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M. Genoni, M. Riva, G. Pariani, M. Aliverti, M. Moschetti, "Spectrograph sensitivity analysis: an efficient tool for different design phases," Proc. SPIE 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 99086Z (9 August 2016); doi: 10.1117/12.2233294

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

Spectrograph sensitivity analysis: An efficient tool for different design phases

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ABSTRACT

In this paper we present an efficient tool developed to perform opto-mechanical tolerance and sensitivity analysis both for the preliminary and final design phases of a spectrograph. With this tool it will be possible to evaluate the effect of mechanical perturbation of each single spectrograph optical element in terms of image stability, i.e. the motion of the echellogram on the spectrograph focal plane, and of image quality, i.e. the spot size of the different echellogram wavelengths. We present the MATLAB®-Zemax® script architecture of the tool. In addition we present the detailed results concerning its application to the sensitivity analysis of the ESPRESSO spectrograph (the Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations which will be soon installed on ESO's Very Large Telescope) in the framework of the incoming assembly, alignment and integration phases.

Key words: Spectrograph sensitivity analysis – Spectrograph image stability – Spectrograph image quality – ESPRESSO spectrograph.

1. INTRODUCTION

Performing Opto-mechanical tolerance and sensitivity analysis is a very relevant step both for the preliminary and final design phases of a spectrograph. Furthermore is fundamental during the assembly, alignment and integration phases. Efficient tools to perform these analyses are then very important and useful when dealing with complex instruments like spectrographs. Although specific commercial software (e. g. Zemax) able to simulate complex instruments have different and reliable analysis tools, the integration of their functionalities with other software capabilities gives the possibility to perform a more intuitive and effective data analysis. For this purpose the software MATLAB can be exploited thanks to its capabilities in efficiently managing and representing large amount of data. This is fundamental when dealing with high resolution spectrograph, where the resulting image on the instrument focal plane is an echellogram composed by many orders and many wavelengths. We present in this work the example of the application of this tool for analyses on ESPRESSO spectrograph in the framework of the incoming assembly, alignment and integration phases. ESPRESSO (the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) is a high-resolution, ultra-stable, fiber-fed cross-dispersed echelle spectrograph built to complete the current 2nd generation Very Large Telescope (VLT) instrument suite[1,2]. It will be installed in the underground Combined Coudé Laboratory (CCL) of the VLT, and will be linked to the four Unit Telescopes (UT). ESPRESSO-VLT main scientific objectives will be the search and characterization of rocky exoplanets in the habitable zone of quiet, near-by G to M-dwarfs, and the analysis of the variability of fundamental physical constants[2].

The paper is organized in the following way: section 2 presents the tool features, explaining inputs data flow and analyses; section 3 refers to the application example, describing instrument overview and results.

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Ground-based and Airborne Instrumentation for Astronomy VI, edited by Christopher J. Evans, Luc Simard, Hideki Takami
Proc. of SPIE Vol. 9908, 99086Z · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2233294

2. THE TOOL FEATURES

The tool is based on the integration between the optical ray-trace software package Zemax and the mathematical modeling software package MATLAB. The integration is done exploiting the MZDDE toolbox for MATLAB, through which the data flow between the two software is established; in this way MATLAB can efficiently invoke Zemax, setting inputs and acquire outputs. The tool is composed by three main analogue codes for the evaluation of the three figures of merit, which are image stability, image quality and efficiency. In the following the features of the tool are described.

2.1 Inputs

As first step the Zemax optical file of the instrument must be prepared for the varying parameters (degrees of freedom) of the opto-mechanical tolerance and sensitivity analyses. This is done by inserting, in the Lens Data Editor (LDE) before and after each single optical component-element of the instrument a surface (called Coordinate Break surface in Zemax) through which it is possible to simulate their position and alignment; in particular the parameters which simulate the position and alignment are the decenters (along x, y, z direction) and tilts (around x, y, z direction) respectively. It must be underlined that in this way decenters and tilts are with respect to a local reference frame for each optical component; the local frame is a frame with the origin located at the vertex of the first surface of the optical element or in the barycenter component, having the local Z axis parallel to the local optical axis and Y axis parallel to the local vertical direction. The need of the second coordinate surface is due to the fact that, in the tool, the optical design with Zemax is considered to be done in the so called Sequential Mode (which means that the position and local frame of a single optical surface is defined starting from the one of the previous one) and thus this second surface is used to leave all the other optical elements in their nominal position while performing the mechanical perturbation analyses on one specific element. The second coordinate break surface is linked to the first one directly in the ray-trace software thanks to the “pick-up” functionality that can be set for each surface parameter. The invariance of all other optical elements can be checked by verifying that Global coordinates of the vertex and the rotation matrix of the last optical surface do not change when the perturbation is applied to another element of the optical train.

