The MUSE Project from the dream towards reality

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ABSTRACT

MUSE (Multi Unit Spectroscopic Explorer) is a second generation instrument developed for ESO (European Southern Observatory) to be installed on the VLT (Very Large Telescope) in year 2012. The MUSE project is supported by a European consortium of 7 institutes. After a successful Final Design Review the project is now facing a turning point which consist in shifting from design to manufacturing, from calculation to test, … from dream to reality.

At the start, many technical and management challenges were there as well as unknowns. They could all be derived of the same simple question: How to deal with complexity? The complexity of the instrument, of the work to de done, of the organization, of the interfaces, of financial and procurement rules, etc.

This particular moment in the project life cycle is the opportunity to look back and evaluate the management methods implemented during the design phase regarding this original question. What are the lessons learn? What has been successful? What could have been done differently? Finally, we will look forward and review the main challenges of the MAIT (Manufacturing Assembly Integration and Test) phase which has just started as well as the associated new processes and evolutions needed.

Keywords: MUSE instrument, project management, development, PBS, WBS, IFU, Integral Field, 3D spectroscopy,

1. INTRODUCTION

After a promising Phase A study concluded in February 2004, the MUSE instrument contract was signed between the MUSE consortium and ESO in July 2006. Since then, the MUSE design phase was carried out, passing one after the other the different major milestones of Optical Preliminary Design Review (OPDR) in July 2006, Preliminary Design Review (PDR) in July 2007, Optical Final Design Review (OFDR) in December 2007 and finally concluded by the Final Design Review (FDR) in March 2009.

The MUSE project has now started the second and maybe most critical phase of its development which is the Manufacturing Assembly Integration and Testing (MAIT) Phase. This phase will be next punctuated by the Preliminary Acceptance in Europe (PAE) and followed by the Preliminary Acceptance in Chile (PAC) occurring after installation and commissioning of the instrument on the Nasmyth platform B of the VLT Unit Telescope 4 (UT4) in 2012.

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2. THE ORIGINAL DREAM

2.1. MUSE INSTRUMENT DREAMED PERFORMANCES

MUSE is an innovative Integral Field Spectroscope which has been imagined to enable direct spectroscopic exploration of the universe and beside many other scientific cases the study of the progenitors of normal nearby galaxies out to high redshift. As described in R. Bacon et al. paper "Probing unexplored territories with MUSE" [1] the tremendous scientific potential of MUSE instrument is based on crucial and of course very challenging top level specifications which are given hereafter:

- **Wide & Integral Field of View**
  - 1×1 arcmin² in Wide Field Mode (WFM)
  - 7,5x7,5 arcsecond² in Narrow Field Mode (NFM)
  - Integral Field of View (FoV) with less than 5% field loss
- **High Spatial Resolution**
  - 0.19 arcsecond² spatial sampling in WFM
  - 0.025 arcsecond² spatial sampling in NFM
- **Broad Spectral bandwidth**
  - Large visible and near IR spectral range from 465 to 930 nm of wave length
- **High Spectral Resolution**
  - R1750 at 465 nm up to R3750 at 930 nm
- **High Efficiency**
  - From 20% of minimum average transmission in NFM for 465- 570 nm wavelengths
  - To 40% in WFM for 600- 800 nm wavelengths

One shall note that the high spatial resolution can only be achieved when using the associated ground layer adaptive optics system named GALACSI which is developed by ESO as part of the VLT Adaptive Optics Facility (AOF).

