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Spanish participation in the development of HARMONI, the first light integral field spectrograph for the E-ELT.

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Abstract

HARMONI is the visible and near infrared integral field spectrograph (IFS) selected as a first-light instrument for the European Extremely Large Telescope (E-ELT). With four spatial scales and a range of spectral resolving powers, astronomers will optimally configure the instrument to overtake a wide range of scientific programs and to address many of the E-ELT science cases. The Centro de Astrobiología del CSIC/INTA (CAB-CSIC) and the Instituto de Astrofísica de Canarias (IAC) form part of the international consortium developing HARMONI, participation that will constitute an unique scientific opportunity for the Spanish astronomical community, allowing the access to the E-ELT as soon as it were operative via the guaranteed time. We describe here the instrument and its capabilities with special attention to the Spanish contribution to HARMONI. At the current stage of the project, HARMONI design is being revised due to significant modifications of the Nasmyth platform affecting the interface with HARMONI.

1 Introduction

ESO has the goal of building a segmented and adaptive telescope with a 39-meter main mirror to be operative the 2020s decade, the E-ELT. This telescope will vastly advance our knowledge in most branches of astrophysics and it is widely supported by the European scientific community. The E-ELT represents a major technological and engineering challenge, being an important opportunity for high technology enterprises.

HARMONI (Thatte et al. 2014) is an instrument concept already selected for E-ELT first-light and, therefore, it will be available as soon as the E-ELT enters into operation. The Centro de Astrobiología (CAB-CSIC) and the Instituto de Astrofísica de Canarias (IAC) have actively participated during HARMONI conceptual design phases as part of an international consortium led by the University of Oxford and also formed by the UK-Astronomy Technology Centre in Edinburg, the Centre de recherche astrophysique de Lyon, the Laboratoire d'Astrophysique de Marseille and ESO providing the instrument detectors. The UK-RAL Space, the Institut de Planetologie et d'Astrophysique de Grenoble and the French aerospace lab also participate in the development of the instrument as associated partners.

1.1 HARMONI science goals

The combination of light grasp, very high spatial and spectral resolutions offered by the E-ELT with HARMONI constitute an exceptional opportunity for an step-forward in astrophysics. The E-ELT science case has three major themes and HARMONI can contribute significantly to each of them, addressing more of the major questions in Astrophysics.

In the exo-planet domain, HARMONI is mainly a follow-up machine, allowing detailed spectroscopy of planets detected by direct imaging instruments such as SPHERE, GPI, SExAO etc. HARMONI will be able to obtain spectra of these planetary mass companions at low spectral resolution (under 3500), allowing us to constrain their bulk properties (e.g. surface gravity) and their atmospheric composition. HARMONI will also provide a step-forward in the circumstellar disks and young stars environment fields, allowing the study of the internal dynamics, structure, composition, etc. HARMONI will also benefit the study of young stellar clusters and the initial mass function (more sensitive to low-mass objects).

Regarding stars and galaxies, HARMONI will provide image and spectroscopy of extragalactic resolved stellar populations. Indeed, resolved stellar populations in external galaxies is one of the holy grails of stellar astrophysics. With HARMONI, we will, for the first time, be able to take spectra of individual stars in galaxies like Cen A. Also it will be able the study of the complexities of galaxy nuclei and e.g. the role of black holes and AGN in limiting the growth of the most massive galaxies.

In the area of high redshift galaxies, HARMONI can allow us to study (in a spatially resolved manner) the morphology, kinematics, chemical abundances, mass function gradients and dynamics of these systems. We can also hope to resolve individual star forming complexes, and measure their dynamical masses. There are obvious synergies with ALMA which will look at cold molecular gas and dust, whereas HARMONI will look at warm molecular gas and stars.

