4MOST: the 4-metre Multi-Object Spectroscopic Telescope project at preliminary design review


*Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany, bRAMS-CON Management Consultants, Assling, Germany, cLund Observatory, Sweden, dUniversity of Cambridge, United Kingdom, eAustralian Astronomical Observatory, Sydney, Australia, fCentre de Recherche Astrophysique de Lyon, France, gMax-Planck-Institut für extraterrestrische Physik, Garching bei München, Germany, hMax-Planck-Institut für Astronomie, Heidelberg, Germany, iEuropean Southern Observatory, Garching bei München, Germany, jZentrum für Astronomie der Universität Heidelberg, Germany, kUniversity of Uppsala, Sweden, lNOVA/ASTRON, Dwingeloo, the Netherlands, mUniversity of Western Australia, Perth, Australia, nKapteyn Astronomical Institute, Groningen, the Netherlands, ñÉcole polytechnique fédérale de Lausanne, Switzerland, òUniversität Hamburg, Germany, ôUniversität Potsdam, Germany, õUniversity of Hertfordshire, United Kingdom, innoFSPEC, Potsdam, Germany

ABSTRACT

We present an overview of the 4MOST project at the Preliminary Design Review. 4MOST is a major new wide-field, high-multiplex spectroscopic survey facility under development for the VISTA telescope of ESO. 4MOST has a broad range of science goals ranging from Galactic Archaeology and stellar physics to the high-energy physics, galaxy evolution, and cosmology. Starting in 2021, 4MOST will deploy 2436 fibres in a 4.1 square degree field-of-view using a positioner based on the tilting spine principle. The fibres will feed one high-resolution (R~20,000) and two medium-resolution (R~5000) spectrographs with fixed 3-channel designs and identical 6k x 6k CCD detectors. 4MOST will have a unique operations concept in which 5-year public surveys from both the consortium and the ESO community will be combined and observed in parallel during each exposure. The 4MOST Facility Simulator (4FS) was developed to demonstrate the feasibility of this observing concept, showing that we can expect to observe more than 25 million objects in each 5-year survey period and will eventually be used to plan and conduct the actual survey.

Keywords: Wide-field multi-object spectrograph facility, VISTA telescope, tilting-spine fibre positioner, wide field corrector, facility simulator, fibre-fed spectrographs, science operations, Gaia, eROSITA, Euclid, PLATO

1. INTRODUCTION

The need for wide-field, high-multiplex spectroscopic survey facilities has been identified in a number of strategic documents like the Science Vision for European Astronomy[1], the ASTRONET Infrastructure Roadmap[2], their

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updates and several others[3][4]. In response, ESO selected in 2011 the MOONS[5] and 4MOST projects to conduct Concept Design Studies for Multi-Object Spectroscopic (MOS) facilities in the near-infrared and the optical, respectively. Both projects went through their Concept Design Reviews in spring 2013 and were selected for implementation. For budget profile reasons at ESO the start of 4MOST was delayed by a year and the official kick-off of the Preliminary Design Phase with ESO was in January 2015. The Preliminary Design Review was conducted in June 2016 and the project is preparing to move into the Final Design Phase.

The goal of 4MOST project is to create a general-purpose and highly efficient spectroscopic survey facility useful for a large fraction of (for most?) astronomers in the ESO community. The 4MOST design philosophy is based on the notion that 4MOST is not just an instrument, but is a survey facility, meaning that:

- **4MOST runs all the time**: there will be no instrument changes, 4MOST will be running all of the time on the telescope during its surveys of 5 year duration,
- **4MOST provides an integrated system**: the target selection, operations and survey strategy, instrument capabilities, and high level data product delivery are all part of facility and are tuned to compliment each other,
- **One design fits many science cases**: the design and operations will minimize the constraints on science cases that need optical spectroscopy, but the number of observing modes (e.g., spectrograph configurations) will be kept to one. The goal is to deliver a general-purpose, reliable, but easy to operate instrument, operations concept and data analysis software that is well suited to most science cases. To increase efficiency all science cases will be running at the same time in parallel, all the time.

In Sections 2 and 3 we describe the main science drivers and the instruments specifications. Section 4 is devoted to the Instrument Design, providing details on the main subsystems. In Section 5 we present the facility operations concept. Performance modeling is described in Section 6, paying particular attention to the results of the 4MOST Facility Simulator (4FS). We conclude with describing the Consortium structure in Section 7.

## 2. SCIENCE

The science opportunities of a dedicated wide-field, high-multiplex spectrograph on a 4m-class telescope are of broad interest and of high impact, as has been identified in numerous recent European strategic documents. 4MOST will complement and enhance many large area sky surveys, such as four space-based observatories of prime European interest: Gaia, eROSITA, Euclid, and PLATO, and many ground-based facilities like VISTA, VST, DES, LSST, and SKA.

The 4MOST Consortium science team is in the process of developing with increasing detail the science to be performed during the Guaranteed Time Observations awarded to the consortium in return for building and operating the facility for ESO. The science plan has been structured in nine Surveys, five dedicated to Galactic Archaeology obtaining spectra of stars in our Milky Way and its nearest neighbours and four dedicated Extragalactic objects. The nine Surveys with their (co-)PIs are listed in Table 1. The next two subsections contain a top-level description of these nine Consortium Surveys.

