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Instrument Physical Model for the SOXS (Son Of X-Shooter) spectrograph

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ABSTRACT

We present the proposal for the physical instrument model of the SOXS (Son OF X-Shooter) spectroscopic facility mainly devoted to the follow-up observation of transient sources. A dedicated suitable instrument to exploit the science of these transients is lacking, resulting in severe science “dissipation”. SOXS will cover the optical/NIR band (0.35-1.75 µm) with a medium resolution (R~4500), down to the limiting magnitude of R~20-20.5 (1 hr at S/N~10) that is perfectly suited to study transients from on-going imaging surveys. Imaging capabilities in the optical are also foreseen to allow for multi-band photometry of the faintest transients with a field of view of at least 2arcmin. We propose to implement a physical modelling approach in order to link the instrument parameters and behaviour to physical quantities, thus providing a description of the instrument that can be connected with measurements. The method has been already successfully applied to the X-shooter instrument. The X-shooter physical model is based on a kernel optical ray-tracing realised by means of matrix optics representation, which can handle a large number of wavelengths. This can be extended to the SOXS design. The foreseen applications of the SOXS physical model are broad, ranging from support to detailed instrument design and development of the data reduction software, wavelength calibration, evaluation of instrument performance as a function of the model parameters, instrument alignment, and support during the commissioning phase and as a tool for quality check during operations.

Keywords: Instrument Model, Spectrograph, Astronomical Instrumentation, Physical Model

1. INTRODUCTION

In the near future we will enter the golden age of time-domain astronomy having in place deep ground-based and space-based optical surveys, high-energy instruments radio surveys, Gravitational Wave (GW) and neutrino experiments all calling for a rapid follow-up and characterization of the detected transients. A dedicated suitable spectroscopic facility able to exploit the science of these transients is lacking, resulting in severe science “dissipation”. SOXS, that is “Son of X-shooter” given its similarities and relationships with X-Shooter, is a spectroscopic facility for the follow-up of transient sources able to cover this lacking in the optical/NIR band ([0.35-1.75]µm).

SOXS is a medium resolution spectrometer (R~4500) from visible to NIR with a sensitivity similar to EFOSC2 and SOFI together ([1.5;6.0]10^{-18} erg.$s^{-1}cm^{-2}A^{-1}$ on short exposure, [2.0;8.0]10^{-19} erg.$s^{-1}cm^{-2}A^{-1}$ on long exposure, BB and NB respectively). It will be built based on the heritage of the X-shooter [1] at the ESO-VLT (for this reason it has been named Son Of X-Shooter).

The limiting magnitude of *R*~20-20.5 (1 hr at S/N~10) is perfectly suited to study transients from on-going imaging surveys. Imaging capabilities in the optical band are also foreseen to allow for multi-band photometry of the faintest transients with a field of view of at least 2arcmin. SOXS shall be operative at the NTT from 2019 onwards.

The implementation of a physical model to describe the instrument behaviour is a consolidated technique that has been used in the past [1,3,4,5], linking the outputs of an instrument to the variation of some typical physical parameter. It was successfully implemented for X-Shooter with the main aim to get wavelength calibration by physical understanding of the instrument [1].

The physical representation can be used to accurately model spectrographs using a series of matrix transformations [2]. The core of this modelling is a matrix kernel that simplifies the instrument design code but, at the same time, makes the performance verification fast and efficient, mainly for the evaluation of wavelengths, slit position and optical component, and parameter configuration. This yields to get a powerful tool for system optimization and calibration able to fit dispersion solutions to a set of physical meaningful parameters. Besides providing a robust physical basis to instrument

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alignment, wavelength calibration and performances optimization, this method supports the development of the data reduction software providing simulated 2D data and it will be used as a tool for quality check during operations.

2. SOXS SPECTROGRAPH

SOXS is a second-generation instrument for the New Technology Telescope (NTT), ESO, in La Silla, Chile. It did still receive the approval from ESO and now it is under evaluation for funding by consortium institutions.

SOXS is a high-efficiency prism-dispersed spectrograph with a Resolution-Slit product of 4500 (goal 5000) over the entire band capable of simultaneously observing the complete spectral range 350-1750 nm (goal 320-1750 nm). The instrument will be located at one of the two Nasmyth interfaces of the NTT. It has a dual-channel scheme with a common path carrying the telescope beams to two dichroics that split them through the UV-VIS and NIR arms, as shown in Fig.1.

