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ELT-HIRES the high resolution spectrograph for the ELT: application of E2E + ETC for instrument characterisation, from efficiency to accuracy in radial velocity measurements

M. Genoni[a], M. Landoni[a], P. Huke[b], N. Sanna[c], E. Mason[d], A. Marconi[c], L. Origlia[e], M. Riva[a], and P. Di Marcantonio[d]

[a]Istituto Nazionale di Astrofisica Osservatorio Astronomico di Brera-Merate, via E. Bianchi 46, I-23807 Merate (LC), Italy
[b]Georg-August Universitat Gottingen, Institut fur Astrophysik, Friedrich-Hund-Platz 1,Gottingen Germany
[c]Istituto Nazionale di Astrofisica Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Firenze, Italy
[d]Istituto Nazionale di Astrofisica Osservatorio Astronomico di Trieste, via G.B Tiepolo 11, I-34131 Trieste
[e]Istituto Nazionale di Astrofisica Osservatorio Astronomico di Bologna, via Gobetti 93 Bologna - IT

ABSTRACT

We present an application of the HIRES End-to-End (E2E) simulator and HIRES Exposure Time Calculator (ETC) to derive a more detailed behavior of the spectrograph efficiency by including physical modeling of diffraction at the echelle grating and the cross-disperser. The result will be used with the Spectral Energy Distributions of calibration lights for wavelength solutions and flat fielding to quantitatively characterize the spectrograph in terms of achieved accuracy. By showing the contribution of photon noise, detector noise and cross talk between adjacent fibers we discuss methods that could be used to determine the overall performance of the instrument, in term of the capability of photon collection as well as especially on the achieved precision on wavelength calibration that translates directly in radial velocity accuracy of the scientific light.

Keywords: High Resolution Spectroscopy, calibration units, Fabry-Perot, End to End

1. INTRODUCTION

1.1 The European ELT - A brief introduction

The first 40m-class telescope, the extremely-large telescope, and its instruments is currently under development with a tremendous amount of effort which is done to enable key science topics in astrophysics. The telescopes aims at superior image quality over a large bandwidth[1] . The wavelength range allows for science cases using high-resolution and high-precision spectroscopy for stars and their companions, cosmology and physics of compact objects and AGN (see e.g.[2,3]).
HIRES is the high resolution spectrograph for the ELT and it is designed for a number of science cases, as described in.[4] Each of them, has proper top-level requirements (TLR) in terms of resolutions, spectral bandwidth and precision/accuracy on the wavelength calibration. For sake of recap, we enumerate here some TLR for the main scientific cases:[4]

1. **Exoplanet atmospheres in transmission**
   This science case requires:

Further author information: (Send correspondence to M. Genoni or M. Landoni)
M. Genoni: E-mail: matteo.genoni@brera.inaf.it
M. Landoni: E-mail: marco.landoni@brera.inaf.it

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- Resolving power > 100.000
- Spectral bandwidth: $0.4 - 1.8\mu m$
- High spectral fidelity* $> 0.1\%$
- Wavelength-calibration accuracy $< 1m/s$.

2. **Variation of the fundamental constants**
This science case requires on top of the requirements of science case 1:
   - Spectral bandwidth: $0.37 - 0.65\mu m$

3. **Exo-planet atmospheres in reflection**
Additional requirements:
   - Single conjugate adaptive optics (SCAO)
   - Integral Field Unit (IFU)

4. **Sandage-test**
Additional requirements:
   - Calibration accuracy $> 2cm/s$*
   *The accuracy of the calibration spectrum has to be known with a precision better than 2 cm/s on the level of the calibration unit. The precision for a set of individual spectral measurements can be on the order of $1m/s$.

The challenging requirements derived from the science cases make necessary to understand the instrumental design and its interaction with the calibration unit to a unprecedented precision. To reach this level, we developed an end-to-end simulator (E2E),[5,6] which is growing parallel to the instrument itself. It will not only help to predict the behavior of the instrument, but also to circumvent difficulties which may not be detected due to the complexity of the system.
In this publication, we demonstrate an application of this model to assess the level of SNR and accuracy obtainable with the current baseline for the HIRES spectrograph. We will show how to use the E2E to detect the contamination level due to cross talk (X Talk) between fibers and the total noise budget coming from various sources (in some cases, however, the crosstalk is not necessarily a "noise" and it may even contribute to a better rv-precision). The paper is organized as follow: we briefly recap the definition of precision, accuracy and stability from the point of view of calibration sources. In section 2 we describe our method used to derive the required quantities and we show our results and discussions in Section 3 and 4.

