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Systems budgets architecture and development for the Maunakea Spectroscopic Explorer

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ABSTRACT

The Maunakea Spectroscopic Explorer (MSE) project is an enterprise to upgrade the existing Canada-France-Hawaii observatory into a spectroscopic facility based on a 10 meter-class telescope. As such, the project relies on engineering requirements not limited only to its instruments (the low, medium and high resolution spectrographs) but for the whole observatory. The science requirements, the operations concept, the project management and the applicable regulations are the basis from which these requirements are initially derived, yet they do not form hierarchies as each may serve several purposes, that is, pertain to several budgets. Completeness and consistency are hence the main systems engineering challenges for such a large project as MSE. Special attention is devoted to ensuring the traceability of requirements via parametric models, derivation documents, simulations, and finally maintaining KAOS diagrams and a database under IBM Rational DOORS® linking them together. This paper will present how the main budgets under development are organised, expand to highlight a case involving several interrelated issues and the tools used to analyse and model how they affect performance and how optimisation can be carried out.

Keywords: systems engineering, KAOS, requirements engineering, multi-object spectroscopy, fibre-fed spectroscopy, Maunakea Spectroscopic Explorer, Canada-France-Hawaii Telescope

1. INTRODUCTION

Requirements engineering at the beginning of any project has some semblance with the chicken or the egg causality dilemma: how can one define what the system should achieve without any definition of what the system is? Conversely, defining the system requires knowing what it should achieve. Two categories of contributions contribute to solving this difficulty: the stakeholders' abstract expression of what they want and general constraints which apply to the project and system. In astronomy, the former is a statement relative to the final scientific products – abstract in the sense of their being irrespective of how they will be attained – and the latter comprises regulations, project management and compatibility with existing interfaces, if any.

MSE[1] is an endeavour to upgrade the 3.6-meter telescope and instrumentation of the Canada-France-Hawaii Telescope (CFHT) into a 10-meter class telescope equipped with fibre-fed spectrographs dedicated to optical and near-infrared (NIR) spectroscopic surveys. The desire to make it a spectroscopic facility, which is as broad a description of the system as can be formulated, stems from the science cases which have been developed by the scientific community involved in the project. These involve complementing existing and up-coming imaging surveys (Gaia, Euclid) and pushing the limits of spectroscopy beyond what is currently attainable or will be in the near future (4MOST,[2] MOONS[3]). These objectives are further refined as the science cases are condensed into scientific requirements summarising the top level observational capabilities of MSE.[4]

Upgrading CFHT differs from projects focusing on the development of new instruments fitting in an existing framework since the telescope is at the core of the observatory. MSE, hence, not only involves replacing the telescope but also developing its entire suite of instruments – namely spectrographs – as well as upgrading the

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observatory as a whole, from the enclosure to match the increased telescope aperture to the structure of the building due to a new distribution of mass and the organisation of the floors based on different use. Accordingly, while regulations and project management directives, such as cost and time-to-first-light for instance, are well defined, MSE has few external interfaces to which it must conform (e.g. the need to reuse the existing inner pier and limits to the possible upgrades to the outer pier) while the scope of the requirements encompasses the complete facility.

Section 2 describes the principles underlying our systems engineering methodology and its application during conceptual design with emphasis on how the constantly evolving system is managed. Section 3 explains how budgets are developed and provides an overview of part of the resulting budget architecture. We then expand on how the facility's sensitivity is optimised in section 4 before concluding on the nature of existing requirements and how they are expected to evolve as MSE get into the preliminary design phase.

2. METHODOLOGY

2.1 Founding principles

MSE's system's engineering follows TMT's approach[5] as concerns its structuring and, as a consequence, the organisation of the documentation (see Fig. 1). The project's response to the scientific requirements (SRD)(level 0 requirements) is described in the Observatory Architecture Document (OAD), which describes the subsystems composing MSE and establishes system budgets, and the Operations Concept Document (OCD), themselves leading to the Observatory Requirements Document (ORD). The three documents contain level 1 requirements. The ORD is then the reference to which all subsystems must adhere, i.e. their own set of level 2 requirements are driven by the observatory requirements.

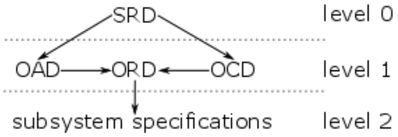

Figure 1. Organisation of the requirements documentation and associated levels indicating precedence.

In terms of requirements engineering, we follow Lamsweerde's model-based objectives-oriented requirement engineering methodology.[6] Although initially developed for software, their approach defines precise and detailed semantics for requirements flow-down far superior to what SysML proposes.[7] Without being exhaustive, KAOS[8] (which stands for Keep All Objectives Satisfied) relies on graphical representations linking objectives[*], requirements, obstacles and agents (Fig. 2). These illustrate the oriented graphs (in the mathematical sense) which establish how objectives will be fulfilled when read top-down or why each each requirement or agent is present when read bottom-up. Used to its full extent the methodology allows for establishing formal proofs that the flow down is complete and that the objectives will be fulfilled − an additional effort mainly considered desirable for security or safety aspects. Section 4 which expands on how MSE's sensitivity objective is refined and gives rise to a number of performance budgets illustrates our use of KAOS.

During a conceptual design phase, requirements and designs are being developed simultaneously: the phase begins with preliminary requirements used to steer the concept designs, which in turn provide feedback on the requirements. Keeping track of their respective evolution requires discipline. The corresponding founding principles which need to be enforced ensure the requirements and their relationships with the emerging concepts are well understood. To this end, we focus on the following four properties.

