The 4MOST Operations System

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ABSTRACT

The 4MOST multi-object spectroscopic instrument (to be mounted on the ESO/VISTA telescope) will be used to conduct an ambitious multi-year wide area sky survey. A disparate set of science goals, requiring observation of tens of millions of galactic and extragalactic targets, must be satisfied by a unified program of observations. The 4MOST Operations System is designed to facilitate this complex task by i) providing sophisticated simulation tools that allow the science team to plan and optimise the 4MOST survey, ii) carrying out optimised medium-term scheduling using survey forecasting tools and feedback from previous observations, and iii) producing sets of observation blocks ready for execution at the telescope. We present an overview of the Operations System, highlighting the advanced facility simulator tool and the novel strategies that will enable 4MOST to achieve its challenging science goals.

Keywords: 4MOST, Operations System, Facility Simulator, Survey Scheduling, Survey Optimization, Figures of Merit, Operations Simulation, Exposure Time Calculator

1. INTRODUCTION

The 4-metre Multi-Object Spectroscopic Telescope (4MOST[1,2]) is a wide-field (>4 deg^2), high-multiplex (minimum 1600 apertures, goal 2400), fibre-fed spectrograph with spectral resolutions of R$\sim$5000 and R$\sim$20 000 to be mounted as the single science instrument on the European Southern Observatory's (ESO) Visible and Infrared Survey Telescope for Astronomy (VISTA) telescope and to be operated from $\sim$2021 within the ESO Paranal Observatory environment. The unique strength of 4MOST lies in its capability to carry out a wide range of large science programs in parallel over a substantial fraction of the observable sky, enabling the gathering of unprecedentedly large spectroscopic samples, but also enabling observational programs that would otherwise be too expensive due to relatively sparse target densities. In any single on-sky exposure, 4MOST is expected to simultaneously collect spectra of both galactic targets (stars) and extragalactic targets (galaxies, AGN). The many light collecting sub-apertures of 4MOST can be reconfigured to target new locations within the focal surface in less than 2 minutes, meaning that the total number of observed targets is potentially very high, and the total number of possible combinations is enormous.

The operations of the 4MOST facility are complicated by the need to operate many parallel science surveys with heterogeneous requirements and goals, over an extended time frame. It is expected that the first five years of 4MOST operations will be used to carry out a coordinated GTO program of observations. Currently, nine different GTO Public Surveys are envisaged[*], taking up to 70% of the total available fibre-hours. These projects are as follows: Milky Way Halo Surveys (at both low and high spectral resolution); Milky Way Bulge and Disk surveys (at both high and low resolution); an X-ray AGN survey; a Cluster Cosmology Survey; a Cosmology Redshift Survey, a Galaxy Evolution Survey (WAVES) and a survey of the Magellanic Clouds (1001MC). The combination of these projects drives both the design of the instrument and the survey strategy, with a goal to provide not only homogenous coverage over very large sky areas ($> 10^4$ deg^2), but also highly complete sampling over smaller specially selected fields. These GTO surveys will be complemented by some number of Community

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[*]see https://www.4most.eu/ for further details of the 4MOST key science goals

Observatory Operations: Strategies, Processes, and Systems VI, edited by Alison B. Peck, Robert L. Seaman, Chris R. Benn, Proc. of SPIE Vol. 9910, 99101Q · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2231855

Surveys, which will utilize the remaining 30% of the fibre-hours, and that will have their own science requirements and resultant impacts on survey strategy. Due to their ambitious scope, the largest surveys using 4MOST will run for around 5 years (significantly longer than the typical 6-monthly ESO proposal/observation cycle). Great care must be taken to balance the desire to fully complete these science surveys by the end of the allocated time, but also to ensure that 4MOST observations remain highly efficient over the same period. The OpSys must accommodate the fact that many aspects of the science surveys and survey strategy will be adjusted/modified during the course of the 4MOST survey, as well as allowing for the addition of new science projects after the start of operations. It is assumed that the primary judgement of success for each science survey will be made at the conclusion of the survey period (i.e. at some date defined at the start of the survey). Therefore, whilst the overall survey strategy will always be planned with the final survey results in mind (i.e. at the end of the 5 year period), the survey operations will be planned and Observation Blocks (OBs) delivered on much shorter timescales (∼weeks to ∼months).

The on-mountain operations of 4MOST will be carried out by ESO staff, following essentially the same pure service-mode model currently employed at VISTA and other ESO telescopes. However, in contrast to normal PI-led programs on ESO telescopes/instruments, each of the Observation Blocks (OBs) necessary for the operation of 4MOST and prepared and supplied by the 4MOST consortium will contain targets from several different surveys, which are being executed in parallel. An accompanying article in this series by de Jong et al.[2] presents an overview of the 4MOST system, and an article by Walcher et al.[3] presents the 4MOST operations plan in more detail.

In this paper we present the 4MOST Operations System (OpSys). It is the OpSys, a core component of the 4MOST system design since inception, which provides the functionality necessary to deliver the powerful survey capabilities of 4MOST. We give an overview of the OpSys and and describe its constituent components. We describe the 4MOST Facility Simulator component (4FS) in somewhat more detail as the development of the 4FS is in advance of the rest of the OpSys. The 4MOST project is currently (Summer 2016) coming to the end of the preliminary design stage, and the description given below is adapted from the documentation submitted to the 4MOST PDR committee.

2. 4MOST OPERATIONS SYSTEM OVERVIEW

The 4MOST Operations System (OpSys) is the collective term for the set of tools used for planning and preparing all science and calibration observations during 4MOSTs scientifically useful lifetime at the telescope, as well as during the earlier survey preparation and instrument commissioning phases. The 4MOST consortium will operate the OpSys as a service to all survey teams who participate in the 4MOST sky survey.

- The three primary functions of the 4MOST OpSys are as follows:
  - To simulate 4MOST operations (medium and long-term) in order to develop and to maintain a near-optimal survey strategy
  - To provide tools to plan, produce and submit OBs for all 4MOST observations (both science and calibration)
  - To monitor the progress of the 4MOST sky survey, and to maintain a database recording the progress towards 'completion' of individual targets

The 4MOST OpSys strives to allow all 4MOST Surveys to achieve the highest possible efficiency, and all three of the capabilities listed above are crucial to this end. In particular, the 4MOST OpSys shall be capable of handling the complexity of a multi-survey program and maximizing the scientific return and providing a fair return on investment for stakeholders. The OpSys shall handle the long-term planning of observations, ensuring that the available observing resources are expended efficiently over the ten normal ESO 6-month semesters spanned by the 5-year 4MOST survey. The OpSys shall ensure that homogenous survey depth is delivered over both extragalactic and Galactic survey areas (where necessary), with inbuilt feedback strategies to cope with e.g. variable weather conditions. The OpSys shall also use these feedback loops to maximise observational efficiency. For example, when a target is deemed to be sufficiently well exposed, its fibre can be reassigned in subsequent observations to collect light from a new target. Past experience shows that short-timescale feedback loops in survey planning lead to an optimization of survey efficiency (e.g. daily feedback in the case of the GAMA survey[4]).

