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ABSTRACT

HARMONI is the first light, adaptive optics assisted, integral field spectrograph for the European Southern Observatory's Extremely Large Telescope (ELT). A work-horse instrument, it provides the ELT's diffraction limited spectroscopic capability across the near-infrared wavelength range. HARMONI will exploit the ELT's unique combination of exquisite spatial resolution and enormous collecting area, enabling transformational science. The design of the instrument is being finalized, and the plans for assembly, integration and testing are being detailed. We present an overview of the instrument's capabilities from a user perspective, and provide a summary of the instrument's design. We also include recent changes to the project, both technical and programmatic, that have resulted from red-flag actions. Finally, we outline some of the simulated HARMONI observations currently being analyzed.

Keywords: integral field spectroscopy, adaptive optics, ELT, image slicer, high contrast

1. INTRODUCTION

Integral field spectrographs (IFS) have grown from being niche instruments to workhorse spectrometers at most 8m-class observatories. They provide spectra of every pixel of a two-dimensional field-of-view on the sky simultaneously, yielding a data cube of intensity as a function of sky position and wavelength (or velocity, via the Doppler effect) for each observation. A second development, also over the last three decades, is the development of adaptive optics (AO), enabling ground-based telescopes to routinely achieve diffraction limited spatial resolution over most of the sky. AO systems sense the atmospheric turbulence using a combination of artificial laser stars and natural stars as reference sources, and drive a deformable mirror (DM) in real time (at ~500 Hz) to correct the aberrated wavefront. This technique has been so successful that the ELT is an "adaptive telescope", with the 5352 element DM being part of the telescope.

Combining these two developments, HARMONI is an AO assisted IFS that expands the discovery space of the ELT through a powerful combination of vast collecting area and diffraction limited spatial resolution (~12-15 milli-arcseconds). The exquisite spatial resolution allows astronomers to distinguish features in a wide variety of targets, ranging from moons in our own solar system to the most distant galaxies. HARMONI employs image slicers to enable slitlet sizes that match the diffraction limit, whilst retaining information over the full FoV. This optimizes observing efficiency, as slit positioning difficulties are eliminated – instead, the observations can be "point-and-shoot". Furthermore, a huge gain in sensitivity is obtained by matching the extraction aperture to the spatial resolution of the AO assisted telescope, providing a D^4 sensitivity gain (observing time scales inversely as the fourth power of the telescope diameter).

2. INSTRUMENT OVERVIEW

The Technical Specifications of the instrument were substantially revised in 2018, following the successful inclusion of LTAO to the instrument's AO capabilities. Notably, there was a step change for the adaptive optics specifications, with the instrument being responsible for delivering an AO corrected PSF, rather than simply being responsible for the sensing. Further changes have also been made as a consequence of the “red flag” process (described below), which are being taken through the formal change control process. In this document, they are incorporated into the instrument specification and design, to provide a consistent and realistic view of the instrument. The key technical and performance attributes achieved by this design are:

- Four spaxel scales (60×30, 20×20, 10×10, and 4×4 milli arcsec), with corresponding FoV, as shown in Figure 1.
- Wavelength range: 0.82 to 2.45µm.
- Resolving powers: *R*~3500, 7000 & 17000, at all spaxel scales.
- Instantaneous wavelength coverage of at least one atmospheric window at R~7000.
- High performance SCAO pyramid-based wavefront sensor working up to 15″ off-axis.
- A high-contrast channel capable of achieving a contrast of 10^6 at 0.2″.
- Average instrument throughput > 35% over 0.82 – 2.4µm.
- Low instrument thermal background (<40% of telescope).
- Excellent image quality (< 20% degradation of telescope PSF).
- LTAO giving peak Strehl of 50% in K-band in best conditions and 30% ensquared energy in 20×20 milli arcsec over ≥50% of the sky at the South Galactic Pole in median seeing.

2.1 Spatial and spectral layout

HARMONI’s core capability is near-IR (0.82-2.45 µm) integral field spectroscopy over a range of resolving powers (*R* = 3500 to 17000) with large instantaneous wavelength coverage, as shown in Figure 1. HARMONI uses Volume Phase Holographic (VPH) gratings for high efficiency. Each grating has a fixed wavelength range, so need to be physically exchanged to change observing band. One of ten different gratings can be chosen, which provide three different resolving powers (R ~ 3500, 7000 and 17000) spanning the various atmospheric windows in the near-IR (atmospheric transmission is shown in grey in Figure 1). Each spectrum is approximately 3300 pixels in length; a fixed length spectrum implies a natural compromise between instantaneous wavelength coverage and resolving power.

