# Plan

## Survey Management Plan: Front-end Operations

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## Change Record

| Issue | Date | Page, Section, Paragraph Affected | Reason, Remarks |
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| 0.01 | 2023-03-11 | All | New document |
| 0.1 | 2023-09-28 | All | Accepted changes + comments from GM, MV etc. |
| 0.2 | 2023-10-13 | All | Updates by PN |
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# 1 Scope

This document describes the overall Survey Management Plan for the Surveys conducted during the first five years of operations of 4MOST. It covers the overall survey concept and strategy, the top-level Work Breakdown Structure and its resourcing, the main standard data reduction pipelines and their calibration and quality control.

# 2 Applicable Documents (AD)

The following applicable documents (AD) of the exact issue shown form a part of this document to the extent described herein. In the event of conflict between the documents referenced herein and the contents of this document, the contents of this document are the superseding requirement.

| AD ID | Document Title | Document Number | Issue | Date |
|---|---|---|---|---|
| [AD1] | | | | |
| [AD2] | | | | |

# 3 Reference Documents (RD)

The following reference documents (RD) contain useful information relevant to the subject of the present document.

| RD ID | Document Title | Document Number | Issue | Date |
|---|---|---|---|---|
| [RD1] | 4MOST Survey Management Plan - Organisation | VIS-PLA-4MOST-47110-9220-0001 | 2.00 | 2024-07-19 |
| [RD2] | 4MOST Survey Management Plan - Back-end Operations | VIS-PLA-4MOST-47110-9220-0003 | 2.00 | 2024-07-19 |
| [RD3] | 4MOST Survey Management Plan - Individual Surveys | VIS-PLA-4MOST-47110-9220-0004 | 2.00 | 2024-07-19 |
| [RD4] | 4MOST Survey Strategy Plan | Guiglon, G., et al., 2019, The Messenger 175, 17 | | |
| [RD5] | An optimize tiling pattern for multi-object spectroscopic surveys: application to the 4MOST survey | Tempel E, et al., 2020, MNRAS 497, 4626 | | |
| [RD6] | Probabilistic fibre-to-target assignment algorithm for multi-object spectroscopic surveys | Tempel E., et al., 2020, A&A 635A, 101 | | |

| RD ID | Document Title | Document Number | Issue | Date |
|---|---|---|---|---|
| [RD7] | 4MOST Calibration Plan | VIS-PLA-4MOST-47110-9830-0001 | 4.00 | 2023-06-19 |
| [RD8] | IWG1 - 4MOST Sky Fibre Allocation Development Plan | VIS-TNO-4MOST-47110-9231 | 0.02 | 2023-03-20 |
| [RD9] | Technical Note<br>Catalogues for commissioning, operations start-up and calibration | VIS-TNO-4MOST-47110-9800-0006 | 0.04 | 2023-03-14 |
| [RD10] | Design and Analysis Report<br>QC and Level-1 Science Data Reduction Pipeline Description | VIS-DER-4MOST-47110-1410-0002 | 2.82 | 2023-09-15 |
| [RD11] | Survey Simulation Prediction website | https://www.eso.org/sci/observing/PublicSurveys/4MOSTsmp.html | ExID=193, RunID=593 | 2025-05-15 |
| [RD12] | Front-End Operations ICD | VIS-ICD-4MOST-47110-9700-0001 | 3.04 | 2023-09-29 |
| [RD13] | Online 4FS User Manual | VIS-MAN-4MOST-47110-1720-0001 | 12.0 | 2023-08-10 |
| [RD14] | Design and Analysis Report – Operations System | VIS-TNO-4MOST-47110-9232-0003 | 3.05 | 2023-10-02 |
| [RD15] | Definition and provenance of target and object identifiers in the 4MOST data | VIS-SPE-4MOST-47110-9700-0001 | 1.00 | 2023-03-29 |
| [RD16] | ICD Data Management System – Operations System | VIS-ICD-4MOST-47110-1417-0001 | 2.4 | 2023-09-27 |
| [RD17] | | | | |

# 4 Definitions

- **Data levels**:
  - Level 0: Raw data with associated meta-data
  - Level 1: Calibrated 1D spectra, catalogue of targeted objects
  - Level 2: Derived scientific parameters, e.g., elemental abundances, redshifts, selection functions, etc.

# 5 Pre-amble

An efficient use of 4MOST is maximal if the Consortium's surveys and all other approved Participating Community Surveys are executed in parallel observing mode (ESO-287481). Parallel observing mode means that targets from several surveys (Consortium and Participating Community Surveys) with clearly different target classes and science aims are targeted simultaneously by different fibres of the 4MOST instrument.

Consortium and Participating Community Surveys will join a common Science Team and this document is part of a series of documents that together provide a coherent and unique Survey Management Plan (SMP). The other documents are:

- *4MOST SMP: Organisation* [RD1] containing the organisational structure of the project including conflict resolution pathways, the work-flow and data-flow concepts, the work breakdown structure, and the schedule including data releases.
- *4MOST SMP: Back-end Operations* [RD2] describing the back-end process with an overview of the hardware required, the creation and quality control of L0, L1, L2 data, and the overall quality control and data delivery, archiving, and publishing process.
- *4MOST SMP: Individual Surveys* [RD3] describing in more detail the management aspects of the individual Surveys in the 4MOST Project, highlighting in particular those aspects where a Survey deviates from the general plan in terms of target scheduling, data analysis and data products, and/or data publication schedule.
- *4MOST SMP: Survey Simulation Prediction website* [RD11] is a website showing the input catalogues and simulation predictions for both the overall survey, as well as for the individual (sub-)Surveys.

In agreement with the Science Team Policies (ESO-286592), the 4MOST PI will represent the full Science Team towards ESO and is responsible for the delivery of the 4MOST survey programme. The combined 4MOST Survey Management Plan will be made public via the ESO Public surveys web pages.

# 6 Survey strategy concept

The basic premise of the 4MOST survey strategy is that sharing the focal surface between different science goals enables science cases otherwise impossible and improves the efficiency of the facility. To deal with the different requirements in target density and exposure times from different science cases, each part of the sky to be surveyed will receive multiple exposures with different fibre configurations and exposure times. This gives the possibility to create exposure times from a few minutes to several hours for different targets in the field and to adjust the tiling of the sky such that it follows the target density and fibre hour needs.

In practice this means that, next to a target list, each (sub)survey needs to define several key parameters to develop a survey strategy:

- On a per target level a success criterium (e.g., signal-to-noise, redshift detection) and an observing continuation criterium. This enables to make an initial estimate for the exposure time needed and if/how to continue taking further observations in case the first observations did not reach the goal success criterium.

- A completeness requirement for targets on the scale of approximately one 4MOST field-of-view (FoV), which is encoded in the Small-Scale Merit (SSM) function. This gives flexibility in fibre assignment by making sure that each part of the sky has at least one large sub-survey that has an input catalogue with many more targets than need to be observed (low completeness requirement), while smaller sub-surveys can still require high completeness when their science case need it.
- A Large-Scale Merit (LSM) map and minimum area requirement, used to identify high priority areas for each sub-survey.
- A Figure of Merit (FoM), reflecting the overall success of each (sub)survey. This can reflect the need for a total number of targets to be successfully observed and/or a total area to be observed with a minimum number or completeness of targets per sub-area. In the 4MOST Project this is described by the Scientific FoM (SciFoM) as defined by each Survey, while other FoMs, purely based on the inputs described above, are made available as well (for instance the FoM based on the Scope of Survey calculation which uses the combination of the SSM and LSM). All FoMs used in the Project are scaled such that *a value of 0.5 means that the Survey requirements are met, and higher values enable a Survey to reach higher level science goals.* The equations for each FoM are captured in the 4MOST gitlab and is provided as part of [RD11].

A further description of these concepts and how they affect the survey strategy can be found in the ESO Messenger “4MOST Survey Strategy Plan” article [RD4]. The details of the tiling algorithm employed is described in Tempel et al. (2020) [RD5], while the basics of the fibre-to-target assignment algorithm are provided in Tempel et al. (2020) [RD6].

To predict the progress of the 4MOST survey, the Operations Simulator (OpSim) was created that largely copies the algorithms used for real operations and supplants the observations on the telescope, including instrument performance and observing conditions, with statistical approximations. In this way observational progress of the 4MOST project can be estimated and the final outcome of a 5-year survey predicted. A large fraction of the key algorithms and code of OpSim are also used for the real observation planning of OpSys.

In running OpSim it is assumed that the survey strategy remains the same over the entire five-year period. In practice this may not be fully tenable, and a feedback loop foresees that adjustments in survey strategy may be made on about a yearly timescale to ensure that all surveys progress on a common scale. However, changes, especially on the target input catalogues, are expected to be kept to a minimum to ensure that the calculation of selection functions is tractable.

## 6.1 Process towards a fiducial survey strategy

The results of the simulations broken down to the sub-survey level are shared with the Survey teams using a dedicated web server, both in graphical and tabular forms. This IWG2 website contains many statistics and graphical information on the input and observed catalogues. A similar set of data will be provided once real observations start and tools will be in place to compare predicted and actual progress. Some plots are included below that highlight the key diagnostics for Surveys to monitor their progress and success. An extensive subset of all plots provided to the Surveys is available at the SMP Survey Simulation Prediction website [RD11].

**It should be noted that at the current stage before commissioning and actual observation start, several important parameters in OpSim are uncertain, making the predictions uncertain at least at the 20% level.** Most notable uncertainties are the actual observing overheads and the instrument sensitivity. Other uncertainties like observing conditions or technical downtime will create some short-term statistical uncertainties but are expected to be averaged out over the five-year survey period[1].

To reach a fiducial survey strategy requires an extensive investigation of the simulation parameter space. This could only start in earnest during the summer of 2024 as close to ready survey input catalogues were only available by late spring 2024 from all surveys. Indeed, the complexity of 4MOST is such that an issue with one survey input catalogue that drives the overall 4MOST survey strategy affects the simulation outcome for all surveys. Even a localised issue with a non-driving survey's input catalogue can affect the outcome of many other surveys in those areas. At the survey strategy level, it is therefore essential to work with fixed and adequate catalogue input packages.