1.2 Precision and accuracy

In Figure 1 is visualized what is meant with high / low accuracy and precision. In mathematical terms, the **precision** is the variance of a set of measurements while **accuracy** is the distance from the expectation value (true value). One could think about these terms as the 2nd moment of probability distribution for the former and as the 1st moment for the latter.

Precision can be measured through subsequent measurements while accuracy is more difficult to achieve since the true value is usually not known a priori. According to the possible measurement process in high resolution spectroscopy is may be useful to define a set of precisions:

- **Single spectral line precisions:** The single spectral line precision is the precision with which we can measure the position of a single line in a spectrum. To this precision is contributing the signal to noise level, the transfer of the calibration frame onto the spectrum, the model used, how well the line can be fitted and also amplitude noise.

*With spectral fidelity the precision in intensity measurements is very high over the full spectral bandwidth, this varies with the mag of the respective target.

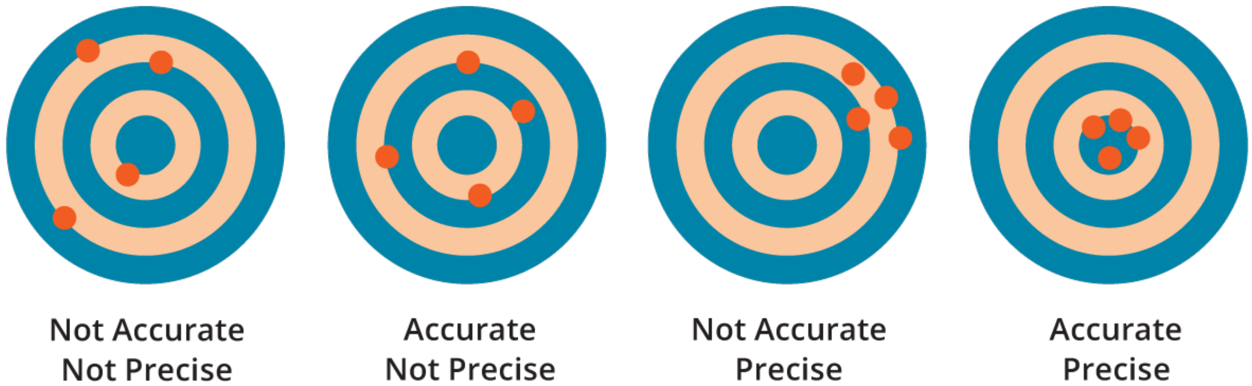


Figure 1. Pictorial view of precision and accuracy (low and high). Courtesy from https://www.filamentlearning.com/backyard-engineers-lesson-3-accuracy-and-precision

- **Single spectrum (multi-line) precision:** This is the precision of a full spectrum in Radial Velocity (RV) space measured with respect to a reference. The spectrum consists of a number of a lines N and their relative wavelength solution where each line has its single spectral line precision. For this the precision of the lines of the reference frame is crucial and the final single spectrum precision is given by the single spectral line precisions divided by the $\sqrt{N}$.
- **Single set (multi-spectrum) precision:** A set of measurements is defined as a number of measurements M taken subsequently to achieve a high precision in RV-space If either the calibration spectrum is stable or it is referenced to a frequency anchor the final single set precision is given by the single spectrum precision divided by $\sqrt{M}$.
- **Multi-set precision:** A multi-set can be defined as a set of sets of measurements K at different epochs to measure the behavior of the target in RV-space. the precision of a multi-set of measurements can be derived from the number of sets of measurements and the precision of the reference frame.

Concerning accuracy, this can be defined for the position of a single line or a spectrum or a set of measurements. It is important to recap that spectrograph for astrophysical applications do not have an own wavelength solution other than the one imposed by the calibration with proper sources. Thus requirements to the accuracy always applies to the calibration units.