The most demanding formal requirements on the OpSys are as follows: i) The ability to predict/simulate the progress of 4MOST science surveys to better than 5% accuracy in less than 1 hour of processing time; ii) The ability to handle target catalogues of at least 500 million objects, distributed amongst >20 science surveys; iii) The ability to balance the (sometimes competing) needs of widely difference science projects, whilst also exploiting the 4MOST observing resources in a highly efficient manner. The OpSys design is intended to satisfy these requirements.

3. 4MOST OPERATIONS SYSTEM TOOLSET

The OpSys consists of a collection of software tools and data repositories, that can be broken down into the following work packages and their main sub-components. The structure of the OpSys is also illustrated graphically in Figure 1.

- Observer Support Software (OSS)
  - OSS Survey Planning tool (OSS_SP)
  - OSS OB Builder tool (OSS_OBB)
- 4MOST Facility Simulator (4FS)
  - 4FS Operations Simulator (4FS_OpSim)
  - 4FS Exposure Time Calculator (4FS_ETC)
  - 4FS Reference Star Tool (4FS_RST)
  - 4FS Queue Scheduler (4FS_QS)
  - 4FS Web Interface (4FS_WI)
- Survey Progress Monitoring (SPM)
  - SPM Status Updater tool (SPM_SU)
  - SPM Report Archive (SPM_RA)
  - SPM Web Server (SPM_WS)
- Operations System Target Database (OSTD)
  - OSTD Live Target Database (OSTD_LTD)
  - OSTD Live OB database (OSTD_LOBD)
  - OSTD Target Submission Interface (OSTD_TSI)
  - OSTD Target Database Updater tool (OSTD_TDU)
  - OSTD OB Database Updater tool (OSTD_OBDU)
  - OSTD Live System Model (OSTD_LSM)
  - OSTD System Model Updater tool (OSTD_SMU)

3.1 Observer Support Software (OSS)

The Observer Support Software (OSS) is the collection of tools that is used by 4MOST survey operators to plan the survey and to prepare all science and calibration OBs for execution by 4MOST.

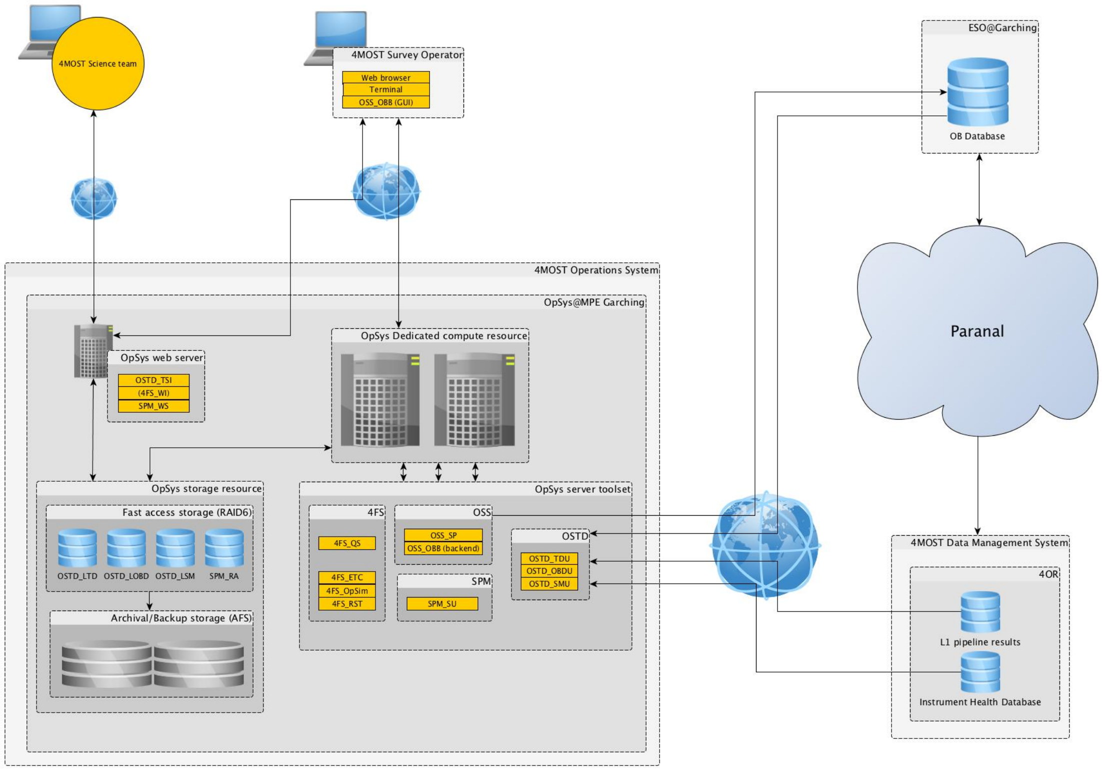

Figure 1. Overview of OpSys components and interfaces during the 4MOST Science Operations Phase.

3.1.1 OSS Survey Planning Tool (OSS_SP)

This tool is the main interface used by the 4MOST survey operators to produce OBs for the forthcoming observations to be carried out by 4MOST. The work done by the OSS_SP tool nominally requires little or no user-interaction. However, it is the role of the Survey Operator(s) to instigate and supervise the operation of the tool, respond to errors/warning messages and to take corrective actions, and to verify the outputs of the tool.

3.1.2 OSS OB Builder Tool (OSS_OBB)

This tool is responsible for designing 4MOST science tiles, and packaging these tiles, together with calibration templates into the OBs that will be uploaded to the ESO OB database. The OSS_OBB will also generate all calibration OBs necessary for 4MOST. When generating science OBs, each run of the OSS_OBB tool will produce a user-defined number of OBs for a single Field. The OSS_OBB functionality will be accessed in three ways: i) Through a set of C/C++ library routines that can be called from within the OSS_SP tool using a well defined API, ii) through a stand-alone non-interactive command line interface, and iii) through a simple graphical interface (GUI) that allows users to inspect and adjust the assignment of fibres to targets calculated via automatic routines. Under normal 4MOST survey operation the OSS_OBB functionality will be accessed through method i) above. In this mode, the fibre-to-target assignments will be generated automatically following predefined algorithmic rules. 4MOST Survey Operators can use the graphical interface of the OSS_OBB to visually inspect the automatically constructed OBs. Note. Manual editing of fibre-to-target assignments will be possible, but will be strongly discouraged and should only be used in extreme cases. OBs that have been manually adjusted will contain a flag indicating that this is the case (and so can be excluded from studies which require a completely reproducible selection function).

3.2 4MOST Facility Simulator (4FS)

The 4FS is the collection of tools that allows simulation of most aspects of the 4MOST instrument, and the surveys that it will carry out. The 4FS must be a versatile tool because it will be used in several phases of the

4MOST project. Use-cases identified so far include a) as a tool to support the development of 4MOST science surveys, b) as an engineering tool to support instrument development, c) as a tool to assist the optimisation of the 4MOST survey strategy, d) as a test-bed for algorithm development and prototyping, and e) as a tool used to optimise the medium- to long-term scheduling of observations during the 4MOST operations phase.