2.2. MUSE INSTRUMENT DESIGN KEYS

The above specifications to be achievable are supported by initial key features of the MUSE Design:

- **Multiple Units Instrument : 24 Integral Field Units (IFU)**
  - Enable multiple Charge-Coupled Devices (CCD) for ~400 million pixels exposures
  - Enable large number of slits with two level of field splitting and slicing
  - Keeps Optics within reasonable size
  - Enable production in small series
- **Implementation of components of high technically**
  - 24 Slicers for FoV recombination
  - 24 Volume Phase Holographic Gratings (VPHG)
  - 24 High efficiency 4k x 4k CCDs
- **High Quality & Efficiency Optical Components and Coatings**
  - Very good wave front error
  - Good homogeneity
  - Optimised efficiency on the given spectral bandwidth

At the end, MUSE performances are given by its optical scheme as the results of individual sub-systems and critical components performances. More details about the MUSE design can be found in "MUSE instrument global performance analysis" [2]

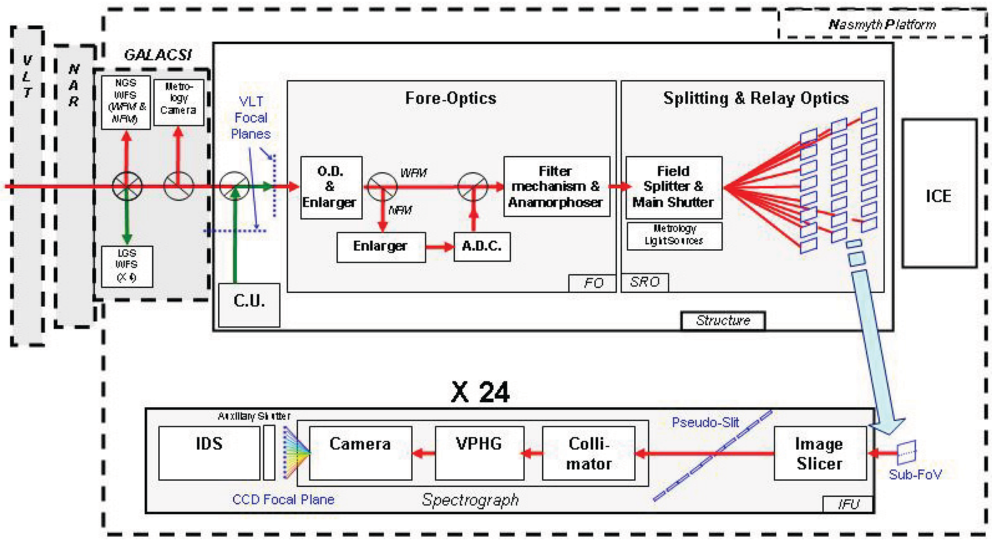

Figure 1: MUSE Optical Schematic

From this original optical scheme the main sub-systems of MUSE instrument have been defined and organised through the following Product Breakdown Structure (PBS).

