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# HARMONI: a single-field, wide-band, integral field spectrograph for the European ELT

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## ABSTRACT

We describe the results of a Phase A study for a single field, wide band, near-infrared integral field spectrograph for the European Extremely Large Telescope (E-ELT). HARMONI, the High Angular Resolution Monolithic Optical & Near-infrared Integral field spectrograph, provides the E-ELT's core spectroscopic requirement. It is a work-horse instrument, with four different spatial scales, ranging from seeing to diffraction-limited, and spectral resolving powers of 4000, 10000 & 20000 covering the 0.47 to 2.45 μm wavelength range. It is optimally suited to carry out a wide range of observing programs, focusing on detailed, spatially resolved studies of extended objects to unravel their morphology, kinematics and chemical composition, whilst also enabling ultra-sensitive observations of point sources.

We present a synopsis of the key science cases motivating the instrument, the top level specifications, a description of the opto-mechanical concept, operation and calibration plan, and image quality and throughput budgets. Issues of expected performance, complementarity and synergies, as well as simulated observations are presented elsewhere in these proceedings[1].

**Keywords:** integral field; spectrograph; diffraction-limited; near-infrared; image slicer; cryogenic; ELT.

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# 1. INTRODUCTION

Integral field spectroscopy has matured as a technique during the last ten years, and now provides the primary medium resolution near-infrared and visible wavelength spectroscopic capability at 8–10 m class telescopes worldwide. Integral field spectrographs (IFS) are best suited for spatially resolved studies of extended objects, where they provide homogenous data cubes in a time-efficient manner, and they are at least as good as slit spectrographs in obtaining spectra of point sources. The latter capability came about when dedicated instruments were built to exploit the advantages of integral field spectroscopy, rather than as add-ons to slit spectrographs. Integral field instruments provide a point-and-shoot capability that minimizes difficulties in acquisition and maximizes telescope operating efficiency, as there is no need for pre-imaging.

The European Extremely Large Telescope (E-ELT) will be the flagship visible and near-IR ground based capability of European astronomers in the next decade. With its unique combination of enormous collecting area, and unsurpassed spatial resolution (it is a fully adaptive telescope), it has the power to transform the landscape in observational near-IR and visible astronomy. HARMONI, the High Angular Resolution Monolithic Optical & Near-infrared Integral field spectrograph, is one of the proposed E-ELT instruments, for which we have carried out Phase A study, partly funded by the European Southern Observatory (ESO).

HARMONI is a visible and near-infrared (0.47 to 2.45 μm) integral field spectrograph, providing the E-ELT's core spectroscopic capability, over a range of resolving powers from R ($\equiv\lambda/\Delta\lambda$) ~ 4000 to R~20000. The instrument provides simultaneous spectra of ~32000 spatial pixels (spaxels) in the near-IR (~8000 in the visible) arranged in a 2:1 aspect ratio contiguous field. HARMONI provides a range of spaxel scales, which permit the user to optimally configure the instrument for a wide range of science programs. HARMONI can also easily adapt to any flavour of adaptive optics (AO) at the E-ELT, ranging from the modest correction of Ground Layer AO (GLAO), to the full diffraction limited capabilities of Single Conjugate AO (SCAO) and Laser Tomographic AO (LTAO), where it will capitalise on the $D^4$ sensitivity gains of the E-ELT.

HARMONI is conceptually simple (for a 42 m telescope instrument), and will be easy to calibrate and operate, providing the E-ELT with a "point and shoot" spectroscopic capability. It is based on a proven concept, and requires no significant R&D before it can be built.

# 2. SCIENCE DRIVERS

The combination of light grasp, very high spatial resolution and spectral resolutions offered by the ELT + HARMONI present an exceptional opportunity for new astrophysics. The spectral coverage from red to near infrared naturally brings cool objects, highly extincted regions and high redshift objects to centre stage in the science case. The evolution of galaxies dominated by old stellar populations, the study of the complexities of galaxy nuclei and the plethora of high redshift exotica are all featured. HARMONI can excel at follow-up spectroscopy of exo-solar planets detected by the upcoming generation of dedicated planet finders. Cases on circumstellar disks, star formation regions and solar system objects are under development.

It is often the combination of high spatial resolution and sensitivity that showcase HARMONI's capabilities best. Galaxy nuclei are complex environments. Stars and gas move in the combined potential of the stellar and black hole mass, nuclear star clusters and star forming regions are common in lower mass galaxies, ionised and molecular gas swirls around the central dormant or active nucleus. In such a diverse environment, HARMONI will slice up the astrophysics into simpler, tractable problems.

## 2.1 Key Science Cases

**Black Holes and AGN:** The stellar motions will be measured with great precision to reveal estimates of the mass of central star clusters or black holes, thus extending the relationship between the central massive object and its host galaxy down to the low mass limit of galaxies. Sophisticated work currently only possible in the nearest AGN (Centaurus A) will be possible out to the Virgo cluster. The evolution of the black hole - galaxy relation will be traced out to z=2, the peak epoch for AGN activity. Exploiting the 3D nature of the data to spectacular advantage, the emission lines from quasar BLRs make ideal beacons of the PSF and by combining photometry from the reconstructed image with kinematic measurements from the stars it will be possible to place quasar host galaxies on the Fundamental Plane. Furthermore these systems will provide a sound basis to cross calibrate the stellar dynamical and "virial mass" (based on the continuum luminosity and H-beta line width) estimates of the central black hole so that these measurements can be extended to still greater redshifts.