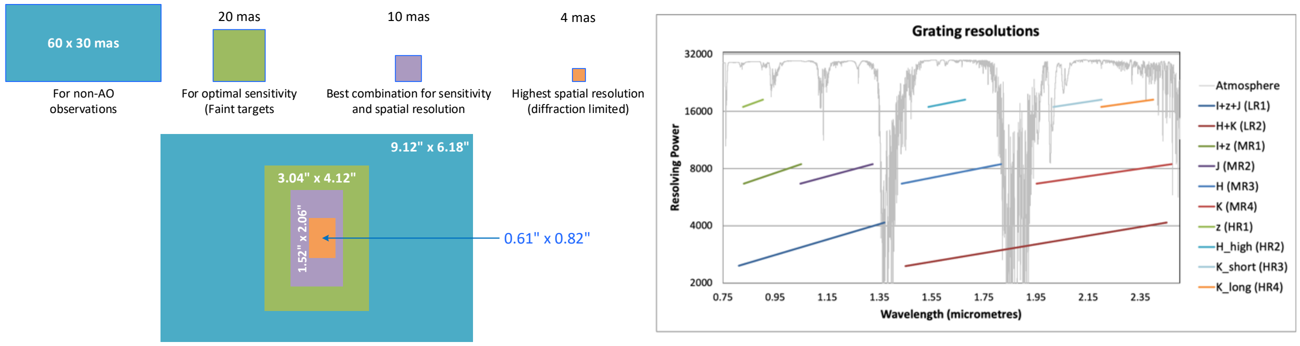

Figure 1: (Left) HARMONI’s four spaxel scales (in milli-arc seconds) and the corresponding fields-of-view (in arc seconds). (Right) Instantaneous wavelength coverage for the different grating settings, overlaid on atmospheric transmission, in grey.

The versatility in choice of spectral resolution is complemented by a choice of spatial plate scales and corresponding fields of view. Both spaxel scale and grating can be chosen “on-the-fly”. The IFS provides spectroscopy for each point in a 204 × 152 element field of view (FoV), at one of four spatial pixel (spaxel) scales, optimized for best sampling, best sensitivity, or maximal FoV, as illustrated in Figure 1. The coarsest spaxel scale is dictated by the étendue (A-Ω product) of the optics – the design has to squeeze light from a 39 metre telescope into a 15×15 µm detector pixel, whilst maintaining excellent image quality. The finest spaxel scale is chosen to Nyquist sample the AO corrected PSF of the telescope at 1.45 µm. There is considerable design freedom for the intermediate scales. The aspect ratio of the FoV is well suited to “nodding-on-IFU”, a popular observing strategy that yields good sky background subtraction.

2.2 Adaptive Optics modes

HARMONI's AO system is comprised of Laser Guide Star (LGS) and Natural Guide Star (NGS) AO sensors, that recover information of the aberrated wavefront through tomographic reconstruction (Laser Tomographic Adaptive Optics – LTAO) or using single bright natural stars (Single Conjugate Adaptive Optics – SCAO). Equally vital is the AO Control System (AOCS), that performs the complex task of stitching together wavefront information from six laser guide stars and up to two natural guide stars, generating commands every milli-second for the ELT's DM that compensates the atmospheric turbulence. The sensing of the wavefront aberrations is done by the science instrument – better rejection of common mode disturbances such as flexure and vibrations is achieved by splitting the wavefront sensing light as close to the science focal plane as possible.

In LTAO operation, six Laser Guide Star (LGS) sensors, each with 68×68 sub-apertures, measure the wavefront aberrations at 480 Hz from six sodium laser stars. The laser stars are located in an asterism with ~1 arcmin diameter, which provides the best compromise between peak performance and robustness to changing atmospheric conditions. LGS are unable to measure the image motion, so a separate natural guide star (NGS) is needed to sense tip-tilt and focus. The off-axis NGS is sensed by HARMONI's NGS System (NGSS), with a probe arm that patrols one half of a 1 arcmin radius field centred on the IFS FoV. The NGS position and focus is sensed at several hundred Hz in the H&K bands, while a slow "Truth Sensor" uses the J band light from the same star to eliminate any low order wavefront errors introduced by the LGS. The NGSS is able to operate with stars as faint as $H_{AB} = 19$, so that HARMONI's LTAO system can provide excellent sky coverage – 75% of the sky at the South Galactic Pole (SGP) with Strehl exceeding 30% at K band under median conditions. A recent addition is a second NGS probe arm that patrols the other half of the same 1 arcmin radius field, but only provides accurate position sensing at slow (< 1 Hz) update rates, capturing slow drifts in plate scale, field orientation, etc.