In the MATLAB code of the tool the inputs are:

- The whole path description of the Zemax optical file location, such that MATLAB can initiate a link and a communication channel with the optical file to be processed;
- The definition of the surfaces to be moved, which are the coordinate break surfaces related to the different optical components of which the analyses are to be performed;
- The definition of the values of the degrees of freedom, which in turn are the decenters expressed in mm and tilts expressed in degrees, for each optical component to be analyzed;
- The number of diffraction orders and wavelengths for each order; since in high resolution spectrograph the number of the resolution elements (which are the image of the spectrograph entrance slit at different wavelengths) is very high it is useful to have the possibility to select a large number of orders and wavelengths on which the figures of merit are evaluated in order to perform a more accurate analysis.

2.2 Zemax - MATLAB data flow and management

The second step in the Zemax optical file preparation, before running the tool, is the setting of the Merit Function Editor (MDE). Thanks to this editor it is possible to perform, in the optical ray-trace software, the calculation of the selected figures of merit, which in this case are the image stability, image quality and efficiency. The definition of the MFE is of course related to the diffraction orders and wavelengths for which these performance are to be evaluated. Specifically each line of the MFE computes the specific figure of merit for a specific order and wavelength. As already said this is particularly useful for high resolution spectrographs which are characterized by a large number of orders and wavelengths per order.

The Zemax – MATLAB data flow is performed in the MATLAB code of the tool cycling five nested loops, three of which are used to set the defined inputs and two for the figures of merit data acquisition. For what concern input setting loops: one loop is related to coordinate break surfaces which simulate the optical component mechanical perturbation, two loops are related to the setting of the specific degrees of freedom to be perturbed and the perturbation value. At this point the optimization of the merit function is called; this operation can be exploited to simply update the merit function editor, after the change of the specific degree of freedom, or to perform an optimization of the set figure of merit acting on a set of variables (e.g. radius of curvature of an optical surface, thickness of an optical element) previously defined in the Lens Data Editor. For the purpose of our analysis the MFE is simply updated. The two data acquisition loops are used to identify and select the specific line in the merit function editor, i.e. the value of the figures of merit.

After the setting of each mechanical degree of freedom value of each optical component and the subsequent MFE update, the figure of merit data acquisition can be done. The data management is based on the MATLAB capabilities to build complex structure. In particular the data are saved in a cubic structure where the vertical dimension is associated to the different component perturbed, the horizontal dimension to the degrees of freedom and the third dimension is associated to the value of the degree of freedom. For our analysis three different degrees of freedom values are considered: negative variation, zero variation and positive variation. Each element of this cubic structure is a matrix which represents the figure of merit data for the different orders and wavelengths per order selected for the analysis, i.e. the information is organized reproducing the spectrograph echellogram format. A schematic of the cubic structure is shown in Figure 1.