**Resolved stellar populations in elliptical galaxies:** The chemical and dynamical evolution of galaxies is imprinted in their resolved stellar populations, which provide the archeological record of their star formation history and dynamical assembly[2]. One of the principle goals of the E-ELT is to study the resolved stellar populations of massive galaxies spanning the full range of morphologies (inc. giant ellipticals for the first time), going beyond the Local Group, with the ultimate goal being to reach the Virgo cluster. The galaxy groups Centaurus (3.5 Mpc) and Leo (10 Mpc) are well within reach (including two ellipticals: Centaurus A and NGC3379), as are spiral systems in Sculptor, starburst galaxies and compact dwarf elliptical galaxies. By making direct measurements of the chemo-dynamical properties of resolved stars, one can trace the relative enrichment by Type II and Ia SNe at any given time in the star formation history of a galaxy. Homogenous spectroscopic surveys enable an accurate study of the current dynamical state and thus dark matter masses and distributions in these systems as well as their chemical evolution.

**Galaxies at the peak of the star formation epoch (z ~2–3):** The most actively star forming galaxies (ULIRGs) are rare and spectacular objects in the local universe, but we know that at high redshifts such objects are increasingly common. Understanding where these objects fit in the evolutionary history of active and quiescent galaxies remains a mystery that will be addressed by HARMONI's combination of sensitivity and resolution together with its ability to penetrate into these highly extincted nuclei. HARMONI will also reveal the structure of star forming and emission line regions, make mass estimates based on kinematics and identify the recent merger history of these objects to identify where they fit in the assembly history of normal galaxies. A detailed description of this science case, including simulated observations, are presented in Arribas et al.[1] in these proceedings.

**First light:** The Lyman-alpha emitters that are the very first galaxies are also amenable to analysis with HARMONI. It should be possible to detect these objects out to redshifts z~10-11 (if they exist), well beyond the reach of MUSE at the VLT. In so doing HARMONI will probe the epoch of re-ionisation and elucidate how the very first heavy elements were created (we know they are in place at z~6). Finally for galaxy evolution a mosaicked 'HDF' (HARMONI Deep Field) will detect tens of extremely high z galaxies.

**Supernovae:** If E-ELT can be operated contemporaneously with JWST, a survey of high redshift supernovae with HARMONI offers the prospect of measuring the evolution of the equation of state of Dark Energy. A positive detection of a changing value of w(z) will rule out models based on the Cosmological Constant and open the way for models of space time based on new physics.

**Extra-solar planets:** Although HARMONI is not optimized for the direct detection (and simultaneous spectroscopy) of extra-solar planets (EPICS is the dedicated Planet Finding instrument at the E-ELT [6]), it will be extremely well suited for follow-up spectroscopy of exo-planets found by the upcoming generation of planet finders (e.g. VLT/SPHERE, Gemini/GPI). These are expected to be typically too faint (H~25) to be observed at moderate (R~4000) and high (R~20000) spectroscopic resolution with 8–10 m class telescopes. HARMONI will answer the key question: What are the physical properties of exo-planets? HARMONI data will unambiguously allow us to determine the spectral type, surface gravity, effective temperature and atmospheric composition of the planets. These four parameters, combined with the age, luminosity and metallicity (derived from analysis of the parent star), can provide stringent constraints to models, where huge uncertainties exist at present. Gladysz et al. [5] present simulations of the high contrast performance of HARMONI in these proceedings.

### 2.2 Object sizes and Fields of View

Experience with the ESO-VLT instrument SINFONI [9] has shown that the most reliable sky background subtraction can be obtained by nodding-on-IFU, i.e. alternately placing the object at two non-overlapping locations within the IFS field of view in sequential exposures, akin to nodding-on-slit for long slit spectrographs. This is likely due to the limitations arising from flat-fielding errors. For this reason, the HARMONI FoV has a 2:1 aspect ratio, as illustrated in Figure 1. In addition, it allows larger source extents to be accommodated along one axis, as required for probing jet physics of AGN, or studying the circum-stellar environments of young massive stars.

The field size and spaxel scales are chosen to match the typical source extents and sizes of structures probed, respectively. At a typical redshift of z~2, an HII region complex with an approximate size of 100–200 pc has an angular extent of 10 to 20 mas, making these spaxel scales ideally suited to the studies of galaxies (and their progenitors) at high redshift. The corresponding FoV size (for 128 spaxels, the short axis of the HARMONI field) is 1.25″– 2.5″, which covers almost the entire range of targets of interest beyond z~1. Note that the full extent of the object is significantly larger than the half light diameter, we adopted a value of $2.5 \cdot D_{\text{half-light}}$ as the source extent for our computations.

