From space to specs: requirements for 4MOST

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ABSTRACT

4MOST,[1] the 4m Multi-Object spectrographic Survey Telescope, is an upcoming optical, fiber-fed, MOS facility for the VISTA telescope at ESO's Cero Paranal Observatory (Chile). The preliminary design of 4MOST features 2,400 fibers split into a low-resolution (1,600 fibers, 390-900 nm, $R > 5,000$) and a high-resolution channel (800 fibers, three arms, ∼20-25 nm coverage each, $R > 18,000$) with an Echidna-style positioner, and covering a hexagonal field of view of ∼4.1 sqdeg. 4MOST's main science goals encompass massive (tens of millions of spectra), all-Southern sky ($> 18,000$ sqdeg) surveys following up both the Gaia (optical) and eROSITA (X-ray) space missions, plus cosmological science that complements missions such as e.g. Euclid. In a novel approach, observations of these science cases, which are very different from another, are to be carried out in parallel (i.e., simultaneously); thus, from the very different science requirements, key user requirements have to be identified, stringently formulated, and condensed into a coherent set of system specifications. Clearly, identifying common grounds and thereby significantly reducing complexity in both the formulated requirements and the final 4MOST facility, is a very challenging task. In this paper, we will present science and user requirements, and how the latter flow down from the former, and eventually further down to the system-specification level. Special emphasis will be put on the identification of key requirements and their validation and verification protocols, so that significant trade-offs can be done as early on in the design phase as possible, with as little impact as possible on the science capabilities upstream.

Keywords: Requirements engineering, requirements management, 4MOST, VISTA, ESO

1. INTRODUCTION

The 4m Multi-Object spectrographic Survey Telescope (4MOST) is a wide-field, high-multiplex, multi-fiber spectroscopic survey facility under development for the VISTA (Visible and Infrared Survey Telescope for Astronomy) telescope of the European Southern Observatory (ESO). Its main science drivers are in the fields of Galactic archaeology, high-energy physics, galaxy evolution, and cosmology. In particular, 4MOST will provide the spectroscopic complements to the large-area surveys coming from space missions such as Gaia, eROSITA and Euclid, and from ground-based facilities such as VISTA, the VLT Survey Telescope (VST), the Dark Energy Survey (DES), the Large Synoptic Survey Telescope (LSST), and the Square-Kilometer Array (SKA). 4MOST features a field of view of 2.5 degrees diameter with ∼2,400 fibers in the focal plane that are configured by an Echidna-style fabre positioner based on the tilting-spine principle. The fibers feed two types of spectrographs: ∼1,600 fibers go to two low-resolution spectrographs (LRS) with a resolving power of $R > 5,000$, and ∼800 fibers to a high-resolution spectrograph (HRS) with $R > 18,000$. Both types of spectrographs are fixed-configuration, three-channel spectrographs. 4MOST will have a unique operations concept in which 5-year, public surveys from both the 4MOST consortium and the ESO community will be combined and observed in parallel during each

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exposure, resulting in more than 25 million spectra of targets spread over a large fraction of the Southern sky ($> 18,000$ square degrees).

In the following, we will discuss how and which science and user requirements have been derived for 4MOST.

2. REQUIREMENTS: STRUCTURE, FLOW-DOWN, AND MANAGEMENT

The flow-down of requirements from the top-level science objectives ("problems in modern astrophysics") to the system level and beyond are shown in Figure 1. Translation of requirements between the different requirement levels are done by *Justification Files*, which, in their most general form, provide justification as to why meeting a requirement at a lower level will actually make it possible to meet a requirement at the next-higher level.

Such a flow-down of requirements combined with the flow-up of justification follows the approach of virtually any telescope observation proposal: from the "big picture" the scientist will reduce the problem to a specific type of observation(s), that are then further described in the "technical justification" part of such a proposal. Hence, the general principle is not unknown to the scientists who have to formulate science requirements.

The major difference here is that, of course, the question is not "what science can be done with a given instrument?", but rather "what instrument is required to do the science?". Simplu because of their work experience, scientists tend to think along the lines of the former question rather than the latter. This inherent difference in the way of thinking is an important source of complexity in the communication between scientists and engineers.