Methods needs to be developed to asses the achievable accuracy and precision with calibration units for spectrographs which aim to measure tiny RV variations in different science cases. This can only be done by adopting proper simulations coupled with End-to-End facilities.[5,6]

2. METHODS.

We used our End-to-end simulator in order to assess two main quantities required:

- **Efficiency of the spectrograph:** For the current baseline, HIRES is considered to posses an average efficiency of ~ 0.13 (see and also http://www.arcetri.astro.it/hires/). We started from this value and we derived a more comprehensive efficiency curve by fully describing the the echelle+XD physical model aiming to obtain, for each order, the usual **blaze function**. These curves consider only the efficiencies of the spectrograph itself, fiber link and front end. Other efficiencies from telescope, atmosphere, etc. are not considered since we refer only to calibration unit for this exercise.
- **Fiber cross talk:** Adjacent fibers could *spill* some light between each other, causing the effect to decrease the overall signal-to-noise ratio of the calibration spectrum extracted. The spilling is mostly pronounced

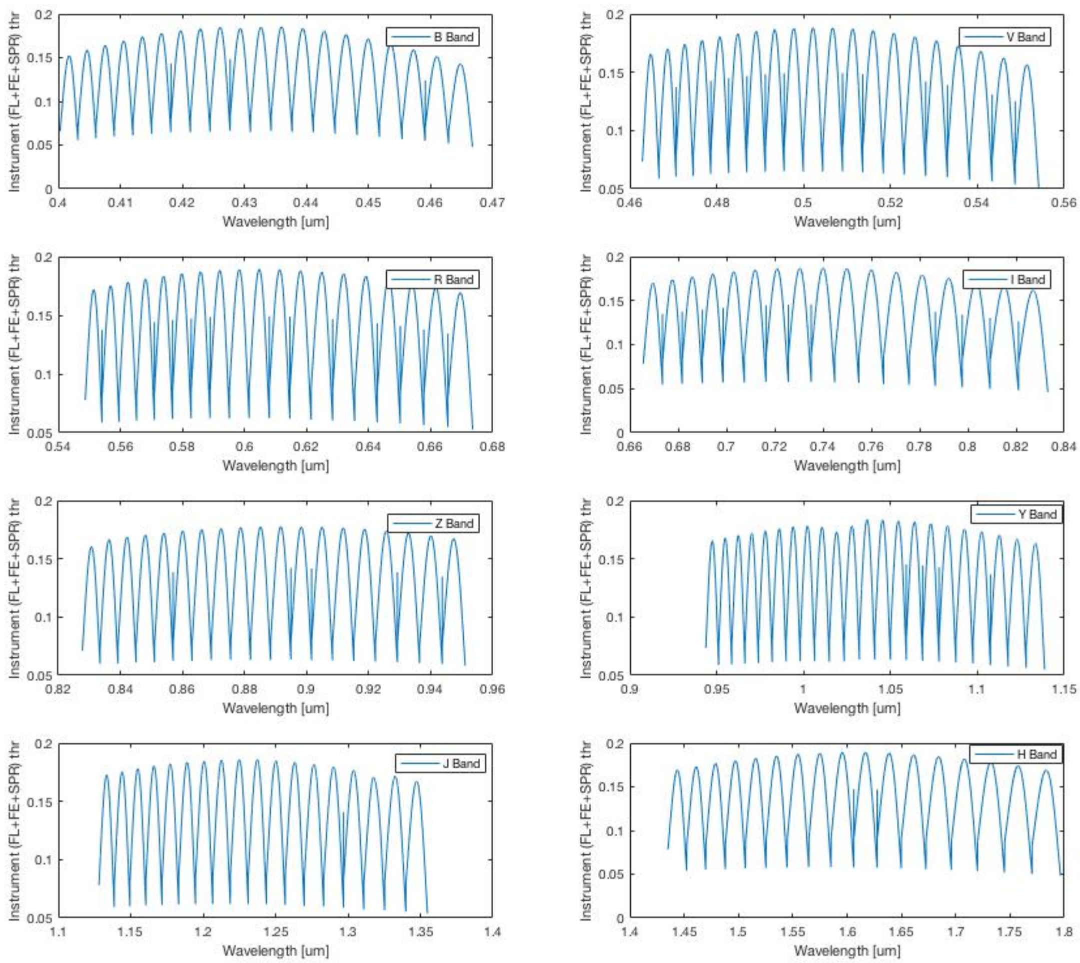
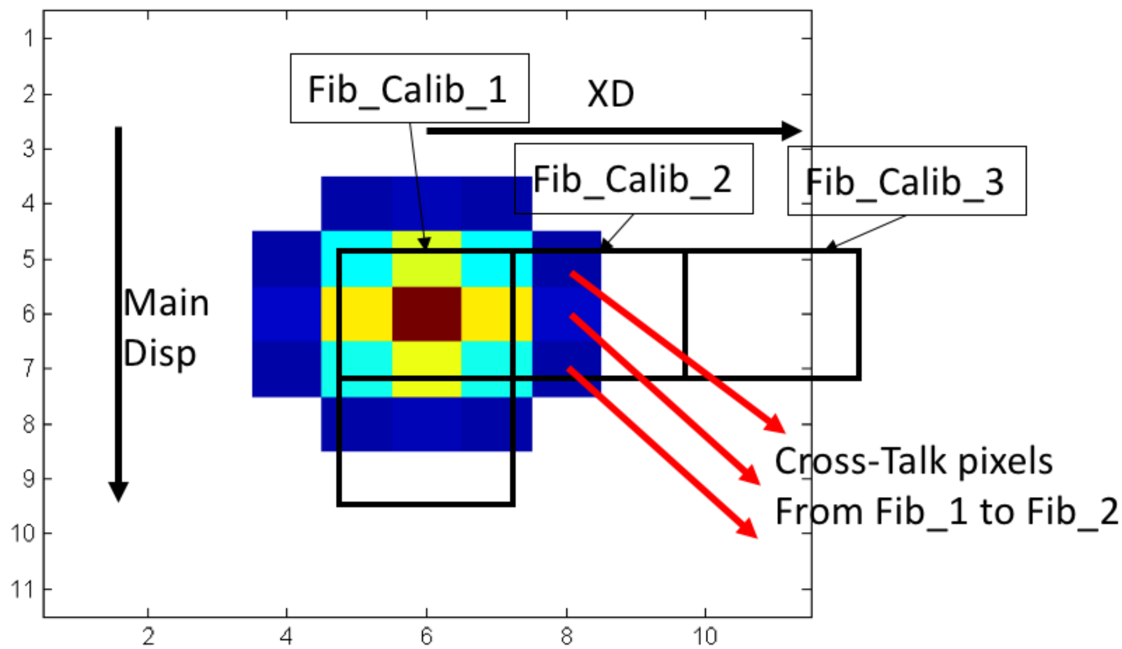


