SYSTEM DESIGN OF THE CROSS-SCALE MISSION

Contract ESA 21602/08/NL/VS

EXECUTIVE SUMMARY

Written by	*Responsibility*	
J. PONCY	Study Manager	
Verified by		
X. ROSER	Head Advanced Projects	
Approved by		
J. PONCY	Study Manager	

CHANGE RECORDS

ISSUE	DATE	§ : CHANGE RECORD	AUTHOR
1	02/07/2009	First Issue	J. Poncy
2	03/07/2009	Sections 4.3 and 5 updated	J. Poncy

TABLE OF CONTENTS

1. INTRODUCTION AND SUMMARY

The Consortium led by Thales Alenia Space, including Deimos and OHB, has completed the Assessment Phase contract "System Design of the Cross-Scale Mission" awarded by ESA. The expertise of the Consortium has allowed analysing the requirements, trading options extensively and selecting a baseline design that has been defined in detail and justified by a comprehensive set of analyses. The robust solution not only fully complies with the requirements, but also implements high TRL and strong design-to-schedule dispositions that lead to safer programmatics, to the maximization of the mass production effect and to the mastery of costs. The technical, schedule and cost elements produced will enable ESA to assess the Cross-Scale Mission in the frame of its Cosmic Vision selection process.

Building upon the success of Cluster, the Cross-Scale mission represents an opportunity to make a further qualitative step in the understanding of the interaction between Earth's magnetosphere and the surrounding plasmas. Two out of the three scales of interest would be provided by ESA, with nominally seven science satellites, potentially complemented by JAXA.

ESA has selected the mission as one candidate for the first M-class launch slots of Cosmic Vision. Two industrial contracts have been awarded for an Assessment Phase of the mission, one of them to the Consortium led by Thales Alenia Space. Our achievements in the frame of this contract are summarized here.

The mission requirements and drivers have been analyzed by the Consortium led by Thales Alenia Space, evidencing the criticality of cost and the required mastery of the programmatics of a large series of satellites. To reach a sufficient maturity in the definition of the mission, a number of options have been investigated and compared to come up with a reference mission architecture before refining this baseline. The reference design illustrated in figure 1-1 opposite includes seven reconfigurable science spacecrafts with identical platforms piled onto a Propulsion Module for their launch by Soyuz. The pile is separated close to the operational orbit to form the Cross-Scale constellation of seven fast-spun satellites.

We first present our study consortium in section 2. The performed activities and the study logic followed are then summarized in section 3, along with the generated documentation.

In section 4 we present the baselined system design. We identify too the trade-offs, analyses and budgets that justify it. The trades have addressed not only the design options but also the different procurement, production, integration and verification strategies. In particular, the selection of the composite configuration includes quantified considerations on cost. The analyses that justify the system design address how we master mission related aspects, how we control the composite, how we ensure a consistent and compliant mechanical behaviour of the composite pile at launch while flowing down requirements to the spacecrafts…

We summarize in section 5 the programmatic assessment, which leads to a launch in 2017 with a 6-month margin, while requiring minimal early developments.

We then conclude in section 6 by summarizing the main achievements of this phase in view of the potential continuation of Cross-Scale in the Cosmic Vision process.

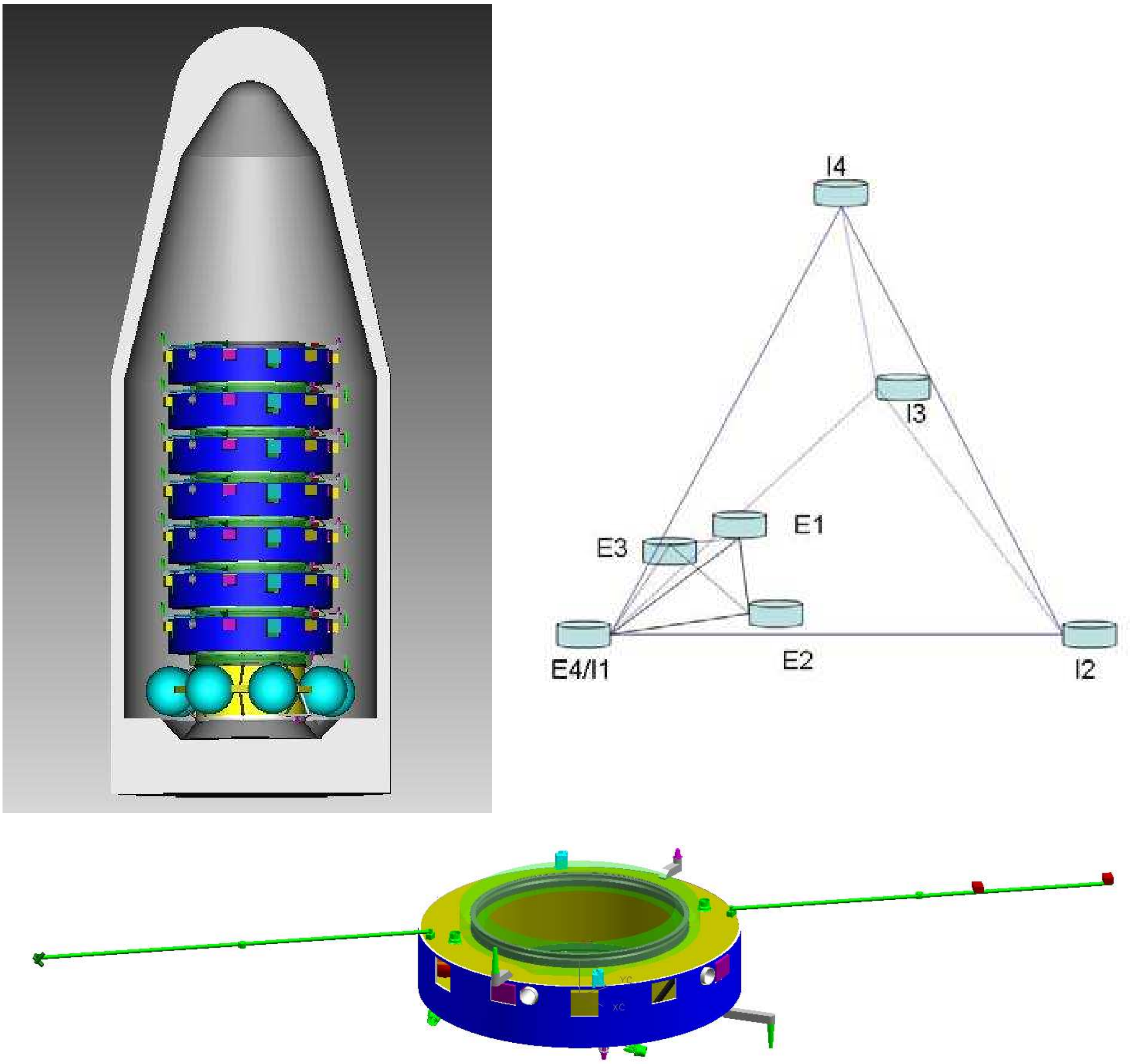


Figure 1-1 The Cross-Scale Assessment Phase reference design

The piled configuration in launch and cruise (top left) with seven science spacecrafts onto a Propulsion Module is more performing mass-wise thanks to the low structural index of the central tubes, cost-wise thanks to lower propulsion costs and schedule-wise thanks to the seven identical platforms. No Moon-gravity assist is needed. Once close to operational orbit, the lowest science spacecraft commands the gradual separation of the other elements. The seven science spacecrafts (bottom) adjust their orbit to the final value, forming the constellation (top right). They are all, by design-to-schedule, reconfigurable on ground at anytime from any payload configuration to any other, ensuring very robust programmatics.

2. STUDY CONSORTIUM

Thales Alenia Space, Deimos and OHB have brought all the background and expertise needed to perform the requested activities. TAS and Deimos have acquired the full understanding of the stakes of the mission thanks to the TRS awarded by ESA in 2006, while TAS and OHB have unequalled experience in Europe for the production of large series of recurring spacecrafts, through Globalstar, Spacebus, SarLupe and Orbcomm.

The consortium of this assessment of the Cross-Scale mission has relied on highly relevant partners, as recalled in figure 2-1:

TAS as a major player of Space Industry has been especially qualified for leading this Study and has in particular:

- an expert knowledge of the Cross-Scale context through a key role in the previous ESA's Technology Reference Study;
- a capacity to produce recurring spacecrafts that is unequalled in Europe, with Proteus, MSG , Spacebus and Globalstar programmes organized so as to develop, manufacture and test large series of identical satellites in extremely short time frames
- Deimos has been in charge of the Mission analysis and mission-related tasks, bringing the expertise gained earlier by leading ESA's Cross-Scale Technology Reference Study.

OHB has intervened essentially in the detailed design phase for the physical architecture of the Science spacecrafts, as well as their structure, thermal control, harness and propulsion subsystems; OHB's experience from the production of the low-cost recurring satellites of SarLupe and Orbcomm has been benefited from.

In addition, Doctor Munsmann has been consulted for his unique expertise of magnetic cleanliness, gained in the frame of Cluster, and of key importance for this Assessment Study.

Galileo Avionica has been consulted too for their knowledge of Star Mappers, a key technology for Cross-Scale..