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[*] "Goals" is a KAOS jargon. In this paper, we choose to name top-level goals "objectives" because in astronomy goals are desirable characteristics which need not necessarily be achieved. Additionally, we extend the use of the term "requirement" to all other goals (irrespective of the fact that they could or could not be refined further which is the distinction KAOS makes).

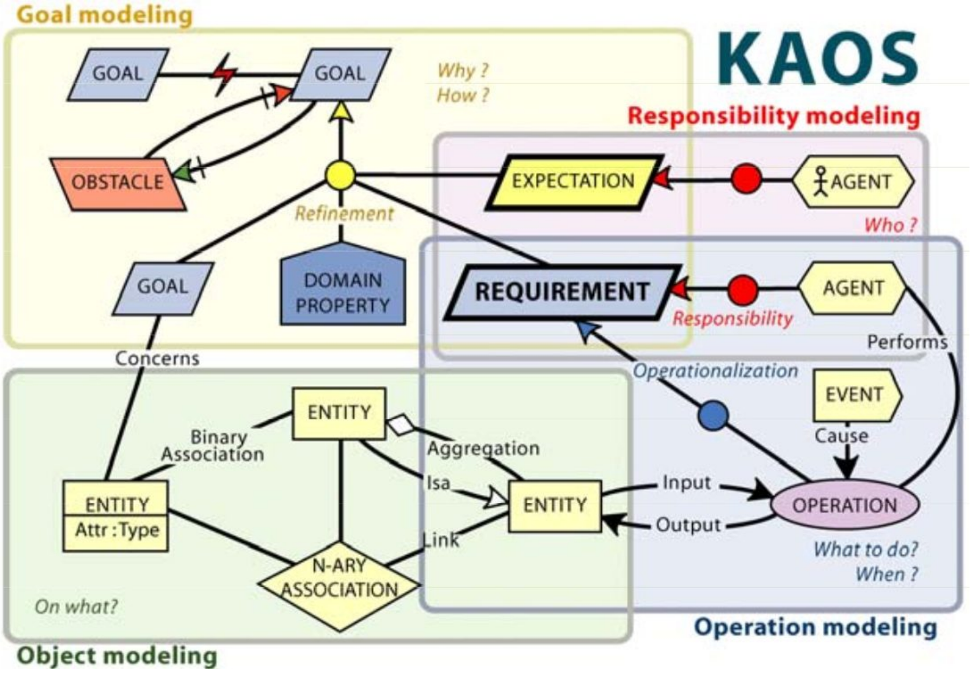

Figure 2. Illustration of the semantics which can be represented with KAOS graphs (from Ref. 9).

1. Completeness and adequacy

   Failure to completely specify MSE would lead to increased risks related to integration, operations and performance. For such a large system as MSE achieving completeness is a challenge given the large number of aspects to be considered. A sound method is of paramount importance for this, especially since there is a risk of over-constraining the design with inadequate requirements, that is requirements which are not strictly necessary and which reduce the number of degrees of freedom in the design. This is another reason why structuring the flow-down from the objectives and being able to assess why each requirement has been included and how it will be fulfilled are so important.

   The first is addressed by organising system budgets in an architecture which connects them to the objectives. Section 3 will illustrate how this has been done for MSE. In our lexicon, a budget is a collection of requirements referring to a given aspect of the system and their respective refinement[†] into lower level requirements which can be allocated to subsystems. As an example, the image quality budget referred to in section 4.2 encompasses the requirements on the profile of the PSF but also on lateral chromatic displacement, geometry of the focal surface, distribution of the angles of incidence and plate scale stability so that the overall performance on the WFC/ADC focal surface is characterised.

   Text-based derivation leads to long lists of requirements whose validity is difficult to assess both in terms of completeness and adequacy. Even building a relational database with links connecting requirements comes short of this objective since browsing the database only provides a very local view of the overall structure. To our mind, especially during the concept design phase, graphical representations with clear semantics like SysML and KAOS help considerably in handling this complexity.

2. Consistency

   The architecture advocated above is also relevant in giving additional contextual meaning to the requirements. Such meaning is of value in the effort to develop a large but coherent set of requirements. The

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[†] Refinement with KASO is the process of decomposing a requirement into lower-level ones which together or alternatively allow for fulfilling it.

existence of conflicting requirements is inevitable and such situations need to be identified, understood and solved at the requirements engineering level. This is achieved by performing trade-offs before they lead to difficulties in the design, fabrication or operation and cause either cost increases, delays or performance losses in unpredicted ways.

3. Traceability

   Traceability consists in recording both why a requirement exists and how it will be met through other requirements until technical requirements are reached. In the frame of KAOS, this translates in refinement links which combine through boolean algebra. In addition to such relationships between requirements, KAOS allows for modelling conflicts between requirements calling for trade-offs and risks[‡] calling for mitigation, that is additional requirements. This rich set of relationships is part of documenting the rationale for each requirement extensively. As such, it is part of preparing for change so the complete system and its model (requirements and design) can evolve coherently during project and subsystem iterations.

4. Correctness and testability

   Evaluating design conformance consists in assessing whether or not objectives will be met based on the refinement graphs and the technical requirements. Traversing the requirements graph, correct refinement implies that meeting the technical requirements translates into meeting the objectives. To this end, detailed mathematical models must be developed when requirements combine in a complex way. The calculations need to be summarised in some central location to efficiently assess the impact of system parameter changes – at least to first order – and allow the systems engineer to understand how sensitive the system is and provide guidance to the design teams or redistribute performance allocation. Finally, the requirements need to be expressed in non-ambiguous quantitative terms so that verification plans can be derived for technical requirements and validation plans for linking them to the objectives.