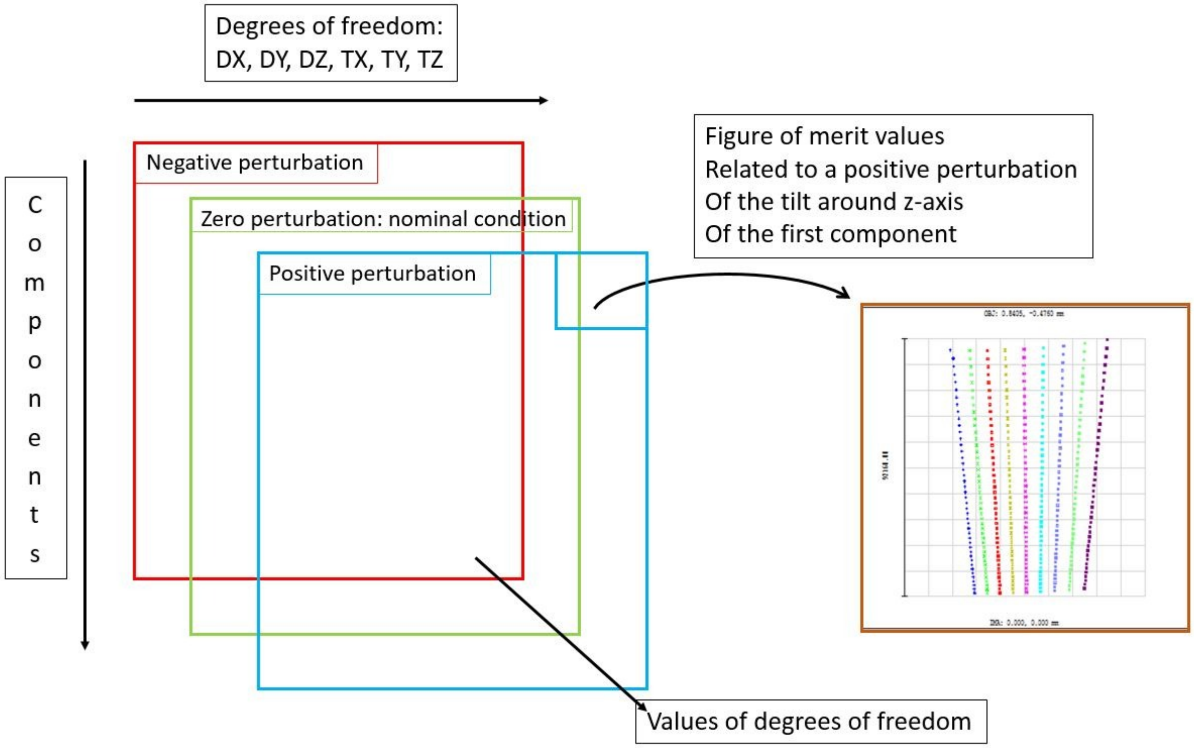

Figure 1. Schematic of the cubic structure exploited in MATLAB to manage the data of the figure of merit. Each cell of this cubic structure contains the figure of merit data related to the different wavelengths per each order reproducing the format of the echellogram of a high resolution spectrograph.

2.3 Analyses

The performances of the opto-mechanical tolerance and sensitivity analysis are image quality, image stability and efficiency; these are defined as RMS spot size, image motion on the instrument focal plane (the detector surface) and throughput (i.e. the percentage of light which actually reach the detector surface and so it is not vignette in the optical train). In particular the analysis performed focuses on the variation of the figures of merit related to the simulated mechanical perturbations; this is done simply by subtracting the performance values in the nominal condition to those in the perturbed conditions (both negative and positive). The image stability sensitivity is computed both for the centroid x and y coordinates on the CCD plane as the average and/or the RMS of the differences between the x and y centroid coordinates from the optical system in the perturbed configuration and the x and y centroid coordinates from the optical system in the nominal design. In this way it is possible to have a single and general indicator of the centroid coordinates variation related to the different wavelengths in the different diffracted orders. The same is done for the variation of the RMS spot size and for the throughput. In addition useful plots are displayed in order to have a direct and effective view of the figures of merit variation; especially for what concern image stability this is useful to understand the whole echellogram motion on the focal plane.

3. TOOL APPLICATION EXAMPLE: ESPRESSO SPECTROGRAPH

We present now the application of the tool to the ESPRESSO spectrograph, showing analysis results that have been useful both for the opto-mechanical alignment-integration phase and for the final design refinement.

3.1 Spectrograph overview

The ESPRESSO instrument is a fiber-fed, pupil-sliced, two-arm (blue and red), bench-mounted, cross-dispersed echelle spectrograph[1,2], placed in vacuum and in a thermally stabilized environment for very high metrological stability. Mechanical (and optical) stability is ensured since no moving parts are foreseen inside the spectrograph. It will be installed in the underground Combined Coudé Laboratory (CCL) of the VLT, and will be linked to the four Unit Telescopes (UT) through four optical paths called Coudé Trains. Thanks to these optical links and to its special Front-End (FEU) subsystem, it will be able to collect the light of any UT independently or together, allowing several different configurations amongst which a 4-UT mode which will make it the first instrument mounted on a 16-m equivalent telescope[1]. ESPRESSO is designed with a dual fiber system: the first is devoted to transfer the celestial object light, while the second can be used either to record the sky or to monitor the spectrograph shifts by recording a simultaneous calibration source. The full spectral coverage is from 380 to 780 nm, with a cut-off between the two arms at about 525 nm. The spectrograph optical layout is shown in Figure 2.