Thales Alenia Space has demonstrated its capability to handle complex science missions from Huygens to Herschel/Planck, to produce series of spinner satellites like MSG and has a unique position in Europe for the design and manufacturing of large constellations of satellites like Globalstar in short time frames

ThalesAlenia Space

- Study management
- Mission and system design
- Composite design
- Science spacecrafts functional design

Cross-Scale System Study

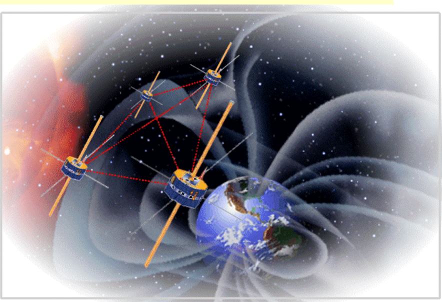
deimos space

- Mission analysis
- Orbits geometry and maintenance
- Debris mitigation

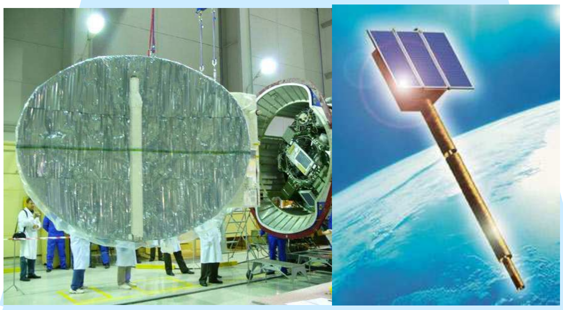
OHB SYSTEM

In phases 2, 3 :

- Science spacecrafts physical design
- Science spacecrafts mechanical, thermal, propulsion, harness S/S



Deimos experience in mission analysis has been benefited from by ESA over many studies, including the Cross-Scale TRS achieved in partnership with TAS



This study has benefited from OHB's experience in designing and producing the series of low-cost recurring satellites of SarLupe and Orbcomm

Figure 2-1 : *The industrial team organisation has combined the prime contractor's experience of Thales Alenia Space with the skills of Deimos for mission-related topics and OHB for production of series of low-cost constellation satellites. Two consultancies have complemented the expertise of the key technical factors, on magnetic cleanliness and star mapping.*

3. COMPLETED ACTIVITIES AND GENERATED DOCUMENTATION

The activities have followed the study logic specified in the statement of work. They converged in three steps after trading options, selecting a baseline and generating all the elements enabling the in-time evaluation of the mission by the Cosmic Vision selection process in 2009.

The activity was kicked off on July 3rd 2008 [RD18]. The Concept Design phase then included two work packages to be run essentially in series:

- WP 1 – Requirements assessment and constraints analysis and consolidation
- WP 2 – Alternative mission architectures, final trade-off and baseline mission definition

WP1 reviewed the documentation provided at kick-off and performed a review of the available mission analysis as well as the environment analysis. The PM1 [RD19] was held on September 3rd 2008 and served as Requirements Review. WP2 then reviewed and selected the mission architecture. At the end of this WP2, the second progress meeting [RD20] was held on November 5th 2008, served as a Mission Architecture Review and concluded the first phase.

After the selection of the Cross-Scale mission architecture, the Detailed Design phase refined the level of definition of the mission architecture and of the elements and built a development plan. It included two work packages:

- WP 3 – Detailed spacecraft and composite design
- WP 4 – Procurement & AIV philosophy and payload programmatics

WP3 established a detailed system design of the Cross-Scale mission. After several months of progress in the Detailed Design phase, PM3 [RD21] was held on February 4th 2009. WP4 started in parallel with the end of WP3 so as to establish the development and demonstration plan and mission programmatics. At the end of WP3 and 4, on May 13th 2009, a Detailed Design Review [RD22] was held, concluding the second phase of the Study.

The last phase completed the study by costing and scheduling the mission and finalizing the documentation. It included:

- WP 5 – Detailed Costing & Overall Mission Programmatics
- WP 6 – Final report

WP5 analyzed the industrial cost of the space segment, as defined by the Detailed Design Review. A Final Presentation [RD23] occurred on June 3rd 2009. Then WP6 covered the compilation of the final report, consisting of a consistent update of all technical documentation produced in the previously outlined sections, as well as the closeouts from the Final Presentation.

The documentation generated is listed in annex 2. All actions have been closed, as reported in document [RD17].

The study has thus generated the elements supporting a decision by the Cosmic Vision mission selection process by mid-2009.

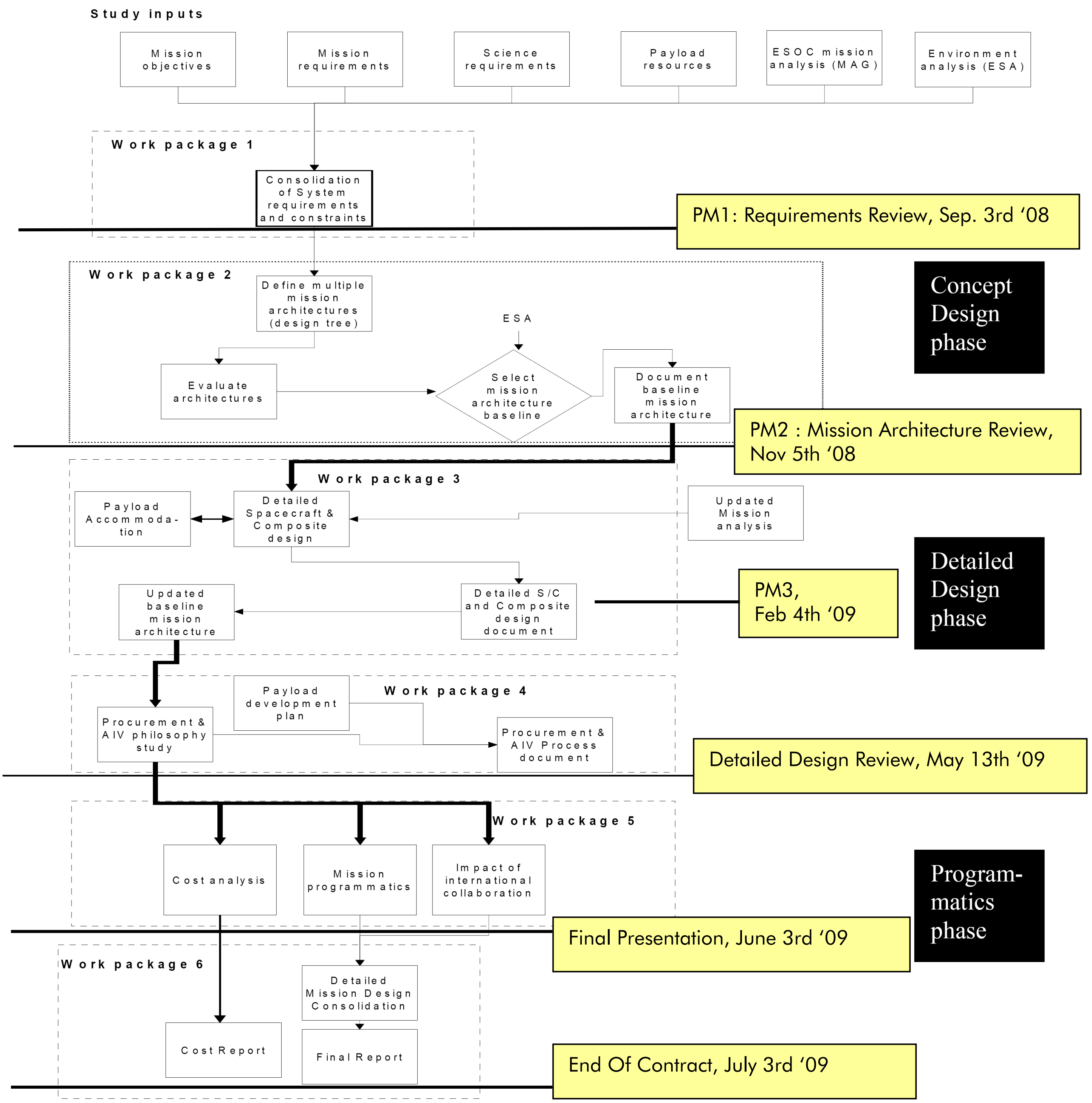


Figure 3-1: Study logic and milestones of the Assessment Phase

The Assessment Phase has provided ESA with all the necessary elements to consolidate the technical, programmatic and cost feasibility of the mission

4. SYSTEM ARCHITECTURE AND REFERENCE DEFINITION

We summarize here the reference definition and its justification. The reader looking for more details is invited to read the Detailed Design Report [RD15], the natural entry point into the technical documentation.

4.1 Drivers

Seven spacecrafts have to be launched towards a [10Re; 25 Re] 14° orbit, through a single Soyuz launch, and the equipment and sub-systems TRL has to be at least 5. The solution has to be mass optimum, while re-using at maximum existing equipments. The review of the requirements carried out in [RD9] identifies a set of System Design Drivers that impact the Cross-Scale optimum design:

- A high TRL
- A single Soyuz launcher, for a set of 7 satellites
- A design adapted to a small series production

Secondary drivers are identified too, especially for power supply via payload consumption, and for thermal design via the need for two satellites to be tilted by 20°.

4.2 Mission design

4.2.1 Launch

The spacecrafts are launched by Soyuz, from Kourou SFC. The seven science spacecrafts (also called "satellites" or S/C) are piled onto a propulsion module (PM). The satellites and the PM are inert, excepted for a minimum TM data flow. The launch phase injects the pile into a typical orbit of [218 km; 5,3 Re] 4° inclination, 205° argument of perigee. At injection the standard Soyuz spin mode is used at a rate of 4 round per minute along the longitudinal axis of the pile and of Fregat. The separation from the launcher occurs at the interface between Fregat and the PM.

At the end of the launch sequence the cruise phase starts. The launch and cruise strategy does not require the more complex moon gravity assistance. Moon gravity assisted sequence is compatible of the present design as well, but the piled configuration we have selected allows, as confirmed in the present study, a mass budget that is compatible with the simpler "direct" insertion.

4.2.2 Cruise

The whole pile performs the cruise as a single assembly, where the command/control chain of Satellite#1 ensures the control. Satellite#1 is the science spacecraft located immediately above the PM. The PM provides the propellant, the main thrust engine as well as the torque-control thrusters assembly. The typical duration in cruise is 4 to 10 days. Communications are ensured by the Satellite#1 TM/TC chain, with the use of two antennas located on the PM. The insertion into the operational orbit is performed by apogee rising followed by perigee rising manoeuvres, by activation of the 420N thruster of the PM.

During the cruise, out of the thrust manoeuvres, the pile is spun at 4 rpm, maintaining the longitudinal axis of the pile orthogonal to the sun direction. This orientation ensures the nominal sun flux on the Satellite#1 solar array, as well as on the other six satellites. A minimum activity is maintained on the six other satellites so as to provide for their heating budget during the cruise.

At the end of the cruise, the upper six satellites are released one after the other, before the separation between Satellite#1 and the PM. The separation strategy that maintains the solar array illumination at the maximum is preferred, mainly because it is easier to achieve the compliance of thermal control and power supply during the sequence. The satellite attitude with respect to sun is indeed close to the nominal attitude, allowing not to size the spacecrafts by the cruise hence a more optimal design.