## 3. SPECIFICATIONS

Based on the requirements derived from the key science drivers, (as described above), the HARMONI Phase A design reflects the following instrument specifications:

- HARMONI has four spaxel scales of 40, 20, 10 and 4 milli-arcseconds/spaxel
- HARMONI provides an instantaneous FoV of ≈128×256 = 32,768 spaxels. For the four spaxel scales, this corresponds to a FoV = 10.0″ × 5.0″, 5.0″ × 2.5″, 2.5″ ×1.25″, 1.0″ × 0.5″.
- HARMONI will cover the wavelength range from 0.47 to 2.45μm
- HARMONI will operate at resolving powers of $R(\equiv\lambda/\Delta\lambda) \approx 4000$, $R\approx 10000$, and $R\approx 20000$
- Instantaneous wavelength coverage of at least one band at a time at R≈10000 (V,R,I,zJ,H,K), two at R≈4000 (VR, IzJ, HK)
- Instrument throughput > 35% average over 0.82 – 2.4μm.
- Instrument thermal background less than 20% of telescope (goal 10%)
- At each spaxel scale, HARMONI's image quality, considering pre-optics, the IFU, and the spectrograph, shall not degrade by more than 20% the FWHM of a source with an intrinsic size of two spaxels (FWHM) in the bands from I to K (goal 10%).

Two of these specifications, namely (a) operating at higher spectral resolving powers (R≈10000 & 20000) and (b) extending the wavelength coverage below 0.8 μm, were optional in the "Call for Proposals" for the HARMONI Phase A study. We performed a trade-off of the scientific benefits of these capabilities against the additional cost, complexity & risk from implementing them, finding overwhelmingly in favour of implementing both these features.

The HARMONI Phase A design also satisfies all the other top level requirements, such as the presence of only a minimal amount scattered light from the instrument, or keeping the ghosts at an acceptably low level. HARMONI includes an internal calibration unit with continuum and emission line lamps illuminating a variety of focal plane masks, so that it is self-sufficient in its calibration needs.

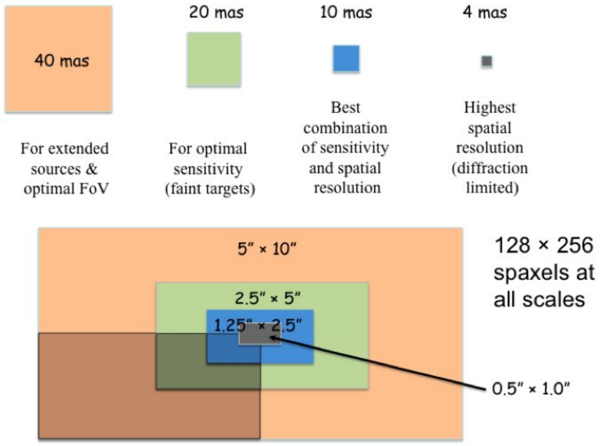

Figure 1: Range of spatial pixel (spaxel) scales provided by HARMONI, with the corresponding fields of view. The FoV at visible wavelengths is a quarter of the near-IR FoV, as shown by the darker rectangles in the lower left corner.

### 3.1 SCAO and Coronagraphic mode

SCAO, the E-ELT equivalent of Natural Guide Star (NGS) AO, is capable of achieving fully diffraction limited performance, albeit over a small field of view. This mode is particularly well-suited for HARMONI, with its modest FoV (smaller than the isoplanatic patch size), especially in the early years of the E-ELT, when the LGS may not be routinely available. Consequently, we have implemented a natural guide star (SCAO) wavefront sensor within HARMONI. Partial to full correction of atmospheric turbulence will substantially benefit several key science programs, such as characterisation of exo-solar planets, weighing supermassive black holes (SMBH) in galaxy nuclei, studying the environments of QSOs and their host galaxies, the circumstellar environments of young stellar objects and detailed studies of objects within our own solar system. The SCAO module of HARMONI is described in Fusco et al.[4] in these proceedings.

We have also studied the addition of a simple coronagraphic capability in HARMONI, which nicely complements the SCAO mode. The Lyot coronagraph involves an occulting mask in the focal plane, and an undersized pupil stop (with an oversized central obscuration). The two together provide effective suppression of both the peak of the light profile of bright objects, and the scattered light halo. The primary science driver is detailed follow-up spectroscopy of exo-solar planetary candidates. Although HARMONI does not benefit from extreme AO correction, and is therefore limited to peak Strehl ratios of ~70%, the unique combination of E-ELT's vast collecting area and very small inner working angle makes it immensely powerful for detailed follow-up spectroscopy, esp. at R~4000. As near-IR detectors have persistence problems when exposed to bright objects, the simple coronagraph also benefits many other science programs, as it allows for long exposures times on fields with bright objects (thus reducing the effect of detector read noise). For example, coronagraphic observations would significantly improve sensitivity for observations of host galaxies of QSOs, or debris disks / circumstellar disks around young stellar objects.