2.2 Requirements engineering process

The science cases and scientific requirements which triggered the MSE project are, by construction, more advanced than the systems requirements when the conceptual design phase begins. They remain under development or, to say the least, are being consolidated during this phase. As a consequence, systems engineering and design have to cope with changes and an incomplete set of objectives. Ideally, all need to be developed jointly based on strong communication between the teams. In practice, even within the conceptual design phase, iterations are carried out. The starting point is the configuration controlled version of the Science Requirements Document (SRD) (released on November 4th 2015), the draft OAD (dated October 9th 2015) and system-level performance spreadsheet (dated November 25th 2015) which define a system decomposition and performance requirements for each subsystem. Based on these, the MSE project office has issued "Objectives documents" to each team to steer their subsystem concept studies. Such documents allow for distributing the responsibilities among the international set of engineering teams involved in MSE.

The "Objectives documents" are not strictly speaking "Statements of Work" because they lack their formal aspect and need instead be considered as initial conditions to the concept phase iterations. As such, the requirements they contain are far from their final form but are at a level of detail sufficient to match the information needs of subsystems which do not yet exist. This implies that they grant subsystem teams enough design freedom in order for innovative concepts to emerge so the system as a whole can converge to an optimal combination meeting the scientific requirements – as is the conceptual phase's whole purpose – and that requirements engineering occurs concurrently to refine and consolidate them. To keep the systems requirements under control in this whole process, change management is an essential part of our process, both to propagate the effects of changing a requirement to others and to incorporate feedback from the conceptual studies. Indeed, subsystem teams need to develop level 2 requirements and the consistency between level 1 and level 2 requirements may lead to revising the former.

MSE's requirements engineering relies on four pillars:

[‡] "Obstacles" in the KAOS jargon.

- KAOS diagrams (Objectiver®) representing the requirements analysis through refinement structures as well as obstacles and trade-offs for each budget,
- budget derivation documents (Word®) containing all the requirements and recording sources, assumptions and discussion for each,
- mathematical models (Mathematica®) to accurately represent how requirements combine when advanced mathematical, geometrical or statistical calculations are involved,
- a system work book (Excel®) summarising the data and summing up contributions for all budgets.

These correspond to the principles evoked in Section 2.1 and are developed simultaneously. The corresponding documents are kept synchronised on DocuShare® which is MSE's document management system. At this stage only the configuration controlled scientific requirements have been imported into MSE's IBM Rational DOORS® database but we expect to import system requirements early and use the semantics of the KAOS diagrams to link them together and fully exploit DOORS®'s capability to handle inter-dependencies between requirements.

Use of DOORS® is expected to become the fifth pillar of MSE's process as it will become the prime reference for each and every requirement and for the content of requirements documents. Each subsystem will be expected to work with DOORS® directly. The intent is to rely on its export module heavily to generate the latter automatically based on the information in the database, thereby ensuring consistency in the wording of common requirements and trace their inclusion in the requirements documents.

3. BUDGET ARCHITECTURE

In designing the budget architecture we choose to distinguish between those relative to science (”performance budgets”) and the ones relative to general constraints (”feasibility budgets”) as described in the introduction. This segmentation is intended to represent the different decision-making processes for the two categories. In addition to this distinction, budgets are classified recursively on different layers[§] by incrementing the layer of the lowest budget they contribute to and placing in layer 0 the budgets which relate directly to SRD, OAD, OCD or ORD requirements. Although budgets do not form hierarchies since one may contribute to several others[¶], this approach allows for ordering the budgets so that priorities are allocated which structure the requirements flow-down and the propagation of changes. Indeed, changes in the reference documents would lead to updating layer 0 budgets, which in turn would lead to updating layer 1 ones, etc..

Layer	Performance		Feasibility	
0	Throughput	Noise	Mass	Volume
	Resolution	Wavelength calibration	Power	Cost
	Stability	Throughput calibration	Lifetime	
	Observing efficiency	Multiplex		
Refinement of throughput budget				
1	On/off-axis variability	M1 reflectivity	WFC/ADC transmission	Dispersion efficiency
	Fibre transmission	Fibre FRD losses	Spectrograph transmission	Injection efficiency
	CCD quantum efficiency	Vignetting	Spectrograph field variability	
Refinement of injection efficiency budget				
2	Image quality	Fibre core diameter	Defocus	Angular losses
	Positioner accuracy	Differential refraction	Tracking	

Table 1. Overview of the MSE systems budgets and their respective categorization, limited to layer 0, refinement of the throughput performance for layer 1 and injection efficiency for layer 2 (M1 is the primary mirror, WFC/ADC stands for the wide-field corrector and atmospheric dispersion corrector pair, FRD for focal ratio degradation).

[§] This a concept distinct from the levels on which the requirements documents are organised in Fig. 1.

[¶] Mathematically speaking they form oriented graphs.

4. REFINEMENT OF SENSITIVITY OBJECTIVES

The SRD defines three sensitivity requirements, one for each resolution mode of MSE. The low resolution requirement is phrased in these terms:

> [REQ-SRD-034] In the low resolution mode, an extracted spectrum from MSE taken in the observing conditions described below shall have a signal to noise ratio per resolution element at a given wavelength that is greater than or equal to two for a 1 hour observation of a point source with a flux density of 9.1×10^{-30} ergs/sec/cm^2/Hz at that wavelength, for all wavelengths longer than 400 nm. Between 370-400 nm, the SNR shall not be less than one at any wavelength. The observing conditions in which this requirement shall be met correspond to a sky brightness of 20.7 mags/sq.arcsec in the V-band and a natural seeing condition of $0.8''$ in the r band, at an airmass of 1.2.