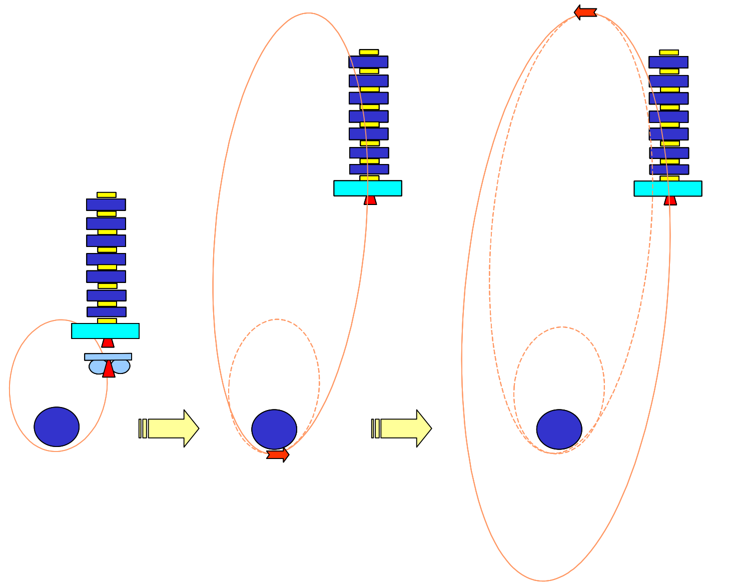


Figure 4-1 Launch and cruise. Piled configuration

After launch into the injection orbit [300 km ; 5 Re] (left), the pile of 7 satellites plus PM cruises towards the final insertion orbit, reached after apogee rising manoeuvre(s) followed by perigee rising manoeuvre(s)

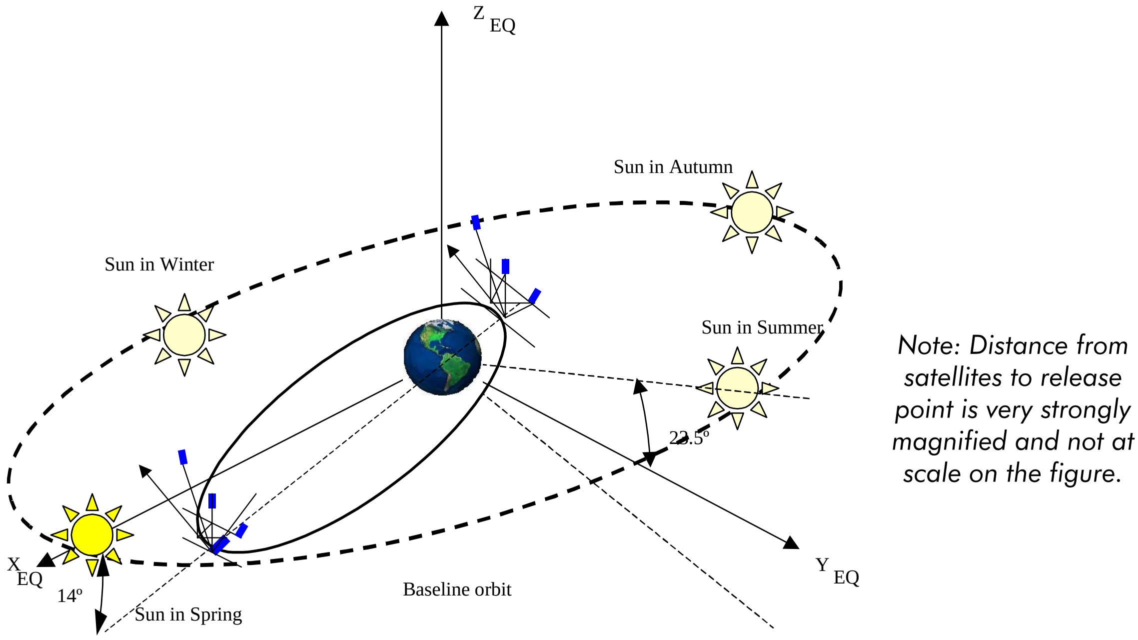


Figure 4-2 Schematic of a typical insertion

At apogee a first sub-set of satellites is released from the pile. A succession of pile reorientations for each release provides for the differential velocities between the satellites and versus the pile. The orientation can be selected so as to maximize the sun flux orthogonal to solar array and prevent sun flux on satellites lower panels. The set of reorientations will depend on the date.

The separation assembly and mechanisms are standard, with SAAB/RUAG heritage. The activation of the separation mechanism is initiated by ground TC sent to Satellite#1, and the pyro signals travel from Satellite#1 to the concerned satellite. Standard separable connectors ensure the link at separation planes.

After separation the satellites drift apart from each other and from the pile (and from the PM) under the relative velocity, which has been impulsed by the springs of the separation mechanism. During all the sequence, the satellites are spun at 4 rpm, directly resulting from the pile spin. At typical drift of 1 m/s provides a separation of 1 km after 15 minutes, at which point thrusters activation will be performed to put each satellite in the exact nominal attitude.

A first health-check sequence of the satellite functional chain is performed, after which the tetrahedron(s) formation is reached by proper thrust manoeuvre of each satellite, at a typical cost of 1 m/s. The deployment of the wire-antenna and the activation of the payload(s) are then performed during the following IOT sequence.

4.2.3 Operational mission

During the operational mission the satellites perform continuously the science measurements, storing on-board the science data. Each satellite ensures its independent command-control and downlink communications with the ground station, while down-link uses a coordinated TDMA schedule between the seven satellites. The communication link can be proposed in X-band or in S-band. Although X-band is more penalizing for the mass budget, getting bandwidth in S-band would require extended interpretation of the regulation rules. To be conservative in the present phase of the program, our baseline design is presented in X-band, and the two options have been derived up to the identification of equipment units.

The satellites are spun at a nominal rate of 15 rpm this phase, which is compatible of the existing Galileo-Avionica existing star-tracker pending an adaptation of the software. All satellites except E1 and E3 are tilted by 5° versus the ecliptic so as to keep the electrical antennas permanently out of the shadow of the spacecraft. E1 and E3 are tilted by 20°. The configuration manoeuvres are performed during the mission, so as to modify the size of the tetrahedron. Note that this study has examined a set of seven satellites, with tetrahedrons sharing the same e-scale satellite at one corner. The analysis of shared mission with additional JAXA satellites can be read in the technical note [RD13], where the main conclusion is that the seven ESA satellites design can be maintained without significant change in their design.

4.3 Design-to-schedule

As soon as in this assessment phase, strong “design-to-schedule” requirements have been generated by the Consortium and implemented, so as to ease the development and minimize the cost.

4.4 Physical design and configurations

4.4.1 Composite

Following the configuration trade-off, the selected launch configuration is a pile comprising from launcher interface to the top:

- A Propulsion Module (PM)
- Science spacecraft #1
- Science spacecraft #2
- Science spacecraft #3
- Science spacecraft #4
- Science spacecraft #5
- Science spacecraft #6
- Science spacecraft #7

All these eight elements are connected by seven identical separation subsystems. A volume has to be kept free between the elements for the operations of clamp-band installation and tightening: this volume specification has been implemented in the study. The design is such that the allocation of the payload sets (e1, e2, e3, i1/e4, i2, i3 and i4) to the spacecrafts and the order in the pile is free, and can be modified at any time in the manufacturing and integration sequence.

The accommodation inside the Soyuz fairing presents ample margins, allowing growth potential both in height and width if need be. It is illustrated in figure 4-3 below.

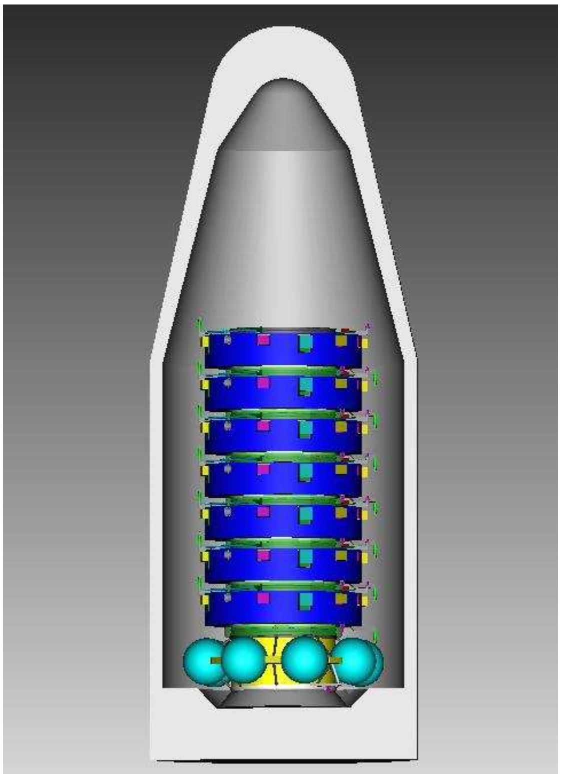


Figure 4-3 Composite configuration and accommodation in Soyuz fairing
Ample margins are available in width and height.

4.4.2 Science spacecrafts

The configuration of the seven science spacecrafts is identical and based on a central tube design with a standard 1666 mm diameter. The main spacecraft dimensions are driven by the power requirement as well as volume constraints on spacecraft level and from the launcher. The accommodation is optimised to fulfil the system re-configurability requirement.

The structural concept of the Cross-Scale spacecraft is a central tube design (diameter 1666 mm) with a surrounding solar generator as typical for a spinning spacecraft. Payload instruments are accommodated inside the spacecraft ring and the mandatory protrusion is guaranteed by provision of appropriate cutouts in the solar generator. All spacecraft bus units are accommodated inside the spacecraft as well, except for antennas, thrusters, etc…

The concept is presented in figure 4-4, in stowed configuration and with superposition of payload instruments sharing the accommodation position for the different payload configurations of the different satellites of the constellation. The main spacecraft dimensions are depicted in figure 4-5. The outer diameter is 2.45 m and the spacecraft height is 0.5 m. These dimensions are driven by the power demand of the spacecraft in combination with the volume requirement for the accommodation of payload instruments and bus components as well as by the volume constraints from the launcher fairing.