Table 1: Consortium Surveys with their (Co-)PIs

<table>
<thead>
<tr>
<th>No</th>
<th>Survey Name</th>
<th>Survey (Co-)PI</th>
</tr>
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<tbody>
<tr>
<td>S1</td>
<td>Milky Way Halo LR Survey</td>
<td>Irwin (IoA), Helmi (RuG)</td>
</tr>
<tr>
<td>S2</td>
<td>Milky Way Halo HR Survey</td>
<td>Christlieb (ZAH)</td>
</tr>
<tr>
<td>S3</td>
<td>Milky Way Disk and Bulge LR Survey</td>
<td>Chiappini, Minchev, Starkenburg (AIP)</td>
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<tr>
<td>S4</td>
<td>Milky Way Disk and Bulge HR Survey</td>
<td>Bensby (LU), Bergemann (MPIA)</td>
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<tr>
<td>S5</td>
<td>Galaxy Clusters Survey</td>
<td>Finoguenov (MPE)</td>
</tr>
<tr>
<td>S6</td>
<td>AGN Survey</td>
<td>Merloni (MPE)</td>
</tr>
<tr>
<td>S7</td>
<td>Galaxy Evolution Survey (WAVES)</td>
<td>Driver (UWA), Liske (UHH)</td>
</tr>
<tr>
<td>S8</td>
<td>Cosmology Redshift Survey</td>
<td>Kitaura (AIP), Richard (CRAL), Kneib (EPFL)</td>
</tr>
<tr>
<td>S9</td>
<td>Magellanic Clouds Survey</td>
<td>Cioni (AIP)</td>
</tr>
</tbody>
</table>
2.1 Galactic Archaeology

With the successful launch of ESA’s Gaia mission in December 2013, the field of Galactic Archaeology and Near-Field Cosmology, i.e. the study of the formation and evolution of the Milky Way and its satellite system in a cosmological context using stellar populations, is expected to go through a dramatic development soon. Gaia will provide distances from parallaxes and tangential velocities from proper motions for more than one billion Milky Way stars down to $m_V = 20$ mag. Gaia will also provide radial velocities and astrophysical characterization for about 100 million stars from its spectrograph, but its sensitivity to measure radial velocities is limited to $m_V = 12–16$ mag depending on spectral type (Figure 1). Obtaining good stellar parameters or even chemical element abundances with Gaia is limited to much brighter objects and here 4MOST will provide the complimentary measurements in the form of radial velocities with $\sim 1$ km/s accuracy to the depth of the faintest Gaia’s astrometry and detailed abundances to $m_V = 16$ mag for millions of stars. These kind of measurements allows one to determine the three-dimensional Galactic potential, measure the influence of the Milky Way’s bar and spiral arms on disk dynamics, determine the Galactic assembly history through chemodynamical substructure and abundance pattern tagging, and find 1000s of extremely metal-poor stars to constrain the earliest epochs of galaxy formation and stellar evolution.

![Radial velocity accuracy Gaia](image)

Figure 1. The 4MOST goal radial velocity accuracy compared to the Gaia end of mission accuracy as function of stellar apparent magnitude. Our aim is to match the spectroscopic magnitude limits of 4MOST to the astrometric limits of Gaia, thereby enabling 6D-phase space studies to Gaia’s limits.

S1 Milky Way Halo Low Resolution Survey: The Milky Way is thought to be embedded in an elongated dark matter halo, and surrounded by thousands of dark clumps. The only way to detect these is using thin stellar streams such as that shown in red in Figure 2. The black circles are clumps “colliding” now with the stream and leading to its fragmented appearance. Gaia will detect hundreds of such streams, and the characterization of how their stars move with 4MOST will allow us to pin-down the nature of the mysterious dark matter. It is expected that 4MOST will obtain resolution R~5000 spectra for about 1.5 million halo stars in its first 5-year survey.

S2 Milky Way Halo High Resolution Survey: The Galactic halo contains some of the oldest and most metal-poor stars known in our Galaxy. These stars conserve, to a large extend, the chemical composition and kinematics of the gas cloud from which they have formed.

With the 4MOST high-resolution spectrograph, we want to acquire spectra of at least several 100,000 such stars and determine their chemical element abundance patterns. These chemical “fingerprints” will help us in disentangling the contributions of various nucleosynthesis processes that occurred in the first generation(s) of stars, which chemically enriched the Universe shortly after the Big Bang, as is illustrated in Figure 2.

Complementery astrometry being collected with the Gaia satellite will allow us to determine the orbits of the metal-poor stars, and to identify the remnants of smaller galaxies that were attracted by the large gravitational force of our galaxy, and eventually merged with it. These observations can then be compared with numerical simulations of spiral galaxy formation, to check how realistic these are, and whether any physics is missing in these simulations.
Figure 2: Left) A simulation of a tidally disrupted stellar system (satellite galaxy or globular cluster) surrounding the Milky Way (red points). The Milky Way halo is thought to consist of hundreds of such stellar streams that will interact with the invisible dark matter substructures contained in the Milky Way halo. Right) A schematic depiction of the galaxy chemical enrichment process, whereby each new generation of stars is enriched by the chemical elements created in previous generations of stars and which were released by Supernovae (SN). The earliest generations of stars contain hardly any chemical elements other than Hydrogen and Helium and have relatively simple spectra, while for later generations the spectra become more and more complicated showing many absorption lines from different chemical elements (middle panel).

