

Project overview of OPTIMOS-EVE: The fibre-fed multi-object spectrograph for the E-ELT

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ABSTRACT

OPTIMOS-EVE (OPTical Infrared Multi Object Spectrograph - Extreme Visual Explorer) is the fibre fed multi object spectrograph proposed for the European Extremely Large Telescope (E-ELT), planned to be operational in 2018 at Cerro Armazones (Chile). It is designed to provide a spectral resolution of 6000, 18000 or 30000, at wavelengths from 370 nm to 1.7 μm , combined with a high multiplex (>200) and a large spectral coverage. Additionally medium and large IFUs are available. The system consists of three main modules: a fibre positioning system, fibres and a spectrograph.

The recently finished OPTIMOS-EVE Phase-A study, carried out within the framework of the ESO E-ELT instrumentation studies, has been performed by an international consortium consisting of institutes from France, Netherlands, United Kingdom and Italy. All three main science themes of the E-ELT are covered by this instrument: Planets and Stars; Stars and Galaxies; Galaxies and Cosmology.

This paper gives an overview of the OPTIMOS-EVE project, describing the science cases, top level requirements, the overall technical concept and the project management approach. It includes a description of the consortium, highlights of the science drivers and resulting science requirements, an overview of the instrument design and telescope interfaces, the operational concept, expected performance, work breakdown and management structure for the construction of the instrument, cost and schedule.

Keywords: OPTIMOS, EVE, Multi Object Spectrograph, Fibre, Positioner, Optical, Near Infrared, E-ELT

1. INTRODUCTION

1.1 Introduction

The European Extremely Large Telescope (E-ELT) is expected to reveal a revolutionary view on the Universe enabling the study of extra-solar planets, of stellar populations in external galaxies, and of faint distant galaxies tracing the early history of the Universe. E-ELT observations will lead to breakthrough results addressing key issues like the origin of the first stars and galaxies, the nature of dark matter and dark energy, galactic evolution and the formation of stars and planets. The large collecting area of the 42 m primary mirror and its novel five mirror design make the E-ELT perfectly suited to perform spectroscopic observations over a large field of view.

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The E-ELT Science Working Group (SWG) recognized “the very strong science case for an instrument which provides multi-object spectroscopy from the R to the H band, with a multiplex of at least 100, a field of view of 10 arcminutes, and a spectral resolution of $R \sim 3000$, or more, subject to a trade-off. A goal would be to extend the spectral range further into the blue (and the red), and to include $R = 5000 - 10000$.” The SWG further noted that JWST will have no capability in this domain.

OPTIMOS-EVE is a fibre-fed, optical-to-infrared multi-object spectrograph designed to explore the large field of view provided by the E-ELT at seeing limited conditions. Therefore, OPTIMOS-EVE is well suited to be used in the early operational phase of the E-ELT and also beyond, when the atmospheric conditions will not be optimal to provide full adaptive optics corrections (estimated at least 30% of the time). OPTIMOS-EVE is one of the few E-ELT instruments under study that will explore the visible to near-infrared wavelength region.

OPTIMOS-EVE has been designed for the E-ELT Nasmyth focus and provides low-, medium-, and high-resolution spectroscopy ($R \sim 6000 - 30000$) from the ultraviolet to the near-infrared (0.37 to 1.7 μm) for multi-object studies of sources nearby and at cosmological distances. The fibre positioner provides the opportunity to observe over 200 single targets within the 10 arcmin field of view, or to combine the fibres into medium- or large-sized IFUs. The wavelength coverage of an individual spectrum ($\lambda/3 - \lambda/6$ in the visible and $\lambda/10$ to $\lambda/20$ in the IR) is a trade-off between spectral resolution, multiplex and detector cost. The baseline design includes a focal plate carousel and fibre positioner, two dual beam VIS/NIR optimized spectrographs where the beams are split by a dichroic. The 4 spectrographs have a very similar optical design and employ VPH gratings for optimal performance. The large wavelength coverage makes an ADC at the intermediate focus of the telescope desirable, especially for targets at large zenith distance (e.g. Magellanic Clouds).

The instrument top-level requirements were derived from the analysis of five key science cases provided by the Science Team. This led to a requirements matrix and the study of six optical designs¹, each with a different score on the scientific performance, the technical and operational feasibility, and the volume-, weight-, cost- and risk-budget. The design concept is compliant with the science expectations.

OPTIMOS-EVE may be a workhorse instrument for the E-ELT based on state-of-the-art technology and is able to address a major fraction of the E-ELT science cases, from extra-solar planets, stellar populations beyond the Local Group, properties of dark haloes, the intergalactic medium, up to the most distant galaxies accessible with the E-ELT. From its concept and design, it is a robust instrument, and it can be developed, manufactured and integrated using existing technologies. It will be ready for the early science operations of the E-ELT and should be considered for first generation. OPTIMOS-EVE provides unique capabilities, scientific potential and will be complimentary to future large ground-based (e.g. ALMA, SKA) and space-born (e.g. GAIA, JWST) facilities.

1.2 Consortium

The OPTIMOS-EVE phase A study is led by PI Francois Hammer (GEPI) and co-PI Lex Kaper (UvA) and Gavin Dalton (RAL;Oxford). The OPTIMOS-EVE consortium builds on the expertise of the FLAMES/GIRAFFE (optical fibre-fed multi-object spectrograph on the ESO Very Large Telescope), VLT/X-shooter (wide-band optical-to-near-infrared spectrograph) and Subaru/FMOS (fibre-fed near-infrared spectrograph) consortia. The following partners constitute the OPTIMOS-EVE consortium:

- GEPI: Galaxies, Etoiles, Physique et Instrumentation, Observatoire de Paris, France
- NOVA: Nederlandse Onderzoekschool Voor Astronomie, University of Amsterdam, Radboud University Nijmegen, NOVA-ASTRON, Dwingeloo, The Netherlands
- RAL: Rutherford Appleton Laboratory, Oxford, United Kingdom
- NBI: Niels Bohr Institute, Copenhagen University, Denmark
- INAF: Istituto Nazionale di AstroFisica (Osservatorio astronomico di Trieste & Brera), Italy

2. PRIMARY SCIENCE DRIVERS

The OPTIMOS-EVE phase A study Science Team studied a number of key science cases covering the three main science themes motivating the development of the E-ELT (Science Case for the E-ELT, Ed. I. Hook): (i) Planets and Stars; (ii) Stars and Galaxies; (iii) Galaxies and Cosmology.

With the advent of the E-ELT it will, for the first time, be possible to detect extra-solar planets in external galaxies and in remote, dense regions of the Galaxy, and to derive their orbits. The detailed spectroscopic study of the resolved stellar

populations in nearby galaxies beyond the Local Group will become feasible. Also, with the E-ELT a major fraction of the Universe becomes accessible for spectroscopic observations, uncovering the early history of the Universe, and its gaseous and galaxy content up to the formation epoch of the first stars and galaxies. The Science Team explored 5 key science cases from which the scientific and technical requirements for OPTIMOS-EVE have been derived:

1. Planets in the Galactic bulge and stellar clusters, and in external dwarf galaxies.
2. Resolved stellar populations in nearby galaxies.
3. Tracking the first galaxies and cosmic re-ionization from redshift 5 to 13.
4. Mapping the ionized gas motions at large scales in distant galactic haloes.
5. 3D reconstruction of the Intergalactic Medium.