Dissecting this requirement leads to:

- identifying reference observing conditions related to sky brightness (dark nights for low resolution), seeing and pointing,
- defining test targets (stars providing the specified flux density for the wavelengths at which MSE's performance is being assessed),
- adopting a performance metric which is the signal-to-noise ratio (SNR) computed based on reduced data and conformance thresholds for one-hour exposures for the two ranges defined (370-400 nm and 400-1800 nm).

Given that the low, medium and high resolution modes of MSE share part of the optical train (up to injection in the fibres), the throughput and noise terms in the SNR are split in two components and the analysis above can be concisely represented by Fig. 3. This figure presents a top-down refinement of the sensitivity specification or, alternatively, combines contributors in a bottom-up fashion. Items relevant to the signal and throughput part are on the left and items relevant to noise on the right. The parallelograms with blue edges are "soft" requirements in the sense that they specify properties of the system instead of functions. Yellow parallelograms are expectations and correspond to using the system in predefined ways rather than to any of its intrinsic properties – the two here correspond to test conditions. Links with yellow circles are refinement links so that the requirements pointed to is only met if all the other requirements connected to the circle are fulfilled. Beyond the graphical representation using short names for the requirements, KAOS allows for writing detailed definitions (and formal ones relevant for establishing proofs), recording issues, assigning patterns[‖] and priorities.

The rest of this section expands on the part of the refinement graph of the low resolution sensitivity requirement related to performances at the telescope's focal surface and provides a quick overview of the geometrical model developed to simulate injection efficiency.

4.1 Throughput and noise budgets

MSE's throughput budget is presented in a companion paper by Flagey.[10] We simply recall here that two bottlenecks strongly impact the overall performance: injection efficiency (with potential losses reaching up to 40%) and the efficiency of the dispersive optics in the spectrograph (with maximum performance of the order of 80-80% and potential losses of up to 30% for volume-phase holographic gratings). It is because the former is significant and involves many subsystems (telescope, WFC/ADC, fibre positioner, fibre link) that it is a real systems concern and is emphasised here. Besides, as presented by a companion paper by Szeto,[11] three parallel positioner studies are under way to support the development of the two multiplexing baselines (Echidna by AAO,[12] $\phi - \theta$ by USTC[13] and $\phi - \theta$ by CSIC[14]) so the associated requirements might become selection criteria.

Fig. 4 and 5 illustrate how the analysis begun in Fig. 3 is further developed. The first shows how the "Noise to injection" requirement faces three independent obstacles (the red parallelograms) which need to be

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[‖] Patterns are requirement categories respectively corresponding to achieving, avoiding, stopping, maintaining or optimising something.

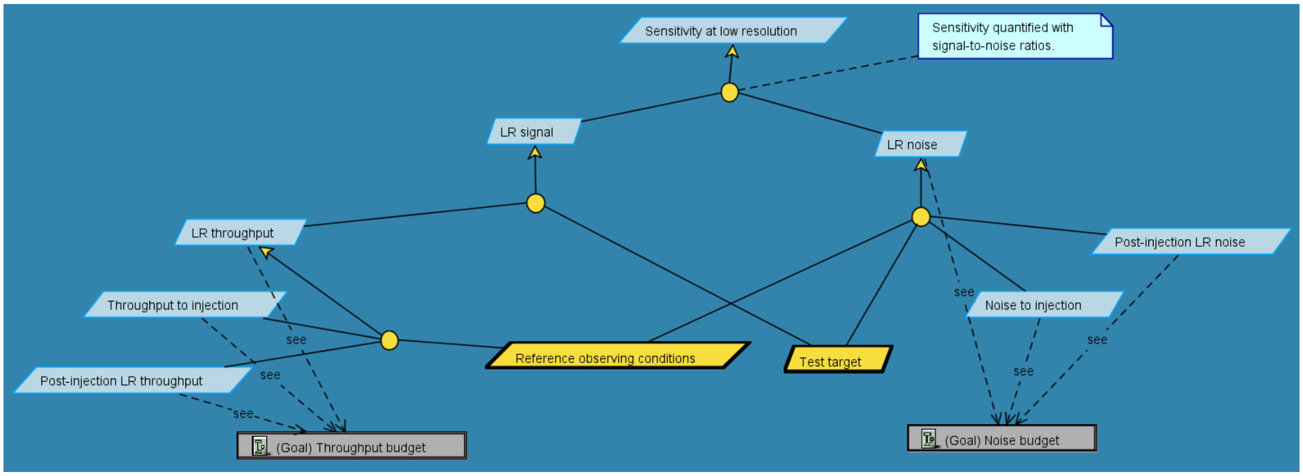

Figure 3. The low resolution refinement of the sensitivity requirement from the SRD according to the KAOS semantics.

mitigated via three requirements which need to be fulfilled simultaneously. Beside the analysis of requirements via refinement, such an identification and mitigation of obstacles via the introduction of new requirements is part of the KAOS requirements engineering which favours completeness and forms the basis of the system's risk analysis. Fig. 5 illustrates how this is applied to the more complex problem of maximising the throughput.

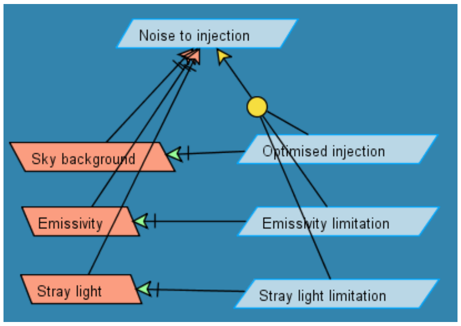

Figure 4. Refinement and resolution of obstacles for the "Noise to injection" requirement according to the KAOS semantics.

