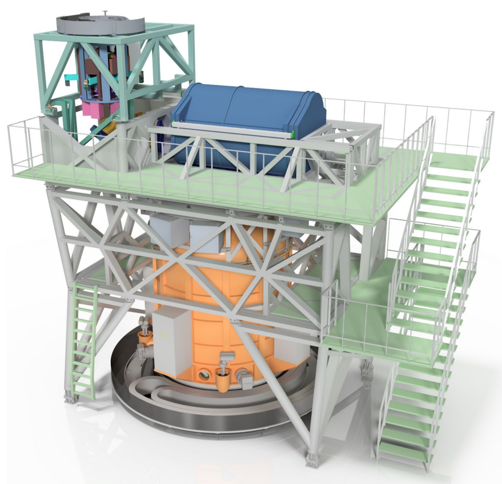


HARMONI at ELT: a virtual instrument to get ready for the real one

A. Jarno, L. Piqueras, J. Richard, A. Pécontal, on behalf of the HARMONI consortium
Centre de Recherche Astrophysique de Lyon

ELT HARMONI

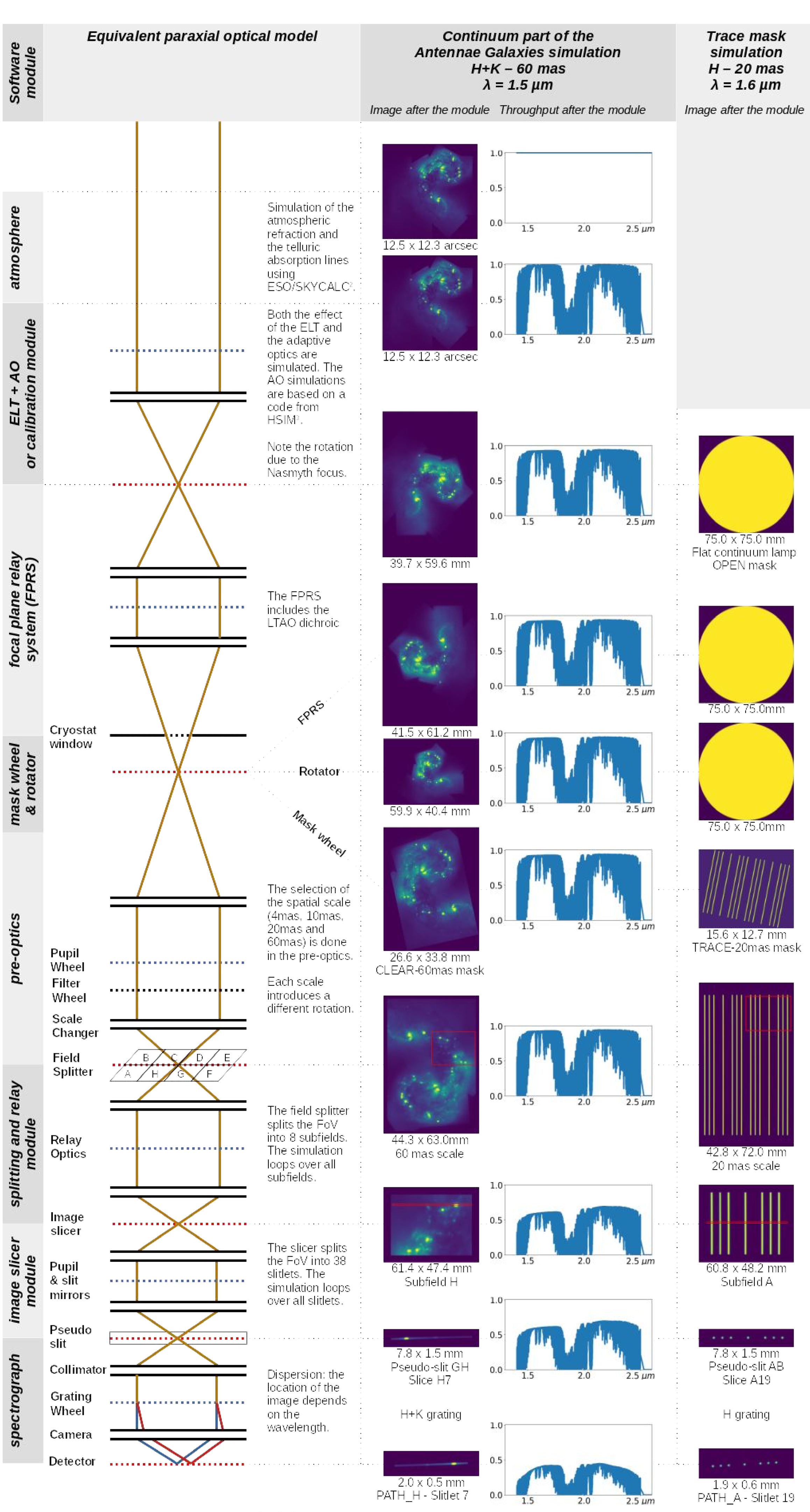
HARMONI[1] is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 470 nm to 2450 nm with resolving powers from 3300 to 18000 using 11 different gratings. It provides 4 different spatial sampling from 60 mas to 4 mas. The field-of-view is first sliced into 8 subfields (labeled A through H) by the field splitter. Each subfield is further divided into 38 slitlets by the image slicer. HARMONI can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO.