## 4. OPTOMECHANICAL CONCEPT

Figure 2 shows the HARMONI instrument concept. HARMONI is positioned on the Nasmyth platform, adjacent to (but de-coupled from) the adapter/rotator (see Figure 4). All instrument sub-systems, apart from the calibration unit, are housed inside a cryostat, and cooled to ≈140K (the near-IR detectors operate at ≤ 80K). The only exception is the K-mirror, operated at ≈250K. Two cryostat windows (with broad band anti-reflection coatings) allow light from the telescope and the calibration unit to enter the cryostat. The instrument has three main components: (a) the pre-optics (b) the IFU and (c) the spectrographs. A slow shutter at the entrance makes the instrument light-tight, allowing daytime calibrations without disturbing anything or being disturbed.

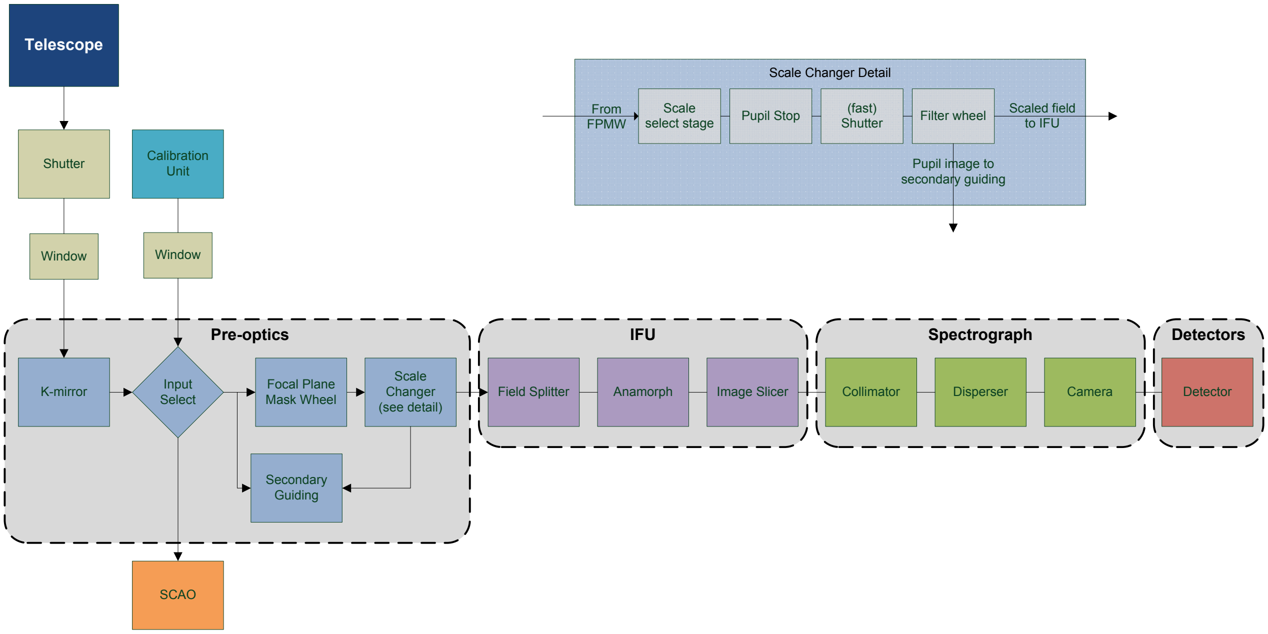

Figure 2: Block diagram showing the conceptual layout of the HARMONI sub-systems. Each sub-assembly is enclosed in a gray box. The details of the scale changer sub-assembly are shown separately.

### 4.1 Pre-optics

The pre-optics performs several functions: field de-rotation, input selection, scale changing, secondary guiding, and pupil imaging. It also provides focal plane masks, pupil stops, a fast shutter and order-sorting filters. Field de-rotation yields a fixed FoV on the sky, and is provided by a K-mirror with a 19″ diameter field, driven by a signal from the telescope control system (TCS). The input select mechanism has three positions, allowing either light from the telescope or from the calibration unit to be fed to the instrument. The third position houses a dichroic, which splits the visible light ($\lambda <$ 0.9μm) to the SCAO wavefront sensor, whilst the near-IR light (0.95 μm $< \lambda <$ 2.45 μm) is used for spectroscopy. The scale changing optics magnifies the incoming beam, resulting in one of four spaxel scales (40, 20, 10 and 4 mas per spaxel). The focal plane at the output of the pre-optics has a fixed size (50 × 100 mm) for all scales. Each scale is implemented as a collimator-camera combination, with an intermediate pupil image formed in between the two. 1% undersized pupil stops are located at this pupil plane, and just behind it is a fast shutter, and a wheel with order-sorting filters.