Even better performance may be obtained by using HARMONI's SCAO system, provided a single, bright, natural guide star is present within 15″ of the science target of interest. SCAO can also deal with extended objects as AO reference "stars" with slight performance degradation, as long as the reference is less than 2.5″ in diameter. Unlike the LTAO system (which uses an off-axis NGS), SCAO uses a dichroic that sends light in the 700–1000 nm range to a pyramid wavefront sensor operating at 500 Hz, with longer wavelengths (1000–2450 nm) available for spectroscopy with the IFS. Both on-axis and off-axis NGS may be used. Optimal performance is achieved for stars down to $M_V=12$, with a limiting magnitude of $M_V\sim17$.

The HCAO mode adds a high contrast capability to HARMONI, using a combination of a pupil plane apodiser and a focal plane mask. Due to uncorrected atmospheric differential refraction (chromatic beam shift), it is not possible to use classical coronagraphs to improve contrast. The novel design by Carlotti et al. achieves good rejection of starlight, with a goal of achieving (post-processed) contrasts of $>10^6$ at separations < 0.2″), whilst enabling inner working angles (IWA) of less than 100 mas for IFS spectroscopy. HCAO works only with an on-axis NGS. It uses the pyramid wavefront sensor of the SCAO system for sensing wavefront aberrations, with a second ZELDA[1] wavefront sensor for improved sensitivity in the high Strehl regime. The ZELDA wavefront sensor operates at 1150–1200 nm (as close to the observing wavelengths as possible), so IFS spectroscopy in HCAO mode is only available over 1250–2450 nm. Angular Differential Imaging (ADI) will also be employed to reduce the impact of quasi-static speckles. Consequently, HCAO mode drives the IFS rotator to track the pupil, rather than field tracking employed in all other modes.

At wavelengths where AO correction is expected to be poor, or AO cannot be used due to weather or technical constraints, HARMONI's NOAO mode can provide "seeing-limited" performance. NOAO utilises a faint (I < 23) natural star for slow (~0.1 Hz) secondary guiding, eliminating slow drifts of the instrument focal plane and ensuring accurate pointing. NOAO is typically expected to be used with the coarsest spaxel scale, as all scales heavily oversample the FWHM of the seeing.

The NOAO and the LTAO modes also support non-sidereal tracking, where the science target can move at non-sidereal rates of up to 100″/hr, provided the reference natural stars remain within the patrol field, and do not cross the exclusion zone around the science field. SCAO mode can support non-sidereal observations provided the non-sidereally moving object is itself the reference object (e.g. a Jovian moon). The HCAO mode does not support non-sidereal observations.

3. THE HARMONI CONSORTIUM

The HARMONI Consortium currently consists of eight partner institutes whose contributions are illustrated in Figure 2.

- University of Oxford (UOX) – with associate partner RAL Space.

- UK Astronomy Technology Centre (UK ATC).
- University of Durham (UOD).
- Centre de Recherche Astrophysique de Lyon (CRAL) – with associate partner EFISOFT.
- Laboratoire D'Astrophysique, Marseille (LAM) – with associate partners IPAG and ONERA.
- Instituto de Astrofísica de Canarias, Tenerife (IAC).
- Centro de Astrobiologia - Consejo Superior de Investigaciones Científicas (CAB-CSIC), Madrid.
- University of Michigan, providing cash and science input.
- ESO – Detector Division (ESO-D) are not officially partners but are considered part of the Consortium in all other respects.

Partners are responsible for delivery of their assigned work packages with a share of Guaranteed Observing Time (GTO) in return. The Consortium Agreement describes how the HARMONI GTO will be allocated and used based on the fraction of build-phase effort provided by each partner (plus a proportional contribution to eligible non-staff costs). Associate partners help deliver the WPs but the full partners remain responsible for their deliverables, and any allocation of their GTO to their associate partner(s). The University of Oxford, which hosts the Principal Investigator, and the UK Astronomy Technology Centre, which hosts the Project Manager, share the project leadership.

