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4MOST: the 4-metre multi-object spectroscopic telescope project in the assembly, integration, and test phase

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4MOST: the 4-metre multi-object spectroscopic telescope project in the assembly, integration and test phase

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ABSTRACT

4MOST is a new high-multiplex, wide-field spectroscopic survey facility under construction for ESO's 4m-VISTA telescope at Paranal, Chile. Its key specifications are: a large field of view of 4.4 square degrees, a high multiplex fibre positioner based on the tilting spine principle that positions 2436 science fibres in the focal surface of which 1624 fibres go to two low-resolution optical spectrographs ($R = \lambda/\Delta\lambda \sim 6500$) and 812 fibres transfer light to the high-resolution optical spectrograph ($R \sim 20{,}000$). Currently, almost all subsystems are completed and full testing in Europe will be finished in spring 2023, after which 4MOST will be shipped to Chile. An overview is given of instrument construction and capabilities, the planned science of the consortium and the recently selected community programmes, and the unique operational scheme of 4MOST.

Keywords: Wide-field multi-object spectrograph facility, VISTA telescope, tilting-spine fibre postioner, wide field corrector, facility simulator, fibre-fed spectrographs, science operations, survey observing strategy

1. INTRODUCTION

Ground based, wide-field, high-multiplex spectroscopic survey facilities fill a need to follow-up the many large sky area surveys being conducted at many wavelengths from both space and the ground (for instance, Gaia, eROSITA, Euclid, PLATO, VISTA, VST, DES, VRO/LSST, and SKA). To fill this need in the Southern sky for the ESO community, the 4MOST Consortium was selected in 2011 to conduct a Concept Design study for such a facility, resulting in a recommendation for implementation in 2013. Currently, after having past its Final Design in 2019, 4MOST is nearing the completion of its construction phase and has started its Assembly, Integration, and Test (AIT) phase in Europe. This phase is scheduled to finish in May 2023 with a Provisional Acceptance Europe (PAE) Review conducted by ESO, after which the instrument will be shipped to Paranal Observatory, Chile to be Assembled, Integrated and Verified (AIV) on the VISTA telescope in the second half of 2023. After an additional extensive science verification phase, normal science operation is expected to start in spring 2024, initiating 4MOST's first five-year survey.

In order to efficiently fill all the fibres in a high multiplex instrument like 4MOST, multiple science cases must be carried out simultaneously. This necessitates effective coordination between different science teams that will share the available fibres in the focal surface, and consequently, share the data on the CCD frames with the recorded spectra. To facilitate this, most of the large Surveys driving the observing strategy and ensuring that enough targets are available across the sky to fill the fibres will be performed by the 4MOST Consortium as Public Surveys using 70% of the available fibre-hours in the first five years of operation. These Public Surveys are part of the Guaranteed Time Observations (GTO) that the Consortium receives in return for building the facility and for supporting ESO in the operation of 4MOST. The other 30% of available fibre-hours in the first five years of operation will be filled by fifteen Public Survey programmes proposed by the ESO and the Chilean host country communities, which were recently selected by an ESO led peer-review process.

The 4MOST project is organised along three branches:

1. Instrument — responsible for the development, construction, and commissioning of the instrument hardware and associated software. The instrument is under construction at a number of Consortium institutes, coordinated by the 4MOST Project Office located at the Leibniz-Institut für Astrophysik Potsdam (AIP);
2. Operations — for the planning, data reduction, archiving, and publishing of the observations including the associated data-flow. The operations branch is led by the Operations Development Group, consisting of the leads of the different subsystems and working groups involved in observation planning and data-flow.;
3. Science — the branch that develops the different Public Surveys and is responsible for science analysis and publication. The science programme is organised into eighteen Surveys led by one or more Survey Principal Investigators (Survey PIs). Coordination between all participating surveys is performed by the Science Coordination Board (SCB). The science branch is overseen by two Project Scientists, one for Galactic and one for extragalactic science, who have both a science guidance and a managerial role.

The instrument and operations branches are mainly performed by the 4MOST Consortium and are jointly called the 4MOST Facility.

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In Section 2 we describe the instrument specification, architecture and the current status of the subsystems. We also summarise the expected performance of 4MOST in this section. In Section 3 provides an overview of the eighteen Surveys that make up the science programme of the first five-year 4MOST survey. The operations scheme and survey strategy that enables these eighteen science cases to be conducted concurrently with 4MOST are detailed in Section 4. Section 5 contains the instrument and software integration, verification and commissioning plans before the start of operations. The efforts made by the 4MOST Project to ensure a truly collaborative, team-oriented, and inclusive project culture are described in Section 6. Finally, the Consortium structure and work package distribution is outlined in Section 7.

2. INSTRUMENT SPECIFICATION, ARCHITECTURE AND STATUS

The 4MOST instrument design was driven by the science requirements of its key Consortium Surveys. Within a 2-hour observation 4MOST has the sensitivity to obtain redshifts of r = 22.5 AB-mag galaxies and active galactic nuclei (AGN), radial velocities of any Gaia source (G < 20.5 mag), stellar parameters and selected key elemental abundances with accuracy better than 0.15 dex of G < 18-mag stars, and abundances of up to 15 elements of G < 15.5-mag stars. Furthermore, in a five-year survey 4MOST can cover > 17 000 square degrees at least twice and obtain spectra of more than 20 million sources with a resolution of R ~ 6500 and more than three million spectra with a resolution of R ~ 20 000 for the typical science cases proposed. The key instrument specifications enabling these science requirements are summarised in Table 1. Figure 1 provides an overview of the main instrument subsystems.

Table 1. 4MOST key instrument specification

Instrument parameter	**Design value**
Field of view (hexagon)	~ 4.2 square degrees (Ø = 2.6 degrees)
Accessible sky (zenith angle < 55 degrees)	> 30 000 square degrees
Expected on-target fibre-hours per year	LRS: > 3 200 000 h yr–1, HRS > 1600 000 h yr–1
Multiplex fibre positioner	2436
Smallest target separation	15 arcseconds on any side
# of fibres in random Ø = 2 arcminute circle	≥3
Fibre diameter	Ø = 1.45 arcseconds
Low-Resolution Spectrographs LRS (× 2)	
Resolution	$< R > = 6500$
Number of fibres	812 fibres
Passband	3700–9500 Å
Velocity accuracy	< 1 km s^{-1}
High-Resolution Spectrograph HRS (× 1)	
Resolution	$< R > = 20\,000$
Number of fibres	812 fibres
Passband	3926–4355, 5160–5730, 6100–6790 Å
Velocity accuracy	< 1 km s^{-1}

2.1 Status of Subsystems

VISTA will be equipped new Wide Field Corrector (WFC) that creates a physical focal surface of 535 mm diameter or of 2.6-degree diameter projected on the sky. The WFC comprises of 6 coated lenses grouped into 4 elements. Two lens groups are cemented doublets that act as an Atmospheric Dispersion Compensator (ADC) that provides corrections to a 55-degree zenith angle distance. The lenses were manufactured by KiwiStar Optics from glass blanks produced by Corning (L1) and Schott (other lenses)[1]. In order for the instrument to meet its required image quality, each of the lenses in the WFC needs to be aligned to ~0.05mm. Alignment and assembly was performed at University College London as described in these proceedings[2]. The WFC/ADC has arrived at AIP Potsdam for the AIT full system testing (Figure 2).

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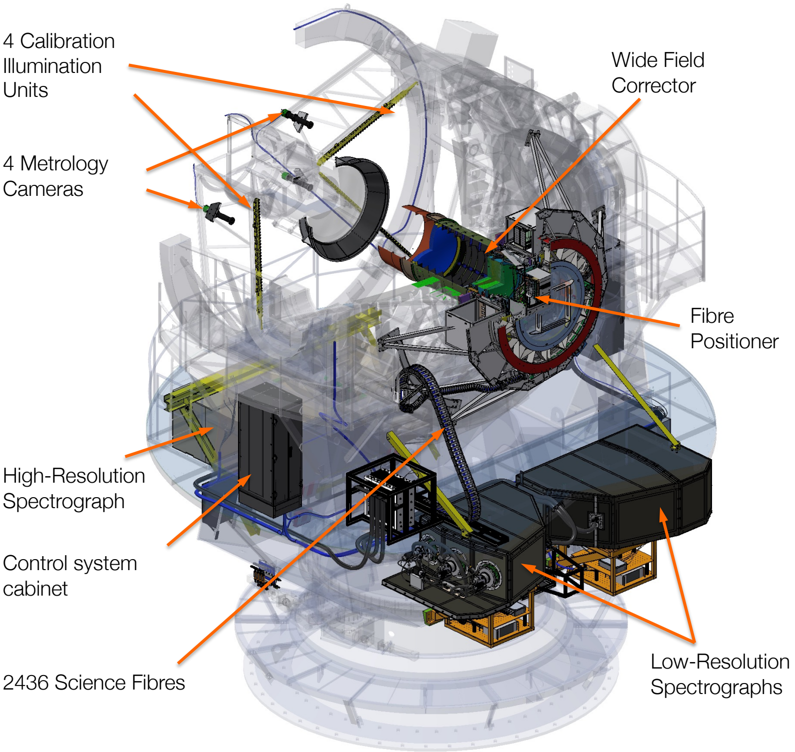

Figure 1. *Left)* Layout of the different subsystems of 4MOST on the VISTA telescope.