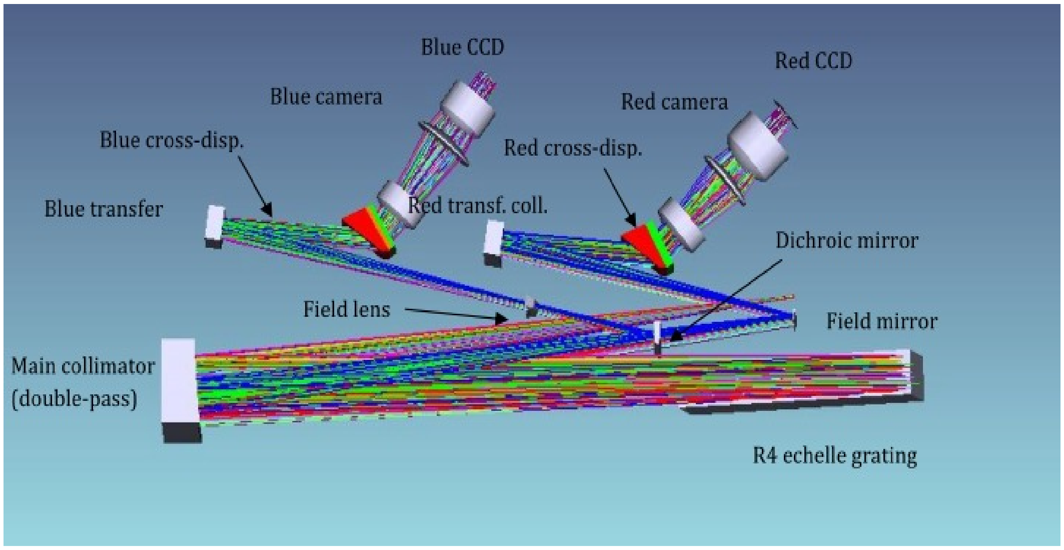

Figure 2. ESPRESSO Spectrograph optical layout: in the figure all the different components of the two arms are shown.

Three different pairs of fiber will feed the spectrograph, depending on the observing mode (1UT, 4 UTs) and the related selected resolving power (High Resolution $R \cong 120000$, Ultra High Resolution $R \cong 240000$ and Medium Resolution $R \cong 50000$).

These high values of resolving power are reached thanks to the presence of the Anamorphic Pupil Slicer Unit[3,4] (APSU) at the spectrograph entrance. The pupil slicer increases the resolving power of the spectrograph effectively decreasing slit width. Two cylindrical objectives with different focal length (1:3) introduce anamorphism. An elliptic pupil 30 X 10mm is realized. Pupil slicing is done with two (almost) achromatic identical couple of prisms likely configured as Risley prisms pair. At the APSU focal plane, which is the effective spectrograph entrance, a multi mini prisms system[4] (6 pairs for a total of 12 mini-prisms) is placed to differently fold each field of the APSU with the final aim of proper illuminating the echelle grating. Each observing modes uses two mini-prism pairs, one for the sky/reference light and one for the scientific object light. The two mini-prisms of each pair are associated to the two pupil slices. The optical layout of the APSU unit is shown in Figure 3.

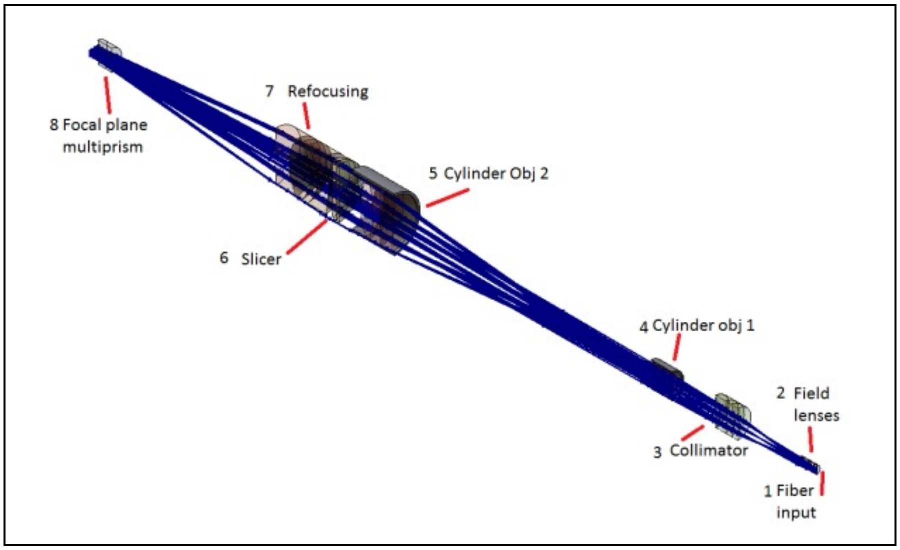

Figure 3. ESPRESSO Anamorphic Pupil Slicer Unit (APSU) optical layout.

3.2 Results

We present now two example of analysis results: one was done to define the tolerances for the alignment and integration of the APSU components, the other refers to the final design phase of the spectrograph camera in the blue arm.