Figure 2. Preliminary spectrograph efficiency including optics and diffraction grating plus cross disperser (XD) efficiency for each band. We assume a constant efficiency for spectrograph optics and fiber while we use the full End-to-End model to assess order efficiency including echelle+XD. Each "bump" is a diffraction order in the relative band (see legend in each panel).



Cross talk %	Fib 1	Fib 2	Fib 3
Fib 1	-	28000 ppm	< 1ppm
Fib 2	28000 ppm	-	28000 ppm
Fib 3	< 1ppm	28000 ppm	-

Figure 3. Fiber cross talk estimation using the End-to-end full image simulator. The black boxes model the position of the calibration fibers arranged on the focal plane (horizontal axis, cross dispersion) in units of px. The table below shows the amount of cross talk between fibers (expressed in ppm) with respect to the injected signal. For sake of simplicity, only geometrical PSF aberrations has been considered.

on the detector since the diameter of the image of a single fiber is a non-integer pixel number and images of nearby fibers will overlap on some pixels (due to geometrical effects and PSFs from light diffraction). It is important to assess the amount of cross talk in order to derive a precise SNR estimation of the final calibration spectrum. We used the End-to-end in order to perform a full simulation (including par-axial model evaluation, image rendering with proper PSF, and pixelisation) of adjacent fibers and evaluating (in pp) the amount of cross talk.

We report in Figure 2 the efficiency computed as explained above for each band of HIRES while in Figure 3 we draw results obtained for the fibers cross talk as seen through full end-to-end simulation. In particular, in Figure 3 we show in the upper panel a small portion of the detector with simulation of a single wavelength from 1 fiber and report with black rectangle the position of the other fibers in the focal plane that could cause cross talk. We evaluate the portion of the signal that overlap in the pixels shared by different fibers. The table below reports show the **cross talk matrix** in ppm that we use for our purposes.