### 6.1.1 Key steps in the survey strategy process

In essence the survey strategy process proceeds as follows:

a. With a fixed set of input catalogue packages, an export is created. In essence, the export can contain either all survey targets provided by Surveys or be limited to a sub-set of the area of the whole 4MOST footprint.
b. A default simulation, without any survey specific tuning, is performed with the export. Such a simulation is entirely driven by the exposure times, target densities and completeness requests provided by the Survey, using all the tools developed by IWG2 (see section 7). There can be several such simulations made, as there are different options on how to balance for example the available sky conditions across the survey footprint.
c. Feedback is sought from surveys (and sub-surveys) on how successful this ("untuned") simulation is in meeting the science requirements of the surveys. Obviously the various

[1] In current IWG2 survey simulations, the following overheads are used: (a) 4.5 minutes per visit; (b) 4.5 minutes per configuration, which includes attached flat and wavecal exposures to each science exposure. The survey simulations beyond those two overheads do not depend on the actual calibration strategy adopted, as long as the time to do them is shorter than what is currently accounted for timewise. In addition, the survey simulations assume a flat 21% time loss due to weather and technical issues, currently implemented by removing full nights.

FoMs are considered in this process, but most often additional investigation of the simulation output is required from the surveys to provide a more holistic description of how surveys (and sub-surveys) are performing.

d. With the feedback from surveys and the understanding of the survey requirements by key IWG2 members, several specifically survey tuned simulations can be made. The process is rather lengthy and requires many iterations. A set of "tuned"[2] simulations are made available to surveys which provide further feedback on them.

e. Some simulations result in the requirement that a survey catalogue package must be modified to some extent to better fit within the whole 4MOST survey strategy. This could be either a reduction of the overall request or taking better advantage of the synergies provided by other surveys etc.

IWG2 focus initially their survey strategy efforts on the larger driving surveys to get an overall survey strategy plan in place. This means that surveys like S3, S7, S9 and S18 form part of an initial focus, as their requirements tend to be the more driving ones overall. Then the issues of the many other surveys which have either much smaller FH requests (and hence do not drive the survey strategy, except possibly very locally) or which requirements are in general more easily met are considered. The last step is to consider the non-driving surveys, i.e. surveys nominally designed to "piggy-back" on the existing survey strategy.

Once a survey strategy has been adopted, i.e. a survey strategy which consists in most surveys being sufficiently happy to proceed with it, IWG2 can start to consider alternative scenarios, in which IWG2 explores the survey outcome if for example the overheads and/or the instrument performance is better or worse than assumed nominally. This is important as IWG2 needs to have alternative survey strategy plans ready if those eventualities happen following commissioning or the survey programme validation phase. This will also highlight which science requirements, which currently are met by the survey simulations, might be either harder or easier to fulfil.

In parallel to this, IWG2 will investigate the impact on the survey strategy and the feasability of delivering specific data levels at certain times, i.e. by including additional survey led constraints onto the Long-Term Scheduler (LTS). This specific LTS information has been gathered from surveys already and is in the process of being included into the simulation pipeline.

### 6.1.2 The fiducial simulation: RunID-593 based on ExID-193

Over the past years, surveys have revised their catalogues as described above to reach requests which are considered realistic considering the total available time and the science goals of all surveys. A final set of input catalogues were agreed upon at the Science Team Meeting in

[2] We refer to "tuned" any simulation for which survey specific parameters have been included in the simulation set up. Not all "tuned" simulations result necessarily in a better outcome and often the tuning process comes at the expense of something else. Hence the quotation marks around the word.

February 2025. These catalogues have been ingested into the database and an export (ExID-193) has been generated on this basis which in turn has been used as input for the following simulations.

ExID-193, presented in the SMP Survey Simulation Prediction website [RD11], is based on the latest stable input catalogue packages uploaded to 4FS_WI by surveys. ExID-193 does not cover the footprint of all targets provided by the Surveys, but is in general limited to -80º < Dec < 1º, with some notable exception to this restricted declination range being the regions of WAVES-WIDE North, WAVES-DEEP DDF-4 and a few special areas above Dec > 5º for stars with asteroseismology information for calibration purposes. This is more explicitly shown in Figure 1, which presents the RA-Dec density distributions of requested input targets (top) and the required dark exposure time (bottom) for the Low-Resolution (LR) targets (left column) and High-Resolution (HR) targets (right column) of all Surveys combined for ExID-193.

The motivation to restrict temporarily the survey footprint to that declination range is in part related to current difficulties for the survey plan to stay within its nominal 5-year limit while observing sufficiently most areas to the required depth. In addition, Northern winds will affect more the observing availability of those declination ranges, while several extra-galactic surveys already benefit from other surveys (like DESI) providing redshifts in some of those regions for many of their potential targets. We note that the aim is still for 4MOST to cover the whole -80º < Dec < 5º range and we will revisit this in the coming year, together with the LTS implementation.

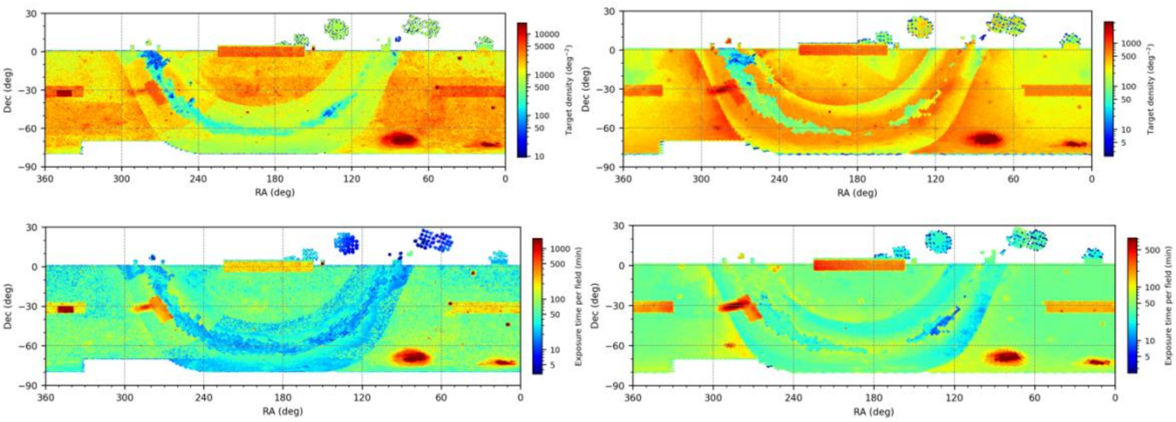


**Figure 1: RA-Dec density distribution of requested input targets (top) and the required dark exposure time (bottom) for the Low-Resolution (LR) targets (left column) and High-Resolution (HR) targets (right column) of all Surveys combined. These panels show the catalogues of ExID-193.**

As outlined in Section 6.1.1, IWG2 performs always an initial ("untuned") simulation on any export to understand better the survey requests for that export. This resulted in RunID-588 not shared here. Despite performing well in some regards, for some Surveys the "untuned" simulation RunID-588 is unsatisfactory, as it results in many science requirements, as expressed by the survey scientific figure of merit (SciFoM), not to be fully met.

RunID-593 is a “tuned” simulation and presented in the SMP Survey Simulation Prediction website [RD11]. In this simulation, specific effort was put towards improving the SciFoM performance of many sub-surveys. This was achieved by increasing the probability of selecting targets from each of these sub-surveys at the fibre-to-target assignment stage by applying specific sub-survey “boost” factors. More than 70 sub-surveys ended up being boosted.

The top panel of Figure 2 shows the expected increase as function of time of the SciFoM of all Surveys for the fiducial simulation RunID-593, where a Survey SciFoM typically reflects either a weighted average or the minimum SciFoM value of the sub-surveys contained in a Survey. The survey SciFoM definitions used in this simulation are provided in [RD11], next to the static sub-survey SciFoM figures. Most surveys have a Survey SciFoM close to the required value of 0.5, if not greater.