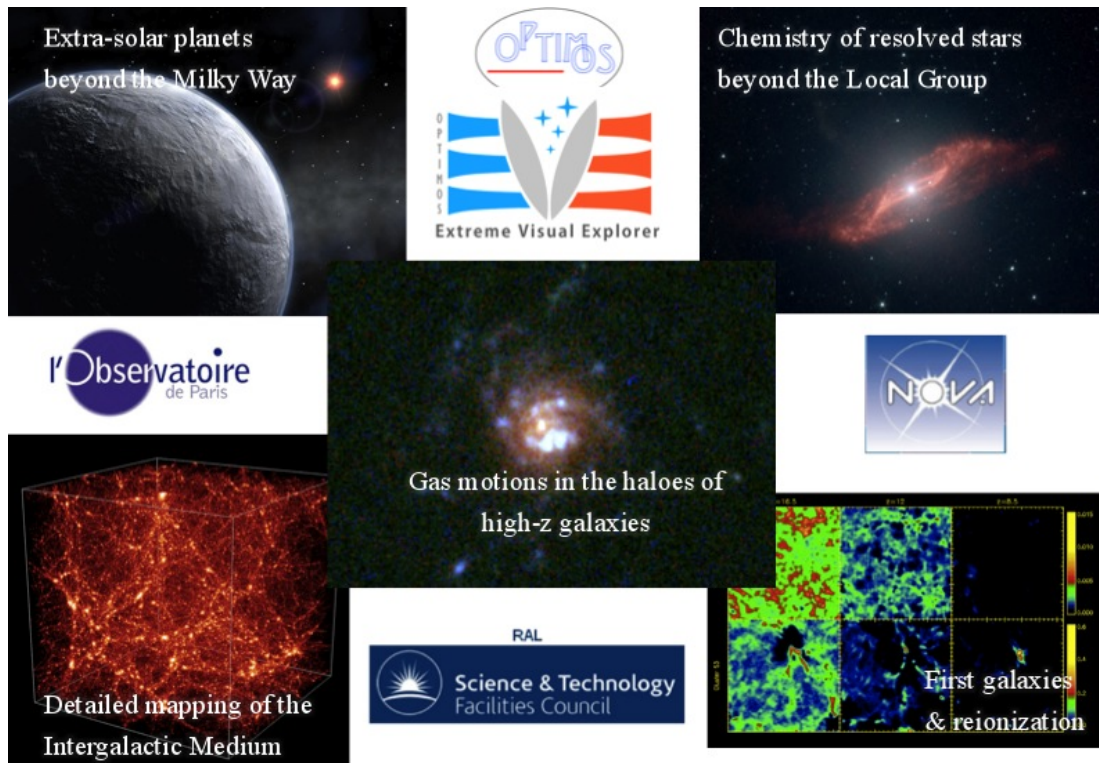


Figure 1. Showing an overview of the OPTIMOS-EVE Science Cases and the main contributing Institutes.

Spectroscopy over the wavelength region available from the ground, from the UV to the non-thermal infrared, has been, and will remain a key technique to investigate virtually all types of astrophysical targets. At $z=0$ most of the spectral lines, fundamental for deriving astrophysical information, are found in the UV-optical range. OPTIMOS-EVE is the only instrument under study for the E-ELT, which offers low-, medium-, and high-resolution spectroscopy ($R \sim 5000 - 30000$) from the ultraviolet to the near-infrared, for multi-object studies of sources nearby and at cosmological distances. Because of this combination, most of the science that will be explored by OPTIMOS-EVE cannot be addressed neither by any other instrument concept under study for the E-ELT, nor by JWST instruments.

The OPTIMOS-EVE targets result from imaging observations obtained with other instruments, e.g. the JWST (possibly also LSST & EUCLID), GAIA and ALMA, and many OPTIMOS-EVE studies will highly benefit from combined observations with JWST and ALMA.

Spectroscopic observations of astronomical objects are, in their broadest definition, the foundation on which we build or discard astrophysical models of the Universe and its constituents. This is true even in the case of the largest known 'object', the cosmic microwave background. The breathtaking progress in astrophysics and cosmology within the last century can be traced back directly to the advances in spectroscopic techniques and instrumentation throughout the electromagnetic spectrum. OPTIMOS-EVE spectroscopy, with a large range in spectral resolution and different apertures on the sky, will be a crucial tool to warrant groundbreaking discoveries, including unexpected ones, in an era (2018+) for which new astronomical challenges and opportunities will occur that are hard to predict.

2.1 Key science cases

- Planets in the Galactic Bulge and in external dwarf galaxies. In spite of the fact that over 400 extra-solar planets are known, these are mostly hosted around stars in the solar vicinity. The few distant planets known do not have orbits, masses etc. We expect, on theoretical grounds, that the environment plays a significant role in the process of planet formation. Therefore, it is important to detect and characterize planets in environments different from the solar vicinity, like the Galactic Bulge and Local Group dwarf spheroidals. With its capability of obtaining a radial velocity precision of 10 m/s for giant stars down to the 20th magnitude OPTIMOS-EVE will make such a study possible. Its multiplex capabilities will allow to monitor up to 40 stars in each observed field.
- Resolved stellar populations in nearby galaxies. With VLT we are beginning to study in detail the stellar populations of the Local Group galaxies. However, many galaxy types are not present in the Local Group. In order to make real progress in our understanding of galaxy formation and evolution we need to study in detail all the different types of galaxies which can be found in the groups of Sculptor and Cen A. The high efficiency low-resolution mode of OPTIMOS-EVE and its high multiplex (70 objects simultaneously) grant this possibility.
- Tracking the first galaxies and cosmic re-ionization from redshift 5 to 13. From the fluctuations of the microwave background we know that at $z=10$ the Universe was already largely re-ionized. Nevertheless, we know little of the objects that produced this re-ionization. The search for the “first lights”, the sources of the photons responsible for the re-ionization can be done with OPTIMOS-EVE, which, thanks to the IR arm, holds the promise of tracing these up to $z=13$.
- Mapping the ionized gas motions at large scales in distant galactic haloes. The observations of the local Universe have shown that galaxies are surrounded by extended haloes of ionized gas. These haloes are the interfaces of the galaxies to the Intergalactic Medium and the way to enrich it of metals. The study of these haloes also allows understanding the history of galaxy-galaxy interactions, since these always leave recognizable signatures on the halo kinematics. Such studies can be conducted with an instrument like GIRAFFE at the VLT up to a redshift of $z\sim 0.5$; OPTIMOS-EVE will make this possible up to a redshift of 3.5.
- 3D reconstruction of the Intergalactic Medium. We know that the space between galaxies and galaxy clusters is not empty, but is filled with a very low density warm medium. Such a medium shows up as Ly alpha absorption in the spectra of distant quasars. Although this affords a “cut through” of the structure of the IGM along the line of sight, nothing is known about its transverse structure. Cosmological simulations show that the IGM has a filamentary structure and filament crossings correspond to the locations of galaxy clusters. Some information on the transverse structure can be obtained in the case of pairs of gravitationally lensed quasars. OPTIMOS-EVE will provide sufficient resolution and sensitivity to use Lymanbreak galaxies of 25th magnitude as background sources. These galaxies have a sufficient space density to allow a 3D reconstruction (tomography) of the IGM, a real 3D picture which may be compared to cosmological simulations.

2.2 Science requirements

From the five main science cases, the top-level requirements (TLR) for OPTIMOS-EVE were defined. These TLRs have been used in the basic design of the instrument as presented here. Of specific interest for the basic design of OPTIMOS-EVE are the TLRs on field size, spectral resolution, multiplicity, fibres vs. IFUs and spectral coverage. A brief outline of the full set of requirements is presented here:

Field-of-view: the required field of view size is set by the surface density of targets at a given magnitude in the key science cases. The most stringent of these is the case of high redshift galaxies ($z>5$), and the 3D reconstruction of the intergalactic medium. For the high-redshift galaxies a sufficiently high surface density per pointing is needed to make the observations efficient for these long integrations. Given their rarity a field of view as large as possible is required. To properly perform the 3D reconstruction of the intergalactic medium one has to probe scales ranging from 2 arcminutes to a degree. A larger field-of-view therefore directly sets the efficiency with which this reconstruction can be done.

Spectral resolution: A minimum spectral resolution is set to $R=5000-10000$ (both in VIS as well as in NIR) by the resolved stellar populations studies. Below this number no meaningful analysis of the stellar spectra can be obtained in terms of metallicity, rotation, binarity, radial velocity, and wind features in massive stars. In the NIR a firm lower limit of $R > 4500$ is set by the density of the OH lines. X-Shooter NIR observations show that at this resolution the OH lines affect only a limited number of pixels and access is gained to the very dark interline continuum background. Spectral resolutions of 10000-20000 are set by the chemical abundance studies in the resolved stellar populations case and 30000 is set by the extragalactic planets case.

