope Module and the Instrument Module foresee different units with specific functionalities. These are: Throughput Unit for the efficiency calculation, Optical-Path Unit for the optical path and distortions evaluation and the Optical-Quality PSF Unit for the computation of the point spread function.

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

We present in this section the current early phase of our End-to-End simulator; in particular we have focused on a specific study case 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; then some preliminary results related to the Instrument Module and the Image Simulation Module are presented.

4.1 E-ELT HIRES overview

The huge photon collecting power of the 39 m primary mirror diameter E-ELT 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[4,5,8]:

- 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 Fig. 2) 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 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.

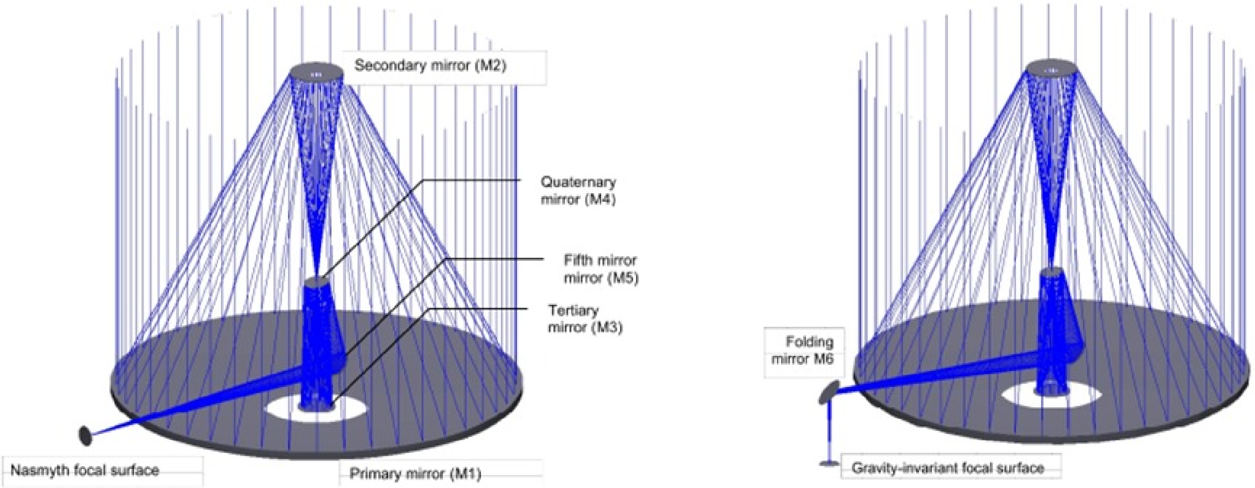

Figure 2. E-ELT optical layout: Nasmyth focus (left) and Gravity invariant focus (right), taken from [1].

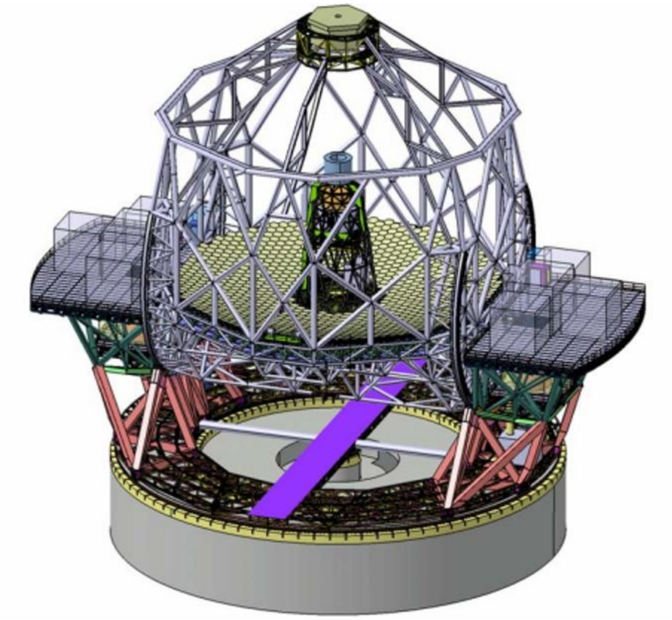

Figure 3. E-ELT structure, rendering, taken from [1].