We have considered 10 diffraction orders and 5 monospaced wavelengths per order, for a total of 50 wavelengths analysis. As explained before the final results are given as the average and/or of the differences between the performances in the perturbed and nominal condition. The results concerning the APSU components are related to a configuration with a single mini-prism; the specific selected mini-prism is representative for the critical ones, which are those illuminated in the Medium Resolution mode.

In Fig. 4 the local frames for the ASPU optical components are shown.

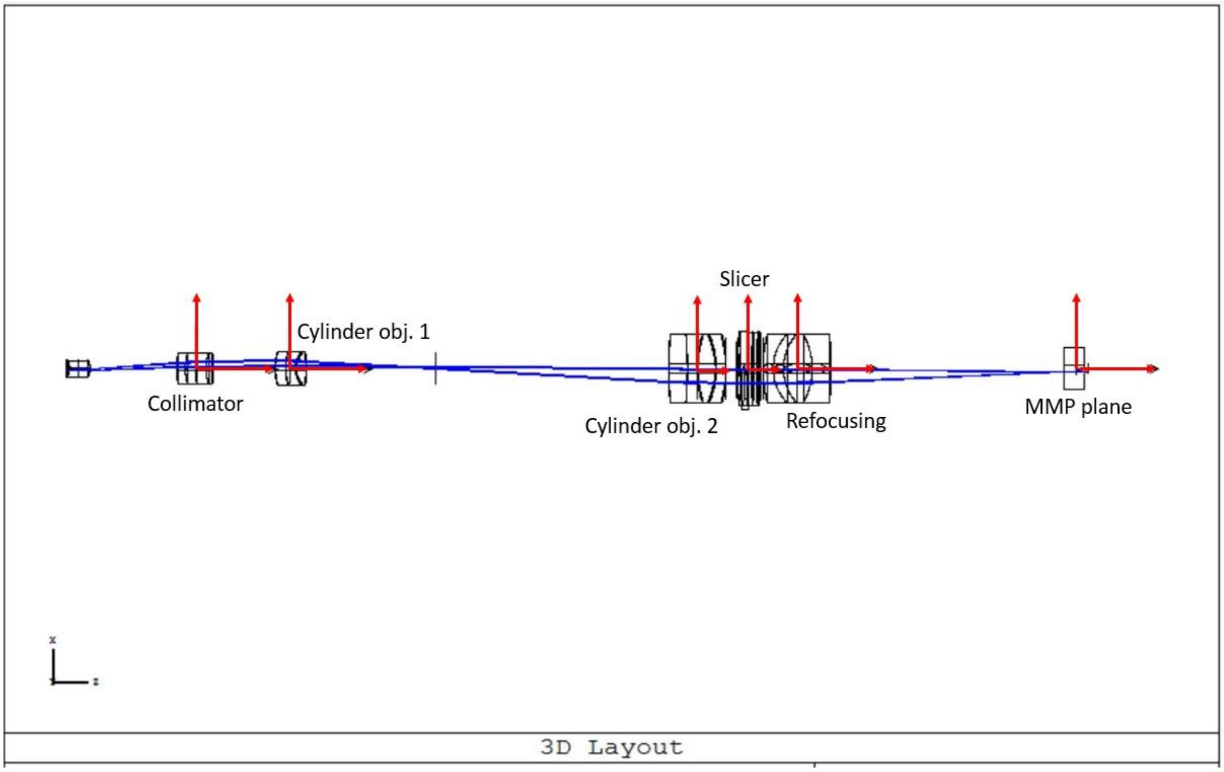

Figure 4. Local frames for the APSU optical components used for the perturbation simulation, top view. The global reference frame is shown in black in the left bottom corner.

In the following tables the figures of merit sensitivities with respect to the components decenters and tilts are presented. Image stability: the average variation of the centroids X (Table 1) and Y (Table 2) coordinates are computed.

Table 1. The centroid X coordinate variations related to the different degrees of freedom of the different APSU elements.

APSU Element	ΔX/Δx [µm/µm]	ΔX/Δy [µm/µm]	ΔX/Δz [µm/µm]	ΔX/Δα [µm/arcmin]	ΔX/Δβ [µm/arcmin]	ΔX/Δγ [µm/arcmin]
Collimator	-0.225	0.005	0.015	0.006	0.236	0
1st Cylinder	-0.248	0	-0.012	0	0.105	0.065
2nd Cylinder	0.264	0	0.012	0.017	0.247	-0.278
Prism Slicer	0.003	0	0	0.002	-0.194	0.049
Refocusing	0.249	0.001	-0.008	0.013	-0.321	0
MMP plane	0.001	0	0.009	0.003	0.289	0.001

Table 2. The centroid Y coordinate variations related to the different degrees of freedom of the different APSU elements.

