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Optical parametric evaluation model for a broadband HIRES at E-ELT

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Abstract. We present the details of a paraxial parametric model of high resolution spectrograph which can be used as a tool, characterized by good approximation and reliability, at a system engineering level. This model can be exploited to perform a preliminary evaluation of the different parameters as long as different possible architectures of high resolution spectrograph like the E-ELT HIRES. The detailed equations flow concerning the first order effects of all the spectrograph components is described; in addition a comparison with the data of a complete physical ESPRESSO spectrograph model is presented as a model proof.

Key words. Spectrograph: high resolution – Spectrograph: paraxial model – Spectrograph: E-ELT HIRES – Spectrograph: field dicing – Spectrograph: echelle cross dispersed

1. Introduction

The huge photon collecting power of the 39m European Extremely Large Telescope (E-ELT) coupled with HIgh REsolution Spectrograph (HIRES) will allow the European high resolution community to make fundamental discoveries and progresses in a wide range of astrophysical areas (Maiolino et al. 2013) like: exoplanets, structures and evolution processes of stars, spectroscopic study of the galaxies evolution, fundamental constants (such as the fine-structure constant α and the proton-to-electron mass ratio μ) variation and the related cosmology.

All these scientific cases have been pointed out by the HIRES Initiative working group, which also has derived the top level requirements and has proposed a preliminary architecture concept, shown in Fig. 1, for the E-ELT HIRES spectrograph. This is a highly modular architecture which foresees different independent fiber-fed echelle spectrometers optimized for different wavelength bands (different modules are fed by different optimized fibers); 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 separating the light into its constitutive wavelengths and then refocus them onto the detector surface.

In the proposed architecture concept, in each module, the fiber optics vertically rearranged feed the pre-slit unit (which re-sizes the light beam at the spectrometer unit entrance introducing anamorphic effect). The different modules may also allow different observing

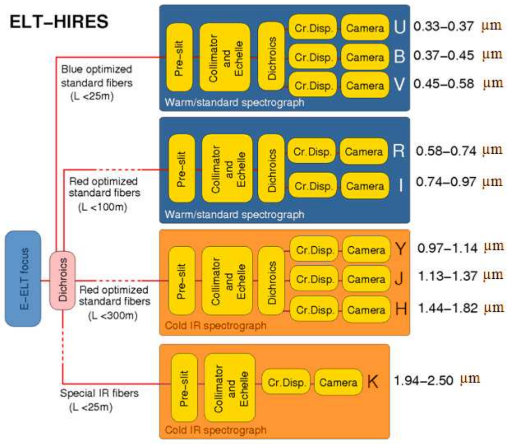

Fig. 1. Preliminary E-ELT HIRES concept: modules and bands division (from Zerbi et al. 2014). The wavelength bands division takes into account the atmospheric transmission profile.

modes, in order to better accomplish the scientific goals, which can be obtained by feeding the spectrograph with different fibers systems (see Maiolino et al. 2013, for details). The main observing mode is a single object mode; the technique used to feed the spectrograph entrance in the proposed architecture is the field dicing, in which the field is diced by the lens array so that each fiber of the optical fibers system is looking at a slightly different part of the object. The optical design of both the pre-slit and spectrometer units of each module foresees the presence of anamorphic effects.

We have developed a flexible paraxial parametric model of the high resolution spectrograph which can be very useful at system engineering level to perform a preliminary evaluation of different possible instrument architectures. The model is detailed starting from the assumptions taken into consideration, then describing all the equations for all the optical components and the related relevant (paraxial) effects; finally a comparison with the ESPRESSO spectrograph physical data is presented in order to show the good reliability of the model.