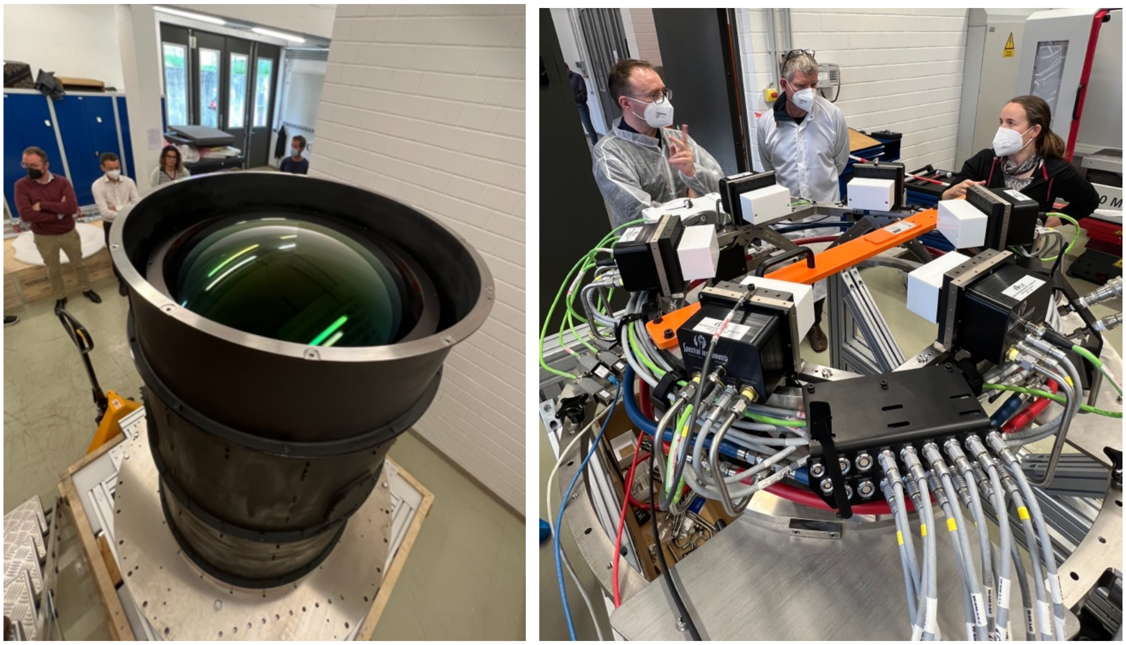

Figure 2. *Left)* The delivery inspection in Potsdam of the Wide Field Corrector with the L1 front lens of 900 mm diameter exposed. *Right)* The Acquisition & Guiding and the Wave Front Sensing assembly. The six technical cameras are connected to their electronics and cooling. The white boxes at the front of the cameras protect the pick-off prisms that fold the light from the focal surface onto the CCD.

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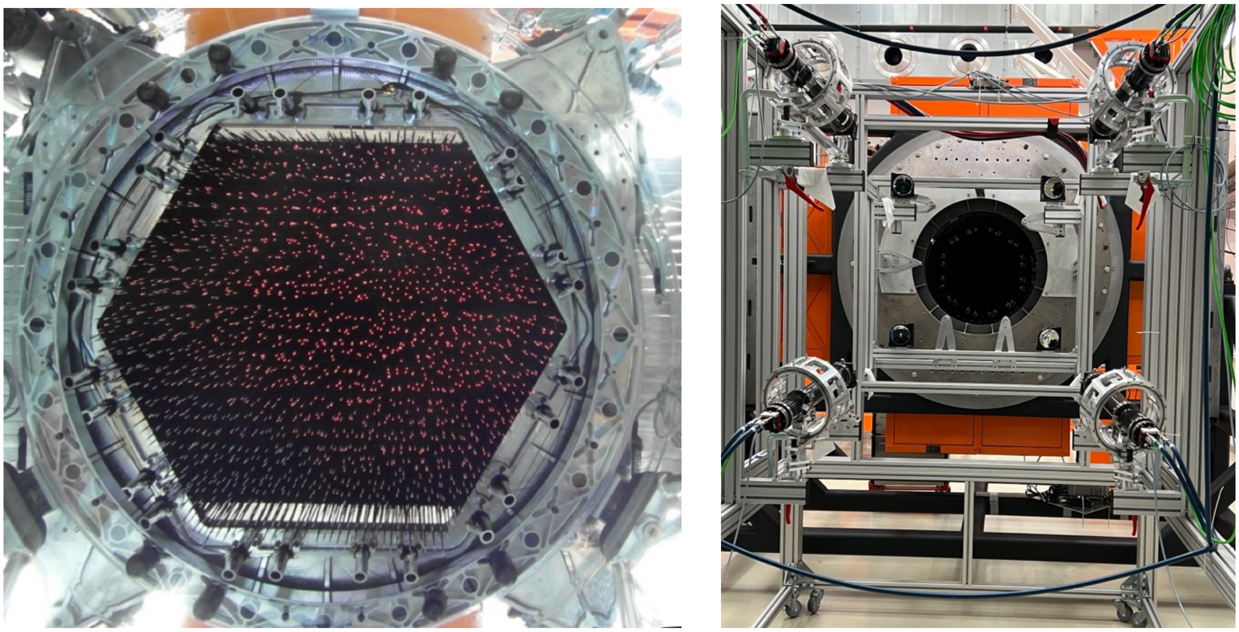
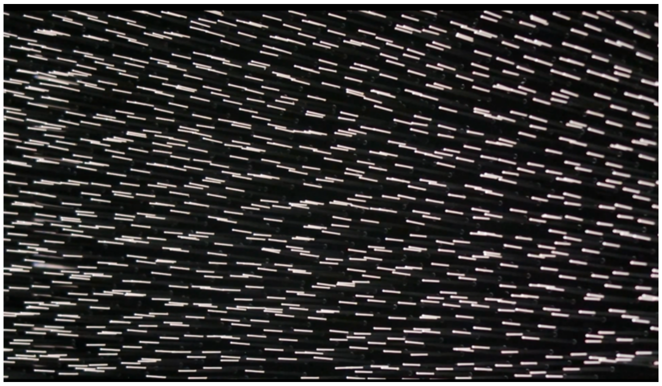


Figure 3. *Left)* The AESOP fibre positioner, showing the 2436 science tilting spines arranged in a hexagonal pattern with fibres being back illuminated with red light. The spines are surrounded by 24 fixed, fiducial fibres that function as a reference frame for the Metrology System. *Right)* Four metrology cameras (black tubes towards the corners) are surrounding the AESOP positioner in the Metrology Test Stand setup.



Video 1. The AESOP fiber spines moving from a random position to their regular grid home position. http://dx.doi.org/10.1117/12.2628965.1

The AESOP fibre positioning system was designed and built by AAO in Australia and is based on the tilting spine principle. It can, within 2 minutes, simultaneously position all of the 2436 science fibres that are arranged in a hexagonally shaped grid at the focal surface (Figure 3; Video 1). The tilting spine positioner has the advantage that each fibre has a large patrol area; each target in the science field of view can be reached by at least three fibres that go to one of the Low-Resolution Spectrographs (LRS) and one or two fibres that go to the High-Resolution Spectrograph (HRS). This ensures a high allocation efficiency of the fibres to targets, even when targets are clustered. There are an additional 12 spines situated around the edge of the field that contain small bundles of 7 fibres that provide low resolution images to the secondary guiding camera to ensure accurate pointing and rotation of the science field of the fibre tips. The edge of the field has also 24 very stable fiducial fibres that function as a reference grid for the metrology camaras. Further details about the engineering principles and measured performance of the AESOP positioner can be found elsewhere in these proceedings [5][6]. The fibre positioner arrived in Potsdam in May 2021 and was, due to the pandemic circumstances, integrated by a team of engineers from European Consortium partners with remote assistance from colleagues in Australia.

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Accurate positioning of the fibre spines in the positioner is achieved by four metrology cameras which are situated on the spider vanes that support the secondary mirror. The metrology cameras image the fibre tips which are back illuminated from the spectrographs and by measuring relative positions with respect to the fixed fiducial fibres positioning accuracy to better than 5 microns (~0.075 arcsec on sky) is achieved. All cameras have been manufactured and characterised. Closed loop testing in combination with the AESOP positioner on a test stand that mimics the optics of the telescope is ongoing[7] (Figure 3).