S3 Milky Way Bulge and Disk Low Resolution Survey: The mechanisms of the formation and evolution of the Milky Way are encoded in the location, kinematics, and chemistry of its stars. Moreover, the Milky Way serves as a template for understanding other galaxies, and hence galaxy formation in general. With the 4MOST low-resolution mode we aim at studying the kinematical and chemical substructures in the Milky Way disks and bulge out to larger distances and greater precision than conceivable with the Gaia mission alone, or with any other ongoing or planned survey. The main goals of this survey are as follows: (i) to understand the current Milky Way disk structure and dynamics (bar, spiral arms, stellar radial migration); (ii) to study the chemo-dynamics of the disk, which, when combined with (i) above will allow us to recover the disk evolutionary history; and (iii) to constrain the formation of the Milky Way bulge using both chemical and dynamical information. To accomplish the above goals and to cover the entire visible disk from the South, we have designed several stellar subsamples consisting of dwarf or giant stars, depending on the distances from the Sun. The Survey will also target all Southern Hemisphere White Dwarfs discovered by Gaia. By combining a large wavelength coverage with a moderate resolution (R > 5000), this Survey promises to deliver not only high precision radial velocities, but also chemical information, delivering individual chemical abundances for other iron-peak, α- and even n-capture elements. The possibility of obtaining other individual chemical elements from the LR mode of 4MOST will also open new opportunities such as the capacity of classifying stars as normal, carbon-enhanced, and among those, carbon-enhanced s-process and carbon-enhanced-no stars (those without -r and -s- process). So far, in the community, this science has been confined to the halo, but there is now much potential of extending it to the disk and bulge. The S3 Survey will provide the largest chemo-dynamical Gaia spectroscopic sample to be ever obtained.

Figure 3 shows on top how we take uncertainties in the radial, tangential and vertical Galactocentric velocities into account for target selection. At the bottom this figure shows the expected target distribution in the Milky Way for the different samples in this Survey of which we expect to observe 10–15 million.
Figure 3: Top) Uncertainties in the radial, tangential and vertical Galactocentric velocities $U$, $V$, and $W$, respectively, using RV error of 2 km/s and distance error of 200 pc for G dwarfs and K giants (as expected from Gaia). Uncertainties in $U$, $V$, $W$ are smaller than $2^{-4}$ km/s at $d<2$ kpc, just as needed for the Extend Solar Neighborhood (ESN) science case. Bottom) Stellar targets will be selected from the Gaia catalogue to sample a large fraction of the Milky Way disk and the inner bulge region as shown is this distribution of targets for the different samples in our mock catalogue.

**S4 Milky Way Bulge and Disk High Resolution Survey:** This survey will be the largest high-resolution spectroscopic survey of stars in the Milky Way disk and bulge to date. The survey will complement astrometric information from Gaia with high-precision chemical element abundances for about 2 million stars. We will provide abundances of all chemical elements, which are critical for testing nucleosynthesis at different epochs of galaxy formation: Li, CNO, p-process, Fe-peak elements such as Cr, Mn, Fe, Ni produced in supernovae, light and heavy neutron-capture such as Sr, Ba, Eu. These extensive element abundance maps will trace the time evolution of abundance gradients in the disk, putting new stringent constraints on models of stellar evolution and Galaxy formation.

Our goal is to provide metallicity-unbiased and volume-limited samples of stars throughout the disk at all galactocentric radii, and, in particular, a comprehensive description of the inner Galactic disk. This will be possible by drawing on the positions, distances, and stellar pre-classification from the Gaia space mission. Currently under investigation is whether 4MOST can observe all stars brighter than $\sim 12^{th}$ magnitude during twilight and/or during poor seeing conditions, thus providing a full characterization of the elemental abundances for nearly all stars that will be observed by ESA’s PLATO space mission to discover and characterize exoplanets and their host stars.

**S9 Magellanic Clouds Survey:** The Magellanic Cloud galaxies, in their first approach to the Milky Way, illustrate a typical example of an early stage of a minor merging event. However, their origin is still a matter of debate, their satellite status is unclear, their mass is uncertain, their gravitational centres are poorly defined, their structure depends strongly on
stellar populations and is severely shaped by interactions, their orbital history is only vaguely associated with star forming events, and their chemical history rests upon limited data.

The main science driver for a large-scale spectroscopic survey of the Magellanic Clouds rests upon the ongoing large photometric effort to obtain photometric multi-wavelength observations of their stellar content, improve our knowledge of their origin and evolution, and remove potential biases. This Survey aims to measure the radial velocity and the iron abundance of many different stellar populations, as well as additional chemical elements for the brightest stars, that sample all structures (bar, disc, halo) and substructures (streams) associated to the interactions of the MCs with each other and with the Milky Way. These spectra are necessary to match the high quality proper motions to become available in the current decade (with VISTA and Gaia) and are crucial to obtain accurate star formation histories and geometrical parameters, and to design dynamical models that reproduce the history of formation and evolution of the system. The Magellanic Clouds Survey will obtain approximately a half million stellar spectra.