An early version of the 4FS was described previously in Refs. 5,6. The early system involved the distribution of the 4FS components over several sites, with three independent teams developing the separate software components. It was found that the rate at which simulations could be executed was severely limited by data transfer times. Therefore, during the 4MOST Preliminary Design Phase the 4FS architecture has been simplified and is now delivered as a single package of tools provided by a single institute (MPE, Garching).

The requirements on the 4FS pull our design in opposite directions; the 4FS must on one hand provide very accurate predictions of the progress of the 4MOST sky surveys, but on the other hand it must make these predictions within very tight time constraints.

It will be vital to be able to model the 1D spectra that will be delivered by 4MOST. To do this, one could conceivably build a tool that, for each simulated 4MOST tile, models the SED and profile of each target, tracking every photon that hits the VISTA primary mirror, and following their paths all the way through the instrument optics to the detectors, then generating mock CCD images on which the full 4MOST data analysis pipeline stack can be run. Whilst it will be feasible to execute such detailed simulations for individual tiles, indeed, such functionality will be provided by the 4MOST Top Of Atmosphere to Detector (TOAD) tool,[7] the computational resources required to carry out highly detailed modelling for each and every tile of a 5 year 4MOST survey would be prohibitively large. We have thus adopted a compromise approach that reduces the computational requirements by a) only attempting to model a set of 'typical' target spectral templates, and b) approximating the full modelling of the atmosphere $\rightarrow$ telescope $\rightarrow$ instrument $\rightarrow$ L1 pipeline with a 1D model of effective system throughput, sampled at each of a grid of points within a parameter space that spans the vast majority of variation in system sensitivity.

In the previous phases of the 4MOST project, simulations produced by the 4FS have typically been carried in an iterative sequence, where the impact of changes to one or two parameters or algorithmic processes being compared to previous simulation runs before starting the next iteration. This means that the 4FS simulation outputs evolve in a 'genetic' fashion, with most changes that result in a positive outcome being adopted for future runs, and those which have a negative impact being dropped. We also expect to use this approach in future project phases, responding particularly to inputs from the relevant Infrastructure Working Groups and the Science Team. It is impossible to anticipate in advance all features that might be requested by these actors, and therefore we expect to support the IWGs/Science team by frequently adding newly requested functionality to the 4FS components, for example in the way that the 4FS models survey strategy.

The 4FS tools will be made available to scientists outside the 4MOST collaboration in support of the expected call for community proposals.

3.2.1 How users interact with the 4FS

The 4FS is operated through two distinct interfaces, i) an Operator mode interface for power users, and ii) A web-based interface for general science users. The power-user interface is intended for use only by trained experts, with all possible parameters exposed and adjustable. The remote mode interface is intended for use by non-experts, with a limited set of parameters exposed to the user (the remaining parameters are set to their default values), and some restrictions on the size of simulations that can be instigated. Both of these user interfaces send simulation requests to a common back end which manages the actual simulation work.

3.2.2 4FS workflow within the Consortium Science preparations phase

We list below an overview of the steps taken within the survey simulation process within the Consortium Science preparations phase. IWG2 is the infrastructure working group responsible for planning and optimising the 4MOST survey strategy.

1. Input Catalogue Preparation steps
   (a) Each survey team defines a set of spectral templates which adequately represent the range of science targets within their survey.
   (b) Each survey team defines a set of spectral quality criteria that define whether a target has been observed successfully. For example, *'The median SNR must be at least 5 per spectral resolution element over the range 400 to 500nm'*. These requirements can be defined separately per spectral class or identically for all targets within the survey.
   (c) Each survey team prepares an input catalogue of science targets, in which each target is associated with a spectral template (1a) and a set of spectral quality criteria (1b).
   (d) Each survey team defines an algorithm to calculate a numerical Figure of Merit (FoM) for their science survey. The various GTO 4MOST surveys, as well as community surveys, will homogenize their FoM definitions so that the minimal scientific requirement for a successful survey will correspond to FoM=0.5, with FoM=1 representing the most optimistic scientific goal.
2. Exposure Time Estimation
   (a) The Instrument Scientist (IS) provides the OpSys team with a detailed description of the 4MOST system, including throughput curves, dispersion curves, wavelength solutions, focal plane layout description, etc.
   (b) The OpSys team fold the spectral templates through the 4MOST response for a set of sky conditions and a range of exposure times using the 4FS_ETC. These folded spectra are then tested against the spectral quality criteria defined in 1b to determine the minimum exposure time required to successfully observe the template.
   (c) The OpSys team update the input catalogue from 1b with the exposure times calculated in 2c.
   (d) The OpSys team communicates the results of steps 2b, 2c and 2d back to the science teams via IWG2.
3. Survey Simulation
   (a) IWG2, PI, IS, OS, or the PSs request/commission new survey simulation(s)
   (b) The OpSys team runs the 4FS_OpSim using as input the updated catalogues from 2c together with a set of (adjustable) parameters that define how the 4MOST survey is to be carried out. As part of its standard outputs, the 4FS_OpSim calculates the numerical success of each survey after the 5-year 4MOST survey, as defined by the survey FoMs given in 1d.
   (c) The OpSys team reports the results of 3b to IWG2 who pass these on to the science teams.
4. Simulation Evaluation and Iteration
   (a) The OpSys team, IWG2 and the survey teams consider the results of the simulation and suggest improvements for the next iteration.

Note: Stages 1 and 2 can be iterated several times until the science teams are happy with the results.

3.2.3 4FS Exposure Time Calculator (4FS_ETC)

The 4FS_ETC is a software tool used to predict the minimum 4MOST exposure times that are required to meet well-defined quality criteria for science and calibration targets under a range of observational conditions (airmass, seeing, sky brightness, cloud cover etc.). The 4FS_ETC is specifically designed to allow bulk processing of large numbers (1000s) of template spectra (c.f. the ESO web ETC, which is designed to simulate individual spectra in an interactive manner). The 4FS_ETC includes a framework within which the data quality of a simulated spectrum can be tested against a predefined set of criteria to evaluate if it has been successfully observed. An advanced beta version of the 4FS_ETC tool is currently (mid-2016) in use within the 4MOST consortium, offering much of the functionality expected in the final tool. Future updates will focus on improving the processing speed, capacity and accuracy of the 4FS_ETC.

The main operation modes of the 4FS_ETC are as follows:

- 'Fold and (optionally) evaluate spectra' mode
  - Each spectral template is folded through the system response for each of a specified grid of exposure times and observational conditions producing 1D vectors of various interesting quantities (photon fluence, noise, SNR, sky etc.)
  - (Optional) Each folded spectrum is then tested against the specified spectral success criteria giving a Boolean result (i.e. SUCCESS or FAILURE).
- 'Calculate Minimum Exposure Time' mode
  - For each input spectral template (re-normalised to a specified magnitude) and for each point on a grid of observational conditions, the 4FS_ETC (iteratively) finds the minimum exposure time that is required to deliver a spectra folded through the system response that meet the specified spectral success criteria.
- 'Calculate Magnitude Limit' mode
  - For each input spectral template and for each point on a grid of fixed exposure times and observational conditions, the 4FS_ETC (iteratively) finds the faintest target magnitude that when folded through the system response still delivers spectra that meet the specified spectral success criteria

The most commonly used mode of the 4FS_ETC is 'Calculate Minimum Exposure Time' mode. The other modes are provided to assist users in diagnostics, visualisation and verification.

