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# Validating data reduction algorithms through advanced instrument simulation - the case of HARMONI

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**Abstract.** In this paper, we briefly present the ELT/HARMONI instrument, its pipeline and its instrument numerical simulator. We then explain how we use the simulator to prototype and validate robust pipeline algorithms for each of the 44 scale/band combinations of the instrument, long before it is built. We give examples of such algorithms and for each of them we detail the gain brought by the simulator, and how it has been used to provide feedback on the instrument design.

## 1. The HARMONI Instrument

HARMONI (Thatte & al. 2016) is the first light visible and near-IR integral field spectrograph for the Extremely Large Telescope (ELT). With four spatial cases ( $60 \times 30$ ,  $20 \times 20$ ,  $10 \times 10$  and  $4 \times 4$  mas<sup>2</sup>) and 3 possible resolving powers ( $\sim 3,200$ ,  $\sim 7,000$ , and  $\sim 18,000$ ) covering the  $0.45 \mu\text{m}$  to  $2.45 \mu\text{m}$  spectral range, it will collect at once spectra of about 31,000 spatial positions, arranged in a 152x204 spaxels format. It can operate both in adaptive optics - SCAO (including High Contrast) and LTAO - or in seeing-limited mode.

HARMONI is conceived as a workhorse instrument. Combined with the enormous 39-meter main mirror of the ELT its versatility will allow the community to address many of the ELT science cases, including the exploration of galaxies in the early Universe, the study of the constituents of the local Universe, and the characterization of exoplanets in great detail. The international consortium developing HARMONI is led by the University of Oxford and the UK-ATC in Edinburgh. The project is preparing for its Final Design Reviews (FDR).

## 2. The HARMONI pipeline

The HARMONI data reduction pipeline (Piqueras & al. 2016) is deliverable as part of the instrument. It handles all the possible settings of the instrument, and most notably each of the 44 scale/band combinations. It takes as input raw exposures either belonging from the four CCD for the visible band or from the eight H4RG detectors for the near-infrared bands. It outputs a 3D data cube, with the associated error cube and quality control (QC) parameters. At the FDR stage, prototypes for HARMONI pipeline

algorithm identified as critical at earlier stages and their associated test data shall be delivered.

### 3. The HARMONI Instrument Numerical Model

In parallel to the HARMONI pipeline, we are developing an Instrument Numerical Model (HINM). This tool written in Python 3 simulates the HARMONI instrument from the optical point of view, reproducing the light path throughout the atmosphere, the telescope and the instrument up to the detectors. It simulates the atmosphere and the adaptive optics, optical aberrations, diffraction, throughput and the detectors effects. It either takes as input a simulated astrophysical scene (data-cube) or the calibration unit settings to simulate calibration exposures. It outputs simulated raw FITS files similar to those provided by the instrument when final. The HINM is an essential tool to procure high-quality mock raw data for designing and testing the data reduction pipeline. Its development schedule is therefore tightly coupled with the pipeline one in order to provide it with simulated data at anytime.

The HARMONI consortium also develops a complementary end-to-end simulator called HSIM (Zieleniewski et al. 2019) which produces mock data-cubes by replacing both the instrument and the data reduction pipeline in a single simulation step. However it does not create the synthetic detector readouts needed by the pipeline.

### 4. Using the HINM to develop the pipeline

HARMONI splits the input field of view into 8 subfields, which are in turn sliced into 38 slitlets dispersed in the spectrograph. The spatial sampling is done optically by the slicer in one direction and by the detector in the other direction leading to a different image quality in both directions.

All of these required to develop an advanced simulator able to create accurate enough mock data to test and prototype pipeline algorithms. An instrument simulator is also more versatile than a real instrument. It provides ways to access or approximate the ground truth and allows pipeline developers to quantify the accuracy of an algorithm. Furthermore, by disabling some effects (for instance the image quality of some subsystems or the detector noise) or by controlling their values in the simulation (for instance misaligned slice or bad pixels on the detectors), it allows pipeline developers to quantify the impact of each effect in the accuracy of an algorithm.

#### 4.1. Wavelength calibration

The wavelength calibration computes the wavelength-pixel solution from exposures obtained with arc lamps illuminating uniformly the focal plane. The solution shall be more accurate than 0.05 pixel RMS for the 11 spectral bands to provide a final accuracy of 0.2 pixel RMS when including all the opto-mechanical parts of HARMONI.

For a given lamp the number of emission lines, but also their location on the detector, depend on the spectral band, and especially on the spectral resolution. A given line is not necessary visible on all slitlets due to the spectrograph distortion and the slit-stagger at the slicer level. For higher spectral resolutions this significantly reduces the number of available lines to fit the wavelength solution, or increases the range where the solution is extrapolated. In both cases the accuracy is poorer.