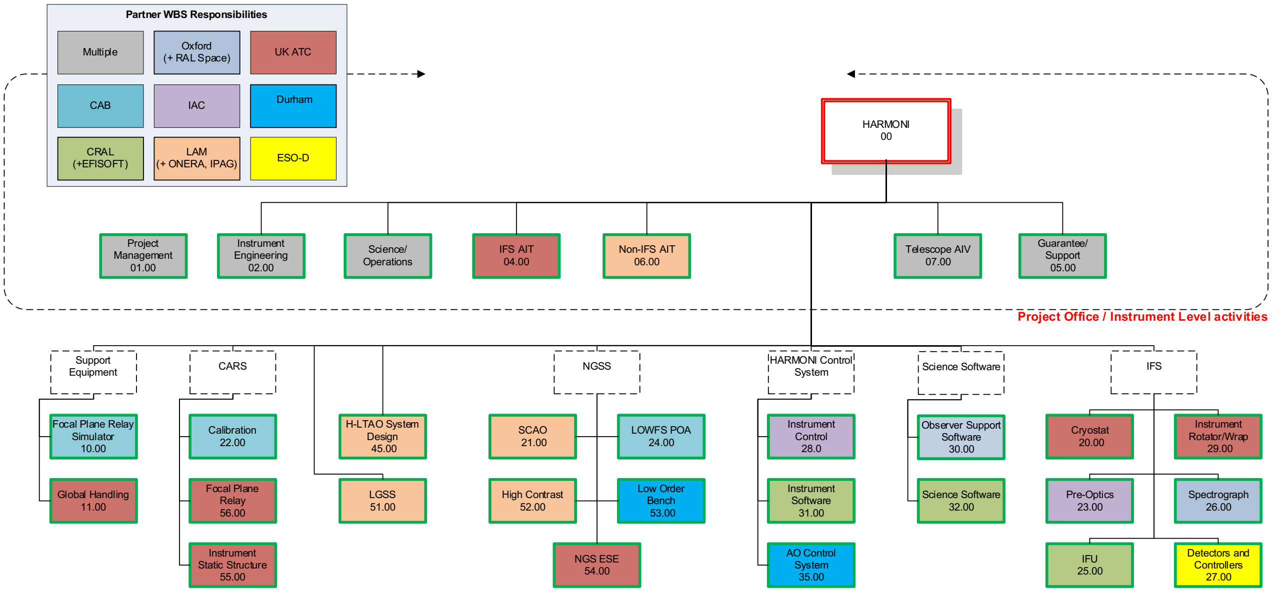

Figure 2: HARMONI Level 1 Breakdown Structure. The colour coding indicates the contributions of the various partners.

3.1 Project Organisation

The Project Organisation and control are described in an extensive Project Management Plan. The project is led by the PI, supported by the Deputy PI. Management is the responsibility of the Project Manager supported by the Deputy PM and the IFS PM. The PMs interface both to the Project Office, Science and Instrument Engineering Teams that are working at the instrument and system levels and to the Institute Project Managers (IPMs).

There is an IPM for each partner institute, and they are responsible for delivery to schedule and budget of all WPs and activities based at their site. They are expected to manage the planning, resourcing, execution and monitoring of all activities at their site, providing regular progress reports as required.

Table 1: HARMONI Key roles, post-holders and their affiliation

Function	Post holder	Inst.
Principal Investigator	Niranjan Thatte	UOX
Deputy PI	Benoit Neichel	LAM
Project Scientist	Oscar Gonzalez	UK ATC
Project Manager	Dave Melotte	UK ATC
Deputy Project Manager	David Le Mignant	LAM
IFS Project Manager	Sandi Wilson	UK ATC
Project Administrator	Vanessa Ferraro-Wood	UOX
Instrument Scientist	Matthias Tecza	UOX
AO Scientist	Thierry Fusco	LAM
Instrument Systems Engineer	Fraser Clarke	UOX
IFS Systems Engineer	Hermine Schnetler	UK ATC
CARS Technical Lead	Jonathon Strachan	UK ATC
Lead Software Engineer/ HSS Technical Lead	Arlette Pecontal	CRAL
HCS Systems Engineer	Asim Yaqoob	UK ATC
NGSS Systems Engineer	Kjetil Dohlen	LAM
LGSS Systems Engineer	Anne Costille	LAM
Lead Optical Engineer	Steven Todd	UK ATC
Lead Mechanical Engineer	David Montgomery	UK ATC
Lead Electronics Engineer	Luis Fernando Rodriguez	IAC

The various work packages and their ownership are summarised in the work breakdown structure (WBS) in Figure 2. The key roles working at the system / instrument level are shown in Table 1. The HARMONI Science Team, led by the Project Scientist, comprises leading researchers from the partner institutes. They have the necessary mix of interests to address the core scientific areas where HARMONI will have an impact. The team is organised into Science Working Groups each addressing a specific science area.