The fibre system contains the 2436 short fibres in the positioner from spine tips to its back connector, the three ~25 m long fibre feed bundles with 812 fibres each going from the positioner connectors through the Cassegrain cable wrap and altitude wrap, strain relieve to the spectrographs slit units with their connected shutter and back-illumination systems. In addition, there are dedicated fibre cables for simultaneous calibration, for secondary guiding, and fiducial reference fibres for metrology. A support and guide system to protect the delicate fibres consists of multiple layers of conduits and cable carriers and in particular a large Cassegrain cable wrap at the back of the telescope that accommodates the rotation of the focal surface area while the Alt-Az telescope is tracking a field on the sky. All fibre bundles have been produced by SQS Vláknová optika with final verification inspections ongoing at the AIP in Potsdam, after which they will be integrated in the spectrograph slit units. The large Cassegrain cable wrap has been manufactured by Kinkele GmbH & Co KG (Figure 4) and is receiving last mechanical adjustments and testing. Details on the manufacture, assembly and test of the optical fibre system are presented elsewhere in these proceedings[8].

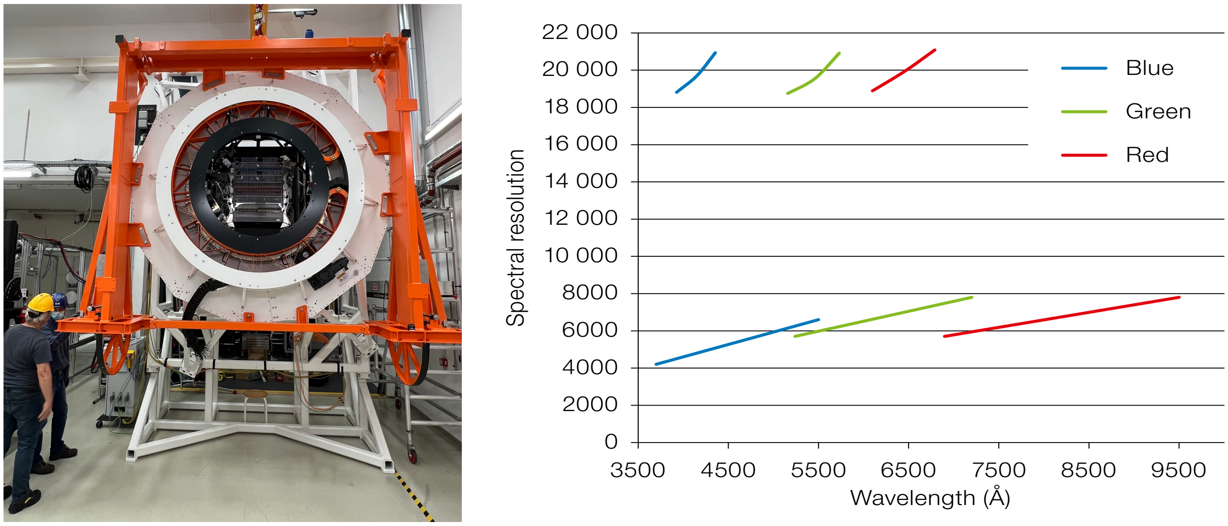

Figure 4. *Left)* The Cassegrain Cable Wrap (white and black circular structures) being put on the Cassegrain Test Stand. In the centre the backside of the AESOP fibre positioner is visible with its fibre connectors. *Right)* Spectral resolution in the three channels of the 4MOST High-Resolution (HRS, upper lines) and Low-Resolution Spectrographs (LRS; lower lines).

4MOST has two Low-Resolution Spectrographs (LRS) and one High-Resolution Spectrograph (HRS). Each spectrograph accepts 812 science fibres and six simultaneous calibration fibres attached to either end of the spectrograph entrance slit. The covered wavelength range and resolution of the LRS and HRS spectrographs are as depicted in Figure 4. Each type of spectrograph has three channels in fixed configurations covering three wavelength bands, and is thermally invariant and insulated (HRS) or temperature controlled (LRS) for stability. Each channel is equipped with a 6k×6k CCD detector with low read noise (< 2.3 electrons per read) and with high, broadband quantum efficiency. The first LRS has passed its Local Acceptance Review at CRAL in Lyon, was shipped to Potsdam and reintegrated meeting specifications (Figure 5). The second LRS is expected in October 2022. Further details on the LRS alignment procedures and its measured performance appears elsewhere in these proceedings[9][10]. The HRS is closing its final action items resulting from its Local Acceptance Review at LSW in Heidelberg (Figure 5) and will arrive in Potsdam soon. While HRS is meeting essentially all specifications, one of the lenses in the green arm camera was known to have developed an issue and needs a new coating. The HRS MAIT is described in these proceedings[11]. All nine science Detector Systems plus one spare system were produced by ESO and have been operating at the spectrograph manufacturing locations for the last 1.5 years.

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Figure 5. *Left)* Reintegration of the first Low-Resolution Spectrograph in Potsdam after delivery from CRAL. One of the detector systems is being installed. *Right)* The High-Resolution Spectrograph during Local Acceptance Review inspection in Heidelberg. The black panels are part of the thermally insulated spectrograph cover. One panel has been removed for inspection of one of the CCDs. The aluminium scaffolding surrounding the HRS is used to provide the same access conditions to the slit unit as at the telescope by means of an access port on the top reached from the observing floor.

A Calibration System equipped with a continuum source, a Fabry-Perot etalon, and ThAr lamps can feed light through the telescope plus science fibres combination by feeding the light through fibres to four illumination units attached to the M2 support vanes. The four illumination units each consists of 30 integrating spheres whose very homogenous light is projected onto the focal surface with a 25 mm diameter lens (Figure 6). During a science exposure, the calibration light can also be fed directly through the simultaneous calibration fibres into the spectrograph slit to ensure accurate wavelength calibration. This will ensure that we can typically reach better than 1 km s^{-1} accuracy on stellar radial velocities. The details of the 4MOST Calibration System design, assembly and testing appear elsewhere in these proceedings[12]. The Calibration has been tested with the HRS spectrograph and will arrive in Potsdam in August 2022.

Figure 6. *Left)* The two main electronic cabinets of the Hardware Facility Control System that will be installed next to the telescope yoke on the Azimuth floor. *Right)* Integration (top) and illumination test (bottom) of the Calibration System illumination units. Even though all 30 integrating spheres are illuminated, because their outputs are near collimated beams through their lenses in front, only 3 beams are seen.

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The 4MOST Hardware Facility Control System adheres as much as possible to the ESO standards. Two control cabinets are located on the azimuth floor near the yoke of the telescope that control many of the instrument functions in the subsystems, including the critical vacuum and temperature control functions of the detector systems (Figure 6). Duplicate systems were built such that the HRS and LRS spectrograph teams in Heidelberg and Lyon could align and test their systems independently. Four electronic cabinets are connected around the AESOP positioner in the rotating Cassegrain area, containing the stand-alone control electronics of AESOP itself such that it could be developed and tested independently, but also some of the controls needed for the A&G and WFS and ADC. Finally, there is a control cabinet to hold the instrument control workstations. Most of the control hardware has been functioning over the last years to support the development of the different subsystems and all cabinets will arrive in Potsdam with the spectrograph deliveries.

The 4MOST Software Facility Control System is based on the standard ESO VLT software architecture and customised to fit the needs of the 4MOST instrument. Critical elements are the accurate positioning of the fibre spine tips taking all atmospheric and telescope optics distortions into account using the positioner and metrology camera control loop, the guiding and wavefront sensing control loop including the secondary guiding, and the detector system readout control. ESO's system is built around observing templates that control a sequence of instrument operations that a user may want to execute. The software will include user-friendly graphical user interfaces that enable users to interact with the facility control system and to monitor all data-taking and calibration tasks of the instrument. The different software control elements were developed in parallel with the subsystem control hardware. This ensured that the different subsystems could be controlled and tested during their development and that the actual software to be used in the ESO VLT framework could already be debugged (for details see[13]).

2.2 Expected Performance

To predict the optical performance of 4MOST, a full Top-Of-the-Atmosphere-to-Detector (TOAD) simulator was coded creating 2D detector images. The details of TOAD with all atmosphere and optical elements taken into account have been published earlier[14]. 4MOST expected sensitivity for a number of typical science cases is depicted in Figure 7. TOAD is extensively used to generate artificial data for testing the data reduction and analysis pipelines (Section 5).