THE DIGITAL TWIN OF HARMONI

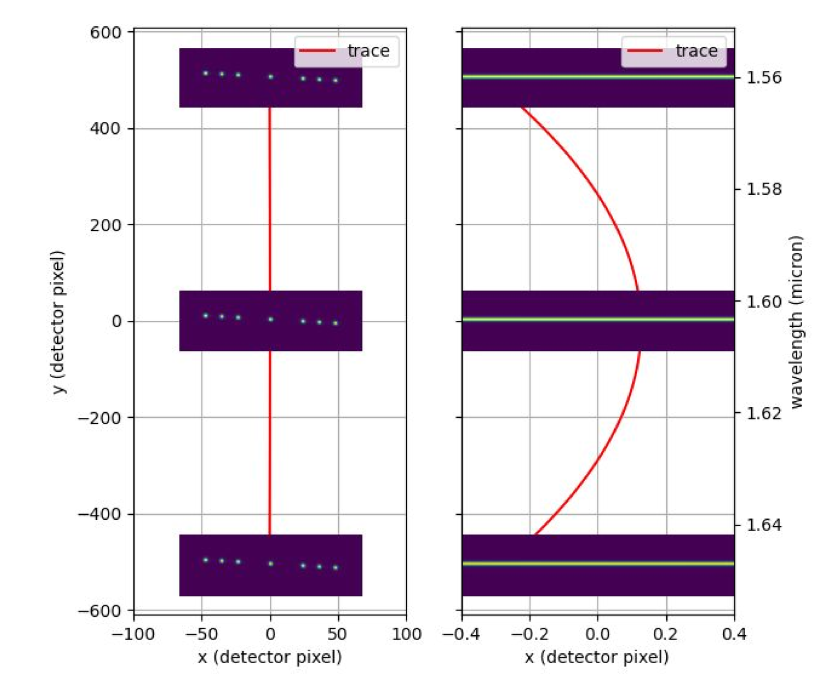
Given the complexity of the HARMONI instrument, it was chosen to develop a digital twin from the optical point of view. This Python based software mimics the light path throughout the atmosphere, the telescope and the instrument, and generates synthetic detector read-outs for both calibration and science exposures.

To simulate an exposure, the software ingests as input a configuration file describing the instrument configuration and the environmental conditions, plus either the configuration of the calibration module or a user-provided astrophysical scene (data-cube). These inputs are translated into a product of a vector (flux spectrum or transmission curve as a function of wavelength) and a list of monochromatic images ordered by wavelength. This product is expressed in W/m^3. The chosen number of images depends on the properties of the input data as for instance the spectral variation being smooth or sharp.