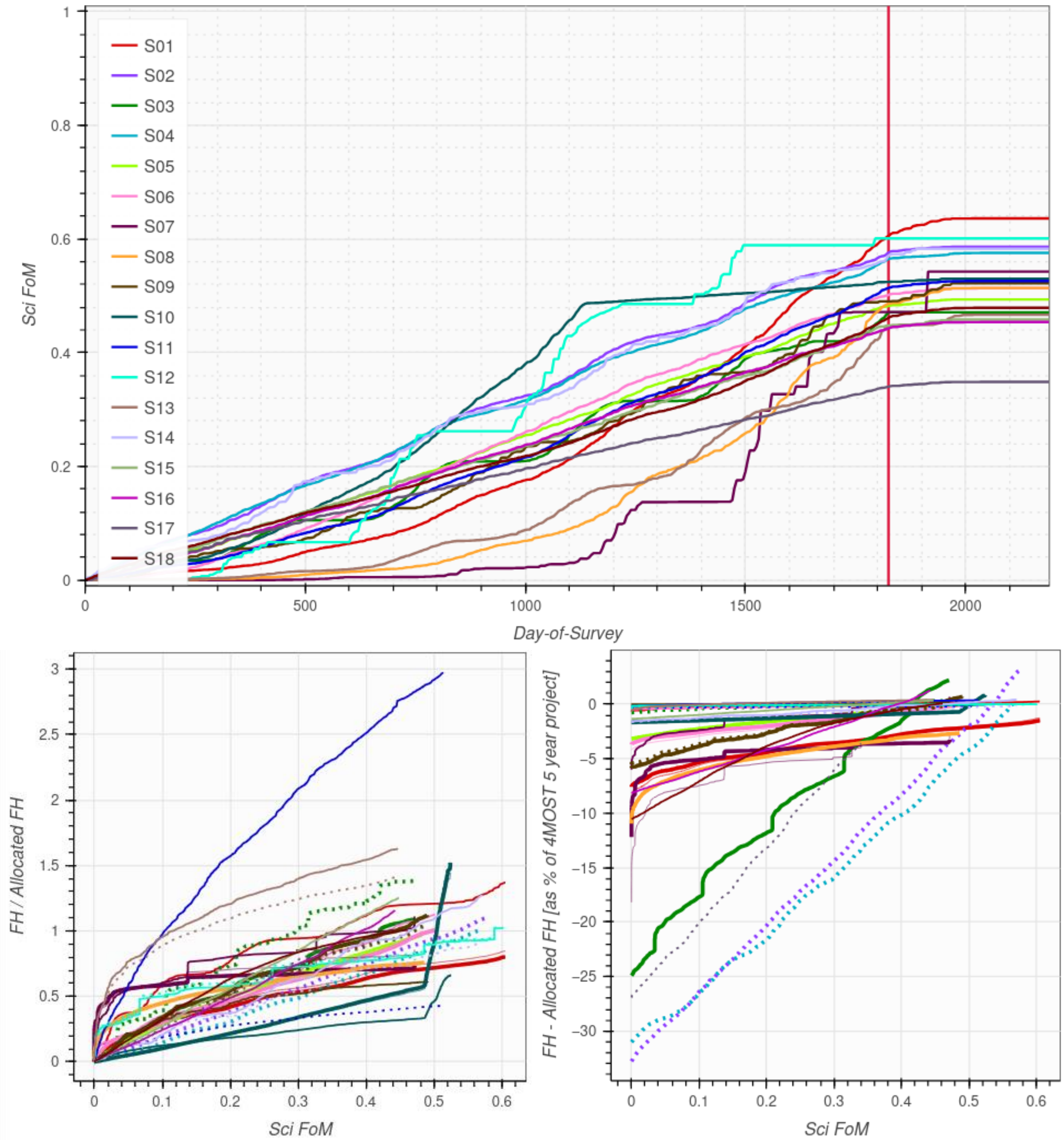


**Figure 2: Top panel: The evolution of the Scientific Figure-of-Merit (SciFoM) for each of the 18 Surveys for the fiducial simulation RunID-593 build on ExID-193. Similar plots for each Surveys with predicted evolution of each sub-survey are available within the SMP Survey Simulation Prediction Web Site [RD11]. The vertical red line indicates the limit of the 5-year plan. Bottom Left Panel: The fraction of Fibre Hours used divided by the allocated fraction for each survey as function of the SciFoM progress of that survey. This gives an indication of the feasibility of the science goals given the amount of allocated fibre hours. Bottom Right Panel: FH as a fraction of 4MOST LR (or HR) survey times. The colour coding is the same in all panels, with solid (dashed) lines in the bottom panels corresponding to LR (HR) allocation. All panels show the results of the fiducial survey simulation RunID-593.**

The bottom panels of Figure 2 shows survey FH consumption as function of the survey SciFoM: the left-hand panel shows it w.r.t. the survey's nominal 5-year allocation, while the right-hand panel provides the context in terms of the actual 4MOST project FH allocation (i.e. fraction of 4MOST LR or HR survey time respectively). The latter panel highlights that some surveys in RunID-593 overshoot their FH allocation somewhat (e.g. S2, S3), while others do not get their expected allocation (e.g. S1, S7). These deviations have been reduced a lot over the past year and in particular the SciFoM values are now in almost all cases close to the desired value of 0.5.

Figure 3 shows the RA-Dec distributions of the expected completeness fraction relative to the requested completeness as derived from simulations for the Low-Resolution (LR) targets (left column) and High-Resolution (HR) targets (right column) of all Surveys combined. A green colour corresponds to unity, implying that the requested completeness is achieved, while a redder colour indicates that the simulation has achieved a higher level of completeness than requested. This figure should be interpreted with some caution, as it combines all Survey targets and their respective completeness requests, and one should really be looking at the corresponding figure for each of the sub-surveys to ensure the relevant level of completeness has been achieved. They are available within the SMP Survey Simulation Prediction website [RD11].

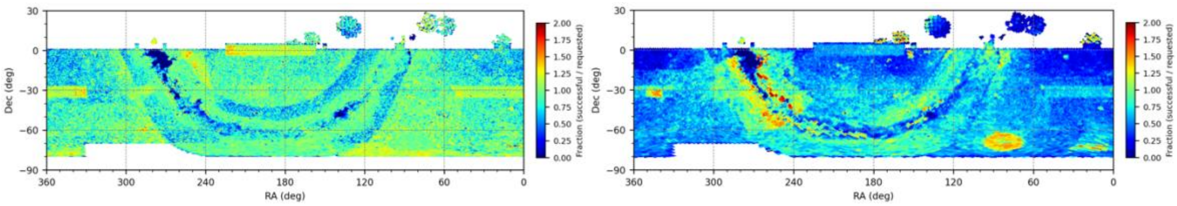


**Figure 3: RA-Dec distribution of the expected completeness fraction relative to the requested completeness as derived from simulations for the Low-Resolution (LR) targets (left column) and High Resolution (HR) targets (right column) of all Surveys combined. These panels correspond to RunID-593, compatible with the content of Figs. 1 and 2.**

### 6.1.3 Next steps (short term) in the survey strategy process

Despite some of the caveats mentioned in previous sections, RunID-593 remains a good representation of what can be achieved with 4MOST in a 5 year survey. As agreed by the Science Coordination Board, RunID-593 is to be considered the 4MOST fiducial survey plan.

However, this does not imply that survey strategy optimisation is over, as there are still further considerations to be taken into account. One of the more important ones, now that the survey catalogues are stable, is to consider the seasonal impact of the weather on the survey strategy. Up to now a simplistic uniform weather pattern has been used with random nights affected by Northern winds. Using weather data from Paranal from the past 10 years, we are able to create statistically a more realistic weather pattern which includes seasonal weather variations and Northern winds. Many simulations will have to be run to ensure we properly map the weather impact as well as possible. If necessary, this could result in some specific catalogue change requests made by IWG2.

Hence the 4CAB process, existing since 2023, is still operational, as it validates any catalogue changes to ensure that catalogue updates do not introduce new unnoticed issues. Surveys are no longer allowed to make catalogue updates, unless triggered by IWG2 for survey strategic reasons or a request is made to 4CAB to fix a bug in the catalogue package.

In summary a major milestone has been achieved within the last year, especially in comparison to where survey simulations were in October 2023 with the catalogue packages available then. Now most surveys catalogue packages are in a stable steady state and most surveys (incl. most sub-surveys) can meet their science goals while working successfully within their nominally allocated FH.

# 7 Operations and feedback loop

For simulation purposes, this section provides a short and concise overview of OpSim and its operational equivalent 4OOP, the 4MOST Operations OpSys Pipeline. The latter is more extensively discussed in section 10, which focuses on the Front-End tools and procedures.

## 7.1 Catalogues

Quality Control is performed on several levels on the input catalogue packages. Formatting of the files is checked on ingest at the 4FS-Web Interface (4FS-WI) and Surveys are provided feedback on the estimated Fibre Hours needed under various observing conditions. Infrastructure Working Group 1 (IWG1) performs coordinate verifications against accurate astrometric catalogues and tracks the code that was used to select the targets. Any proposed changes to the catalogues need to be approved by the Catalogue Coordination and Change Control Advisory Board (4CAB) before they are ingested in the simulation pipeline. Once operations have started, updates to target catalogues will be kept to the strict minimum (most likely only once, unless a force majeure requires it) to keep the selection functions for all Surveys as tractable as possible. A carefully devised shared target algorithm developed by IWG1 is used by OpSys to properly associated targets from different sub-surveys as unique 4MOST objects on the sky.

## 7.2 Survey planning preparation: Visit Planner, Long-Term Scheduler and Tile Target Probabilities

The desired completeness is reached by carefully tiling the entire sky based on the observing pressure to large extent indicated by the bottom row in Figure 1 (requested hours), but also on target density (top row of Figure 1), survey completeness requirements, dark, grey, bright and super-bright (DGBS) time available throughout the five years per sky area and other factors. This sky tiling is done by the Visit Planner developed within IWG2 and run within the Operations System OpSim WP. This Visit Planner assigns to each visit a DGBS observing condition and the required number of exposures with a sequence of exposure times that is tuned to the distribution of requested target exposure times in the tile. With the list of visits known, an important step is the computation of the Tile-Target Probabilities (TTP), which largely define the probabilities with which a target should be observed in a given tile.

The next step is the Long-Term Scheduler (LTS[3]) that makes an initial distribution of the visits over the five years by setting an earliest date the visit can be scheduled, which can also be used to create observing cadence and drive contiguous areas to be observed in each year, as requested by many Surveys. This mechanism will for instance be used to drive a repeat cadence for the deep drilling fields for AGN reverberation mapping and quality control purposes and for deeper areas in the Magellanic Clouds and the Milky Way bulge to measure variable stars.

## 7.3 Survey Operations: nightly/daily operations

During each night and whenever required, the Short-Term Scheduler (STS) selects a new visit to be scheduled from the available Planned Visits, based on a set of criteria, like the current telescope Alt-Az, moon conditions, seeing, wind, and cloudiness, observing conditions, laser guide star constraints, etc. Once a visit has been selected, the Fibre-to-Target Assignment (FTA) software creates a fibre configuration, probabilistically selecting objects accounting for the target completeness requirements and other observational constraints (including calibration targets, sky positions, etc.). Such a Configured Visit is then converted into one or more Observing Blocks (OB) with the necessary attached calibration exposure and with the tile exposure time potentially scaled based on the actual observing conditions, and then uploaded in the VISTA observing queue to be observed next.

The process by which visits are routinely selected by STS, configured by FTA, split into OBs via the OB Builder (OBB) and uploaded to the observing queue is known as the designated Visitor Mode (dVM) schema, which is run by OpSys from MPE. All data taken by 4MOST are transferred at the end of each night to the 4MOST Data Management System (DMS) at CASU (IoA), where it is analysed and the Spectral Success Values for each target measured and returned to OpSys. Spectral Success Values are usually based on either signal-to-noise (S/N) criteria in specified wavelength ranges or on a measurement of a secure redshift.

For many extragalactic targets the needed exposure time to obtain a redshift is hard to estimate from the available photometry. For Surveys that require a high redshift completeness, significant observing time can be saved by analysing the data for a measurable redshift before further observations are made. A data reduction feedback loop has therefore been implemented, allowing OpSys to decide to stop observing or set a new exposure time to continue observing based on the already acquired S/N or the (non-)detection of a redshift. This feedback loop through DMS back to OpSys shall function on a timescale of less than three days and operates automatically on Continuation Criteria specified by the Surveys for each target.