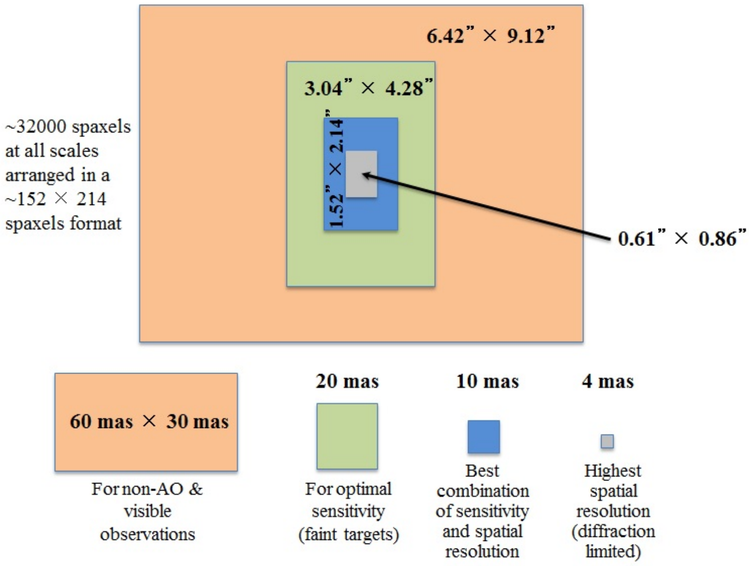

Figure 1: Schematic picture of the four scientific fields of view selectable in HARMONI and their corresponding spaxels scales.

2 Overview of the HARMONI capabilities

HARMONI is the first light high-angular resolution spectrograph for the E-ELT, providing simultaneously spatial and spectral information of the observed field. It is conceived as a work-horse instrument that will support a broad range of science programs. HARMONI is ideally suited for spatially resolved, detailed morphological, kinematic and chemical (via line ratios) studies of extended objects, as well as providing a *point and shoot* capability for ultra-sensitive spectroscopy of point sources. Although the size and mass of the instrument make it challenging to realize, HARMONI is based on a proven concept and requires no significant research and development before it can be built.

HARMONI will provide simultaneous spectra of 32528 spatial positions, arranged in a 152×214 spaxels format, allowing four spatial scales that can be selected on-the-fly. Depending on the choice of spaxel scale, the field of view (FoV) may vary from $\sim 0.61'' \times 0.86''$ to $6.42'' \times 9.12''$ (see figure 1). The finest scale is chosen to Nyquist sample the telescope's diffraction limit at H band, with 0.4 mas squared spaxels. The largest spaxel scale has rectangular spaxels on the sky (60×30 mas^2) due to design constrains. Using the coarsest scale, observer could bin two spaxels to get a 60×60 mas^2 square spaxel, or take a second exposure offset by 30 mas along one axis to get 30×30 mas^2 sampling in the resulting data cube. At visible wavelengths, using CCD detectors, user has the option of binning along one dimension to make the spaxels even larger and more sensitive.

HARMONI is being designed to work with all the different types of adaptive optics (AO) correction that will be available at the E-ELT. Through the Ground Layer AO (GLAO), or even without any AO correction, users will get a small improvement over seeing using just natural stars in the outer annulus of the E-ELT FoV (∼2.5 to 5 arc minute radius). For Single Conjugate AO (SCAO) or standard natural guide star AO, HARMONI will sense the incoming wavefront and the correction will be done with M4 (deformable mirror) and M5 (tip tilt) of the E-ELT. Laser Tomographic AO (LTAO) will use six laser stars and natural guide stars up to 1 arc minute from the science field for close to diffraction limited performance (∼30-50% worse than SCAO).

HARMONI will provide visible and near infrared integral field spectroscopy at resolving powers ranging from 500 to 20000 that can be chosen on-the-fly. The spectrographs (see O'Brien et al. 2014) will use two different types of detectors: CCDs up to 0.8 μm, and Hawaii 4RG for the near-IR channel. In this way, the total wavelength covers from ∼0.45 to 2.45 μm. In the simultaneous large wavelength coverage mode, a dichroic separates the visible light from the near-IR; the visible goes to fixed disperser camera that provides R∼3500 across V and R bands. The near-IR goes to a prism disperser, providing resolutions in the ∼500 to 700 range from I to K bands. In all other modes, we do NOT envisage using the visible at the same time as the near-IR channel. Any spectral resolving power can be combined with any spatial resolution.