APSU Element	ΔY/Δx [µm/µm]	ΔY/Δy [µm/µm]	ΔY/Δz [µm/µm]	ΔY/Δα [µm/arcmin]	ΔY/Δβ [µm/arcmin]	ΔY/Δγ [µm/arcmin]
Collimator	-0.018	0.466	-0.008	0.496	0.024	0
1st Cylinder	-0.015	0	-0.001	0.003	0.010	-0.570
2nd Cylinder	0.024	0	0.001	-0.022	0.023	0.289
Prism Slicer	0	0.002	0	0.141	-0.017	0.003
Refocusing	0.022	0.178	0.003	0.242	-0.037	0
MMP plane	0	0	-0.003	-0.203	0.024	0

Image quality: the RMS spot size average variation is computed.

Table 3. The RMS spot size variations related to the different degrees of freedom of the different APSU elements.

APSU Element	ΔRMS/Δx [μm/μm]	ΔRMS/Δy [μm/μm]	ΔRMS/Δz [μm/μm]	ΔRMS/Δα [μm/arcmin]	ΔRMS/Δβ [μm/arcmin]	ΔRMS/Δγ [μm/arcmin]
Collimator	0.003	0.004	-0.011	-0.002	0.004	0
1st Cylinder	0.005	0	0.005	0.004	-0.011	0.007
2nd Cylinder	-0.001	0	-0.005	-0.002	0.012	0.030
Prism Slicer	0	0	0	0.004	0	0
Refocusing	0	0.003	0.006	0.004	-0.018	0
MMP plane	0	0	0	-0.001	0	0.002

Efficiency: the average variation of the throughput is computed.

Table 4. The efficiency variations related to the different degrees of freedom of the different APSU elements.

APSU Element	ΔEff/Δx [%/μm]	ΔEff/Δy [%/μm]	ΔEff/Δz [%/μm]	ΔEff/Δα [%/arcmin]	ΔEff/Δβ [%/arcmin]	ΔEff/Δγ [%/arcmin]
Collimator	-0.004	-0.005	0	-0.002	0.018	0
1st Cylinder	-0.011	0	0	0.002	0.0147	0.004
2nd Cylinder	-0.001	0	0	0.002	-0.009	0.002
Prism Slicer	0.004	0	0	0.002	-0.002	-0.005
Refocusing	-0.001	0	0	0.003	0.005	0
MMP plane	0	0	0	0	0	0

The relevant general result derived from the tables is that the APSU optical components do not require tight opto-mechanical tolerances[3]; thus the alignment and integration procedures can be done considering tolerances in the order of 30-50 μm for decenters and 1-5 arcmin for tilts, which can be achieved with the current technological capabilities.

For what concern the application of the tool to a final design phase we show the re-centering of the blue echellogram on the CCD plane, by exploiting one of the useful plots that can be generated through the integration of Zemax - MATLAB software. In Figure 5 the local frame of the blue arm camera is shown; note that this local frame is placed on the camera flange, which will be the reference for the alignment and integration of this component.