2. Paraxial parametric model

2.1. Assumptions

According to the paraxial nature of the derived model the aberrations that may be induced by the collimating, focusing optics and other optical elements are not specifically modelled; the other general assumptions are:

- The optic systems that can be exploited to dice the field and to feed the spectrograph entrance are not modelled; only the relevant parameters directly related to the spectrograph design (number of fibres and fibre core diameter) are taken into consideration.
- The anamorphic effects are modelled simply by using different x and y beam resizing coefficients; these coefficient are always formally defined as the ratio of the beam size (both for x and y directions) after the effect over the beam size before.
- The echelle grating works in Littrow condition and its efficiency (which is related to the coating that will be proposed, designed and developed in future steps of the project) has been modelled, according to the scalar theory described in Schroeder (2000), only for the useful wavelength range determination in each spectral order.
- The cross dispersing element efficiency is modelled according to the Bragg condition.

2.2. Model equations flow

Starting from the fixed data of the telescope diameter D_T and the angular aperture diameter

χ of the object image on the telescope focal plane (due to the seeing condition), the number of fibers N_f used to dice the field and the physical constraint on their working input focal ratio F_{fib} set the fibers core diameter as:

$$D_{fib} = \frac{D_T F_{fib}}{\sqrt{N_f}} \frac{\chi}{206265} \quad (1)$$

Setting the main collimator x and y F-ratio ($F_{coll,X}$ and $F_{coll,Y}$), directly related to its design and manufacturing complexity, the pre-slit anamorphic factor and the x and y dimensions of the effective entrance slit of the spectrometer unit (related to a fiber core) are:

$$PS_{AF} = F_{coll,Y}/F_{coll,X} \quad (2)$$

$$D_{eqslit,X} = (F_{coll,X}/F_{fib})D_{fib} \quad (3)$$

$$D_{eqslit,Y} = (F_{coll,Y}/F_{fib})D_{fib} \quad (4)$$

The total illuminated length of the echelle grating mosaic, W, is derived form the imposed resolving power R (a top level requirement) and from the grating blaze angle value δ (known from echelle gratings available on the market):

$$W = \frac{D_{eqslit,X} R}{2sin(\delta)F_{coll,X}} \quad (5)$$

The collimated beam x and y size (after the main collimator) can be expressed then as:

$$d_{coll,X} = Wcos(\delta) \quad (6)$$

$$d_{coll,Y} = d_{coll,Y}/PS_{AF} \quad (7)$$

The required number of echelle gratings ($N_{grat,X}$ and $N_{grat,Y}$) to form the mosaic are related to the data on the gratings ruled width, Rul_W and groove length G_l, as:

$$N_{grat,X} = W/Rul_W \quad (8)$$

$$N_{grat,Y} = d_{coll,Y}/G_l \quad (9)$$

Through the transfer collimator coefficient the x and y size of the beam after it are:

$$d_{TC,X} = d_{coll,X} TC_{coeff} \quad (10)$$

$$d_{TC,Y} = d_{coll,Y} TC_{coeff} \quad (11)$$

The anamorphic effects of the cross disperser are modelled with the coefficients $XD_{AF,X}$ and $XD_{AF,Y}$ through which the x and y size of the collimated beam at the camera optics input are:

$$d_{XD,X} = d_{TC,X} XD_{AF,X} \quad (12)$$

$$d_{XD,Y} = d_{TC,Y} XD_{AF,Y} \quad (13)$$

The camera optics F-ratios are derived by the spectral and spatial sampling value (S_X and S_Y) and by the pixel size for the available detectors according to the specific wavelength band (optical CCD or IR detectors) as:

$$F_{cam,X} = (d_{pix} S_X / D_{eqslit,X}) F_{coll,X} \quad (14)$$

$$F_{cam,Y} = (d_{pix} S_Y / D_{eqslit,Y}) F_{coll,Y} \quad (15)$$

So the camera focal length is:

$$f_2 = F_{cam,X} d_{XD,X} = F_{cam,Y} d_{XD,Y} \quad (16)$$

To derive the parameters related to the cross disperser the total linear separation between two consecutive orders on the detector surface, Δy must be set; it has been expressed in terms of the number of fibers, pixel size, required spatial sampling, required separation between object and sky fibers ($\Delta y'$) and separation between consecutive orders ($\Delta y''$):

$$\Delta y = (2N_f S_y + \Delta y' + \Delta y'')d_{pix} \quad (17)$$

From the cross disperser angular dispersion the working angle for the Bragg condition is:

$$\alpha_{cd} = atan(\lambda_b \Delta y / 2 f_2 \Delta\lambda_b) \quad (18)$$

where in this case λ_b is the central blaze wave of the specific wavelength band and $\Delta\lambda_b$ is the difference in wavelengths between the central blaze wave and the consecutive one. From the classical diffraction equation (with the cross disperser working spectral order $m_{cd} = 1$) the cross disperser groove density is:

$$\rho_{cd} = (2sin\alpha_{cd}/m_{cd}\lambda_b) \quad (19)$$

From the linear dispersion equation the total echellogram central height is expressed as:

$$\Delta y_{tot,1} = \Sigma_i (f_2 A_{cd,i} \Delta\lambda_i) \quad (20)$$

where $A_{cd,i}$ is the cross disperser angular dispersion at the different blaze wavelengths. To model the orders' tilt the tilt angles of the maximum and minimum order at the blaze wave are computed (see Schroeder 2000) as:

$$tan\psi(m_{min}) = \frac{A_{cd}(\lambda_b(m_{min}))}{A_{ech}(\lambda_b(m_{min}))} \tag{21}$$

$$tan\psi(m_{max}) = \frac{A_{cd}(\lambda_b(m_{max}))}{A_{ech}(\lambda_b(m_{max}))} \tag{22}$$

Then a first order approximation of the additional vertical portion of the covered detector surface is computed assuming a constant orders tilt and by knowing the effective half width of minimum and maximum order:

$$\Delta y_+(m_{min}) = tan(\psi(m_{min}))\Delta x_+(m_{min}) \tag{23}$$

$$\Delta y_-(m_{max}) = tan(\psi(m_{max}))\Delta x_-(m_{max}) \tag{24}$$

where the effective half width of minimum and maximum order are computed according to the linear dispersion in the main dispersion direction, so similarly to what done in eq. 20 but now referring to the echelle grating angular dispersion. The total echellogram height on the detector surface is then:

$$\Delta y_{tot,2} = \Delta y_{tot,1} + \Delta y_+(m_{min}) + \Delta y_-(m_{max}) \tag{25}$$

The total echellogram width is due to the total width of the minimum order, computed as the sum of the two effective half width derived from the linear dispersion in the main dispersion direction:

$$\Delta x_{tot,2} = \Delta x_+(m_{min}) + \Delta x_-(m_{min}) \tag{26}$$

2.3. Model comparison results

The derived parametric paraxial model has been tested and verified doing a comparison with Zemax data of the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO), which will be soon installed on the Very Large Telescope (VLT) at Cerro Paranal in Chile. The pupil slicing effect, instead of the field dicing, has been modelled since the ESPRESSO design foresees this technique to meet the resolving power requirement (see Mégevand et al. 2014, for details). The pupil slicing effect is given by the Anamorphic Pupil Slicer Unit (APSU). Tab. 1 presents the relevant output parameters, according to a system engineering point of view, related to system complexity and cost issues, showing the good matching between model and physical results.

Table 1. Parametric paraxial model results comparison with ESPRESSO Zemax data. ψ_X and ψ_Y are the fraction of detector surface width and height covered by the echellogram.

Results	Paraxial model	ESPRESSO
δ $[deg]$	76	76
ρ $[l/mm]$	31.6	31.6
$N_{grat,X}$ $[-]$	3.033	3
$N_{grat,Y}$ $[-]$	0.978	1
$F_{cam,X}$ $[-]$	2.7	2.7
$F_{cam,Y}$ $[-]$	2.7	2.7
ψ_X $[-]$	0.62	0.65
ψ_Y $[-]$	0.87	0.91
α_{cd} $[deg]$	20.43	21.24
ρ_{cd} $[l/mm]$	1478	1500

3. Conclusions

A reliable paraxial parametric model for spectrograph design has been derived; it also has a good flexibility in the simulation and evaluation of the wide range of parameters (as well as their interdependencies) involved in the design and architecture definition of such a complex instrument. Focusing on the system engineering level it is possible to exploit this model in order to easily compare different architecture concepts and to perform sensitivity analyses.

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