3.2 Project Oversight

The project has an Executive Board with a senior member from each partner institute (e.g. Institute Director or Head of Department) to make decisions about the allocation of staff effort to the project within their institutions, to help maintain the project schedule. The Executive Board also has national agency and ESO representation. It will formally consider and approve any change in work share between partners. External oversight is provided by ESO, who organize formal reviews at each major project milestone, and require quarterly progress and finance meetings. The PI, PM and their deputies meet regularly with the Co-Is as a Management Board to provide oversight of the project and to identify and resolve any potential issues at an early stage. The HARMONI risk register is a live tool updated regularly, and presented periodically to the various oversight bodies.

3.3 Red Flag and possible scope changes

After the Preliminary Design Review (PDR) was passed in 2018, substantial progress has been made in the detailed design of the subsystems, along with their MAIT plans. 15 of 19 subsystem Critical Design Reviews (CDRs) have already been held. A first Final Design Review (FDR), focused on the flowdown of requirements and opto-mechanical interfaces was completed. The overall design of the instrument is mature; however, in particular the instrument level engineering leading to well defined interfaces and flowed-down requirements was very time and effort consuming.

The first FDR session highlighted several topics and areas of concern where there was a lack of common understanding, between ESO and the HARMONI consortium, of the issues and way forward. This on-going problem with effective communication was exacerbated by travel restrictions imposed by pandemic lockdowns and precipitated an independent Communication Review commissioned by STFC in Spring / Summer 2021.

In parallel, ESO raised a ‘Red Flag’ in September 2021 to highlight their concerns. The main ones were: significant technical and managerial challenges in realizing the instrument; the need for additional, more focused effort; an urgent need to re-establish a common view of the project (particularly on compliance with key science requirements) and to regain team spirit between the ESO and consortium teams working on HARMONI.

Together with ESO, the management team agreed a process, based around nine task forces, to look into all the issues raised in the Red Flag Report and the Communication Review. The process was logistically and ideologically difficult and it took a lot of dedication, tolerance and hard work from both sides to reach a common position. There is now a mutually agreed way forward between the HARMONI consortium and the ESO follow-up team; we are jointly seeking approval for the changes to the project.

The most significant outcomes are:

- Improvement of the working relationship with ESO through dialogue about the process, changes of personnel and modified methods of interaction.
- Additional sensing and control for long exposure image quality and absolute coordinate knowledge via addition of a second natural guide star sensor located on a probe arm.
- Proposal to remove the visible channel with advantages to reduced complexity and risk, schedule and cost (hardware and effort), even though it will slightly reduce the instrument’s capability.
- Change in set-point of cooled chambers around focus relay optical path (-15°C to 2°C) with reductions to schedule, risk and future maintenance, albeit at the expense of long wavelength sensitivity.
- Addition of technical and managerial staff, relieving the continuous overload of people in key leadership roles in addition to filling some gaps arising from staff leaving. ESO are also strengthening their HARMONI follow-up team.
- A revision of the cost and schedule for HARMONI, showing a requirement for significant additional cash (hardware) and effort funding based on improved understanding of the design and implementation issues.

Early discussions with the partners indicate that the longer and larger effort commitment can be supported across the consortium. Discussion is ongoing with all the HARMONI stakeholders on options to meet the non-staff (hardware) funding gap. Following successful agreement between ESO and the HARMONI consortium on the future course of action, it is expected that ESO will lift the Red Flag early in the Autumn of 2022.

3.4 Project Schedule

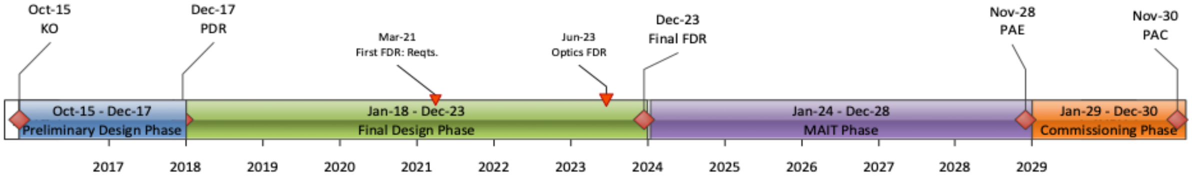

Figure 3:Outline of HARMONI schedule and major milestones.