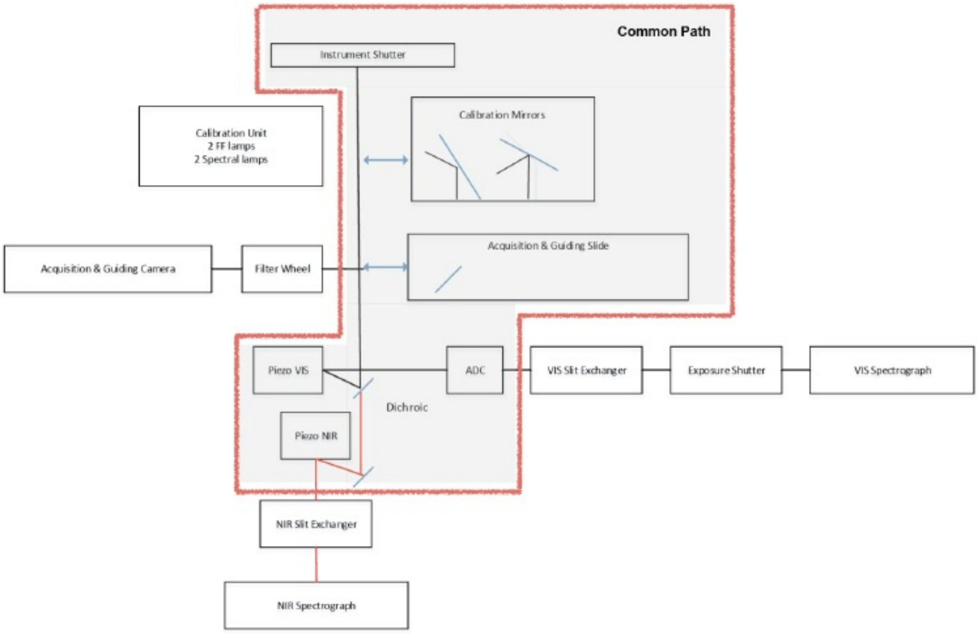

Fig.1 SOX instrument schematic diagram

3. PHYSICAL INSTRUMENT MODEL - PIM

The SOXS physical instrument model will be implemented to describe the two UV-VIS and NIR arms separately, from the input slit to the detector output and we foresee to embed it in an end-to-end simulator taking into account other relevant instrument subsystems, such as detectors characteristics, electronics, calibration unit, etc.

The UV-VS and NIR arms are very similar so that the same physical model can be applied to the two arms with minor variations of the instrument parameters. A representative instrument layout is given in Fig.2.

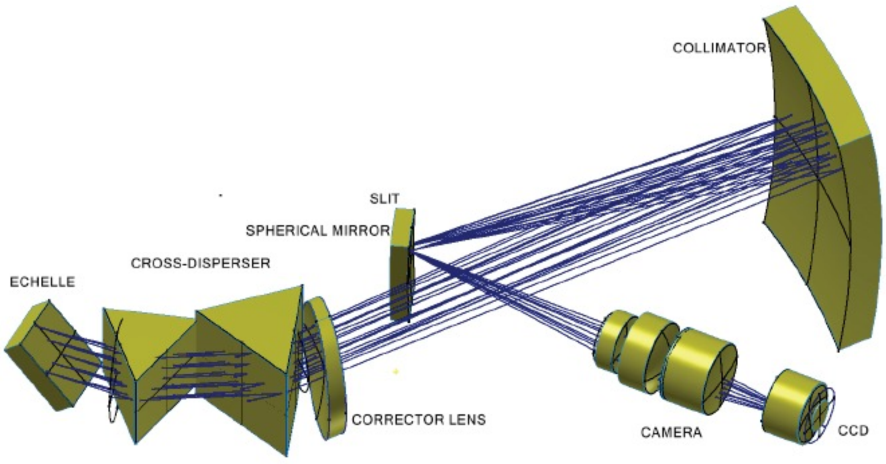

Fig.2 SOXS representative layout

Referring to the approach described in [2], the SOXS model will consists of a series of matrices, each matrix being the representation of an optical surface in the spectrograph. The matrix elements will be filled based on the prescriptions from optical cad (ZEMAX, CODEV).