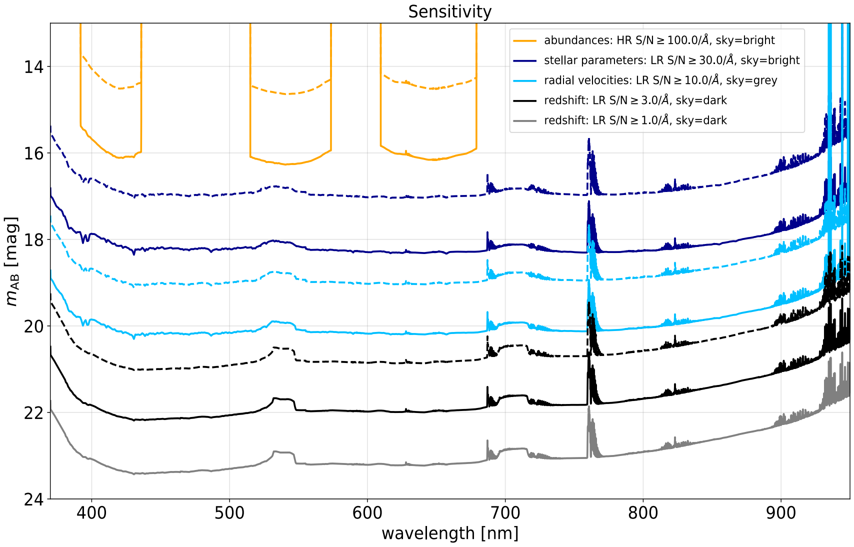

Figure 7. The expected 4MOST point-source sensitivities for the signal-to-noise levels and lunar conditions indicated in the legend. The solid lines are for a total exposure time of 120 minutes, whereas the dashed lines are the limits for 20-minute exposures. For clarity, sky emission lines are removed. Mean (not median) seeing conditions, airmass values, fibre quality and positioning errors, etc., are used, in order to ensure that this plot is representative for an entire 4MOST survey, not just for the optimal conditions. Typical science cases for obtaining detailed elemental abundances of stars (orange), stellar parameters and some elemental abundances (dark blue), stellar radial velocities (light blue), and galaxy and AGN redshifts (black: 90% complete, grey: 50% complete) are shown.

A critical element in the performance of an instrument is to maximise observing efficiency and minimise observational overheads. The current aim and expectation that many of the observing overheads such as telescope slewing, guide star acquisitions, instrument configuration setting, etc., can be hidden by performing them during the ~110 seconds it takes to read out the previous science exposure in unbinned, normal read speed mode. The current planning foresees that during the first year of operations each night-time science exposure is accompanied with "attached" flatfield and wavelength calibration exposures in order to be able to calibrate any throughput and wavelength variations induced by the tilting spines and the moving fibres in the fibre system. These exposures will add an additional 120 seconds overhead to each science exposure. The expectation is that the variation observed with these extra calibration exposures are reproducible and predictable enough such that they can be shifted to the daytime or skipped altogether after the first year of observations.

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The 4FS-ETC uses a more simplified parameterization of the system throughput than TOAD to calculate with high efficiency typical 1D signal and noise spectra for millions of targets in different observing conditions (e.g., moon and airmass dependent sky brightness and transmission, seeing). This allows prediction of the needed exposure times in different observing conditions for the tens of millions of targets given the spectral success requirements provided by the different Survey teams. The 4FS-Visit Planner optimally tiles the sky with 4MOST field-of-views pointings, assigning each visit a sky condition and a sequence of exposure times based on the local target density and exposure time needs, aiming to maximise target completion and minimising over exposure[15]. A long-term scheduler distributes the visits over the five survey years such that they can always be observed close to the meridian, while a short-term scheduler picks the optimal visit to schedule in the next minutes given the current and predicted observing conditions. The next 4FS module assigns fibres to targets, using a probabilistic assignment scheme that takes the positioner's capabilities and constraints into account, the requested and available observing time for each target and aims to produce homogeneous target selections independent of, for instance, spatial and magnitude distribution in the input catalogues. The advantage of this selection algorithm is that it allows for easy and accurate selection function calculation[16]. Finally, the precalculated exposure time of the prepared visit that was based on a typical observing condition is adjusted to match the actual observing conditions.

4FS produces many diagnostic plots that the different science teams can analyse to ensure that the observed sample matches their needs in terms of, for instance, number of targets, spatial distribution on different large and small scales, (local) sample completeness, and magnitude distribution. Figure 8 shows some typical results of a recent simulation that resulted in the successful observation of about 28 million LRS and 8 million HRS targets not including the poor observing conditions program.

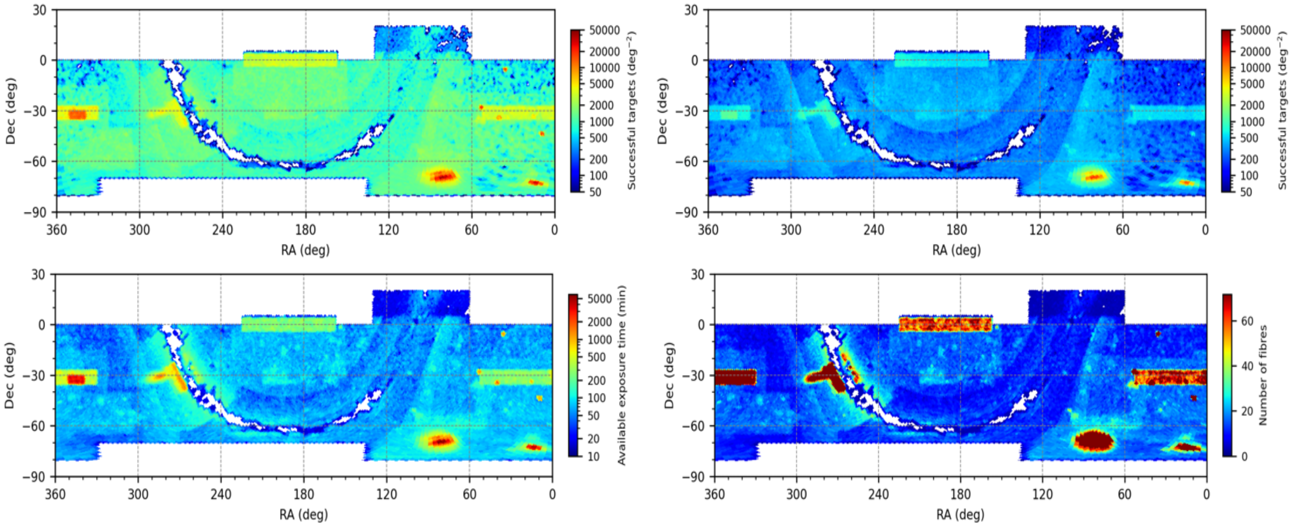

Figure 8. Examples of the 4MOST Facility Simulator output sky distributions. *Top-left)* Successfully observed LRS objects. *Top-right)* Successfully observed HRS objects. *Bottom-left)* Available exposure time. *Bottom-right)* Number of independent exposures.

3. SCIENCE AND SURVEYS

The science programmes of 4MOST are organised in Surveys that share the focal surface and are observed together. For the first five-years of operation, ten Surveys have been defined by the 4MOST Consortium to fill the Guaranteed Time Observations in return for building and operating the instrument. In December 2021 ESO announced the results of a two-year peer-review selection process for the community science programmes to be executed in the first 5-year survey. Fifteen science programmes were selected from the ESO and the Chilean host country communities. Some of these community programmes have been combined with the existing consortium Surveys such that eighteen Surveys (Table 2) will be executed in the first 5-year observing programme. Almost all Surveys benefit from the Southern hemisphere location of 4MOST, either by exploiting the fact that the Galactic Centre and the Magellanic Clouds are best observed from the South, or by complementing other Southern hemisphere facilities like VRO/LSST, SKA pathfinders, SkyMapper, or the VISTA/VIRCAM surveys.

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Table 2. 4MOST Surveys and Sub-Surveys (without IDs) with their Principal Investigators

ID	Survey Title	PI
S1	The Milky Way Halo Low-Resolution Survey	Else Starkenburg, Clare Worley
	4MOST Gaia RRLyrae Survey (4GRoundS)	Rodrigo Ibata
S2	The Milky Way Halo High-Resolution Survey	Norbert Christlieb
S3	Milky Way Disk and Bulge Low-Resolution Survey (4MIDABLE-LR)	Cristina Chiappini, Ivan Minchev
S4	Milky Way Disc and Bulge High-Resolution Survey (4MIDABLE-HR)	Thomas Bensby, Maria Bergemann
S5	eROSITA Galaxy Cluster Redshift Survey	Johan Comparat
S6	Active Galactic Nuclei	Andrea Merloni
	The 4MOST–Gaia Purely Astrometric Quasar Survey (PAQS)	Jens-Kristian Krogager
S7	Wide Area VISTA Extragalactic Survey (WAVES)	Simon Driver, Jochen Liske
	4C3R2: 4MOST Complete Calibration of the Color-Redshift Relation	Daniel Gruen
	Optical, Radio Continuum and HI Deep Spectroscopic Survey (ORCHIDSS)	Kenneth Duncan
	4MOST-StePS	Angela Iovino
S8	Cosmology Redshift Survey (CRS)	Johan Richard, Jean-Paul Kneib
S9	The One Thousand and One Magellanic Fields (1001MC) Survey	Maria-Rosa Cioni
	Spectroscopic Discovery of Binaries with Dormant Black Holes	Michał Pawlak
S10	The Time Domain Extragalactic Survey (TIDES)	Isobel Hook
	4SLSLS: The 4MOST Strong Lens Spectroscopic Legacy Survey	Thomas Collett
S11	The White Dwarf Binary survey (WDB)	Odette Toloza, Alberto Rebassa-Mansergas
S12	The 4MOST Survey of Young Stars (4SYS)	Giuseppe Germano Sacco
S13	Stellar Clusters in 4MOST	Sara Lucatello, Antonella Vallenari, Angela Bragaglia
S14	4MOST survey of dwarf galaxies and their stellar streams (4DWARFS)	Asa Skúladóttir
S15	CHileAN Cluster galaxy Evolution Survey (CHANCES)	Christopher Haines
S16	4MOST Chilean AGN/Galaxy Evolution Survey (ChANGES)	Franz Erik Bauer, Paulina Lira
S17	High-Resolution Quasar Spectroscopy (4HI-Q)	Celine Peroux
S18	The 4MOST Hemisphere Survey of the Nearby Universe (4HS)	Edward Taylor, Michelle Cluver