Multiplicity: A minimum of 200 fully deployable mono-object fibres is required for efficient use of the required telescope time in the high-redshift case, as well as more than 20 medium sized IFUs (MI) for the 3D reconstruction of the IGM case and more than 20 mono-object fibres for the extra-solar planets science case at high resolution. Sky aperture is set by the natural seeing condition and has been set at 0.9". The Galactic halo case, the resolved stellar populations case and the 3D mapping case all strongly benefit from medium sized IFUs (few square arcseconds) as well as at least one large IFU (< 100 square arcseconds). A typical example is a moderate redshift merger system surrounded by a large number of globular clusters and/or tidal tails. The medium sized IFUs (>20) should be fully deployable where as the large IFU can be fixed at the field center.

Spectral coverage: Simultaneous VIS & NIR observations are crucial for all science cases. The extrasolar planet case will benefit from a maximum number of VIS spectral lines, and the NIR lines will be required to distinguish planets from stellar oscillations. Access to a minimum number of metal lines in all other cases requires an instantaneous wavelength coverage of at least $\lambda/10$ in the VIS and $\lambda/20$ in the NIR. The full wavelength range between 370 nm and 1700 nm should be available; the 370 nm cut-off corresponds to the reflectivity of protected Ag. Extended blue coverage down to 310 nm would strongly boost the resolved stellar population and IGM at intermediate redshift science cases.

Throughput: As in any instrument throughput is always to be maximized. We aim at reaching targets up to $m(AB)=30$ (at $R = 5000$, for very high redshift galaxies), for $z=3$ Ly break galaxies, to reach high S/N in the continuum for targets with $m(AB)=25$ (for $R = 5000-10000$) as well as for stars with $m(AB)=23.5$ (for $R = 20000-30000$).

Data Reduction Software: it should warrant removal of all instrumental signatures and provide calibrated data products with physical units (flux, wavelength, position).

In summary, the top-level requirements are:

- Number of targets: >200 VIS and NIR single objects, several IFUs
- Patrol field of view: >7 arcmin diameter (unvignetted) with a goal of 10 arcmin
- Wavelength range: 370 nm – 1700 nm
- Spectral resolution: 5000 – 10000 (low); 15000 – 20000 (medium); 30000 – 40000 (high)
- Apertures on sky: The apertures on the sky of OPTIMOS-EVE are designed in such a way that the instrument can work in seeing-limited mode, from UV to NIR, or in GLAO assisted mode. Higher order corrections are not necessary and are not matched to the apertures.

3. KEY CAPABILITIES

3.1 Field of view

The fibre/positioner approach provides the advantage of avoiding flexure issues when invoking such a large physical field of view (\varnothing 10 arcmin = \varnothing 2 m). Another noticeable advantage is that fibres can be positioned at any available location over the largest field of view of the telescope.

3.2 Multiple apertures on sky: Mono-Object-fibres and Integral Field Units

Astrophysical sources have many different apparent sizes on the sky, ranging from unresolved stars or QSOs to ≥ 10 arcsec extended sources, even at high redshift (e.g. galactic haloes, Ly alpha blobs). For unresolved sources or Mono-Objects (MO) the aperture has been optimised to be 0.9 arcsec. Other apertures are matching the size of distant galaxies (Medium IFU (MI) = 1.8×2.9 arcsec²) and extended sources (Large IFU (LI) = 7.8×13.5 arcsec²). The sampling of the IFU is settled to 0.3 arcsec for a seeing limited instrument covering the UV to the NIR.

3.3 Spectral resolution and wavelength coverage

OPTIMOS-EVE is unique in covering a very large space in the spectral resolution ($R=5000-30000$) versus multiplex (40-240) plane, and this for a large wavelength range (370-1700nm): many scientific programs are feasible with this instrument and cannot be done by JWST or by other first-generation E-ELT instruments under study. A spectral resolution larger than 5000 is needed in the NIR to provide sufficient spectral regions that are only limited by sky background and not affected by strong OH skylines. The covered spectral ranges are all adjusted to the OPTIMOS Science Cases. NIR spectroscopy is strongly affected by OH skylines and many science cases require to work in between the skylines, implying a minimal spectral resolution (Fig. 2). For an emission line with an observed FWHM of 200 - 300km/s (typical values for $z > 6$ galaxies, see Kashikawa et al. 2006), the problem is even more complex because the

fraction of spectral windows free of skylines decreases rapidly. It may reach $\sim 25\%$ at $R=5000$. Such a resolution is a good compromise because it also significantly helps to remove unresolved skylines when they coincide with the source emission.

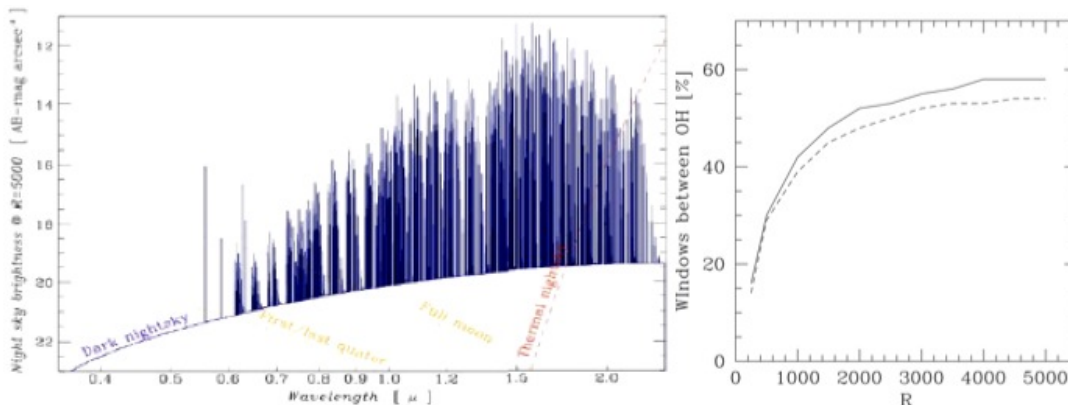


Figure 2. (Left) Night sky in the visual and the near-infrared; notice that OPTIMOS-EVE does not extend beyond 1700 nm; (Right) Fraction of sky background limited regions in the J (solid line) and H (dashed line) band, as a function of spectral resolution.

3.4 Sky correction

Sky correction is a crucial issue especially for the detection of faint sources that are in reach of the EELT. It is often believed that fibre-fed spectrographs are less efficient to perform robust sky corrections, mostly because of the possible different throughput of individual fibres and the difficulty to sample the sky very close to the object. These can be overcome by the fact that we can model the sky variations by placing (sky and MO) fibres in the overall field of view, by the possibility to calibrate the fibre throughput or to use beam-switching observations. With the use of the OPTIMOSEVE simulator we have tested the above assumptions and verified to which accuracy the sky correction can be performed⁵. We have used a model of the sky variations over the OPTIMOSEVE FOV, together with existing FLAMES data, to investigate the reliability of sky subtraction in a variety of observing scenarios. From these simulations, it has been shown that the accuracy of the sky removal can easily reach 1% of the sky signal, with a number of sky fibres that depends on the amplitude of the sky fluctuations (see Figure 3). A significantly better value (0.3-0.4%) is expected for the Medium IFU (MI), which design includes 4 sky-fibres allocated to each MI (see Figure 3).

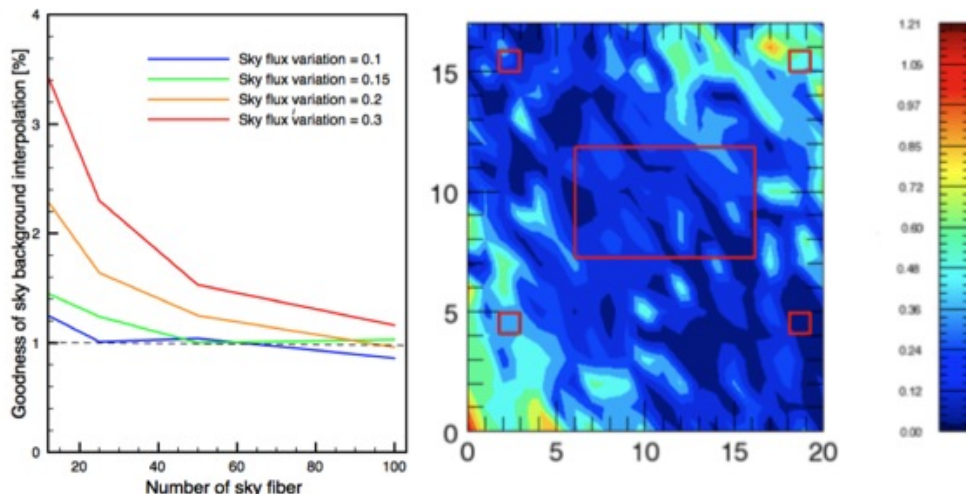


Figure 3. (Left) Fraction of sky residuals (to the sky signal) as a function of the number of allocated sky fibres (MO mode); in the visible and near-IR, the average sky variation is 10% and 20%, respectively (see RD13); (Right) fraction of the sky residual (see the color-coded ruler, in %) for the MI mode. It assumes that the target (a very distant galaxy) illuminates a fraction of the IFU and that sky is sampled from other IFU pixels as well as from the four sky fibres surrounding the IFU (see RD13). Size is indicated in pixels.