4FS_ETC inputs: The 4FS_ETC takes as input a parameterized model of the 4MOST system and its operating environment, and models of the targets that are to be observed including: For each spectrograph arm: a throughput curve (that includes all effects apart from the atmosphere and the fibre coupling); a spectral resolution curve; a nominal wavelength solution ; detector characteristics; spectral extraction parameters. The target-to-fibre coupling efficiency is represented as a look-up table, giving the fraction of incoming light transmitted down the fibre, as a function of several parameters including: wavelength; delivered IQ; fibre tilt angle; fibre-target misalignment and target profile shape. The 4FS_ETC represents the Paranal atmospheric environment (derived from the outputs of the ESO SkyCalc web tool[†]) as a 2D grid of sky emission curves as a function of airmass and zenithal sky brightness, and a 1D grid of sky transparency curves as a function of airmass. The 4FS_ETC contains a model for the attenuation by various levels of cloud cover. The user supplies a matrix of observing conditions and exposure times under which observations should be simulated, spanning at least the following parameter space: airmass, sky brightness, sky transparency class (cloud cover), and delivered image quality at the fibre-aperture. The targets to be simulated are described by the combination of spectral templates of science/calibration targets in physical flux density units, and a set of spectral success criteria expressed as Rulesets that are used to judge the success of each folded spectrum. The user also specifies a list of magnitudes+filters to which the template should be re-normalised, a list of redshifts to which the (rest frame) template should be shifted and a list of Galactic obscuration values, $E(B-V)$, by which the template should be reddened.

4FS_ETC Outputs: In 'Calculate Minimum Exposure Time' mode, the 4FS_ETC produces the following outputs: i) a grid of estimated minimum exposure times for each requested normalisation, redshift and reddening of each input template, for each simulated set of observational conditions ii) (optional) folded signal, noise, SNR, and sky vectors for each combination of re- normalised input template and each combination of observational conditions.

4FS_ETC Workflow: When running in 'Calculate Minimum Exposure Time' mode, the 4FS_ETC has the following workflow:

- Read in all inputs
  - sky emission and transmission vectors

[†] https://www.eso.org/observing/etc/skycalc/

- instrument description
- template spectra
- spectral success criteria (Rules+Rulesets)

- Prepare system redistribution matrix for each spectrograph arm
- for each observing condition
  - Setup system effective area vectors
  - Fold sky emission through system response
- for each spectral template
  - Prepare rebinning vectors for each Rule
  - for each combination of redshift, extinction
    - modify template by redshift, extinction
    - estimate magnitude of modified template through standard filters
    - fold modified template through system response to calculate normalised flux vectors at a single reference magnitude
    - **Start iteration loop:** (continue iterating until exposure time is sufficiently constrained for all magnitudes+conditions)
    - for each requested magnitude and for each observing condition
      - choose the next exposure time to test
      - calculate target fluence, sky fluence, noise and SNR vectors for this exposure time
      - calculate Rules
      - test Ruleset
    - (Optional) write fluence, SNR vectors etc to disk
- Write out lookup table of exposure time estimates for all templates

Because in general a Ruleset gives only a binary result (success or failure), the iterative step is currently carried out using just a simple bisection algorithm. Future improvements to the 4FS_ETC will exploit more advanced root finding algorithms to reduce the number of iterations.

Performance of the 4FS_ETC: Exposure time estimation is expected to be one of the most computationally demanding tasks carried out by the 4FS. Therefore we have carried out various benchmarking tests to estimate the computational resources that will be required to carry out the necessary 4FS simulations in the permitted time. These tests were carried out on a system based around Intel Xeon 2.7GHz processors running 64bit Ubuntu 14.04.

We have used the current (early 2016) version of the 4FS_ETC to estimate required exposure times for a set of 100 arbitrary spectral templates, each folded through the system response of the 4MOST LRS, and a grid of 216 observational conditions (3x airmass, 3x IQ, 4x sky brightness, 3x tilt angle, and 2x fibre-to-target misalignment values), and with 10 brightness renormalization levels per template. The processing time (using a single CPU core) to estimate the minimum exposure needed to successfully observe each of these 100 templates under each observational condition and magnitude renormalisation was 40.3 minutes. This is equivalent to 24.2 s template^{-1} core^{-1}, or 0.011 s template^{-1} core^{-1} condition^{-1} mag^{-1}. Scaling with the number of templates is very close to linear. Therefore, the processing of e.g. 10000 templates would require $\sim$67 hours using a single CPU core, or equivalently, 4.2 hours by dividing the work over 16 CPU cores i.e. half the processing resource of a dedicated 64 core server. We have already identified and are working to implement further algorithmic improvements and optimisations that will significantly increase the computational efficiency of the 4FS_ETC.

3.2.4 4FS Operations Simulator (4FS_OpSim)

The 4FS_OpSim simulates the execution of a full 4MOST sky survey (nominally 5 years). The 4FS_OpSim takes as input a set of real or mock target catalogues, with required exposure times estimated for each target for a limited set of observing conditions. The 4FS_OpSim incorporates detailed models of the 4MOST facility, the observing conditions at Paranal, and various observational constraints. The 4FS_OpSim models the various survey strategy algorithms (sky tiling, OB scheduling, fibre assignment, progress monitoring) that will be used by the real 4MOST survey, and assesses the success of these strategies quantitatively by calculating numeric Figures of Merit (FoM) for each science survey.

An advanced prototype version of the 4FS_ETC tool is currently in use within the 4MOST consortium, with a large fraction of the functionality expected from the final tool. Future development tasks include making the 4FS_OpSim more modular, revising the internal model of operations closer to that envisioned for the real 4MOST survey, incorporating a more realistic model of observing environment, and optimising the computational efficiency of the tool.

The inputs to the 4FS_OpSim are many and varied; the inputs describe the 4MOST facility itself, the environment in which it operates, and the science surveys that it will perform. The inputs are supplied to the 4FS_OpSim through a set of parameter files, and include the following:

- An input target catalogue from each survey to be considered
- A unique target catalogue, including estimated exposure times
- A catalogue of valid locations for sky fibres
- A catalogue of flux calibration stars
- A parameterised description of the science survey FoMs
- A parameterised model of the 4MOST operating environment, including:
  - PDF of seeing (free air, zenith, V-band, FWHM, arcsec)
  - PDF of cloud cover distribution (by grade, including dome closed)
  - PDF of wind direction and speed
  - Note that it may be necessary to take account of the correlations between the weather distributions and their seasonal dependences
- Tabulated ephemerides for the VISTA site as a function of JD, including:
  - Sky coords of zenith, Sun, Moon, brightest planets
  - Moon phase
- A Parameterised description of the 4MOST observation sequence and overheads, including:
  - Field acquisition time
  - Time for CCD readout
  - Time for spine repositioning
  - Night-time calibration exposures
  - Slew speed, acceleration and settling speed Time for small dithers/offsets
- A parameterised model of the 4MOST focal surface, including:
  - home position, resolution mode, patrol radius, status flag, and relative throughput for each science spine
  - the mapping of spines to locations in spectrographs