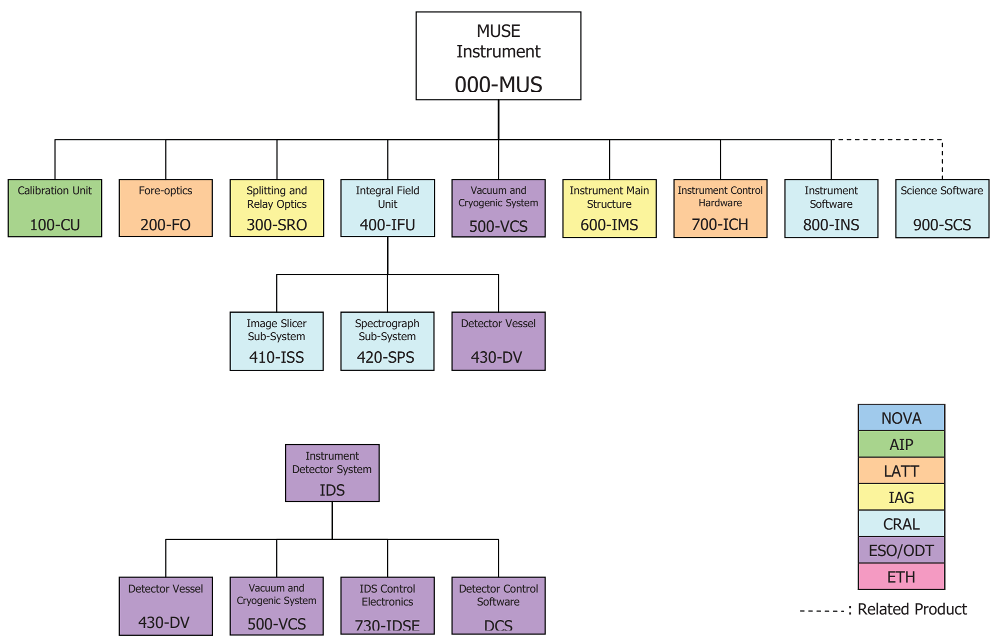

Figure 2: MUSE Product Breakdown Structure

The given optical scheme and associated PBS defined as an input of the design phase were kept stable and confirmed along the development. On the other hand, the initial design had to undergo drastic evolutions in order to keep the performances of MUSE.

2.3. Feasibility

As we all know the brightest ideas are not worth much if they cannot become reality. That is where the heart of the project management comes in: To take into account all practicable constraints in order to make real and usable an innovative concept. To be feasible and operational the MUSE instrument has therefore to have:

- **Affordable Manpower**
  - 180 Full Time Equivalent (FTE) or Men-year of total manpower was estimated at MUSE Kick off
  - Necessity to have skilled people to take in charge the different tasks of different competencies
- **Affordable Cost**
  - Initial instrument hardware cost estimate of ~8,4 M€
  - Necessary additional support cost for institutes equipment
- **Reasonable Development and Realisation Time Line**
  - MUSE instrument to be operational on the VLT in 2012
- **Easy Operation & Durable Life Time**
  - To be acceptable MUSE instrument shall have a reasonable operational and maintenance cost as well as a very good availability
  - It shall be contractually operational for at least 10 years but can be expected to be operated longer regarding the effective operational life time of previous generation of VLT instruments.

2.4. The Means

To answer the above feasibility constraints the following means have been identified and jointly provided by ESO and MUSE Consortium.

- **MUSE Consortium & Manpower Initial Commitment**
  - The responsibility of the different tasks to be completed are taken in charge by the MUSE Consortium and distributed according the scheme given bellow in accordance with the institute's capabilities and experience.

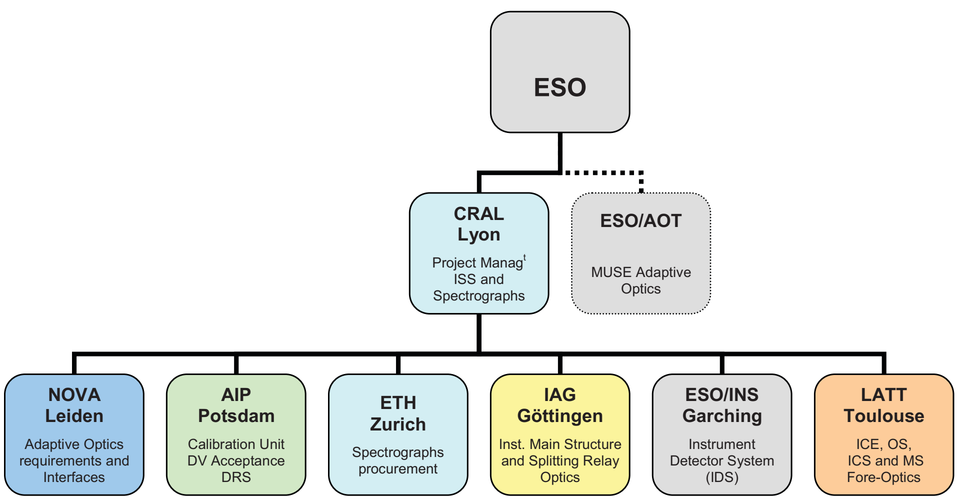

Figure 3: MUSE Consortium Organisation

  - It has to be noted that ESO act as customer and final recipient of the MUSE instrument but as well as a partner of the MUSE consortium as provider the detector system.
  - The associated personnel allocation in each institute corresponding to the manpower need of each sub-system.