A simple way to increase the throughput to injection would be to increase the diameter of the optical fibres. As described in a companion paper by Flagey,[15] however, one of the objectives for MSE is to achieve sky-limited observations in both low and high resolution, and increasing the fibre diameter naturally leads to injecting more sky background. As Fig. 6 shows, a possible way around this could be to increase the plate-scale since the sky brightness is measured in magnitudes per square arc-seconds. While this would improve the situation for high resolution observations, it would require increasing the low-resolution fibre core to be able to observe extended objects to maintain the desired signal-to-noise ratio. Additionally, in both cases, the price to pay is the increased difficulty to achieve the required resolution. Alternatively, accepting the possibility of using fibres of different core sizes for high and low resolution spectrographs, smaller fibres could be used for the former based on how efficient the other contributors to injection can be made and larger ones for the latter based on the typical size of the extended objects to be observed. While reducing the pressure on the spectrographs, this leads to more difficult requirements on the telescope and top end assemblies as the following sections will show.

4.2 Injection efficiency budget

Injection efficiency characterises what fraction of the light from a target reaching the focal surface at each wavelength is actually injected in the corresponding optical fibre to be transmitted towards one of the spectrographs. In the sense KAOS gives to refinement, meeting both the injection efficiency budget requirements and the "Optical throughput to injection" requirement leads to fulfilling the "Throughput to injection" requirement.

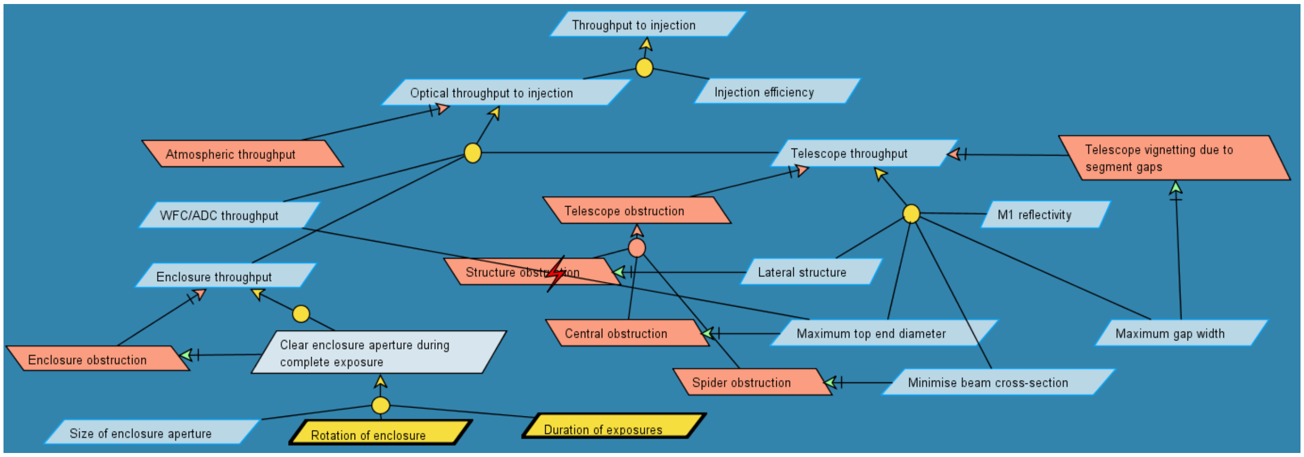

Figure 5. Refinement and resolution of obstacles for the "Throughput to injection" requirement according to the KAOS semantics. The link featuring a red zigzag pictograph indicates that the connected requirements are conflicting. The "WFC/ADC throughput" requirement is voluntarily not expanded in this figure and "Injection efficiency" is addressed in section 4.2.

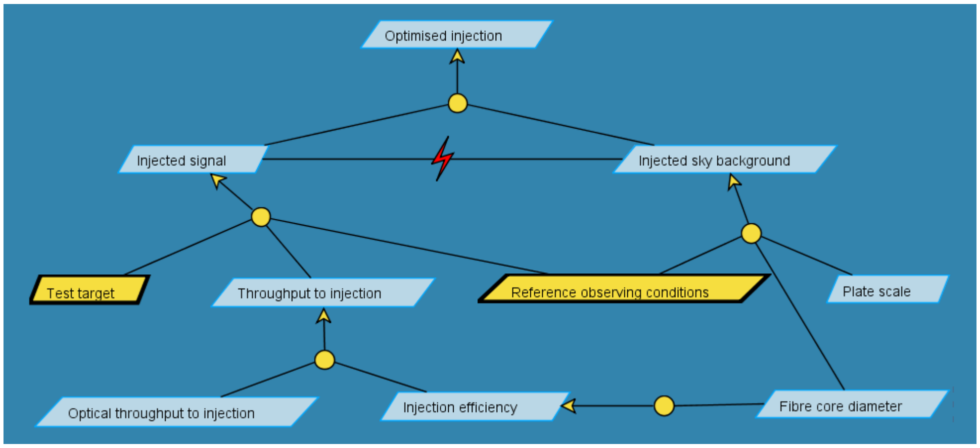

Figure 6. Simplified view of the fibre core trade-off required to achieve the optimum SNR according to the KAOS semantics.

Injection efficiency critically depends on the match between the image of the object of interest and the aperture and location of the fibre. However, there are angular aspects to injecting light in a fibre which are susceptible of leading to very significant losses. Indeed, all rays outside the fibre's admission cone are quite simply reflected off the fibre tip.