Each spacecraft is by design reconfigurable on ground from any payload configuration to any other one, bringing both cost savings by preserving the recurrence of the platform, and schedule robustness by enabling late payload arrival and management of anomalous payload schedule. This strong design-to-schedule requirement is of major importance when building this development plan, especially when addressing the series production.

Moreover, the proposed baseline architecture for the spacecrafts includes two modules per spacecraft:
- The **Upper Module**: Structure and Thermal control (excepted lower panel), Propulsion
- The **Lower Module** (or "base deck"): Lower panel equipped with all platform electronics, all payload, harness and local thermal control

They are assembled onto each other and are then complemented by the mounting of the Solar Array panels on their periphery. The Solar Array panels (MSG-type) are dismountable at any time, ensuring accessibility to payload and platform units at every phase of the AIT/AIV.

The Cross-Scale mission involves a constellation of seven satellites with different science payload configurations in accordance with the Payload Definition Document that divides the seven satellites into five different payload configurations. All science payloads are accommodated fulfilling a number of requirements with respect to:
- Angular separation of payload units of the same type and of different types
- FOV requirements including avoidance of FOV intrusion for different instruments
- Avoidance of contact between mechanical/supporting payload parts
- CoG trimming of payload as part of overall spacecraft CoG trimming
- Position sharing between payloads to reduce the total cut-out area of the solar generator as well as to maximise the volume available for the accommodation of the spacecraft bus units

The payload configurations E1 and E2 contain the highest number of science instruments, which have the highest mass and volume needs and drive the cut out-factor in the solar panel. Thus, E1 and E2 mainly drive the accommodation of the spacecraft bus components in terms of available volume and locations.

The other payload configurations use the solar generator cutouts, which are driven by E1 and E2 as consequence of the re-configurability requirement on spacecraft level.

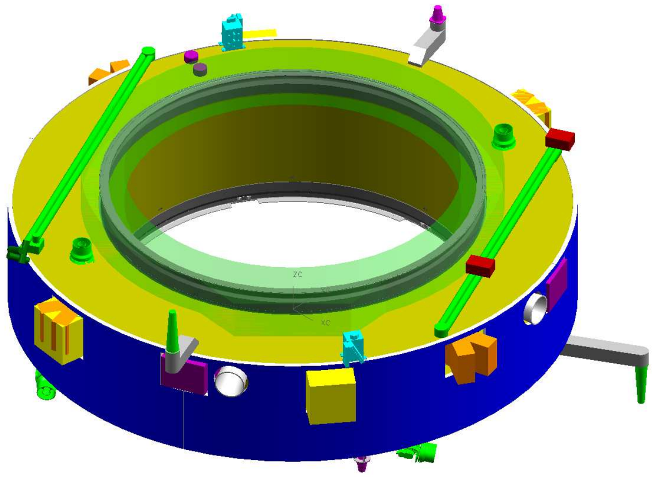


Figure 4-4: Cross-Scale satellites design concept (launch configuration)

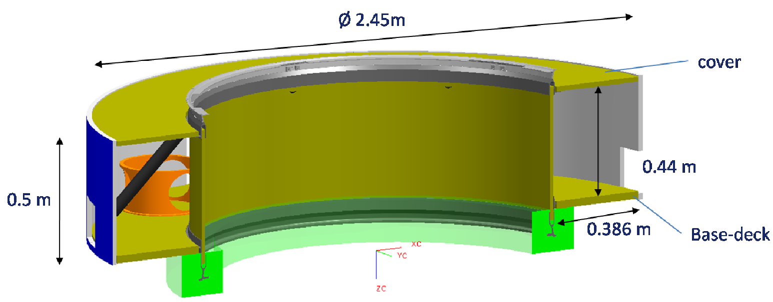


Figure 4-5: Main dimensions of the Cross-Scale satellites

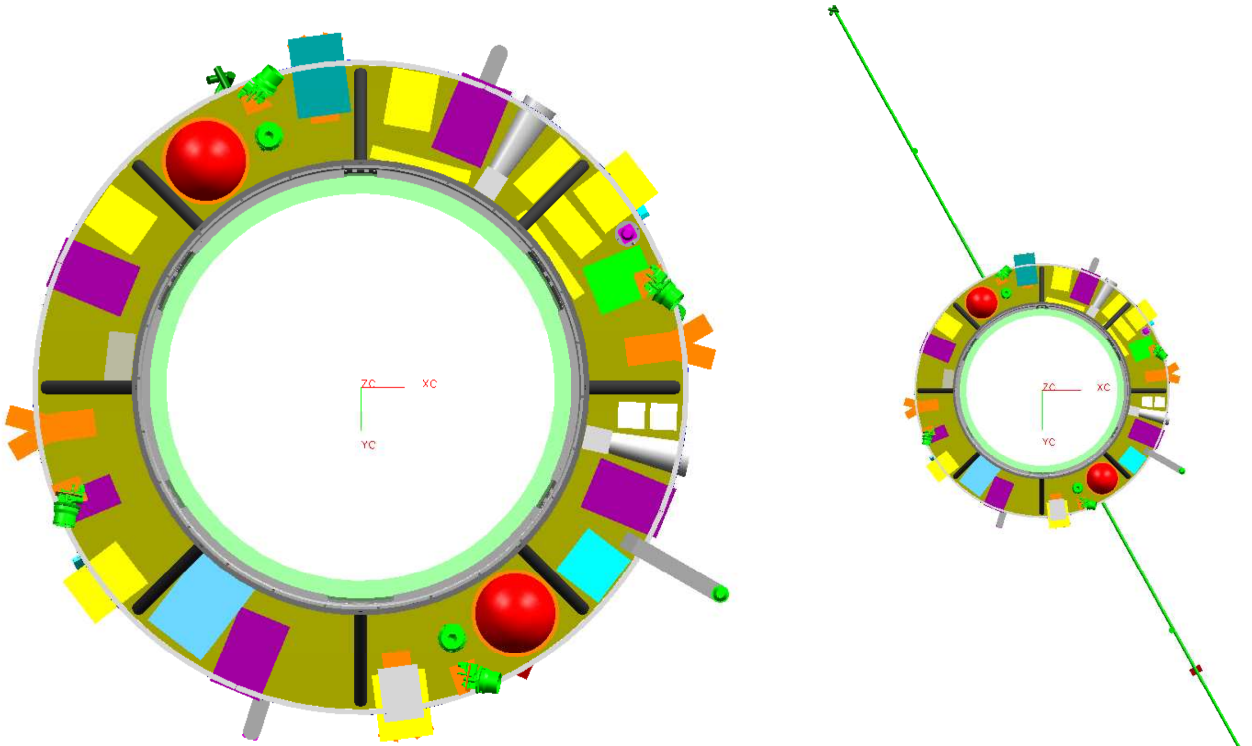


Figure 4-6 Accommodation of payload and platform units

The figure presents the superposition of all science payload configurations including the spacecraft bus components. The available volume and locations for the units is well visible, showing how we achieve the re-configurability versus the seven payload sets, preserving schedule and costs. The grouping of units is mainly driven by the centring requirements.

4.4.3 Propulsion Module

The Cross-Scale propulsion module is based on the central tube concept as result of the overall mission composite architecture. The selected concept is simple and mass efficient.

The design of the Cross-Scale propulsion module is based on a 1666 central tube, surrounded by 8 propellant tanks. The fixation of the propellant tanks is realized by a tank support panel, which is stabilized by rods. A deck inside the central tube is included to accommodate the PCA and PIA assemblies. The two boxes shown in the figures on the PCA/PIA deck represent the volume needs by the two assemblies.

On the lower side of the PCA/PIA deck two pressurant tanks are accommodated. The level of the PCA/PIA deck is chosen in a way to prevent the PIA and PCA components to protrude the separation plane to the first satellite of the Cross-Scale stack. The main engine is placed on the launcher separation plane. Its protrusion is in line with the respective volume offered by the Soyuz/Fregat launcher adapter.

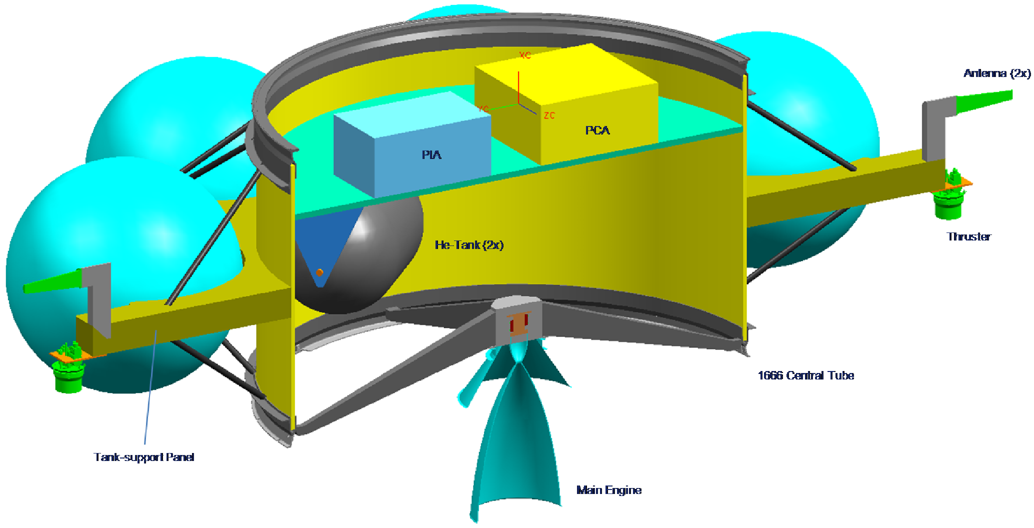


Figure 4-7: Cross-Scale propulsion module accommodation

The Propulsion Module is built in continuity of the stack of science spacecrafts, minimizing the mass.