2.2 Extragalactic Science and Cosmology

Constraining the origin of the accelerating universe is expected to be a significant driver of the observations that are going to be done with 4MOST. However, other Extragalactic science cases are very important as well, like determining the nature of Dark Matter, understanding the formation and evolution of galaxies, and studying the cosmic evolution of super-massive Black Holes in the centres of galaxies. Four distinct Extragalactic Surveys will be carried with 4MOST as described below.

S5 Galaxy Clusters Survey: Clusters of galaxies are exquisite probes of the growth of structures in the Universe and very sensitive tracers of structure formation in current cosmological models. eROSITA will perform all-sky X-ray surveys in the years 2017 to 2021 to a limiting depth that is a factor of 30 deeper than the ROSAT all-sky survey, and with broader energy coverage, better spectral resolution and better spatial resolution. Redshift information is critical to exploit the full potential of the eROSITA cluster samples. We will use 4MOST to survey the >50,000 southern X-ray galaxy clusters that will be discovered by eROSITA, measuring redshifts for 3–50 galaxies in each cluster. Thanks to these measurements we will be able not only to provide stringent tests of the cosmological paradigm, but also to calibrate the cluster mass via velocity dispersion estimates, study the large scale distribution of clusters, and determine the evolution of galaxy populations in high density environments up to z~1.

S6 AGN Survey: The 4MOST AGN survey will represent one of the largest, and most complete spectroscopic survey of Active Galactic Nuclei ever undertaken. Built around the sample of X-ray selected AGN detected by the eROSITA X-ray all-sky survey, it aims at obtaining highly complete spectroscopic follow-up of about 1 million sources, smoothly distributed over a very wide redshift range (0 < z < 6). The X-ray selection for the majority of the AGN guarantees minimal bias against obscured accretion and objects with significant contamination from stellar light from the host galaxy. Combining X-ray, optical and IR AGN selection criteria, we will also be able to probe the history of accretion onto supermassive black holes, also for the most heavily obscured AGN, and study AGN vs. host galaxy co-evolution, while at the same time probing the Large Scale structure with enough accuracy to test the geometry of the Universe via QSO BAO studies.

S7 Galaxy Evolution Survey ( WAVES): WAVES is a massively multiplexed spectroscopic survey of 2 million galaxies addressing galaxy evolution. The Survey will build upon the excellent imaging data provided by two of the European Southern Observatory’s ongoing Public Surveys: VST KiDS and VISTA VIKING. The survey design is not yet fully fixed, but at this stage the survey is proposed to comprise of two distinct sub-surveys: WAVES-Deep and WAVES-Wide.

WAVES-Deep will cover ~100 deg² to r < 22 mag and extend the power of SDSS-like population statistics out to z~1. The deep survey will yield ~1.2 million galaxies allowing for the detection of ~50,000 dark matter halos (to 10¹² M☉) and 5000 filaments, representing the largest group and filament catalogue ever constructed, and forming the first detailed study of galaxy evolution as a function of halo mass. The groups themselves will be used in turn as telescopes in their own right to probe to the most distant corners of the Universe using gravitational lensing.

WAVES-Wide will cover ~1500 deg² to r < 22 mag with photometric redshift pre-selection (z < 0.13). This will result in ~0.9 million galaxy targets and uncover a further 85,000 dark matter halos, allowing a detailed study of the halo occupancy in 10¹¹ – 10¹² M☉ halos to a stellar mass limit of 10⁷ M☉, and providing a field dwarf galaxy sample over a volume of > 10 Mpc³. A comparison of WAVES with previous surveys in terms of target density and area and redshift coverage is presented in Figure 4. Further information is available at http://www.wave-survey.org/.
The 4MOST cosmology survey aims at studying the nature of gravity and dark energy, responsible for the structure formation in the Universe and its expansion, respectively. To this end, it will map the three-dimensional matter distribution in the Southern Galactic sky. We aim at performing precise measurements of baryonic acoustic oscillations and redshift space distortions from the three dimensional distribution of galaxies with an unprecedented accuracy at redshifts up to about 1.

In particular the aim is to measure redshifts for 1–2 million Luminous Red Galaxies (LRGs) and for 10–20 million emission Line Galaxies (ELGs) on 13–15k square degrees. While LRGs are massive red galaxies tracing the high density peaks of the dark matter density field, ELGs are blue galaxies distributed across the cosmic web, which redshifts can be determined thanks to their OII doublet emission line caused by their star forming activity. The combination of both LRGs and ELGs permits to set tight constraints on the cosmological parameters performing a multitracer analysis.

Additionally, this Cosmology Redshift Survey will measure the distribution of quasars and the Lyman alpha forest between redshift 2.2–3.5 and the redshifts of >200,000 SNe 1a or their host galaxies using triggers from DES and LSST. The Survey will allow for a number of additional projects cross-correlating with weak lensing surveys, studying secondary anisotropies in the cosmic microwave background, and studying the cosmic web.

The 4MOST Cosmology Redshift Survey will be complementary to Euclid and other galaxy redshift surveys by focusing on the Southern Extragalactic sky and on the z<1 and z>2.2 redshift ranges.