  - a geometric description of the spine envelope (for the collision avoidance algorithm)
  - location and characteristics of each ancillary focal plane component (guide fibre, A&G camera, WFS)
  - focal surface-to-sky coordinate transformation parameters

- Rules for reserving fibres for non-science targets
  - Minimum number of fibres per tile to reserve for sky
  - Minimum number of fibres per tile to reserve for reference stars
  - Details of any other reserved fibres

- Tiling pattern
  - Coordinates of field centres and their position angles
  - Dithering strategy
  - Declination limits

- Observational constraints
  - Start of survey (JD)
  - Duration of survey (years)
  - Maximum airmass
  - Minimum zenith angle
  - Moon avoidance criteria
  - Any other bright object avoidance criteria
  - Wind constraints
  - Sun elevation defining start and end of a night
  - Predicted length and frequency of maintenance/technical downtime
  - Number and timing of nights reserved for non-survey operations (e.g. Chilean time)

- Survey strategy
  - Desired total exposure time per field
  - split by conditions (sky brightness, seeing, cloud, airmass)
  - Which targets to observe in which observing conditions
  - Strategy for multiple passes

- Fibre allocation strategy
  - Fibre-to-target assignment algorithm o Target priority rules
  - Bright neighbour avoidance criteria
  - to avoid placing bright stars next to faint galaxies on the spectrograph

- Scheduling strategy
  - Cadence+Phase at which OBs are submitted by the OpSys to the ESO database
  - Mean time for observed OBs to pass through the 4MOST Data Management System (DMS) pipelines
  - Parameters controlling relative priority of each OB
  - Scaling with summed target priority
  - Bonus for part-finished fields

– Bonus for hard-to-reach fields
– Bonus for contiguous fields
– Bonus for multi-pass fields

The main outputs of the 4FS_OpSim are simulated catalogues of observed targets, and numerical measures of survey success (FoM), from which the outcomes of the proposed survey can be estimated. The 4FS_OpSim also produces a large quantity of diagnostic output, in both graphical and tabular form, that can be used to understand the execution of the 4MOST survey, and to identify areas in which the survey strategy can be improved. For example, standard simulator products describe the balance between demand and supply of observing time as a function of Local Sidereal Time (LST), and the efficiency with which the fibres have been deployed to science targets. Figure 2 shows a selection of figures produced by the 4FS_OpSim.

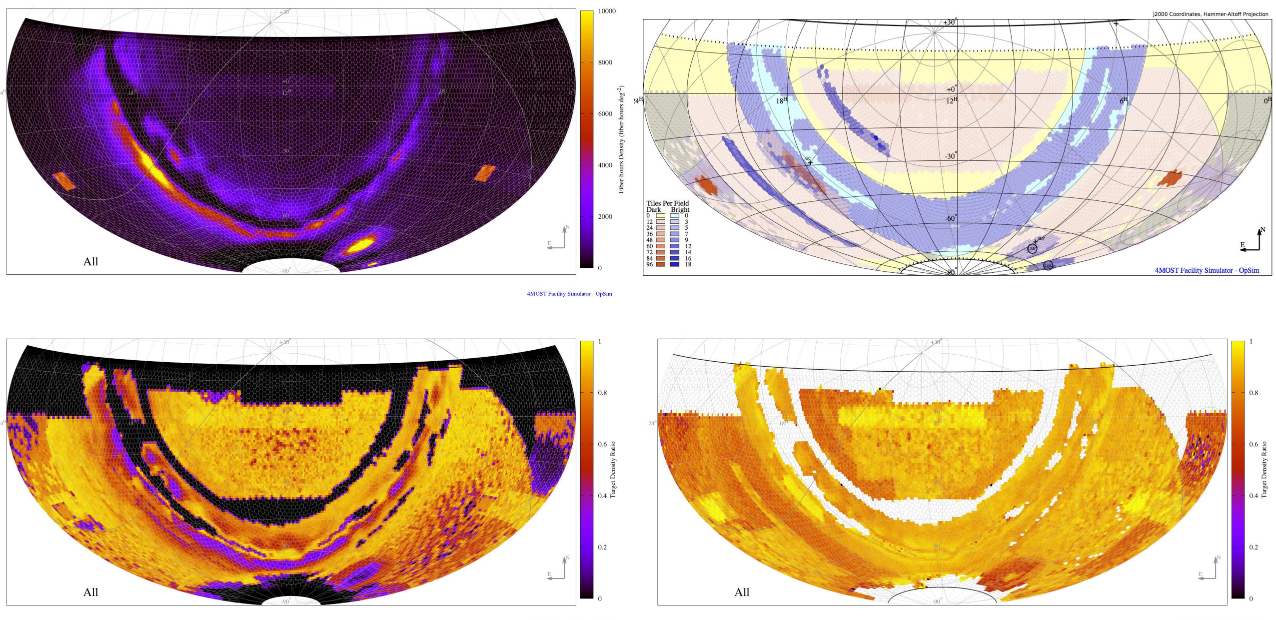

Figure 2. A selection of 4FS_OpSim outputs from a representative simulation run. *Top left panel:* Summed distribution of fibre-hours required by GTO targets over the 4MOST survey footprint. *Top right panel:* Delivered sky tiling at end of 5-year survey, darker areas indicate fields that have been observed to greater depth (blue=bright time; pink= dark/grey time). *Bottom left panel:* Fraction of input targets that have been assigned a fibre in at least one 4MOST tile. *Bottom right panel:* Fraction of observed targets that have reached their required exposure times.

4FS_OpSim Workflow: The 4FS_OpSim models the operations of 4MOST during an N-year (nominally 5-year) sky survey. It does this by stepping through the 4MOST survey night-by-night and OB-by-OB. The 4FS_OpSim models which of the input targets will be observed under which conditions, and models the quality of the collected spectra. The progress at a survey level is recorded by monitoring the numbers of successfully observed targets. The workflow of the 4FS_OpSim is described in Figure 3, and below:

- Read all input parameters and catalogues and calculate statistics from input catalogues
- Predict the visibility of fields over the N-year survey
- Plan an initial sky tiling that as closely as possible matches the requested observations, whilst fitting within the predicted time allocation
- Start the survey sequence:

  - Empty any unobserved OBs from the ESO OB queue
  - Prepare a batch of OBs sufficient for the forthcoming nights (number of nights set by input parameter)
    * Predict the visibility of fields over the coming weeks
    * Select fields and number of OBs per field according to scheduling strategy and visibility
    * Select subsets of targets as candidates for observation paying attention to any targets that have already been partially/fully observed
    * Build mock OBs, allocating fibres to targets, sky and calibration stars according to the chosen algorithm and rules defined in input parameters
  - Send mock OBs to an internal model of on-mountain operations, including a model of the ESO OB queue
    * The on-mountain operations model makes mock observations of OBs, paying attention to randomised sky conditions, sky visibility, observing constraints, downtime, OB priorities etc
    * The equivalent of the QC0 status of these observations is made available immediately
    * The equivalent to the spectral success metrics produced by the DMS L1 pipeline is made available for these OBs after a few days delay (controlled by input parameters)
  - After several nights of observations (set by input parameter), models update the OB status table and the target observational status tables with the available status information
  - Update the various metrics of survey progress and produces diagnostic output
  - Repeat sequence until end of the N-year survey
- At end of the simulated survey, collate all information and build summary products and write results to disk