- **Financial Funding**
  - The funding of MUSE project is done principally through the contractual agreement with ESO.
  - As part of the contract, the procurement of Instrument Detector System (IDS) is taken in charge by ESO.
  - The procurement of the IFU's 24 Spectrographs is taken in charge by the MUSE consortium member ETH.
  - Some significant financial supports internal to the different institutes and associated supervisory bodies have also to been involved as part of their implication in the consortium.

2.5. The Initial Schedule

Is given hereafter the main contractual milestones of the project indentified at the time of the signature in July 2006.

Milestone	Date
Preliminary Design Review (PDR)	January 2007
Final Design Review (FDR)	July 2008
MAIT Progress Meeting 1	July 2009
Preliminary Acceptance Europe (PAE)	July 2011
Preliminary Acceptance Chile (PAC)	December 2012
Final Acceptance	December 2014

Table 1: MUSE Contractual Planning

2.6. The Project Mission

Finally, the MUSE project global goal can be defined by the following mission sentence:

In 2012, provide ESO with a unique high performance integral field spectroscopic instrument mounted on the VLT bringing new opportunities of scientific discoveries

From this global mission, one can derive the different project targets or constraints which will have to be met and kept balanced

Figure 4: MUSE Project Goal

As showed above in the orange areas, we can easily see the possible consequences of departing from a balanced management of the project different constrains.

3. THE INITIAL KNOWNS & UNKNOWNS

Before going into more detail on the project management of MUSE and the analysis of the evolution since the initial situation it is worth to look back on what was identified as the main project risks and what was the assets present from the beginning of MUSE development.

3.1. RISKS AND UNCERTAINTIES

At the beginning of an ambitious project like MUSE the number of risks and uncertainties is of course very important. As it has been showed previously, the MUSE concept was supported by key components, performances or assumptions which included a part of risk. Moreover the global complexity of the instrument and the ability to make everything and everyone work together was a pending question and part of a real challenge. Finally, the main risks and uncertainties originally identified on the project are listed hereafter:

- **Technical Complexity**
  - Numerous, difficult and sometime of opposite constrains of high level specifications to be derived into sub-systems ones.
  - Key performances like image quality and throughput resulting of many components in different sub-systems
  - Number and complexity of interfaces between sub-systems and institutes
- **Critical Components to Develop**
  - The Image Slicer was the most ambitious and risky development in MUSE project from the beginning. No such slicer was existing at that time and the uncertainties about feasibility, cost and manufacturing time were more than significant.
  - At a different level, the Volume Phase Holographic Gratings (VPHG), the CCDs and the whole spectrograph had to be newly developed by sub-contractors without real guaranties at the beginning that all performances could be achievable.
- **Organisation Complexity**
  - MUSE is a 7 institute's consortium of 4 different European countries which represents over 60 different persons working on the project. People of different countries, native language, culture ...
  - Several institutes and countries mean also different governmental laws, administrative rules and constrains.
  - The amount and the complexity of the work to be done to be dispatched among institutes and responsible person following capacity and competency.
- **Budget Keeping and Estimated Savings**
  - One big assumption in the contractual price of MUSE was the potential saving related to the modular approach chosen with 24 IFUs and the associated small series. Even, if preliminary quoted this assumption would only be confirmed when signing the main contracts for the multiple elements.
  - More generally on high technically product and optical industries addressed the range of price can often vary very much, typically from 1 to 3. The uncertainty about the real instrument cost was therefore quite important.
- **Time Line**
  - Last but not least the capacity for the suppliers to produce the24 series of the main IFU's components within a reasonable time (about 1 year) was to be proven. The capacity of the consortium to assemble, integrate and test the IFUs as well.
  - The duration of the project in itself brings risks of loss of motivation through time and turnover to deal with.