3. RESULTS

Starting from the quantities derived before, we aim to evaluate the signal-to-noise ratio of calibration spectrum by adopting these formulas:

$$\frac{S}{N} = \frac{N_\gamma}{\sqrt{N_\gamma + n_{px} \times D_c \times t + n_{px} \times RON^2 + N_\gamma^{XT}}} \tag{1}$$

where N_γ is the number of photon collected by a single fiber from the calibration source, n_{px} is the number of pixels where the image of single fiber for a single resolution element is sampled (usually 3-4 pixels), RON is the detector noise (assumed for our purpose to be around 3 e^- and N_γ^{XT} is the number of photons from cross talk between adjacent fibers (assuming uniform illumination and ppm level as reported in Figure 3).

So, the total signal-to-noise ratio for a set of full-illuminated fibers (as in the case of pseudo slits) is:

$$\frac{S}{N} = \frac{N_\gamma \times \sqrt{N_f}}{\sqrt{N_\gamma + n_{px} \times D_c \times t + n_{px} \times RON^2 + N_\gamma^{XT}}} \tag{2}$$

where N_f is the number of homogeneously illuminated fibers.
We used the end-to-end model to recover the flux in each pixels coming from a calibration sources that, at the level of the front end fiber injection, possess a spectral radiance of about 2 mW m^{-2} and a total exposure time of ~ 60 s.
We report in Figure 4 the obtained spectrum from the End-to-end. In the first panel, we report in red the Fabry-Perot calibration spectrum injected by the calibration unit while in blue diamonds the flux recorded by pixels (summing along the spatial direction). In the lower panel we report instead all the noises coming from instrument and light from cross talk. We show in Figure 5 the overall SNR and the extracted spectrum of FP calibration as seen from the full End-to-end simulation chain. We made this exercise for a small portion of the spectrum of the HIRES I band although this approach could be extended infinitely to the whole bands and arms of the instrument. As one could easily see, the main sources of noises come from the shot noise itself and cross talk of adjacent fibers. For what concerns the noises of detector (RON and dark current) they are negligible for these level of illuminations. We do not considered any gain applied to the detector at the moment.

4. DISCUSSION AND CONCLUSIONS

From other measurements we know that variations in the amplitude of spectral lines are influencing their single line precision. The systematic variations in the efficiency will cause spectral lines to move slightly and it is very important to know this effect in advance, when we want to fulfill the challenging requirements of HIRES. Therefore we developed the E2E-simulation. The living environment of this simulation increase in complexity as more physical effects are taken into account, but in the same way it also becomes more and more precise in its