Armed with such results, we have performed simulations of faint (Science Case 5) or very faint (Science Case 3) sources that are the most demanding regarding the sky correction. These show that for a $m(AB)=25$ galaxy, 10 hrs exposure may help to reach a sky residual that is less than 1% of the source continuum, which is sufficient to recover the absorption lines from the IGM (case 5). For a much fainter source, 40 hrs exposure is enough to recover the Ly alpha emission (EW above 20 Angstrom) of several hundreds of Ly Alpha Emitters (LAEs) or a $m(AB)$ of 28. This warrants the strategy delineated in RD4 to observe a large number of very distant LAE candidates with the MO mode and to re-observe them with the MI to better study their properties.

3.5 Multiplex

The effective multiplex of OPTIMOS-EVE depends on the science observations and can reach a maximal value of 240 for programs not very demanding in sky correction (bright targets). For the faintest targets we have tested several configurations for which from one third to one half of the fibres have to be allocated to the sky, either by using a staring or a beam switch mode. These numbers are well matched to the expected LAEs density at very high redshifts. For other Science Cases, the OPTIMOS-EVE multiplex is compliant with the Top Level Requirements.

3.6 Overall efficiency

The throughput of the whole instrument (including detectors) is provided in ¹ and ². It averages to 26% in the R=5000 mode, for the mono-object fibres, including an estimated 67% throughput of the fibre system. On the other hand the comparison of the overall efficiencies of different instrument concepts depends on each science case goal. For the most demanding one (very distant and faint galaxies, Science Case 3), the detection of the Lyman alpha line depends on 7 different factors, including (1) the spectrograph efficiency, (2) the sky correction efficiency, (3) the aperture losses, (4) flexure effects if the instrument is mounted to the telescope, (5) the spectral resolution that ensures sufficiently large spectral regions not affected by OH lines, (6) the effective multiplex of the instrument and its consistency with the actual number density of targets and (7) the overall field of view that can be attained in one observational set-up. A fibre-fed spectrograph is likely less efficient with respect to item (1) and, depending on the actual number density of very high-z sources, for item (6). For the factor (2) OPTIMO-EVE is probably less efficient in its MO mode, while the MI mode may allow a better sky correction for very compact objects (sky is sampled in all directions surrounding the object). Because astrophysical sources do not have a rectangular shape oriented along the numerous slits of a multiple object spectrograph, OPTIMOS-EVE takes the advantage regarding item (3) and is the best option for items (4), (5) and (7).

3.7 OPTIMOS-EVE: a modular/flexible instrument

OPTIMOS-EVE provides a number of different observing modes that allow the same spectrograph to sample the telescope plane in different ways. This concept allows for the best use to be made of the prevailing conditions, and enables the implementation of a wide range of science goals with one single instrument. This modularity also ensures that OPTIMOS-EVE will be well matched to the development path of the telescope, and can be adapted to new scientific topics that could be prioritized after the completion of the E-ELT.

4. OPERATIONAL CONCEPT

For each of the five observing modes required by the science case there is a specific set of fibre buttons within each positioner plate. Two plates are allocated for the MO-LR and MO-MR modes to allow configuration of the next field to take place in parallel with the current observation. This allows a considerable flexibility in changing observing modes during the night, without loss of time. Each set of buttons is routed to a pair of fibre slits (one for each spectrograph). At the start of each observation the focal plate containing the configured fibre buttons is moved into the observing position, and the corresponding slits are moved into the active position in each of the two spectrographs. The gratings required for the observation are then selected in each of the four arms and the field is acquired using the fiducial fibres that have been deployed as part of the fibre-field configuration. Once the observing focal plate has moved into position, the robots will begin to reconfigure the opposing plate ready for its next target field. Each field that is to be observed on a given night will be fully configured during the day, so that daytime flat-field calibrations can be recorded in advance of the observations.

5. INSTRUMENT OVERVIEW

The design of OPTIMOS-EVE results from the scientific and technical trade-offs made during the study. Six different designs for the positioner and six different designs for the spectrograph have been studied¹, resulting in the adopted Phase A design.

The instrument is designed to tackle the highest priority science targets identified for the E-ELT. It is compliant with all the OPTIMOS-EVE Top Level Requirements as well as the interfaces to the telescope.

The instrument consists of three main sub-systems:

1. a pick-and-place positioner
2. fibre bundles for various spectral resolutions and integral field units
3. and two highly efficient VIS-NIR spectrographs with VPH gratings working in 1st order.

A schematic overview of this system is shown in Figure 4. It is designed to fit within the volume and mass limits of the focal plane station. A more detailed description of the instrument can be found in papers^{1,2,3,4,6} and references therein. With five different observing modes the instrument is perfectly adapted to match the scientific needs.

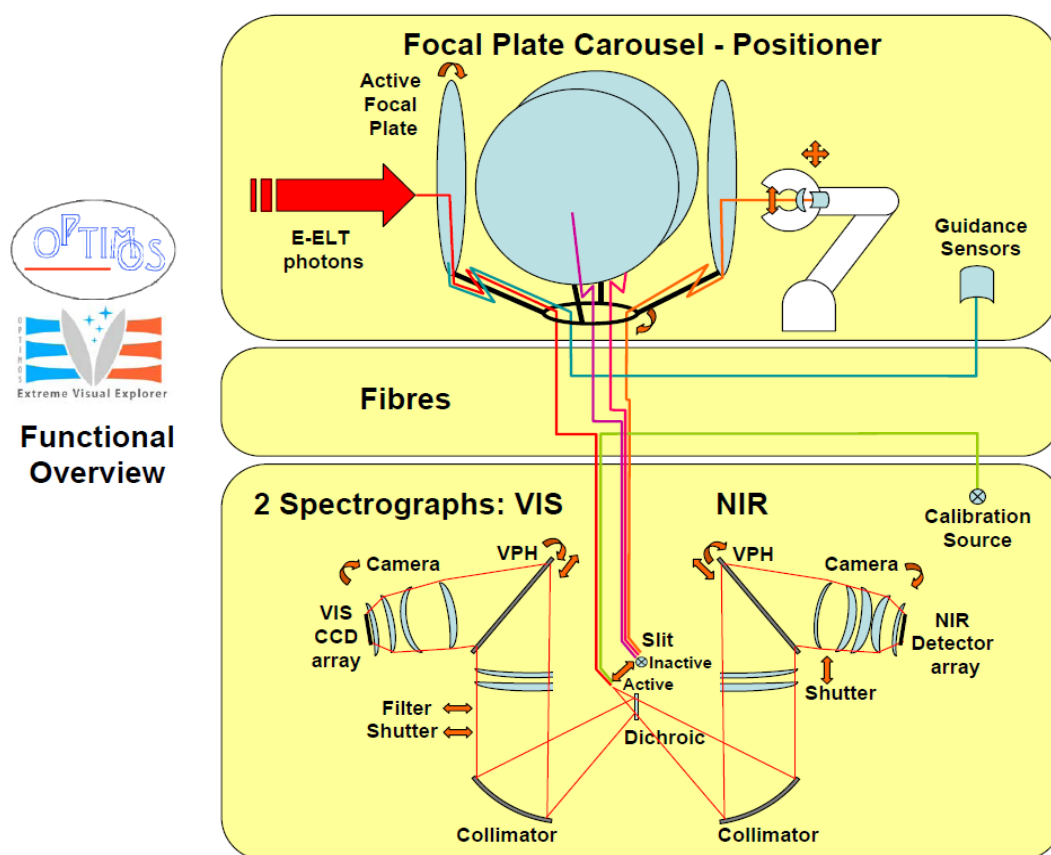


Figure 4. Schematic overview of OPTIMOS-EVE. The 3 main subsystems of the instrument are clearly indicated: The Focal Plate Carousel - Positioner, containing 4 Focal plates with various Mono Objects Fibre inputs and IFUs as well as a robot positioner; The fibres, to transport the collected light to the spectrograph, guidance sensors and from the calibration source; The Spectrographs, consisting of a VISible and an Infrared arm, separated by a dichroic. The dispersing element is a Volume Phase Holographic Grating (VPH).