Following the first FDR meeting with ESO and the discussions resulting from the Red Flag Review, a full re-assessment of the project has been made by the consortium, resulting in revised schedule, cost and effort forecasts. With the architecture, design, Bills of Materials and MAIT plans at a much higher level of maturity, and taking account of the current status, the forecast is on a much firmer basis than previous estimates.

The HARMONI schedule is based on a high-level master schedule maintained by the PM, with each IPM maintaining more detailed sub-system level plans which feed into it. The critical path runs through procurement release of the long-lead optics (via Optics FDR), assembly of the four spectrographs in Oxford and integration of the IFS in Edinburgh. The cash and effort forecasts are managed by combining the forecasts for each work-package provided by the IPMs. An outline of the project schedule including the main phases and milestones is shown in Figure 3.

4. INSTRUMENT DESCRIPTION

4.1 HARMONI Subsystems

Figure 4 shows a CAD rendering of the overall layout of the instrument, which will be located on the ELT's Nasmyth Platform A, at one of the side-looking ports. Light from the telescope is fed into HARMONI via the ELT's M6 fold mirror, at a beam height of 6 m above the Nasmyth platform. The instrument is ~8 m tall, and has a footprint of 5×6 m, with a total weight of approximately 36 tonnes. The opto-mechanics of the integral field spectrograph (IFS) consists of the pre-optics scale changer, the integral field unit (IFU) and four spectrograph units. The IFU re-arranges the light from the FoV into four 500 mm pseudo long slits, which form the input to the four spectrograph units. The IFS opto-mechanics reside in a large cryostat (ICR), about 3.5 m in diameter, and 4 m tall, at a constant operating temperature of 130 K to minimize thermal background. The near-IR detectors (eight 4096×4096 pixel HAWAII 4RG arrays) are operated at a lower temperature of 40 K. The instrument rotator and cable wrap (IRW) allow the entire cryostat to rotate about a vertical axis to follow field rotation at the ELT's Nasmyth focus. The vertical rotation axis guarantees an invariant gravity vector, improving the instrument's stability by minimizing flexure.

The Natural Guide Star System (NGSS) is located on top of the IFS cryostat, and co-rotates with it. It houses all the natural guide star sensors for all four operating modes. As the telescope's back focal distance is insufficient to relay the telescope light directly into the upward-looking cryostat, a focal plane relay system (FPRS) re-images 2 arcminutes of the telescope focal plane to the top of the cryostat and the NGSS. Both FPRS and NGSS are maintained in a dry gas environment at a constant temperature of 2°C, reducing thermal background for improved K band sensitivity, and minimizing thermal drifts.

The LGS System (LGSS) and the Calibration Unit (CU) are located just past the instrument slow shutter, close to where telescope light enters the instrument, at a beam height of 6 m above the Nasmyth platform. The first element in the instrument light path is the LGS dichroic, which sends 589 nm light from the ELT's six LGS to the LGSS. As the LGS asterism is projected from the periphery of the ELT primary (M1), it co-rotates with the telescope pupil, and the LGSS needs its own de-rotator to compensate. The Calibration Unit can insert light from calibration lamps via fold mirrors into the beam path, mimicking the telescope f-ratio and pupil location. It provides line and continuum sources for all science and technical calibrations, including all AO calibrations. The Instrument Static Structure (ISS) provides a robust mechanical structure and access to all instrument systems. The LGSS, NGSS, Focal Plane Relay System (FPRS) and the Calibration Unit (CM) will be integrated at LAM, Marseille. In parallel, the IFS will be integrated at the UK ATC, Edinburgh.