As an illustrative example, figure 2 shows some simulations (see Zieleniewski et al. 2014 for details on HARMONI simulations) of a Luminous IR galaxy at redshift ∼2 as observed on the VLT and the improvements on the E-ELT with HARMONI using different spatial scales. There is always a trade-off between spatial resolution and sensitivity: finer spaxel scales improve the sensitivity to point sources, but extended emission is better detected at coarser spatial resolutions. For reference, table 1 shows the limiting AB magnitude for a point source spectrum.

Table 1: Limiting AB magniude for which signal-to-noise ratio of 5 per spectral pixel is achieved in five hours (20 exposures of 900 seconds each), for a point source spectrum extracted from a 2×2 spaxel box, when using LTAO. The computation assumes OH avoidance, and 0.67" seeing towards zenith at 0.5 μm, observations 30 degrees from zenith.

Spectral	**4 mas**		**10 mas**		**20 mas**		**30×60 mas**	
Resolution	R_{AB}	H_{AB}	R_{AB}	H_{AB}	R_{AB}	H_{AB}	R_{AB}	H_{AB}
500		27.42		27.36		26.90		26.02
3500	22.93	26.64	23.89	27.44	24.69	27.53	25.64	26.98
7500		25.82		26.66		26.84		26.43
20000		24.76		25.63		25.87		25.63

3 Instrument description

HARMONI will be installed on the E-ELT Nasmyth platform and it will be conformed of different modules (see figure 3). Note that the current (December 2014) modifications on the