4.5 Functional design

The centralized functional architecture minimizes the number of units, eases the control of the functional validation and enables to benefit from Sentinel3 heritage. The maximization of the recurrence and the need to reduce risks command to use the inherited subsystems and units most adapted to the technical challenges:

- LISA and GAIA RF subsystem
- SPIRALE power management unit
- Solarbus Solar Array's cells
- New Horizons Star Tracker from Galileo Avionica
- Data handling from a Thales Alenia Space product line (the one used for GMES Sentinel 3), able to interface RF, power, AOCS subsystems, instruments

Their arrangement as a consistent architecture is illustrated in figure 4-8. The recurrence from previous (or on-going) programs is privileged whenever most adapted. This is clearly the case for the RF and power subsystems. For AOCS, the main equipment units are recurrent (in particular the STR). A low number of

modes make a simple AOCS units set appealing, which is compatible of the large variation of inertia between separation and deployment of the wire antenna .
The data handling shall subsequently have enough flexibility to interface such power, RF and AOCS subsystems from different heritage, along with a large number of instruments. It shall be low-cost, available from a product line well in place in 2012-2016 when Cross-Scale is built. This led to select the Thales Alenia Space roadmap avionics that is applied on GMES Sentinel 3.

The Data Handling Subsystem controls the functional coherence of the satellite and will be based on the following major elements:
• A computer, called 'Satellite Management Unit' (SMU), managing all the satellite platform and payload elements
• A Solid State Memory, (SSM), collecting and storing the science packets issued by the instruments

The SSM has been sized with Cross-Scale mission profiles and data link budget.

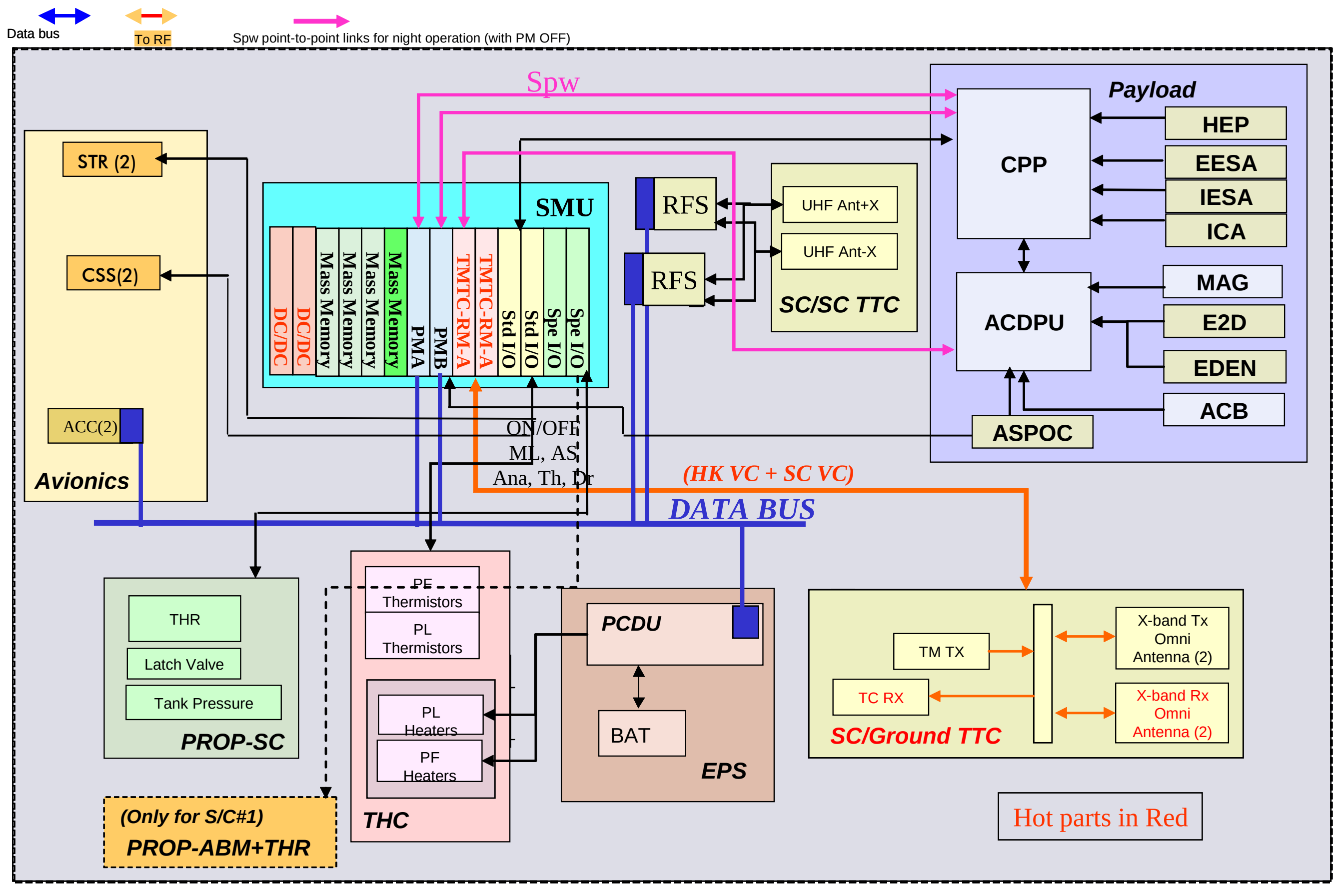


Figure 4-8 Functional architecture : implementation

The figure illustrates the implementation of the functional architecture. The computer SMU and the mass memory SSM are implemented in a single box. The CPP unit collects the payload science data. A SpaceWire bus ensures the link between the CPP and the SMU. The computer from TAS product line has the capacity to interface the payload and the other platform units preserving their respective heritages.

4.6 Justification of the reference design

The design results from an extensive set of justifications, whether in the form of trades as performed in Work Package#2, or in the form of analyses or budgets in Work Package#3.

4.6.1 Summary of trade-offs

The trade-offs covered during the study are identified in figure 4-9. The solutions retained are framed in green in the figure. The main conclusions are the following:

Composite:

- The configuration trade-off, summarized in next page in figure 4-10, led to select 7 identical spacecrafts with light and cheap hydrazine propulsion, borne to their orbit by a bi-propellant propulsion module,
- The separation strategy is: each S-C is separated from the pile, the pile is in slow spin (4 rpm), and the separation consists in a linear translation ensure by a standard assembly separation mechanism. The control of the pile is ensured by the Satellite#1 located just above the Propulsion Module.
- The GNC is ensured by a Star sensor on satellite#1 which is the same sensor as for the Spacecraft in science orbit.
- The composite propulsion configuration makes use of off-the-shelf tanks. The selection rationale starts from the propellant required mass, as determined from launcher capability, and infers the minimum mass of identical tanks capable of the identified propellant mass.

Constellation:

- The inter satellite distance measurement uses an RF-sensor on-board the 4 e-scale satellites.
- The command control is distributed: each satellite has its own dedicated link to ground.
- The data return is distributed too: each satellite has its own dedicated data link to ground
- The link from/to Spacecraft to ground can be proposed in S-band or X-band. Our current design selects the X-band solution, although it is the most demanding in terms of mass and power, mainly because the compatibility with RF ITU regulation is immediately met in X-band.

Science spacecrafts:

The spacecraft configuration trades have been conducted for both the science spacecrafts and the propulsion module. They have supported the detailed design of each subsystem.

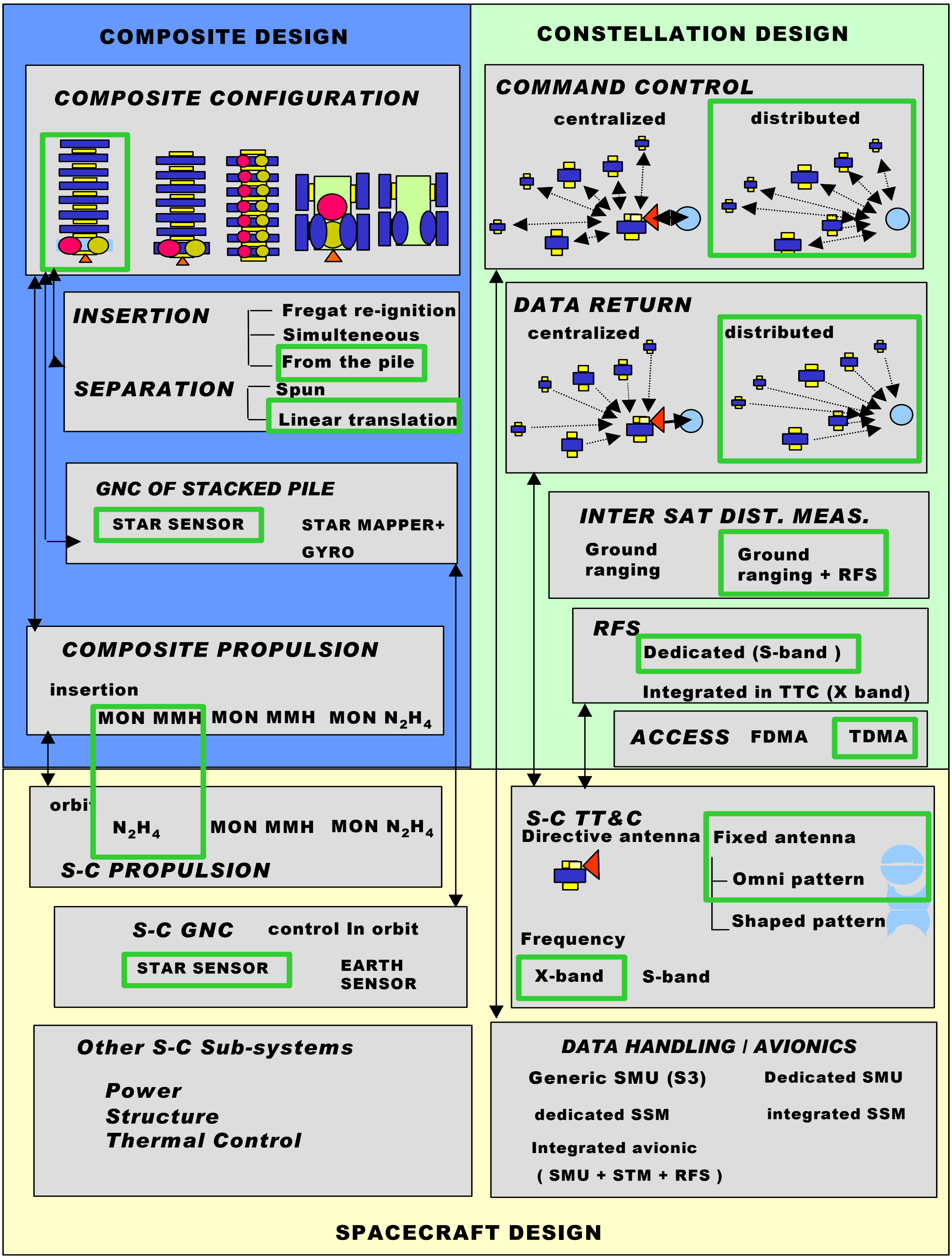


Figure 4-9 Overview of trades

The trade elements are identified for the three system fields: Composite, Constellation, and Spacecraft. The selected solutions are framed in green