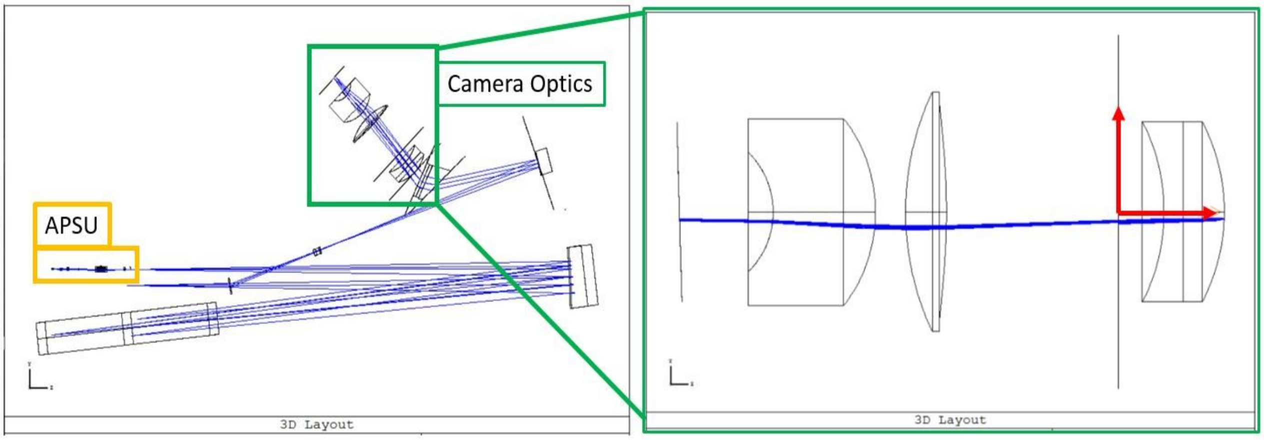

Figure 5. Local frame of the Spectrograph camera in the blue arm (right image), extracted from the global ESPRESSO 3D layout (left image). The global reference frame is shown in black at the left bottom corner of the left image, while in the right it has be temporary set to be aligned with the camera local frame only for a better picture visualization.

Before the re-centering part of the blue echellogram did not fall onto the blue CCD surface; in particular part of the diffraction order spanning from 517 nm to 523 nm (the top order in the following figure).

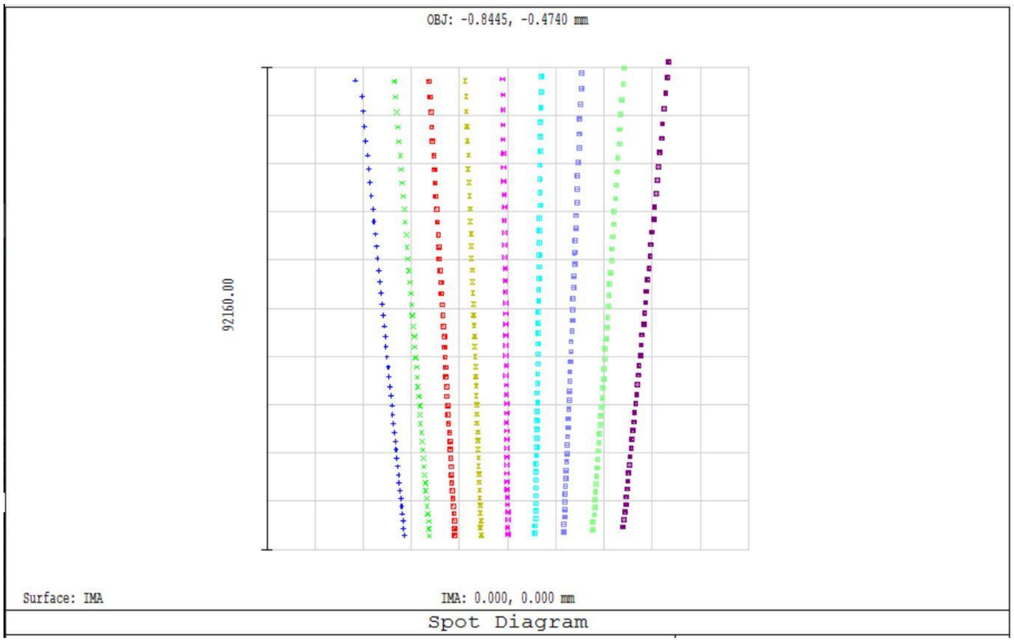

Figure 6. Echellogram of the ESPRESSO spectrograph blue arm, before re-centering.

From the sensitivity analysis plot it has been possible to find out what blue camera positioning degrees of freedom can be exploited to re-center the echellogram. This is the camera tilt around its local X-axis, whose effect is a global rigid vertical shift, with a minimal and negligible horizontal shift, as shown in Figure 7. Note that the detector will be mounted together with the camera optics and simple translation of the detector was not possible.