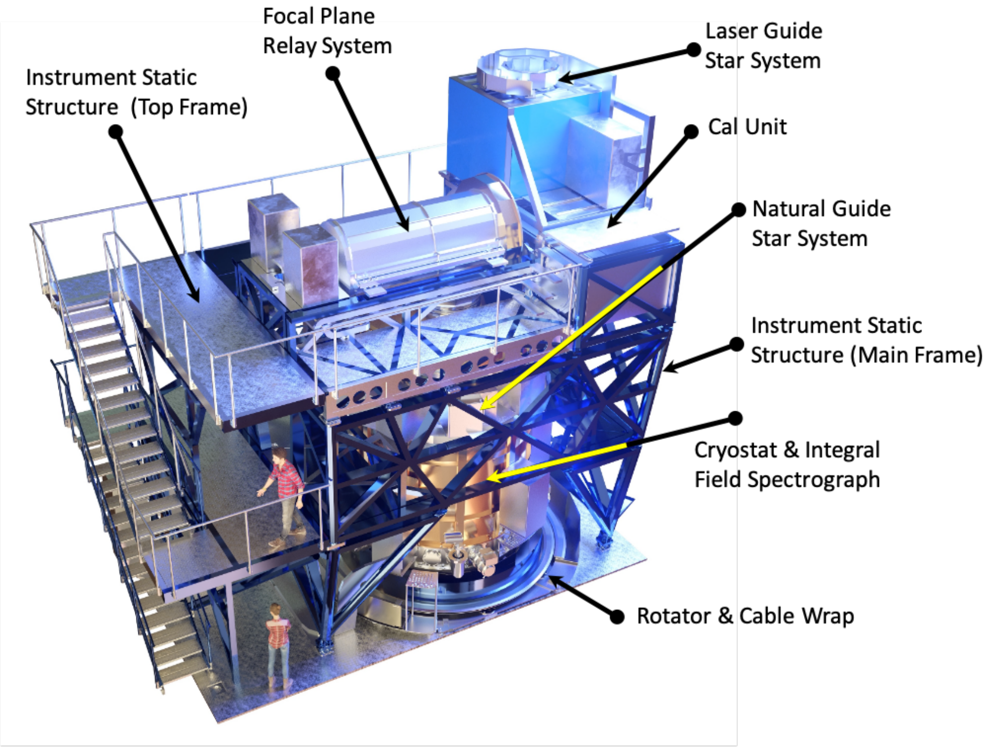

Figure 4. CAD layout of the HARMONI instrument, located on the ELT's Nasmyth platform, with the major sub-systems identified.

5. TRANSFORMATIONAL SCIENCE

HARMONI provides a range of spaxel scales and spectral resolving powers, enabling a huge leap in understanding the physical phenomena that underpin the formation and evolution of a wide range of astrophysical sources. Combining superb sensitivity with diffraction limited spatial resolution, HARMONI will carry out studies of physical properties (via morphology), chemical composition (via abundances and line ratios), kinematics (via line-of-sight velocities) and dynamics (via line widths and velocity dispersions) of astrophysical sources.

In what follows, we showcase some key science areas where HARMONI is expected to revolutionize the field, with the help of our detailed HARMONI simulator, HSIM[2]. It goes far beyond computing SNR, providing quantitative predictions for the accuracy of physical parameter estimates of targets.

5.1 Science simulations:

SN Ia: Confirming type Ia supernovae with HARMONI spectroscopic observations will enable studies of cosmic expansion rates to be pushed to substantially higher redshifts. In recent simulations, Bounissou et al.[6] (2018) showed that HARMONI LTAO can provide direct spectroscopic classification of a supernova in a galaxy at z~3 in a 3 hour observation, up to 2 months past maximum light, using the Si II feature (at 400 nm in the rest frame).

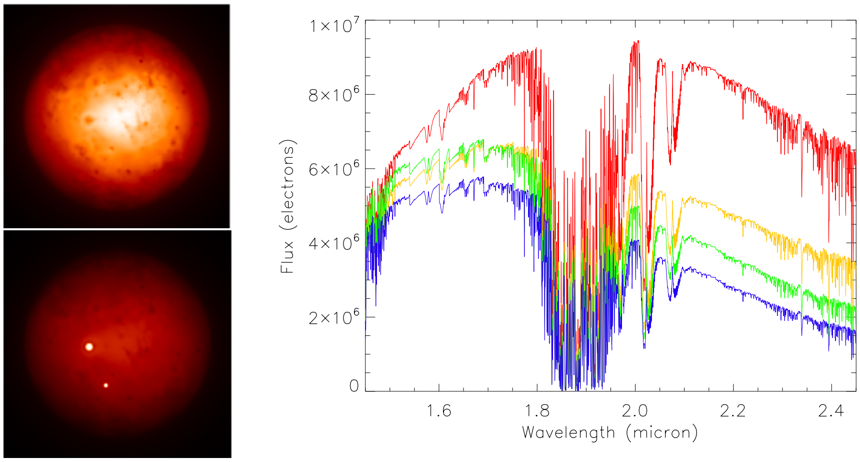

Figure 5: Simulated images of Io, observed with HARMONI at 4×4 mas scale, without deconvolution. The bottom image shows two volcanic hot spots that dominate the near-IR emission, while the top image is in a quiescent state. Simulated spectra of four hot-spots at different temperatures ranging from 600 K to 1200 K are also shown.