3.2. Opportunities and Assets

Facing the complexity and the unknown, the strength of a project team lies often in its own people and their ability to deal with them. For MUSE the following assets could be noticed:

- **Strong Motivation of the Institutes and of the People**
  - The far-reaching performances of MUSE not only are a challenge but also represent a strong source of motivation and achievement.
  - The project was really supported financially and in manpower by the consortium's institutes and associated supervisory bodies.
- **People of Different Skills and Experiences**
  - The skills, the experience and domain of expertise are very different and complementary throughout the consortium, from designer, lab engineer, manager to astronomer.

4. DISCUTION ON PROJECT MANAGEMENT IMPLEMENTED

4.1. Organisation per Sub-Systems

As shown in Figure 2 one of the first steps of organisation was done through the definition of the first level of the instrument Product Breakdown Structure (PBS) i.e. the definition of the main sub-systems. As we will see afterward this initial splitting of the instrument is crucial and has to be regarded not only as a convenient functional splitting of the instrument but also as a splitting of the associated design studies, procurements, manufacturing, deliveries tasks and schedule. Furthermore the splitting in sub-system also defines the different interfaces and their level of complexity.

What can be noticed about MUSE sub-systems is that they are all of them sub-units of the instrument which are nearly physically and functionally independent so that can be tested, validated and shipped individually.

4.2. Organisation per Institute

The MUSE consortium presented in Figure 3 show the 7 institutes involved in the MUSE project. The choice done was not only to distribute the workload among the institutes but really to give the responsibility of 1 or 2 complete sub-systems per institute with associated local project team, Local Project Manager (LPM), manpower management, financial budget and schedule.

The sub-systems development and manufacturing is therefore to be considered as sub-projects in all aspects. Distributing sub-systems responsibility among different autonomous teams was an answer to the instrument complexity. Moreover it also gives people working at sub-system level more accessible targets, deadlines and finally a clearer view of their contribution which is not “diluted” at the global level.

For the same reason, it was decided that as the Centre de Recherche Astrophysique de Lyon (CRAL) being responsible of the global project management as well as the IFU development should have separated global and local organization with an independent Local Project Manager different than the Project Manager (PM).

Even if relatively formalized with independent internal management, the global/local interface shall however not be regarded as some kind of sub-contracting. Indeed, as showed in the next sections some parallel global management methods have also been implemented in order for the whole system not to be just the result of the sub-systems addition.

4.3. ORGANISATION PER WORK PACKAGE

The Work Breakdown Structure (WBS) for MUSE design phase is given bellow in Figure 5. The management by work package is done to have manageable, clearly identified tasks and expected output. They should be self consistent and have again their own manpower management, financial budget and schedule. In line with the organization per institute described previously, each work package is clearly put under the responsibility of one institute and one identified person who is most of the time the Local Project Management but not mandatorily.