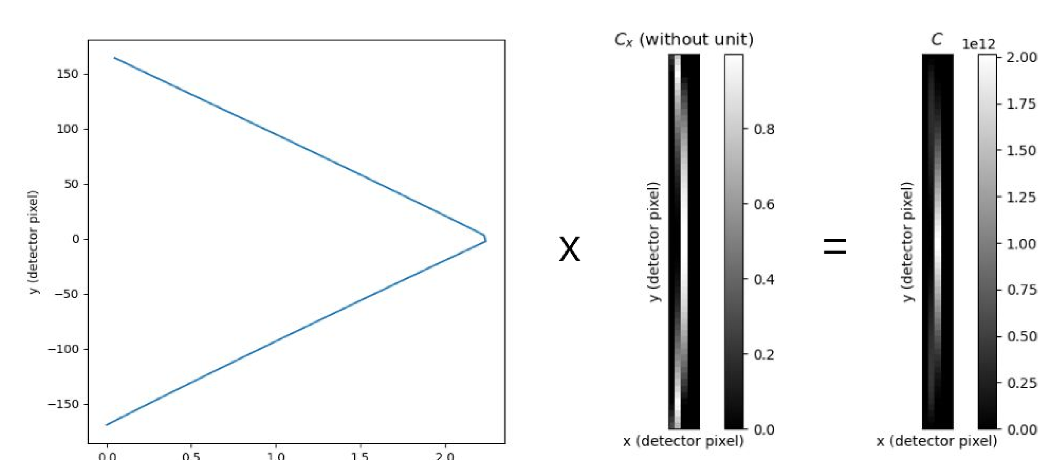
The list of images and the vector are then propagated through the chain of instrument modules representing the instrument, up to the detectors, and for each optical path when optics split the field of view. The figure below illustrates this process for a given slice for both a calibration image and a science image. At each step the output image is computed from the input image, taking into account the point spread function (PSF) and the geometric transformation introduced by the optics of the instrument module. In parallel the output vector is derived from the input vector, considering the throughput of the instrument module. In both cases resampling may be necessary to model the effects with sufficient precision.



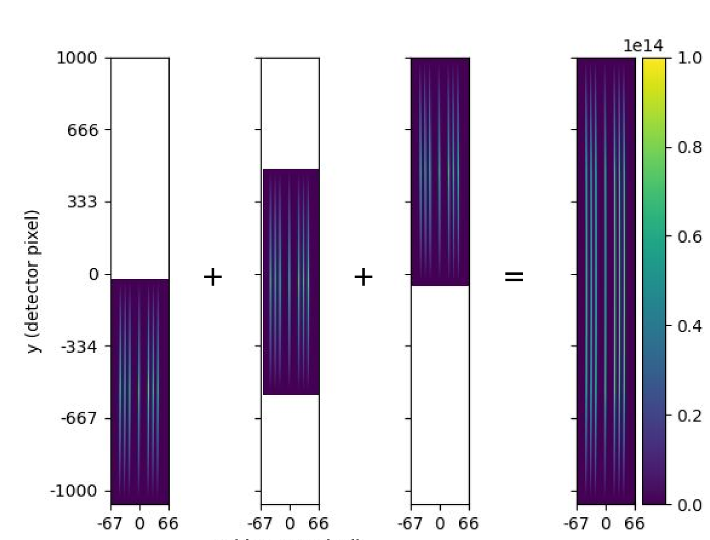
The propagation through the chain of instrument modules results, at the detector level and per slice, in a list of images. Each image will end up in a specific location on the detector, following the dispersion law. These data need to be interpolated in the wavelength direction in order to be summed on an oversampled detector map of a factor 3. For that we first compute the centers of the corresponding slice on the detector plane as a function of wavelength, which provides us with the trace that the images will follow on the detector. The left figure below shows this trace as a red line between three successive images. The right figure exhibits a zoomed-in view of the trace to highlight the distortion effect.