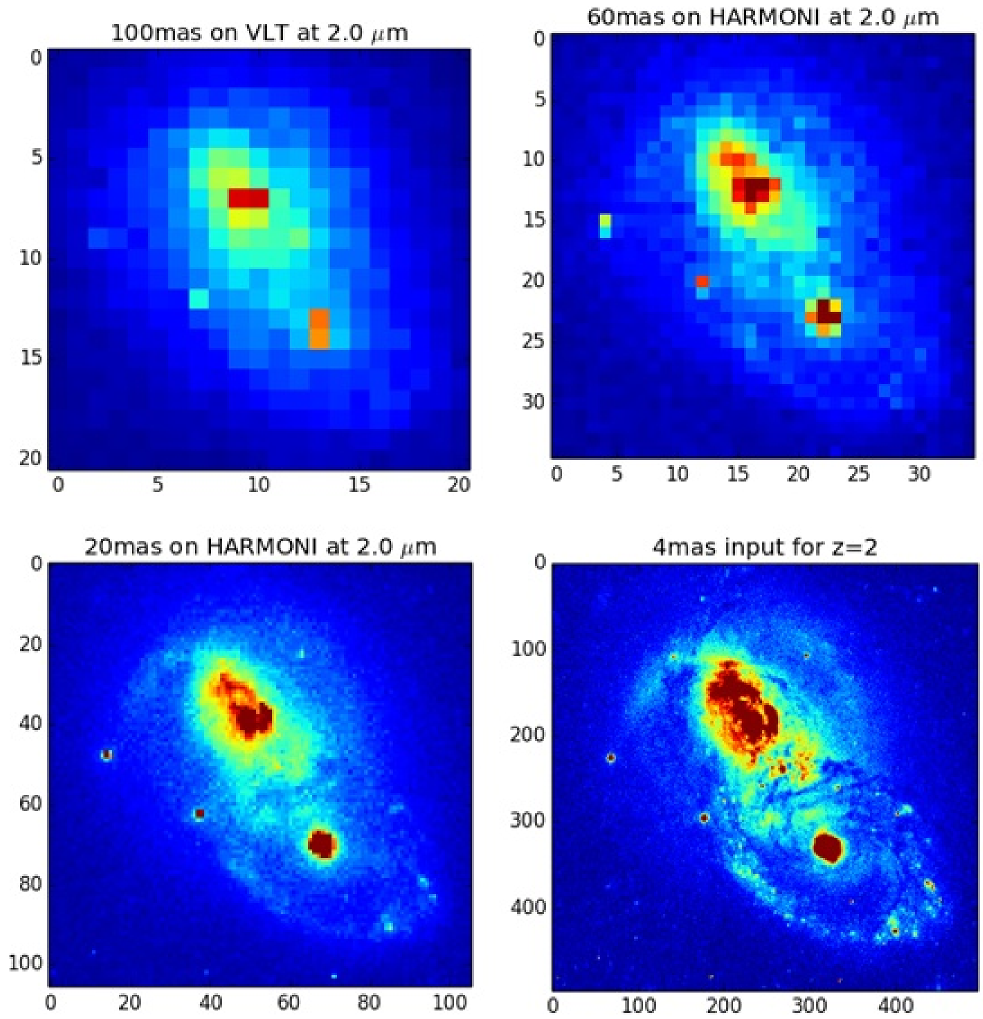

Figure 2: Results of simulations showing the exquisite detail HARMONI will achieve: (top-left) A typical Luminous infrared galaxy (LIRG) at z$\sim$ 2 as observed using SINFONI on the VLT with a 100 milliarcsec (mas) scale. These data constitute the input data for HARMONI simulations shown in the other three panels. Simulations showing the same LIRG as observed using HARMONI+E-ELT with LTAO at (top-right) 60 mas, (bottom-left) 20 mas, and (botton-right) 4 mas spaxel scales. These maps were recovered by integrating the simulated data-cubes around the Hα emissin line in the K-band at this redshift.

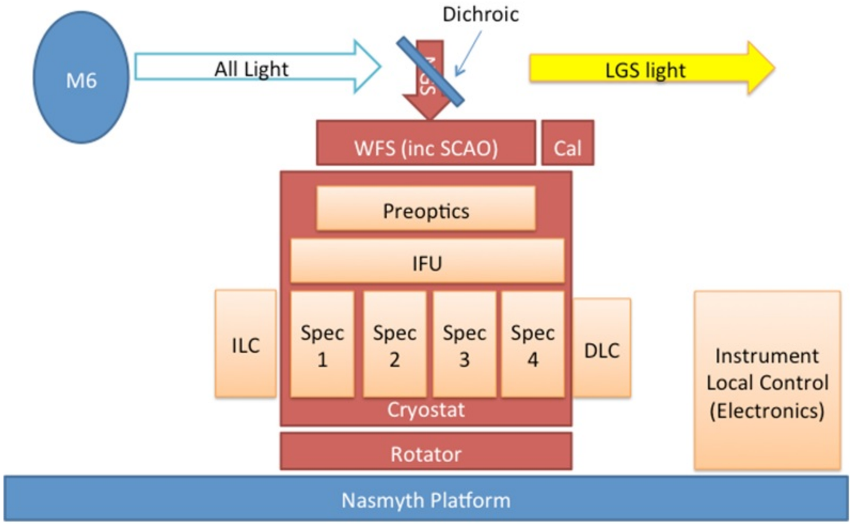

Figure 3: A schematic view of HARMONI showing the major subsystems forming the instrument, located assuming a rotating criostat. The responsabilities of Spain in the HARMONI project during the conceptual phase are focused on the Calibration Unit, pre-optics and Instrument Control Electronic subsystems.