2.3 Science Requirements

To achieve the science goals described in the subsections above, 4MOST shall be able to obtain:

- Redshifts of 22.0 r-mag galaxies and AGN in ≤2 hour, where densities >4 per arcmin² shall be reachable;
- Radial velocities of at 2 km/s accuracy (goal 1km/s) of the faintest Gaia stars (V~20 mag) in ≤2 hour;
- Stellar parameters and alpha-element abundances of stars ≤ 18 V-mag in ≤ 2 hour;
- Abundances of 15 elements of ~15.5 V-mag stars in ≤ 2 hour.

In a 5-year survey 4MOST shall:

- Cover at least twice an area of ≥16,000 degree² (goal >20,000 degree²);
- Obtain >15 million (goal >25 million) spectra at resolution R~5000;
- Obtain >1 million (goal >2 million) spectra at resolution R~20,000.
3. INSTRUMENT SPECIFICATIONS

The instrument specification was derived from the science requirements and the operations plan. The main 4MOST instrument specifications and the values achieved by the current design are listed in Table 2.

Table 2: Main 4MOST instrument specifications and current design values.

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<thead>
<tr>
<th>Specification</th>
<th>Requirements</th>
<th>Design value</th>
</tr>
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<tbody>
<tr>
<td>Field-of-View (hexagon)</td>
<td>&gt;4 degree²</td>
<td>~4.1 degree² (~θ&gt;2.5°)</td>
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<tr>
<td>Multiplex fiber positioner</td>
<td>&gt;1500</td>
<td>2436</td>
</tr>
<tr>
<td>Low Resolution Spectrographs (2x)</td>
<td></td>
<td></td>
</tr>
<tr>
<td># Fibres</td>
<td>R &gt; λ*10 for 400nm &lt; λ &lt; 500nm</td>
<td>R &gt; λ*10 for 400nm &lt; λ &lt; 500nm</td>
</tr>
<tr>
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<td>R &gt; 6000 for 500nm &lt; λ &lt; 885nm</td>
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<tr>
<td>Velocity accuracy</td>
<td>&gt;800 fibres</td>
<td>812 fibres</td>
</tr>
<tr>
<td></td>
<td>400-885 nm</td>
<td>370-950 nm</td>
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<tr>
<td></td>
<td>&lt; 1 km/s</td>
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<td>Passband</td>
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<td>812 fibres</td>
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<tr>
<td>Velocity accuracy</td>
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<tr>
<td></td>
<td>&lt; 1 km/s</td>
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<tr>
<td>Fibre diameter</td>
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<td>θ=1.45 arcsec</td>
</tr>
<tr>
<td>Observing efficiency</td>
<td>&lt;20% overhead</td>
<td>&lt;20% overhead for 3x20 min</td>
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</table>

4. INSTRUMENT DESIGN

Figure 5 provides an overview of the 4MOST instrument system mounted on the VISTA telescope. A new Wide Field Corrector creates a 2.5 degree Field-of-View on the focal surface, where optical fibres positioned by the AESOP fibre positioner lead the light to two resolution R~5000 spectrographs and one R~20,000 spectrograph. A metrology system supports the accurate positioning of the fibres in the focal surface, while a calibration system provides the illumination from the M2 support spiders for wavelength and flatfield calibration. An overview of the instrument and its system engineering can be found in [5] and [6]. A more detailed description of the main new elements brought to the VISTA can be found in the following subsections.

Figure 5: Physical layout of the new 4MOST elements on the VISTA telescope.
4.1 Wide Field Corrector and Focal Surface Units

The 4MOST Wide Field Corrector with Atmospheric Dispersion Corrector (WFC/ADC) is a key optical component for the 4MOST facility in that it performs the critical image correction to the VISTA telescope optics in order to deliver the requisite field of view, image quality, plate scale, and target alignment (Figure 6). It provides a minimally vignetted field of view of the 2.5 degrees diameter, and it contains an ADC based on rotating prisms to allow good chromatic coupling of stellar images with the fibre optics over a wide range of zenith angles. The design delivers an image quality anywhere in the FOV containing 80% of the light for a point source in a 0.8 arcsecs circle anywhere in the specified wavelength range for zenith angles from 0 to 55 degrees. More details can be found in [7].

Figure 6: Left) Cutaway of VISTA/4MOST showing the Wide Field Corrector with Atmospheric Dispersion Corrector (WFC/ADC) in relation to other telescope components. Right) The WFC/ADC with attached at the back some of the Acquisition and Guiding and Wave Front Sensing Units.

The quality of the sky image created on the focal surface is assured by two Acquisition and Guiding Units (A&G) for pointing and four (two pre-focus and two post-focus) Wave Front Sensing (WFS) Units for controlling the M1 shape and M2 position (Figure 6). All A&G and WFS Units use identical COTS Peltier cooled cameras with 2k x 2k CCDs.