Fig. 7 refines the "Injection efficiency" requirement into requirements relative to matching the fibre tip to the image and to controlling angular effects. The aperture on the sky of the fibre tip is the combination of its core diameter, the plate scale and its positioning accuracy. The image derives from the intrinsic angular size of the object (e.g. point-like objects like stars, extended objects like galaxies) and the delivered image quality of the facility which encompasses seeing (natural, dome, etc.), vibrations and optical quality contributions (Fig. 8). Angular aspects correspond to the correspondence between telescope speed and the numerical aperture of the fibres, and the alignment of the chief ray with the latter's optical axis for both positioner technologies (Fig. 9).

4.2.1 Injection model

Beside the identification of performance and error terms as presented in Fig. 7 and 8, the elaboration of the budgets requires determining how to combine their respective contributions. While this can be carried out easily as part of the system work book when the mathematics are simple, more elaborate mathematical models are required otherwise. It is the case for the computation of the injection efficiency based on the system parameters

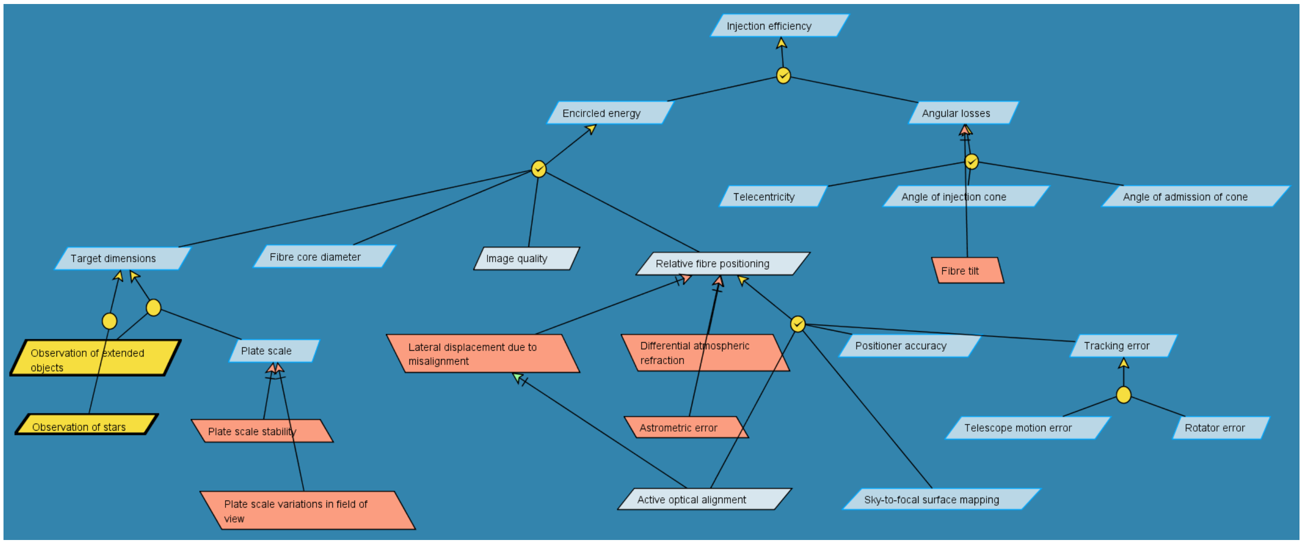

Figure 7. Refinement and resolution of obstacles for the "Injection efficiency" requirement according to the KAOS semantics.

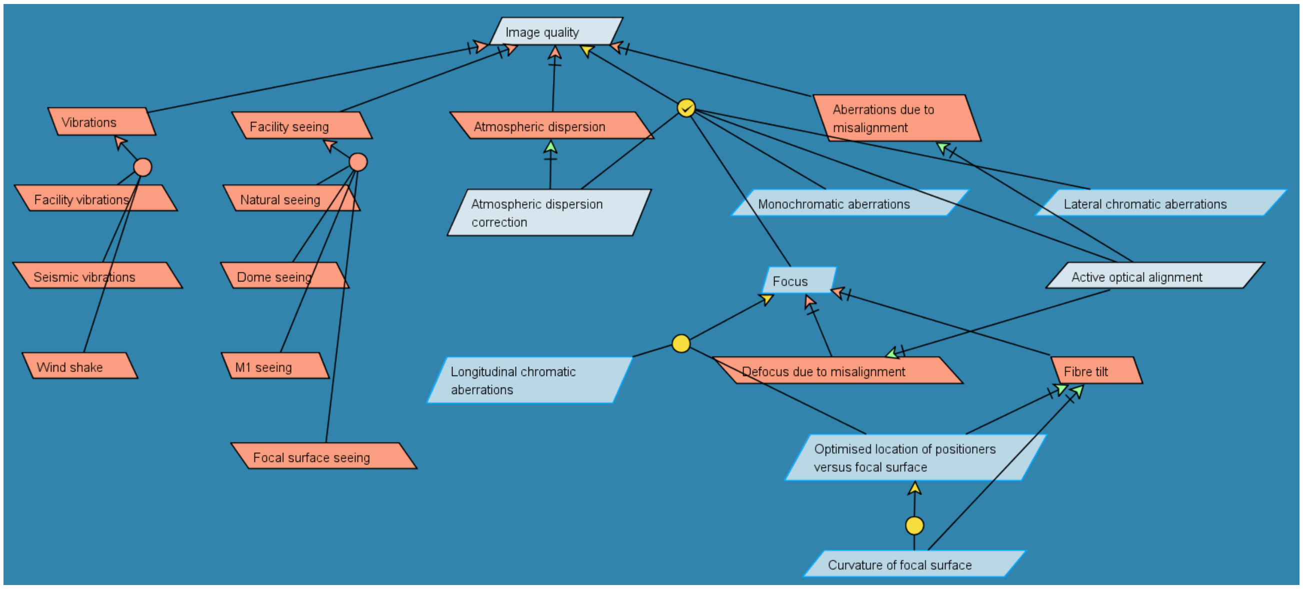

Figure 8. Refinement and resolution of obstacles for the "Image quality" requirement according to the KAOS semantics.

so performance allocation can be carried out. A Mathematica® notebook has been developed for this purpose and is described in this section.