In turn, engineers might be tempted to "close the case" too early, i.e. to settle prematurely on an instrument design, either to avoid long and cumbersome iterations with the science-use side, or because pre-conceived and/or implicit assumptions on the "true needs" of the scientists exist. This form of (explicit or implicit) second-guessing is also an important source of misunderstanding and discontent.

In the 4MOST project, next to the general challenges in establishing coherent and clear requirements, additional complexity arises from the fact that the needs or seven, greatly different science cases (and thus, science-user groups) need to be accommodated by the 4MOST Facility. To facilitate the science and science-requirements management, the 4MOST project has introduced an interface between the *Project Science*, who is in charge of generating and maintaining the scienc cases and the corresponding science requirements, and *Systems Engineering*, whose task is, among other, the management of all low-level (systems level and below) requirements. This interface layer is called *Instrument Science*.

2.1 Design Reference Surveys

To establish a list of top-level requirements, we have adopted the concept of *Design Reference Surveys (DRS)*. As the name implies, these DRS are used to span the requirements (i.e., design-parameter) space of the 4MOST facility. DRS do this either individually, in the sense that one DRS might push one design parameter in particular more than any other DRS, or in combination, i.e. 4MOST needs to be able to execute them all successfully, where success is defined and verified in a certain way (also see Section 4). From the onset 4MOST has been conceived as a survey facility that is able to execute the different surveys (DRS plus additional science) in *parallel*, to maximize 4MOST's information-gathering capability through improved on-field fiber usage.

Thus, the DRS play a pivotal role in the entire 4MOST endeavor. They are very detailed and carefully designed, high-profile science cases that will become the 4MOST Key Science Surveys (KSS), and are expected to be produce highly competitive science in 2025 and beyond. Even though the DRS will be carried out by the 4MOST consortium as return for the constrcution and operation of the 4MOST facility, these DRS are fully public surveys whose raw data and high-level science products will be made available to the community though the ESO archive.

For the Conceptual Design Phase, the 4MOST consortium identified the following seven* DRSs as main design drivers:

1. Gaia follow-up of the Galactic Disk and Bulge (low-resolution, LR);

*After writing of this manuscript, another, extra-galactic DRS has been defined.

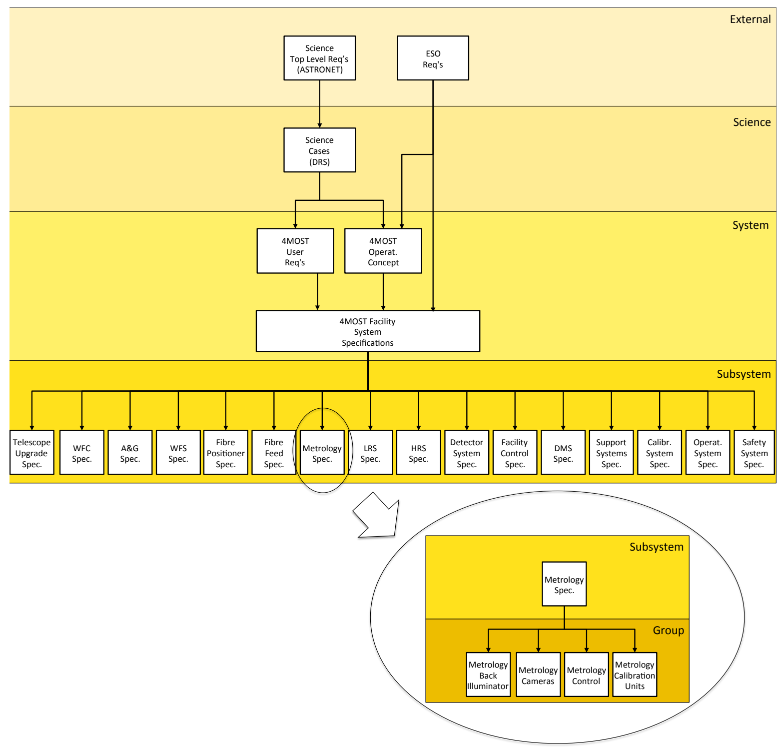

Figure 1. Structure[2] and flow-down of 4MOST requirements, from the top-level to the system level. Justification Files are used to flow-down requirements from one level to the subsequent level.