Secondary guiding senses a natural star (or compact galaxy) outside the HARMONI field, but within the K-mirror's 19″ diameter field, to provide compensation (at ~1Hz) for any differential image motion between the telescope (or AO) wave-front sensor and the instrument focal plane. The HARMONI FoV is offset from the telescope optical axis, so as to provide a larger sky coverage for the secondary guiding. Depending on the telescope PSF, the required accuracy changes substantially, so the secondary guiding implements both visible and near-IR sensing to optimise the sensitivity (near-IR is more sensitive when the PSF is sharper). Pupil imaging is performed by redirecting the light from the scale-changer, picked-off past the pupil stop, to the secondary guiding near-IR detector. The pupil image shows the instrument pupil stop superimposed on the telescope pupil illumination pattern, permitting a one-off alignment

The focal plane mask wheel allows various field stops to be inserted in the focal plane, as well as line and pinhole masks for trace and PSF calibration, respectively. An occulting stop is also available, which, combined with a Lyot stop in the pupil plane, provides a simple coronagraphic mode for HARMONI. All optics before the disperser, apart from the cryostat window, order sorting filters and one lens in the scale-changer, are reflective, with protected silver coatings, ensuring high performance over a wide wavelength range. Only the 4 mas scale contains a lens, as it is foreseen to use this scale only in the near-IR.

### 4.2 Integral Field Unit

The light from the scale changer feeds the integral field unit, whose task is to reformat the HARMONI FoV into 256 slitlets, each 128 spaxels long. The reformatting is done in two stages, a 4-way field split, followed by 4 image slicers, each producing twin long slits, comprised of 32 slitlets, 128 spaxel long. All splitting and slicing is done in a focal plane, so as to provide sharp boundaries and preserve high throughput (with very little scattered light). The 4-way field splitter, located at the exit focal plane of the scale changer, feeds 4 anamorph modules. Each anamorphic magnifier re-images a quarter of the field on to an image slicer (also located in a focal plane). The magnification is a factor of 2 larger in the direction that runs across the slices, than along the slices. Thus, each slice maps onto 128 detector pixels along its length, and 2 across its width, but maps to 128 × 1 square spaxels in the FoV. Anamorphic magnification increases the packing density of spectra on the detector (1 spectrum per detector column), whilst maintaining the Nyquist sampling criterion along the spectral axis (i.e. two detector pixels per slice width).

The image slicer(s)[7] at the heart of the IFU converts a two-dimensional input field to a pair of pseudo "long slits". The HARMONI slicer uses two sets of flat slicing mirrors (to ensure better surface quality, a heritage from SINFONI & the Oxford SWIFT spectrograph[8]), and a set of spherical de-magnifying mirrors at the exit. The slicer will be made from Zerodur, with optically contacted surfaces, ensuring close to 100% fill-factor, and high throughput. It should be emphasized that although each slice subtends 4 mas on the sky at the finest spaxel scale (corresponding to half the diffraction limited FWHM of the telescope), the light loss from diffraction at the image slicer is below 4% at the finest scale. Scale-changing takes place prior to the IFU, thus the IFU and spectrograph optics are sized to accommodate the 40 mas spaxel focal ratios, resulting in the HARMONI optics being oversized by a factor of 10 when operated with 4 mas spaxel. Although diffraction at the slicer increases the focal ratio of the beam, all the diffracted light is correctly processed by the IFU and spectrograph optics, ensuring very little light loss, and sharp images at the detector.

### 4.3 Spectrographs

HARMONI consists of eight spectrograph modules, two of which are additionally equipped with visible wavelength capability (these two modules use one of the fold mirrors to re-direct light to an alternate disperser wheel, followed by a visible camera and a CCD $4096^2$ pixel detector). Each of the eight near-IR spectrographs dispersers the light from one pseudo long slit on to a Hawaii4 ($4096^2$ pixel) detector, producing ~4000 spectra, each 4000 pixels long. Each spectrograph is composed of a three element (TMA) collimator, a set of dispersers (10 in the near-IR, 5 in the visible), and a camera. Volume Phase Holographic gratings (VPHG) are chosen as the dispersers, chiefly due to their high throughput (>75% average). However, to achieve the high efficiency, each disperser must work at a specific angle (Bragg angle), making it impossible to use the same disperser for different bands or different resolutions. Consequently, a grating wheel mechanism in each spectrograph module houses 2 low-resolution (R~4000), 4 medium-resolution (R~10000) and 4 high resolution (R~20000) dispersers. Figure 3 shows the layout of a quarter-field module, comprising of one image slicer feeding two spectrographs.