4.2 AESOP Fibre Positioner and Metrology

The light is collected at the Focal Surface into 85μm fibres that are arranged to match the sky target positions by the AESOP Fibre Positioner (Figure 7). AESOP, based on a tilting spine principle first implemented in FMOS-Echidna [8] on Subaru telescope, holds an array of 2436 fibres. Accurate fibre positioning is done by a feedback loop using four metrology cameras looking through the WFC at the fibre tips that are back-illuminated from the shutter/back-illumination unit at the slit entrance of the spectrographs. A set of fixed spines around the field with back-illuminated fibres provides a reference frame for positioning the fibres. A set of 12 guide-spines around the edge of the science field are equipped with fibre bundles feeding a camera providing secondary guiding yielding similar bending behaviour under gravity variations as the science spines, thus accurately tracking pointing, field rotation, and plate scale. AESOP is described in more detail in [9].
The 2436 science fibres are distributed in a hexagonal array on 28 two-row modules. Each spine tip can be deployed anywhere within a circular patrol area. These patrol areas overlap, allowing subsets of fibres to maintain full area coverage and to increase fibre allocation completeness for clustered targets. The fibres are to be positioned to within 10 μm rms radial error. The positioner must then hold the relative positions of the science spines and the guide spines for the duration of each observation to similar accuracy. The control system allows repositioning of all spines in parallel and experience with prototype 4MOST spine modules (Figure 7) shows that the required <10 μm accuracy can be achieved in less than 90s with a fast metrology system.

The Metrology System will accurately determine the position of the fibre tips in the focal surface. It consists of a Back Illumination Unit that illuminates the fibres at the slit exit within the spectrographs and four Metrology Cameras that are attached to the spider vanes that support the M2 secondary mirror. The Back Illumination Units get light fed through fibres and also function as shutters for the spectrographs. The optical layout of the system for one camera is shown in Figure 8. Extreme care is taken to make sure that the cameras are thermally stable to ensure that their imaging plate scale remains unchanged throughout observations. Using four instead of one metrology camera allows us to use COTS imaging CCD cameras with 4k x 6k pixels by averaging the results of the four cameras. It also provides redundancy (with reduced performance) in case one camera fails. More details about the metrology system can be found in [10] and [11].

Figure 7: Left) AESOP spines and modules (oblique view from front of focal plane) showing the hexagonal layout of the field. At the bottom the fibre connectors can be seen that will connect to the long fibre feed going to the spectrographs. Right) AESOP prototype with 64 spines.
4.3 Fibre System

An overview of the main components of the Fibre System is presented in [12] and consists of science and calibration support fibres and their routing structures (conduits, cable wraps). The science fibre feed may be regarded as two distinct sections:

- The first section is called the Positioner Cable and runs from the fibre positioner to the AESOP output fibre connector unit. This (short) section includes the fibre probes (positioner spines) with the fibres mounted in ceramic ferrules at the spine tips, one side of the fibre connectors and the first level of positioner probe to connector mapping.

- The second section is called the Spectrograph Cable and runs from the fibre connector unit on the AESOP modules to the spectrograph slit units. This (long) second section starts from the AESOP output fibre connector unit, includes the main cable run through the fibre de-rotator unit, the elevation fibre chain, the fibre strain relief units (with a second level of fibre to spectrograph-slit mapping) and ends at the spectrograph slit assemblies. The slit consists of 28 fully populated smaller slitlets blocks holding 29 fibres each and a slitlet block holding 5 calibration fibres at each end (Figure 9).

In addition to the science fibres, the fibre-feed system also takes care of the following fibres:

- The guide fibre bundles that run from the positioner to the secondary guiding monitor.
- The fiducial fibres that run from the positioner to the back-illumination unit.
- The calibration fibres that feed light from the calibration system into the spectrograph outer parts of the fibre-slits.
- The back-illumination fibres, that transport the LED light to these units:
  - the back-illumination units at the HRS & LRS fibre-slit assemblies
  - the back-illumination sphere for the fiducial fibres
  - the back-illumination optics within the secondary guiding monitor

Both guide and fiducial fibres mostly follow the same route as the science fibres (i.e. connectors, rotation and elevation chains, fibre loop box). The calibration and back-illumination fibres are stationary and are not affected by the telescope rotation.

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Figure 8: Left) Optical layout of the metrology system with the light path through the WFC and off the mirrors of one of the four cameras shown. Middle) Cross-cut of the metrology camera using three carbon rods to obtain high stability. Right) Model of one of the metrology cameras attached to the M2 support spiders.
Figure 9: Left) Layout of the main fibre feed elements from the fibre positioner to the spectrographs, and calibration and back-illuminatiion units. Right) Top and front view of the double-curved slit assembly consisting of 28 slitlets with 29 fibres each plus two additional slitlets, one at each end of the slit, with 5 calibration fibres each.

In order to optimize the fibre feed subsystem design and to provide essential information required for the spectrograph design, prototyping and testing has been undertaken. Apart from bare fibres, a prototype including ferules, connectors and slitlets was built and tested for throughput, Focal Ratio Degradation (FRD), scrambling, and system performance dependencies, resulting from input spine tilt, offset- spot feeding, fibre connectors, and cable movement. A measurement of FRD dependency on fibre tilt angle is shown in Figure 10. The prototype testing has shown that the design is expected to meet all requirements.