Configuration trade-off

A wide spectrum of solutions has been reviewed for the mission architecture concepts through three main steps, summarized in figure 4-10 opposite:

- step 1 short-listed two configuration cases out of the initial four envisaged (labelled cases 1 to 4)
- step 2 identified sub-cases of cases 1 and 2, and selected the variants of case 2 in 1666mm diameter
- step 3 finally baselined one of the 1666mm variants where the spacecraft controlling the pile jettisons the bi-propellant propulsion

We eliminated case 3 and 4 in step 1 for cost and mass reasons, plus fairing accommodation issues in case 4. In step 2, the mass, development risks and cost have been compared for cases 1 and 2:

- Case 1 (seven "identical" spacecrafts, raising their orbits by their own):
  - The full identity of all seven spacecrafts could not be achieved with a Soyuz launch
  - The structure had to be differentiated and a high-Isp propulsion has to be used
  - The mass compatibility remains marginal for a Soyuz launch, below the 20% required system margin
- Case 2 (one mother spacecraft raising the orbit of the constellation, plus six daughter spacecrafts):
  - All 6 daughter spacecrafts and the upper part of the mother spacecraft could be kept fully identical
  - The mother spacecraft can be designed so as to differ only in its lower part for structure and propulsion, hosting one hydrazine subsystem for its orbital phase and using bi-propellant for cruise
  - The overall cost (non-recurring+recurring) is found lower in case 2 than in case 1

Case 2 ensures therefore the best margins vs Soyuz launch mass, being 300kg lighter than case 1, while providing for the lower overall cost by more than 5% of total with 7 satellites. This assessment on cost advantage remains valid even with a decrease in the total number of satellites to 6 or 5.

In addition, a generic design based on Spacebus practices can be achieved on Cross-Scale to master the variability between the seven payloads and spacecrafts. This minimizes costs and programmatics risks, by ensuring full reconfigurability/interchangeability between all spacecrafts functional modules, all units, all payload sets. This is a key success factor that ensures the control of non-recurring costs and of schedule.

In step 3, we had to secure the question of payload field of view accommodation that is an issue in case 2 if the spacecraft controlling the pile also hosts the bi-propellant propulsion). A version has been derived where the mother spacecraft jettisons its bi-propellant propulsion part, resulting in the selected configuration called "Case2_1". There, seven simple hydrazine spacecrafts are stacked on a carrier that bears the tanks and the ABM. This solution is typically 30 kg heavier than an integrated mother ship (labelled case 2_0). But in addition to securing the fields of view, the advantage is that all science spacecrafts remain identical, leading to a better cost and a safer schedule.

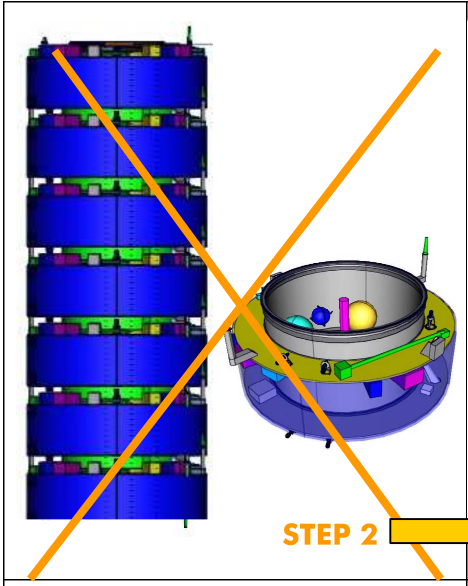
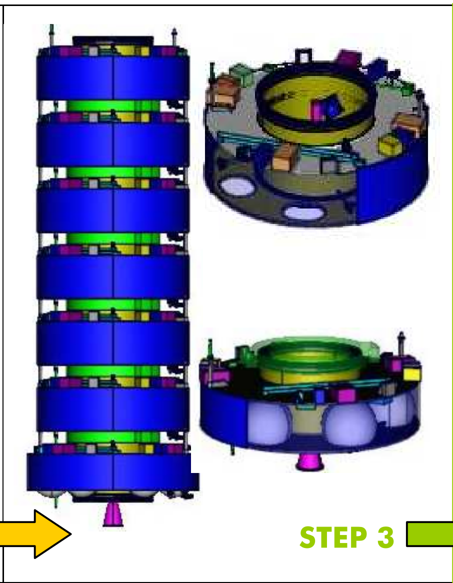
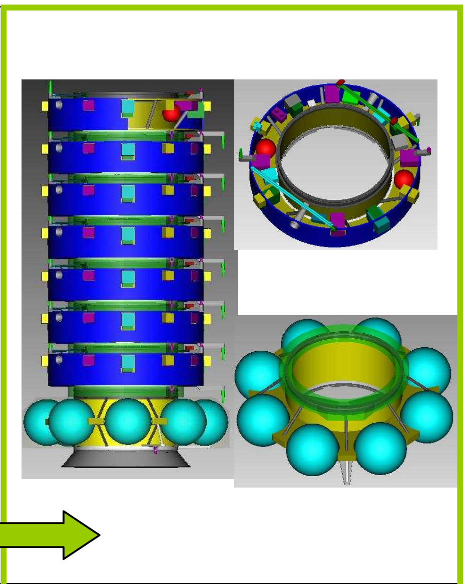
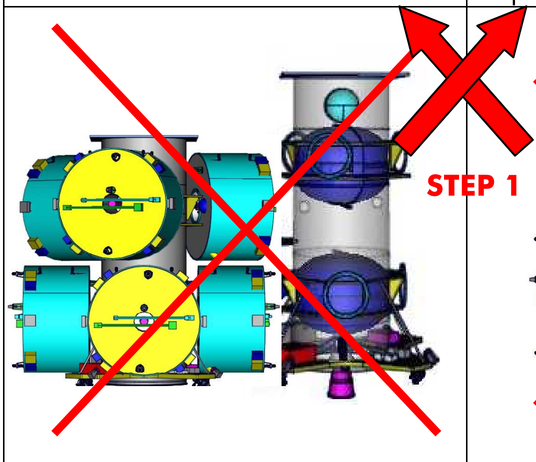
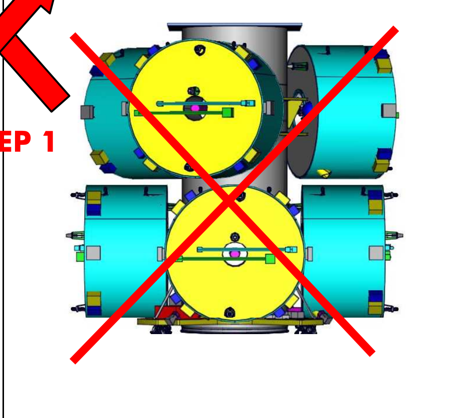
		
Case 1: 7 identical autonomous satellites (bi-propellant) stacked	Case 2 family: 7 stacked S/Cs with 7 hydrazine subsystems + 1 bi-propellant subsystem Sub-case 2_0 above is 6 identical satellites + 1 mother hosting the bi-propellant	**Case2_1: Variant with seven identical S/C (hydrazine), stacked on a jettisoned propulsion module (bi-propellant)**
		*Case1 is too heavy by 300 kg.* *Case3 is at higher cost and mass.* *Case4 is estimated not compatible of Soyuz (mass and accommodation)* ***Case2_1 is selected**.* *Case2_0 is compatible (lighter by 30kg but more expensive than Case 2_1).*
Case 3: 7 identical satellites (hydrazine) around a transfer module	Case 4: 7 identical autonomous satellites (bi-propellant) around an inert dispenser	

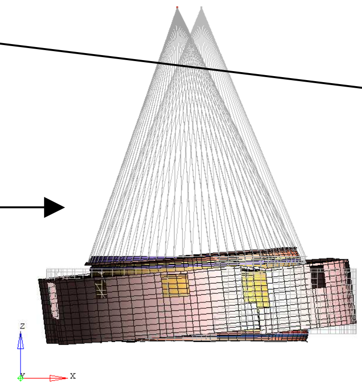
Figure 4-10 Traded configurations and selection

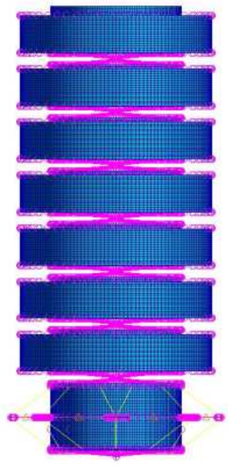
The first step of the trade down-selected cases 1 and 2 as the penalty in terms of cost and schedule induced by configurations 3 and 4 seem incompatible with the "300 M€ - 2017" programmatic frame. The second step then chose case 2 rather than case 1 for mass and cost reasons (deltas of 300kg and >5% respectively), and among case 2 variants, the ones with a 1666mm tube diameter to guarantee the feasibility of the band clamping. We finally selected in a third step a variant of case 2 where the spacecraft in control of the pile jettisons its bi-propellant propulsion module to form a standard science spacecraft: the induced mass penalty of 30kg due to the additional interface is accepted so as to favour instruments fields of view, and to benefit from the lowest cost and safest schedule brought by the identity of the seven science spacecrafts.