2. Gaia complement of the Galactic Disk and Bulge (high-resolution, HR);
3. Gaia follow-up Galactic Halo (LR);
4. Gaia complement of the Galactic Halo (HR);
5. eROSITA follow-up of X-ray selected active galactic nuclei (LR);
6. eROSITA follow-up of X-ray selected galaxy clusters (LR);
7. Euclid complement: A general galaxy redshift survey (LR)

While the Galactic DRSs constitute follow-up and complementary observations of the ESA-Gaia mission, two of the extra-galactic DRSs do so for the eROSITA (X-ray) and Euclid (galaxy redshift) space missions. Furthermore, all extra-galactic plus the Galactic Halo surveys observe fields off the Galactic plane ($|l| > 15°$).

2.2 Top-level and science requirements

Both the 4MOST Facility itself and the 4MOST DRS are a direct reaction to the Astronet Infrastructure Road Map,[3] and the strategic science questions laid out therein. Additional science drivers follow from the space missions that 4MOST is will follow-up and complement (mainly Gaia and eROSITA). In terms of requirements structure, the *top-level science objectives and requirements* of the respective DRS, i.e. their classical science rationale, are hence deeply rooted in the pressing questions of modern astrophysics.

So far, the different DRS have been regarded and treated as independent surveys. However, it is possible, and in some cases even naturally follows from the nature of the science, that DRS complement each other. An example are the two low-resolution Galactic surveys that will cover the Halo, the Disk, and the Bulge of the

Milky Way, and thus obtain a picture of the Galaxy that (in conjunction with the Gaia data) is as complete as possible.

While this has already been considered during the Conceptual Design Phase of 4MOST, the potential for synergy between the DRS will be looked into in more detail in more advanced project phases. Once both the hardware design solutions and the operation concept are more advanced, a more detailed forecast of 4MOST's science return can be made (also see Section4).

The DRS are managed by the 4MOST Science Working Group, that is chaired by the two 4MOST Project Scientists, one an expert in Galactic (Gaia-related) science, one an expert in extragalactic science. Each DRS is considered as a Science Work Package, and taken care of by a team of scientists who are member of the 4MOST consortium institutes. For each DRS, the respective science teams derive, from the top-level science objectives, the *4MOST Science Requirements*. That is, they determine how and by which kind of observations the science objectives of the DRS are best achieved.

This flow-down of the science requirements (and flow-up of validation and justification) is done with the help of science-grade, state-of-the-art simulations, which means that very complex input physics is taken into account and simulated observations are carried out and analyzed just as if real data were used. With this approach the science requirements are thoroughly linked to the top-level science objectives and it is verified that meeting the former actually will make it possible to achieve the latter.

Moreover, two extremely important outputs of these simulation efforts are obtained: *i*) highly realistic, mock data catalogs containing millions of targets with their position, target (spectral) type, template spectrum, scaled to (appropriately reddened) magnitude, radial-velocity (or, in the case of extragalactic objects, redshift) information, etc; *ii*) an overall figure of merit (FoM) for the respective DRS that encodes all relevant, top-level science objectives such as, e.g. total area, magnitude range, completeness criteria, etc. These two ingredients are pivotal for validating the scientific performance of the 4MOST facility with the so-called *4MOST Facility Simulator*; the simulator and the validation process will be described in somewhat more detail in Section 4.

Each set of science requirement (one set per DRS) is then flown-down to the next-lower, user level, and, after potentially conflicting requirements have been taken care of, merged into a single set of coherent user requirements (see next section).

2.3 Systems-level requirements

In the following we will describe three sets of requirements. Although all of them reside at the same level, there is a hierarchy to them that determines how and which requirements flow-down from one to the other.