An input vector containing the beam (*x,y,z*) coordinates and the wavelength will be conjugated to the output vector by the relation:

$$\begin{pmatrix} \boldsymbol{\lambda} \\ \boldsymbol{x} \\ \boldsymbol{y} \\ \boldsymbol{z} \end{pmatrix}_{\boldsymbol{output}} = \boldsymbol{M}_{\boldsymbol{system}} \cdot \begin{pmatrix} \boldsymbol{\lambda} \\ \boldsymbol{x} \\ \boldsymbol{y} \\ \boldsymbol{z} \end{pmatrix}_{\boldsymbol{input}} \tag{1}$$

The operator M_{system} is the resulting operator obtained by the multiplication of the (geometrical) contribution of each optical element (matrix). Each matrix M_i describes the effect of the optical element on the beam path, taking into account the tip-tilt of the element itself.

In the case of modeling a spectrograph, the kernel of this procedure is the matrix describing the echelle grating that is in the form:

$$M_E = \begin{pmatrix} \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{m/\sigma_E} & \boldsymbol{-cos\theta} & \mathbf{0} & \boldsymbol{sin\theta} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{sin\theta} & \mathbf{0} & \boldsymbol{cos\theta} \end{pmatrix} \tag{2}$$

Being m the dispersion order, σ_E the echelle number, θ the off-blaze angle.

By using the complete set of physical parameters (angles, distances, temperatures etc.) that describe the actual status of components, we can map the passage of a photon through the spectrograph. Each one of these parameters can be adjusted at any time to match the observed behaviour of the instrument or to predict the effects of modifying a component.

The model is started up with the reference parameters from the optical design. At pixel level, the real instrument will differ from design and the PIM is used to fit the model parameter to real behavior. For this reason, usage of the PIM during instrument operation needs for a verification and validation procedure. This is done using robustly identified calibration features. Typically, the centroids of a few reference spectral lines obtained from the real instrument with a calibrated source are measured. The centroids of the spectral signatures are used to realize a calibration database.

The PIM is iteratively run while the instrument parameter are adjusted to match the signatures in the database. Parameters first guess is the value given by design. In Fig.3, the workflow of the model is shown.