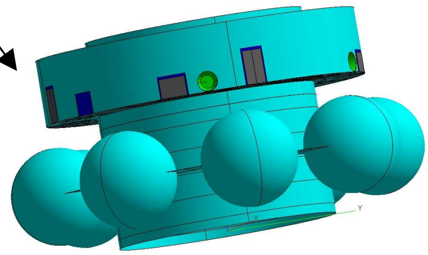
4.6.2 *Summary of analyses and budgets*

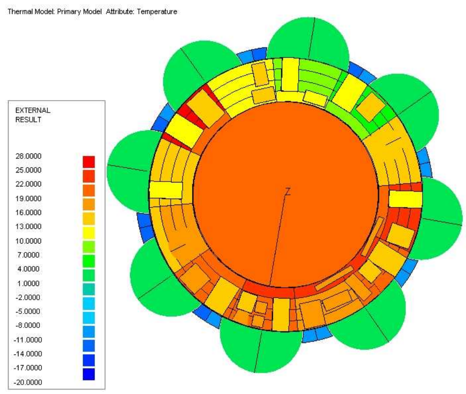
A comprehensive set of analyses have been run to justify the design, as presented in [RD15]. None of them has identified issues. They included:

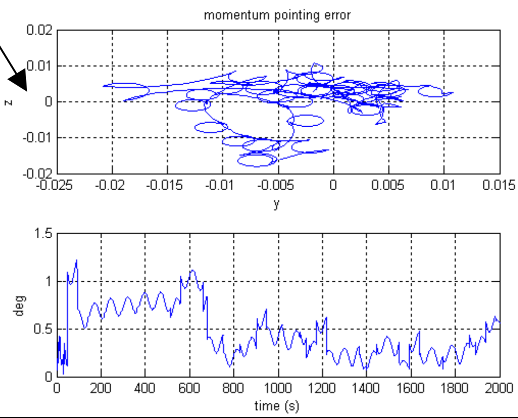
- the mechanical sizing of the pile, along with the specifications to the science spacecrafts
- the mechanical sizing of the spacecrafts and of the PM
- the thermal sizing of the spacecrafts and of the PM
- the sizing of the TTC
- the sizing of the RF sensor
- the sizing of the data handling
- the assessment of the control of the pile for AOCS
- the assessment of the control of the science spacecrafts AOCS
- the identification of the needs for magnetic cleanliness
- the PM pressure drop analysis
- the Orbit Design and Analysis
- the Launch and Transfer Analysis
- the Analysis of Separation and Relative Distance Evolution
- the Constellation Design and Analysis
- the Inter-S/C Localisation & Synchronisation Analysis
- …

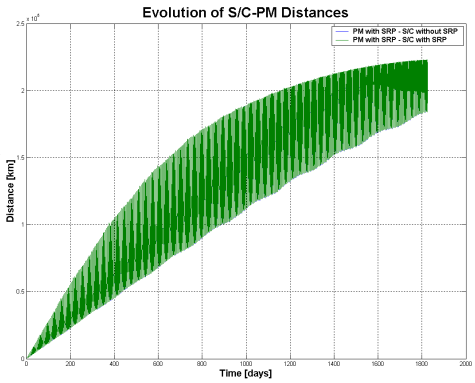


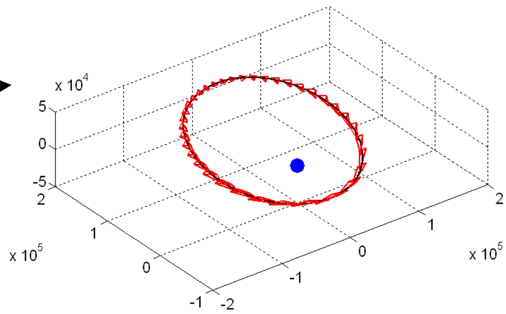












The budgets have been established for mass, power, communication link, pointing…

They all indicate the feasibility within the requirements of the MRD, complying with the specified margins.

In particular, the mass budgets margins have been established by comparing the assessed mass with mass allocations for the propulsion module and each spacecraft with averaged payload mass. These allocations are such that:

- the PM allocation of 1762.5kg (including launcher adapter)
- plus seven times the average allocation per spacecraft of 258kg (including the separation mechanism at each spacecraft lower interface),
- result in an overall allowed launch mass of 3568.5kg.

The margins in kg are displayed for the average science spacecraft and the Propulsion Module versus their respective allocation in figure 7-11.

The total system margin at launch is then 20%+1.7 % for the reference design, without moon gravity assist. Note too that we use a 400N for TRL reasons. The use of a 500N thruster would increase the mass margin, still avoiding the moon gravity assist.

Cross Scale		
Science spacecrafts		
Target Spacecraft Mass at Launch	**258**	**kg**
Below Mass Target by:	2,8	kg
nb of satellites	7	
Propulsion Module		
Target Spacecraft Mass at Launch	**1762,5**	**kg**
Below Mass Target by:	2,5	kg
nb of satellite	1	
Total Target Spacecraft Mass at Launch **launcher capability 3570 kg ; adaptor mass 73 kg**	**3497**	**kg**
Below Mass Target by :	**22**	kg

Figure 7-11 Overall mass budget: compatible with Soyuz

The satellite budget provides a slight additional mass margin above the required 20% system margin, showing the compatibility with Soyuz. The values for the science spacecraft are the average ones versus payload, RF sensor and propellant masses. In case of need for an increase in the allowable dry mass, we have back-ups such as the Moon Gravity Assist manoeuvres and/or the 500N thruster. None of them are currently needed with our design, which preserves respectively the operation cost and the TRL.

5. DEVELOPMENT AND PROGRAMMATICS

5.1 Early development

The delta-development of units for units with TRL<8 has been identified as encompassing:

- for the Star Tracker: a need for software adaptation plus a delta-qualification on QM
- for the RF sensor: a need for a refurbished EM/EQM from Formation Flying developments
- for the PCDU, the Solar Array and the Battery: a need for an early test campaign in two steps:
  - STEP1: With EM/EQM, measure magnetic cleanliness
  - STEP2: If needed, refurbish EM / EQM to implement back-wiring / magnetic cleanliness recommendations, and check functionality, performance and the magnetic cleanliness achieved

The computer and the XPND are being developed by other programmes.

Some early development is therefore desirable in the 2010-2011 period to minimize latter risks. We recommend anticipating unit-level delta-design in the Definition Phase. However, tests can be run after the implementation phase Kick-Off, meaning no need for expensive activities before the final selection of the mission.

5.2 Schedule

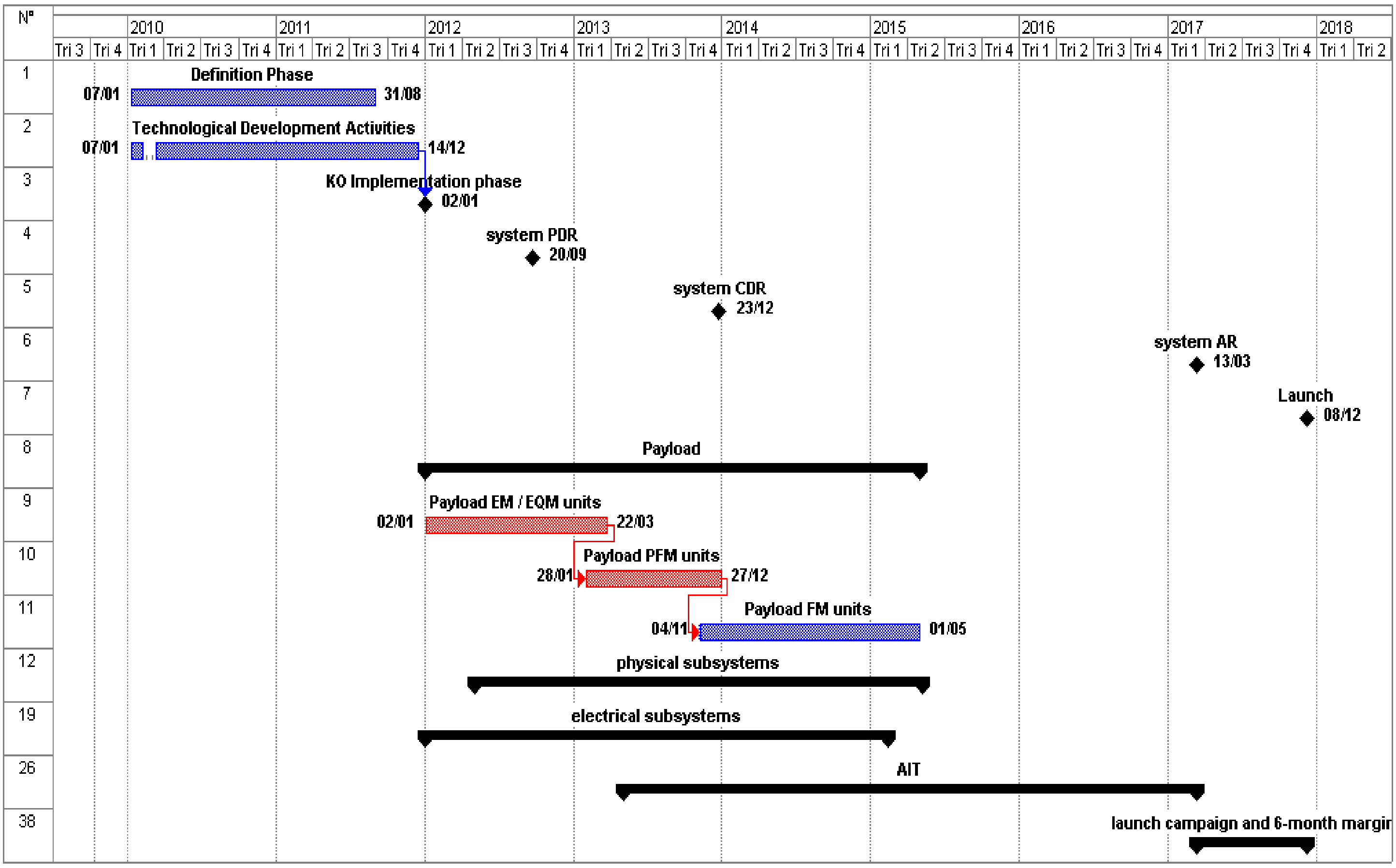
The development schedule is based on the general development philosophy described in document [RD16] with as main assumptions:

- The Implementation Phase starts in January 2012,
- The development of the instruments is carried out in parallel,
- Minor early development tasks are carried out in 2010-2011 (advanced definition effort for units with TRL 5 to 7), but no tests
- LLI can be ordered from beginning of 2012
- One contingency island of two month is added in the S/C elementary sequence
- The payload delivery dates for EMs/EQMs/PFMs/FMs defined in [RD16] are met

Under these conditions we succeed in providing a margin of 6 months with respect to a launch in December 2017. The payload is found to be on the critical path.