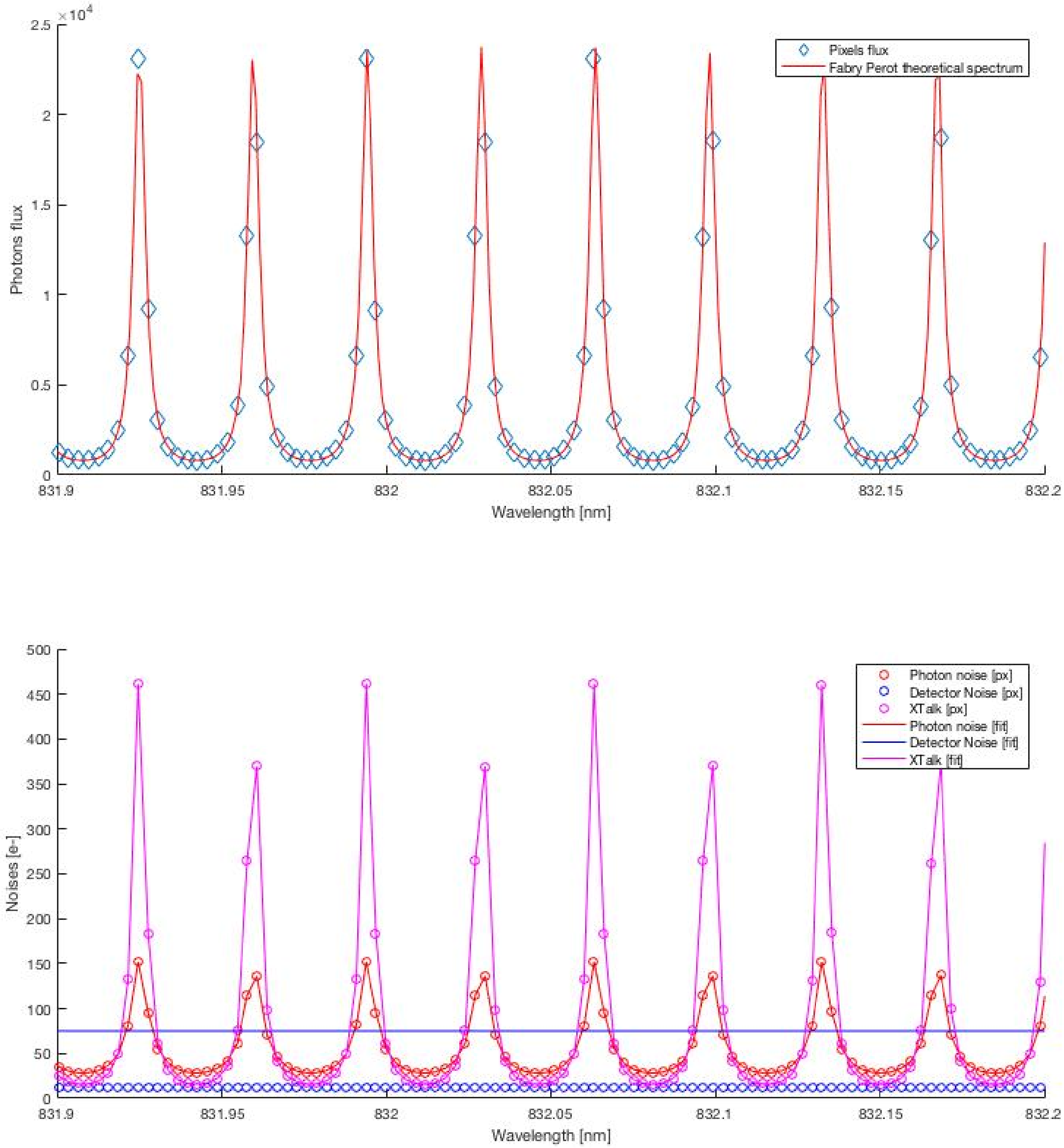


Figure 4. FP Spectrum as seen through HIRES I-Band in the region ∼ 831-832 nm. Upper panel: (red) Theoretical FP spectrum as output from Calibration Unit . (blue diamonds): Photon flux in each pixel (3 px ∼ 1 Resolution Element). Lower panel: Noise plot and overall SNR ratio (blue): detector noise, (red) photon noise, (magenta) Fibers X-Talk.