The HINM has been used to simulate arc lamp exposures for all spectral bands and also to provide the ground truth. From these we determined the reachable accuracy for each band and concluded that for higher spectral resolutions the lamps chosen earlier in the project do not fit the requirements. Fortunately, the HINM is of great help to investigate other lamps.

#### 4.2. Flat-fielding strategy

The flat-field calibration is computed on exposures obtained using a continuum lamp illuminating uniformly the focal plane. The designed recipe of the HARMONI pipeline outputs both a pixel-to-pixel response and an instrumental response. The pixel-to-pixel response corresponds to the detector response and is assumed to be stable with time while the instrumental response can be shifted to correct for possible temperature drifts or opto-mechanical positioning errors.

The HINM enables accurate simulations used to test various algorithms to separate both responses. For instance it can simulate a dust spot on the slicer or a bad column on the detector, both resulting in a similar effect at a first glance (see Figure 1).

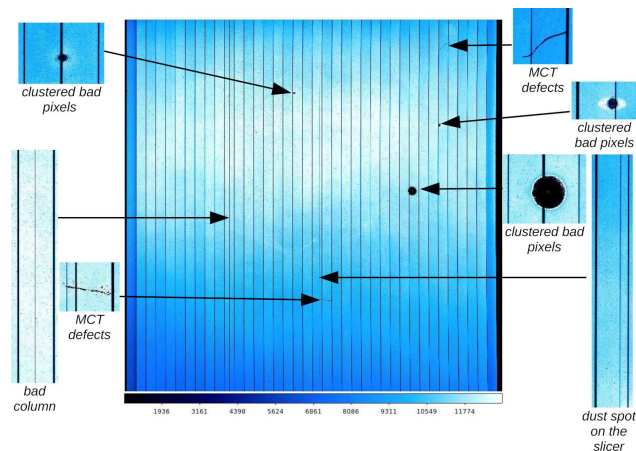


Figure 1. Simulated continuum lamp exposure for one detector in H band (z-scale).

#### 4.3. Geometrical calibration

The geometrical calibration computes the transformation between coordinates in the instrument object focal plane and in the detector plane allowing to estimate the relative location in the field-of-view of each detector pixel. It corrects for magnification, distortion, misalignment and rotation effects. For HARMONI this transformation shall be known with an accuracy better than 0.05 pixel.

The geometrical calibration is specific to each scale/band combination. To keep the calibration time acceptable, we have developed an advanced algorithm using only two exposures, one acquired using a trace mask and one using a multi-pinholes mask (Piqueras & al. 2020). The HINM was used to generate many sets of these exposures including alternatively small slices misalignment or various mask angles. From them, we learnt that both exposures should be acquired during the same acquisition sequence and that detector effects have almost no impact on the final accuracy. These also allowed us to increase the accuracy by tweaking the masks.

#### 4.4. Possible zero-point shift

The calibration exposures are taken the day following the science exposures. Due to possible temperature drifts or opto-mechanical positioning errors between acquisition and calibration there might be a non-neglectable zero-point shift of wavelength solution, the geometrical calibration or the instrumental response part of the flat-field. We plan to measure this zero-point shift in both spatial and spectral direction using the sky emission lines. The HINM and the ESO SkyCalc tool allowed us to simulate raw calibration and science exposures with various sky conditions. From these we developed and tested an algorithm based on phase-only correlation that can measure the induced zero-point shift with the required accuracy for most of the science cases.

#### 4.5. Future usage

Extensively using simulated exposures for the designing the pipeline proved to be a good way to debug and improve the HINM. We will therefore continue use the it way beyond the FDR to produce synthetic detector readouts for the pipeline development, and for early validation of requirement specifications before the on-sky commissioning.

It will notably be used to develop an astrometric calibration strategy. Given the size of the HARMONI field of view it is known to be a challenging task for the smaller scales and will likely require bootstrapping the calibration solution from one scale to another. The sky subtraction is another challenging development given that the target objects observed with HARMONI are expected to be very faint. We will use the HINM coupled with the ESO SkyCalc tool to develop advanced sky subtraction techniques able to derive the sky background information from parts of the science field-of-view (typically the periphery).

### 5. Conclusion

The new generation of super-telescopes and associated instrumentation projects enter such ambitious scales and complexity of design that advanced data reduction pipelines are now essential to meet the increasing performance requirements of these instruments. This brings development of sophisticated instrument simulators able to provide synthetic detector readouts long before the instrument is built. Such simulators can also help finding the best compromise on performances or science preparation.

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