One light ray is injected in the fibre if and only if it hits the fibre tip and is within the fibre's cone of acceptance (light is otherwise reflected). As a consequence, we consider as the starting point the two-dimensional monochromatic distribution of energy on the focal surface. This distribution is obtained as the convolution of the target's angular energy distribution, the facility's seeing and the instrument's point spread function at each position in the field of view. We then integrate the light injected in the fibre by considering each point on the fibre tip and scanning all rays (based on angles i and j) within the admission cone (with angles of incidence $\beta < \beta_{max}$) which are within the focal surface's emission cone (with angles $\sigma < \sigma_{max}$), as Fig. 9 shows. For each of these rays, the amount of energy is determined based on the distribution of energy on the focal surface scaled as a result of defocus.

This model of the geometry was first developed to assess the injection efficiency when using an Echidna[12] positioner and placing the fibre tip at focus when the tilt angle is null. As a matter of facts, defocus occurs as soon as the fibre tip is not on the focal surface and tilt results from the misalignment of the chief ray and the fibre's optical axis. Hence, given that the focal surface is not flat and that the WFC/ADC design is not fully telecentric, the model is applicable to the two positioner technologies being developed for MSE, i.e. also for $\phi - \theta$ positioners.

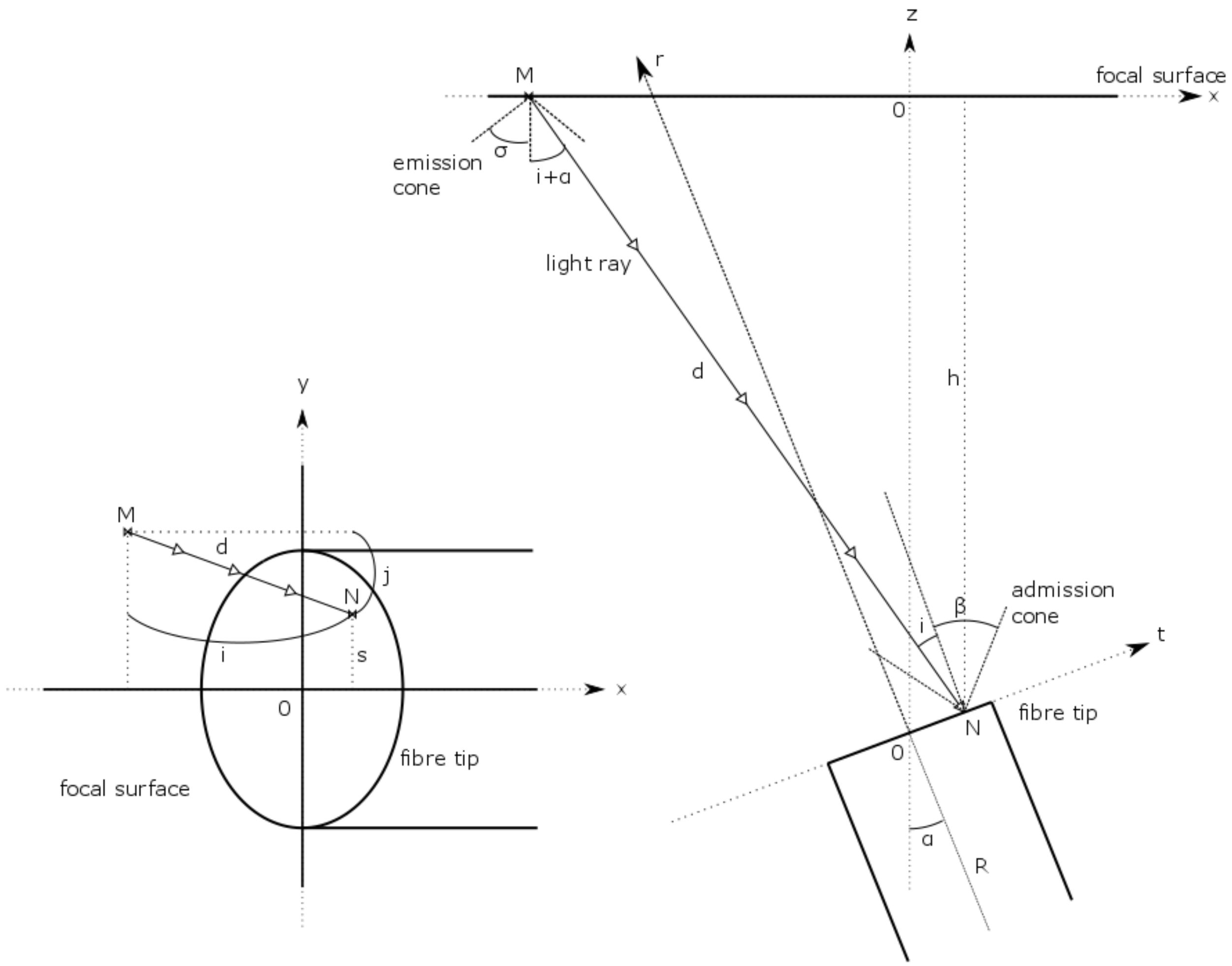

Figure 9. Geometry of the injection of the light rays into an optical fibre. *Left:* Top view (the circular fibre tip becomes an ellipse after projection on the (xOy) plane due to the tilt of the fibre). *Right:* Side view (xOz plane).