[3] *LTS is currently in development and not yet in use by the simulation pipeline. A prototype has been used for tests.*

## 7.4 Survey Simulations: OpSim

OpSim simulates the previous process described in 7.2 and 7.3, using the same or very similar algorithms to 4OOP (the 4MOST Operations OpSys Pipeline), using statistical observing conditions (typical seeing, seasonal cloud and wind conditions) and replacing the telescope with expected performance.

The presented predictions on the dedicated simulations website [RD11] are based on OpSim simulations using the actual input catalogues of the Surveys. A very similar website presentation will be used during operations, as part of the Survey Progress Monitor (SPM).

# 8 Special survey strategy considerations

Most observations with 4MOST will be obtained with the standard survey mode[4] where a large fraction of the sky between 5º ≥ Dec ≥ -80º will be observed with 3–6 exposures of 10–25 minutes. However, there are subset of target classes that require special attention and will be observed in special observing modes on a best effort basis.

## 8.1 Special fields

A few Surveys have identified several special areas where more observing time shall be spent than the typical 1.5-2hrs available over most of the sky visible to 4MOST. The longer exposure fields, ranging between 4hrs and 50+hrs, will enable for instance observations of faint objects, enhanced target density, high completeness, or a higher number of repeats. Coordination with other Surveys is still ongoing to further exploit these special areas. The special areas identified are:

- WAVES Wide – The 1,000 sq.deg. KiDS area requiring higher target density and completeness, resulting in longer exposures and more visits.
- WAVES Deep – Four LSST Deep Drilling Fields (DDF) used also by several Community programmes to get high target densities and high completeness for faint targets, high S/N for velocity dispersion measurements on faint galaxies, regular two-weekly cadence observations of AGN for reverberation mapping, HRS spectra of faint, outer halo stars. Those DDF fields will also be used for monitoring purposes.
- Inner Milky Way bulge – higher target density and fainter star of this special location.
- Magellanic Clouds inner area – High repeat areas to address high target densities and to obtain cadence observations of variable stars.

[4] The way 4MOST operates is that either the observing conditions are adequate for normal survey operations or not adequate. In the latter case, either the dome is closed, or 4MOST conducts the poor weather programme. The short-term scheduler selects the visit to be observed taking into account the observing conditions. Once a visit has been selected, only targets associated with that visit can be scheduled. Seeing variations are dealt with by changing the exposure time of the OB at the last moment before it gets send to the telescope using the dVM observing mode (i.e., at most a few minutes before observation starts). There are some specific exclusions that can be implemented, like not to observe too faint targets for the sky condition considered. Some of those implementations are not yet included in the survey simulator, but the aim is for them to be implemented together with seasonal weather variations.

- Dwarf satellites – Extra observations for high target densities of faint stars in the Sagittarius and Sculptor dwarf galaxies.
- Asteroseismic areas – Relatively low density, bright stars with asteroseismic information used for pipeline calibration and validation.

## 8.2 Cadence

As 4MOST is a multi-object survey facility, it cannot deliver timed observations for individual targets. However, using minimal constraints on the scheduling of the observations, variable sources and transients are part of the science cases for some of the 4MOST Surveys. To deliver reliable scientific output for these targets, the 4MOST Survey needs to adopt a cadence in its observations. The executed time sequence may be irregular and there can be no guarantee that all repeats will be performed at the scheduled time. The schedule of re-observation of targets is independent of the final total S/N ratio. However, in many cases there is a requirement on the minimum S/N ratio to be reached for a given visit.

Some areas have been identified for having regularly timed observations for special science cases:

- The Deep Drilling Fields will be observed every two weeks to accommodate the AGN reverberation science case, thereby enabling many other science cases (monitoring, variable stars, faint objects, transients).
- The inner Magellanic Clouds area will be used for monitoring pulsating variables and various types of binary stars.

Other science cases will be using the so-called “for free” cadencing where the only request is to have a minimal time between two planned observations, for instance to identify radial velocity binary stars. Such target-based cadence requests can only be implemented on a best effort basis.

## 8.3 Transients

Imaging surveys like VRO/LSST will discover many transients, such as supernovae and tidal disruption events, that will be observable for several weeks by 4MOST after their discovery. These targets will be added to the 4MOST target database every day using a dedicated automatic interface (4FS API). In any field observed following the standard survey strategy there will then always be several live transients that will be observed with high priority. Once some transients have faded, their host galaxies may be added to the 4MOST target database using 4FS API to obtain their host galaxy spectra for redshifts. Only S10 and S16 can make use of this capability and their target rate will be low enough that the selection functions of other Surveys will not be affected by those additional targets.

## 8.4 Supplementary targets programme

The target completeness requirements of Surveys result in inefficiencies in assigning all fibres to targets once most targets have been completed. To increase the 4MOST scientific outcome, the science team will add targets to fill these unallocated fibres. Supplementary targets are targets that come with no completeness requirements and no guarantee that any one target in particular will be observed. These extra targets are only added to avoid empty fibres. Therefore, the observed number of such targets in any region will depend on the availability of main survey targets and observing time in any given area. *At the current stage no Supplementary Targets catalogues have been prepared nor are they included in the simulations. This is currently a low priority as by definition these targets shall not influence the main survey strategy. Preparatory steps have been made to develop this programme, its call for input and their inclusion in the FTA software.*

## 8.5 Poor observing conditions programme

When observing conditions are too poor to carry out the normal survey programme, 4MOST will switch to a dedicated poor observing conditions programme. Poor conditions are, for instance: twilight, full moon without a visible Milky Way, seeing full width half maximum (FWHM) > 1.5 arcseconds, and cirrus. The optimal boundaries for each of these condition constraints that are required to switch to this special programme will have to be determined at Instrument Commissioning. This all-sky programme consists primarily of very bright stars in Gaia Data Release 3 (DR3).

The nominal survey strategy for this bright star programme consists in short exposure time tiles created by the Visit Planner and some offset fibre positioning to avoid saturation and cross-talk on the spectrograph. *This programme is still being worked on*.

# 9 Required data calibration

A comprehensive overview of the 4MOST calibration is provided in the “4MOST Calibration Plan document” [RD7] of which the most relevant points for carrying out the survey are described in this section. The full details, with algorithms etc, are presented in the “Design and Analysis Report QC and Level-1 Science Data Reduction Pipeline Description” [RD10].

For 4MOST we distinguish three different types of calibration:

- **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 “4MOST Operations and Maintenance Plan” [RD8]. The software required to carry out the Instrument Calibration steps is part of the Instrument Control Software, which deals with the calibration of technical cameras, fibre-to-sky coordinate calibration, and guiding calibration. This is only indirectly relevant to the Surveys and hence not detailed further here.
- **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 Data Management System (DMS, which is part of the 4MOST Facility) performs to specification. The

details of the data reduction and calibration can be found in the SMP - Back-end Operations document [RD2].

- **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 which are not part of the Facility but are provided by the Surveys that utilize 4MOST. It is the data required by the Infrastructure Working Groups to train, calibrate and validate their pipelines and to validate 4MOST results against the results of surveys carried out on other telescopes/instruments.

The Instrument and Data Calibrations are the responsibility of the 4MOST Instrument Scientist, while the Science Calibration plans are mainly developed by IWG3.

The 4MOST Calibration Plan contains some 4MOST specific definitions and terminology related to 4MOST calibration, reproduced as is from Table 1 of [RD7]. Details on how the various calibrations listed in this section are used is presented in [RD10], describing the L1 data reduction pipeline.

**Table 1: List of 4MOST calibration specific definitions, as per Table 1 in [RD7].**

| Term | Definition |
|---|---|
| **Calibration beam** | Beam generated by the Calibration System that illuminates the telescope pupil, and thus passes through the entire optical system M1-M2, WFC/ADC-fibers and into the spectrograph slits. |
| **Facility calibration** | A term to describe when the calibration light (continuum or spectral) from the Calibration System's light source is fed into the calibration beam, i.e. through the full optical train M1-M2-WFC/ADC-fiber. Facility fiber flats and facility fiber wavecals thus indicate that the illuminating beam comes via the integrating spheres, i.e. the calibration beam. |
| **Simultaneous calibration** | A term to describe when the calibration light (spectral) from the Calibration System's light source is fed directly into the spectrograph slits. Simultaneous calibrations don't suffer from fiber-tilt induced effects, and can be used to correct for any drifts in the positions of the FPE lines across the field of view. |
| **Calibration System** | A 4MOST subsystem that provides both facility and simultaneous calibrations to the spectrograph slits. |
| **Daytime calibrations** | Calibrations taken during daytime, usually high-quality (high S/N ratio) and thus relatively time-consuming. |

| | |
|---|---|
| **Night-time calibrations** | Calibrations taken during night-time. Also called “attached” calibrations because they accompany science observations and are “attached” to them in the sense that they are taken at the same sky position and fiber configuration as the science observations. |
| **Twilight calibrations** | Calibration taken during twilight. Twilight flats are taken during “bright” (civil and nautical) twilight (sun altitude $-12° \leq alt_{\odot} \leq 0°$), bright stars ($m_G < \sim 12$ mag, TBC during commissioning**)** can be taken during “dark” (astronomical) twilight ($alt_{\odot} \leq -12°$). |
| **Facility fiber flats** | Science fibres are illuminated via the calibration beam, i.e. the light goes through the integrating spheres. This is in essence a spectral trace for each fibre. |
| **CCD flatfields, LED flatfields** | 2D flatfields illuminated by internal LEDs. This is used for pixel-to-pixel response measurements. |
| **Facility fiber wave (wavecal)** | Science fibers are illuminated via the calibration beam, i.e. the light goes through the integrating spheres. This always provides a FPE spectrum in each fiber. |
| **Simultaneous (simucal) wave or flat** | Obtained through Calibration Unit light fed directly to the spectrograph slit. If LDLS+FPE, then simucal relative wavecals. If LDLS-FPE, then simucal flats. If ThAr, then simucal absolute wavecals. |
| **Absolute wavecal** | Wavecal obtained with a light source (typically, a high-pressure lamp) that produces a spectrum with sharp, unresolved emission lines whose absolute wavelengths are very accurately known for absolute calibration of the FPE arc lines. |
| **Relative wavecal** | Wavecal obtained with a light source (e.g. Fabry-Pérot étalons or frequency combs) that produces a spectrum with many sharp, ideally unresolved and almost equidistantly spaced in frequency emission lines. |

## 9.1 Data Calibration

Data calibration encompasses all steps and procedures that are needed to remove any instrument signature on the scientific exposures (“data reduction”). In the following, we describe the strategy of how scientific data are calibrated, and which calibrations have to be executed (i.e. which calibration data need to be taken) to ensure a successful data calibration. More details of the specific data-reduction and calibration algorithms are given in [RD10].