<table>
<thead>
<tr>
<th>Fibre cable</th>
<th>Input fibre tilt angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con 24F fibre 12 top row</td>
<td>0°</td>
</tr>
</tbody>
</table>

Figure 10: Far-field fibre images showing the Focal Ratio Degradation measurements induced by tilting the fibres in the positioner. At the f/3.0 entrance of the spectrograph collimators about 10 percent more light is lost at maximum tilt.
4.4 Spectrographs and detectors

All 4MOST spectrographs are single-configuration, three-channel spectrographs with VPH gratings as dispersive elements and with refractive cameras projecting the spectra on identical 6k x 6k CCDs with 15 µm pixels. Special attention is paid to spectrograph stability and calibration to ensure that accurate radial velocity measurements can be made. The two Low Resolution Spectrographs [13], handling 812 fibres each, cover a contiguous wavelength range from 370 to 950 nm and have a spectral resolution of R≈4000–8000 (Figure 11). The High Resolution Spectrograph [14] is also handling 812 fibres and has a simultaneous wavelength coverage of 392.6–435.5, 516–573, 610–679 nm at a resolution of R=18500–21000 (Figure 12). In both types of spectrographs each spectral resolution element is sampled with at least 2.5 pixels. The detector cryostats are based on the design of the ESPRESSO instrument [15], while the Cryo-Vacuum system is based on the MUSE instrument design [16], ESO/VLT instruments such that ESO has already extensive experience with manufacturing, operations and maintenance.

![Figure 11: Low Resolution Spectrograph. Left) Optical layout. Right) Spectral resolution as function of wavelength.](image1)

![Figure 12: High Resolution Spectrograph. Left) Optical-mechanical layout. Right) Spectral resolution as function of wavelength.](image2)

4.5 Calibration System

The Calibration System provides light sources for relative flux and wavelength calibration of the data. It consists of a Lamp Cabinet that will be located below the Nasmyth floor of the telescope and Illumination Units attached to the M2 support spiders (Figure 13). The light from the Lamp Cabinet will be transported to the Illumination Units by four optical fibre bundles, each to one of the four M2 spiders. From the Illumination Units light is fed through the optical train to provide relative flux calibration of individual fibres (“flatfield”) using a broadband light source and wavelength and resolution calibration by using a light source with narrow, well characterized spectral lines. The Calibration Illumination Units are created such that illumination increases with radius thus simulating an illumination pattern of the full aperture instead of just from the spiders once azimuthal scrambling in the fibres is taken into account. The line spectrum is
created with a Fabry-Perot etalon and is also fed in dedicated calibration fibres permanently connected to the edges of the fibre slit entrance block in the spectrograph (Figure 9).

Figure 13: Left) Two Calibration Illumination Units (yellow) attached to the vanes supporting the M2 secondary mirror. Middle) Crosscuts of the Illumination Units providing homogeneous illumination across the entire 2.5 degree Field-of-View. Right) Prototype of the Calibration Illumination Unit.

5. SCIENCE OPERATIONS

Due to its high multiplex, 4MOST requires a new model of operations compared to the usual operation model in use at ESO and most other observatories. Few science cases provide enough targets consistently at all pointings to fill all fibres effectively. Therefore, targets from different science programs will be observed simultaneously, requiring modifications in the science operations and data flow model both at the front end (Phase I and II: proposal selection, schedule and Observing Block creation) as well as at the back end (Phase III: data reduction, quality control and progress monitoring, data archiving and public access). Because of these exceptional requirements, the 4MOST Consortium, under oversight by ESO, will handle several of these tasks that are normally handled by ESO.

Few science cases have high enough target densities to fill all fibres in a 4MOST field-of-view, but there are many important science cases that need only a few targets in each field-of-view but have targets spread over the entire sky. To efficiently fill all fibres and to make low target density surveys possible, all 4MOST surveys will be merged in one survey and observed simultaneously. The results of the 4FS demonstrate that the following common survey strategy enables simultaneous and successful observing of Galactic and Extragalactic science programs:

- Each sky location is observed with a sequence of exposures with pre-determined duration, typically two visits of 3x20 minutes. Exposure times from 20 minutes to 2 hours are feasible depending on brightness and signal-to-noise needs of the targets, and, if needed, even longer in more often visited special areas (Galactic Bulge, Magellanic Clouds, deep fields, etc.),
- The sky is subdivided into areas that will be preferentially observed under certain circumstances (predominantly moon phase and seeing), such that, with the predefined exposure time limits from the point above, magnitude ranges of targets can be set.

The 4MOST Consortium Surveys are designed to fully exploit the 4MOST capabilities, yet leave many fibres free for other surveys. The Consortium Surveys will set the observing strategy using 70% of all available fibre time (fibre-hours). Community consultation during survey design, peer review during Phase 1, and ~yearly data release schedules similar to ongoing public spectroscopic surveys with ESO facilities (Gaia-ESO, PESSTO), will make sure this large consortium fraction of telescope time is invested in the interest of the community.

The merging of surveys in one OB results also in merged data reduction treatment. The Consortium Data Management System will process all raw data to calibrated 1D spectra. Given that all Consortium Surveys are Public Surveys, it is assumed that most Community Surveys are also Public Surveys, with similar data release policies. Data Management is also involved in quality control on same-night (technical failures), few-days (spectra of sufficient S/N and quality) and ~yearly time scales (are enough spectra produced for the survey science goals). The Science Operations concept is described in more detail in [17] and [18].
6. PERFORMANCE MODELING

Performance modeling for the 4MOST Project consists out of three elements: 1) a full instrument model simulating the full transmission of photons through the atmosphere, the telescope, and the instrument onto being registered on the detector (TOAD: Top-Of-Atmosphere-to-Detector), 2) an exposure time calculator using a parameterized version of TOAD results to quickly calculate exposure time requirements for thousands of targets (4FS-ETC), and 3) a simulator of a merged survey of 5 year duration including target-fibre assignments and tiling on the sky (4FS-OpSim).