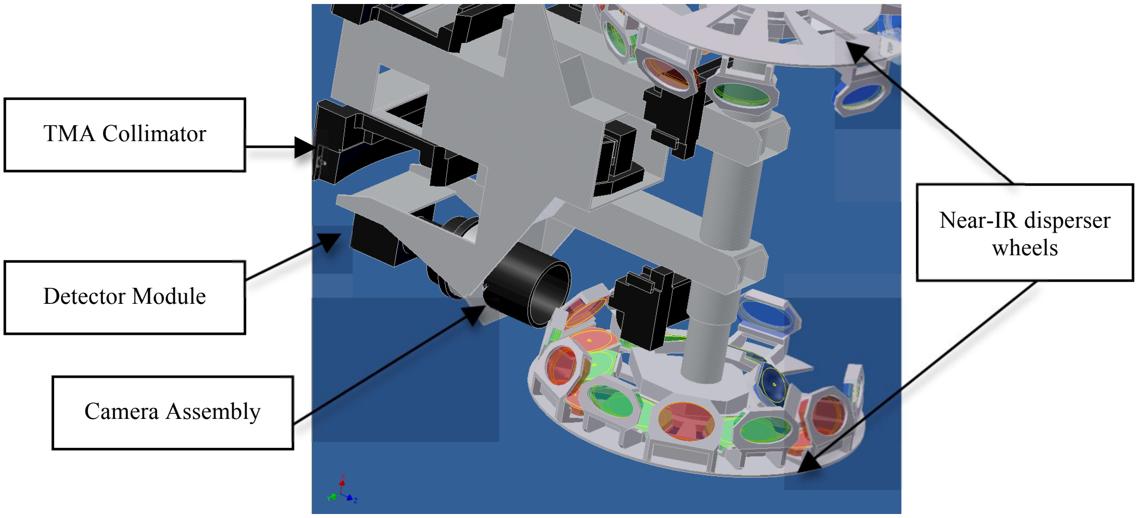

Figure 3: Layout of the quarter field module of HARMONI, showing the near-IR disperser wheels, camera and detector assemblies (the visible cameras / disperser wheels are not shown).

Only two spectrograph modules have a visible channel, because the coarser resolution provided by the E-ELT AO at visible wavelengths obviates the need to use finer spaxel scales, and a 64 × 128 spaxel FoV is sufficient. Five dispersers, 1 low-resolution, 2 med-resolution and 2 high-resolution cover the visible range. Light is directed to the visible channels through an "open" position in the near-infrared disperser wheel (see Figure 3).

The detectors are housed in their own module, which includes thermal and electrical circuits, and a focus mechanism. 8 near-infrared and 2 visible $4096^2$ detectors are used, plus one $2048^2$ near-IR and one $1024^2$ CCD for secondary guiding (the latter two are located in the pre-optics)

## 4.4 Cryostat

Sensitive H&K band observations require that the instrument's contribution to the thermal background be a small fraction (20%, goal 10%) of that from the telescope. This requirement translates to the need for HARMONI to be a fully cryogenic instrument. All the opto-mechanical elements are housed inside a cryostat, and cooled to a temperature of ~140K, except the near-infrared detectors, which are operated at ~80K. A radiation shield, also at ~140 K, reduces the heat flux, and ensures that the detectors are never exposed to any radiation from warm surfaces.

The cryostat (see Figure 4) is a cylinder of ~4.3m diameter, ~4.1 meters long, and is composed of removable front and back sections, attached to a fixed mid section. The radiation shield is also in two removable parts, and connects to a central ring, which is attached to the mid-section by thermally isolating, mechanically stiff, A frame composite trusses. The central ring, with its two cross-bars forms the "bench", providing the mounting point for all opto-mechanical assemblies. The mid-section is held by a cradle, which in turn provides the rigid attachment to the telescope Nasmyth platform via a pedestal. The pedestal also elevates the cryostat axis to be 4m above the Nasmyth platform, so as to align the main window with the telescope optical axis. The central section is also the entry and exit point for all cryogenic services, including cooling (both cryo-coolers and LN2 pre-cool system), vacuum pumps & gauges, and electrical feedthroughs for detectors, moving mechanisms and house-keeping functions. Electronics cabinets (temperature controlled by a chilled water system) located close to the cryostat, within its footprint, house the instrument electronics, with the exception of the NGC detector controllers, which are mounted to the cryostat mid-section, to minimise cable lengths to the detectors.

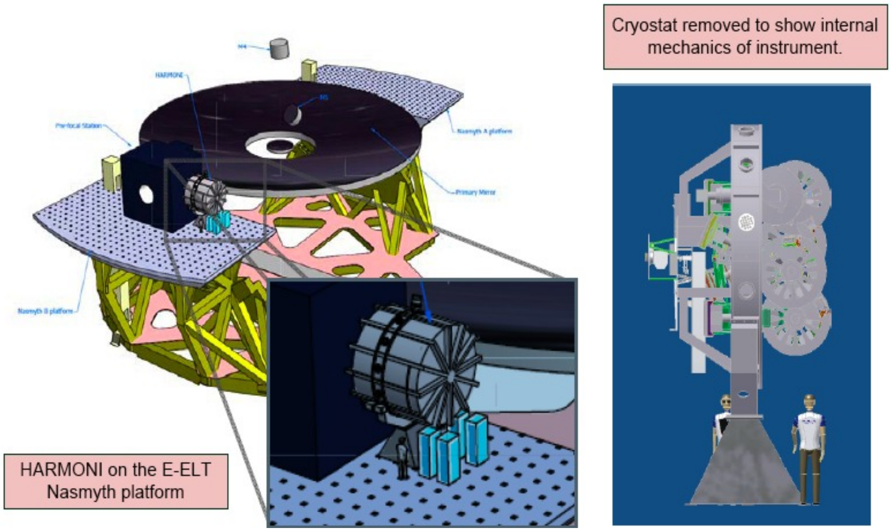

Figure 4: CAD rendering of HARMONI located at the Nasmyth platform of the E-ELT (note that the E-ELT primary mirror is represented unrealistically). The right panel shows the instrument opto-mechanics, the pre-optics are on the left side of the pedestal, and the disperser wheels can be seen to the right. (cryostat removed for clarity)