We adopt the following preliminary performance budgets:

- relative fibre positioning: 10 µm for positioner accuracy, 25 µm lateral chromatic displacement of centroids and 16 µm related to the motion of the target versus the fibre during the exposure (differential atmospheric refraction, tracking errors),
- image quality based on a $0.5''$ seeing and optics delivering 80%-encircled-energy within $0.35''$.

Based on $1.2''$ fibres, a plate scale of 105 µm/arcsec (on axis) and 108.6 µm/arcsec (on axis) and an Echidna positioner design with spines 250 mm long able to patrol areas with radii of 10.4 mm,[12] Fig. 10 shows best and worst case injection performances. The focal surface is here assumed to be flat − the curvature of the real surface would lead to reducing the defocus by 2.4% at the maximum tilt angle since the two surfaces are curved in the same direction and to a contribution to non-telecentricity of 0.06°, both of which are neglected here. As previously mentioned, the injection efficiency undergoes significant variations depending on pointing, the accuracy of the positioning and the tilt: as shown in Fig. 10 maximum losses amount to 40%.

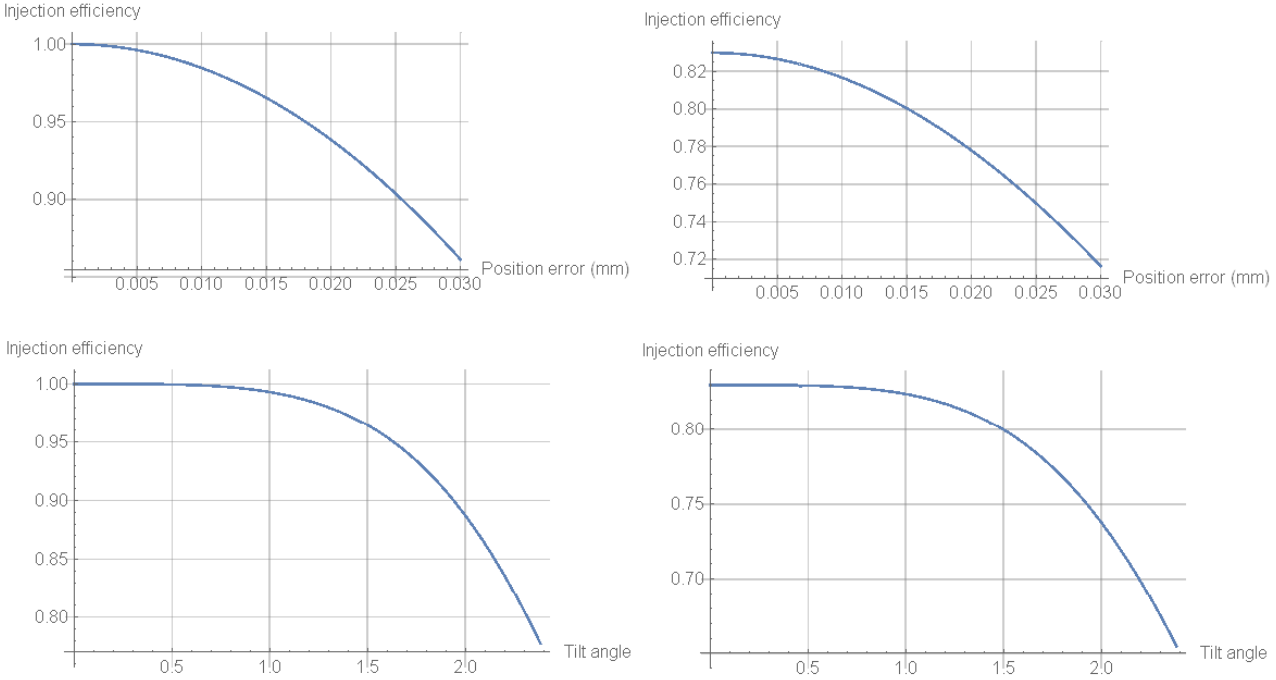

Figure 10. Relative injection efficiency (the on-axis, zenith pointing and perfectly centred fibre position without tilt is the reference). *Left:* On axis when pointing at zenith. *Right:* At the edge of field with a zenith distance of 50°(worst case). *Top:* Performance as a function of the decentring of the fibre. *Bottom:* Performance as a function of fibre tilt.

5. CONCLUSION

We have described our on-going effort to define MSE's systems requirements. Systems engineering in the current conceptual design stage is work in progress. The focus is now on defining a performance baseline based on draft budgets to steer the conceptual studies. As subsystems are being designed, the requirements will be discussed which each group to adjust the existing allocations if need be. As conceptual design draws to a close, we expect to achieve consolidated systems requirements in the sense of defining expected values, acceptable ranges and prioritising requirements.

The example of performance evaluation and requirement derivation we have provided in section 4.2.1 shows that $[min; max]$ specifications are not very satisfactory when variations are significant since they are likely to lead to over-design. A possible improvement would be to base the specifications on selected instrumental configurations if any can be justified to be typical of regular operations. Better still, achieving a statistical representation of the behaviour of the system would average extreme cases out and therefore avoid over-constraining the design, favour homogeneous performance, provide representative performance estimates and provide a firm mathematical framework allowing for estimating performance in any operational configuration.

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