2.3.1 4MOST User Requirements

Due to the fact that in 4MOST, seven greatly different and, thus, potentially conflicting science cases need to be accommodated, the flow-down of science requirements directly to the systems level is complex and thus very much prone to errors. To more readily consolidate the requirements, and thus to facilitate the translation of science requirements into engineer-readable systems requirements, we have chosen to introduce an additional step in the derivation of requirements, the *4MOST User Requirements*.

In the past, the borderline between science and user requirements has been left somewhat fuzzy. We are working towards a clear separation between (more) science-related or a (more) hardware-related requirements. As indication, we use the fact that science requirements are formulated in "science speak", whereas user requirements are more equivalent to requirements that describe or assure a certain data quality (also see Section below).

2.3.2 4MOST Operations Concept

There are additional requirements that feed into the systems level, even though the do not flow down from the science. Operations is such a source of systems requirements. The 4MOST Facility will be operated by the 4MOST consortium, within existing ESO standards of operations (for both hardware and software) and under legally binding service-level agreements between ESO and the 4MOST consortium. The *4MOST Operations Concept* describes how this will happen, from which follow the operations requirements that state how the 4MOST Facility is to be used to achieve the top-level science goals.

A significant amount of software packages need to be developed, e.g. quick-look and quality-control tools, data-reduction and data-analysis pipelines, data archives for low-level (raw and reduced) and high-level (analyzed, meta) data products, etc.. Just as for any other subsystem, requirements for these software packages flow down from the systems level, but existing ESO standards (operations of hardware and software) have to be observed.

2.3.3 4MOST Facility Systems Requirements Specification

The 4MOST Facility Systems Requirements Specification defines the product to be developed, states the requirements the designed facility must fulfill, and specifies the main requirements the subsystems must comply with. The facility systems requirements are derived from the user requirements, the operations concept, and additionally from any applicable ESO (ie., external) requirements.

3. REQUIREMENTS FLOW-DOWN IN 4MOST: AN EXAMPLE

To illustrate how the requirements structure described above works in practice, we will give an example for the flow-down of a top-level science requirement (TLR) to the science requirements (SCI), user requirements (USR), and, finally, the systems requirements (SYS).

We chose an example for the low-resolution channel of 4MOST. Please note that all requirements and quantities are preliminary values only, and do not necessarily apply to the final 4MOST design.

REQ-TLR-001: *Models of the formation of the Milky Way and its evolution shall be constrained.*

To achieve this science objective, scientists need to construct a sufficiently accurate, chemo-dynamical map of a sufficiently large area of the Milky Way, covering the Disk, Bulge, and Halo of the Galaxy. This means, six-dimensional phase-space information (position, velocity) plus chemical abundances of useful elements (let's call them element A, B, and C) for a sufficiently large number of Galactic stars need to be obtained.

While the position and proper motion will be obtained with Gaia, the radial-velocity (RV) component and the chemistry need to be obtained through follow-up spectroscopy. Ignoring for a moment that for the Disk/Bulge and Halo, individual DRS have been defined (see above), we can already see what the science requirements will look like: spectral features of the elements A, B, and C need to be covered so that their abundances can be derived by measuring equivalent widths; additionally, RVs needs to be measured from the stellar spectra. Both needs to be done with a certain accuracy, for a certain number of stars, and within a meaningful volume of the Milky Way.

Ignoring the former two requirements for the sake of brevity, from the above top-level science objective follow the science requirements:

REQ-SCI-001: *Useful spectral features of elements A, B, and C shall be covered.*

REQ-SCI-002: *Equivalent widths of said spectral features shall be measured with an accuracy better than 0.2 dex individually.*

REQ-SCI-003: *Stellar RVs shall be measured with an accuracy better than 2 kms^{-1}.*

These science requirements are validated by the science teams through highly realistic, "simulated observations of simulations"; that is, it is shown that is these science requirements are met, the top-level science objectives can be tackled successfully.

Now comes the translation of these requirements into user requirements; essentially, we need to answer the question: "Which data quality is required to carry out the proposed science (i.e., to meet the science requirements)?". Again, sophisticated simulations that are equivalent to the scientific analysis of real data are carried out.