The E-ELT spectrograph preliminary architecture concept, proposed by the E-ELT HIRES Initiative working group, 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 330 nm to 2500 nm. 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.

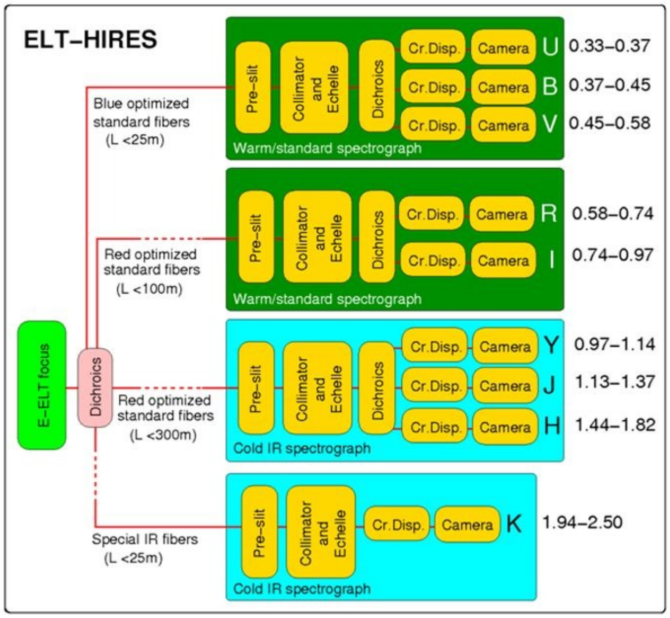

Figure 4. E-ELT HIRES preliminary architecture concept.

In order to better accomplish the scientific goals, which would be obtained by feeding the spectrograph with different fibers systems, the different modules may also allow different observing modes:

- High Resolution mode (main mode): resolving power R = 100000, 2 fibers (object and sky) which subtend 0.76 arcsec on sky;
- MOS Medium Resolution mode (ancillary mode): resolving power R ≥ 10000, 10 fibers each looking at different object subtending 0.86 arcsec on sky;
- IFS High resolution mode (ancillary mode): resolving power R = 80000, 35 fibers for integral field spectroscopy of 35x49 milliarcsec (mas) of field of view.

The main observing mode is a single object mode, in fact the basic scheme foresees two fibers, one fiber for the selected celestial object and the other for sky light subtraction or for calibration purpose, which collect the light from the telescope image plane. The technique used to feed the spectrograph entrance in the proposed architecture is the field dicing (IAN), in which each fiber of the optical fibers system 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. In addition anamorphic effects are also foreseen 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 are: radial velocity precision < 10 cm/s (related in particular to the exoplanets science) and the signal-to-noise ratio ≥ 100.

4.2 Preliminary results: Instrument Module and Image Simulation Module

4.2.1 Instrument Module

The purpose of the 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. In the current state we have developed the Paraxial Unit, i.e. a paraxial parametric model for the high resolution spectrograph, which can be adapted for the different spectrometers module. The optic systems (fore optics and optical fibers) that are exploited to dice the field and to feed the spectrograph entrance are considered part of this module. According to its paraxial nature, aberrations that may be induced by the collimating, focusing optics and other optical elements are not specifically modeled; furthermore the simulation of these aspects and effects is foreseen in the optical Ray-Tracing Unit. Also 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 another paper within this same proceeding[9]; here a list of the main parameters is given, while figure 5 shows a schematic representation.

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 relevant 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 optics working F-ratios, number of detectors required the collect the whole echellogram.