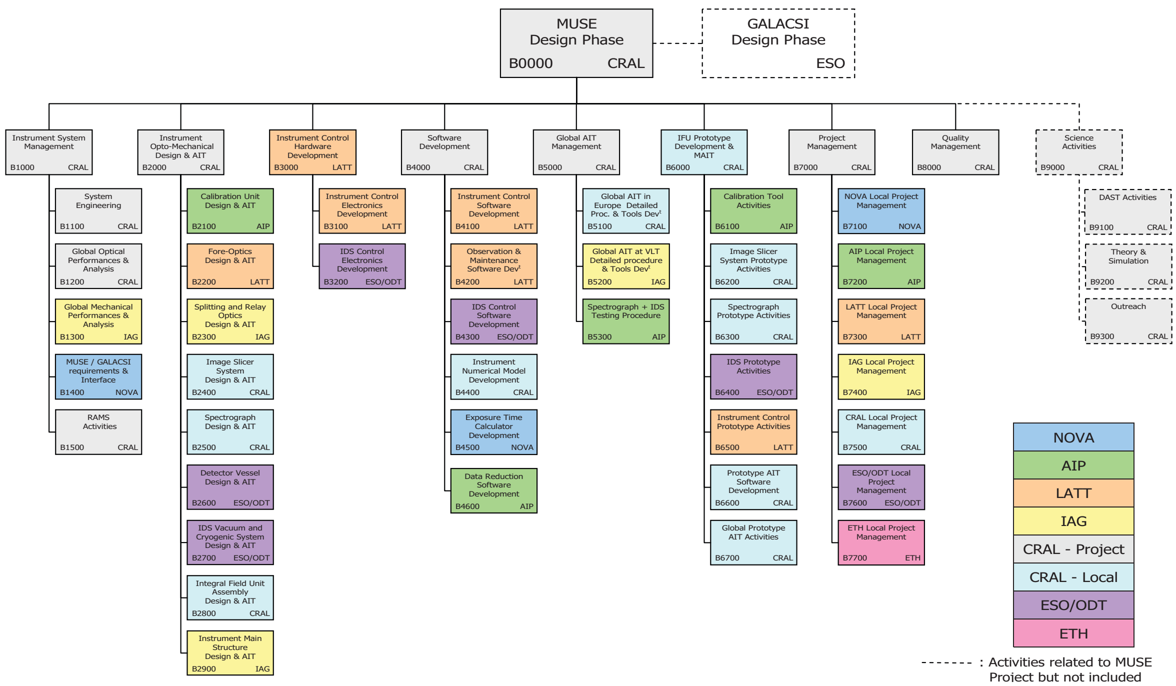

Figure 5: MUSE Design Phase WBS

At the end of the design phase, one conclusion about this WBS is that it was a bit too detailed and that work packages were maybe too numerous or not best split. The most obvious point was the definition of separated work packages for the Integral Field Unit (IFU) prototype (B6000). Although this prototype had clearly separated planning and hardware delivery, the work associated to it was too close to the general development of the sub-system (B2000) which made the two sometime difficult to separate. Moreover it induce additional management load which weren't really justified. On the other hand the gathering of design and MAIT development per sub-system or sub-assembly was a good idea.

A general feedback on the definition of the WBS would then be that work package shall be defined in such way that different work packages have clearly different associated sub-system or sub-assembly and different work type. Although work packages are used also to manage the schedule, the separation of work packages by phase is at the end questionable. The different work packages have different time line and even if punctuated by different validation reviews the transition of phases is a more or less continuous process which makes the work package management difficult when separated by phase. Finally the level of detailed of the WBS shall really be balanced with the size of the working team. This has been taken into account as much as possible when defining the following MAIT Phase work package which has been slightly simplified.

4.4. INTERNAL PROJECT VALIDATION MILESTONES

The previous described structures are mostly there to clearly identify and organize the product, the work, the responsible people or entity, etc. By themselves they don't ensure that the different identified goals of the project will be met.

To do so, a management base frame is carried out through what is called Gate Reviews. The Gate Reviews are internal global reviews checking the project status with regards to all the different goals defined previously.

This process ensures that the different goals are measured and followed. Moreover it also ensures anticipation of the work to be done and check that the project is well organized, sized and generally speaking in an acceptable condition in view of the phase to come.

The detailed role of those reviews is the following:

- Ensure status of project at current time and check deviations from the different goals
- Ensure respect and taking into account of all project's constraints
- Define mid-term clear targets and ensure later phases are well anticipated
- Ensure synchronization and coherence of tasks between themselves
- Prevent increasing negative consequences linked to unsolved problems

The implementation of this process is done for MUSE through 4 types of gate reviews: These reviews are applicable at the project level and also at the level of main sub-system:

- SGR : Specification Gate Review
- PGR : Preliminary Gate Review
- CGR : Critical Gate Review
- MIA : Manufactured Item Acceptance

As showed bellow these reviews are linked together in parallel process including the contractual reviews with ESO (PDR, FDR, PAE, PAC in blue)