The 4MOST calibration system consists of a light box that can feed light through fibres to integrating spheres illuminating the focal plane and attached to the spider vanes that hold up the secondary mirror of the telescope and directly to the three spectrographs using 6 simultaneous calibration fibres at each outer end of the fibre input slits (simultaneous calibration fibres). The light box contains a very bright Laser Driven Light Source (LDLS) to feed continuum light with no strong spectral features. A Fabry-Pérot Etalon (FPE) can be placed in its light path to produce many hundreds of regularly spaced lines over the full wavelength coverage of the spectrographs. Both continuum light and FPE modulated light can be fed to the integrating spheres and/or directly to the slit ends of the spectrographs. In the former case we have “facility fiber” wave or flat, while in the latter case we have “simucal” wave or flat. However, because the FPE does not provide an absolute calibration by itself and because the FPE may not be entirely stable under temperature and pressure changes, absolute calibrations are provided through a ThAr lamp with a well-known emission line spectrum. Such a ThAr lamp does not provide enough photons to be used through the integrating spheres in reasonable exposure times and hence its light is only fed directly to the simultaneous calibration fibres at the spectrograph slit ends. By the way, the ThAr light never sees the focal plane.

In general, using this system the calibration observing strategy has two main components:

- **Daytime calibrations** are taken for instrument performance measures that are not expected to change significantly during a night, e.g., detector characteristics. These measures are taken during daytime, immediately after the end-of-night shutdown procedure. This approach ensures that calibration data needed for the reduction of the science data are available for data transfer to DMS on the shortest possible timescales after the science data were obtained. The standard CCD calibration data, like bias and dark current subtraction, as well as pixel-to-pixel flatfielding of the data in 2D are part of the daytime calibrations. If present, non-linearity and electronic quadrant cross-talk are also determined at daytime.
- **Attached night-time calibrations**, which are either facility fiber flat and/or facility fiber wave, are taken to correct any fast-changing aspects, in particular those related to the configuration with which the science data were obtained (i.e., fibre tilt or telescope orientation), those related to variations in sensitivity due to atmospheric effects (e.g., seeing, airmass), and those caused by instrument variations (e.g., spectrograph stability under temperature variation).

  Of particular note here is that 4MOST has a tilting spine fibre positioner. This means that target light may come into the fibre under different angles, which is not expected to lead to any significant shifts in wavelength of the spectra due to the scrambling nature of fibres, but may lead to a very small variation in the shape of line profiles. This effect shall be calibrated with the Facility Calibration measures, with a combination of attached night-time and daytime calibrations.

  Next to the attached calibrations, each science exposure will receive FPE modulated light through its simultaneous calibration fibres at its slit end to track any wavelength drifts in the spectrographs. In case it is determined that the fibre tilt effects are negligible or can be predicted from spine tilt angle alone, these simultaneous calibrations can become the main reference calibration for wavelength offsets.

Once detector specific characteristics have been characterised and removed, there are four main steps in the required data reduction that need calibrations:

- **The location of the spectral traces and their spatial distribution** coming from each of the fibres to determine their optimal extraction profile and cross-talk with neighbouring fibres. The traces and inner spatial distribution will be determined from attached night-time flatfields. The extended wings of the spectral images are expected to be rather stable and will be measured from lab measurements before the spectrographs are mounted on the telescope.
- **Wavelength calibration of each of the individual spectra** coming from the different fibres. These will in first instance be obtained from the attached night-time wavelength calibrations (relative wavecal) with the fibres in the same position as the science exposure. If needed, the simultaneous calibration spectrum observed during the science exposure can provide an offset relative to the simultaneous calibration spectrum observed during the attached calibration for all fibres. Absolute wavelength calibration is then obtained with ThAr simultaneous fibre exposures, during commissioning maybe during night-time, but it is assumed that the FPE is stable enough that this is only required during daytime. Further validation of the accuracy of the calibration is possible against night sky emission lines, which could provide yet another means to calculate wavelength offsets for individual fibres. The spectral line shape profile for each fibre/spectrum will be derived from the FPE relative wavecals, which need to be deconvolved from the intrinsic FPE line shapes which are not unresolved for the HRS spectrograph in particular. The intrinsic FPE profile is derived by comparing the FPE and ThAr line shapes in the simucal fibres.
- **Relative fibre-to-fibre sensitivity for homogeneously filled fibre apertures** is needed for accurate sky subtraction, as are spectra obtained with fibres deliberately put on regions representative of the underlying background of the field (sky fibres). This is in first instance obtained by taking flatfield exposures both during twilight (modulo large scale background) and with the facility calibration system with all fibres in their nominal home position. Relative throughput variations as function of wavelength due to the fibre positioner tilts and movement of the fibres in the full fibre run can then be monitored through the night with the attached night-time flatfield exposures coming with each science exposure. A certain fraction of fibres will be dedicated background ("sky") fibres, pointing at patches of sky free of resolved sources, while in the crowded regions of the inner Milky Way and Magellanic Clouds those sky positions will be representative of the average non-target light. The fraction of fibres needed will be determined during commissioning (currently assumed to be ~10%) and will be evenly spread both across the field-of-view of the telescope as well as along the slits of the spectrographs. Suitable

sky fibre positions is described in the "IWG1 - 4MOST Sky Fibre Allocation Development Plan" [RD8].

- **Absolute target-by-target flux calibration** to correct for atmospheric transmission and fibre input coupling effects. White dwarfs and, if needed, other targets with well understood spectra will be observed with several fibres during each science exposure. These will be used either to model the telluric corrections with the software package *molecfit* (Smette et al. 2015), which are then applied to all targets in the exposure, or used as validation targets when using *molecfit* directly on all targets in the field (TBD during commissioning). The number of required calibration targets needed per field is TBD during commissioning and depends on the stability of the instrument. Absolute flux calibration is not possible for a fibre-fed spectrograph without calibrations against external flux measurements due to varying light coupling and fibre throughput affects due to for instance seeing, fibre positioning errors, and atmospheric refraction effects. Therefore, spectra of targets with available photometry will be scaled to match the photometry using a low order polynomial. For especially Gaia targets with Bp-Rp spectra this should lead to accurate results. This will be done for every observation as there will always be many Gaia targets observed and, hence, after one year there will be millions of calibrations available to create an accurate model to calculate the relative scaling needed for each fibre and for each condition to flux calibrate the targets without accurate external photometry.

After the stability and the repeated ability to remove instrument profile effects from 4MOST data has been modelled and demonstrated via monitoring for at least a year (TBD), it would be prudent to move the night-time attached calibrations to the daytime, since this will free up valuable night-time for science observations.

In the next subsections all calibration observations planned are summarized.

### 9.1.1 Daytime calibrations

During daytime, the following standard calibrations are taken with the dome closed, the telescope in parking position, and the fibres in nominal home position:

f. With the Calibration System: fibre flatfields and wavecals
   - CCD calibrations: zero (bias), dark, flatfields, and linearity measurements
   - Technical CCD calibrations part of the Instrument Calibration: zero (bias) and darks for Metrology cameras; bias, dark and flux calibration for Secondary Guiding Camera.

### 9.1.2 Twilight calibrations

Before sunset, the following standard calibrations are taken with the dome open, the telescope pointing at zenith (TBC), and the fibre spines in nominal home position:

g. Twilight flatfields

The twilight observations of flatfields will start 1 hour before sunset. Due to the sky gradient, twilight flats will be taken at 180 degrees field rotation, i.e., the telescope will change rotation in between exposures but will not change altitude. Taking twilight flats in the morning is impractical for a variety of safety and personnel-related reasons and therefore no morning twilight flats will be taken during normal operations.

### 9.1.3 Attached night-time calibrations

During night-time (i.e. nominal science operations), following standard calibrations are taken with the dome open and both the telescope position and the field rotation and fibre state as the accompanying science exposure:

h. With the Calibration System: facility fibre flatfields and/or wavecals;
i. Every science and calibration exposure has its own simultaneous wavecal.

We note that if the integrated FPE spectrum contains enough flux to measure fibre-to-fibre throughput differences with meaningful accuracy (≤0.5-1%, i.e. total counts between 10,000 and 40,000), only an attached wavecal will be taken.

### 9.1.4 Simultaneous calibrations

Simultaneous calibrations refer to the spectra obtained with the simultaneous calibration fibres during day or night-time operations. Simultaneous calibration fibres provide a way to bring night-time observations in the reference frame of daytime calibrations in the case of any temporal or spatial drifts in, e.g., the positions of the FPE lines across the field of view during the night.

### 9.1.5 Calibrations obtained during science exposures

j. **Sky subtraction**: During a science exposure, some science fibres will be targeting empty sky regions. These will be somewhat uniformly spaced out across the field-of-view and across the spectrograph slits. More information on empty sky positions is given in the “IWG1 - 4MOST Sky Fibre Allocation Development Plan” [RD8]. A sky model will be interpolated across the field of view and an individual sky subtracted from every science spectrum.
k. **White dwarfs for flux calibration**: Some science fibres will be observing white dwarfs to enable flux calibration of 4MOST spectra. The L1 pipeline will implement a “statistical flux calibration” approach, whereby gradually over time enough white dwarfs will be observed to construct a reasonably good flux calibration over the entire field of view. For this purpose, a catalogue of white dwarfs is already prepared [RD9]. In addition, it is foreseen that all stars with Gaia *Bp-Rp* spectra can be used for this purpose.
l. **Telluric standards**: Some science fibres will be observing telluric standards, typically A0V and G2V stars, but also white dwarfs. These observations will be used to correct for the strong absorption caused by rotational and vibrational transitions of molecules in the atmosphere.

## 9.2 Science Calibration

The requirements on science calibration and validation observations are still in development, but a general summary is provided below. An initial sample will be used during the Commissioning and the Operations Start-up Phase (OSP), but many classes of calibration and validation objects will continue to be observed throughout the entire 5-year survey program. All catalogues are described in the "Technical Note on Catalogues for Commissioning, Operations Start-up and Calibration" [RD9]. The observations are used internally by the Infrastructure Working Groups and Surveys to train, calibrate and validate their pipelines and also externally to validate 4MOST results against the results of other surveys carried out with different telescopes/instruments. The subsections below summarise the main science calibration catalogues being developed by IWG3.