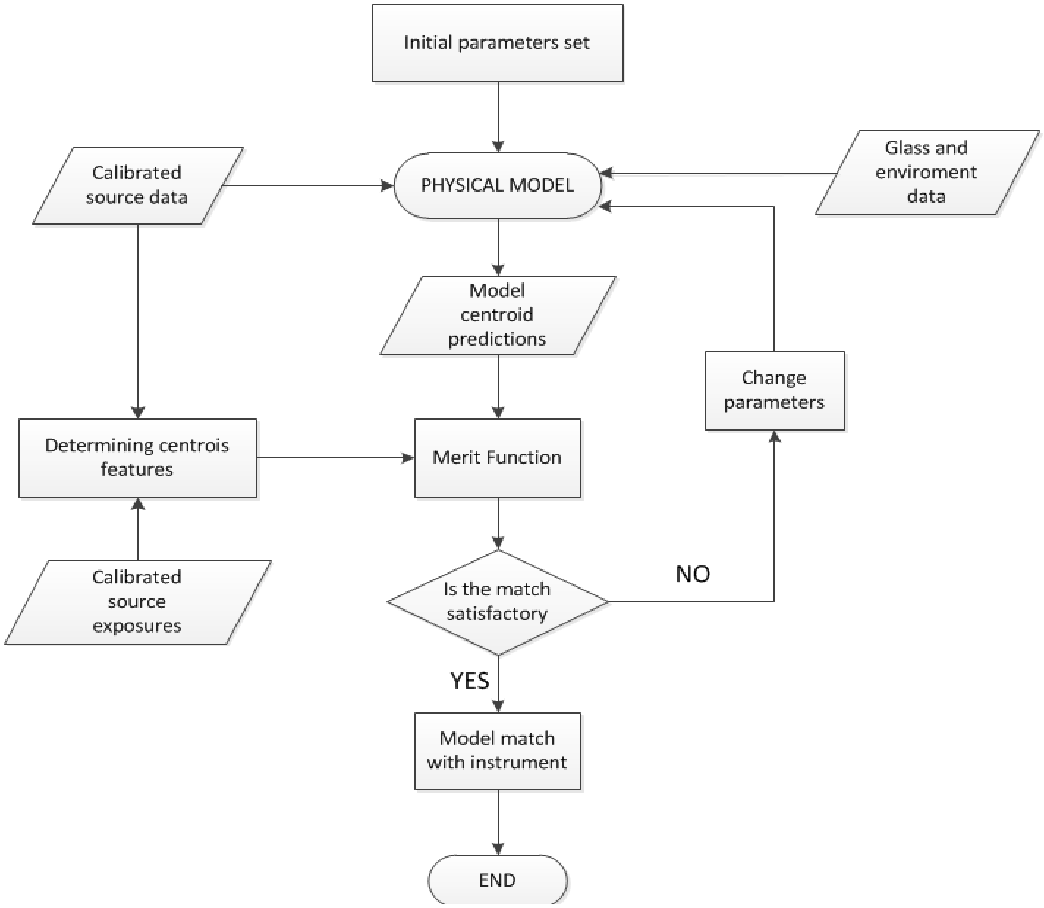

Fig. 3 Work flow for the PIM

The outputs from the initial configuration are compared with the ones available in the calibration database. The merit function (MF), *e.g.,* the centroid, is analysed to give back the degree of fitting between expectation and real behaviour. If the MF is within some percentage of matching the model is accepted, otherwise a further iteration starts. The matching threshold is selected looking at the number of iteration that retrieve the smallest values. If the matching degree does not change after some iteration, the modelling procedure stops and gives out the instrument optimized parameters.

Even if this approach cannot be considered as substitutive of the ordinary methods using the optical design Packages (CODE V, ZEMAX …), it is a sufficiently accurate and fast tool for wavelength calibration and for iterative use to get synthetic exposures and optimizing the parameter set.

Experience shows that the main challenge is the determination of the refractive index of the materials used for cross-dispersion that are function of wavelength and temperature. This dependence cannot be described by solving with the iterative algorithm used to determine the other model parameters. High quality laboratory measurements of the refractive indices of the materials will be needed.

4. MODEL OPTIMIZATION SOLUTION

The optimization solution is the process that, starting from a nominal configuration of the system, is iteratively run to get the actual configuration of the system. The actual configuration can be perturbed to check the system changes acting on the physical parameters. On the other hand, the image evolution can be monitored getting back to the system perturbations that can have produced them.

The starting configuration, or nominal, is the one obtained from the optical parameter made available by the design code (CODE V, ZEMAX…). The real instrument differs from this and we need to match the model to reality. This matching can be done by wavelength and geometry calibration, using identified features obtained from dedicated exposure done with calibrated sources.

Once a dataset of well-calibrated data is available, the physical model is iteratively run in order to compare the real exposure with those present in the dataset and to identify the calibrated wavelength.

The procedure for the optimization of the instrument model moves from a reference set-up that takes some of the instrument parameters fixed and some other variable. As already experienced in other instruments, some set of parameters can show a high degree of degeneracy, making difficult to both interpret their real physical meaning and retrieve the instrument configuration.

Classical methods (such as Least Square or Maximum Likelihood) can show problems related to local maxima/minima confinement. Accurate parameters initial estimate or Simulated Annealing can overcome this [6].

The matching of the model to the real instrument is done by considering the mean value for the residuals between the model and the actual exposure. These residuals are defined as:

$$\overline{\Delta x} = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{M}\sum_{j=1}^{M}\left\|\delta x_j\right\|$$

The same for Δy

Being N the number of exposures, and M the number of lines matched at any exposure. The residuals obtained from the physical model implemented for the X-Shooter show a the typical value of the order of [0.025,0.1]pixel, depending on the wavelength.

5. CONCLUSIONS

In this paper, we present the proposal for the physical instrument model of the SOXS spectrograph. The physical instrument model is an approach widely and successfully used in the past for the modelling of spectrographs and it has shown great versatility and precision in the description of the instrument behaviour under different operation situation. SOXS is a spectrographic facility mainly aimed at the follow-up observation of transient sources. This kind of instrument is well suited to fill the lacking in the transient study, and it is expected to provide a critical improvement of this science. It will cover the optical/NIR band (0.35-1.75 μm) with R~4500, and imaging capabilities in the optical are also foreseen to allow for multi-band photometry of the faintest transients with a field of view of at least 2arcmin. We propose to implement a physical modelling approach in order to link the instrument parameters and behaviour to physical quantities, thus providing a description of the instrument that can be connected with measurements, giving a fast feedback about any variation of the instrument status, without the need for using classical raytracing.

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