TOAD provides the most extensive modeling of the system throughput and sensitivity as well as performance previews. It is being used for trade-off decisions. It is based on forwarding 2D light distributions and angles as function of wavelength through models of each subsystem, using ZEMAX where needed for detailed calculations [19]. At a later stage TOAD will be used to create artificial images that will be used to test the data reduction pipelines.

4FS-ETC uses a more simplified parameterization of the system throughput to calculate 1D signal and noise spectra for targets in different observing conditions (e.g., sky brightness and transmission, seeing, target-fibre alignment). This allows calculation of limiting magnitudes in different observing conditions and required signal-to-noise as needed per science case (Figure 14). By providing many spectral templates with signal-to-noise requirements for each of the science cases, 4FS-ETC also quickly calculates the needed exposure times for thousands of different target types. These exposure time estimates are then used in the next step to determine whether a target was successfully observed in a simulation of a full 5-year survey with 4MOST.

![Figure 14: Limiting AB-mag sensitivity for seeing FWHM of 1.0", airmass of 1.2 and for the S/N requirements, exposure times, and moon conditions indicated in the legend.](image)

The 4FS_OpSim takes as input a set of real or mock target catalogues, with required exposure times estimated for each target for a limited set of observing conditions. The 4FS_OpSim incorporates detailed models of the 4MOST facility, the observing conditions at Paranal, and various observational constraints. The 4FS_OpSim models the various survey strategy algorithms (sky tiling, OB scheduling, fibre assignment, progress monitoring) that will be used by the real 4MOST survey, and assesses the success of these strategies quantitatively by calculating numeric Figures of Merit (FoM) for each science survey.
These simulations have been run using a large number of different survey strategies, leading already to a good understanding on how to optimize the survey strategy. The simulations prove the full feasibility of running different surveys in parallel with all of them progressing in well tuned balance using the appropriate weighting scheme between the different targets and field pointings. Figure 15 shows the area coverage obtained in a recent simulation using the current Consortium Surveys. In this figure, darker colours represent more loitering time per field pointing, ranging from 20 minutes to 32 hours during dark/grey time and from 20 minutes to almost 5 hours during bright time. Based on the 4FS simulations we estimate that about 25 million targets can be observed with the LRS and 2.5 million with the HRS for the Consortium Surveys, while leaving ample room for other targets to be proposed by the ESO Community.

The 4FS software tools are described in more detail in [18].

![Figure 15: 4MOST Facility Simulator resulting sky coverage for bright (bottom, blue) and dark/grey (top, salmon) time. The legend lists the number of 20 minute exposures obtained.](image-url)

7. CONSORTIUM

The 4MOST Project is supported by a consortium of 14 major partner institutes jointly designing, building, operating and scientifically exploiting the facility. The Project Office of the 4MOST Project is located at the Leibniz-Institut für Astrophysik, Potsdam (AIP). The full consortium will share the survey development and science exploitation, i.e. any consortium member can join any of the consortium surveys; however, Table 3 also lists which institutes have the lead responsibility for the different consortium surveys.
Table 3. 4MOST Consortium Major Partners work package distribution.

<table>
<thead>
<tr>
<th>Institute</th>
<th>Instrument responsibility</th>
<th>Science lead responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australian Astronomical Observatory (AAO)</td>
<td>Fibre Positioner</td>
<td>Galaxy Evolution Survey (WAVES)</td>
</tr>
<tr>
<td>Centre de Recherche Astrophysique de Lyon (CRAL)</td>
<td>Low Resolution Spectrographs</td>
<td>Cosmology Redshift Survey</td>
</tr>
<tr>
<td>European Southern Observatory (ESO)</td>
<td>Detectors System</td>
<td>Milky Way Halo LR Survey</td>
</tr>
<tr>
<td>Institute of Astronomy, Cambridge (IoA)</td>
<td>Data Management System</td>
<td>Milky Way Halo LR Survey</td>
</tr>
<tr>
<td>Max-Planck-Institut für Astronomie (MPIA)</td>
<td>Instrument Control System Hardware</td>
<td>Milky Way Disk and Bulge HR Survey</td>
</tr>
<tr>
<td>Max-Planck-Institut für extraterrestrische Physik (MPE)</td>
<td>Science Operations System</td>
<td>Galaxy Clusters Survey, AGN Survey</td>
</tr>
<tr>
<td>Zentrum für Astronomie der Universität Heidelberg (ZAH)</td>
<td>High Resolution Spectrograph, Instrument Control System Software</td>
<td>Milky Way Halo HR Survey</td>
</tr>
<tr>
<td>NOVA/ASTRON Dwingeloo</td>
<td>Calibration System</td>
<td>Milky Way Halo LR Survey</td>
</tr>
<tr>
<td>Rijksuniversiteit Groningen (RuG)</td>
<td></td>
<td>Milky Way Disk and Bulge HR Survey</td>
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<td>Lunds Universitet (Lund)</td>
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<tr>
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<tr>
<td>Hamburg Universität (UHH)</td>
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<td>Galaxy Evolution Survey (WAVES)</td>
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<td>École polytechnique fédérale de Lausanne (EPFL)</td>
<td></td>
<td>Cosmology Redshift Survey</td>
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</table>

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REFERENCES