Typically, science calibrations are carried out during night-time, i.e. targets are queued in the same mode as normal science targets. Some of them (e.g. very bright Benchmark stars, etc.) will be done during late twilight before the night begins so that they do not affect the available time for science observations.

### 9.2.1 Spectrophotometric and radial velocity standard stars

A subset of stars from these classical standard stars will be observed during commissioning to verify the flux calibration and radial velocity pipeline. They will not play an important role in normal operations as the statistical power of the cross-correlation to hundreds of thousands of stars overlapping with Gaia data with radial velocities will provide a much better estimate of the accuracy and precision of the 4MOST Galactic Pipelines (4GP).

### 9.2.2 Monitoring stars

The 4MOST survey strategy encompasses several deep, repeat fields that will be visited at least every two weeks while the fields are visible (~6–8 months per year). In each of these fields we expect to identify a small number of stars that will be repeated every visit to monitor the wavelength and sensitivity stability of the instrument.

### 9.2.3 Benchmark stars for Galactic pipeline validation

Calibration stars are a set of stars with well-known accurate and precise atmospheric parameters and abundances that will be used to validate, and eventually calibrate, the results of the main galactic pipeline.

Up to now, only a small set stars, the Gaia Benchmark stars, have been used in spectroscopic surveys as calibrators. Gaia Benchmarks sample is a small set (~40 objects), very bright ($0<G<8$), of F-G-K stars, with atmospheric parameters and abundances that have been derived using different techniques (e.g., spectroscopy, interferometry). A special observing strategy of pointing the fibre next to the star to catch its scattered light will be needed due to their brightness.

The Gaia Benchmarks, unfortunately, do not cover the entire parameter space explored by 4MOST surveys, nor the different classes of targets that will be observed. For this reason, 4MOST created a sample of extra calibrators: a set of ~100,000 targets, with well-known parameters from literature, divided in 12 classes. These classes of targets have been designed for each different module of the Galactic pipeline and following the specifications of each Galactic survey (see Table 2). The 4MOST extra calibrators have been constructed by collecting all high precision and accuracy of the parameters and abundances available in literature (although with less constraints than the Gaia Benchmarks). This sample, the primary 4MOST calibrators, is composed of ~ 40,000 targets.

**Table 2: Table of classes of objects covered by the Galactic pipeline validation sample.**

| CALIBRATOR CLASS | $T_{eff}$ range [K] | Evolutionary state | [Fe/H] range [dex] | Pipeline labels to be validated |
|---|---|---|---|---|
| Binaries | 3,000-7,500 | MS → AGB | | Teff, log(g), Fe/H, vsini, RV, ages (*) |
| Young stellar objects | 3,000-5,000 | PMS | -0.5 < [Fe/H]< 0.5 | Teff, logg, RV, Fe/H, vsini, activity |
| O-B-A | 8,000-30.000 | MS - TO | | Teff, log(g), vsini |
| White dwarfs | | WD | | Flux |
| Metal-poor stars | 3,500-7,500 | MS to RGB | [Fe/H]<-1 | Teff, log(g), abundances |
| Open Clusters | 3,500-7,500 | MS to RGB | -0.3<[Fe/H]<+0.3 | Teff, log(g), abundances, ages (*) |
| Globular Clusters | 3,500-7,500 | MS to RGB | -2.5<[Fe/H]< -0.5 | Teff, log(g), abundances, ages(*) |
| F-G-K Lit. | 3,500-7,500 | MS to RGB | -2.5 <[Fe/H]<+0.5 | Teff, log(g), abundances |
| Seismic Giants | 3,500-7,500 | RGB | -2.5 <[Fe/H]<+0.5 | Teff, log(g), abundances, ages(*) |

| | | | | |
|---|---|---|---|---|
| AGB and C stars | 3,000-4,750 | AGB | | Teff, log(g), abundances |
| RR-Lyr | | | -3 <[Fe/H]<+0.25 | Teff, log(g), abundances |
| Cepheids | | | | Teff, log(g), abundances |

(*): as part of survey science validation. Age is an inferred quantity, derived under a large set of assumptions (evolutionary tracks or isochrones families, seismic parameters adoption, external data, chemical clocks, etc.) specified by individual surveys.

### 9.2.4 Galactic cross-surveys validation catalogue

A dedicated catalogue of stars to validate and calibrate abundance scales and atmospheric parameters between 4MOST-SDSS-DESI- WEAVE has been created. This catalogue is mainly a subsample of the Galactic Pipeline validation sample located at –30º < Dec < +30º, to be observable by all surveys.

Each Galactic survey propose the classes of objects they want to be cross-calibrated, and, if not enough targets are in the Dec range of interest, provide their cross-calibration catalogues. A joint working group between these four surveys has defined this catalogue and 4MOST is committed to observing these targets to benefit common interests.

### 9.2.5 Galactic pipeline training catalogue

A training set is a sample of stars for which atmospheric parameters and abundances, or labels, are measured with high precision and accuracy, usually with classical physical pipeline. Machine learning pipelines will be trained on this sample. Once properly trained, the pipeline will infer the labels for the rest of the targets. The quality of the labels, then, depends on the quality of the training set and on the parameters space it covers. The training set of the Galactic pipeline is a dynamic sample, that will grow as long as the survey continues to observe and analyse data with the classical pipeline. 4MOST will be proactive in the construction of the training sample, to be able to guarantee the proper parameter space coverage since early operations time. For this reason, we integrated the sample of 4MOST calibrators, with a catalogue of over 60,000 targets, called secondary calibrators. The properties of this sample are of lesser quality than those present in the sample for pipeline calibration, but they are sufficient to fill the parameter space that needs to be measured.

Both Calibration and Training 4MOST catalogues have been constructed to cover the entire RA range and -80<Dec<+30 deg, to ensure the observability of a minimum sample for calibration and training during OSP.

### 9.2.6 Special Galactic verification catalogues

Some special catalogues will be observed predominantly during the OSP for specific tasks. Examples include deep fields with long exposures on bright to faint targets to test the Galactic

Pipeline as function of S/N, sky contamination, and fibre cross-talk, special fields with targets selected to test sky subtraction in crowded fields.

### 9.2.7 Extragalactic cross-surveys validation and pipeline training

Observations of this target catalogue provide validation and training spectra for the Extragalactic Pipeline (4XP) and are to be performed predominantly during the Survey Programme Validation phase. The catalogue contains galaxies and AGN with known redshift and velocity dispersion from the literature or current surveys (e.g., from surveys such as SDSS, GAMA, DESI and WEAVE). A balance is struck between having good quality measurements and probing the range of signal-to-noise ratios expected in the 4MOST survey.

This catalogue is separated in four components: REDSHIFTS, SIGMAS, AGN and REPEAT. The REDSHIFTS component has the more relaxed constraints and covers the same range in redshift as it will be probed by the 4MOST survey. Galaxies in the SIGMAS component have accurate measurements of velocity dispersion and exclude AGN or star-forming galaxies to avoid measurement issues due to for instance strong emission lines. The AGN component only includes AGN at $z > 0.1$ and it is there to ensure a sizeable sample of AGN spectra to test the pipeline when dealing with AGN. The REPEAT component contains a small subset of the REDSHIFTS component, spanning a suitable range of the parameter space (e.g., in terms of brightness). The goal is to perform repeat observations of these targets to evaluate the evolution of the quality of the results with increased SNR, as well as to test their measured uncertainties.

### 9.2.8 Benchmark galaxies and AGN

Observations of this target catalogue are expected to be performed and completed early during OSP. The targets are drawn from known surveys such as SDSS and the requirements specify redshifts with very high confidence (i.e., absolute redshift errors below $10^{-5}$). The goal is to verify the quality of the first 4MOST extragalactic spectra.

### 9.2.9 Faint extragalactic sources

Observations of this target catalogue are expected to be performed and completed early during OSP. Targets are drawn from known surveys such as SDSS and only sources with g-band magnitude fainter than 22 are included. The goal is to verify that the instrumental setup achieves the required SNR [RD9].

# 10 Front-End software tools and procedures

This section provides a summary of the software tools and procedures needed by the 4MOST OpSys Operations Pipeline (4OOP), as well as that required by the OpSim pipeline. Significantly more details on these two front-end pipelines are provided in [RD12], [RD13], and [RD14]. Those documents also provide the relevant information regarding the hardware in place to run the operations.

4OOP is the operational pipeline that takes survey inputs via 4FS WI [RD13] (or 4FS API for transient targets) and prepares the survey input before ingesting them into the Operations

System Target Database (OSTD) [RD14]. The latter is the central repository of all Front-end data which serves both operations and the input for survey strategy simulations, as done with OpSim by IWG2. As 4OOP and OpSim are tightly connected once the appropriate data has been ingested into the OSTD, it is practical to describe OpSim, which is to some extent self-contained, followed by 4OOP, as the latter uses the Visit Planner solution and Long-Term Scheduler constraints provided by OpSim. Whereas OpSim simulates all effects related to observations on the mountain, 4OOP connects with ESO and the VISTA telescope through the bespoke designated Visitor Mode (dVM), a remote automated scheduler.

Finally, the front-end operations depend intrinsically on information provided by the back-end operations (DMS), through the development of a feedback loop.

## 10.1 4FS WI and API

The 4FS Web Interface (4FS WI) offers to the 4MOST users the possibility to upload all the data needed for IWG2 to simulate the execution of the 4MOST survey with OpSim and for OpSys to run the operations of the 4MOST project. 4FS WI is designed to host all survey and calibration catalogues, with their requirements, as constructed by the Surveys and IWG3, while 4FS API is designed to accept transient targets that two specific Surveys are allowed to provide on a daily basis to be included in the operations pipeline. For more information about 4FS WI, see [RD14].

In summary, the 4FS WI and 4FS API form the entry point for all target information to 4OOP, with 4FS WI running a database to keep track of the information provided.