Nasmyth focus design of the E-ELT could drastically affect the instrument; the description given here corresponds to the mechanical concept for a rotating cryostat (although different mechanical concepts are under study). Light from the telescope will be relayed to the instrument by a dichroic, providing a ~15-30 arcsec science field and a ~90-120 arcsec technical field. The dichroic will also separate laser guide stars (LGS) light from natural guide stars (NGS) and science lights. The NGS and science beams are relayed down into the instrument, allowing an "up-looking" gravity invariant rotating instrument configuration. Indeed, the whole instrument will rotate to compensate the rotation of the field at the Nasmyth focus station of the E-ELT. Light from the calibration unit can also be fed into the cryostat instead of science light to take reference exposures. A single cryostat, 3.5 meters high by 3.8 meters in diameter at ~140 K to minimise thermal background, hosts the bulk of the instrument optomechanics. A pre-optics subsystem (see Sánchez-Capuchino et al. 2014) relays the telescope focal plane, which is outside the cryostat, and provides four selectable spatial scales. Pre-optics also allows other beam conditioning functions such as filters and pupil masks. To provide the integral field capability, the rectangular pre-optics output field is reformatted into four linear slits by an image slicer; each linear slit feeds one of the four spectrographs subsystems. The spectrographs collimate, disperse, and focus the light onto detectors, providing a choice of spectral ranges and resolving powers (see table 2). Each spectrograph has one camera for the NIR and one for the visible, which can be used simultaneously only for the largest wavelength range mode. The cold bench structure forms a "tree trunk" in the centre of the cryostat, connecting the pre-optics bench, the Integral Field Unit (IFU), and the spectrographs. Outside the cryostat, a SCAO wavefront sensor is fed by visible light from deployable dichroic covering the science field. Additionally, a few wavefront sensors are capable of patrolling a 90-120 arcsecond technical field of view to provide LTAO-NGS atmospheric compensation. Further wavefront sensors for GLAO/seeing limited operation may also be included. All these weavefront sensing subsystems are mounted on the outside top of the instrument cryostat, but co-rotating with it on the instrument rotator. The instrument (ILC) and detector (DLC) control systems are mounted near the cryostat, minimising cable lengths, although part of the instrument local control system will be mounted on the Nasmyth platform.

Table 2: Spectral coverage and resolving powers provide by the different disperser settings in HARMONI. While the infrared channel has many options, the visible has a fix resolving power.

Bands	R
Simultaneous V to K	∼500
"V+R" or "I+z*+J" or "H+K"	∼3500
"I+z" or "J" or "H" or "K"	∼8000
"Z" or "J_{high}" or "H_{high}" ot "K_{high}"	∼20000

4 Spanish responsabilities on HARMONI

At the current phase of the project, the Spanish activities within HARMONI include: (1) the development of the calibration unit ,(2) the development of the HARMONI pre-optics including offner relay and pre-optics bench, (3) the development of the secondary guiding module, (4) the electrical harness and control electronics for the whole instrument, and (5) participate in the definition and development of the science cases for the HARMONI scientific exploitation. These activities are being carried out in a coordinated manner between the two Spanish research centers involved in HARMONI, the CAB-CSIC and the IAC, in contact with the national technological industry. At this stage, it is important to form and consolidate the working groups for future phases in the development of the instrument.

4.1 Calibration unit

The calibration subsystem will provide all functions necessary to remove the instrumental signatures from the observed science data. In order to provide maximum common path with the science beam, the calibration system will be located outside the cryostat and as early in the optical path as possible. The main functional requirements of the calibration system are:

- To provide calibration of pixel-to-pixel (and spaxel-to-spaxel) sensitivity variations.
- To provide the calibrations necessary to transform detector pixel coordinates to (α,δ,λ) coordinates in the input field.

- To provide calibration of the instrument point spread function (spectrally and spatially).
- To provide the ability to measure the location of focal plane masks (e.g. coronagraphic spot).

The calibration unit will be on top but outside of the cryostat. The CAB-CSIC is currently in charge of the development of the HARMONI calibration unit.

4.2 Pre-optics

The pre-optics sub-subsystem relays the telescope focal plane into the cryostat, where the pre-optics is located. Taking light from the telescope or the calibration system, the pre-optics basically reimage the focal plane onto the IFU. The telescope focal plane is imaged wih four different magnificaions for samplings in figure 1. The main functional requirements of the pre-optics are:

- To relay the science field of view to the IFU.
- To provide different spatial scales and to switch between spaxels scales.
- To filter undesirable wavelengths.
- To block thermal radiation from outside the telescope pupil.
- To provide an image of the instrument and telescope pupils allowing to align them.
- To provide control of the instrument exposure time.
- To mask sections of the focal plane and/or the telescope pupil, if required.