From REQ-SCI-001, scientists have constructed line-lists that contain a maximum of the strongest and least blended features of the respective elements. Combining the line-lists for each strategic element into one master line list, and considering the expected radial-velocity regime that governs most stars in the Milky Way stars, makes it possible to define the required wavelength coverage (i.e., $\lambda_{\rm start}$ and $\lambda_{\rm end}$) of the spectra. By attributing weights to the different lines, i.e. taking into account their relative scientific value, scientists have constructed a merit function to quickly assess the relative value of a proposed design's wavelength coverage.

From REQ-SCI-002 follows a requirement on spectral resolving power R, sampling s, and the signal-to-noise ratio (SNR) *or a combination of these three requirements.*

REQ-SCI-003 will also drive wavelength coverage (as a function of the target's spectral type), resolution and SNR and, to a lesser degree, sampling.

Thus we have:

REQ-USR-001: *The spectral coverage shall be from 420 to 540 nm and from 640 to 770 nm.*

REQ-USR-002: *The spectral resolving power shall be* $R = \lambda/d\lambda \geq 5,000$ *everywhere, where* $d\lambda$ *is the resolution element, defined as the full-width at half maximum (FWHM) of an unresolved comparison-arc (or sky) line.*

REQ-USR-003: *The spectral sampling shall be* $2.0 \leq s \leq 3.0$ *everywhere, where* s *the number of CCD pixels covering a resolution element as defined above.*

REQ-USR-004: *Everywhere in the covered spectral range, the effective signal-to-noise ratio shall be SNR*≥ 100 *per Angstrom.*

We here note that tacitly implying an analysis method can introduce a dependence on that method that can be very strong, and even drive requirements to levels that could be relaxed if only another method was applied. Also, one must be very careful that the employed methods are robust, applied well within their validity limits, and fully understood to avoid suffering from "hidden assumptions".

For instance, REQ-SCI-002 implies that the method to derive abundances, is to measure equivalent widths; in late-type stars, this is done by fitting Gaussians to absorption lines. This fitting method pretty much determines the required data quality in terms of spectral resolving power, sampling, and signal-to-noise ratio per Angstrom, because the fit needs to converge and produce meaningful results.

On the other hand, the method implied by REQ-SCI-003, viz. cross-correlation of a broad wavelength band, is much more robust against resolution, sampling, and SNR than fitting a single line. Hence, REQ-SCI-003 cannot be used to meaningfully constrain these requirements.

Testing with fits of un-blended lines yielded that in the case of under-resolved lines (as is the case with the 4MOST science targets), resolving power and SNR can be traded against each other. In principle, thus, it would seem that hardware costs can be traded against operations costs (exposure times). However, in late-type stars the equivalent-width measurements are severely affected by blending of lines. Blending not only renders more difficult the proper fit of a line, but also does it strongly affect the quality of the continuum placement. If lines blend too much, the result will be a pseudo-continuum and deviation from the true continuum thus becomes an error source in the measurement of a line's equivalent width. Moreover, the derivation of stellar effective temperature and surface gravity equally requires a minimum resolution, otherwise the stellar parameters become so uncertain that their errors dominate the abundance measurements.

Thus, test need to be appropriate and very realistic to explore the parameter space that is given by resolving power, sampling, and SNR; this leads to exponentially complex modeling approaches and, thus, time that needs to be spent in the requirements analysis. While opting for very conservative methods (i.e., ignoring the probable methodological improvements between now and, say, 2025 when the full data will be available) makes sure that required science results can be obtained no matter what, it can lead to over-designed (and thus, very costly) requirements. Unfortunately, defining merit functions to carefully balance the solution might not always be possible at a reasonable cost, either.

Resuming the flow-down of requirements, we now have to establish the systems requirements that follow from the user requirements. While in the case of spectral coverage, resolving power, and sampling this is straightforward, the SNR is more difficult. In a noisy system, the photon (Poisson) limit can only be reached asymptotically. Hence, either the contribution of noise sources need to be decreased by reasonable effort, or throughput and/or exposure time need to be increased until photon noise becomes the (by far) dominating noise term.