The Galactic Community Surveys are designed to help us understand the Milky Way and how it evolved to its present-day configuration. Which internal and external processes have shaped our Galaxy? Taking advantage of the unique characteristics of 4MOST, a set of Surveys has been designed that will address key objectives in Galactic Archaeology, including: determining the density profile, shape and characteristic parameters of the dark matter halo of the Milky Way; better understanding the current Milky Way disk structure and dynamics (bar, spiral arms, vertical structure, stellar radial migration, merger history); reconstructing the growth history of the Milky Way; finding and characterizing kinematic and chemical patterns within the Magellanic Clouds system; and identifying stars that were accreted to the Galactic halo and quantifying their contribution to the build-up of the halo. Further stellar (sub-)Surveys are dedicated to particular classes of stellar object, like White Dwarfs, Planetary Nebulae, Asteroseismic targets, and various kinds of variable and binary stars, which will improve our understanding of stellar physics and evolution.

The Galactic Community (sub-)Surveys tackle a broad range of science goals in stellar and Galactic astrophysics. Their design is highly complementary to the Consortium Surveys, whose main focus is on Milky Way field stars and the Magellanic Clouds. The Community Surveys will add several systems to the observing programme that are critical to understanding the build-up of the Milky Way; namely the Sagittarius stream, three of the largest satellite galaxies, and hundreds of stellar clusters in all Galactic components. The unique properties of RR Lyraes will help us form a clearer view of structure in the Galaxy out to large distances. Another key focus of the Community Surveys is to determine accurate stellar ages, by tracing stellar evolution all the way from newborn stars to stellar remnants, thereby being able to address fundamental questions about how stars form, live their lives and die in violent explosions.

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The five extragalactic Consortium surveys are designed to carry out a number of fundamental measurements of the growth of large scale structure in the Universe; to test theories for the nature of dark matter and dark energy; to constrain the cosmological equation of state; to study when and how the first stars, black holes and galaxies were born; to measure and understand the formation, masses, evolution and growth of supermassive black holes and their role in the formation and evolution of galaxies over cosmic time out to redshifts of 6. Furthermore, there is a Survey dedicated to time domain discoveries, mainly in synergy with the Vera Rubin Observatory/LSST facility survey where supernova transients and quasar luminosity variability will be complemented with spectroscopic observations.

The nine Extragalactic Community Surveys target a broad range of extragalactic sources, ranging from galaxies in the local Universe to quasars at redshift 4 and beyond, and strongly complement the science goals of the Consortium Surveys. Several provide vital spectroscopic followup of sources detected by other major new facilities, such as eROSITA galaxy clusters, strong lens systems discovered by the Euclid and Rubin observatories, radio continuum detections from the MeerKAT SKA pathfinder, and quasars detected from lack of proper motion by Gaia. Others investigate the detailed astrophysics of the baryon cycle in the circumgalactic medium, or the connection between stellar populations, gas properties and environment. All fully exploit the unique capabilities of 4MOST and its synergy with other leading southern hemisphere facilities to further our understanding of the extragalactic Universe.

4. SURVEY STRATEGY, OPERATIONS SCHEME, AND DATA ANALYSIS

The operational model for 4MOST will differ in several respects from normal ESO operations. The 4MOST science time will be devoted to a coordinated set of Consortium and Community Surveys. A distinctive advantage of 4MOST lies in the capability to carry out many different science programs in parallel, thereby allowing not only unprecedented sample sizes, but also making it possible to observe programs that would otherwise be too expensive due to low target densities. In parallel mode, data for different Surveys are observed simultaneously at the telescope. In order to run the telescope efficiently in parallel mode, the 4MOST Consortium will take a service role for the user community of 4MOST, fulfilling some of the functions normally carried out by each individual programme PI. In particular this includes the preparation of the Observing Blocks (OB) and the data processing.

4.1 Survey Strategy

Running 4MOST efficiently with many Surveys in parallel demands an observing plan that can accommodate targets that require very different exposure times. Some of the bright stars may reach their required Signal-to-Noise (S/N) ratio in five minutes in the Low-Resolution Spectrograph (LRS), while faint extragalactic targets or faint stars with the High-Resolution Spectrograph (HRS) could require two hours of total exposure time. The operations scheme must also be able to adapt to different observing conditions (e.g., sky brightness and seeing).

To accommodate the different exposure times, the total exposure time in an area on the sky is broken up into individual exposures. For each exposure, the fibres are repositioned in a new configuration such that targets that can be finished in one exposure receive a fibre only once, while other targets receive a fibre multiple times in the different fibre configurations until they reach the required *S/N*. To save the overheads of repositioning the telescope and acquiring guide stars, several fibre configuration exposures can be grouped in one Observation Block (OB) that is then observed in one telescope visit at that pointing. While we expect that exposure times will be typically of order 20 minutes, shorter times will be used in areas with many bright sources at the cost of some extra overheads, while the maximum individual exposure time for a configuration is set at 30 minutes, because changing differential refraction across the field would cause fibres to drift if exposed much longer.

Because many targets from different Surveys are observed simultaneously, proposers cannot request certain observing conditions (seeing, moon) on a per target level. The scheduling algorithm groups preferentially targets that can be observed in similar conditions and optimises a sequence of exposure times to maximise the number of targets that can be completed. Surveys therefore need to provide, next to their target catalogues, a number of other parameters such that target selections and observing schedules can be optimised to be both efficient and reproducible at least in a statistical sense. These parameters include: 1) spectral S/N or redshift success criteria to estimate needed exposure time and to signal target completion after the data is analysed, 2) a Small Scale Merit that defines the target completeness required for a sample on the scale of about a 4MOST Field of View, 3) a Large Scale Merit that describes a Survey's sky area preference, and 4) a total Figure of Merit that provides an overall measure of a Survey's scientific success.

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The 4FS (Section 2.2) is used to tune the many parameters of the scheduling algorithms to maximise the total Figure of Merit of all Surveys as well as various other requirements from the Surveys (e.g., homogenous sample completeness in spatial and magnitude distribution, area coverage, cadence). The entire simulation process is automated such that with a given set of input catalogues and parameters, new 5-year simulations can be produced in a day. A large set of plots and data is provided to the users to evaluate the feasibility of their science goals with each simulation. Some results of resent simulations is presented in Figure 8. The 4MOST survey strategy is described in more detail in [17].

4.2 Operations Scheme and Data Analysis

Figure 9 shows the main actors and software modules of the 4MOST operations and data flow between them. The process starts with the Surveys submitting their target catalogues with their observing requirements and goals (e.g., S/N, completeness) to the front-end Science Operations System (OpSys). OpSys ingests all input catalogue in a database, calculates the exposure times needed and plans the optimal tiling on the sky given the total target density and exposure time pressure. Using ESO's Designated Visitor Mode of remote observations, OpSys uses the current observing conditions (moon, seeing, wind, clouds, etc.) and observing strategy parameters to select the next field to observe and assign fibres to objects in a fully probabilistic algorithm[16]. An Observing Block (OB) with instrument instructions is created and send from MPE, Garching to Paranal Observatory to be executed on VISTA as soon as the previous OB is finished.

The data of all executed OBs is transferred at the end of the night through ESO's Science Archive Facility (where all raw data is public immediately) to the 4MOST Data Processing Centre located at IoA, Cambridge. The Data Management System removes the instrument profile and extracts the science-ready, calibrated 1D spectra. Additional pipelines created by Infrastructure Working Groups then process the data further to perform machine learning object classifications, determine for instance radial velocities, stellar parameters and abundances for stars or redshifts and star formation histories for galaxies and AGN. Also, the target selection and observing completion probability is determined for all parameters of all targets. Finally, after various quality checks and data curation, the data is made available to the users through the 4MOST Public Archive and the ESO Science Archive Facility.