Performance of the 4FS_OpSim: In order to investigate the performance of the 4FS_OpSim, and to examine how it scales with target multiplex, we have simulated the following scenario, (designed to meet the minimum complexity specified in the OpSys specifications). We generated mock target catalogues for 20 different survey projects, with each project containing somewhere between 1.4 and 71 million targets randomly distributed over the sky (Declination range $-75 <\text{Dec}< +25\,\text{deg}$). The total number of targets summed over the 20 projects is 524 million. We then carried out a number of simulation runs of the 4FS_OpSim with each run using a different subset of these 20 catalogues. Each simulation run models the operations of a 4MOST survey over either a 5 or 10 year period, taking into account the night-by-night scheduling, randomized weather, seasonal visibility constraint etc. We recorded the wall-clock time required to carry out each simulation. Figure 4 shows how the run time scales with the number of mock targets. We can see that the scaling is approximately linear for large catalogues. The wall-clock processing time required to simulate the largest 10-year survey was 4.7 hours. Note that in our prototype code (early 2016), the main process of the 4FS_OpSim is executed on a single CPU core.

3.2.5 4FS Reference Star Tool

The 4FS_RST is a software tool used to assess the availability of suitable reference stars to supply the guiding and wavefront sensing needs of 4MOST. The 4FS_RST is a software tool used by Survey Operators to assist in the planning of the layout of 4MOST fields on the sky. A prototype version of the 4FS_RST (early 2016) has already been used in engineering experiments to estimate the fraction of the sky that can be observed by 4MOST, given an approximate description of the focal surface components and a set of nominal reference star criteria. The current 4FS_RST software includes a simple strategy to reduce the number of fields failing the reference star criteria by exploiting the 6-fold (approximate) rotational symmetry of the science focal plane and the 2-fold rotational symmetry of the guiding and wavefront sensing components. The reference star catalogue is expected to be rather large, with many billions of entries. Therefore we utilise a spatial indexing scheme to accelerate the selection of small subsets of potential reference stars from the full catalogue. A prototype version of the 4FS_RST is currently (early 2016) in use within the 4MOST consortium, and has a large fraction of the functionality expected from the final tool. The prototype 4FS_RST is able to select reference stars for 10000 4MOST fields in <5 minutes, using a single core.

The 4FS_RST takes the following inputs:

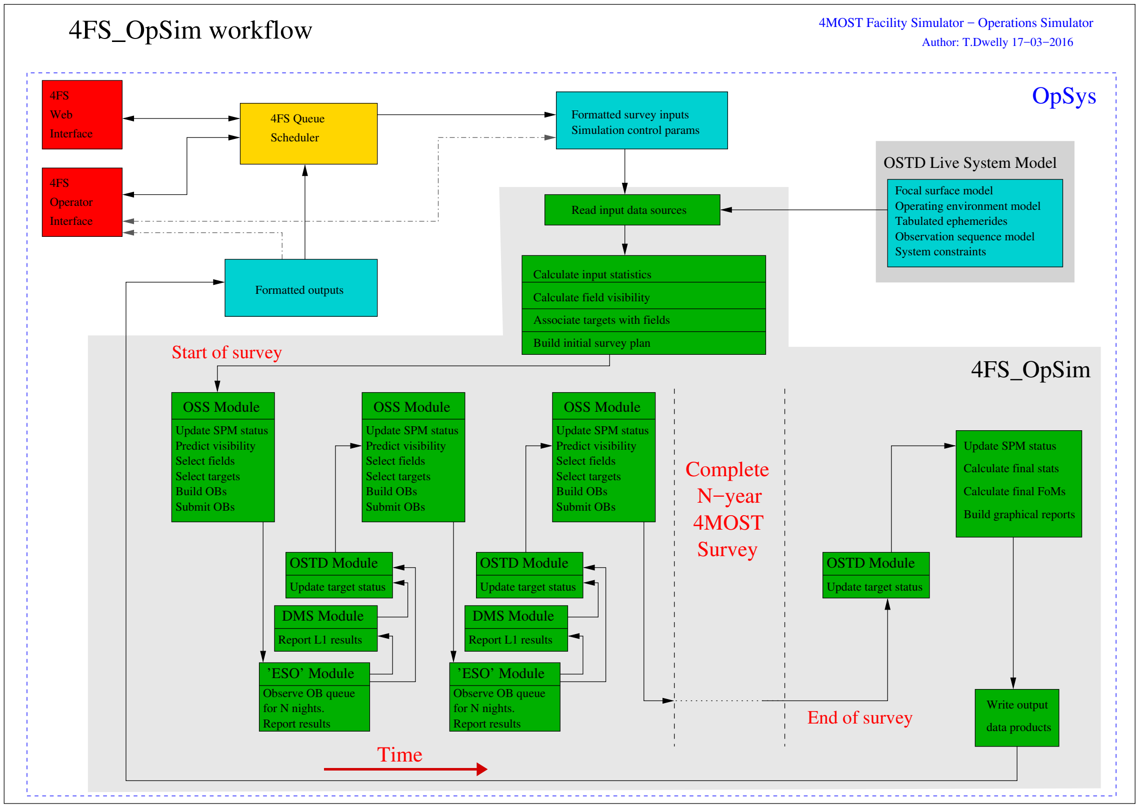

Figure 3. A schematic of the 4FS_OpSim workflow.

- A parameterised description of the 4MOST focal surface components
  - A&G cameras (coordinates of corners of active area)
  - LOWFS cameras (coordinates of corners of active area)
  - Guide spines (base position and patrol radius)
  - The magnitude limits (both faint and bright) for stars suitable for use within each focal surface component
  - The minimum number of stars in each type of focal surface component
  - Any further restrictions, e.g. the minimal distance between stellar pairs, the distribution of stars around the focal surface
  - The criteria that must be met for a field to be considered to have sufficient reference stars
- A processed catalogue of potential guide stars.
  - Current experiments use the USNO B1.0 catalogue,[8] but we expect to move to a Gaia-based catalogue after the first Gaia data release (c. Summer 2016)
  - The catalogue is filtered to remove flagged detections and resolved objects (mainly galaxies)
  - Magnitude estimates appropriate for the bandpass(es) of the focal surface components are estimated from the original catalogue native system
  - Each star is associated with a HEALPix pixel, and the catalogue is sorted in order of ascending HEALPix pixel index
  - A catalogue index file giving the first and last row in the catalogue for stars lying within each HEALPix pixel which allows the 4FS_RST to locate just the rows of interest in the catalogue