Thus, once more, we here deal with a complex interplay between requirements at different levels and from different sources:

- science requirements, namely the faintest target magnitude that is attached to REQ-SCI-002;
- user requirements, namely the minimum SNR per Angstrom (REQ-USR-004),
- operations requirements, e.g. the exposure time that must not exceeded to keep in check both differential-refraction effects and cosmic-ray hits, or observing policies (observations at dark instead of bright time);
- the noise contribution from the respective subsystems that can not or not sensibly be reduced, most notably the detector read-noise and dark current;
- on-detector cross-talk, and how it translates into the final, extracted data;

The complexity is further illustrated by one of the items in above list: on-detector cross-talk itself. Cross-talk occurs in whenever spectra of differently bright objects are projected onto the same detector. In the presence of optical aberrations and/or scattered light from surface imperfections –as is always the case–, the spatial intensity distribution of these spectra will display more or less pronounced wings. Thus, if spectra are too tightly packed onto the detector, cross-contamination of flux is the result.

Even if the employed data-reduction methods are advanced enough to fully subtract the (coherent) flux contribution of a neighboring spectrum, its (incoherent, stochastic) noise contribution cannot be removed. As a consequence the SNR of the extracted spectra deteriorates as a function of separation of the spectra, their spatial profile, and the flux ratio (magnitude difference) between the sources.

Moreover, the (supposedly perfect) data-extraction algorithms might require a minimum data quality to work properly; we hence have the case where requirements from a subsystem (here: the data-extraction module) flow up to higher levels, e.g. the operations concept (target-allocation policy) and even to science requirements (dynamic range of targets in the target catalogs).

At the time of writing, the 4MOST project is in a Concept Optimization phase with the aim to reduce costs of the spectrographs in particular. Different re-designs and design iterations have been obtained. However, in view of the intricate issues outlined above, not yet all key requirements have been established firmly enough to allow a proper flow-down, and a down-selection of existing design alternatives.

4. THE 4MOST FACILITY SIMULATOR

We have briefly sketched the requirements structure in 4MOST; justification works down-stream, validation works up-stream. However, these iteration (or feedback) loops work *locally* between two successive levels or even sideways within a level.

For *global* feedback, i.e. verification of whether the proposed design solution satifies the top-level science requirements, we have implemented the *4MOST Facility Simulator (4FS)*[5] (see Figure 2). The 4FS works with the mock target catalogs and the template spectra that were created through simulations for each DRS (see Section 2.2). In total, we have ∼50 million mock targets, both Galactic and extra-galactic, with some 4000 template spectra for good (if somewhat coarse) representation of the real targets.

The 4FS is a complex software code that consists of the following modules: *i*) a *throughput simulator (TPS)*, *ii*) a *data-quality control tool (DQCT)*, and *iii*) an *operations simulators (OpSim)*. The TPS takes the template spectra, which are appropriately reddened, velocity- or redshifted, and scaled to apparent magnitudes, and propagates them through a system-throughput model to generate noised spectra. These are then analyzed by the DQCT that determines the exposure-time requirements for each template spectrum.

The OpSim module tiles the sky into hexagonal fields with a wanted overlap, and allocates the targets to fibers. It takes into account the focal-plane properties (positioner fiber tilt, field of view size and shape), the seasonal target visibility, lunation, meteorological conditions on Paranal (randomized seeing, cloud cover, wind speed and -direction), and unscheduled and scheduled instrument downtime, and many more operational parameters.