Solar system objects: As an example of its huge potential, we highlight an exciting case that has been developed in tandem with the instrument design. Groussin et al. (2022, in prep) have simulated observations of Io, a volcanically active moon of Jupiter, using the HARMONI simulator HSIM[3]. The active volcanism is expected to show up as hot spots on the moon's surface, as shown in Figure 5. SCAO observations at 4×4 milli-arcsecond scale, with the HK grating (R~3000), would allow measurement of the temperature and possibly plume chemistry of the hot-spots. Expected spectra for a range of temperatures, ranging from 600K to 1200K, are also shown in Figure 5.

These observations can easily distinguish between two different compositions of the ejecta – ultra-mafic or sulphuric. Io's size is small enough, and it is bright enough to be used as a reference for the SCAO wavefront sensing. Integral-field spectroscopy is ideal for this type of object, where accurate measurement of the ejecta's temperature requires deconvolution in both spatial dimensions, impossible with a long slit. Detailed work providing accurate estimates of the instrument point spread function (PSF) are also being undertaken, both via recording of the telemetry data (part of the AO control system (AOCS) work package), and through the development of TIPTOP[4], a PSF estimator led by B. Neichel at LAM, Marseille. A few minutes exposure with HARMONI has the potential to provide an information-rich data set for Io, comparable to that obtained by probes sent to the Jovian system.

Understanding the physics of galaxies from the very young Universe to cosmic noon: A key science area where HARMONI is expected to make significant contributions is in our understanding of galaxy mass assembly and evolution. With HARMONI we can study the structure, gas inflows and outflows, and gravitational instabilities in the rapidly growing galaxies in the young Universe at redshifts > 3. Simulation work in this area has already shown promising results. Using the adaptive mesh refinement cosmological simulations from the NEW HORIZON suite we have predicted how high-z galaxies will be viewed by HARMONI (Richardson et al. 2020[5]). We are able to extract a spatially resolved rotation curve for a 1.25 L_* galaxy (with an SFR of 3 $M_\odot$/yr) at z~1.5 with only one hour of observing time.

Stellar kinematics and dynamic studies require longer exposures, as they use absorption lines of starlight. Kendrew et al.[10] (2016) showed that a 10 hour observation with HARMONI can achieve sufficient signal-to-noise (SNR) for log $M_\star/M_\odot$=11 galaxies with de Vaucouleur light profiles at redshifts up to 3, and for log $M_\star/M_\odot$=12 galaxies at z < 4 and beyond with any light profile. For spatially resolved observations of the stellar light, a 15 hour observation with HARMONI can provide spatially resolved line of sight velocities (i.e. stellar rotation curves), as well as velocity dispersions, for 30L_* objects at z~3, 13L_* objects at z~1, and 0.1L_* objects at z~0.1.

In a follow-up study, Grisdale et al.[7] (2021) used NEW HORIZON simulations, post-processed using the CLOUDY[A] radiative transfer code (the LCARS pipeline) to show that HARMONI LTAO could confirm the presence of the first stars (Pop III stars) in galaxies at very high redshifts (z = 3-10). Pop III stars are expected to be substantially more massive than their metal-rich cousins, and burn hotter, with high UV luminosities. The strength of the He II 1640 Å line is thus a good observational diagnostic for the presence of Pop III stars. Our simulations show that HARMONI LTAO would detect the He II line with good signal-to-noise from a substantial fraction of z>6 galaxies in a ~10 hour exposure.

Our latest effort has focused on simulations of 'cosmic noon' galaxies, and how HARMONI observations will provide a detailed insight into their physical and dynamical properties. As an example, we have used the LCARS[B] pipeline to investigate the impact of minor mergers on 'Main Sequence (MS)' galaxies and looked for evidence of disk settling using v/σ ratios. Using the NEW HORIZON simulations of z~2 galaxies and the LCARS pipeline (which includes radiative transfer computations using CLOUDY[9]), we have been able to predict Hα emissivities for each galaxy cell. The effects of dust extinction within each simulated galaxy are also included, as the light from each cell is propagated through all other cells along the line of sight. These input datacubes are 'mock observed' using the HARMONI simulator, HSIM[3]. We are also able to discern the efficacy of well-understood analysis techniques (such as diskfit, Galpak3D, Barollo3D) to analyze potential HARMONI observations of gas kinematics. Results are presented in Grisdale et al.[8] (2022) and Hogan et al. (2022, submitted).

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[A] For details on the CLOUDY radiative transfer code see Ferland et al. 2017[9]

[B] LCARS stands for Light from Cloudy Added to RAMSES (Grisdale et al. 2022[8])