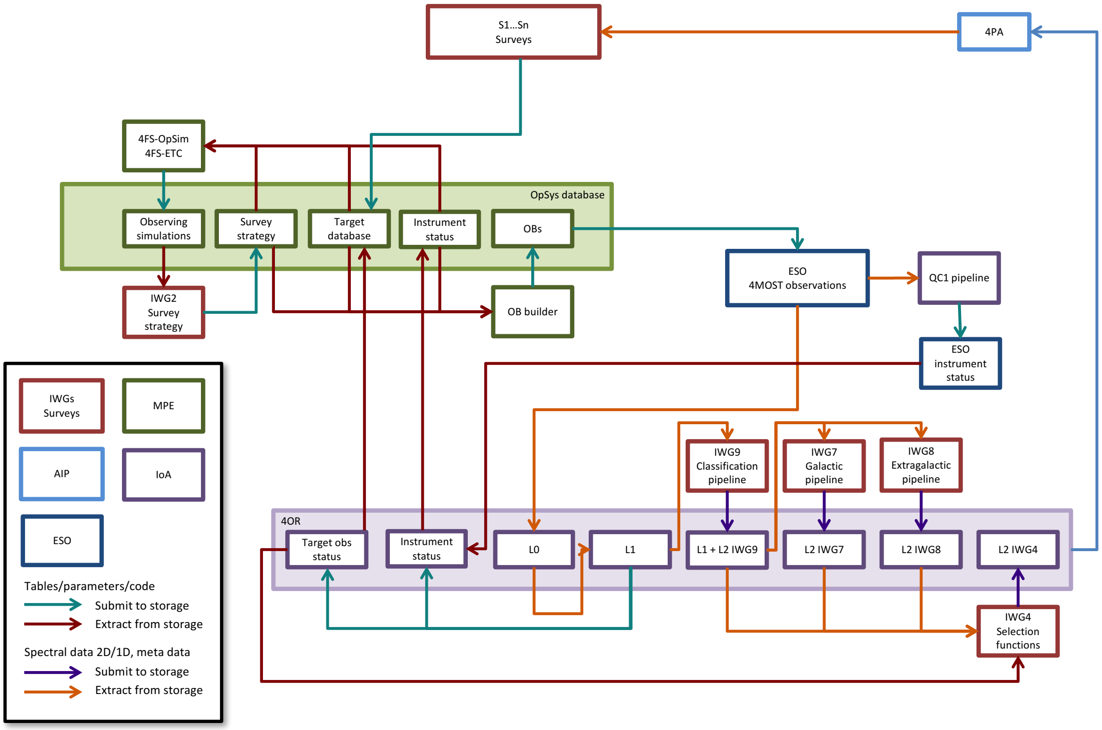

Figure 9. Main actors and software modules in the 4MOST data flow.

4.3 Calibration

In the 4MOST Calibration Plan, described in more detail elsewhere in these proceedings[18], we distinguish three different types of calibration:

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- **Instrument Calibration** deals with all calibration and monitoring efforts that are required to guarantee proper function and operation of the 4MOST instrument (and telescope, where applicable). It is strongly linked to the Operations and Maintenance Plan of 4MOST. This deals with calibrating the Technical CCDs (for Primary and Secondary Guiding, WFS, and Metrology for flatfield and linearity, using internal LEDs or the Flatfield illumination of the Calibration unit. A special calibration is required to calibrate the translation between the focal surface and the sky coordinates, which will be achieved through raster scanning areas on the sky well populated with stellar targets with good astrometry from the Gaia mission.
- **Data Calibration** deals with all calibration and monitoring efforts that are required to remove instrument signature from the scientific exposures during the data-reduction process. It thus provides the necessary calibration files so that the 4MOST Data Management System performs to specification. Different aspects include 1) *Science CCD characterization* like bias, dark current and read noise, pixel-to-pixel flats and linearity through internal LEDs, 2) *fibre spectrum flatfielding and tracin*g through twilight and night time attached Calibration Illumination Unit continuum light source exposures, 3) *wavelength and projected fibre image calibrations* through night time attached Calibration Illumination Unit Fabry-Perot light source exposures and Fabry-Perot and Thorium-Argon light exposures through the simultaneous calibration fibres during science exposures, 4) *sky subtraction* modelled using the spectra from about 10% of the fibres dedicated to empty sky regions both spread over the 4MOST field-of-view and along the slits of the spectrographs, and 5) *Flux calibrations* that will be achieved by a combining the various twilight and attached night time flatfield exposures with measurements of White Dwarf and other standard stars and Gaia BP and RP low-resolution spectroscopic measurements.
- **Science Calibration** deals with all calibration and monitoring efforts that are required to ensure proper scientific exploitation of the 4MOST data products by the high-level data-analysis pipelines, provided by each Survey that utilizes 4MOST. Observations will include for instance Gaia Benchmark and asteroseismology stars, well studied open and globular cluster stars, and stars and galaxies with accurate parameters in the literature. A special sample of stars covering a large range in parameter space will be observed early on during the 4MOST Start-up Phase to be fully characterised using classical spectral modelling methods and then used as a training set for a Machine Learning based stellar pipeline. 4MOST will observe targets that are also covered by other spectroscopic surveys such as RAVE, Gaia-ESO, GALAH, GAMA, WEAVE, MOONS, DESI, in particular in deep, repeat field areas. These observations will allow checking for consistency, to establish zero-points among relevant parameters (for example, stellar parameters, chemical abundances, redshifts, star formation rates), and validate sample completeness determinations as function object and observing parameters.

5. SYSTEM ASSEMBLY, TEST, VERIFICATION, AND COMMISSIONING

During the entire process of constructing and commissioning 4MOST, many steps are made to verify that 4MOST is meeting its requirements and that it can deliver on its science goals. This not only holds true for the instrument itself, but also for its operations system. In this section we detail the verification and characterisation steps still needed before 4MOST can start full operations of its first survey.

5.1 Assembled, Integrated and Test (AIT) configurations in Europe

Following usual ESO procedures, 4MOST will be fully Assembled, Integrated and Tested (AIT) to the extent possible in Europe before being shipped to Paranal Observatory. This AIT phase is concluded with the Provisional Acceptance Europe (PAE) review conducted by ESO.

Without a telescope it is impossible to verify all functions and performance in one go in Europe. Therefore, the 4MOST instrument will be verified using four different test configurations:

- **Metrology Calibration and Functionality**: A metrology test stand has been created that mimics the VISTA telescope with the WFC using a set of mirrors to create the same focal length (Figure 3). In the first step the four metrology cameras and their two spares are characterized by placing a back illuminated test plate with a very accurate grid of tiny holes in the focal surface that can be rotated. By taking many images after rotating the test plate and the cameras independently to different angles, the distortions in the metrology cameras and their detectors can be characterized. Replacing the test plate with the AESOP positioner with its fibres back illuminated, the control loop between the Metrology System and AESOP is functioning correctly, including start-up and recovery procedures when the identity and location of individual spines is uncertain due to their overlapping

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patrol areas. What cannot be tested in this setup is the software that does the ray-tracing to calculate the transformation from sky-to-focal-surface and focal-surface-to-metrology coordinates.

- **Cassegrain Integration**: A Cassegrain Test Stand (CTS) has been created that mimic the mechanical, electrical, control, and cooling interfaces of the Cassegrain area of the telescope, including its height several metres above the floor (Figure 4 & Figure 10). An important aspect of the tests using the CTS is verifying all handling and integration procedures for all subsystems connected in this area (the WFC, the A&G and WFS cameras, EASOP, and the Cassegrain Cable Wrap) to ensure safety to the instrument and personal. Furthermore, functional tests will be performed to test all interfaces, including mechanical performance tests of especially the cables and fibre conduits in the Cable Wrap when rotating the entire Cassegrain area and the ADC. Also, the safety features of the control functions will be tested.
- **Focal Surface Alignment**: A test stand that can be tilted is used to align the various optical systems around the focal surface. Using precise mechanical measurements with a laser tracker, the offsets of the optical reference surface of the A&G and WFS assembly, the Focal Surface Test Tool with the imager and wave front sensor that will be used to commission the WFC on the telescope, and the AESOP fibre positioner will be measured in relation to the WFC and its focal surface. Shims and hexapod support screws on the FSTT and AESOP will be used to bring all optical elements in alignment.
- **End-to-End Test**: In this configuration all subsystems except the WFC are connected to perform a full functionality test from the tip of the fibres to the CCD detectors in the spectrographs. All systems will be tested in connection with the final control hardware and software. Next to a white light flatfield illumination to test relative flux transmission of all fibres, a star simulator will be used as well to validate the full system throughput. This configuration will most likely also be used to perform the Electromagnetic compatibility (EMC) testing.