5.3 Costing

The preliminary ROM of the cost has been assessed. The reuse of off-the-shelf equipment and of heritage-secured designs, the identity of the spacecraft platforms and the design-to-schedule enable to keep reasonable values and to master the series effect by maximizing the learning curve factor.



The preliminary schedule complies with the target launch date of 2017 with a 6-month margin

Figure 5-1: Cross-Scale master schedule

6. CONCLUSION

The assessment study enabled to first analyse the mission requirements and drivers, evidencing the criticality of cost and the required mastery of the programmatics of a large series of satellites.

To reach a sufficient maturity in the definition of the mission, a number of options have been investigated and compared to come up with a reference mission architecture before refining this baseline.

The reference design includes seven reconfigurable science spacecrafts with identical platforms piled onto a Propulsion Module for their launch by Soyuz. This piled configuration in launch and cruise with seven science spacecrafts onto a Propulsion Module is more performing versus the other configurations, mass-wise thanks to the low structural index of the central tubes, cost-wise thanks to lower propulsion costs and schedule-wise thanks to the seven identical platforms. No Moon-gravity assist is needed as the compatibility with a regular insertion by Soyuz is obtained. Once close to operational orbit, the lowest science spacecraft commands the gradual separation of the other elements. The seven science spacecrafts adjust their orbit to the final value, forming the constellation.

A strong design-to-schedule has been implemented successfully, enabling to guarantee that all seven science spacecrafts are reconfigurable on ground at anytime from any payload configuration to any other. This ensures very robust programmatics, in particular versus potential issues in the series production of the payload.

The consortium achieved a detailed design of this baseline at all its levels (composite, constellation, spacecrafts, subsystems, critical units…) and a thorough justification whether in the form of trade-offs, budgets or analyses.

This detailed design has allowed to identify the TRL of the components and to subsequently establish a design and development plan, with programmatics and costing of the Cross-Scale mission.

This enables the evaluation by ESA of this mission, in the frame of the Cosmic Vision process, in view of a potential Definition Phase. By then, the consortium will keep its strong motivation and its experience of Cross-Scale so as to propose its services to the Agency for this Definition Phase, if ESA decides to proceed.

(page intentionally left blank)

ANNEX1: APPLICABLE AND REFERENCE DOCUMENTS

APPLICABLE DOCUMENTS

The following documents are applicable documents:

[AD 1] Cross-Scale Science Requirements Document, [SCI-SM-2007-11-CPE], Document providing Science objectives and science requirements, including measurement specifications

[AD 2] Cross-Scale Mission Requirements Document [SCI-PA/2007-020], Document providing the mission statement

[AD 3] Cross-Scale Payload Definition Document [SCI-PA/2008-005], Document providing preliminary mass and power budgets for the possible science payload configurations

[AD 4] CDF Model Input Specification Issue 3 rev 1, Ref: CDF-IFS-001, and associated Excel workbooks 'Mission Input Issue 3 rev 1.xls' and 'data exchange.xls'

[AD 5] Margin Philosophy for SCI-PA Studies, [SCI-PA/2007-022]

[AD 6] Cross-Scale Environmental Specification [SCI-PA/2007-021]

[AD 7] ESOC WP510 Cross-Scale Mission Analysis Global Orbit Properties, Issue 1.0

[AD 8] ESOC WP511 Cross-Scale Mission Analysis Transfer Using Moon Resonances, Issue 1.0

[AD 9] ESOC WP522 Cross-Scale: Mission Analysis Guidelines, Issue 1.0

[AD 10] European Code if Conduct for Space Debris Mitigation, Issue 1.0

[AD 11] Support to Implementation of the Code of Conduct for Space Debris Mitigation, Issue 1.0

[AD 12] ECSS-E-10 series, available from http://www.ecss.nl

[AD 13] ECSS-M-30A, available from http://www.ecss.nl

[AD 14] Arnaud Boutonnet, “Cross-Scale: Transfer to the Operational Orbit”, ESA, 01/12/2008

REFERENCE DOCUMENTS

The following documents are ESA reference documents:

[RD 1] Cross-Scale Technology Reference Study Summary; SCI-PA/2007/155/CS

[RD 2] Cross-Scale CDF study report CDF 69 (A)

[RD 3] Yuichi Tsuda et al., "Mission design of SCOPE – small satellites formation flying mission for magnetospheric tail observation," presentation at AIAA International Conference on Low Cost Planetary Missions, Kyoto, 2005

[RD 4] Comic Vision Presentation to Industry, F. Safa

They are complemented by the following reference documents:

[RD5] TAS-Cross-Scale-TN04, nov 2006

[RD6] TAS-Cross-Scale-TN05, dec 2006

[RD7] TAS-Cross-Scale-TN06, feb 2007

[RD8] Cross-Scale Mission Analysis Report XSCALE-DMS-TEC-TNO01-E (DEIMOS)

[RD9] Cross Scale TN1 requirements review [CS-TAS-TN 100289825E]

[RD10] Cross Scale TN2 Mission Architecture [CS-TAS-TN 100289826F]

[RD11] Cross Scale Star-sensor feasibility and development logic (from Galileo Avionica)

[RD12] Cross-Scale Refined Mission Analysis Report XSCALE-DMS-TEC-TNO02-E (DEIMOS)

[RD13] Assessment of implications of merging Cross-Scale with SCOPE [CS-TAS-TN-100337839R]

[RD14] Cross Scale Mechanical Requirements [CS-TAS-SP-100306867D]

[RD15] Cross Scale Detailed Design Report [CS-TAS-TN-100336506S]

[RD16] Plan for the design, development, procurement, manufacturing, integration and verification of the Cross-Scale space segment [CS-TAS-TN-100336505R]

[RD17] Cross-Scale Assessment Phase Final Actions List [CS-TAS-RP-100350225G]

The Minutes of Meeting of the Assessment Phase are referenced as follows:

[RD18] Kick-Off Minutes of Meeting [CS-TAS-MN-100267950C]

[RD19] PM1 Minutes of Meeting [CS-TAS-MN-100276811I]

[RD20] PM2 Minutes of Meeting [CS-TAS-MN-100289827G]

[RD21] PM3 Minutes of Meeting [CS-TAS-MN-100317758P]

[RD22] DDR Minutes of Meeting [CS-TAS-MN-100344009A]

[RD23] Final Presentation Minutes of Meeting [CS-TAS-MN-100344006U]

ANNEX2: DELIVERED ITEMS

WP	Deliverable documentation	Number as per SoW	DOC Code	Format	Contractor's Reference	Title
1	System requirements and constraints document	1.1	1_1	MS WORD	CS-TAS-TN 100289825E	Cross Scale Requirements Review
2	Identification of applicable mission architecture concepts	2.1	2_1	MS WORD	CS-TAS-TN 100289826F	Cross Scale Mission Architecture
			2_1a	MS WORD	XSCALE-DMS-TEC-TNO01-E	Cross-Scale Mission Analysis Report
3	Detailed design report	3.1	3_1	MS WORD	CS-TAS-TN-100336506S	Cross-Scale Detailed Design Report
			3_1a	MS WORD	XSCALE-DMS-TEC-TEC01-E	Cross-Scale Mission Analysis Summary Report
			3_1b	MS WORD	XSCALE-DMS-TEC-TNO02-E	Cross-Scale Refined Mission Analysis Report
			3_1c	MS WORD	G. Munsmann (Geonumerix)	Guidelines for Magnetic cleanliness on the Cross Scale Spacecrafts
			3_1d	MS WORD	Galileo Avionica	Cross Scale Star-sensor feasibility and development logic
			3_1e	MS WORD	CS-TAS-SP-100306867D	Cross Scale Mechanical Requirements
	Excel work sheets detailing budgets (delta-V, mass, volume, power etc.)	3.2	3_4&2	MS EXCEL	(merged with 3.4)	(merged with 3.4)
	CAD files of spacecraft design(s)	3.3	3_3a	CATIA format	CS DOC3_3a cs_daughter_bsl-assy_v06.zip	CAD model science spacecrafts
			3_3b	CATIA format	CS DOC3_3b cs_propulsion-stage_bsl-assy_v02.zip	CAD model Propulsion Module
	CDF model input	3.4	3_4&2	MS EXCEL	CS DOC3_4&2 data_exchange.xls	CDF model
	Spreadsheets according to [AD4]		3_4	[AD4]	(merged with 3.4)	(merged with 3.4)

WP	Deliverable documentation	Number as per SoW	DOC Code	Format	Contractor's Reference	Title
4	Technical note on procurement and manufacturing	4.1	4_1to5 §11	MS WORD	CS-TAS-TN-100336505R	Plan for the design, development, procurement, manufacturing, integration and verification of the Cross-Scale space segment
	Technical note containing detailed processes concerning AIV and P/L calibration	4.2	4_1to5 §8&12	MS WORD		
	Technical note on logistics of a large number of payload for integration on all S/C	4.3	4_1to5 §13	MS WORD		
	Technical note on mission programmatics, multiple S/C AIV philosophy and mass production issues	4.4	4_1to5 §14	MS WORD		
	Technical note containing detailed development plan	4.5	4_1to5 all§	MS WORD		
	Technical note on assessment of implications of merging Cross-Scale with SCOPE	4.6	4_6	MS WORD	CS-TAS-TN-100337839R	Assessment of implications of merging Cross-Scale with SCOPE
5	Detailed specification of cost analysis	5.1	5_1	MS WORD	CS-TAS-TN-100350221C	Cross-Scale Cost Analysis *[The document contains financial data and is therefore provided separately from the folder]*
			5_1a	MS EXCEL	CS DOC5_1a Cross-Scale Cost Analysis Filled Template.xls	Cross-Scale Cost Analysis Filled Template
6	Final Report (consisting of all previous consolidated TN and reports)	6.1	6_1	MS WORD	CS-TAS-RP-100350226H	Final Report
			6_1a	MS WORD	CS-TAS-RP-100350225G	Final actions list
	Executive summary		E_S	MS WORD	CS-TAS-TN-100350224F	Executive Summary
all	All presentations under this contract		(PMs)	MS PPT	(delivered separately)	
all	Mathematical models		7_1		CS DOC7_1 Cross-Scale Thermal models GMM_TMM.zip	Thermal models
			7_2		CS DOC7_2 CrossScale_FE-Models(issued_09-05-04).zip	Mechanical models

END OF THE DOCUMENT