## 10.2 4OOP & OSTD

The first 4OOP task is to ingest into the OSTD all relevant data provided by the surveys and stored within 4FS WI. During this operation, the shared target algorithm is run to identify which targets surveys have in common (the so-called shared targets), but also which targets required both LR and HR exposures, which would be referred to as competing targets (as LR and HR fibres cannot reach the same position on the sky at the same time within the same pointing). During this ingest process, all key 4MOST identifiers, like TargetID, ObjectID, CNAME, etc (see [RD16] for more information) are created and associated with all targets. A similar process is in place for the ingestion and the cross-matching of calibration catalogues.

## 10.3 OpSim

OpSim stands for the Operations Simulations. OpSim provides not only the Visit Planner solution and the Long-Term Scheduler information to be used by the operations, but it provides also a full projection of how the different Surveys and sub-surveys are expected to progress over the 5 year survey programme using a comprehensive simulation pipeline mimicking in great detail the actual survey operations.

The key software components of OpSim are, with more details provided in [RD14]:

- The Visit Planner (VP) which provides all the visits, composed of one or several tiles with exposure times and associated sky condition. The VP algorithm, described in Tempel et al. (2020) [RD5], determines the optimal set of visits required to observe all required targets to meet the Surveys' requirements.
- The Long-Term Scheduler (LTS) which provides information by when a visit should have been scheduled. The LTS is guided by constraints provided by the Surveys and their need to reach specific goals at specific points in time. It will include constraints related to the VRO/LSST observing strategy that is relevant for some 4MOST surveys. Only a prototype LTS exists within OpSim for the moment.
- The Tile-Target Probability (TTP) which provides the probability for each target to be selected in each tile. The TTP algorithm, described in Tempel et al. (2020) [RD6], determines the probability that a target should be selected for observation in a given tile. OpSim TTP uses the same algorithm as 4OOP TTP, even though each software is written in a different language for operational reasons.
- The Short-Term Scheduler (OpSim STS) which ensures the optimal visit is selected for observation given the simulated observing conditions. The OpSim STS is somewhat different to 4OOP STS as not all instrumentation constraints are considered within OpSim (like cable wrap constraints, strict availability of Guide Stars, etc), nor does it require access to real time ambient conditions (like Paranal forecasts and Laser Guide Star (LGS) avoidance), but it uses instead simulated observing conditions.
- The Fibre-Target Assignment (OpSim FTA) which associates the required calibration targets, science targets and necessary sky positions to 4MOST fibres. To a large extent the OpSim FTA will be identical to 4OOP FTA, with only minor differences (like the daily up-to-date list of available fibres, a more precise saturation cross-checks per spectrograph arm for neighbouring fibres, etc.). The internal feedback loop required for FTA to operate will be identical in OpSim FTA and 4OOP FTA.

Within OpSim, the general feedback loop is currently simulated in a more simplistic way than what is planned for operations. Within OpSim, it is based primarily on the progress of the requested exposure time, with the availability to provide a delayed feedback response to mimic the actual processing time needed by the back-end operations (DMS) before real feedback information can be returned to OpSys and acted upon.

OpSim is operated using the Airflow system and a separate tool, SELFIE Stick, has been designed by OpSys to run and serve simulation outputs to the consortium. The input for OpSim is sourced directly from the OSTD, while the OpSim output comes in different forms: files, plots and data stored in a separate database. The latter content can be dynamically visualized through SELFIE Wall, a prototype for the Survey Progress Monitor (SPM) that will be used for visualizing the survey progress during operations.

## 10.4 4OOP: from visits with LTS information to OBB and feedback loop

Given that OpSim provides the VP and LTS solution, the main software components of 4OOP once all the information is in the OSTD are (with more details in [RD12] and [RD14]):

- The Shift and Rotate Visits (SRV) ensures that all visits are fully acceptable in terms of guide and wave front sensing star availability for observations, which can imply minor shifts and rotations of the visits.
- The Tile-Target Probability (TTP) which provides the probability for each target to be selected in each tile. Algorithmically identical to TTP used in OpSim.
- The Short-Term Scheduler (STS) which ensures the optimal visit is selected for actual observation conditions. Similar to OpSim STS but with numerous additional interfaces with the live status of the telescope/instrument and conditions at Paranal. This is to ensure that live constraints are adhered to (e.g. 4MOST cable wrap constraints, Laser Guide Star (LGS) avoidance, etc.).
- The Fibre-Target Assignment (FTA) which associates the required calibration targets, science targets and necessary sky positions to 4MOST fibres.
- The OB Builder (OBB) which takes the configured tiles and creates the OB and submits it to ESO.
- The OpSys Feedback Loop (OFL) which takes the L1 data product provided by DMS to OpSys and estimate the progress of each target following observations. During that process OFL updates the OpSyS internal feedback loop information created by FTA.

However, to operate these key software modules a number of operational triggers are required. In sub-section below we only present a few essential ones, which often are built on a sequence of additional triggers. This is further explained in [RD12] which provides a comprehensive set of trigger sequences that visually explains the process.

### 10.4.1 designated Visitor Mode (dVM)

This section summarizes the concept of the designated Visitor Mode (dVM), further described in the Front-end Operations ICD [RD12].

In the context of 4MOST, the designated Visitor Mode (dVM), with a remote rather than human scheduler, will be the process by which the consortium drives survey operations at the VISTA telescope through a remote interface from Europe. Specifically, and in an ideal case, this means that an automated scheduler software will determine which OB to submit at any specific moment in time to optimise the common progress of all participating surveys. The night assistant would then only have one optimal OB to choose from.

The remote scheduler should have as much real-time information available, including live status from the ESO observatory, so that the scheduler software can design the best OB. During Live Operations (i.e. nightly dVM), visits are selected and submitted in near-real-time via a remote interface, based on current observing conditions. Visits will be selected and ranked via the STS based on primarily airmass, current weather conditions, Paranal forecasts and Laser Guide Star (LGS) avoidance, and current pointing of the telescope to minimise slew overheads. For each selected visit and its specific tile exposure time(s), fibres are assigned to objects using FTA. Finally, the OB is submitted to ESO via the OBB. This selection+ranking+submission loop is repeated regularly throughout the night, and in particular during an ongoing OB to ensure the OB execution sequence includes the next optimal OB at any time.

We show in Figure 4 (taken from [RD12]), a simplified schematic overview of dVM and its various interfaces, particularly the main links between OpSys and ESO.

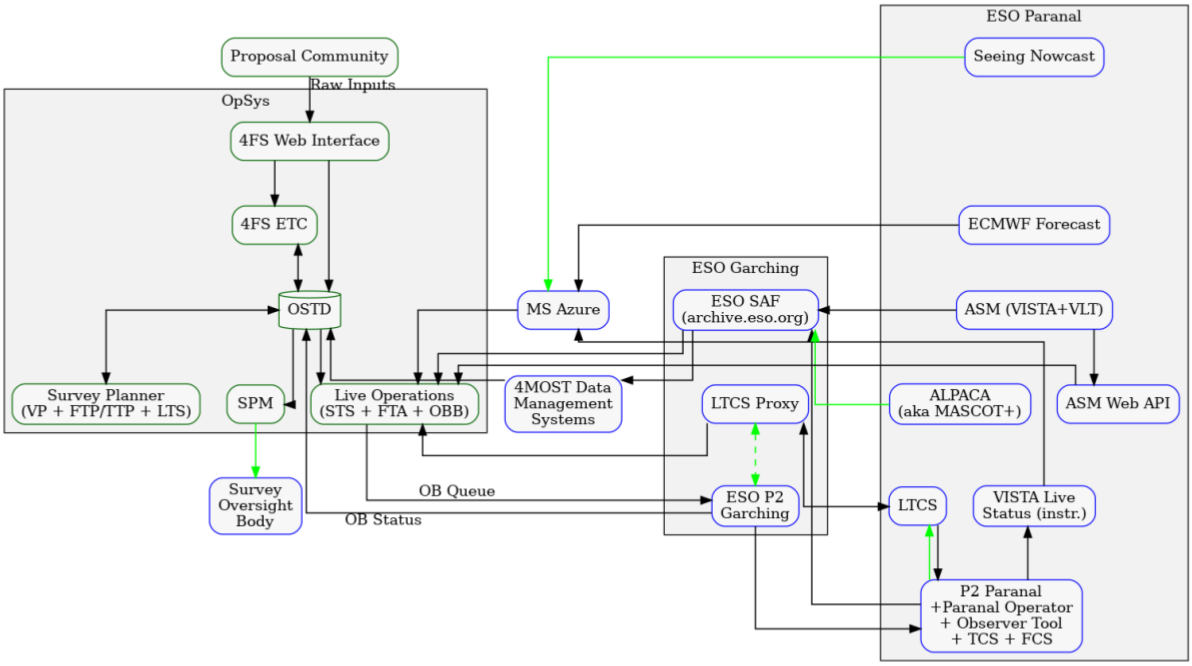


**Figure 4: Remote interfaces between ESO and 4MOST (from [RD13]).**

### 10.4.2 Backup OBs

The dVM will have to run in unsupervised mode at consortium premises (primarily at MPE) for a large part of the survey. It would be prohibitively expensive for the consortium to hire sufficient people to do the supervision on a 7/7 basis during the night. While we will strive to prepare for all eventualities, we still foresee the need to maintain some set of backup OBs at Paranal, such that 4MOST will not sit idle in case dVM breaks down for whatever reason (including loss of communication with Paranal).

Backup Mode may be activated at any time in which the standard dVM OB execution sequence is empty. Whereas the lack of valid OBs available in the dVM execution sequence implies a failure in standard operations and hence requires activation of Backup Mode, OpSys shall always continue to try to maintain the dVM execution sequence. In case the failed dVM condition has been resolved, the standard dVM execution sequence shall again contain valid OBs and the Paranal Operator shall have an opportunity to revert back to standard dVM operations whenever they see fit.

Backup OBs will be maintained by OpSys daily for the coming 2 weeks of operations.

It must be carefully noted here that brief failures under dVM shall not constitute a condition for activating Backup Mode. The nominal expectation is that Backup OBs are going to be used less than 1% (TBD) of the time throughout the duration of the project. If backup OBs are used more often than 5% (TBD) of the time as reported by the SPM, OpSys would consider the dVM as not functional as originally envisaged. This would likely have a significant impact on the overall progress of the 4MOST project, especially if it is not improved over time.