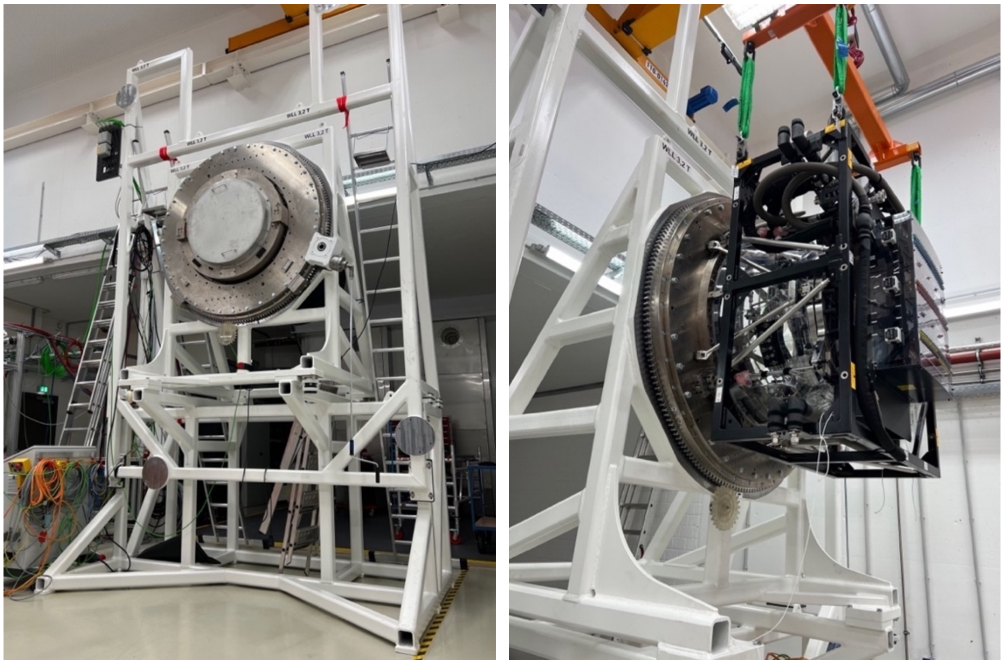

Figure 10. The Cassegrain Test Stand (CTS) that mimics the backside of the VISTA telescope in terms of its various interfaces and especially its height to test installation procedures. *Left)* with WFC installed. *Right)* test installation of the fibre positioner.

5.2 Operational Rehearsals

In parallel to the instrument development and verification effort, the 4MOST Project is conducting Operational Rehearsals (OpRs) to test and perform quality assurance on the entire data flow and the software modules. Initial OpRs were focussed on completing all interfaces and the data flow with all systems involved. The Fourmost operations Rehearsals Observational data Generator (FROG) is used on a computer cluster to run TOAD (Section 2.2), generating the many

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artificial data frames needed to simulate several nights worth of observations. Because it takes several days to generate one night of artificial data, current OpRs tend to be more focussed on particular streams. For instance, one OpR concentrates mainly on testing the front-end observation planning in Garching and its interface to the observatory to send an Observing Block with command instructions for the instrument and telescope. In another OpR only the primary back-end section is tested where calibrated 1D spectra are extracted from the artificial 2D data and feedback information on target completion status is generated and send to the front-end observations planning.

During earlier OpRs it was discovered that the original operations model with the Level 2 (L2) enhanced data products pipelines distributed at different physical locations created bottlenecks in the data flow. While the amount of data that needed to be transferred is not huge by modern standards, the transfers of the large number of individual files created enough interruptions that the pipelines that need to create the stellar, galaxy, and AGN physical parameters were not reliable enough on the time scales required. The operations model was hence changed, where the L2 pipelines are still being developed by teams distributed across the globe, but the execution of all the code takes place in the 4MOST Data Processing Centre (4DPC) located at the IoA in Cambridge. All processed L1 and L2 data are then transferred to AIP, where a quality assurance team curates the data before it is transferred for internal Data Releases to the 4MOST Science Team on a three-monthly basis. Approximately yearly Data Releases are performed through the 4MOST Public Archive and the ESO Science Archive Facility.

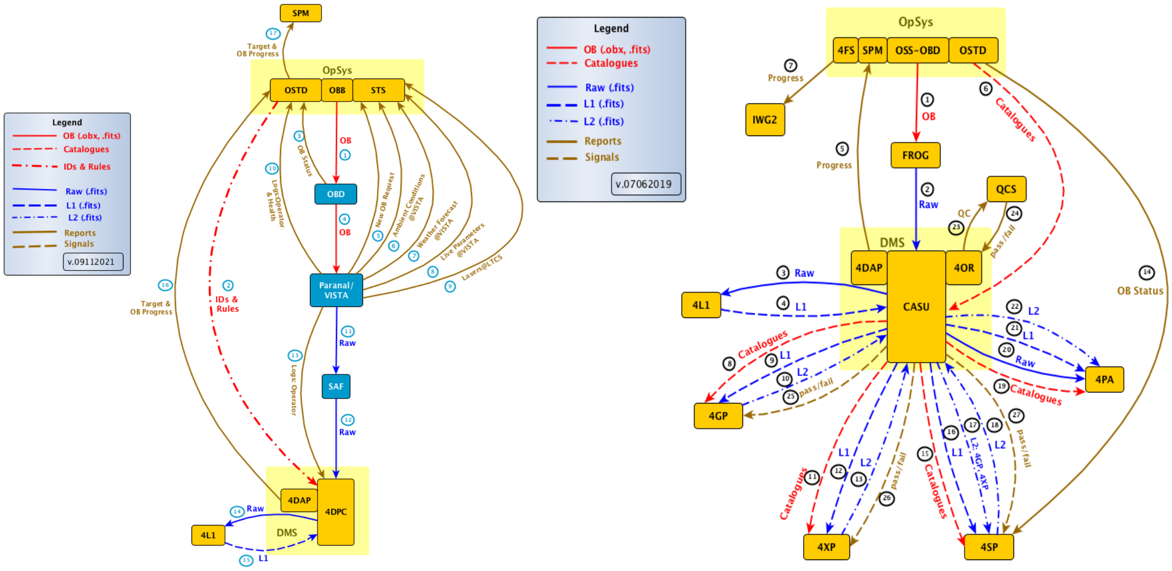

Figure 11. Examples of modules and data flow involved in different Operational Rehearsals (OpR). *Left)* An OpR mainly testing the primary data flow running observations with ESO, where observing conditions are extracted from and instrument commands are sent to Paranal Observatory by OpSys, raw simulated data is extracted from the ESO SAF archive and, after analysis by DMS, target observing progress information is fed back to OpSys. *Right)* An OpR concentrating on the secondary data flow, where DMS extracts calibrated 1D spectra (4L1) from the 2D spectrograph data simulated by FROG, which is then further analysed by the various Level 2 pipelines to determine the physical parameters of the targets as L2 data products.

5.3 Assembly, Integration and Verification (AIV) at the telescope

After shipment of the instrument, subsystems will be reassembled in the Paranal integration hall in so far necessary. The different subsystems will be integrated with the telescope according to a detailed installation plan, with various verification steps along the way.

In the first step the Focal Surface Test Tool (FSTT) plays a key role. Its primary goal is to enable the recommissioning of the telescope with its new WFC. For this an imager and a wave front sensor combination is installed on a rotation and linear stage to analyse image performance across the focal surface. This will also test the A&G and WFS software that has been updated to accommodate the new WFC and focal surface technical CCD layout. The FSTT will also be equipped with a test plate to measure the alignment of the Calibration System illumination units on the M2 spider and the back illuminated plate with small holes to calibrate the cameras of the Metrology System.

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In the next step the full instrument will be integrated on the telescope after which the commissioning of the 4MOST instrument will commence. All functions will be tested and all remaining top-level requirements will be verified by on-sky performance. Key parameters to verify include sensitivity, spectral resolution, and overhead constraints. An especially crucial step here will be the calibration of the metrology-positioner loop, making sure that all fibres are positioned to better than 0.1 arcsec on the projected sky target positions under various circumstances (telescope zenith distance, ADC rotation angle, temperature, focus, etc.). This will be achieved by performing many raster scans, where, after the fibres have been positioned for a field with many fairly bright stars, the telescope is stepped in a fixed grid-like pattern while taking a science exposure with all spectrographs at each position. In this way the position where the maximum flux is received for each stellar position can be determined, the relative distortions between the fibre positions, the sky target positions, and the calculated metrology measurement positions can be calculated and any necessary corrections in the telescope and ray tracer model of the metrology system can be optimised.

In parallel with commissioning, the different elements in the operations data flow will be tested step by step in the final Operations Rehearsal to verify the operations software. Initially the instrument will be controlled by OBs generated on the mountain, but the first data will stream quite early to the Data Management System in the intended fashion for quick data analysis and to support instrument verification. Once the instrument behaviour is largely calibrated, the designated Visitor Mode operations from MPE in Garching, Germany will be tested and the remote scheduling will be tested. The different pipelines will start analysing the data to optimise their parameters and to deal with unexpected features in the data. Once all elements work individually, a few nights of constant operations will be performed to fully test the functioning of the data flow. Once this is functioning, we will start the last verification step before starting the first five-year 4MOST survey.