### 4.5 Cryo-mechanics

HARMONI houses 40 mechanisms within the cryostat (+ 2 for the SCAO module). This is made up of 10 disperser wheels, 10 articulated fold mirrors for the dispersers, 12 detector focus mechanisms (for spectrographs & secondary guiding), scale-changer, filter-wheel, fast-shutter, focal plane mask wheel, input select, pupil imaging selector, and the K-mirror. All mechanisms, including the large disperser wheels, have a heritage from cryogenic instruments already built, and are (or have been) in regular operation. A possible exception is the K-mirror, for which a commercial solution has been found that satisfies thermal, vacuum, and operational specifications.

The optics are grouped into sub-assemblies that are functionally well defined, and usually interface with other sub-systems at focal or pupil planes. They have been designed so that they can be assembled and tested as sub-units, easing the assembly, integration and verification (AIV) process dramatically. Tighter tolerances within sub-systems can be achieved with good engineering, allowing entire sub-assemblies to be positioned within the cryostat using reference surfaces and pads. Individual components, such as mirrors, lenses, and gratings, are mounted using tried-and-tested mount designs, that make allowance for thermal contraction without stressing the optical element. Most sub-systems are fully reflective, and can be tested at visible wavelengths. We plan to cryo-test most sub-assemblies, although in some cases we will also design null lenses to aid room-temperature alignment and calibration, especially those where multiple iterations are required to optimise many performance specifications simultaneously.

## 5. OPERATION AND CALIBRATION

HARMONI is very simple and easy to operate. There is only one observing mode, IFU spectroscopy. This is broken into two sub-modes, (i) visible and (ii) near-IR IFU spectroscopy, due to different observing strategies, as a consequence of the use of different detectors (in number and characteristics), telescope image quality, atmospheric properties (background, dispersion), etc. In all aspects of acquisition, observation, and calibration, HARMONI is no different than its pre-cursor instrument at the ESO-VLT, SINFONI (except for secondary guiding). Aspects such as nodding, jittering, mosaicking are entirely analogous to the same operations carried out with SINFONI, and we can build upon the years of experience gained from operating and calibrating SINFONI. Even the diffraction limited mode is a direct parallel of the same mode on SINFONI.

### 5.1 Acquisition and science observations

Operation involves a sequence of activities that are broadly divided into acquisition and science observations. Acquisition consists of a telescope preset, and in parallel, an instrument set-up which involves setting the spaxel scale, choosing the disperser, setting the Position Angle (PA) on the sky, and inserting any additional components (e.g. coronagraphic mask), if required. The various sensors in the telescope and AO system then need to acquire their reference stars (natural or artificial) before observations can commence. The exact details depend on the flavour of AO being used. When the telescope and AO system are tracking, an optional short acquisition exposure is taken to verify the location of the target within the FoV, and make any adjustments to its position, if required. This is aided by a special real-time display (RTD) that shows reconstructed images of the HARMONI FoV, summed over a user-defined wavelength range, mimicking an acquisition camera. Once the target is at the desired position, science observing can commence.

Science observations typically consist of a sequence of 4n exposures, following an ABB′A′ pattern. Typically, the object is nodded between the left and right halves of the FoV between A & B exposures, and its position is adjusted by a few spaxels (jittered) between A & A′ (or B and B′) exposures. The quick-look pipeline will be capable of handling such a "nodding-on-IFU" sequence to produce reduced data-cubes (from which the instrument signature has been removed) on a ~15 min time-scale, that can be used to judge the quality of the data.

### 5.2 Secondary guiding

Secondary guiding provides an on-instrument image position sensor, compensating for differential flexure. As shown in Figure 5, the HARMONI FoV is offset w.r.t. the telescope optical axis, so as to allow part of the light passing through the K-mirror to be directed to a secondary guiding sensor. This sensor provides slow compensation (~1 Hz) for any flexures or mis-alignments of the instrument relative to the de-rotated focal plane. It does this by measuring the centroid of natural stars / galaxies down to $K_{Vega} > 23$, providing almost complete sky coverage. Visible wavelength sensing is also available, for use with GLAO. The secondary guiding only provides a differential correction signal, which is used to drive the telescope pointing. HARMONI can also operate without secondary guiding, using a look-up table, and running open loop to correct known mis-alignments.