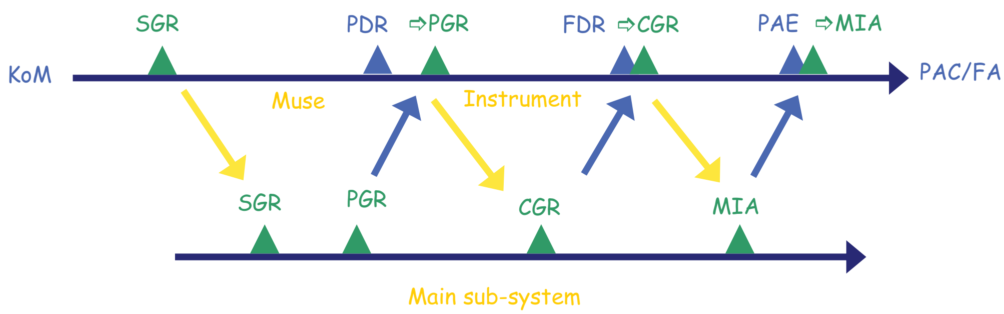

Figure 6: MUSE Gate Reviews Process

Although the main reason of gate reviews is to ensure control and quality to the project management we can see that, more than that, it completely structures the project in term of goals, work and schedule. The gate reviews are therefore the real backbone of the development and management process. This process was not implemented from the start and was long to implement and to get people familiar with. However now that we are entering the real hardware these validation steps seems more and more natural.

4.5. DECISION PROCESS

To follow and maintain the different project goals through the different milestone till the end, it is not only sufficient to check and control the project parameters, it is necessary to adapt ones strategy and influence the project course. This is done all along the project life by the different choices which are made and decisions which are taken. On MUSE the key decisions to be taken were mostly technical options and main sub contractor choices.

For these critical choices a quite formal decision process based on comparison matrices has been implemented. The prerequisite to use such a tool in an efficient way is to first let open as much as solutions as possible and take the time to investigate them. This first step is not always easy because the natural tendency is to intuitively focus on one solution or one supplier and develop it from there. Developing other solutions or new supplier often seems like a waste of time. The evaluation parameters are also important to be chosen on a wide range on all the project aspect (performance, cost, planning, etc.).

When the different solutions or potential suppliers are clearly identified then all the relevant people at the system and sub-system level meet to fill in the associated matrix. After being implemented on MUSE, it has been found that the asset of this method is not only to ensure that all parameters potentially impacting the project are taken into account. The other and maybe most significant positive aspect is that this process enable every valuable inputs from many people with different experiences and point of view to be taken into account without being in direct confrontation and argumentation. Moreover, the neutral process and associated output often makes the decision obvious or at least understandable and acceptable even for those who were not in favour.

5. OUTPUT AFTER FINAL DESIGN REVIEW

5.1. MUSE INSTRUMENT EXPECTED PERFORMANCES

At the end of the Design phase, the MUSE design presented was not only fully compliant with its specified functionalities such as FoV and spectral range but had also comfortable margins:

- 24% to 41% in image quality, thus ensuring spatial and spectral resolution
- 4% to 17% in throughput, thus ensuring limiting magnitude sensitivity
- No field loss
- Less than 25% light loss on only 17% of the pixels

Thanks to an efficient system engineering (see "MUSE instrument global performance analysis" [2]) and an optimized opto-mechanical design and despite of all the technical issues raised during development, the expected performances of the instrument are still there at the end of the design phase with a fully promising scientific output.

5.2. COST STATUS

As explained in §6, the risk not to keep budget was quite high at the project kick-off mostly due to the IFU cost uncertainty. Technology like the slicer was still to be developed and a cost effective design of the spectrograph was still to be done. Thanks to the skills of MUSE designers and the manufacturing technology brought by Winlight Company (see "MUSE Integral Field Unit: Test results on the first out of 24" [3] and "MUSE image slicer: test results on largest slicer ever manufactured" [4]) the technical solutions found were not only well within specifications, there were also within the budget. In addition, the broad selection of potential suppliers coupled with a refined comparison process (see §4.5) enabled also for the other main contracts to select the Companies the most in line with the different needs and the budget.