The IAC is responsable of developing the pre-optics module for HARMONI.

4.3 Secondary guiding

The secondary guiding will provide dynamic information of a possible misalignment between the telescope focal plane and instrument focal plane. The secondary guiding will be integrated within the pre-optics subsystem. It is in charge of the CAB-CSIC, in close contact with the IAC to define the interfaces with the pre-optics.

4.4 Control electronics

The control subsystem (see Gigante et al. 2014), developed at the IAC, provides the ability of monitoring and control all functions within the instrument. The control electronics will provide control and monitoring of all the optomechanical functions in the instrument, including housekeeping monitoring. The IAC is also in charge of the electrical harness, connecting the individual subsystems to the main instrument local control unit. Due to interfaces, the development of the control electronics requires a close contact with all the institutions developing the different subsystems conforming HARMONI.

Phase	Contractual Review, Milestone	Sub-System Review, Milestone	Comment
PD	Preliminary Design Review	Requirements Reviews, Preliminary Design Review	flowdown of requirements
DD	Final Design Review	Critical Design Reviews Manuf.Readiness Review	Ahead of the system FDR All drawings etc ready for release
MAIT		Integration Readiness Reviews Test Readiness Reviews Acceptance Tests	Ready to assemble sub-sys? Ready for acceptance test? sub-system meets specification?
AIV	Integration Readiness Review Test Readiness Review Preliminary Acceptance Europe		Ready to assemble system? Ready for acceptance test? System meets specification?
Comm & SV	Preliminary Acceptance Chile		Firstly engineering integration and then science commissioning. Both will probably be in series of steps associated with operating mode.
GP	Final Acceptance Chile		Guarantee Phase of 2 years – costs not in PPRP submission

Figure 4: Main milestones identified for the HARMONI project development.

5 HARMONI project timetable and costs

The HARMONI project will follow the normal phases of Preliminary Design (PD), Detail Design (DD), sub-system manufacture, assembly and test (MAIT), instrument assembly and verification (AIV) and telecope integration and commissioning (TIC). The Guarantee periods (GP) of two years follows acceptance of the instrument in Chile. ESO have stated that the Telescope will not be ready to integrate first light instruments until ∼summer 2024. This gives almost 10 years to get Preliminary acceptance of HARMONI in Europe and ship the instrument to Chile. However, based on VLT experience, the HARMONI consortium estimates that the instrument could be built in about seven years.

A preliminary Gantt chart of the project has identified the milestones in table 4 against a set of deadline dates with some schedule margin, assuming a project kickoff in April 2015 as advised by ESO. The Preliminary design review will be about two years later, the final design review is schedule for ∼March 2019, and in ∼April 2024 is expected the preliminary acceptance of HARMONI in Europe, and one year later in Chile. The detectors feeding into the spectrographs and the long lead procurement of the IFU slicers which are highly challenging, are the two critical points in the traced schedule.

The current estimate of hardware costs for HARMONI, including a working margin and contingency, exceeds 23 million euros. ESO will fund the hardware costs of the project and a porcentage for contingency. The institutions taken part in the consortium will provide the human resources and a working allowance; moreover, national funds will be required for some non-deliverable infrastructures. The total effort estimated by the consortium required to deliver HARMONI instrument is ∼358.1 FTEs (full-time equivalent). These estimates are based on both a bottom-up analysis against each working package and the deliverables required, but also by comparison with similar elements from several recent 8 meter class instruments such as KMOS, MUSE, SPHERE, EMIR, OSIRIS, etc.

The total effort in HARMONI from the Spanish side, about 96 FTEs, is slightly larger than the effort to deliver OSIRIS to GTC, and slightly smaller than the current effort dedicated to EMIR.

Acknowledgments

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