The overall complexity of OPTIMOS-EVE is comparable to that of FLAMES/GIRAFFE with the OzPoz positioner at the VLT, however there are differences: the number of different fibre bundles is 5 instead of 3; the positioner is easier because of relaxed tolerances at the size of the E-ELT; The camera rotates in order to use high efficiency VPH Gratings; The instrument must be located in a cryogenic environment because the wavelength range is extended to 1700 nm.

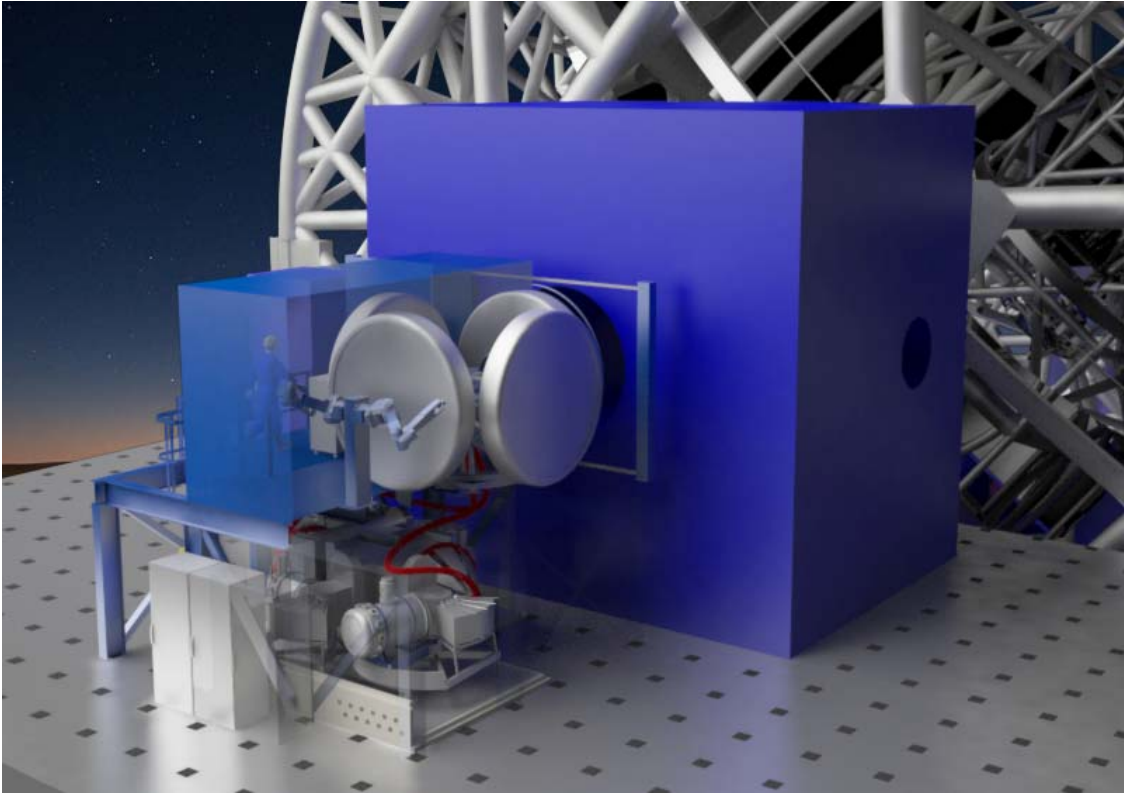


Figure 5. Artist Impression of OPTIMOS-EVE on the Nasmyth platform of the E-ELT. Full video on www.optimos-eve.eu

5.1 Fibre positioner

The fibre positioner is based on a pick-and-place design with magnetic fibre ends. It contains 4 focal plates mounted on a carousel that can be rotated. One focal plate is used for active observations on sky, while 2 robots are reconfiguring another focal plate in order to minimize reconfiguration times and allowing continuous observation with the E-ELT. Two focal plates are for the MO-LR mode, and two other are for the MO-MR mode, which are assumed to be the most demanding modes for changing the target configuration. The four focal plates are necessary to warrant that any change between the different observing modes of the instrument can be done without losing time for reconfiguration⁴.

5.2 Fibre system

The Mono-Object (MO) field of view is 0.9'' for Low and Medium Resolution and 0.81'' in High Resolution. Micro lenses re-image the telescope pupil onto the fibre core, creating a very efficient light injection into the fibres. Each micro lens acts as a field lens as shown in Figure 6.

At the output side, the bare fibres are aligned to form the spectrograph entrance slit. Smaller fibre diameters are used to create a narrower slit and thereby increasing the spectral resolution (Figure 6). However more fibres are needed to cover the same aperture on sky and therefore the multiplex is lower in high resolution.

The Integral Field Unit modes MI and LI have 0.3'' spatial sampling on sky and operate in Low Resolution (LR) only. Table 1 summarizes the sampled strategies adopted by OPTIMOS-EVE.

Table 1. Multiplex, actual spectral resolution, aperture and on sky sampling for the 5 observing modes.

Observing Mode	Multiplex	Spectral Resolution	Aperture	Microlens sampling on sky
MO-LR	240	6000	0.9''	0.3''
MO-MR	70	18000	0.9''	0.18''
MO-HR	40	30000	0.81''	0.09''
MI-LR	30	6000	1.8'' x 3''	0.3''
LI-LR	1	6000	7.8'' x 13.5''	0.3''

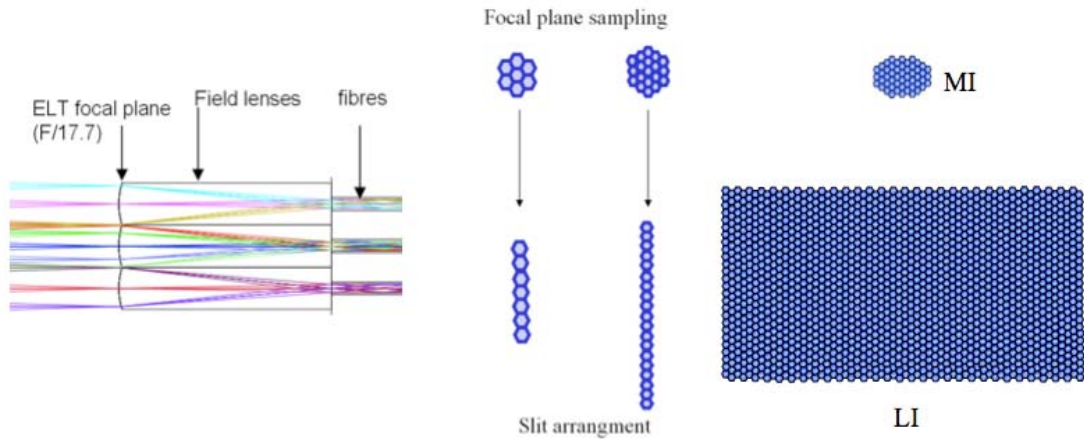


Figure 6. (Left) Fibre injection at the ELT focal plane; (Centre) slit arrangement for the MO-LR mode and MO-MR mode; (Right) The MI and LI modes

5.3 Spectrographs

The spectrograph concept is selected from 6 concepts in a trade-off which is a mix of meeting the top level requirements, cost, efficiency, mass, volume, modularity, technical risks and whether the components could be manufactured at all. Two identical copies of the spectrograph are required to meet the number of fibres that need to be accommodated. Each spectrograph consists of two arms: one covering the visual regime (370-930 nm) and one covering the near-infrared regime (930-1700 nm).