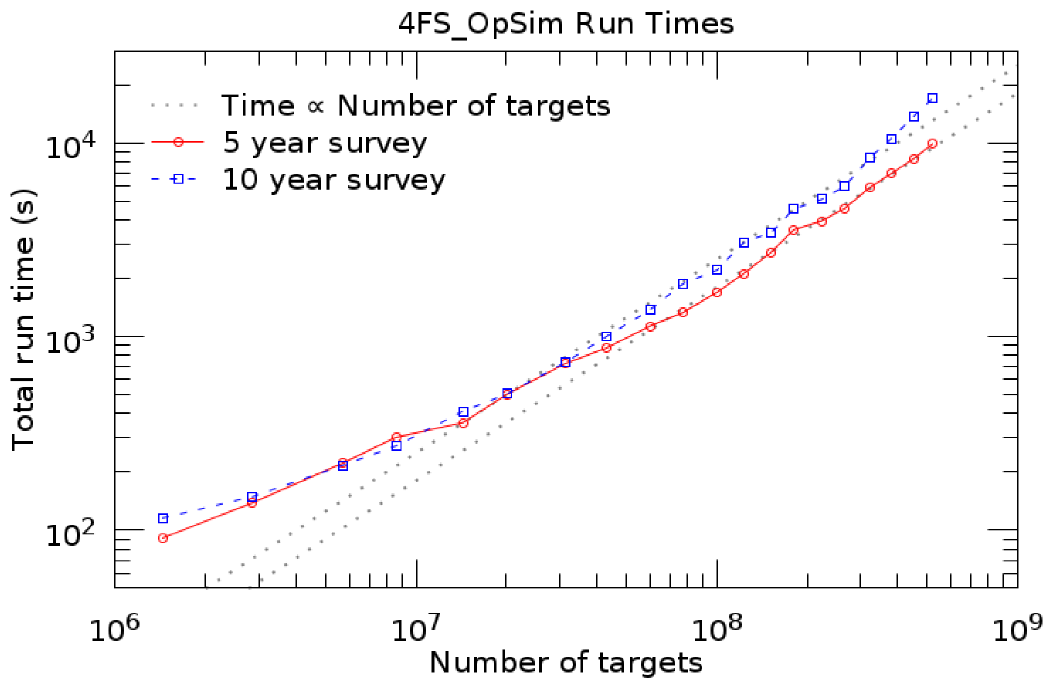

Figure 4. Illustration of the processing time required to complete simulations of 4MOST survey operations (using 4FS_OpSim) as a function of the number of targets. Each point in the figure shows the time taken to simulate a 4MOST survey with between 1 and 20 catalogues, with the total number of targets per simulation indicated. Simulations are carried out for survey durations of 5 and 10 years. A roughly linear trend is seen for simulations having >50 million targets.

- A list of fields (central coordinates and position angles) to be considered

The 4FS_RST produces an output file giving the results for each field (central coordinate + position angle) that was considered. For each surface plane element (A&G camera, LOWFS, guide spine) the 4FS_RST produces a ranked list of the five best stars that are accessible by that component. Summary information is supplied indicating whether or not 4MOST would have access to sufficient reference stars (meeting all of the specified criteria) if it were to observe at the location of each field. Additional columns indicate if and by how much the 4FS_RST had to rotate or translate the field in order to find sufficient reference stars.

The 4FS_RST works in a serial fashion, treating each field independently. For each field the 4FS_RST carries out the following steps:

- Transform the central position of each focal surface component from focal surface coordinate system into sky coordinates
- Calculate the list of HEALPix pixels that lie within a radius of the focal component centre that encompasses the full accessible area of that component
- Read in from the catalogue file all potential stars lying in HEALPix pixels having centres within an appropriate radius (using the catalogue index file to accelerate this process).
- Calculate positions of these stars in focal surface coordinate system
- Discard stars that fall outside the useable area of each focal surface component or that do not meet the minimum criteria for stars used by that component

- Build a ranked list of the best five stars for each component
- Determine if all criteria have been met for the field
- If criteria are not met, then rotate the field by 60 degrees (or 120 degrees) and repeat the above process

3.2.6 4FS Queue Scheduler (4FS_QS)

The 4FS_QS is used to manage a queue of incoming 4FS simulation requests, to farm out simulation jobs to the available compute resources, to return simulation results to users and to manage the available storage space. The 4FS_QS will be sufficiently robust to run autonomously without operator intervention for∼weeks at a time.

The 4FS_QS will receive simulation requests from the 4FS_WI and from Survey Operators. A survey request will consist of a package (e.g. tar file) containing a set of input parameter files that describe a single simulation run. The package will also contain a parameter file for the 4FS_QS itself, describing e.g. the user who initiated the request, the sequence in which the various 4FS tools should be run, the priority of the request and the destination for the output results package. When processing of a simulation run has completed successfully, the 4FS_QS collects the output products produced by each 4FS component, bundles these up into a tar file, and returns this file to the location specified in the simulation request.

The 4FS_QS operates on two levels. The top-level process manages the queue of simulation requests and attempts to balance the load across the available compute resources. New child processes will be spawned to shepherd each individual simulation request to completion. We expect that a simple load balancing scheme will be sufficient. A small number of simultaneous simulation requests will be permitted to run in parallel on each server, each with allocated CPU resources that avoid direct competition between runs. When the quota of simultaneous runs is filled then any further simulation requests will wait until one of the running simulation requests has completed.

Prioritisation will only take place when the job quota is filled. The 4FS_QS will determine which job should be added to the queue nest by ranking the pending simulation requests according to a numerical scheme based on e.g. length of wait, the recent use of resources by an each user, expected time to completion and estimated simulation size/length.

3.3 Survey Progress Monitoring (SPM)

The Survey Progress Monitoring (SPM) component is used to generate graphical and tabulated reports of the progress of the 4MOST survey.

3.3.1 SPM Status Updater tool (SPM_SU)

The live status of the 4MOST survey will be made available to the public via a set of web pages. It is the SPM_SU that builds the content of these web pages. The SPM_SU will produce products that contain at least the following information:

- Sky maps showing:
  - number of tiles observed per field to date, subdivided by dark/grey/bright moon time
  - density of observed fibre hours
- Figures showing the simulated vs predicted curves of:
  - cumulative unique sky area covered to date
  - cumulative fibre-hours observed
  - cumulative number of science targets observed/completed etc
- One set of figures will be presented for each distinct science survey, including:
  - The progress of the survey FoM as a function of time (vs prediction/goal)

- The fraction of science targets that have been successfully observed as a function of time (vs prediction/goal) and as a sky map
- The total number of fibre-hours expended on the survey as a function of time (vs prediction/goal) and as a sky map

The SPM tools will produce a fresh set of metrics, figures and reports each time (typically daily during normal operations) that the contents of the target database or the OB database are updated. Each new report will be marked with a time stamp and published to the SPM_RA (see below).

Note. A very similar set of progress reports to those described above is produced routinely by the current prototype (early 2016) 4FS_OpSim software, based on simulations of mock catalogues. The relevant parts of the 4FS_OpSim software will be updated where necessary and will be accessed from within a stand-alone tool that will produce progress reports from the real 4MOST survey data.

3.3.2 SPM Report Archive (SPM_RA)

The SPM_RA is simply the collection of all status reports that have been generated to date. The contents of the SPM_RA are served to the public via the SPM_WI. The status reports in the SPM_RA will be organised in a hierarchical chronologically organised directory structure.

3.3.3 SPM Web Interface (SPM_WI)

New reports produced by the SPM_SU and stored in the SPM_RA will be published by the SPM_WI immediately after they are produced. Visitors to the SPM web pages will first be presented with the current status, but will also be able to access an archive of earlier status pages. The physical location of the SPM_WI is not yet finalised, but would most likely be hosted by MPE, Garching.