### 10.4.3 Daily operations

As dVM concerns the live nightly operations of 4OOP, there is a set of operations that need to be done during daytime to ensure night-time operations are running smoothly. A non-exhaustive list of the daily operational tasks include:

- Update the list of successfully observed OBs from the previous night
- Update the target progress with the feedback loop, based on L1 pipeline information provided by DMS (see next sub-section).
- Update the list of back-up OBs
- Retrieve from 4FS API and ingest within OSTD new transients

### 10.4.4 OpSys-DMS interface and feedback loop

The interface between the front-end and back-end operations, the so-called OpSys-DMS interface, is described in great detail in the DMS-OpSys ICD [RD17]. There are two main aspects in terms of data flow:

- OpSys to DMS: in this process OpSys passes to DMS all target attributes that cannot be passed through the dVM process via ESO associated with the OBs that are observed and subsequently passed to DMS. Essential attributes, beyond target properties provided by the Surveys, include the target identifiers (TargID, ObjID, CNAME, …). This process operates each time survey catalogues have been updated in 4FS WI and ingested into OSTD. Transient targets are exempt from this data-flow process.
- DMS to OpSys: in this process DMS passes to OpSys the essential information acquired on target spectra processed by the DMS L1 pipeline following observations. OpSys retrieves the new available information daily to be processed by the OpSys Feedback Loop in time for the preparation of the nightly operations.

# 11 Staff Effort

This section provides the FTE allocation devoted to front-end operations, split by front-end group. It concludes with a summary table.

## 11.1 IWG1

The IWG1 co-chairs estimate, using previous resource reporting as a guide, an average of 0.5 FTE/year of IWG1-related activities over the 5 years of 4MOST survey operations. They anticipate this IWG1 effort will likely taper from a start of about 1 FTE for the first year to about 0.3 FTE/year by the final year due to initial challenges with the input target catalogue processing and possible updating at the start of operations. The expected IWG1 activity will likely be unevenly distributed throughout the year with the greatest activity around the 4CAB assessment periods and will strongly depend on how many catalogue changes are planned/allowed during the survey operations, something which is still TBD.

## 11.2 IWG2

The IWG2 co-chairs estimate, using previous resource reporting as a guide, an average of 2.0 FTE/year of IWG2-related activities over the 5 years of 4MOST survey operations. This includes some time to manage and possibly further develop OpSim during the operations, but primarily to run and to analyse new survey simulations that will guide the survey strategy during the 5-year project. Unlike IWG1, IWG2 FTE resourcing is unlikely to change during operations, even though the focus of the activities is likely to evolve during that period.

## 11.3 IWG3

The IWG3 co-chairs estimate that nominally IWG3 will not need any real FTE effort during survey operations per see, beyond finishing off the analysis of data acquired during the OSP phases. Therefore, IWG3 co-chairs estimate that 0.2 FTE/year/co-chair is needed in year one of operations, and none thereafter.

## 11.4 OpSys

OpSys estimate that during operations there is a need for an average of 2.0 to 2.5 FTE/yr to ensure maintenance and support of all OpSys software, including dVM (nightly and daily operations), 4FS WI and API, OSTD, OpSim support and any additional tasks that are related to the 4MOST project over its initial 5-year operations. OpSys notes also that in the initial stages of operations there will be a need for more than two active people working within OpSys, due to the 24/7 nature of the 4MOST operations. OpSys estimates that this enhanced level of support will only be needed in the first year of science operations and expects this additional support to be provided by the 4MOST consortium members directly.

## 11.5 Instrument Science

The Instrument Scientist (IS) is responsible for the science performance of the 4MOST Instrument. Before normal operations this translates mainly in planning and execution of the commissioning and calibration plans. Once normal operations have started, IS activities consist of continued execution of the calibration plan, performance monitoring of the instrument, and investigating avenues to further optimise instrument performance (reducing overheads, improved use of poor observing conditions like twilight and cirrus overcast). All instrument parameters relevant for operations (sensitivity, overheads, positioner and fibre performance, etc.) are recorded in the Instrument Central Repository (ICR) maintained by the Instrument Scientist. Before commissioning and during the first year of operations this is expected to be a full-time position, at later times slowly reducing to ~0.5 FTE/yr.

## 11.6 Front-End staff effort: summary

Table 3 provides the average FTE/year over 5 years of operations. The reader should refer to the individual sub-sections that describe how these numbers have been obtained for each front-end group. The names and institutions listed in the table reflect those who are active in those roles/functions, as of October 2024.

**Table 3: Front-end staff effort summary table**

| Name | Function | Affiliation and Country | <FTE/yr> |
|---|---|---|---|
| Robert Schmidt | IWG1 co-chair | Heidelberg University, Germany | 0.1 |
| Sabine Bellstedt | IWG1 co-chair | ICRAR UWA, Australia | 0.1 |
| Roberto Raddi | IWG1 co-chair | UPC, Spain | 0.1 |
| IWG1 survey reps. (18) | IWG1 team | 4MOST institutions | 0.30 |
| Peder Norberg | IWG2 co-chair | Durham University, UK | 0.30 |
| Jesper Storm | IWG2 co-chair | AIP, Germany | 0.30 |
| Elmo Tempel | IWG2 co-chair, SELFIE developer | Tartu Observatory, Estonia | 0.25 |
| Gal Matijevic | SELFIE-Stick developer | 4MOST Contractor | 0.25 |
| N.N. | IWG2 OpSim operator | 4MOST institution | 0.50 |
| IWG2 survey reps. (18) | IWG2 team | 4MOST institutions | 0.20 |
| Dimitri Gadotti | IWG3 co-chair | Durham University, UK | 0.04 |
| Marica Valentini | IWG3 co-chair | AIP, Germany | 0.04 |
| Peder Norberg | Operations Scientist | Durham University, UK | 0.30 |
| Andrea Merloni | OpSys Manager | MPE, Germany | 0.20 |
| Jake Laas | OpSys dVM Operator | MPE, Germany | 1.00 |
| Gal Matjievic | OpSys Developer & DB Manager | 4MOST Contractor | 0.75 (Y1) to 0.25 (Y5) |
| Nikolay Kacharov | OpSys Developper | AIP, Germany | 1.0 (Y1 only) |

| Name | Function | Affiliation and Country | <FTE/yr> |
|---|---|---|---|
| Genoveva Micheva | Instrument Scientist | AIP, Germany | 1.00 (Y1) to 0.50 (Y5) |

# Appendix A List of Acronyms

| List of Acronyms | |
|---|---|
| 4MOST | 4-metre Multi-Object Spectroscopic Telescope |
| 4FS | 4MOST Facility Simulator |
| 4FS API | 4MOST Facility Simulator Application Programming Interface |
| 4FS-WI | 4MOST Facility Simulator-Web Interface |
| 4GP | 4MOST Galactic Pipeline |
| 4OOP | 4MOST Operations OpSys Pipeline |
| 4OR | 4MOST Operational Repository |
| 4PA | 4MOST Public Archive |
| 4PRAP | 4MOST Pre-Release Access Point |
| 4SP | 4MOST Selection Function Pipeline |
| 4XP | 4MOST eXtragalactic Pipeline |
| AD | Applicable Document |
| AGB | Asymptotic Giant Branch |
| AGN | Active Galactic Nucleus |
| AL2 | Additional Level 2 |
| CCD | Charge Coupled Device |
| CCF | Cross-correlation Function |
| CNN | Convolutional Neural Network |
| DBGS | Dark, Grey, Bright and Super-bright |
| DL2 | Deliverable Level 2 |

| List of Acronyms | |
|---|---|
| DL2-SURV | Deliverable Level 2 - Survey (data product not delivered by an IWG, but by a 4MOST Survey) |
| DMS | Data Management System |
| DOE | Detection Of Extrema |
| DR | Data Release |
| DRC | Data Release Candidate |
| DRM | Data Release Manager |
| DRPD | Design Report Pipeline Description |
| dVM | designated Visitor Mode |
| DXU | Data eXchange Unit |
| ETC | Exposure Time Calculator |
| FITS | Flexible Image Transport System |
| FoM | Figure of Merit |
| FP | Fabry-Pérot |
| FPE | Fabry-Pérot Etalon |
| FTA | Fibre-to-Target Assignment |
| FTE | Full Time Equivalent |
| FWHM | Full Width at Half Maximum |
| HB/RC | Helium Burning/Red Clump |
| HR | High Resolution |
| ICD | Interface Control Document |
| IDR | Internal Data Release |

| List of Acronyms | |
|---|---|
| IWG | Infrastructure Working Group |
| JOG | Joint Operations Group |
| L1 | Level 1 |
| L2 | Level 2 |
| LDLS | Laser Driven Light Source |
| LR | Low Resolution |
| LSM | Large Scale Merit |
| LTS | Long Term Scheduler |
| MS | Main Sequence |
| OB | Observation Block |
| OBB | OB Builder |
| ODG | Operations Development Group |
| OFL | OpSys Feedback Loop |
| OpSim | Operations Simulator |
| OpSys | Operations System |
| OSP | Operations Start-up Phase |
| OSTD | Operations System Target Database |
| PCA | Principal Component Analysis |
| PDR | Public Data Release |
| PN | Planetary Nebulae |
| QA | Quality Assurance |
| QC | Quality Control |

| List of Acronyms | |
|---|---|
| QE | Quantum Efficiency |
| RD | Reference Document |
| RGB | Red Giant Branch |
| RV | Radial Velocities |
| S/N | Sign-to-Noise ratio |
| SAF | Science Archive Facility |
| SB1 | Single Lined Binary stars |
| SCB | Science Coordination Board |
| SciFoM | Scientific Figure of Merit |
| SED | Spectral Energy Distribution |
| simulcal | Simultaneous Calibration |
| SMP | Survey Management Plan |
| SPM | Survey Progress Monitor |
| SPV | Survey Programme Validation |
| SRV | Shift and Rotate Visits |
| SSM | Small Scale Merit |
| ST | Science Team |
| STS | Short Term Scheduler |
| TBC | To Be Confirmed |
| TBD | To Be Determined |
| ThAr | Thorium Argon |
| TO | Turn-Off |

| List of Acronyms | |
|---|---|
| TTP | Tile-Target Probabilities |
| VALD | Vienna Atomic Line Database |
| VP | Visit Planner |
| wavecal | Wavelength calibration |
| WD | White Dwarf |
| WP | Work Package |