At the end the MUSE expected cost alone remained along the development always within the budget with a margin varying around a couple hundred thousand Euros. The expected cost including contingency for risks remained stable around a hundred thousand Euros above the budget with a very good level of confidence that in the unlikely event were the budget was not kept it would then be exceeded by not much.

5.3. SCHEDULE STATUS

Is given hereafter the main contractual milestones of the project indentified at the time of the signature in July 2006 versus the real review dates or updated expected date with an (*).

Milestone	Planned Date	Real Date
Optical Preliminary Design Review (OPDR)	-	July 2006
Preliminary Design Review (PDR)	January 2007	July 2007
Optical Final Design Review (OFDR)	-	December 2007
Final Design Review (FDR)	July 2008	March 2009
MAIT Progress Meeting 1	July 2009	Feb 2010
Preliminary Acceptance Europe (PAE)	July 2011	January 2012*
Preliminary Acceptance Chile (PAC)	December 2012	December 2012*
Final Acceptance	December 2014	December 2014*

Table 2: MUSE Realized Planning

The immediate result of this comparison is that the MUSE project shows some delay. One see that this delay was there almost from the beginning with a 6 months delay on the PDR, 8 months delay on FDR which are expected to be kept for PAE and hopefully recovered at PAC. This initial delay was mostly due to the time necessary for the consortium "to get in motion" and the critical feasibility study on the slicer still needed at the beginning of the project. Even if not completely satisfying, we can see that the delay has at least from then been contained quite well. One can note also that this corresponds also to the time when the project management as described in this proceeding has started to be implemented. Finally, the decoupled anticipated validation process of the IFU in relation more with OPDR and OFDR enabled also not to lose time on this critical serial item.

5.4. VALIDATION & RISK STATUS

As showed in proceeding "MUSE Integral Field Unit: Test results on the first out of 24" [3], the anticipated realization of one IFU enabled the critical part MUSE design to be validated in real conditions. The IFU testing revealed very good performances which are very reassuring for the serial production. On the other hand, this first IFU also revealed several coating defects which imposed this IFU to be retrofitted. As confirmed after that on other MUSE optics the coating aspect is most critical risk remaining at the end of the design phase with pending issues on the throughput and lifetime performances.

5.5. CONCLUSION ON DESIGN PHASE

Looking back on the original uncertainties and risk detailed in §3.1, one can say that at the end of the design phase most of those risk are gone. The complexity of the instrument and of the organization was properly managed and the MUSE consortium was able present at FDR a fully compliant design. The most critical components were prototyped and validated and industrial partners identified. The instrument cost is clearly under control. The schedule delay is contained to a somewhat reasonable amount which still leaves the possibility to start the scientific exploitation in time. The coating aspect could however have been better addressed. The strategy to rely completely on the coating supplier's validation process was a clear failure and has now been reviewed. On the other hand, it confirmed the relevance of global validation plan based on a preliminary validation of one complete IFU which avoided this coating problem to impact the whole series.

6. MAIT PHASE & UPCOMING CHALLENGES

The MAIT phase has now started one year ago. All main contracts have been finalized and sub-system components are being delivered to the different MUSE institutes. The project status is still quite good and similar to the one described previously. Of the original risks indentified, the schedule aspect remains the most critical. Indeed, as only very little margin remains, the delivery delay on critical components have a direct impact on the project schedule.

With the MAIT phase new challenges arose. The management of deliveries, delays, non-conformances imposes a quick reaction time and therefore a new organization of the consortium partners to tighten the links and pace of interaction. The management of quality is and will become ever more crucial as the different institute will have to receive, control and assemble hundreds of parts in order to integrate complete sub-system which will have to be thoroughly tested and validate before shipment to the integrating site in Europe. Finally the capacity to integrate and test the different sub-system and the system itself correctly and in due time within the consortium is still to be demonstrated. It may be the most difficult upcoming challenge of project to be met but it is also the most exiting one.

The MUSE dream has never been so close to become true, it is now at hand and with a little more effort we will be able to embrace it completely and open a new door on the astronomic field.

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