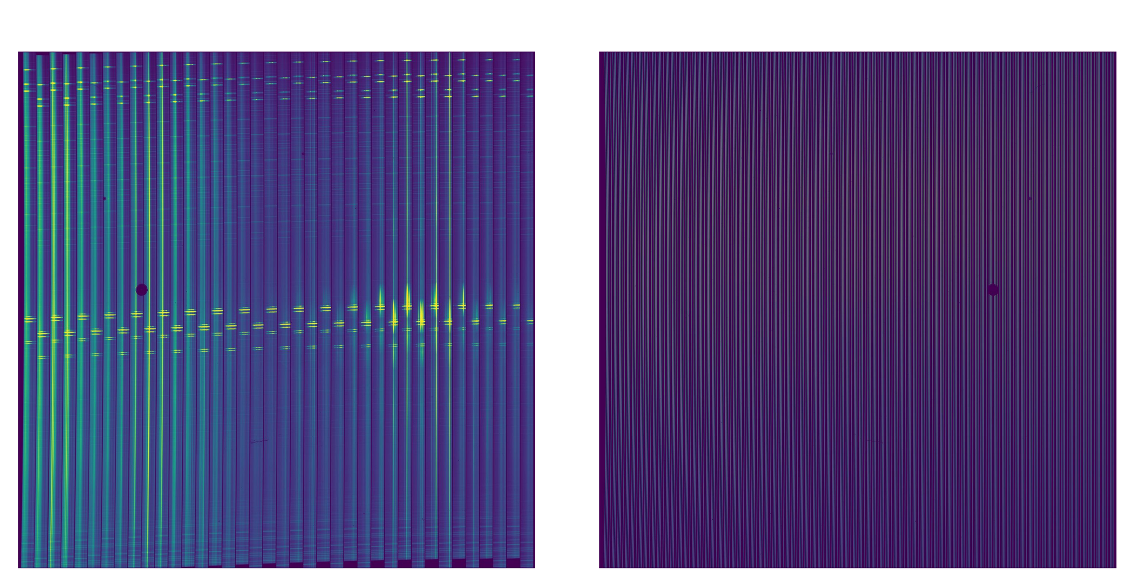
The distance between images is used to compute a "ramp coefficient" per oversampled detector pixel (called C_y) from a triangular function along the dispersion direction (y in the figures) modulated by the vector and the photon energy and then integrated over the wavelength range covered by the pixel. The trace provides the sub-pixel position of the x-center of the slice as a function of the vertical position on the detector. Using this information, we assign coefficients per detector row to spread the flux over the detector pixels (matrix C_x). The two matrices C_x and C_y are multiplied to form, for each image in the list, the matrix C as shown on the figure below.



Each image from the list of the monochromatic images is then resampled to the same grid as the oversampled detector map and convolved with the corresponding matrix C to obtain the flux map associated with the image footprint on the detector, i.e. on the pixels in between the centers of the previous and following images. Flux maps are then summed to obtain the total flux. The figure below illustrates this operation for three successive images.



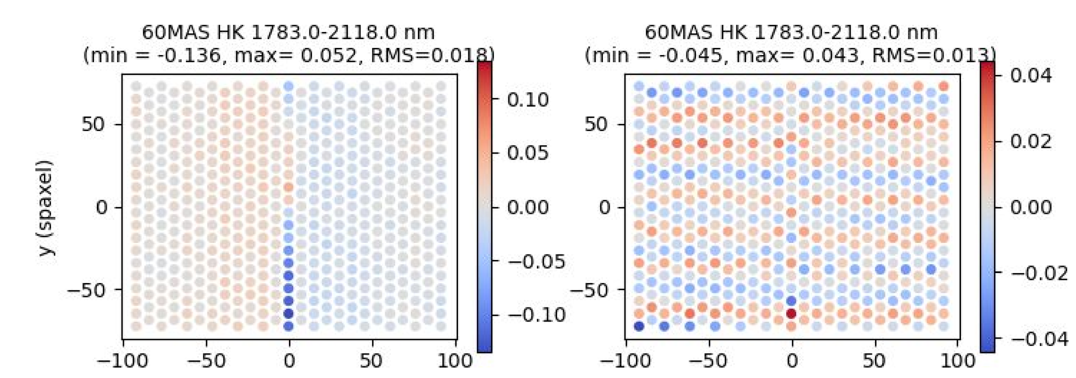
After all the images are propagated and summed, the resulting oversampled map is then re-binned to the detector pixel size, detector effects added and read-outs simulated. The final output is saved as a FITS file containing the data for the 8 detectors of HARMONI, along with adequate headers describing observing parameters, just as the real instrument will do. The left figure below shows the path H of the Antennae Galaxies exposure and the right figure shows the path A of the trace mask calibration exposure.