The Spectrograph has a fast but feasible camera (F/1.86) and a very large field of view (12k spatial pixels on the detector). The design presents a high efficiency thanks to the use of VPH gratings. All optics have a reasonable size (collimator lenses fit inside a rectangle of 30x50 cm and the largest camera lens is 37 cm diameter). The camera is composed of 7 lenses, with glasses available in large and homogeneous sizes.

The large slit lengths, associated with a fast camera, allow accommodating the 240 MO-LR on only two dual beam spectrographs (120 objects per spectrograph). The resolution adaptation is simply done by changing the grating and filters, and rotating the camera. The whole spectral range is covered with 3 gratings for VIS (3 setups in LR, 9 setups in MR or HR) and two gratings for NIR (2 setups in LR, 6 setups in MR or HR).

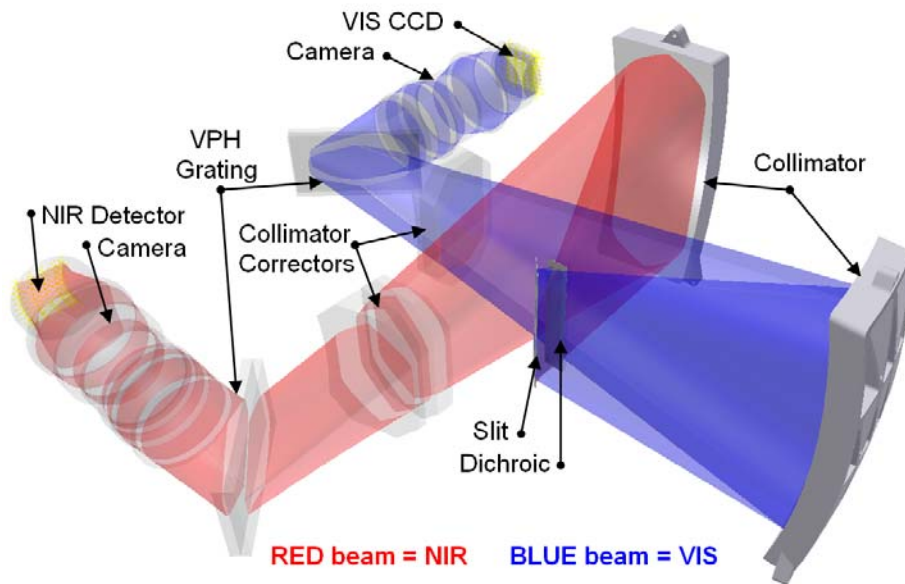


Figure 7. OPTIMOS-EVE spectrograph optical design.

5.4 Detectors

For the Visible Detectors we plan to use e2V CCD231 family, 6kx6k pixel format, deep depletion (baseline) or high-rho, in either case with a 'standard astro' coating or enhanced multilayer coating for improved broad-band response. The 12k x 12k focal plane will be obtained with a mosaic of 2x2 chips. For the NIR detector we plan to use HAWAII-4RG, 1.7 micron cut, substrate removed devices. We use a mosaic of three chips to cover 4k (spectral) x12k (spatial). This could possibly be upgraded to 9 chips to cover 12k x 12k.

5.5 Cryogenics

Most sub-systems of OPTIMOS-EVE will be located in the normal dome environment, like the positioner plates with carousel and robots, the positioner support frame and the fibres. Also the electronic cabinets, chiller for the cold chamber, vacuum systems and calibration box will be located in the dome environment, but thermally insulated and cooled by the water cooling system of the telescope. The spectrographs are located in a thermally controlled cold chamber filled with dry air. This cold chamber is cooled by a commercial chiller that is used in industry for thermal treatment of steel constructions down to 170 K, but also applied in the FMOS IR spectrograph for the Subaru telescope. This cold chamber will be cooled to 193 K. Inside this cold chamber there are four cryostats located; two for the VIS channels focal plane mosaic detectors (running at 173 K) and two for the NIR channels camera/detector combination (running at 120 K). Those four cryostats are based on the same technique of Continuous Flow Cryostats, as more often used in VLT instruments nowadays. The four cryostats are fully independent and also the vacuum systems are separated, to prevent them from influencing each other during operation or maintenance. Further study of this concept will be done in Phase B to ensure the compliance (e.g. vibrations) with the Telescope requirements.

5.6 Instrument control electronics

Instead of using the traditional VME crate LCUs, we plan to use one or more of the following:

- National Instruments crate (either PXI platform or Compact RIO)
- Siemens Simatic S7-300 series PLC
- Beckhoff PLC - probably

For temperature control & monitoring we plan to use LakeShore units. For control of the LN2 continuous flow cryostat we plan to use the ESO TeePee. For vacuum monitoring we plan to use Pfeiffer gauges and readouts (previously known as Balzers). For enclosure control we plan to use a Polycold liquid chiller.

5.7 Instrument control software

One of the key concepts adopted in the design of OPTIMOS-EVE control software architecture is to consider the instrument as a distributed system composed of three collaborating/communicating subsystems: the positioner and the two spectrographs. Taking into account the interface requirements and experience gained by the team for the development of the VLT/FLAMES instrument, the baseline architecture foresees several levels of coordination software (OSS and OSeS, using VLT nomenclature) and additional interacting software packages to control Instrument specific parts. At the top, OSS is the only entity that dialogues with the E-ELT TCS and OH; its main responsibility is to coordinate the activities of the positioner and spectrograph specific OSeS and to properly handle the archiving of the produced scientific frames. The management and coordination of the spectrograph electronics and detector sub-systems is delegated to the dedicated spectrograph OS, whereas the positioner OS has the responsibility to handle and coordinate the various activities during the plate configuration and acquisition processes.

Even though, at the very high level, the proposed design is similar compared to the VLT software model, our approach differs in the sense that we do not propose to implement the various software packages as a set of stand-alone interacting processes but to follow the component/container paradigm. The system is modeled as a set of collaborating Components located inside one or more Containers. Adopting this philosophy, we designed the overall control software architecture based on the ACS framework; the main concepts are in any case very general and may be easily adapted even in case that the E-ELT will adopt a different framework.

The resulting overall software architecture design is to some extent complex especially considering the number of software interfaces to deal with, but it easily allows to cope with some of the critical operational aspects of OPTIMOS-EVE. The necessary high degree of parallelism (spectrographs shall and will work in parallel, different field plate can be

configured during an on-going observation etc.) and, on the other side, the flexibility needed to handle each sub-system independently follows naturally from the proposed architecture.

5.8 Telescope interface

Focal station: The instrument is designed for the Nasmyth straight-through port. Its total mass is 20 tons and its volume is 6x6x5.7 m³. A part of the volume is reserved for electronics and for maintenance operations.

ADC in E-ELT intermediate Focus: Many science cases of OPTIMOS-EVE would benefit of the implementation of an ADC, however for none of them is such an implementation mandatory. Several methods and positions for this Atmospheric Dispersion Corrector (ADC) have been investigated, and the best location is in the E-ELT intermediate Focus. Therefore it is proposed to ESO to allow for an ADC in E-ELT Intermediate Focus.

Large Field of View: The unvignetted Field of View of the E-ELT is only 5 arcminutes in diameter. The full field of 10 arcmin FoV can be used, assuming that the laser guide star pickoff mirrors can be taken out of the field of view when GLAO is not useable.

UV transmission of Telescope: UV transmission of the telescope is important for the efficiency down to 370nm.

5.9 Technical developments and risks

The principle of the technical roadmap of OPTIMOS-EVE is to keep the instrument simple and the concept low risk. Therefore we decided to adopt well-known existing technologies and components only and we do not rely on developments in the coming years, However, we are keeping an eye on technical and manufacturing advances and can incorporate them in our design at the moment when it becomes beneficial. For the high-resolution fibres we intend to develop a specific R&D program in 2010 to validate the performance of the exiting design.