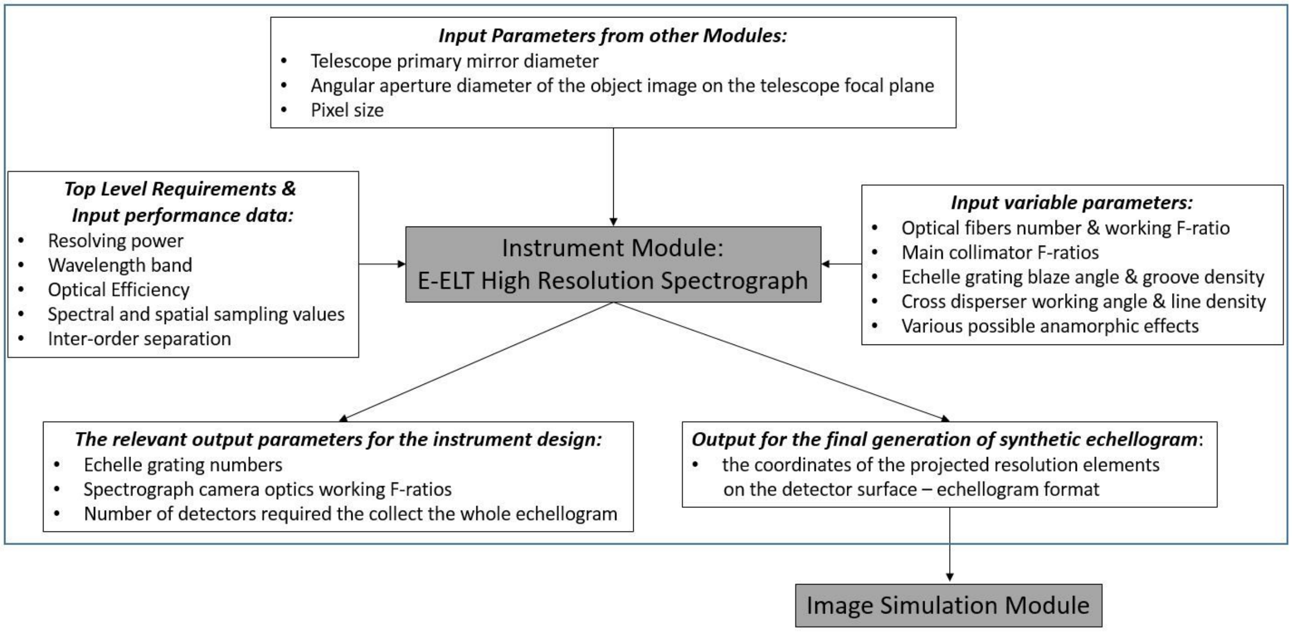

Figure 5. Schematic of the Instrument Module for the E-ELT high resolution spectrograph main input and output (for both the instrument design at a system engineering level and for the final generation of synthetic echellogram) parameters.

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 outputted by the Instrument Module is shown in the following figure, where only five wavelengths (among which the blaze wavelength, lower and upper free spectral range wavelength) for the diffracted orders are shown to avoid an over-plotting of spectral resolution elements which would result in a not clear echellogram representation. Of course in the complete simulation the position of all the spectral resolution elements will be evaluated and passed to the Image Simulation Module.