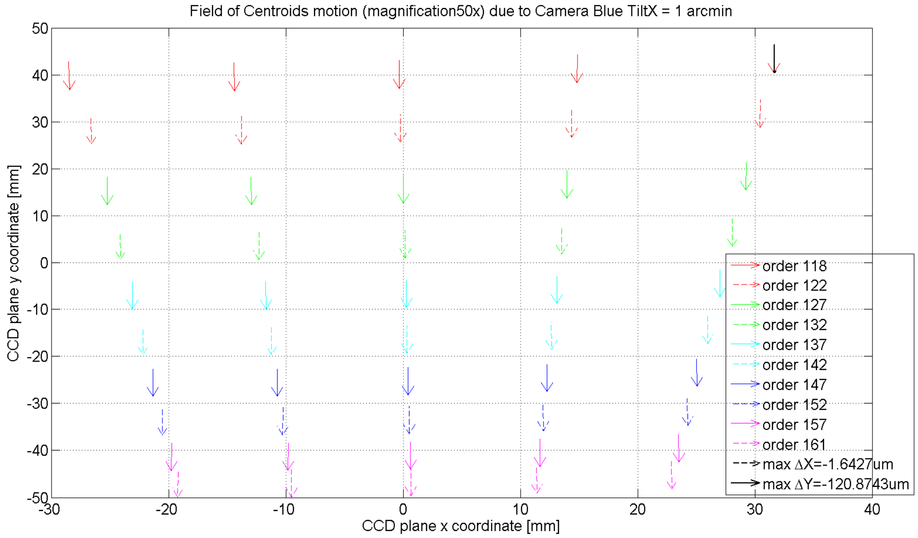

Figure 7. Effect of the Blue camera tilt around x-axis on the centroid coordinates of different echellogram wavelengths (colored per order); the effect of centroids motion has been magnified of a factor 50 in order to have a clear representation with respect to the scale size of the CCD.

Applying a 13 arcmin tilt around X-axis of the whole camera element (camera optics and detector) the echellogram is re-center, as shown in the following figure.

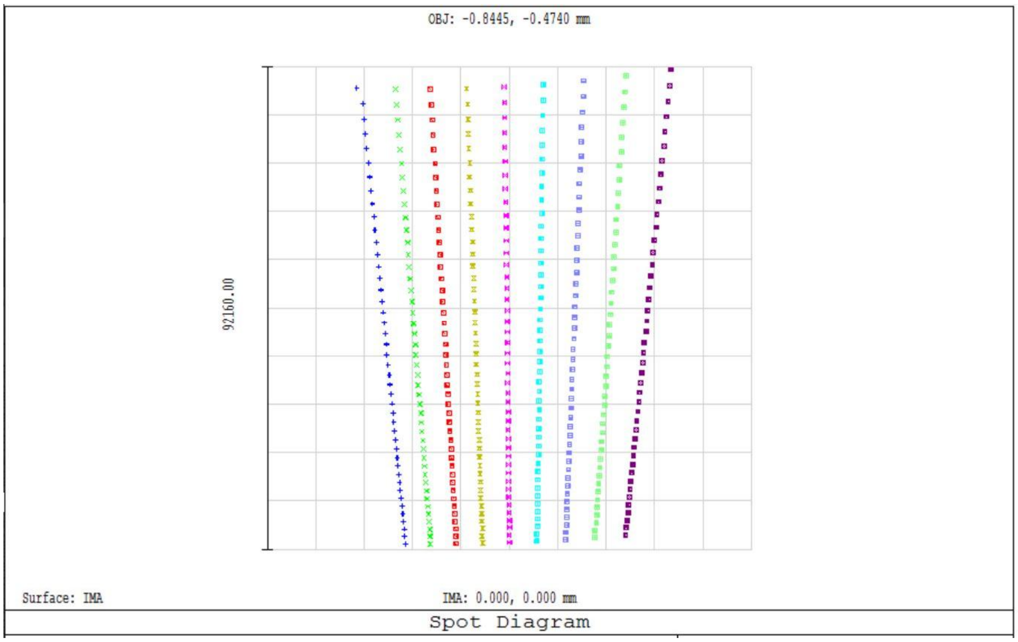

Figure 8. Echellogram of the ESPRESSO spectrograph blue arm, after re-centering.

4. CONCLUSION

In this work we presented a useful and efficient tool developed to perform opto-mechanical tolerance and sensitivity analysis, simulating mechanical perturbation of each single optical element, both for the preliminary and final design phases of a spectrograph. We have described the MATLAB -Zemax architecture of the tool, specifying how to prepare the optical file in the Zemax ray-tracing software (in terms of both Lens Data Editor coordinate break surfaces to receive inputs from MATLAB and Merit Function Editor for the specific performance evaluation), how to set input data in the MATLAB codes as well as to acquire figures of merit computation from the Zemax MFE. We have described how the data are stored and organized in the exploited MATLAB Structures and the analysis performed on the figures of merit data, which for the spectrograph are image stability, image quality and efficiency. In addition we presented the detailed results concerning its application to the sensitivity analysis of the ESPRESSO spectrograph, specifically for the opto-mechanical alignment of the Anamorphic Pupil Slicer Unit and for a final design refinement of the orientation of the blue arm camera. In the first case the tool results have shown that the alignment and integration procedures can be done considering tolerances in the order of 30-50 μm for decenters and 1-5 arcmin for tilts, which can be achieved with the current technological capabilities; in the second case the tool has been used to re-center the blue arm echellogram.

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