5.10 Research and Development for the high resolution mode

Further R&D after Phase A is required to demonstrate the feasibility of the HR button, especially for the assembly of small fibres with diameter smaller than 100 μ m. The goal of this mode is to achieve a scrambler to obtain a good homogeneity at the fibre output. It will warrant the high accuracy required on the measures of radial velocities of objects observed (10m/s). R&D on this prototype is scheduled and financially supported for a first manufacturing during summer 2010. It will be conducted in collaboration with François Bouchy, who conducts an independent R&D on this topic. The main goal is to test it in laboratory and results are expected at the end of 2010. Further tests might be done on sky, at the OHP on the spectrograph AURELIE.

5.11 Relation with industry

A strong link with industry is needed for a cost effective realization of both the spectrographs and the fibres. Because fibres drive the EVE system, their study is advanced and first contacts with industry have been established already during the Phase A Study. Due to the large quantities all manufacturing procedures concerning fibres and micro-lenses must be industrialized and contacts with industrial partners have been done, and no showstoppers have been identified. For the spectrographs, contact with industry will be started immediately after phase A.

6. SIMULATIONS AND EXPECTED PERFORMANCE

Simulations have been performed for all Science Cases using the OPTIMOS-EVE Instrument model, see figure 8. The simulations illustrate that OPTIMOS-EVE is compliant with each Science Case demand.

For the SC1 (mode MO-HR), simulations give the radial velocity precision as a function of the S/N ratio in the VIS arm (blue solid line) and in the NIR arm (red solid line: with a 80 nm wide spectra range; red dashed line: with a 160 nm wide spectral range, i.e. using a larger number of detectors). Simulations show that for K=19 (Vega magnitude) star, the S/N ratio reaches 100 for 1-hour exposure.

For the SC2 (mode MO-MR), shows a simulated spectrum in MO-LR mode for a red giant star in NGC 5128 (at a radius of 5"Re) corresponding to 50 hours of integration. The simulated spectrum has S/N=6.5, and by using the numerous Fe I and Ti II lines, one may determine the radial velocity and the mean metallicity with an accuracy of a few km s⁻¹ and about 0.3 dex, respectively.

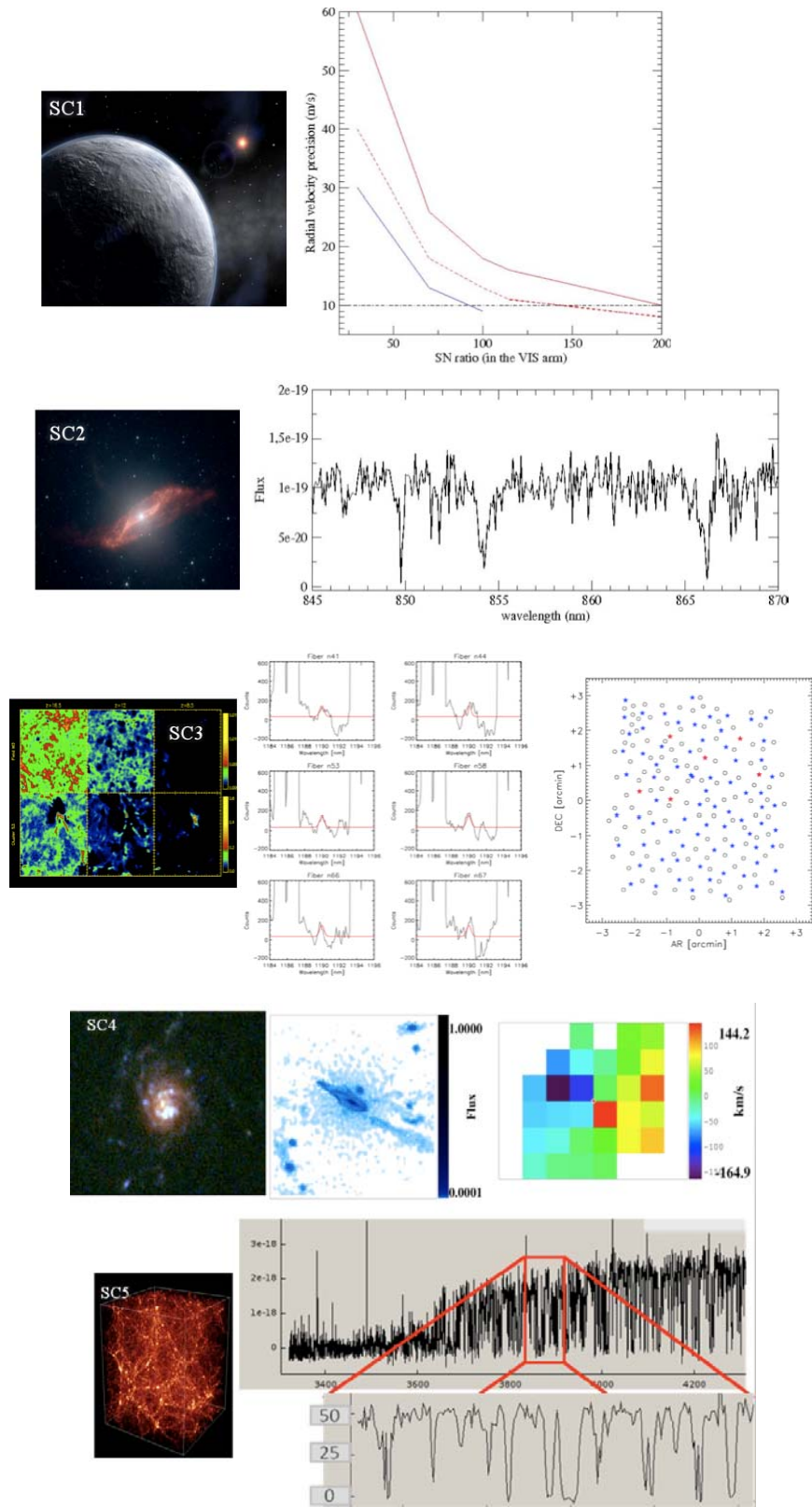


Figure 8. Simulated results for each OPTIMOS-EVE Science Case (see description in the text).

For the SC3 (mode MO-LR), 82 galaxies at $z=8.8$ ($m(AB)=28$, $f(Ly\alpha)= 10^{-19}$ ergs/cm²/s) have been simulated all over the FOV, assuming an exposure time of 40 hours with GLAO. The middle panels show the Lyman alpha line (S/N averaging to 8) detected after sky background subtraction in different fibres (black line) and the input spectrum is shown as reference (red line). Sky emission lines have not been subtracted. The right panel shows the OPTIMOS-EVE FOV and the observational setup. The sky has been sampled with 120 fibres (half of the total number of available MO bundles; see open circles). The 82 simulated galaxies are shown in blue, while the red ones correspond to the panels on the left.

For the SC4 (mode LI), simulations show the stellar distribution of a galaxy at $z=3$ from an hydrodynamic model of a merger. The velocity field over the 100kpc internal halo is recovered (upper-right panel, S/N from 3 to 100) after a spatial binning of 4x4 spaxels (10 hrs of integration).

For the SC5 (mode MI): the simulated spectrum of a $m(AB)=24$ compact Lyman Break Galaxy is obtained by binning over four spaxels in 10 hours of integration (the scale is in erg/s/cm²/Å). A zoom on absorption lines is shown on the bottom with a scale in S/N, which is sufficient to perform this science case.

7. MANAGEMENT AND DEVELOPMENT PLAN

7.1 Work breakdown and management structure

The work breakdown structure for the OPTIMOS-EVE instrumentation project aims to maximally benefit from the experience available in the consortium whilst limiting interface risks as much as possible. OPTIMOS-EVE therefore follows a modular approach: the responsibilities for three main items of the instrument (spectrographs, fibre system and positioner) are split at three different national sites (NOVA, OP-GEPI and STFC–RAL). Important contributions from NBI/DTU-Space and OAB-INAF are expected within the WP Spectrograph, and from OAT-INAF for the WP Instrument Control Software. The WP Data Reduction Software will be under the responsibility of OP-GEPI with contributions of NOVA and RAL. The advantages of this distribution are due to the fact that OPTIMOS-EVE team has already a significant experience in working together in such frames, either on this project or in former, successful instruments (e.g. X-SHOOTER). The work breakdown structure is shown in Figure 9.