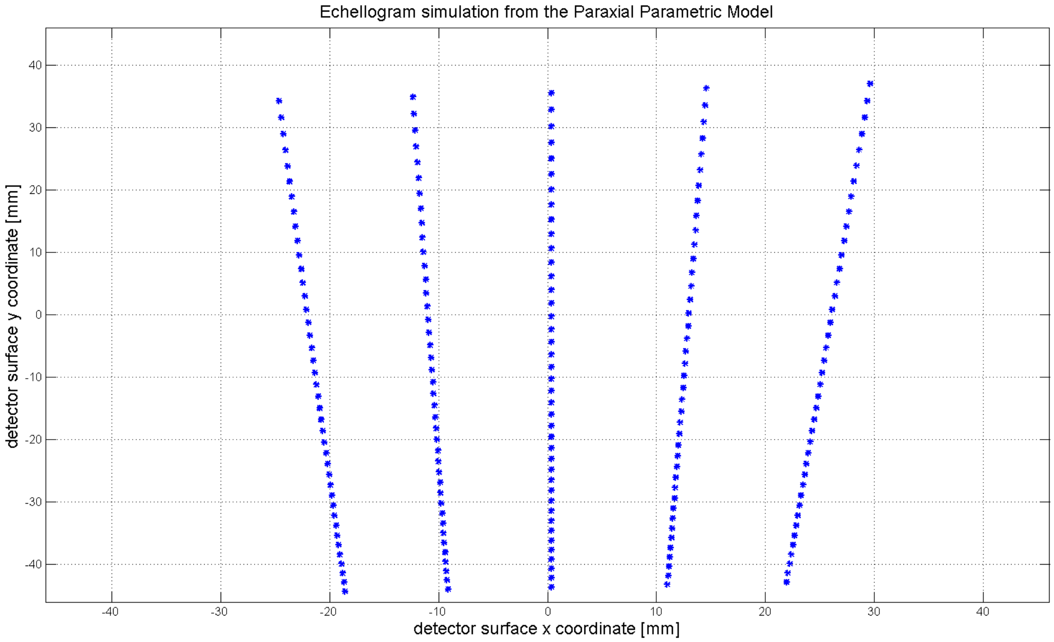

Figure 6. Echellogram format example from the Instrument Module *Paraxial Parametric Model* computation; only five wavelength (among which the blaze wavelength, lower and upper free spectral range wavelength) for the diffracted orders are shown to avoid an over-plotting of spectral resolution elements which would result in a not clear echellogram representation.

4.2.2 Image Simulation Module

The aim is to model the image on the detector surface by generating synthetic images, low resolution spectra or high resolution echellograms according to the user required simulation; 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 fidelity of the output format can be checked by evaluating the barycenter of the different object images or spectral resolution elements. As done before, 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 lower than ~ 1nm.

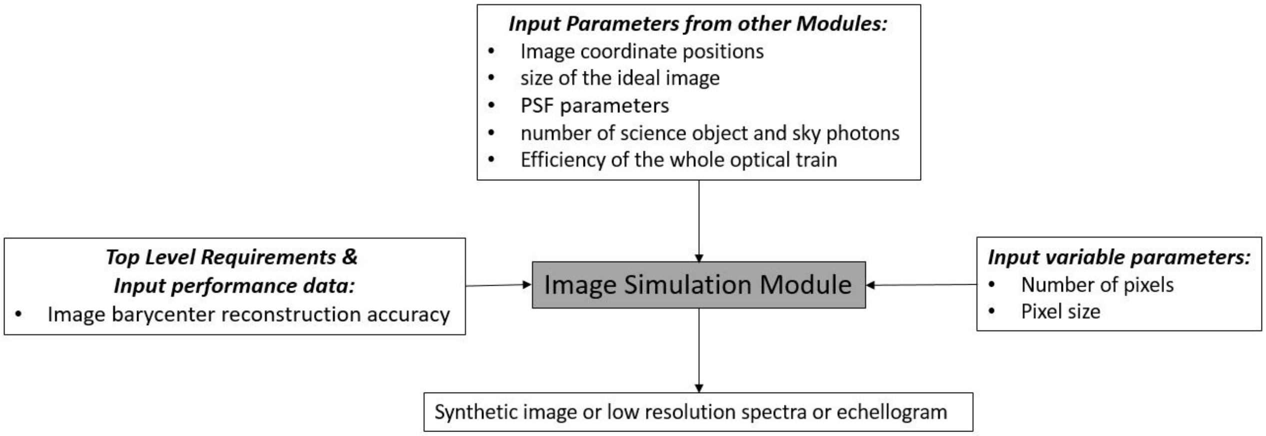

Figure 7. General schematic of the Image Simulation Module with main input and output parameters.

We have develop our own integral computation procedure, for the current moment implemented in MATLAB, for the evaluation of single point convolution value, on a set of nodes inside each pixel, and for the integral calculation of the flux density on each single pixel. The procedure is based on the Simpson 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 MATLAB software package has been exploited to verify the convolution calculation algorithm.