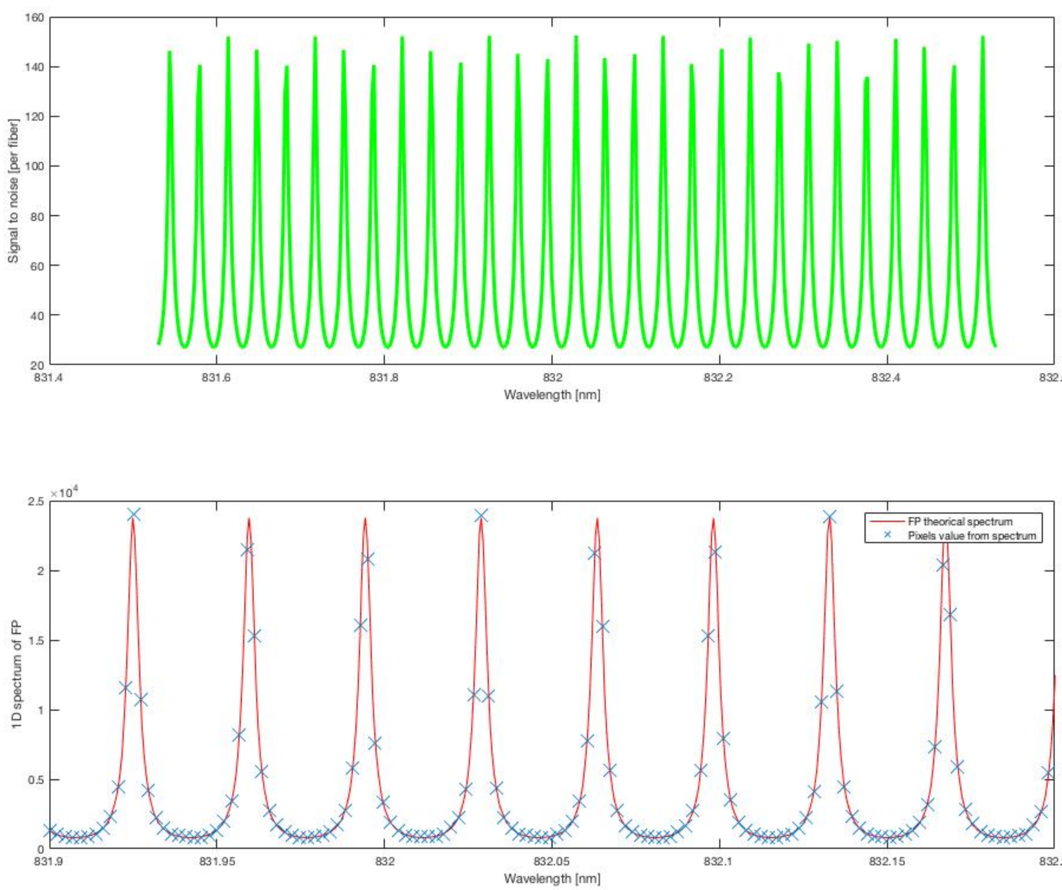


Figure 5. Upper panel: signal-to-noise ratio obtained in a single fiber as calculated from end-to-end simulation including all the noises. Lower panel: Theoretical FP spectrum (red) and the pixel flux values (1d spectrum) as obtained from End-to-end, including noises and discretization from detector's pixels (blue crosses, error bar within the signal).

predictions. Despite the variations in efficiency, we already learned how much the different (up to now included) noise sources contribute to the SNR of a single spectral line and thus deteriorates its precision. From the single spectral line precision the multi-line precision or more common the precision of the spectrum in RV-space can be derived. To do this several a calibration procedure has to be derived, which includes the single line precision as we determine it from the E2E-simulation.

Further work on the E2E-simulation will aim to integrate modal noise of the fibers and slit-errors. The derivation of the different types of precision, their influence and how they apply for the science cases of HIRES will be shown in a future publication. This will be also integrated into a package for data analyses for E2E frames as well.

REFERENCES

[1] de Zeeuw, T., Tamai, R., and Liske, J., "Constructing the E-ELT," *The Messenger* **158**, 3–6 (Dec. 2014).

[2] Landoni, M., Falomo, R., Treves, A., Scarpa, R., and Reverte Payá, D., "What Is the Redshift of the Gamma-ray BL Lac Source S4 0954+65?," *AJ* **150**, 181 (Dec. 2015).

[3] Paiano, S., Landoni, M., Falomo, R., Treves, A., Scarpa, R., and Righi, C., "On the Redshift of TeV BL Lac Objects," *ApJ* **837**, 144 (Mar. 2017).

[4] Maiolino, R., Haehnelt, M., Murphy, M. T., Queloz, D., Origlia, L., Alcala, J., Alibert, Y., Amado, P. J., Allende Prieto, C., Ammler-von Eiff, M., Asplund, M., Barstow, M., Becker, G., Bonfils, X., Bouchy, F., Bragaglia, A., Burleigh, M. R., Chiavassa, A., Cimatti, D. A., Cirasuolo, M., Cristiani, S., D'Odorico, V., Dravins, D., Emsellem, E., Farihi, J., Figueira, P., Fynbo, J., Gansicke, B. T., Gillon, M., Gustafsson, B., Hill, V., Israelyan, G., Korn, A., Larsen, S., De Laverny, P., Liske, J., Lovis, C., Marconi, A., Martins, C., Molaro, P., Nisini, B., Oliva, E., Petitjean, P., Pettini, M., Recio Blanco, A., Rebolo, R., Reiners, A., Rodriguez-Lopez, C., Ryde, N., Santos, N. C., Savaglio, S., Snellen, I., Strassmeier, K., Tanvir, N., Testi, L., Tolstoy, E., Triaud, A., Vanzi, L., Viel, M., and Volonteri, M., "A Community Science Case for E-ELT HIRES," *ArXiv e-prints* , arXiv:1310.3163 (Oct. 2013).

[5] Genoni, M., Riva, M., Landoni, M., and Pariani, G., "End-to-end modeling: a new modular and flexible approach," in [*Modeling, Systems Engineering, and Project Management for Astronomy VI*], **9911**, 99112G (Aug. 2016).

[6] Genoni, M., Landoni, M., Riva, M., Pariani, G., Mason, E., Di Marcantonio, P., Disseau, K., Di Varano, I., Gonzalez, O., Huke, P., Korhonen, H., and Li Causi, G., "The end-to-end simulator for the E-ELT HIRES high resolution spectrograph," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], **10329**, 103290Z (June 2017).