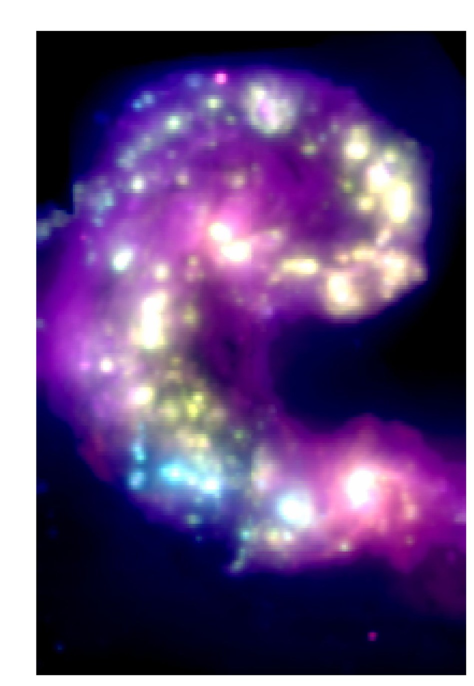
USE CASES

This digital twin of HARMONI is constantly updated to match the evolving design of the instrument. It is used extensively to develop the data reduction pipeline[4], which performs the inverse process, producing a 3D data cube from the raw detector data.

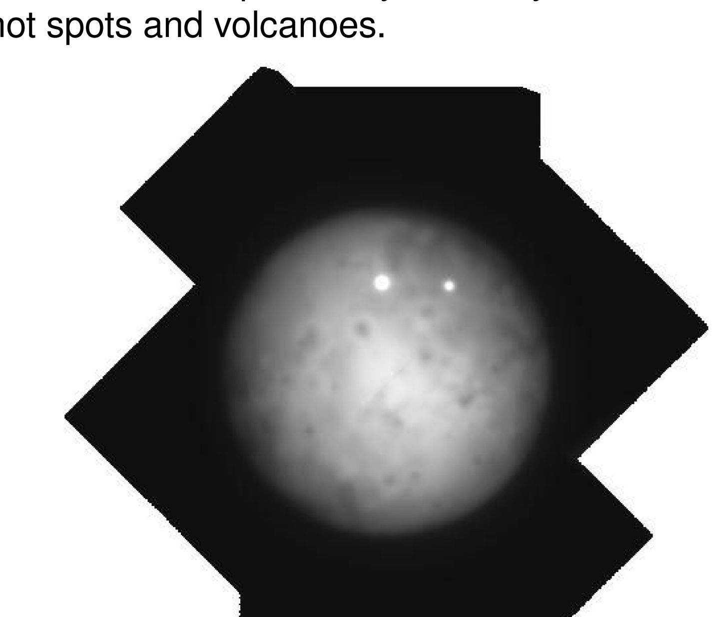
For instance, we used it to develop and test the algorithm of the geometric calibration[5], a key step in the data reduction process. This algorithm determines the coordinate transforms from detector pixels to wavelength and relative spatial position in the telescope focal plane. The diversity of configurations in the HARMONI instrument, and the stringent accuracy requirements required the development of a challenging algorithm minimizing the number of calibration exposures per configuration and keeping the calibration time reasonable. The digital twin allowed us to simulate the foreseen exposures. They were processed with the algorithm being prototyped, and accuracy maps were derived as shown on the figure below.



Our digital twin was also used to simulate some typical HARMONI science cases, such as the Antennae Galaxies (NGC 4038/39) redshifted to z=2. This astrophysical scene was created from a VLT/MUSE observation[6] and consists in a continuum cube and 8 smaller cubes centered around the emission lines, observed with the H+K grating. It took approximately 12 hours to simulate it. This simulation allowed us to successfully test our data reduction prototype on multiple scales, various position angles, and also to validate the wavelength calibration process. The figure below shows a color image of the 60 mas scale, created by extracting the [SII], Hα, [OIII] lines from the reduced data-cube and mapping them to the RGB channels.



Another science case for HARMONI is the observation of solar system bodies. Here we present an observation of Io, one of Jupiter's largest moons, simulated at the 4 mas scale using the H+K grating. The observation is made of eight exposures with different pointings, and allowed us testing the mosaicking feature and the correction of the differential atmospheric refraction of the pipeline prototype. The image below shows the white light image, but the full data cube was also produced and offers the possibility to study Io's surface and obtain spectra of hot spots and volcanoes.



ACKNOWLEDGMENTS

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