Each DRS comes with an overall, DRS-related figure of merit that encodes the high-level science requirements (e.g., number of observed targets, covered area, completeness per field, etc.) to quantitatively assess 4MOST's

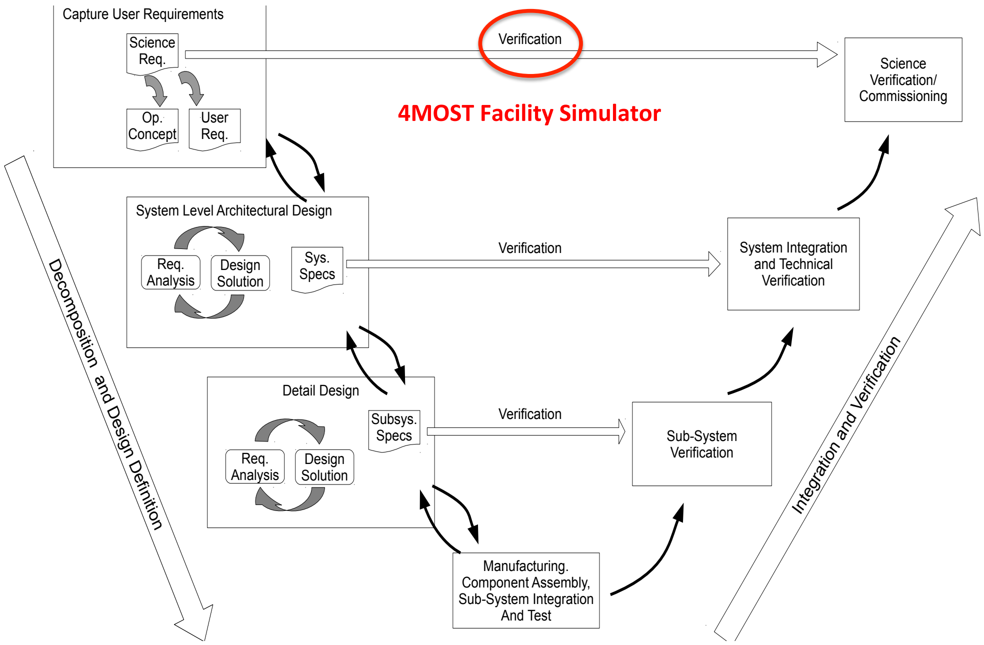

Figure 2. The vee model[4] that described how the top-level science requirements are verified, ultimately, by the operational instrument. During the design phases, 4MOST will employ the 4MOST Facility Simulator that incorporates highly realistic mock catalogs and design descriptions. For details, see text.

performance in a combined (i.e. all DRS executed in parallel), 5-year survey. During the Conceptual Design Phase, the 4FS and these figures of merit were used to compare different focal-plane properties, e.g. to trade-off positioner designs and the VISTA and the NTT telescopes with their different field of views. It was also used to verify that the proposed baseline facility indeed delivers the required science performance.

Due to the global nature of the 4FS simulations, instrumental properties other than those of the focal plane are not addressed. Any optimizations of the observing strategies and policies were not carried out during the Concept Design phase; both actions are intended in future project phases once the requirements have been stabilized.

5. SUMMARY AND OUTLOOK

In this paper, we have briefly presented the requirements structure and flow-down within the 4MOST project. When the 4MOST Facility becomes operational in 2019, it is to carry out, simultaneously and over a period of 5 years, seven greatly different key science surveys that accommodate both Galactic and extra-galactic science. To define the requirements, seven Design Reference Surveys (DRS) have been established that will eventually evolve into the key science surveys.

Hence, these DRS have very high-profile, top-level science cases. With the help of science-grade simulations, the flow-down of science requirements and the flow-up of validation and justification has been established. An outcome of these simulations are highly realistic mock catalogs with millions of targets defined by position and flux information. These mock catalogs are have been used as input of the 4MOST Facility Simulator (4FS). With its highly realistic simulations, the 4FS provides a forecast of the scientific performance of the 4MOST facility, and hence a global validation and verification loop.

We have also presented an example of how requirements are validated on a more local level, and demonstrated the inherent complexity of the validation process already at the science and user (systems) level. We are currently making great efforts (and progress) to establish independent (orthogonal), coherent, and stable requirements. The next steps will be to establish a validation and justification process for the requirements below the systems level, in preparation of the manufacturing, assembly, integration, and verification (MAIV) phase.

5.1 Acknowledgments

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