3.4 Operations System Target Database OSTD

The Operations System Target Database (OSTD) subsystem is a structured collection of data, together with the tools and interfaces required to insert and update those data.

3.4.1 OSTD Live Target Database (OSTD_LTD)

The OSTD_LTD is the name for the structured collection of files with associated indices that will be used to hold information about all targets that have ever been considered for observation by 4MOST. The OSTD_LTD will be regularly updated with information about the current status of targets as they are observed at the telescope, using metrics of target success that are calculated per target by the 4MOST DMS level-1 pipeline. Unless otherwise stated, all files within the OSTD_LTD will be stored in FITS format, with the bulk of the information in binary table extensions. The files will be arranged in a hierarchical directory structure.

- The OSTD_LTD will contain the following file classes:
  - Input science target catalogues (INP_CAT)
  - Unique target catalogue (UNIQ_CAT)
  - Input spectral templates (INP_TEMPLATE)
  - Estimated exposure time lookup tables (TEXP_LUT)
  - Target observational status tables (OBS_CAT)

3.4.2 OSTD Target Submission Interface (OSTD_TSI)

This is a web interface that allows authorised science team members to upload and view the status of target catalogues, spectral templates and meta-data for ingestion into the OSTD_LTD. The OSTD_TSI will be hosted in the same location as the OSTD_LTD, most likely at MPE, Garching. Users will primarily access the OSTD_TSI in order to upload their input target catalogues, sets of template spectra, and associated meta-data (spectral success criteria, survey FoMs). Users will also be able to view basic information about files that they have previously uploaded, including flags to show if those files have passed format verification/validation checks. Users will be able to delete or flag for deletion old versions of files. A quota system will be enforced to prevent domination of the storage resources by individual users.

3.4.3 OSTD Target Database Updater Tool (OSTD_TDU)

The role of the OSTD_TDU is to update the target database with information derived from 4MOST observational data. The OSTD_TDU will normally run autonomously, typically daily, responding to new information collecting information from the DMS and the OSTD_OBDU. The OSTD_TDU can also be triggered manually by a Survey Operator. It will also be the job of the OSTD_TDU to generate/update the OSTD_LTD unique target table. In order to track the observational status of targets that are part of OBs that have been observed at the telescope but that have not yet fully passed through the DMS L1 pipeline, the OSTD_OBDU must take account of the most up to date listing of OBs retrieved from the ESO OB database.

3.4.4 OSTD OB Database Updater Tool (OSTD_OBDU)

The task of the OSTD_OBDU tool is to maintain an up-to-date listing of all 4MOST OBs that have ever been produced. This task included gathering status information that records which OBs have been observed at the telescope, and inserting the gathered information in the OB Status Table of the OSTD_LOBD. The OSTD_OBDU tool will normally run autonomously, periodically ($\sim$daily) checking the OSTD_LOBD, the ESO OB database and the 4MOST Operational Repository (4OR) for any new information, but can also be triggered manually by a Survey Operator. Note. The OSTD_OBDU tool must retrieve information from both the ESO OB database and the 4OR in order that it can identify the subset of OBs that have been observed at the telescope but that have not yet fully transited through the DMS L1 pipeline.

3.4.5 OSTD Live System Model (OSTD_LSM)

The OSTD_LSM is a structured collection of data files, parameters and documentation that together describes all aspects of the 4MOST system and its operating environment that are relevant to the Operations System. The OSTD_LSM includes methods to access these data in a structured way. The OSTD_LSM is somewhat akin to the HEASARC CALDB framework[‡] that is used to store the system description and calibration information for many high-energy missions. The various OpSys tools will retrieve information from the OSTD_LSM in a uniform way via calls to a shared library of routines. During the 4MOST Commissioning and Operations phases, the OSTD_LSM will be updated regularly with instrument health information collected and processed by the DMS, this job is done by the OSTD_SMU, see below. The information stored by the OSTD_LSM will be collected from a variety of sources (e.g. TOAD, DMS, 4MOST Instrument Scientist, ESO etc.). The scope of the OSTD_LSM will inevitably evolve as our knowledge of the 4MOST instrument and operating environment improves with experience. However, as a baseline, we expect the OSTD_LSM to include at least the following information:

- A description of the properties of each spectrograph arm:
  - a nominal throughput curve (that includes all effects apart from the atmosphere and the fibre coupling)
  - a nominal spectral resolution curve
  - a nominal wavelength solution (e.g. dispersion curve)
  - detector characteristics (read noise, dark current, gain etc)
  - spectral extraction parameters
  - scattered light description
- A lookup table of target-to-fibre coupling efficiency, giving the fraction of incoming light transmitted down the fibre, as a function of several parameters including:
  - wavelength
  - delivered IQ
  - fibre tilt angle
  - fibre-target misalignment o target profile

[‡]http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/

- Per-fibre performance information
  - relative throughput of each fibre
  - operational status of each fibre positioner (accuracy, speed, constraints etc)
- A model of the Paranal atmospheric environment (derived from the outputs of the ESO SkyCalc web tool) comprising:
  - A 2D grid of sky emission curves as a function of airmass and zenithal sky brightness
  - A 1D grid of sky transparency curves as a function of airmass
  - A model for the attenuation by various levels of cloud cover
- A parameterised description of the 4MOST focal plane including:
  - home position, resolution mode, patrol radius, status flag, and relative throughput for each science spine
  - mapping of spines to locations in spectrographs
  - geometric description of spine envelope (for collision avoidance algorithm)
  - location and characteristics of each ancillary focal plane component (guide fibre, A&G camera, WFS)
  - parameters describing focal surface → sky coordinate transformation
- A parameterised description of the 4MOST operating environment, including:
  - PDF of seeing (free air, zenith, V-band, FWHM, arcsec)
  - PDF of cloud cover distribution (by grade, including dome closed)
  - PDF of wind direction and speed
  - Note that it may be necessary to take account of the correlations between the weather distributions and their seasonal dependencies
- Tabulated ephemerides for the VISTA site as a function of JD, including:
  - Sky coordinates of the zenith, Sun, Moon, and brightest planets
  - Moon phase
  - Can be generated by reprocessing the output of John Thorstensens skycalc software, or the python module pyephem[§].
- A parameterised description of the 4MOST observation sequence and overheads, including:
  - Field acquisition time
  - Time for CCD readout
  - Time for spine repositioning
  - Night-time calibration exposures
  - Slew speed, acceleration and settling speed o Time for small dithers/offsets

3.4.6 OSTD System Model Updater Tool (OSTD_SMU)

The OSTD_SMU is a tool that collects live system health information from the DMS 4OR, reformats this information, and stores it within the OSTD_LSM. The OSTD_SMU will run in an autonomous way, polling the DMS 4OR for updates on a daily basis, retrieving and processing any new information as it is made available.

[§]https://pypi.python.org/pypi/pyephem/

4. SUMMARY

In this paper we have presented the preliminary design of the 4MOST Operations System. The next phase of work will be to refine the details of the OpSys design, including development and prototyping of the algorithms that will allow the smooth running of 4MOST observations with high efficiency.

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