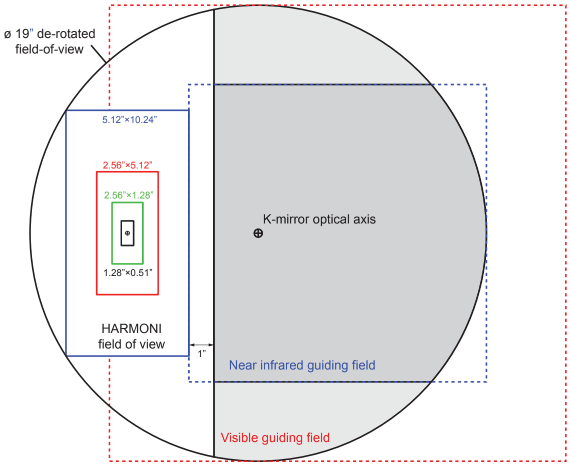

Figure 5: Layout of the HARMONI fields of view at different spaxel scales, and the secondary guiding fields (at near-IR and visible wavelengths) within the 19 arcsec diameter K-mirror de-rotated field.

### 5.3 Calibration

HARMONI is equipped with a self-contained calibration system, that provides uniform white light and arc lamp illumination over the entire field of view, with the required flux levels at all spaxel scales. A focal plane mask wheel located in the telescope focal plane provides trace and pinhole masks to calibrate each detector pixel in terms of its x,y co-ordinates on the sky relative to the field centre, and its wavelength, λ. In addition, the pinhole mask also allows a measurement of the spectral and spatial PSF of the instrument over the entire field.

Calibrations are very similar to those required by VLT-SINFONI, and the required exposure times are similar too (~ 3 to 4 hours of daytime calibration, in total, dominated by long exposure dark frames). The E-ELT instruments are specified to be light-tight, and can be calibrated in parallel.

## 6. IMAGE QUALITY AND THROUGHPUT

The HARMONI Phase A design satisfies two important top level requirements that dictate the scientific performance of the instrument. The throughput requirement specifies that HARMONI provides an average throughput of 35% in the near-infrared range (0.82 to 2.4μm) in its primary mode (R~4000). The image quality requirement for an integral field spectrograph needs a complex defintion, as the image is "sampled" in one dimension at the image slicer, but in the other dimension at the spectrograph detector. Furthermore, different spaxel scales that span an order of magnitude in spatial resolution need a specification that refers to each spaxel scale. Thus, HARMONI is specified to not degrade an input PSF with FWHM of 2 spaxels (min. Nyquist sampling) by no more than 20% (goal 10%). This specification applies in one axis (across slices) to all optics up to the image slicer, and in the other axis (along slices) up to the spectrograph detector. Naturally, the spectrograph PSF is part of one budget, but not the other, so that, HARMONI, like all other slicer-based IFS, has a slightly better PSF along one axis (across the slices).

The table below shows the image quality and throughput budgets, and achieved values for the Phase A design for the main instrument sub-systems, following the level 1 breakdown shown in the block diagram (see Figure 2). It should be noted that the total image quality number is computed from combining ZEMAX PSFs that result from a full end-to-end optical model of the instrument – demonstrating that the HARMONI optical design is not a set of disparate sub-systems, but a unified whole where the sub-systems are properly integrated.

Table 1: Image quality and throughput budgets and Phase A design achieved values for HARMONI

| **Sub-system** | **Image Quality (FWHM pixels)** | | **Throughput (%)** | |
|---|---|---|---|---|
| | Budget | Achieved | Budget | Achieved |
| Pre-optics | 0.4 | 0.5 | 0.78 | 0.77 |
| IFU | 0.5 | 0.4 | 0.85 | 0.86 |
| Spectrograph | 0.94 | 0.4 | 0.6 | 0.61 |
| Detector | 0.4 | 0.4 | 0.94 | 0.95 |
| Margin | 0.56 (quadrature) | 1.0 (quadrature) | 0.02 | 0.03 |
| Total | 1.33 | 0.85 | 0.37 | 0.38 |

## 7. CONCLUSIONS

HARMONI at the E-ELT has strong synergies with other upcoming ground and space based facilities. E-ELT will be commissioned after ALMA has been operational for a few years and after the launch of JWST and GAIA. HARMONI will have similar resolution to ALMA, together they will elucidate the evolutionary connections between gas and dust, planets and star formation, AGNs and galaxy assembly. Both facilities are optimized for detailed studies of extended objects, probing their kinematics and composition, and illuminating the physical processes driving their evolution. By probing metallicities of main sequence stars deep into the Galactic halo, HARMONI will augment the picture of halo assembly built by GAIA. JWST will probe deep into the universe at thermal infrared wavelengths, but E-ELT will be more sensitive at the short infrared wavebands for medium / high resolution spectroscopic work, where the angular resolution gain over JWST will be a factor of seven. Therefore, HARMONI provides ideal complementarity to the imaging and low spectral resolution modes of JWST.

HARMONI is proposed as a work-horse instrument that provides the core near-infrared and visible spectroscopic capability of the E-ELT. It has a wide range of spaxel scales and spectral resolutions, so as to allow the observer to tailor the instrument configuration to the needs of the observing program, w.r.t. sensitivity, spatial and spectral resolution, field of view, simultaneous wavelength coverage and flavour of adaptive optics. It will harness the E-ELT's niche, providing ultra-sensitive, spatially resolved spectroscopy of distant (faint) objects, transforming the landscape of observational astronomy.

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