We have simulated two different kind of ideal image to be convolved with a symmetric Gaussian PSF: a circular image (15 µm radius) with constant flux density and a symmetric Gaussian distribution flux density (10 µm standard deviation). In the simulation a single convolved spectral resolution element has been computed considering a pixel size of 10 µm, 11 partitions per pixel, a convolution pitch of 0.5 µm and Gaussian PSF with a standard deviation of 10 µm. In the case of the ideal circular image with constant flux density the error in the barycenter reconstruction is more than 50 nm and the computational time is about 900 s; in the case of the ideal image with a symmetric Gaussian distribution flux density the error is of the order or 0.8 nm and the simulation time of about 400 s. The bad accuracy in the former case is due to the sharpness of the ideal image 3 dimensional profile; while the high computation time is due to the code structure used for the evaluation of the ideal function point values, required for the convolution calculation, which is not efficient in the interpreted language MATLAB framework. The smoothness of the Gaussian function of the latter case allows to achieve good accuracy even if the required computational cost is too high for a complete echellogram simulation. To achieve an acceptable accuracy also in the case of ideal circular image the convolution pitch should be in the order of nm, thus meaning an increased required simulation time. For this reason we foresee a wide use of high efficiency programming procedures and languages for the implementation of computationally onerous functions and scripts.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this paper we have presented an alternative philosophy for the development of an End-to-End simulator and of its architecture. This alternative approach foresees the development of the physical model of the different modules, which compose the entire End-to-End system, directly during the project design phase. In addition 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 presented the End-to-End model architecture, describing the main functionalities and interfaces of the main modules. Focusing on the model study case of the high resolution spectrograph at the E-ELT (E-ELT HIRES) the preliminary results regarding two modules have been described. In particular the definition of the parameters and the implementation of Paraxial Unit of the Instrument Module have been illustrated (referring to another paper of this same proceeding[9] for further details), showing an example of echellogram format simulation. For what concern the Image Simulation Module the key parameters for the calculation of the ideal image convolution with a symmetric Gaussian PSF have been defined. In the future steps of the project the detailed development of the other modules is planned, including the evaluation of different strategy in the implementation of the computationally onerous functions and scripts, which will be coded in efficient programming languages.

REFERENCES

[1] European Soutern Observatory, [The E-ELT construction proposal], (2011).

[2] Goodwin, M., Smedley, S., Barnes, S., Farrel, T., Barden, S., “Data simulator for the HERMES instrument”, Proc. SPIE 7735, 77357U-1 (2010).

[3] Jarno, A., Bacon, R., Ferruit, P., and Pécontal-Rousset, A., “Numerical simulation of the VLT/MUSE instrument” Proc. SPIE 7017, 701710 (2008).

[4] Maiolino, R., Haehnelt, M., Murphy, M., et al., “A Community Science Case for E-ELT HIRES”, arXiv:1310.3163, (2013).

[5] Origlia, L., Oliva, E., Maiolino, R., et al “SIMPLE: a high-resolution near-infrared spectrometer for the E-ELT”, Proc. SPIE 7735, art.id 77352B, 9pp. (2010).

[6] Parry, I., Bunker, A., Dean, A., et al. “CIRPASS: description, performance and astronomical results”, Proc. SPIE 5492, p. 1135 (2004).

[7] Schmalzl, E., Meisner, J., Venema, L., et at., “An end-to-end instrument model for the proposed E-ELT instrument METIS”, Proc. SPIE 8449, 84491P-1 (2012).

[8] Zerbi, F. M., Bouchy, F., Fynbo, J., et al. “HIRES: The High Resolution Spectrograph for E-ELT”, Proc. SPIE 9147, 914723-1, (2014).

[9] Genoni, M., Riva, M., et al., “Optical parametric evaluation model for a broadband high resolution spectrograph at E-ELT (E-ELT HIRES)”, *this Proceeding* 9911-99 (2016).