During this last Operations Start-up Phase the aim is to fully characterise the instrument in a variety of different observing conditions in order to optimise the survey strategy parameters (exposure times, next field selection, etc.), estimate the survey efficiency, and to verify that all science goals of the different Surveys can be expected to be achieved in five years of observations. In the first few weeks of this period, we will target special areas with for instance good quality data in the literature, where we will expose longer than we expect to do during normal operations to establish optimal exposure times, determine best magnitude limits for the different target classes, and in general to vary observing strategy parameters to establish settings for the most efficient survey. While this data is being analysed, the instrument will be used for a month to observe a training sample for the machine learning component of the Galactic pipeline. Finally, using the best estimate for observing strategy parameters we will run normal for at least one lunar cycle to verify that observing efficiency meets expectation. Once verified, operations of the main five-year survey will be started.

5.4 Schedule

The current planning foresees that all subsystems will arrive in Potsdam by end of October 2022. The first AIT full system verification configurations are already being tested, with final testing expected to be completed in March 2023 and a PAE review in May 2023. In parallel to this activity, ESO will stop operations of VISTA with its current VIRCAM infrared camera in January 2023 to enable corrections to the M1 primary mirror support actuators, installing upgrades and modifications to the telescope infrastructure and interfaces to accommodate 4MOST, and to re-aluminise M1. 4MOST shipment to Chile will take place June-August 2023, after which first the telescope will be recommissioned with the WFC and A&G and WFS assembly. Full instrument installation and commissioning is expected in Feb 2024, after which a few months are scheduled for the Operations Start-up phase to optimise survey strategy and verify the feasibility of the science goals in a five-year survey.

6. PROJECT CULTURE

The 4MOST Project is a large collaboration that, with the new community scientists who recently joined, now consists of more than 725 engineers, scientists, software developers, managers and support personal. Such a large collaborative enterprise, geographically spread across the entire globe, is necessarily realised by people from different backgrounds and cultures. Its ability to excel is enhanced by establishing a truly collaborative, team-oriented, and inclusive project culture. Maintaining a strong and healthy collaboration requires open, respectful communication and a shared commitment to a set of values that include ethical conduct, civility, inclusiveness, and diversity. The 4MOST Project has therefore adopted a Code of Conduct[1] that expresses the expectation that 4MOST members will actively incorporate these important

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[1] https://www.4most.eu/cms/wp-content/uploads/2021/11/4MOST_Code_of_Conduct.pdf

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principles in their work environment. The Code of Conduct also provides a course of action to address complaints and/or start conflict resolution for those members who feel the principles described in the Code of Conduct have been violated.

To support 4MOST Project members, two Ombudspersons (with a third expected soon) have been appointed, who can provide informal, confidential, nonjudgmental, impartial, and independent advice and arrange mediation for 4MOST members for the purposes of dispute resolution. There are multiple 4MOST Ombudspersons to provide a choice of whom to speak with, and to ensure that there is at least one Ombudsperson available at Collaboration meetings. The 4MOST Executive Board appoints the Ombudspersons for a term of 3 years, with the option of renewal. Due consideration will be given to the diversity of the candidates. The 4MOST Ombudspersons will be full members of 4MOST, with a strong understanding of the organizational structure of the collaboration. They will not hold any other leadership positions within the collaboration and will report only to the 4MOST PI.

To guide 4MOST leadership a project culture working group was established. This working group on issues related to diversity, equity and inclusion will assess and report the Project status on a regular basis, advice management on actions that could address any issues found, and help implement any actions that improve 4MOST project culture.

7. CONSORTIUM STRUCTURE

The 4MOST Project is supported by a consortium of 17 Major Partner and 9 Minor Participant 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 exploitation of the ten Consortium Surveys. Table 3 lists which institutes have the lead responsibility for the different hardware and primary data-flow operations work packages, and leading the different Consortium Surveys.

Table 3. 4MOST Consortium Major Partners and their work package distribution.

Institute	**Instrument responsibility**	**Science responsibility**
Leibniz-Institut für Astrophysik Potsdam (AIP)	Management and System Engineering, Telescope interface (including WFC), Metrology, Fibre System, Instrument Control SW, System AIV and Commissioning, 4MOST Public Archive	Milky Way Disk and Bulge LR Survey, Cosmology Redshift Survey, Magellanic Clouds Survey (1001MC)
Australian Astronomical Optics, Macquarie Univ.(AAO)	Fibre Positioner	Galaxy Evolution Survey (WAVES)
Centre de Recherche Astrophysique de Lyon (CRAL)	Low Resolution Spectrographs	Cosmology Redshift Survey
European Southern Observatory (ESO)	Detectors System	
Institute of Astronomy, Cambridge (IoA)	Data Management System	Milky Way Halo LR Survey
Max-Planck-Institut für Astronomie (MPIA)	Instrument Control System Hardware	Milky Way Disk and Bulge HR
Max-Planck-Institut für extraterrestrische Physik (MPE)	Science Operations System	Galaxy Clusters Survey, AGN Survey
Zentrum für Astronomie der Universität Heidelberg (ZAH)	High Resolution Spectrograph, Instrument Control System Software	Milky Way Halo HR Survey
ASTRON (NOVA-ASTRON)	Calibration System	
Rijksuniversiteit Groningen (RuG)		Milky Way Halo LR Survey
Lunds Universitet (Lund)		Milky Way Disk and Bulge HR
Uppsala Universitet (UU)		
Hamburg Universität (UHH)	User Management System, Helpdesk	Galaxy Evolution Survey (WAVES)
École polytechnique fédérale de Lausanne (EPFL)		Cosmology Redshift Survey
Durham University, Department of Physics (Durham)	Calibration System fibres	
University of Bath, Department of Physics (Bath)	Science Operations System contribution	
University of Western Australia (UWA), International Centre for Radio Astronomy Research (ICRAR)		Galaxy Evolution Survey (WAVES)

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REFERENCES

[1] Azais, N., Barden, S.C., Smith, G., Jones, D., Delabre, B., et al., "Wide-field corrector for 4MOST: design details and MAIV processes", Proc. SPIE 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 990889, pp. 15 (2016)

[2] Cunningham, M., Brooks, D., Doel, P. et al., “The assembly and alignment of the 4MOST Wide Field Corrector”, Proc. SPIE, 12184-257, (2022).

[3] Holzlöhner, R., et al., “Active optics upgrade using curvature WFS of VISTA for 4MOST”, Proc SPIE, 12188-40, (2022)

[4] Bellido-Tirado, O., et al., “4MOST Guiding and Wavefront Sensing cameras - Requirements and early testing”, Proc. SPIE, 12182-74, (2022)

[5] Brzeski, J., Chin, T., et al., “Overall performance of AESOP, the 4MOST fibre positioner”, Proc SPIE, 12184-248, (2022)

[6] Brzeski, J., Chin, T., et al., “AESOP, the 4MOST fibre positioner: engineering principles”, Proc SPIE, 12184-249, (2022)

[7] Winkler, R., et al., “4MOST Metrology System Lab Calibration and Performance, Proc. SPIE, 12188-80, (2022)

[8] Kelz, A., et al., “4MOST: manufacture, assembly and test of the optical fiber system”, Proc. SPIE, 12184-263, (2022)

[9] Laurent, F., Disseau, K., et al., “4MOST low resolution spectrograph alignment”, PROC SPIE, 12184-255, (2022)

[10] Disseau, K., et al., “4MOST low resolution spectrograph performances”, Proc. SPIE, 12184-272, (2022)

[11] Seifert, W., et al., “4MOST: MAIT of the high-resolution-spectrograph”, Proc. SPIE, 12184-250, (2022)

[12] Politopoulos, I., et al., “4MOST calibration system: design, assembly, and testing”, Proc SPIE, 12184-265, (2022)

[13] Rothmaier, F. M., et al., “The 4MOST facility control software on its way to a fully fledged subsystem”, Proc. SPIE, 12189-83, (2022)

[14] Winkler, R., Barden, S. C.; Saviauk, A., “4MOST metrology system image processing”, Proc. SPIE 9908, 990891, pp. 20 (2016)

[15] Temple, E., et al., “An optimised tiling pattern for multi-object spectroscopic surveys: application to the 4MOST survey”, MNRAS 497, 4626 (2020)

[16] Temple, E., et al., “Probabilistic fibre-to-target assignment algorithm for multi-object spectroscopic surveys”, A&A, 635, A101 (2020)

[17] Guiglion, G., et al., “4MOST Survey Strategy Plan”, The Messenger, 175, 17 (2019)

[18] Micheva, G., et al., “The 4MOST calibration plan”, Proc. SPIE, 12186-30, (2022)

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