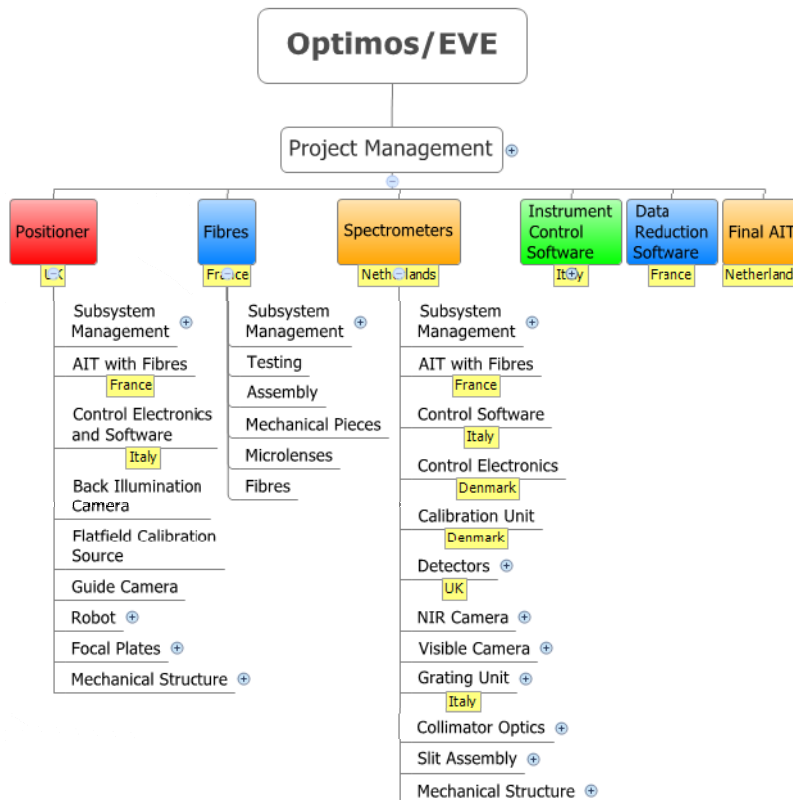


Figure 9. Work Breakdown Structure of OPTIMOS-EVE.

The management structure facilitates and integrates this work breakdown. The work for the Positioner, Fibres and Spectrograph work packages is coordinated by national work package managers. Together with the responsible for the Instrument Control Software, Data Reduction Software and Final AIT they function directly under the project manager. The project is led by the PI board including three PIs from NOVA (L. Kaper), GEPI (F. Hammer) and RAL (G. Dalton) with complementary expertise and skills. The chair of the PI Board will represent the project to the outside world and is the contact person for ESO. The PI Board ensures that the instrument will meet its scientific requirements. The PIs therefore guard that the input from the Project Scientist is disseminated throughout the instrument. The Instrument Scientist and Systems Engineer play a key role in accomplishing this. From Phase A to Phase B an evolution is expected in the roles of some managerial positions (PM, PS, SE and IS), therefore several experienced individuals have been contacted. Phase B and next Phases are particularly demanding on day-by-day management and documenting. The definitive location of the PM may also depend on the actual location of the chair of the PI Board, and that will be decided before Phase B. The participating institutes have also identified potential WP Managers. The project is overseen by a Project Board. The full management structure is shown in Figure 10.

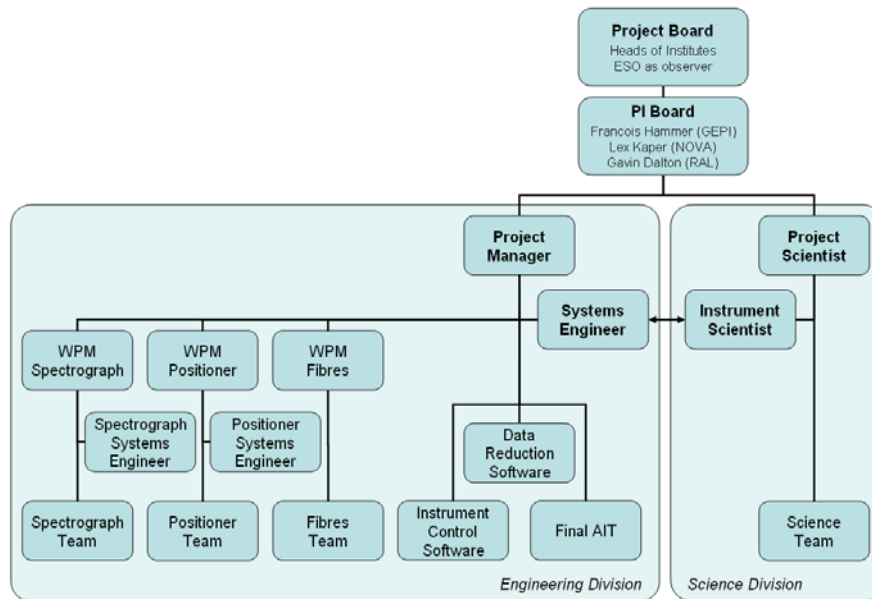


Figure 10. Management structure of OPTIMOS-EVE for Phase B.

7.2 Project management: schedule and cost

The project management approach combines the stage-gate and the Project Management Body Of Knowledge (PMBOK) project management methods to match the necessary short term detailed planning with long-term objectives. The project management will use tools from the PMBOK to manage scope, time, cost, quality, human resources, communication, risks, procurement and integration. The subsequent stages and gates of the project are shown in Figure 11.

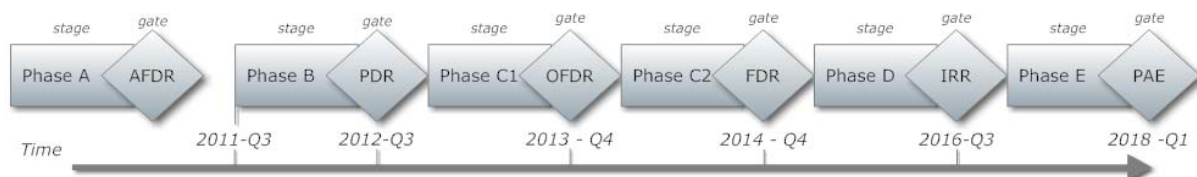


Figure 11. Stage-gate overview of the Optimos-EVE project.

The schedule of OPTIMOS-EVE is compliant with the expected development of the Telescope: the instrument can be ready in 2018 when development starts in 2012. The necessary prototyping will be done before the start of Phase B. An optical FDR is planned well in advance of the FDR to avoid delays in the procurement of the optical components from industry. The integration phase consists of a partial integration of the fibres with both the Positioner and the Spectrograph at two different locations, followed by a full integration of the whole instrument in the Netherlands, although other sites in the Consortium are investigated, both in France and in the UK.

The total hardware cost for realization of OPTIMOS-EVE is estimated to be close to the 12 M€ budget envelope provided by ESO with an additional workload of 154 staff-year for the entire duration of the project. These numbers have been provided from estimates given at WP and sub-WP levels that take into account quotes from industry. The numbers were verified with high-level analysis of the cost of the subsystems. The workload is relatively consistent to what is expected for developing, manufacturing and assembling an instrument of this size.

8. CONCLUSIONS

The phase A study⁷ has clearly shown that OPTIMOS-EVE is a very attractive instrument that will produce breakthrough discoveries in numerous scientific areas. OPTIMOS-EVE operates in seeing limited mode and GLAO mode, and could provide excellent scientific results even during the 30% of the nights when the atmosphere turbulence is too bad for significant improvements of image quality with AO.

OPTIMOS-EVE is a workhorse instrument because of its versatility. In combination with the large multiplex and the photon collecting power of the E-ELT the instrument is extremely productive. There is an excellent synergy between OPTIMOS-EVE, JWST (possibly also EUCLID), GAIA and ALMA, as they observe the same targets and many studies will highly benefit from the combined observations of OPTIMOS-EVE to JWST and ALMA. OPTIMOS-EVE gets wide support from the astronomical community and has a good chance of getting funded.

The instrument can be build with technologies that are widely used today and no technical “show stoppers” have been identified. We verified that its present design is compliant with all the scientific objectives. The interfaces between OPTIMOS-EVE and the telescope are straightforward and the project schedule agrees well with the E-ELT roadmap. Considering all the above, we conclude that OPTIMOS-EVE is an ideal instrument for the E-ELT!

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